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Design and Construction of Driven Pile Foundations

Reference Manual – Volume I



National Highway Institute

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| 16. ABSTRACT This manual is the reference text used for the FHWA NHI course Nos. 130221 Driven Pile Foundations – Design and Construction and 130222 Driven Pile Foundations – Construction Monitoring and reflects the current practice for pile foundations. The manual is also intended to serve as the FHWA's primary reference of recommended practice for driven pile foundations. The Design and Construction of Driven Pile Foundations manual is directed to geotechnical, structural, and construction engineers involved in the design and construction of pile supported structures. This manual is intended to serve as a practical reference of driven pile foundations. Volume I of the manual addresses design aspects including subsurface exploration, laboratory testing, static analyses, as well as specifications and foundation report preparation. Volume II covers construction aspects including dynamic formulas, wave equation analysis, dynamic pile testing, static load testing, Statnamic testing, Osterberg cell testing, as well as pile driving equipment, pile driving accessories, and pile installation inspection. Step by step procedures are included to facilitate use of most analysis procedures. | | | |
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U.S. - SI Conversion Factors

| From English | To SI | Multiply by | Quantity | From SI | To English | Multiply by |
|----------------------|-------------------|-------------|---|-------------------|----------------------|---------------------|
| ft | m | 0.3048 | Length | m | ft | 3.2808 |
| inch | mm | 25.40 | | mm | inch | 0.039 |
| | | | | | | |
| ft ² | m ² | 0.0929 | Area | m ² | ft ² | 10.764 |
| inch ² | mm ² | 645.2 | | mm ² | in ² | 0.0015 |
| | | | | | | |
| ft ³ | m ³ | 0.028 | Volume | m ³ | ft ³ | 35.714 |
| inch ³ | mm ³ | 16387 | | mm ³ | inch ³ | 61x10 ⁻⁶ |
| | | | | | | |
| ft ⁴ | m ⁴ | 0.0086 | Second Moment of Area | m ⁴ | ft ⁴ | 115.856 |
| inch ⁴ | mm ⁴ | 416231 | | mm ⁴ | inch ⁴ | 2x10 ⁻⁶ |
| | | | | | | |
| lbm | kg | 0.4536 | Mass | kg | lbm | 2.2046 |
| | | | | | | |
| lbm/ft ³ | kg/m ³ | 16.02 | Mass Density | kg/m ³ | lbm/ft ³ | 0.062 |
| | | | | | | |
| lb | N | 4.448 | Force | N | lb | 0.2248 |
| kip | kN | 4.448 | | kN | kip | 0.2248 |
| | | | | | | |
| lbs/ft | N/m | 14.59 | Force/Unit- Length | N/m | lbs/ft | 0.0685 |
| kips/ft | kN/m | 14.59 | | kN/m | kips/ft | 0.0685 |
| | | | | | | |
| lbs/in ² | kPa | 6.895 | Force/Unit- Area; Stress; Pressure; Elastic Mod. | kPa | lbs/in ² | 0.145 |
| kips/in ² | MPa | 6.895 | | MPa | kips/in ² | 0.145 |
| lbs/ft ² | Pa | 47.88 | | Pa | lbs/ft ² | 0.021 |
| kips/ft ² | kPa | 47.88 | | kPa | kips/ft ² | 0.021 |

U.S. - SI Conversion Factors (continued)

| From | To | Multiply by | Quantity | From | To | Multiply by |
|----------------------|-------------------|-------------|-----------------------|-------------------|----------------------|-------------|
| English | SI | | | SI | English | |
| lbs/ft ³ | N/m ³ | 157.1 | Force/Unit- Volume | N/m ³ | lbs/ft ³ | 0.0064 |
| kips/ft ³ | kN/m ³ | 157.1 | | kN/m ³ | kips/ft ³ | 0.0064 |
| | | | | | | |
| lb-inch | N-mm | 112.98 | Moment; or Energy | N-mm | lb-inch | 0.0089 |
| kip-inch | kN-mm | 112.98 | | kN-mm | kip-inch | 0.0089 |
| lb-ft | N-m | 1.356 | | N-m | lb-ft | 0.7375 |
| kip-ft | kN-m | 1.356 | | kN-m | kip-ft | 0.7375 |
| ft-lb | Joule | 1.356 | | Joule | ft-lb | 0.7375 |
| ft-kip | kJoule | 1.356 | | kJoule | ft-kip | 0.7375 |
| | | | | | | |
| s/ft | s/m | 3.2808 | Damping | s/m | s/ft | 0.3048 |
| | | | | | | |
| blows/ft | blows/m | 3.2808 | Blow count | blows/m | blows/ft | 0.3048 |

PREFACE

Engineers and contractors have been designing and installing pile foundations for many years. During the past three decades this industry has experienced several major improvements including newer and more accurate methods of predicting capacities, highly specialized and sophisticated equipment for pile driving, and improved methods of construction control.

In order to take advantage of these new developments, the FHWA developed a manual in connection with Demonstration Project No. 66, Design and Construction of Driven Pile Foundations. The primary purpose of the 1985 Manual was to support educational programs conducted by FHWA for transportation agencies. These programs consisted of (1) a workshop for geotechnical, structural, and construction engineers, and (2) field demonstrations of static and dynamic load testing equipment. Technical assistance on construction projects in areas covered by this Demonstration Project was provided to transportation agencies on request. A second purpose of equal importance was to serve as the FHWA's standard reference for highway projects involving driven pile foundations.

The original Manual was written by Suneel N. Vanikar with review and comment from Messrs. Ronald Chassie, Jerry DiMaggio, and Richard Cheney.

1996 Edition

After a decade of use, the Manual was updated in 1996. The manual was modified to include new developments that had taken place in the intervening years and to take advantage of the experience gained in using the Manual in the many workshops that were presented by Demonstration Project 66. The 1996 version of the Manual was prepared by Goble, Rausche, Likins, and Associates, Inc. under contract with the FHWA.

The authors' recognize the efforts of the project technical manager, Mr. Jerry DiMaggio, FHWA Principal Geotechnical Engineer, who provided invaluable guidance and input for the new manual. The authors' also acknowledge the additional contributions of the following technical review panel members of the 1996 manual listed in alphabetical order:

Mr. Chien-Tan Chang - FHWA
Mr. Tom Cleary - New Hampshire DOT
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Mr. Kerry Cook - FHWA
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The following individuals of the author's internal peer review team are also acknowledged for their technical advice and contributions in preparing the 1996 version of the manual.

Dr. Joseph Caliendo - Utah State University
Dr. D. Michael Holloway - InSituTech
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Lastly, the authors' wish to thank the following Goble, Rausche, Likins, and Associates, Inc. employees for their vital contributions and significant effort in preparing the manual: Ms. Barbara Strader, Ms. Beth Richardson, Mr. Scott Webster, Mr. Neil Harnar, Mr. Jay Berger and Mr. Joe Beno.

2006 Edition

The 2006 version of the Manual is the third major version of the manual and was prepared by GRL Engineers, Inc. under contract with Ryan R Berg & Associates, Inc. The 2006 version of the Manual was once again updated to include new developments that had taken place since 1996 and to again serve a dual purpose. First, as a workshop participant's manual for the FHWA's National Highway Institute Courses on Driven Pile Foundations, and second to serve as FHWA's primary reference of recommended practice for driven pile foundations.

The authors' again recognize the efforts of the FHWA project technical manager Mr. Chris Dumas, and of Mr. Jerry DiMaggio, FHWA Principal Bridge Engineer - Geotechnical.

The manual is presented in two volumes. Volume I addresses design aspects and Volume II presents topics related to driven pile installation, monitoring, and inspection.

Design and Construction of Driven Pile Foundations - Volume I

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LIST OF SYMBOLS

- A - Pile cross sectional area.
- A_b - Brown's regression analysis factor based on soil type.
- A_p - Pile cross section area at pile toe of an unplugged pile section.
- A_s - Pile shaft exterior surface area.
- A_{si} - Pile shaft interior surface area.
- A_t - Pile toe area.
- A_{tp} - Actual steel area at pile toe.
- B - Width of pile group.
- B_b - Brown's regression analysis factor based on soil type.
- B_d - Projected width of pile group at depth d .
- b - Pile diameter.
- b_f - Distance from midpoint of slope to centerline of embankment fill.
- b_o - Critical punching shear perimeter.
- C - Wave speed of pile material.
- C_f - Conversion factor for cone tip resistance to sleeve friction.
- C_c - Compression index.
- C_{cr} - Recompression index.
- C_d - Pile perimeter at depth d .

LIST OF SYMBOLS

- C_F - Correction factor for K_δ when $\delta \neq \phi$.
- C_N - Correction factor for SPT N value.
- C_s - Dimensionless shape factor.
- C_{sc} - Shaft correlation coefficient.
- C_{tc} - Toe correction coefficient.
- C_v - Coefficient of consolidation.
- c - Cohesion.
- c' - Effective cohesion.
- c_a - Adhesion or shear stress between the pile and soil at failure.
- c_u - Undrained shear strength or can be determined from $q_u/2$.
- c_{u1} - Average undrained shear strength around pile group.
- c_{u2} - Undrained shear strength below pile toe level.
- D - Pile embedded length.
- D_B - Pile embedded length into bearing stratum.
- D_r - Relative density.
- d - Depth.
- Δd - Length of pile segment.
- E - Modulus of elasticity of pile material.
- E_r - Manufacturers rated hammer energy.

LIST OF SYMBOLS

- E_s - Soil modulus.
- e - Void ratio.
- e_c - Eccentricity of applied load for free-headed pile.
- e_0 - Initial void ratio.
- F_{vs} - Reduction factor for vibratory installed piles.
- F_p - Plug mobilization factor.
- F_z - Largest factored axial load of the superstructure.
- f_s - Cone unit sleeve friction.
- $\overline{f_s}$ - Average cone unit sleeve friction.
- f'_c - Ultimate compression strength for concrete.
- f_n - Negative unit shaft resistance over the shaft surface area.
- f_{pe} - Effective prestress after losses.
- f_s - Positive unit shaft resistance over the shaft surface area.
- f_{si} - Interior unit shaft resistance.
- f_{so} - Exterior unit shaft resistance.
- f_y - Yield stress of pile material for steel.
- H - Original thickness of stratum.
- H_v - Maximum vertical drainage path in cohesive layer.
- h - Ram stroke.

LIST OF SYMBOLS

- h_f - Height of embankment fill.
- I - Moment of inertia.
- I_f - Influence factor for group embedment.
- j - Stress exponent.
- K - Ratio of unit pile shaft resistance to cone unit sleeve friction for cohesionless soils.
- K_c - Cone bearing capacity factor.
- K_h - Coefficient of horizontal subgrade reaction.
- K_o - Coefficient of earth pressure at rest.
- K_p - Rankine passive pressure coefficient.
- K_δ - Coefficient of lateral earth pressure.
- k - Slope of soil modulus.
- L - Total pile length.
- ΔL - Length of pile between two measuring points under no load conditions.
- M_u - Bending moment.
- M_x - Factored moment about the x-axis acting on the pile cap.
- M_y - Factored moment about the y-axis acting on the pile cap.
- M_y - Broms resisting moment of the pile.
- m_n - Dimensionless modulus number.
- m_r - Dimensionless recompression modulus number.

LIST OF SYMBOLS

- N - Uncorrected field SPT resistance value.
- N_{60} - SPT resistance value corrected for 60% energy transfer.
- N' - Corrected SPT resistance value.
- \bar{N}' - Average corrected SPT resistance value.
- N_b - Number of hammer blows per 25 mm.
- N_c - Dimensionless bearing capacity factor.
- N'_q - Dimensionless bearing capacity factor.
- N_t - Toe bearing capacity coefficient.
- n - Number of piles in pile group.
- n_1 - Empirical coefficient for calculating the coefficient of subgrade reaction.
- n_2 - Empirical coefficient for calculating the coefficient of subgrade reaction.
- P_m - P-multiplier for p-y curve.
- p - Soil resistance per unit pile length.
- Δp - Change in pressure.
- p_c - Preconsolidation pressure.
- p_d - Effective overburden pressure at the center of depth increment d .
- p_f - Design foundation pressure.
- p_i - Pressure.
- p_o - Effective overburden pressure.

LIST OF SYMBOLS

- \bar{p}_o - Average effective overburden pressure.
- p_t - Total overburden pressure, also effective overburden pressure at the pile toe.
- Q - Load.
- ΔQ - Load increment.
- Q_a - Allowable design load of a pile.
- Q_d - Dead load on a pile.
- Q_l - Live load on a pile.
- Q_m - Maximum allowable lateral working load.
- Q_n - Drag load on a pile.
- Q_u - Ultimate pile capacity.
- Q_{ug} - Ultimate pile group capacity.
- q_c - Cone tip resistance.
- \bar{q}_c - Average cone tip resistance.
- q_E - cone tip resistance after correction for pore pressure and effective stress
- q_{Eg} - geometric average of the corrected cone tip resistance over the influence zone.
- q_L - Limiting unit toe resistance.
- q_t - Unit toe resistance over the pile toe area.
- q_u - Unconfined compressive strength.
- R_f - Friction ratio or f_s/q_c .

LIST OF SYMBOLS

- R_s - Ultimate pile shaft resistance.
- R_t - Ultimate pile toe resistance.
- R_u - Ultimate soil resistance.
- S - Section modulus about an axis perpendicular to the load plane.
- SRD - Soil resistance to driving.
- S_t - Sensitivity of a cohesive soil.
- s - Estimated total settlement.
- s_b - Set per blow.
- s_f - Settlement at failure.
- T - Theoretical time factor for percentage of primary consolidation.
- t - Time for settlement to occur.
- t_{cap} - Thickness of pile cap.
- U - Displacement.
- u - Pore water pressure (neutral pressure).
- V - Volume of soil displaced per unit length of pile.
- v - Design shear stress.
- v_c - Nominal shear strength of concrete.
- W_c - Estimated weight of pile cap.
- W_g - Effective weight of pile/soil block.

LIST OF SYMBOLS

- W_s - Estimated weight of soil above pile cap.
- w_p - Weight of soil plug.
- w - Width of pile cap.
- y - Lateral soil (or pile) deflection.
- Z - Length of pile group.
- Z_d - Projected length of pile group at depth d .
- z - Pile spacing.
- α - An empirical adhesion factor.
- α' - Ratio of pile unit shaft resistance to cone unit sleeve friction for cohesive soils.
- α_t - Dimensionless factor in Nordlund method (dependent on pile depth-width relationship).
- β - Beta shaft resistance coefficient.
- β_h - Dimensionless length factor for lateral load analysis.
- Δ - Elastic compression.
- Δu_m - Maximum excess pore pressure.
- δ - Friction angle between pile and soil.
- ϵ - Strain.
- ϵ_{50} - Strain at $1/2$ maximum principal stress.
- η - Dimensionless length factor for lateral load analysis.
- η_g - Pile group efficiency.

LIST OF SYMBOLS

- γ - Total unit weight of soil.
- γ' - Buoyant unit weight of soil.
- γ_D - Dry unit weight of soil.
- γ_f - Unit weight of embankment fill.
- γ_w - Unit weight of water.
- σ - Normal or total overburden stress (pressure).
- σ' - Effective stress or $(\sigma - u)$.
- σ_a - Maximum allowable stress in compression parallel to the wood grain.
- σ'_p - Preconsolidation pressure or stress.
- σ'_{vc} - Vertical consolidation stress.
- σ'_1 - Effective stress after stress increase.
- σ'_o - Effective stress prior to stress increase.
- σ'_r - Constant reference stress.
- τ - Shear strength of soil.
- ϕ - Angle of internal friction of soil.
- ϕ' - Effective angle of internal friction of soil.
- ψ - Ratio of undrained shear strength divided by effective overburden pressure, c_u/p_o' .
- ω - Angle of pile taper from vertical.

LIST OF SYMBOLS

Chapter 1

NEED FOR A PILE MANUAL

In 1985 the Federal Highway Administration published the first edition of this manual. Twenty years have elapsed since the original manual was developed and seven years since the last published update. Changes in pile design, construction, and performance requirements make it necessary to once again update the manual. Significant changes in practice addressed by this edition of the manual include:

routine use of higher strength pile materials and higher foundation loads,
emphasis on a rational economic evaluation of the foundation design,
updates in software programs for pile foundation analysis and design,
use and quantification of soil set-up in foundation design and construction,
improvements in pile installation equipment and equipment performance monitoring,
increased use of instrumented static load test programs.

The goals of the original manual are unchanged. It is useful to repeat them here with modest updating.

1. There exists a vast quantity of information on the subject of pile foundations which presently is not compiled in a form which is useful to most practicing engineers. There are proven rational design procedures, information on construction materials, equipment and techniques, and useful case histories. Unfortunately, much of this information is fragmented and scattered. Standard textbooks and other publications on the subject tend to be theoretically oriented; practicing design and construction engineers often find them lacking in practical aspects.
2. Many of the methods currently in practice often lead to unnecessarily conservative designs because they are based solely on experience and tradition with little theoretical background. Newer and more rational design procedures and techniques can be applied to provide more economical pile systems which will safely support the applied structural loads without excessive safety factors.
3. During fiscal year 2000, FHWA and the State Transportation departments spent approximately 8.8 billion dollars for constructing, replacing, or rehabilitating bridges. Of that amount approximately 2.6 billion dollars were spent on bridge substructures and of that, at least 1.3 billion dollars were spent on foundations. In addition, city and county governments, whose practices closely follow the State practices, spend large

amounts on construction of bridges. There are opportunities for substantial savings in foundation construction costs, specifically in the area of pile foundations.

Cost savings can be achieved by the use of improved methods of design and construction technology. A minimum of fifteen percent of the substructure cost can be easily saved by utilizing such methods and, in most cases, the savings are more significant.

4. A comprehensive manual has been needed for some time to transfer available technology and to upgrade the level of expertise in pile foundations. This manual is intended to fulfill that need as well as to establish minimum design standards.
5. Design criteria for major and unusual bridge structures are becoming more complex and sophisticated. Extreme design events such as scour, debris loading, vessel impact, and seismic events require that foundation performance be evaluated under lateral and uplift loading, group behavior, and substructure - superstructure interaction. This new series of performance criteria frequently results in foundations which are more costly, more complex to design, and more difficult to construct.
6. The loading conditions noted above can have a substantial impact on the structural design of the piles. In the past, driven piles have usually been designed structurally for axial loads only using an allowable stress approach. The allowable stresses had been set primarily to assure pile drivability. Modern pile driving hammers may make it possible to exceed these traditional allowable stresses. However, the requirement that piles be analyzed for combined horizontal and axial loads requires a change in the evaluation procedure. The pile top is subjected to both horizontal and axial loads and in a pile group the pile resistance to lateral loads varies with each pile row. Of course this complicates the geotechnical analysis. It also complicates the structural analysis of the pile. A combined bending and axial load analysis of the structural behavior of the pile must be made. Particularly for concrete piles this analysis must be made based on an ultimate strength analysis and it is not always obvious which pile is the critical one. Excellent software is now available to perform the necessary analyses.
7. The final selection of a design should involve a cost evaluation. In the past, such evaluations have been implied but they were not a routine part of the design process. Methods have been developed to perform cost evaluations of pile foundations that include the effects of soil set-up. These concepts will be presented in this edition of the manual.

The original manual represented a major advance in that it included the most modern technology for pile design that was available. At the same time, the manual presented this technology so that it was usable to the practicing engineer. The work was very successful helping many transportation departments to modernize their design procedures.

1.1 SCOPE OF MANUAL

Since most piles used for highway structures are driven piles, and to keep this manual to a manageable size, this manual is limited to driven piles. The manual has been divided into two volumes. Volume I covers the design of pile foundations and Volume II covers installation, construction control, and inspection. However, sufficient information is provided in Volume I so that spread footings and drilled/bored piles, *e.g.*, drilled shafts, auger cast piles, *etc.*, can be considered in the foundation type selection process. This manual is intended to serve as a reference to all practical aspects of the design and construction of driven pile foundations.

All aspects of pile foundation design and construction, including subsurface exploration and laboratory testing, geotechnical and structural design analysis, foundation report preparation, and construction monitoring are covered in a systematic manner. Theoretical discussions have been included only where necessary. Specific recommendations are made wherever appropriate. Workshop exercises are included to provide hands-on knowledge to workshop participants and manual users.

It is important for design and construction engineers and pile construction inspectors to be familiar with pile driving equipment, accessories and inspection procedures. A separate section on this subject is included in this manual to fulfill this need.

During the period that the first edition of this manual was in use, several changes occurred in design requirements. For example, more stringent requirements for scour, vessel impact and seismic events have been implemented in design. The scour requirements make pile driveability analysis more critical. For vessel impact and seismic considerations, both pile uplift and lateral analyses are becoming more important. It has become much more common to consider the effects of soil strength changes with time in the design and construction process. In the past ten years, a better understanding of pile group behavior has been gained and this knowledge is now being put into practice. Finally, this edition of the manual is presented in both Systems International (SI) and customary U.S. English units.

As with the previous document, this edition is still the basis for a course on the design of driven pile foundations. This course will continue the original goal of modernizing transportation department practice in this area. Also, new engineers continue to join transportation department organizations and require updating of their knowledge in the practical aspects of pile design and installation.

The use of Load and Resistance Factor Design (LRFD) for highway bridges has been approved by the Subcommittee for Bridges and Structures of the American Association of State Highway and Transportation Officials (AASHTO). It has been mandated that all bridge design be based on this approach by October 2007. This design philosophy includes foundations and, of course, driven piles. This manual will continue to follow the working stress design philosophy. However, an overview of LRFD design of driven pile foundations is provided in Appendix G. NHI Course 130082A, LRFD for Highway Bridge Substructures and Earth Retaining Structures, has been developed on the use of LRFD in foundation design and is now available.

1.2 INFORMATION SOURCES

The information presented in this manual has been collected from several sources. The information has been condensed, modified and updated as needed. The sources include state-of-the-art technical publications, manufacturers' literature, existing Federal Highway Administration (FHWA), National Highway Institute (NHI) and Transportation Research Board (TRB) publications, standard textbooks, and information provided by State and Federal transportation engineers. Reference lists are provided at the end of each chapter. Many of the documents used in the development or updating of this manual, as well as useful industry links are available at www.fhwa.dot.gov/bridge/geo.htm.

Chapter 2

OVERVIEW OF PILE FOUNDATION DESIGN AND CONSTRUCTION

2.1 DESIGN OF PILE FOUNDATIONS

As stated by Professor R. B. Peck, “driving piles for a foundation is a crude and brutal process”. The interactions among the piles and the surrounding soil are complex. Insertion of piles generally alters the character of the soil and intense strains are set up locally near the piles. The non-homogeneity of soils, along with the effects of the pile group and pile shape, adds further difficulties to the understanding of soil-pile interaction.

Broad generalizations about pile behavior are unrealistic. An understanding of the significance of several factors involved is required to be successful in the design of pile foundations. Because of the inherent complexities of pile behavior, it is necessary to use practical semi-empirical methods of design, and to focus attention on significant factors rather than minor or peripheral details. The foundation engineer must have a thorough understanding of foundation loads, subsurface conditions including soil/rock properties and behavior, the significance of special design events, foundation performance criteria, and current practices in foundation design and construction in the area where the work is to be done to arrive at the optimum foundation solution.

2.2 CONSTRUCTION OF PILE FOUNDATIONS

Construction of a successful driven pile foundation that meets the design objectives depends on relating the requirements of the static analysis methods presented on the plans to the dynamic methods of field installation and construction control. The tools for obtaining such a foundation must be explicitly incorporated into the plans and specifications as well as included in the contract administration of the project.

A pile foundation must be installed to meet the design requirements for compressive, lateral and uplift capacity. This may dictate driving piles for a required ultimate capacity or to a predetermined length established by the designer. It is equally important to avoid pile damage or foundation cost overruns by excessive driving. These objectives can all be satisfactorily achieved by use of wave equation analysis, dynamic monitoring of pile driving, and static load testing. Commonly used dynamic formulas, such as Engineering News formula, have proven unreliable as pile capacities increased and more sophisticated pile installation equipment was routinely used by contractors.

Knowledgeable construction supervision and inspection are the keys to proper installation of piles. State-of-the-art designs and detailed plans and specifications must be coupled with good construction supervision to achieve desired results.

Post construction review of pile driving results versus predictions regarding pile driving resistances, pile length, field problems, and load test capacities is essential. These reviews add to the experience of all engineers involved on the project and will enhance their skills. In addition, the implementation of LRFD in pile foundation design with rationally determined resistance factors makes it possible to use data from the post construction review to improve the resistance factors. Particularly, if substantial amounts of dynamic testing is done for job quality control then that data can feed directly back into improved resistance factors.

2.3 FOUNDATION SPECIALIST INVOLVEMENT IN PILE FOUNDATION PROJECTS

The input of an experienced foundation specialist from the planning stage through project design and construction is essential to produce a successful driven pile foundation. A foundation specialist has both a structural and geotechnical background in design and construction. The foundation specialist is the most knowledgeable person for selecting the pile type, estimating pile length, and choosing the most appropriate method to determine ultimate pile capacity. Therefore, the foundation specialist should be involved throughout the design and construction process. In some project phases, *i.e.* preliminary explorations, preliminary design, and final design, the foundation specialist will have significant involvement. In other project phases, such as construction, and post construction review, the foundation specialist's involvement may be more of a technical services role. The foundation specialist's involvement provides the needed continuity of design personnel in dealing with design issues through the construction stage.

2.4 DRIVEN PILE DESIGN-CONSTRUCTION PROCESS

The driven pile design and construction process has aspects that are unique in all of structural design. Because the driving characteristics are related to pile capacity for most soils, they can be used to improve the accuracy of the pile capacity estimate. In general, the various methods of determining pile capacity from dynamic data such as driving resistance with wave equation analysis and dynamic measurements are considerably more accurate than the static analysis methods based on subsurface exploration information. It must be clearly understood that the static analysis based on the subsurface exploration

information usually has the function of providing an estimate of the pile length prior to going to the field. The final driving criterion is usually a blow count that is established after going to the field and the individual pile penetrations may vary depending on the soil variability. Furthermore, pile driveability is a very important aspect of the process and must be considered during the design phase. If the design is completed, a contractor is selected, and then the piles cannot be driven, large costs can be generated. It is absolutely necessary that the design and construction phases be linked in a way that does not exist elsewhere in construction.

The driven pile design-construction process is outlined in the flow chart of Figure 2.1. This flow chart will be discussed block by block using the numbers in the blocks as a reference and it will serve to guide the designer through all of the tasks that must be completed.

Block 1: Establish Global Project Performance Requirements

The first step in the entire process is to determine the general structure requirements.

1. Is the project a new bridge, a replacement bridge, a bridge renovation, a retaining wall, a noise wall, or sign or light standard?
2. Will the project be constructed in phases or all at one time?
3. What are the general structure layout and approach grades?
4. What are the surficial site characteristics?
5. Is the structure subjected to any special design events such as seismic, scour, downdrag, debris loading, vessel impact, *etc.*? If there are special design events, the design requirements should be reviewed at this stage so that these can be factored into the site investigation.
6. Are there possible modifications in the structure that may be desirable for the site under consideration?
7. What are the approximate foundation loads? What are the deformation or deflection requirements (total settlement, differential settlement, lateral deformations)?
8. Are there site environmental considerations that must be considered in the design (specific limitation on noise, vibrations, *etc.*)?

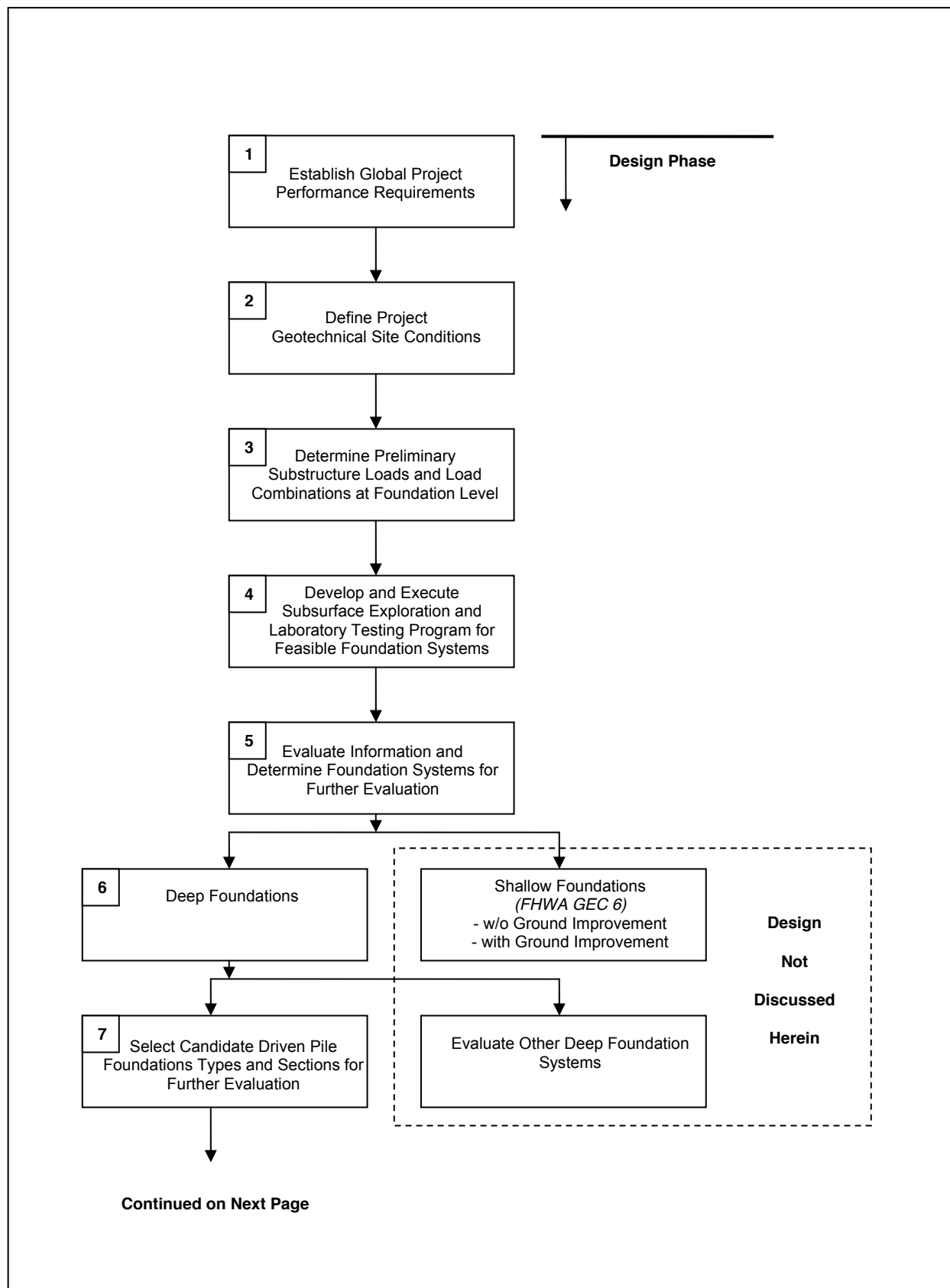


Figure 2.1 Driven Pile Design and Construction Process

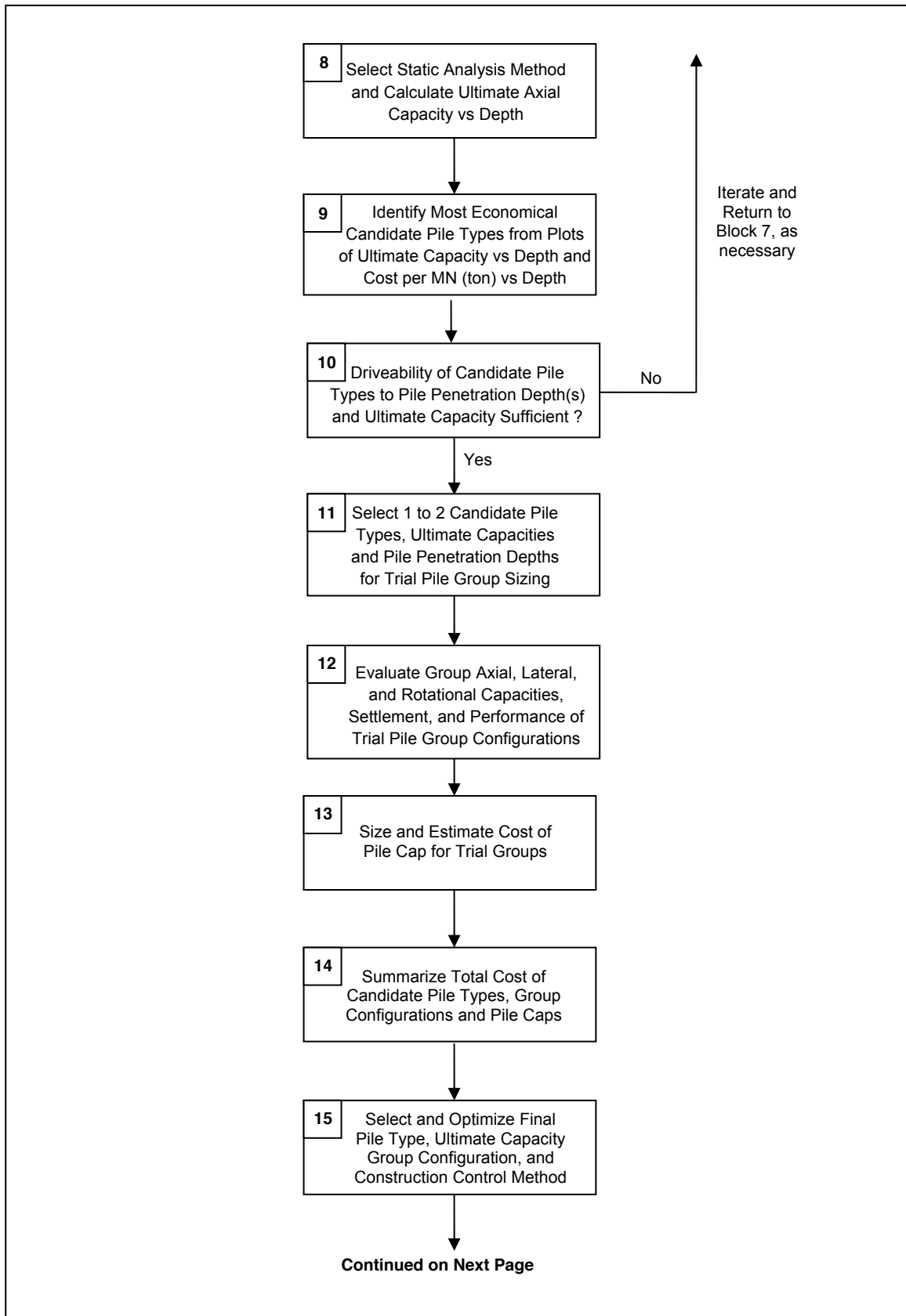


Figure 2.1 Driven Pile Design and Construction Process (continued)

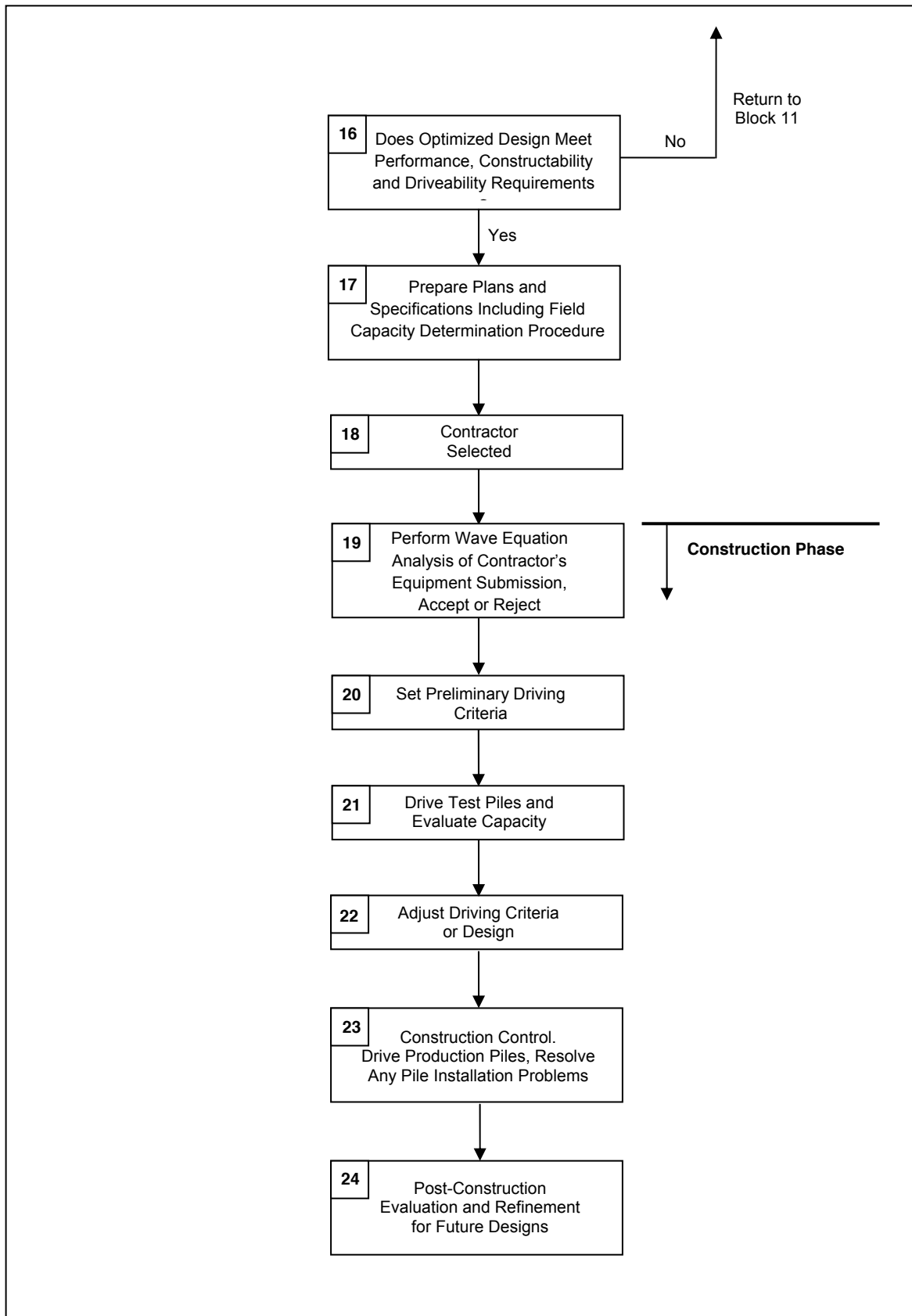


Figure 2.1 Driven Pile Design and Construction Process (continued)

Block 2: Define Project Geotechnical Site Conditions

A great deal can be learned about the foundation requirements with even a very general understanding of the site geology. For small structures, this may involve only a very superficial investigation such as a visit to the site. The foundation design for very large structures may require extensive geologic studies.

Frequently there is information available on foundations that have been constructed in the area. This information can be of assistance in avoiding problems. Both subsurface exploration information and foundation construction experience should be collected prior to beginning the foundation design. Unfortunately, this step is not often done in practice.

Block 3: Determine Preliminary Substructure Loads and Load Combinations

Substructure loads and reasonable vertical and lateral deformation requirements should be established at this time. This issue was considered in Block 1. The result of that effort has probably matured in the intervening time (which might be quite long for some projects) and is now better defined. It is imperative that the foundation specialist obtain a completely defined and unambiguous set of foundation loads and performance requirements in order to proceed through the foundation design process. Accurate load information and performance criteria are essential in the development and implementation of an adequate subsurface exploration program for the planned structure.

Block 4: Develop and Execute Subsurface Exploration Program for Feasible Foundation Systems

Based on the information obtained in Blocks 1-3, it is possible to make decisions regarding the necessary information that must be obtained for the feasible foundation systems at the site. The subsurface exploration program and the associated laboratory testing must meet the needs of the design problem that is to be solved at a cost consistent with the size of the structure. The results of the subsurface exploration program and the laboratory testing are used to prepare a subsurface profile and identify critical cross sections. These tasks are covered in greater detail in Chapters 4, 5, and 6.

Block 5: Evaluate Information and Select Candidate Foundation Systems

The information collected in Blocks 1-4 must be evaluated and candidate foundation systems selected. The first question to be decided is whether a shallow or a deep foundation is required. This question will be answered based primarily on the strength and compressibility of the site soils, the proposed loading conditions, the project performance criteria and the foundation cost. If settlement is not a problem for the structure, then a

shallow foundation will probably be the most economical solution. Ground improvement techniques in conjunction with shallow foundations should also be evaluated. Shallow and deep foundation interaction with approach embankments must also be considered. If the performance of a shallow foundation exceeds the structure performance criteria, a deep foundation must be used. The design of shallow foundations and ground improvement techniques are not covered in this manual. Information on design consideration for shallow foundations can be found in Kimmerling (2002), and in Munfakh *et al.*, (2001). Information on ground improvement techniques can be found in Elias *et al.*, (2004). The problem of selecting the proper foundation system is discussed in detail in Chapter 7.

Block 6: Deep Foundations

The decision among deep foundation types is now divided between driven piles and other deep foundation systems. These other deep foundation systems are primarily drilled shafts, but would also include micropiles, auger cast piles, and other drilled-in deep foundation systems. The questions that must be answered in deciding between driven piles and other deep foundation systems will center on the relative costs of available, possible systems. Foundation support cost can be conveniently calculated based on a cost per unit of load carried. In addition, constructability must be considered. This manual is concerned with driven piles so the other types of deep foundations will not be discussed here. Design guidance on drilled shafts can be found in O'Neil and Reese (1999). For micropile design guidance refer to Sabatini *et al.*, (2005), and for auger cast piles refer to in Brown and Dapp (2006). The need for and selection of a deep foundation system is discussed in Chapter 7.

Block 7: Select 2 to 5 Candidate Driven Pile Types for Further Evaluation

At this point on the flow chart, the primary concern is for the design of a driven pile foundation. The pile type must be selected consistent with the applied load per pile. Consider this problem. The general magnitude of the column or pier loads is known from the information obtained in Blocks 1 and 3. However, a large number of combinations of pile capacities and pile types can satisfy the design requirements. Should twenty, 1000 kN (225 kip) capacity piles be used to carry a 20,000 kN (4,500 kip) load, or would it be better to use ten, 2000 kN (450 kip) capacity piles? This decision should consider both the structural capacity of the pile and the realistic geotechnical capacities of the pile type for the soil conditions at the site, the cost of the available alternative piles, and the capability of available construction contractors to drive the selected pile. Of course, there are many geotechnical factors that must also be considered. At this point in the design process, 2 to 5 candidate pile types and/or sections that meet the general project requirements should be

selected for further evaluation. Pile type and selection considerations are covered in Chapter 8.

At this stage the loads must also be firmly established. In Block 1, approximate loads were determined which were refined in Block 3. At those stages of the design process the other aspects of the total structural design were probably not sufficiently advanced to establish the final design loads. By the time that Block 6 has been reached, the structural engineer should have finalized the various loads. One common inadequacy that is sometimes discovered when foundation problems arise is that the foundation loads were never really accurately defined at the final stage of the foundation design.

If there are special design events to be considered, they must be included in the determination of the loads. Vessel impact will be evaluated primarily by the structural engineer and the results of that analysis will give pile loads for that case. There may be stiffness considerations in dealing with vessel impact since the design requirement is basically a requirement that some vessel impact energy be absorbed.

Scour presents a different requirement. The loads due to the forces from the stream must be determined as specified in the AASHTO Standard Specification for Highway Bridges, Section 3.18 and this should be included in the structural engineer's load determination process. The depth of scour must also be determined as directed in AASHTO Specification, Section 4.3.5. In the design process, it must be assured that after scour the pile will still have adequate capacity.

In many locations in the country, seismic loads will be an important contributor to some of the critical pile load conditions. Since the 1971 San Fernando Earthquake, much more emphasis has been placed on seismic design considerations in the design of highway bridges. The AASHTO Standard Specifications for Highway Bridges has been substantially expanded to improve the determination of the seismic loads. Usually the structural engineer will determine the seismic requirements. Frequently the behavior of the selected pile design will affect the structural response and hence the pile design loads. In this case, there will be another loop in the design process that includes the structural engineer. The geotechnical engineer should review the seismic design requirements in Division I-A of the AASHTO Bridge Design Specification for a general understanding of the design approach.

Block 8: Select Static Analysis Method and Calculate Ultimate Capacity vs Depth

A static analysis method(s) applicable to the pile type(s) under consideration and the soil conditions at the site should now be selected. Static analysis methods are covered in detail

in Chapter 9. The ultimate axial capacity versus depth should then be calculated for all candidate pile types and sections.

Block 9: Identify Most Economical Candidate Pile Types and/or Sections

The next step is to develop and evaluate plots of the ultimate axial static capacity versus pile penetration depth and the pile support cost versus pile penetration depth for each candidate pile type and/or section. The support cost, which is the cost per kN (ton) supported, is the ultimate capacity at a given penetration depth divided by the pile cost to reach that penetration depth. The pile cost can be calculated from the unit cost per meter (ft) multiplied by the pile length to the penetration depth. These plots should be evaluated to identify possible pile termination depths to obtain the lowest pile support cost. This process is introduced in Chapter 3.

Block 10: Calculate Driveability of Candidate Pile Types

Candidate pile types should now be evaluated for driveability. Can the candidate pile type and/or section be driven to the required capacity and penetration depth at a reasonable pile penetration resistance (blow count) without exceeding allowable driving stresses for the pile material? This analysis is performed using the wave equation program. All of the necessary information is available except the hammer selection. Since the hammer to be used on the job will only be known after the contractor is selected, possible hammers must be tried to make sure that the pile is driveable to the capacity and depth required.

Pile driveability is introduced in Chapter 9 with additional details on the use of wave equation analysis to check pile driveability described in Chapter 16. Allowable pile driving stresses are presented in Chapter 10.

If candidate pile types or sections do not meet driveability requirements they are dropped from further evaluation or modified sections must be chosen and evaluated. For H-piles and pipe piles, it may be possible to increase the pile section without increasing the soil resistance to driving. For concrete piles, an increase in section usually means a larger pile size, and therefore, an increase in soil resistance must also be overcome. Hence, some section changes may cause the design process to revisit Block 8. If all candidate pile types fail to meet driveability requirements, the design process must return to Block 7 and new candidate pile types must be selected.

Block 11: Select 1 to 2 Final Candidate Pile Types for Trial Group Sizing

The most viable candidate pile types and/or sections from the cost and driveability evaluations in Blocks 9 and 10 should now be evaluated for trial group sizing using the final loads and performance requirements. Multiple pile penetration depths and the resulting ultimate capacity at those depths should be used to establish multiple trial pile group configurations for each candidate pile type. These trial configurations should then be carried forward to Block 13.

Block 12: Evaluate Capacity, Settlement, and Performance of Trial Groups

The trial group configurations should now be evaluated for axial group capacity, group uplift, group lateral load performance, and settlement. These computations and analysis procedures are described in Chapter 9.

Block 13: Size and Estimate Pile Cap Cost for Trial Groups

The size and thickness of the pile cap for each trial group should be evaluated, and the resulting pile cap cost estimated. It is not necessary to design the cap reinforcement at this time only to determine cap size. Pile cap cost is a key component in selecting the most cost effective pile type and should not be overlooked. A procedure for preliminary sizing of pile caps is provided in Chapter 10.

Block 14: Summarize Total Cost of Final Candidate Piles

The total cost of each candidate pile should now be determined. A given pile type may have several total cost options depending upon the pile penetration depths, ultimate capacities, group configurations, and pile cap sizes carried through the design process. The cost of any special construction considerations and environmental restrictions should also be included in the total cost for each candidate pile.

Block 15: Select and Optimize Final Pile Type, Capacity, and Group Configuration

Select the final pile foundation system including pile type, section, length, ultimate capacity and group configuration for final design. A complete evaluation of the group lateral and rotational resistance should be performed. The design should be optimized for final structure loads, performance requirements, and construction efficiency.

Block 16: Does Optimized Design Meet All Requirements?

The final pile type, section, capacity and group configuration optimized in Block 15 should be evaluated so that all performance requirements have been achieved. If the optimization process indicated that a reduced pile section could be used, the driveability of the optimized pile section must be checked by a wave equation driveability analysis. This analysis should also consider what influence the group configuration (pile spacing) and construction procedures (i.e., cofferdams, etc.) may have on pile installation conditions.

Block 17: Prepare Plans and Specifications, Set Field Capacity Determination Procedure

When the design has been finalized, plans and specifications can be prepared and the procedures that will be used to verify pile capacity can be defined. It is important that all of the quality control procedures are clearly defined for the bidders to avoid claims after construction is underway. In the former use of the dynamic formula, the pile load specified was a design or working load since a factor of safety was contained in the formula. Modern methods of pile capacity determination always use ultimate loads with a factor of safety (or in LRFD a resistance factor) selected and applied. This should also be made clear in the project specifications so that the contractor has no question regarding the driving requirements. Procedures should be in place that address commonly occurring pile installation issues such as obstructions and driveability. Construction specifications are discussed in Chapter 11 and the preparation of the foundation report is covered in Chapter 13.

Block 18: Contractor Selection

After the bidding process is complete, a successful contractor is selected.

Block 19: Perform Wave Equation Analysis of Contractor's Equipment Submission

At this point the engineering effort shifts to the field. The contractor will submit a description of the pile driving equipment that he intends to use on the project for the engineer's evaluation. Wave equation analysis is performed to determine the driving resistance that must be achieved in the field to meet the required capacity and pile penetration depth. Driving stresses are determined and evaluated. If all conditions are satisfactory, the equipment is approved for driving. Some design specifications make this information advisory to the contractor rather than mandatory. Chapters 10, 11, and 16 provide additional information in this area.

On smaller projects, a dynamic formula may be used to evaluate driveability and the modified Gates Formula should be used. If a dynamic formula is used, then driveability and hammer selection will be based on the driving resistance given by the formula only, since stresses are not determined. Dynamic formula usage is covered in Chapter 15.

Block 20: Set Preliminary Driving Criteria

Based on the results of the wave equation analysis of Block 19 (or on smaller projects the modified Gates Formula) and any other requirements in the design, the preliminary driving criteria can be set.

Block 21: Drive Test Pile and Evaluate Capacity

The test pile(s), if required, are driven to the preliminary criteria developed in Block 19. Driving requirements may be defined by penetration depth, driving resistance, dynamic monitoring results or a combination of these conditions. The capacity can be evaluated by driving resistance from wave equation analysis, the results of dynamic monitoring, static load test, the modified Gates Formula, or a combination of these. Dynamic monitoring is described in Chapter 17. Static load test procedures are discussed in greater detail in Chapter 18 and dynamic formulas are covered in Chapter 15.

Block 22: Adjust Driving Criteria or Design

At this stage the final conditions can be set or, if test results from Block 21 indicate the capacity is inadequate, the driving criteria may have to be changed. In a few cases, it may be necessary to make changes in the design as far back as Block 8.

In some cases, it is desirable to perform preliminary field testing before final design. When the job is very large and the soil conditions are difficult, it may be possible to achieve substantial cost savings by having results from a design stage test pile program, including actual driving records at the site, as part of the bid package.

Block 23: Construction Control

After the driving criterion is set, the production pile driving begins. Quality control and assurance procedures have been established and are applied. Construction inspection items are discussed in greater detail in Chapter 23. Problems may arise and must be handled as they occur in a timely fashion.

Block 24: Post-Construction Evaluation and Refinement of Design

After completion of the foundation construction, the design should be reviewed and evaluated for its effectiveness in satisfying the design requirements and also its cost effectiveness.

2.5 COMMUNICATION

Good communication between all parties involved in the design and construction of a pile foundation is essential to reach a successful completion of the project. In the design stage, communication and interaction is needed between the structural, geotechnical, geologic, hydraulic, and construction disciplines, as well as with consultants, drill crews and laboratory personnel. In the construction stage, structural, geotechnical and construction disciplines need to communicate for a timely resolution of construction issues as they arise. Figures 2.2 and 2.3 highlight some of the key issues to be communicated in the design and construction stages.

| DESIGN STAGE COMMUNICATION | | | | | | |
|--|------------|--------------|-----------|--------------|-------------|------------|
| Subject | Structural | Geotechnical | Hydraulic | Construction | Field Crews | Laboratory |
| Preliminary Structure Loads and Performance Criteria. | X | —X— | —X | | | |
| Determination of Scour Potential. | X | —X— | —X | | | |
| Determination of Special Design Event Requirements. | X | —X— | —X | | | |
| Review of Past Construction Problems in Project Area. | X | —X— | —X— | X | | |
| Implementation of Subsurface Exploration and Testing Programs. | X | —X— | —X— | X— | X— | X— |
| Determination of Pile Type, Length and Capacity. | X | —X | | | | |
| Effect of Approach Fills on Design. | X | —X | | | | |
| Prepare Plans and Specifications. | X | —X— | —X— | X | | |

Figure 2.2 Design Stage Communication

| CONSTRUCTION STAGE COMMUNICATION | | | |
|---|------------|--------------|--------------|
| Subject | Structural | Geotechnical | Construction |
| Establish Appropriate Methods of Construction Control and Quality Assurance. | X — | —X— | —X |
| Perform Wave Equation Analysis of Contractors Driving System to Establish Driving Criteria. | X — | —X— | —X |
| Perform Static Load Test(s) and/or Dynamic Monitoring and Adjust Driving Criteria. | X — | —X— | —X |
| Resolve Pile Installation Problems / Construction Issues. | X — | —X— | —X |

Figure 2.3 Construction Stage Communication

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Chapter 3

ECONOMICS OF FOUNDATIONS FOR HIGHWAY STRUCTURES

Foundation design and construction involve engineering, economic, and constructability considerations pertinent to the particular site in question. The engineering considerations are addressed by determining the foundation loads and performance requirements, development of the foundation design parameters, and design analysis. The design analysis coupled with past experience will provide several feasible foundation alternatives.

The next step involves an economic evaluation of potential foundations. Several foundation alternatives may be satisfactory for the subsurface conditions while also meeting superstructure requirements. However, of all the foundation alternatives, generally only one will have the least possible cost.

Last, the constructability of a potential foundation must be considered. A potential foundation solution may appear to be the most economical from purely a design perspective, but may not be most economical when limitations on construction activities are fully considered. Constructability issues such as impact on adjacent structures, equipment, access, methods, work hours, etc., must be considered in design.

3.1 FOUNDATION ALTERNATIVES

To determine the most feasible foundation alternatives, both shallow foundations and deep foundations should be considered. Deep foundation alternatives include driven piles, drilled shafts, micropiles, and auger cast piles. Proprietary deep foundations systems should not be excluded as they may be the most economical alternative in a given condition. This manual covers the design and construction of driven pile foundations. Therefore, design and construction procedures for shallow foundations, drilled shafts, micropiles and auger cast piles will not be covered herein. Additional details on spread footings for highway bridges may be found in FHWA/RD-86/185 Spread Footings for Highway Bridges by Gifford *et al.* (1987) and Geotechnical Engineering Circular No. 6, Shallow Foundations by Kimmerling (2002). The FHWA/ADSC publication FHWA-IF-99-025 by O'Neill and Reese (1999) summarizes design methods and construction procedures for drilled shafts. Details on micropiles can be found in FHWA-NHI-05-039 by Sabatini, *et al.*, (2005), and auger cast piles details are summarized in Brown and Dapp (2006).

A cost evaluation of all feasible foundation alternatives using the foundation support cost approach is essential in the selection of the optimum foundation system.

Cost analyses of all feasible alternatives may lead to the elimination of some foundations qualified under the engineering study. Other factors that must be considered in the final foundation selection are availability of materials and equipment, local contractor and construction force experience, as well as any environmental limitations/considerations on construction access or activities.

For major projects, if the estimated foundation support costs of alternatives during the design stage are within 15 percent of each other, then alternate foundation designs should be considered for inclusion in the contract documents. If an alternate design is included in the contract documents, both designs should be adequately detailed. For example, if two pile foundation alternatives are detailed, the bid quantity pile lengths should reflect the estimated pile lengths for each alternative. Otherwise, material costs and not the installed foundation cost will likely determine the low bid. Use of alternate foundation designs will generally provide the most cost effective foundation system.

Proprietary pile types should not be routinely excluded from consideration. In a given soil condition, a proprietary system may be the most economical foundation type. Therefore, a proprietary system should be considered as a viable foundation alternate when design analyses indicate the cost to be within 15% of a conventional design. A conventional design alternate should generally be included with a proprietary design alternate in the final project documents to stimulate competition.

3.2 EXAMPLES OF COST SAVINGS BY UTILIZING MODERN DESIGN AND CONSTRUCTION CONTROL PRACTICES

There are many factors which enter into the cost of a structure foundation. A failure to understand and consider any one of them will add to the total cost of the work. Use of overly conservative designs and inappropriate construction practices may result in significantly greater foundation costs. These practices are also often associated with increased risk of large change orders or claims.

Use of modern design and construction methods, techniques, and equipment provides an efficient foundation system without compromising safety or the service life of the structure. Modern methods allow significant cost savings through better quality control, optimization of pile type, and optimization of pile section. Outdated pile foundation practices usually lead

either to extremely conservative and inefficient piling systems or unsafe foundations. Opportunities for rational design, construction, and cost savings exist in several areas of pile foundations. These opportunities are summarized in Table 3-1.

Transportation agencies that are taking advantage of modern design and construction control methods have reduced foundation costs while obtaining greater confidence in the safety and the service life of their structures.

3.3 OPTIMIZATION OF FOUNDATION COST

3.3.1 Definition of Foundation Support Cost

A rational comparison of potential foundation systems can be made based on the foundation support cost of each candidate foundation type. The foundation support cost is defined as the total cost of the foundation divided by the load the foundation supports in MN (tons). The total foundation cost should include all costs associated with a given foundation system including the need for excavation or retention systems, pile caps and cap size, environmental restrictions on construction activities, etc. A detailed case history describing the foundation support cost concept can be found in Komurka (2004).

For driven pile foundation projects, the total foundation support cost can be separated into three major components; the pile support cost, the pile cap support cost, and the construction control method support cost.

3.3.2 Cost Optimization for One Pile Section

Figure 3.1 presents a layered soil profile that will be used to illustrate the cost optimization process. The first step in the cost optimization of a selected pile section is to perform a static analysis to determine the ultimate capacity versus the pile penetration depth. Static analysis methods are described in greater detail in Chapter 9. A static analysis was performed for the example soil profile presented in Figure 3.1 using the DRIVEN computer program. Figure 3.2 presents the results of this static analysis and consists of a plot of the calculated ultimate pile capacity versus pile penetration depth. The ultimate capacity versus depth results are for a HP 360 x 174 (HP 14x117) H-pile.

Several logical pile penetration termination depths and associated ultimate pile capacities are apparent in Figure 3.2a (SI units) or 3.2b (US units). Piles could be driven to the medium dense sand layer at a depth of 18 m (59 ft) for an ultimate pile capacity of 650 kN

| TABLE 3-1 COST SAVING RECOMMENDATIONS FOR PILE FOUNDATIONS | | | |
|--|--|--|--|
| Factor | Inadequacy of Older Methods | Cost Saving Recommendations | Remarks |
| A. Design structural load capacity of piles. | 1. Allowable pile material stresses may not address site specific considerations. | 1. Use realistic allowable stresses for pile materials in conjunction with adequate construction control procedures, (<i>i.e.</i> , load testing, dynamic pile monitoring and wave equation). 2. Determine potential pile types and carry candidate pile types forward in the design process. 3. Optimize pile size for loads. | 1. Rational consideration of Factors A and B may decrease cost of a foundation by 25 percent or more. 2. Significant cost savings can be achieved by optimization of pile type and section for the structural loads with consideration of pile driveability requirements. |
| B. Design geotechnical capacity of soil and rock to carry load transferred by piles. | 1. Inadequate subsurface explorations and laboratory testing. 2. Rules of thumb and prescription values used in lieu of static design may result in overly conservative designs. 3. High potential for change orders and claims. | 1. Perform thorough subsurface exploration including in-situ and laboratory testing to determine design parameters. 2. Use rational and practical methods of design. 3. Perform wave equation driveability analysis. 4. Use design stage pile load testing on large pile driving projects to determine load capacities (load tests during design stage). | 1. Reduction of safety factor can be justified because some of the uncertainties about load carrying capacities of piles are reduced. 2. Rational pile design will generally lead to shorter pile lengths and/or smaller number of piles. |
| C. Alternate foundation design. | 1. Alternate foundation designs are rarely used even when possibilities of cost savings exist by allowing alternates in contract documents. | 1. For major projects, consider inclusion of alternate foundation designs in the contract documents if estimated costs of feasible foundation alternatives are within 15 percent of each other. | 1. Alternative designs often generate more competition which can lead to lower costs. |
| D. Plans and specifications. | 1. Unrealistic specifications. 2. Uncertainties due to inadequate subsurface explorations force the contractors to inflate bid prices. | 1. Prepare detailed contract documents based on thorough subsurface explorations, understanding of contractors' difficulties and knowledge of pile techniques and equipment. 2. Provide subsurface information to the contractor. | 1. Lower bid prices will result if the contractor is provided with all the available subsurface information. 2. Potential for contract claims is reduced with realistic specifications. |
| E. Construction determination of pile load capacity during installation. | 1. Often used dynamic formulas such as Engineering News are unreliable. Correlations between | 1. Eliminate use of dynamic formulas for construction control as experience is gained with the wave equation analysis. 2. Use wave equation analysis coupled with dynamic monitoring for construction control and load capacity evaluation. 3. Use pile load tests on projects to substantiate capacity predictions by wave equation and dynamic monitoring. | 1. Reduced factor of safety may allow shorter pile lengths and/or smaller number of piles. 2. Pile damage due to excessive driving can be eliminated by using dynamic monitoring equipment. 3. Increased confidence and lower risk results from improved construction control. |

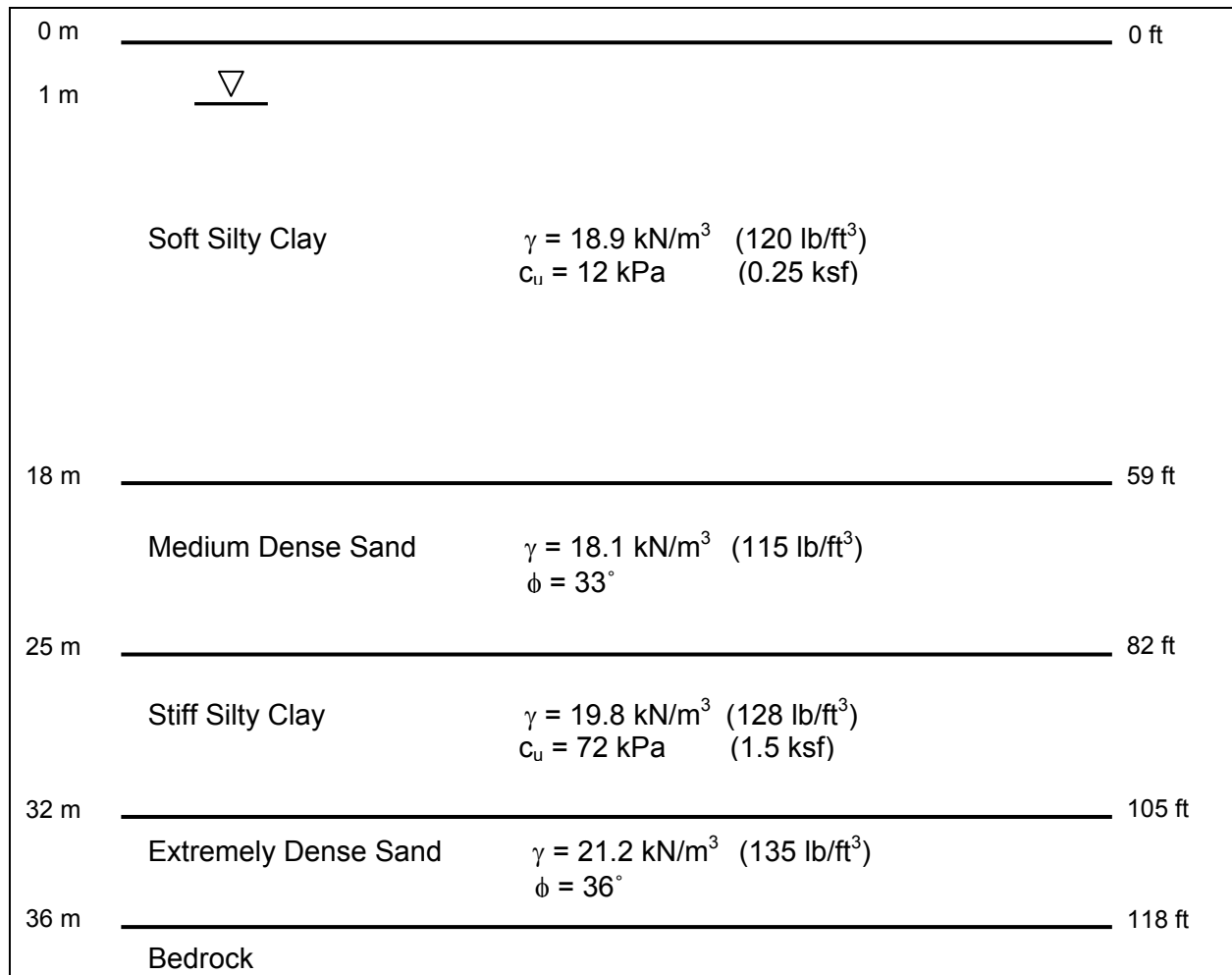


Figure 3.1 Example Soil Profile

(73 tons); seated into the medium dense sand layer near a depth of 21 m (69 ft) for 1100 kN (124 tons); driven through the medium dense sand layer and underlying stiff clay layer and into the extremely dense sand layer at 32 m (105 ft) for 3080 kN (346 tons); or driven to bedrock near 36 m (118 ft) for 5780 kN (650 tons). A rational economic assessment of these potential pile termination depths and ultimate pile capacities is needed for cost effective design. For most pile types, the pile cost can usually be assumed as linear with depth based on unit price as illustrated in Figure 3.3. However, this may not be true for very long concrete piles or long, large section steel piles. These exceptions may require the cost analysis to reflect special transportation, handling, or splicing costs for the concrete piles or extra splice time and cost for steel piles.

The pile cost at a given depth from Figure 3.3 can be divided by the ultimate capacity at that same depth from Figure 3.2a or 3.2b to obtain a plot of the pile support cost in dollars per ultimate kN supported or dollars per ultimate ton supported versus depth. Since pile

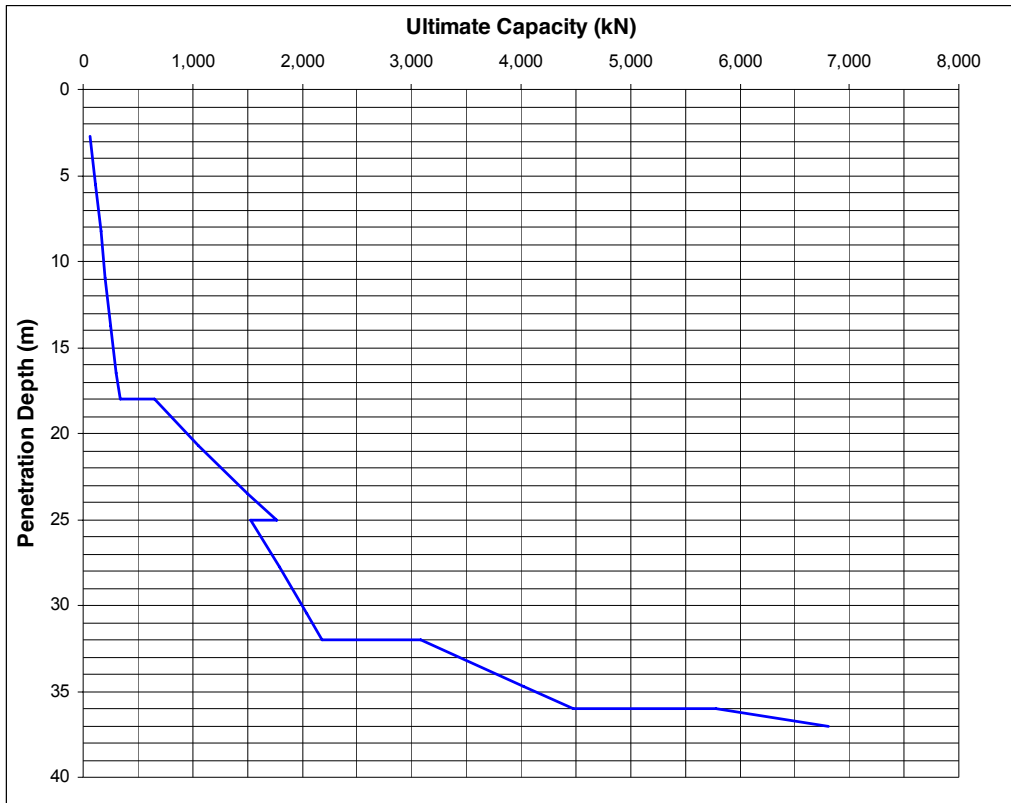


Figure 3.2a Ultimate Capacity in kN Versus Pile Penetration Depth in Meters.

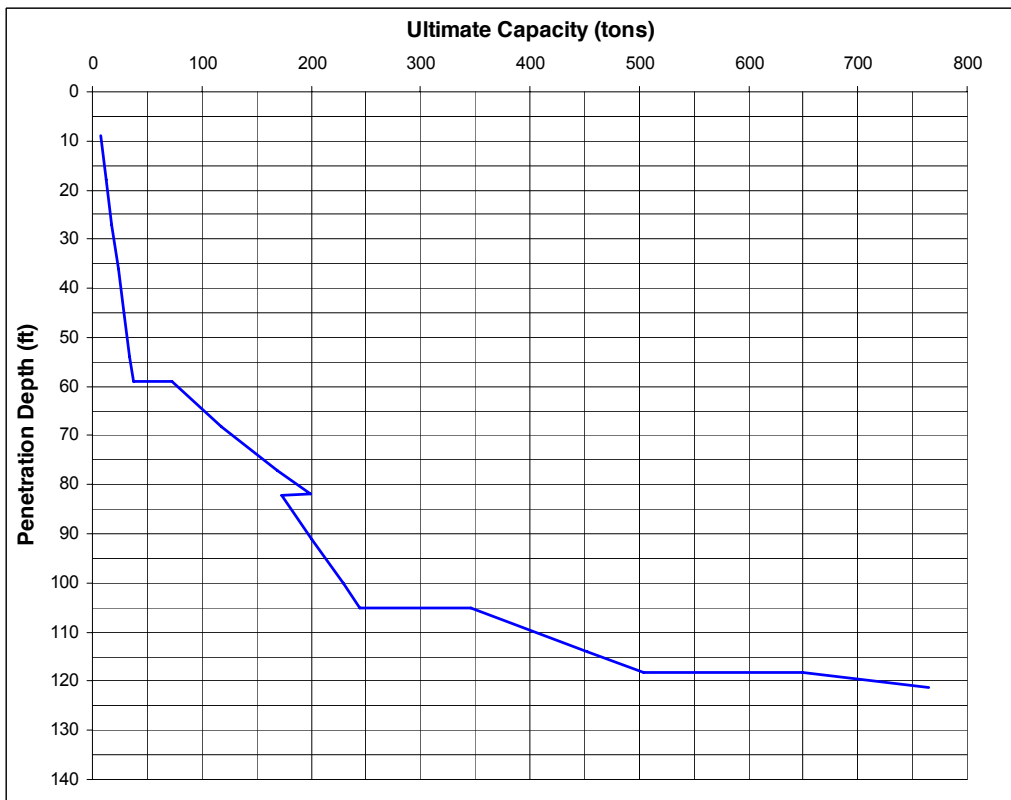


Figure 3.2b Ultimate Capacity in Tons Versus Pile Penetration Depth in Feet.



Figure 3.3 Pile Cost versus Pile Penetration Depth

capacities are ultimate capacities, this is the pile support cost – ultimate. Figure 3.4a (SI units) and 3.4b (US units) present plots of the pile support cost – ultimate versus depth and the ultimate pile capacity versus depth. For the pile section evaluated, a general conclusion can quickly be reached that longer, higher capacity piles appear more cost effective than shorter piles. At the 18 m depth and an ultimate pile capacity of 650 kN (73 tons), the pile section has a pile support cost – ultimate of \$4.28 per kN (\$38.05 per ton). At a depth of 21 m (69 ft) and an ultimate capacity of 1100 kN (124 tons), the pile section has a pile support cost – ultimate of \$3.03 per kN (\$26.99 per ton). The pile support cost – ultimate drops to \$1.59 per kN (\$14.19 per ton) at a depth of 32 m (105 ft) and an ultimate capacity of 3080 kN (346 tons). The pile support cost – ultimate continues to decrease to \$0.96 per kN (\$8.51 per ton) at a depth of 36 m (118 ft) and an ultimate pile capacity of 5780 kN (650 tons).

The next step in the optimization process is to plot the allowable design load versus pile penetration depth for different construction control methods as illustrated in Figures 3.5a and 3.5b for SI and US units. These figures also identify the maximum allowable AASHTO design loads based on the construction control method. Methods for determining the

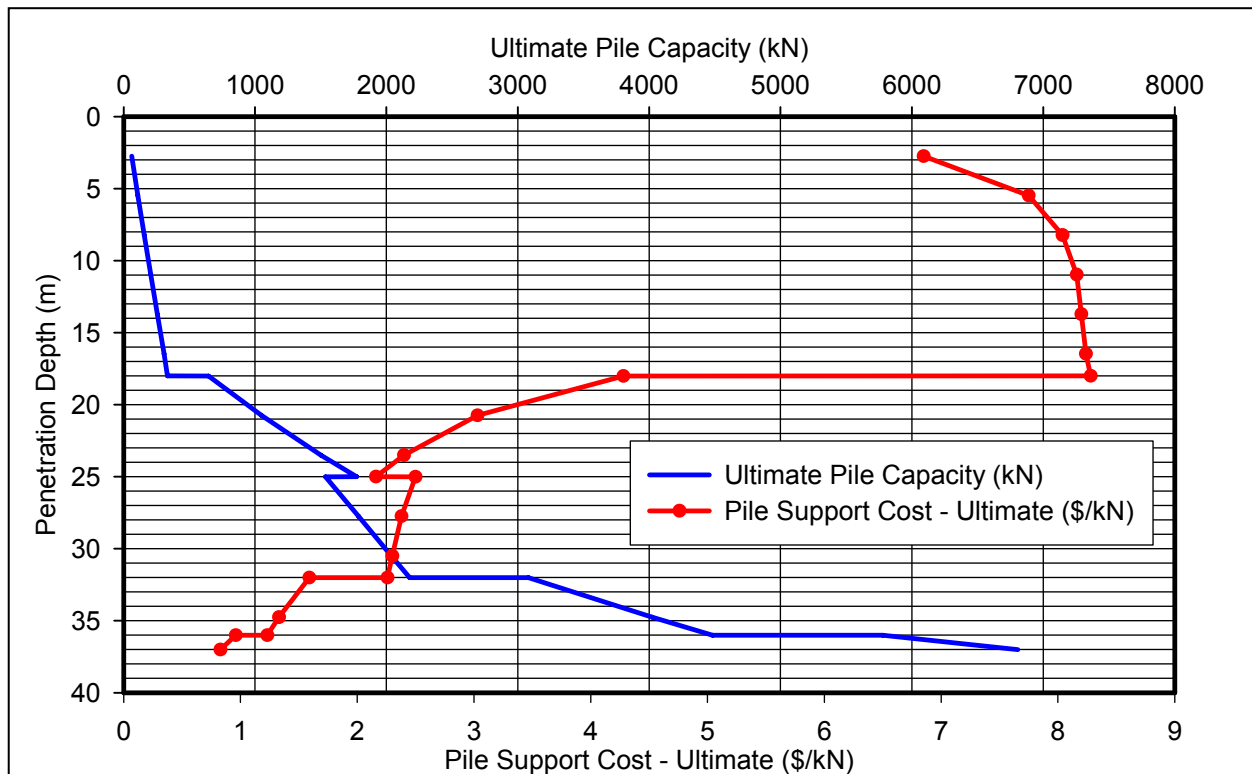


Figure 3.4a Ultimate Pile Capacity (kN) and Pile Support Cost - Ultimate Versus Depth (m)

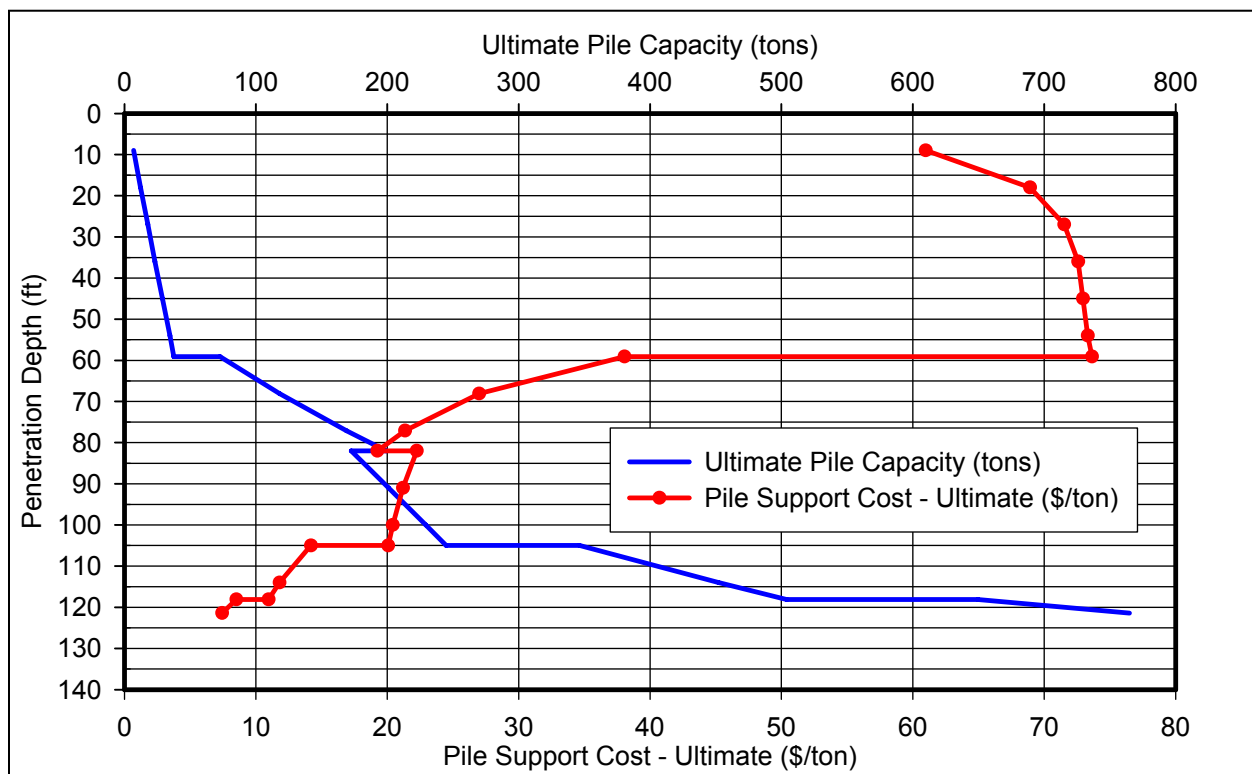


Figure 3.4b Ultimate Pile Capacity (tons) and Pile Support Cost – Ultimate Versus Depth (ft)

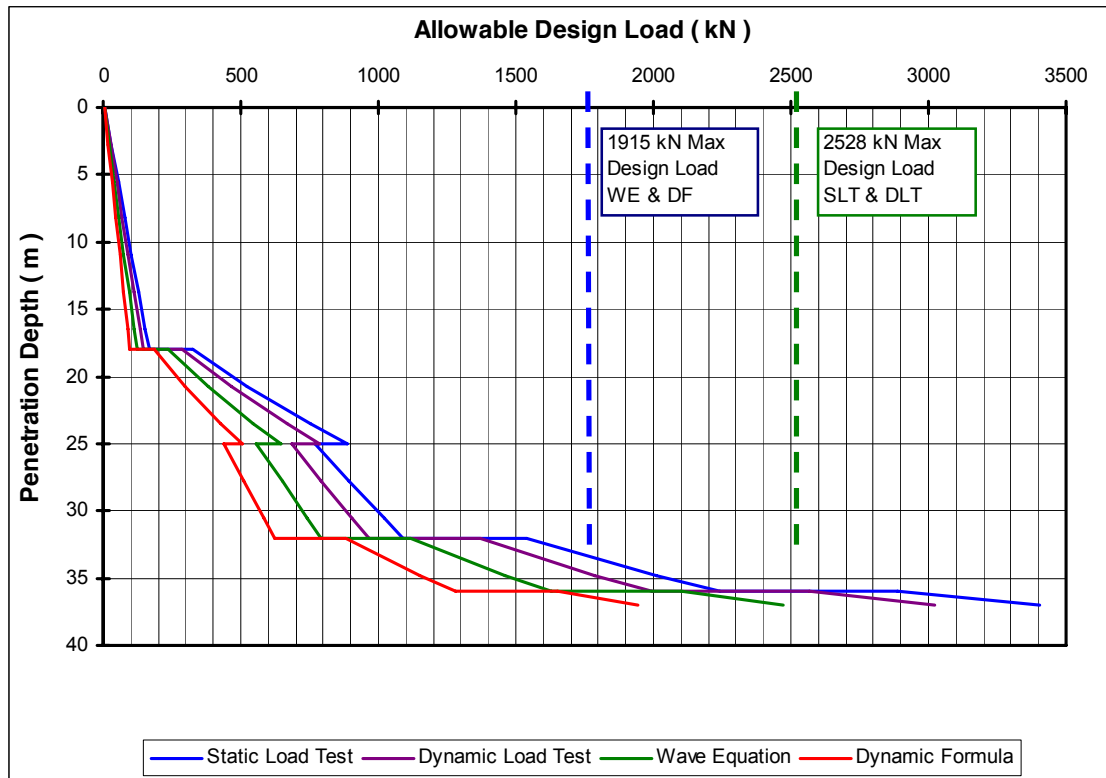


Figure 3.5a. Allowable Design Load in kN Versus Depth Based on Construction Control

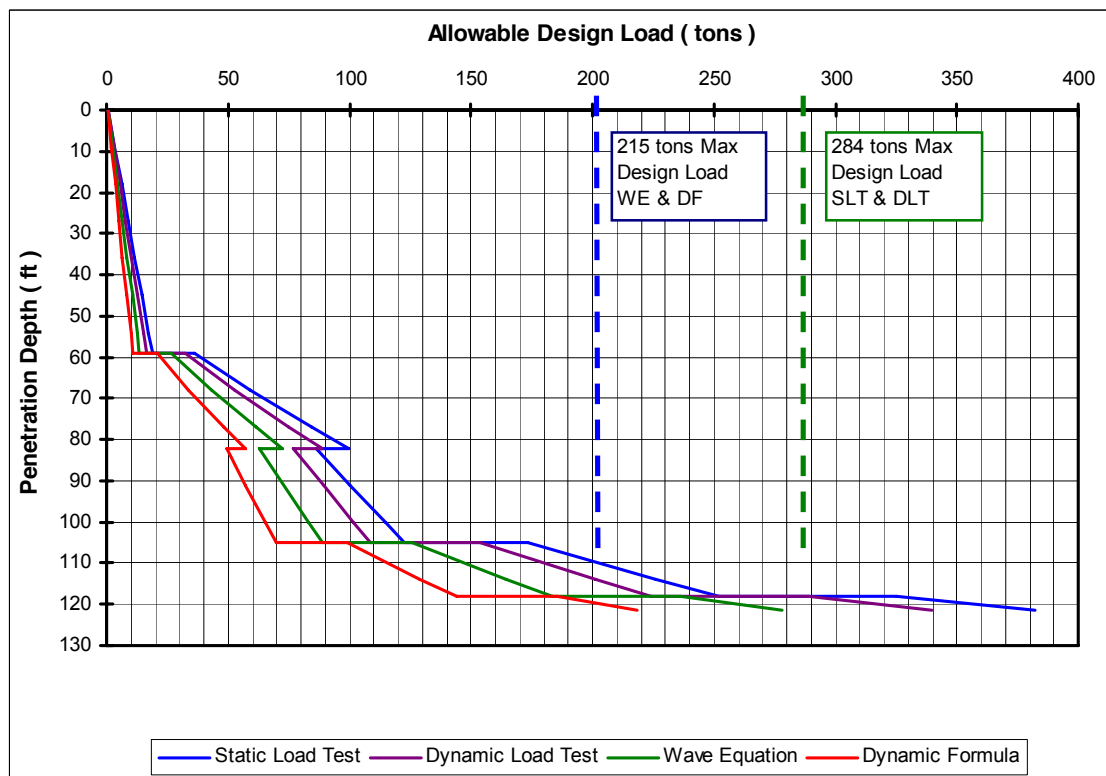


Figure 3.5b. Allowable Design Load in Tons Versus Depth Based on Construction Control

AASHTO maximum allowable design load on a given pile type are provided in Chapter 10. Design loads greater than the AASHTO limits should not be considered.

For the H-pile section used in the example, the maximum allowable design load varies from $0.25 F_y A_s$ for construction control with either wave equation (WE) or dynamic formula (DF) to $0.33 F_y A_s$ for construction control with either a dynamic load test (DLT) or static load test (SLT). These maximum allowable design loads are identified by the dashed vertical lines in Figures 3.5a and 3.5b. The allowable design load plots appear from right to left in order of the highest factor of safety to lowest factor of safety, i.e., dynamic formula (FS=3.5), wave equation (FS=2.75), dynamic load test (FS=2.25), and static load test (FS=2.0).

For the example give, the estimated pile penetration depth for the maximum design load allowed by each of the construction control methods are as follows:

| Construction Control Method | Pile Depth | Maximum Design Load |
|-----------------------------|-----------------|---------------------|
| Gates Dynamic Formula | 36.9 m (121 ft) | 1915 kN (215 tons) |
| Wave Equation | 36 m (118 ft) | 1915 kN (215 tons) |
| Dynamic Load Test | 36 m (118 ft) | 2528 kN (284 tons) |
| Static load Test | 36 m (118 ft) | 2528 kN (284 tons) |

The pile support cost in dollars per allowable kN (ton) versus the allowable design load as a function of the construction control method should then be plotted as illustrated in Figures 3.6a (SI units) and 3.6b (US units). Since design loads are used, the pile support cost in these plots is the pile support cost – design. These plots allow a quick evaluation of the most cost effective construction control methods for a given design load. The dashed horizontal lines in these plots also indicate the maximum allowable design load that can be used on the pile section with a construction control method. Allowable design loads greater than the values indicated by the dashed line are not permissible for that construction control method but may be possible for a construction control method that uses a lower factor of safety. Figures 3.6a and 3.6b illustrate, the pile support cost at the maximum allowable design load for the pile section ranges from lowest to highest using dynamic formula, dynamic load test, wave equation analysis and then static load test as the method of construction control.

The next step in the optimization process is to determine the approximate pile cap size and cost for the required number of piles. Sections 10.5 and 10.6 of Chapter 10 discuss preliminary layout of pile groups and sizing of pile caps. The pile cap support cost can then be approximated using bid price information per cubic yard of reinforced concrete. The pile

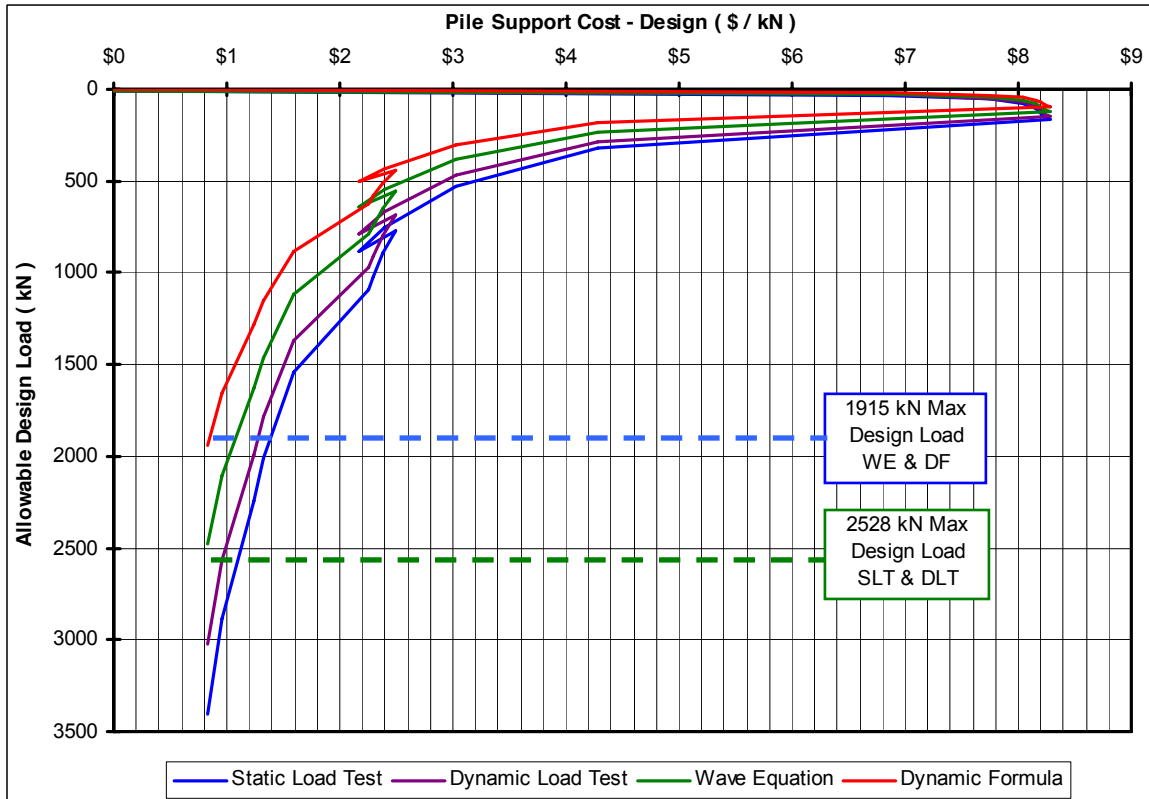


Figure 3.6a Pile Support Cost – Design Versus Allowable Design Load in kN

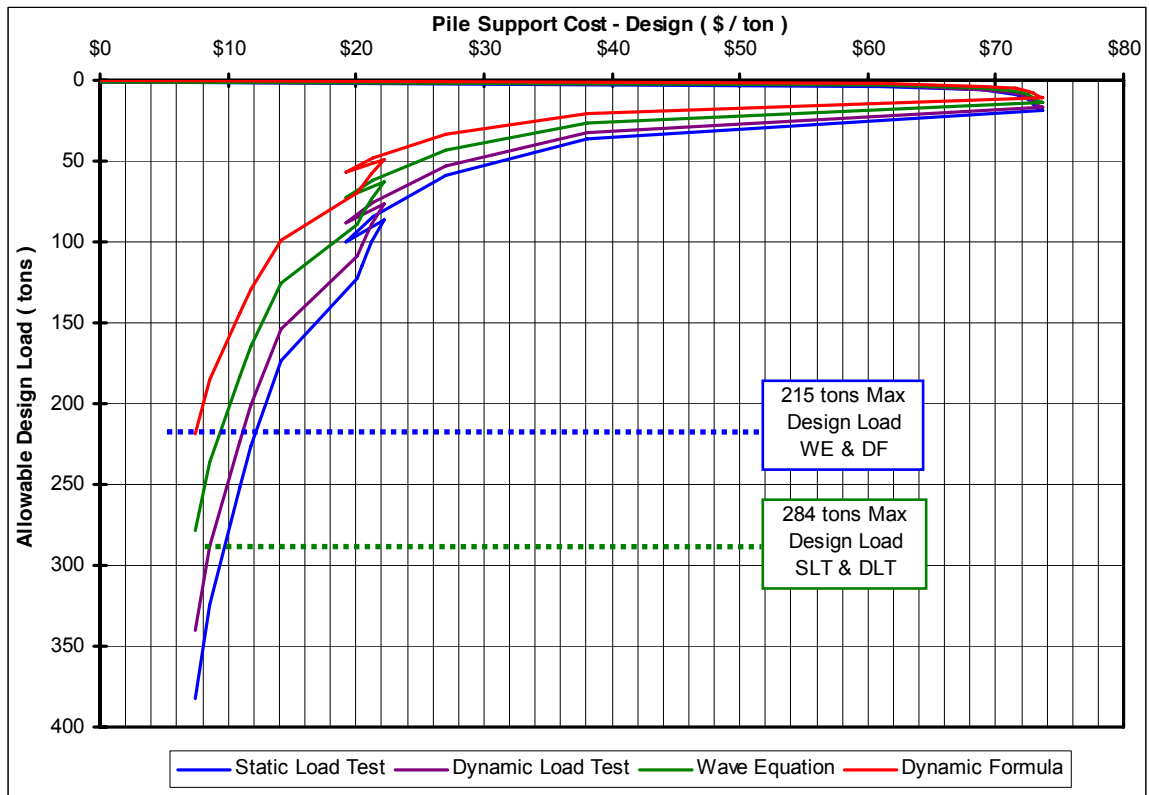


Figure 3.6b Pile Support Cost – Design Versus Allowable Design Load in Tons

cap support cost should also include construction considerations in addition to material costs. For example, the cost of excavations, cofferdams or retention systems, utility relocations, and removal and disposal of any contaminated soils should be included in the pile cap support where applicable.

For a common pile section and loads, a graph of approximate pile cap support cost as a function of column load could also be developed to allow for quicker cost estimates. An example plot of pile cap support cost versus column load for various pipe pile design loads is presented in Figure 3.7. This plot was specifically developed for 273 mm (10.75 inch), 324 mm (12.75 inch), 356 mm (14 inch), and 406 mm (16 inch) O.D., concrete filled pipe piles. The chart considers that 273 mm (10.75 inch) O.D. piles were used for design load up to an including 890 kN (100 tons), 324 mm (12.75 inch) O.D. piles were used for a design load of 1335 kN (150 tons), 356 mm (14 inch) O.D. pipe piles were used for a design load of 1780 kN (200 tons), and 406 mm (16 inch) O.D. pipe piles were used for a design load of 2224 kN (250 tons). Pile spacing was set at 3 times the pile diameter.

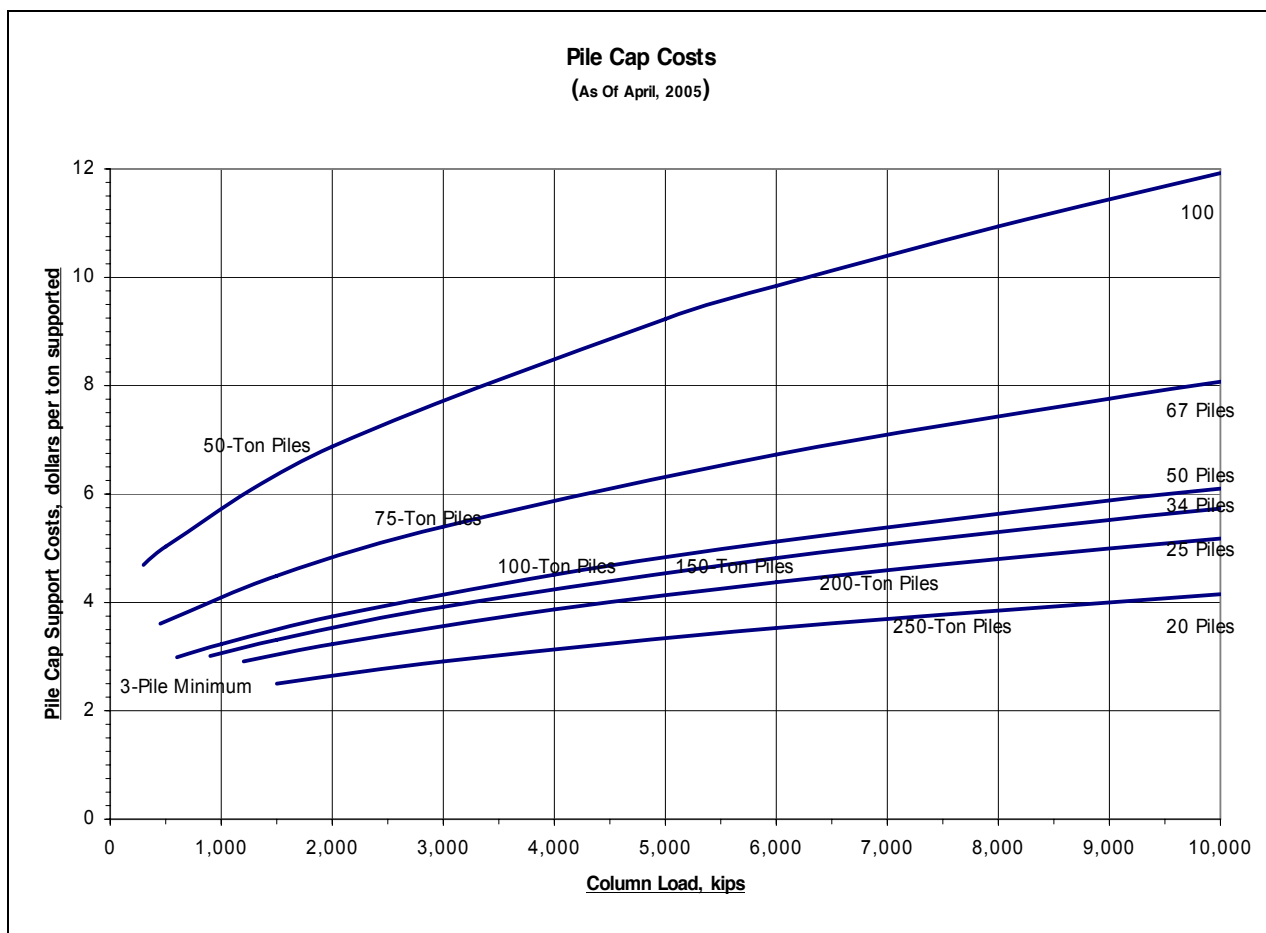


Figure 3.7 Pile Cap Cost as a Function of Column Load and Pile Design Load

The cost optimization process requires an evaluation of the total foundation support cost including the number of piles required, the pile cap size, cost of the construction control method, construction costs such as cofferdams, cost of any environmental restrictions, utility relocation costs, etc.

For example, consider a four span structure where preliminary estimates indicate maximum vertical column loads of 20,000 kN (2,250 tons). For the potential pile termination depths and ultimate capacities discussed in Figure 3.2a and 3.2b, determine the approximate number of piles, pile cost, cap cost, construction control method cost, and total cost. An example cost computation for this example is presented in Table 3-2.

The construction control methods being considered for the four span bridge include:

- a) one static load test (at up to 3 times design load) and wave equation analyses (SLT),
- b) dynamic testing of one test pile at each substructure location during initial driving and during restrike with signal matching and wave equation analyses (DLT),
- c) wave equation analyses for each substructure location (WE),
- d) the modified Gates dynamic formula (DF).

A review of Table 3-2 indicates high capacity piles driven to bedrock at 36 m (118 ft) for support of the maximum design load allowed on the section of 2528 kN (284 tons) with either dynamic load tests or a static load test for construction control will be the most cost effective. This cost evaluation example was based only on axial load considerations. In some cases, a minimum number of piles may be required to resist lateral load performance requirements. A wave equation analysis of pile driveability should also be performed to confirm that the pile can be driven to the required depth and capacity. Pile driveability is discussed later in Chapters 9 and 16.

Additional factors and their effect on the design economics that should be factored into the final section selection in the above example include construction limitations on time or space and any minimum penetration depth requirements for uplift loads (section driveability). Similar foundation support cost evaluations of other viable shallow and deep foundation systems should be performed for optimization of the final design.

3.3.3. Cost Optimization for Multiple Pile Types and/or Pile Sections

The steps described above for optimization of one pile section should be followed for economic evaluation and optimization of all candidate pile type and sections. Rational

Table 3-2 Example Cost Computation for Foundation Optimization

| Pile Penetration Depth (m) | Ultimate Pile Capacity (kN) | Construction Control Method (C.C.M.) | Allowable Design Load (kN) | Approx. Number of Piles | Pile Support Cost at \$154/m | Approx. Pile Cap Support Cost | Cost of C.C.M. Tests | C.C.M. Support Cost Per Substructure Unit | Total Foundation Cost |
|----------------------------|-----------------------------|--------------------------------------|----------------------------|-------------------------|------------------------------|-------------------------------|----------------------|---|-----------------------|
| 18 | 650 | SLT | 325 | 62 | \$ 171,864 | \$ 23,062 | \$ 25,000 | \$ 6,250 | \$ 201,176 |
| | | DLT | 289 | 70 | \$ 194,040 | \$ 24,750 | \$ 15,000 | \$ 3,750 | \$ 222,540 |
| | | WE | 236 | 85 | \$ 235,620 | \$ 25,875 | \$ 2,000 | \$ 500 | \$ 261,995 |
| | | DF | 186 | 108 | \$ 299,376 | \$27,000 | \$ 200 | \$ 50 | \$ 326,426 |
| 21 | 1100 | SLT | 550 | 37 | \$ 119,658 | \$ 18,000 | \$ 30,000 | \$ 7,500 | \$ 145,158 |
| | | DLT | 489 | 41 | \$ 132,594 | \$ 19,125 | \$ 15,000 | \$ 3,750 | \$ 155,469 |
| | | WE | 400 | 50 | \$ 161,700 | \$ 21,375 | \$ 2,000 | \$ 500 | \$ 183,575 |
| | | DF | 314 | 64 | \$ 206,976 | \$ 23,060 | \$ 200 | \$ 50 | \$ 230,086 |
| 32 | 3080 | SLT | 1540 | 13 | \$ 64,064 | \$ 9,340 | \$ 35,000 | \$ 8,750 | \$ 82,154 |
| | | DLT | 1369 | 15 | \$ 73,920 | \$ 9,560 | \$ 15,000 | \$ 3,750 | \$ 87,230 |
| | | WE | 1120 | 18 | \$ 88,704 | \$ 9,900 | \$ 2,000 | \$ 500 | \$ 99,104 |
| | | DF | 880 | 23 | \$ 113,344 | \$ 10,460 | \$ 200 | \$ 50 | \$ 123,854 |
| 36 | 5780 | SLT | 2890* | 8 | \$ 44,352 | \$ 6,190 | \$ 40,000 | \$ 10,000 | \$ 60,542 |
| | | DLT | 2609* | 8 | \$ 44,352 | \$ 6,190 | \$ 15,000 | \$ 3,750 | \$ 54,292 |
| | | WE | 2101** | 11 | \$ 60,984 | \$ 8,440 | \$ 2,000 | \$ 500 | \$ 69,924 |
| | | DF | 1651 | 13 | \$ 72,072 | \$ 9,340 | \$ 200 | \$ 50 | \$ 81,462 |

* - load limited to maximum allowable of 2528 kN

** - load limited to maximum allowable of 1915 kN

economic evaluation and optimized selection of the pile type and section can be made by following the single pile procedure provided above for each candidate pile type.

A real four span structure such as the one used in the single pile optimization example may have abutment loads that are about $\frac{1}{2}$ the pier loads. In this case, the minimum number of piles may govern the foundation design at the abutments. Figures 3.8a and 3.8b provide comparison plots of the pile support cost – ultimate versus depth for the HP 360 x 174 (HP 14x117) H-pile used in the single pile optimization example along with an HP 360 x 108 (HP 14x73) H-pile. The HP 360 x 108 section has a lower pile support cost – ultimate at the same depth compared to the HP 360 x 174 section. Hence, if the minimum number of piles governs the foundation design at the abutments, use of shorter, lower capacity, smaller section piles may be more cost effective.

Use of the foundation support cost concept allows sound economic and engineering decisions to be made in evaluating candidate pile types or sections, and in selecting the optimum structure foundation. The foundation support cost concept is a decision making process, not an estimating process. Therefore, the accuracy in the cost estimates is not as important as the relative difference between the cost estimates as long as consistent cost estimating methodology is maintained between all foundation alternatives.

3.4 USE OF VALUE ENGINEERING PROPOSALS

Value engineering is a cost saving technique that can be used either in the pre-bid or post bid stage of a contract. Value engineering consists of a five step logical thought process used to obtain the desired performance for the lowest cost achievable.

Value engineering can readily be applied to foundation engineering by allowing the use of value engineering change proposals in design or construction contracts. The obvious benefit of value engineering to the owner is a lower cost foundation. The consultant or contractor reward for an alternative foundation solution is typically a percentage of the cost savings realized by the owner.

For value engineering to be successful, the owner must be assured that the foundation performance criteria (total settlement, differential settlement, and lateral deformations) remain satisfied. This requires the owner to engage knowledgeable experts to review and comment on submittals as well as to be actively involved in resolution of technical details. In some cases, design verification testing or more sophisticated construction control may be required in order to confirm foundation performance criteria. Lastly, the review of submitted proposals must also be completed in a reasonable time period.

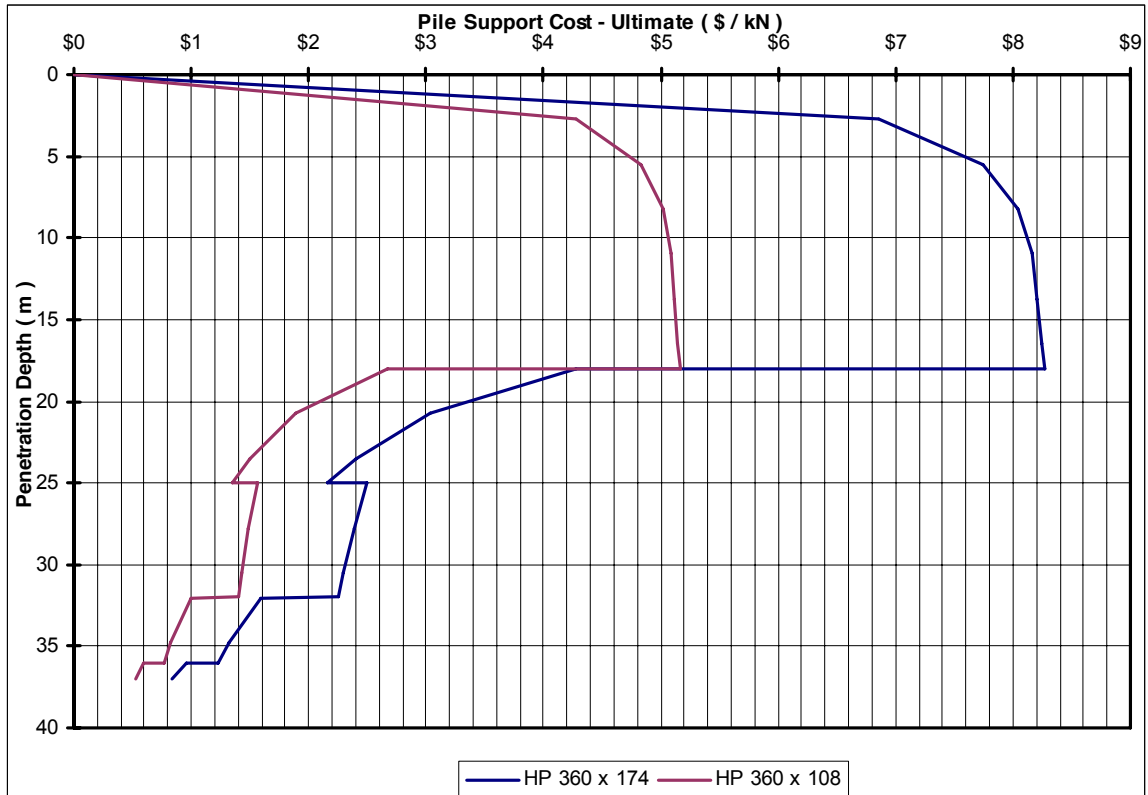


Figure 3.8a Pile Support Cost – Ultimate (\$/kN) vs Depth (m) for Two H-pile Sections

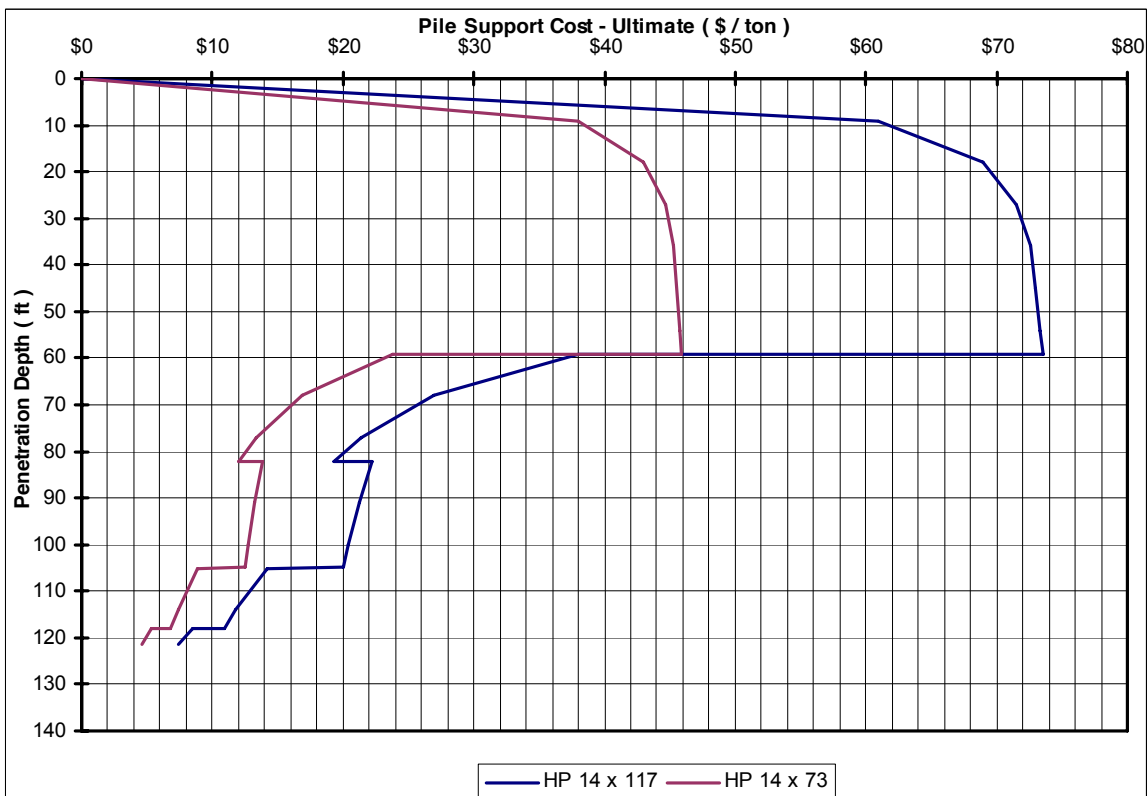


Figure 3.8b Pile Support Cost – Ultimate (\$/ton) vs Depth (ft) for Two H-pile Sections

Significant cost savings can result from value engineering. However, the cost savings should not be achieved by acceptance of unproven pile types, splices, *etc.* Proposed substitutions should be of equivalent quality and have a documented performance record in similar foundation installation conditions.

3.5 DESIGN - BUILD CONTRACTS

Another potential cost saving method is the use of design - build contracts. In this approach, the owner details the general project scope and performance requirements and solicits design - build proposals. Advantages associated with design – build contracts include quicker delivery of the project, use of new cost effective solutions to design and construction issues, and use of the contractor's knowledge of special equipment or procedures.

Some of the greatest difficulties in design - build contracts surround the scope of the subsurface exploration program, adequate definition of the project performance requirements, and determining the minimum requirements of the quality control and assurance program. Therefore, it is important for the owner in design – build contracts to understand and clearly communicate the project scope, performance requirements, and desired end product as well as method of measurement for payment. Failure to do so may result in a constructed product not meeting the owner's expectations or failing to meet the agreed-upon budget.

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Chapter 4

SUBSURFACE EXPLORATIONS

The design of a structure's foundation requires adequate knowledge of the subsurface conditions at the construction site. If the designer has the appropriate information, then an economical foundation system can be designed. The absence of a thorough foundation study or adequate geotechnical data often leads to (1) a foundation system with a large factor of safety which is generally a more expensive foundation and in some cases one that may be difficult to construct, or to (2) an unsafe foundation, or to (3) construction disputes and claims.

A thorough foundation study consists of a subsurface exploration program (which includes borings, sampling, groundwater measurements, and in-situ testing); laboratory testing; geotechnical analysis of all data; a determination of design properties; and design recommendations. This chapter covers the subsurface exploration portion of a foundation design study in a concise manner. A more detailed treatment of this chapter's subject matter may be found in the AASHTO Manual on Subsurface Investigations (1988) and in FHWA publication FHWA-NHI-01-031, Subsurface Investigations – Geotechnical Site Characterization (2002). Chapter 5 of this manual focuses on in-situ testing which is also considered part of a subsurface exploration, and Chapter 6 discusses laboratory testing. This chapter assumes that a decision with regard to the foundation type, *i.e.*, shallow or deep has not yet been made.

4.1 SUBSURFACE PROPERTIES FOR PILE DESIGN

Static analysis procedures described in Chapter 9 of this manual are used to estimate a pile foundations ability to support the applied compression, uplift, and lateral loads. Knowledge of the subsurface stratigraphy, soil classification and index properties, shear strength, compressibility, stress history, and the ground water table location is required for design. In addition, the pile selection process described in Chapter 8 will require knowledge of the aggressiveness of the subsurface environment on possible foundation types. The subsurface exploration program must be planned to delineate the subsurface stratigraphy and retrieve quality soil and rock samples so that the design soil profile and soil parameters can be subsequently developed.

Table 4-1 provides a summary of the design parameters needed for pile design as well as the sampling and/or test methods commonly used to obtain the design parameter. Subsurface stratigraphy and soil classification including gradation, Atterberg limits, and moisture content must be determined so that applicable pile design methods for capacity

and settlement computations are utilized for the subsurface conditions. Accurate determination of the effective friction angle or undrained shear strength of the soil strata is particularly important for piles designed to carry their loads through shaft resistance or for foundations subject to significant uplift loading. For pile foundations designed to transfer a majority of their load through end bearing on soil or rock, the soil strength parameters of the bearing layer or determination of the rock quality is important. Knowledge of the preconsolidation pressure of cohesive deposits is important in pile foundation designs that transfer load to or are supported above cohesive layers. Many of the design methods are effective stress based procedures that require information on soil unit weights and water table location. A pile foundation design will be more efficient when the subsurface parameters described in Table 4-1 are adequately and accurately defined.

| TABLE 4-1 SUMMARY OF FIELD OR LABORATORY TESTS FOR PILE DESIGN PARAMETERS | | | |
|---|---------------------|-------------------------|-------------------|
| Design Parameter or Information Needed | Subsurface Material | | |
| | Cohesionless | Cohesive | Rock |
| Subsurface stratigraphy | SPT, CPTu, CPT, DMT | SPT, CPTu, CPT, DMT | Rock Core |
| Classification | Lab | Lab | Lab |
| Gradation | Lab | Lab | |
| Atterberg Limits | | Lab | |
| Moisture Content | Lab | Lab | |
| Unit Weight, γ | SPT, DMT | USS-Lab | USS-Lab |
| Sensitivity | | VST, USS-Lab | |
| Effective friction angle, ϕ' | SPT, CPTu, CPT, DMT | USS-Lab | USS-Lab |
| Undrained shear strength, c_u | | Lab | |
| Preconsolidation pressure, p_c | | USS-Lab, DMT, CPTu, CPT | |
| Rock quality, RQD | | | Rock Core |
| Groundwater table elevation | Well / Piezometer | Well / Piezometer | Well / Piezometer |

Table Key:

SPT – Standard Penetration Test (Section 4.4.1)

CPTu – Cone Penetration Test with pore water pressure measurements (Section 5.1)

CPT – Cone Penetration Test (Section 5.1)

DMT – Dilatometer Test (Section 5.3)

VST – Vane Shear Test (Section 5.4)

Lab – Laboratory test on a disturbed or undisturbed soil sample (Chapter 6)

USS-Lab – Laboratory test on undisturbed soil sample (Section 4.4.2 and Chapter 6)

4.2 SUBSURFACE EXPLORATION PHASES

There are three major phases in a subsurface exploration program. These phases are (1) planning the exploration program (office work), (2) completing a field reconnaissance survey, and (3) performing a detailed site exploration program (boring, sampling, and in-situ testing). Each phase should be planned so that a maximum amount of information can be obtained at a minimum cost. Each phase also adds to, or supplements, the information from the previous phase. Table 4-2 lists the purpose of each exploration phase.

4.2.1 Planning the Exploration Program (office work)

The purpose of this phase is to obtain information about the proposed structure and general information on the subsurface conditions. The structural information can be obtained from studying the preliminary structure plan prepared by the bridge design office and by meeting with the structural designer. Approach embankment preliminary design and performance requirements can be obtained from the roadway office. General information about the subsurface conditions can be obtained from a variety of sources listed in Table 4-3. **The planning phase prepares the engineer for the field reconnaissance survey, and identifies possible problems and areas to scrutinize.**

4.2.2 Field Reconnaissance Survey

The purpose of this phase is to substantiate the information gained from the office phase and to plan the detailed site exploration program. The field reconnaissance for a structure foundation exploration should include:

- a. Inspection of nearby structures to determine their performance with the particular foundation type used.
- b. Inspection of existing structure footings and stream banks for evidence of scour (for stream crossings) and movement. Large boulders in a stream are often an indication of obstructions which may be encountered in pile installations.
- c. Visual examination of terrain for evidence of landslides.
- d. Recording of the location, type and depth of existing structures which may be affected by the new structure construction.

| TABLE 4-2 SUBSURFACE EXPLORATION PHASES | | | |
|---|---|--|---|
| Phase | Activity | Purpose | Remarks |
| 1. | Planning the exploration (Office Work). | <p>A. Obtain structure information. Determine:</p> <ol style="list-style-type: none"> 1. Type of structure. 2. Preliminary location of piers and abutments. 3. Loading and special design events. 4. Allowable differential settlement, lateral deformations, and other performance criteria. 5. Any special features and requirements. <p>B. Obtain drilling records for nearby structures and from local well drillers.</p> <p>C. Perform literature reviews including maintenance records, pile driving records, scour history, <i>etc.</i></p> <p>Obtain overall picture of subsurface conditions in the area.</p> | See Table 4-2 for sources of information. |
| 2. | Field Reconnaissance Survey | <p>Verify information gained from the office phase and plan the detailed subsurface exploration.</p> <p>A. Observe, verify and collect information regarding:</p> <ol style="list-style-type: none"> 1. Topographic and geologic features. 2. New and old construction in the area including utilities. Performance of existing structures. 3. Drilling equipment required, cost, and access for the equipment. <p>B. If appropriate, conduct geophysical testing to obtain preliminary subsurface information.</p> | Field reconnaissance is often conducted by a multi-disciplined team. |
| 3. | Detailed Subsurface Exploration | <p>Develop a preliminary boring plan based on phases 1 and 2. Conduct a preliminary evaluation for viable foundation systems including ground improvement. Determine subsurface requirements for all of the viable foundation systems. The boring plan should be modified if needed as the borings are performed and detailed subsurface information is obtained.</p> <p>The subsurface exploration should provide the following:</p> <ol style="list-style-type: none"> 1. Depth and thickness of strata (subsurface profile). 2. In-situ field tests to determine soil design parameters. 3. Samples to determine soil and rock design parameters. 4. Groundwater levels including perched, regional, and any artesian conditions. | For major structures, the pilot boring program is often supplemented with control and verification boring programs. |

- e. Relating site conditions to proposed boring operations. This includes recording the locations of both overhead and below ground utilities, site access, private property restrictions, and other obstructions.
- f. Recording of any feature or constraint which may impact the constructability of potential foundation systems.

Table 4-4 contains an example of a field reconnaissance form modified from the AASHTO Foundation Investigation Manual (1978) for recording data pertinent to a site.

4.2.3 Detailed Site Exploration

The purpose of any boring program is not just to drill a hole, but to obtain representative information on the subsurface conditions, to recover disturbed and undisturbed soil samples, and to permit in-situ testing. This information provides factual basis upon which all subsequent steps in the pile design and construction process are based. It's quality and completeness are of paramount importance. Each step in the process directly or indirectly relies on this data.

The first step in this phase is to prepare a preliminary boring, sampling, and in-situ testing plan. For major structures, pilot borings are usually performed at a few select locations during the preliminary planning stage. These pilot borings establish a preliminary subsurface profile and thus identify key soil strata for testing and analysis in subsequent design stage borings. During the design stage of major structures, a two phase boring program is recommended. First, control borings are performed at key locations identified in the preliminary subsurface profile to determine what, if any, adjustments are appropriate in the design stage exploration program. Following analysis of the control boring data, verification borings are then performed to fill in the gaps in the design stage exploration program.

| TABLE 4-3 SOURCES OF SUBSURFACE INFORMATION AND USE | | |
|---|---|--|
| Source No. | Source | Use |
| 1. | Preliminary structure plans prepared by the bridge design office. | Determine: 1. Type of structure. 2. Preliminary locations of piers and abutments. 3. Footing loads and special design events. 4. Allowable differential settlement, lateral deformations, and performance criteria. 5. Any special features and requirements. |
| 2. | Construction plans and records for nearby structures. | Foundation type, old boring data, construction information including construction problems. |
| 3. | Topographic maps prepared by the United States Coast and Geodetic Survey (USC and GS), United States Geological Survey (USGS) and State Geology survey. | Existing physical features shown; find landform boundaries and determine access for exploration equipment. Maps from different dates can be used to determine topographic changes over time. |
| 4. | County agricultural soil survey maps and reports prepared by the United States Department of Agriculture (USDA). | Boundaries of landforms shown; appraisal of general shallow subsurface conditions. |
| 5. | Air photos prepared by the United States Geological Survey (USGS) or others. | Detailed physical relief shown; gives indication of major problems such as old landslide scars, fault scarps, buried meander channels, sinkholes, or scour; provides basis for field reconnaissance. |
| 6. | Well drilling record or water supply bulletins from state geology or water resources department. | Old well records or borings with general soils data shown; estimate required depth of explorations and preliminary cost of foundations. |
| 7. | Geologic maps and Geology bulletins. | Type, depth and orientation of rock formations. |

TABLE 4-4 EXAMPLE FIELD RECONNAISSANCE REPORT FORM

Bridge Foundation Investigation
Field Reconnaissance Report
_____ Department of Transportation

Project No: _____ County _____ Sta. No. _____

Reported By: _____ Date _____

- | | |
|---|---|
| <p>1. Staking of Line Well Staked _____ Poorly Staked (We can work) _____ Request Division to Restake _____</p> <p>2. Bench Marks In Place: Yes _____ No _____ Distance from bridge - m (ft) _____</p> <p>3. Property Owners Granted Permission: Yes _____ No _____ Remarks on Back _____</p> <p>4. Utilities Will Drillers Encounter Underground or Overhead Utilities? Yes _____ No _____ Maybe _____ At Which Holes? _____ What Type? _____ Who to See for Definite Location _____ _____</p> <p>5. Geologic Formation _____</p> <p>6. Surface Soils Sand _____ Clay _____ Sandy Clay _____ Muck _____ Silt _____ Other _____</p> <p>7. General Site Description Topography Level _____ Rolling _____ Hillside _____ Valley _____ Swamp _____ Gullied _____ Groundcover Cleared _____ Farmed _____ Buildings _____ Heavy Woods _____ Light Woods _____ Other _____ Remarks on Back _____</p> <p>8. Bridge Site Replacing _____ Widening _____ Relocation _____ Check Appropriate Equipment Truck Mounted Drill Rig _____ Track Mounted Drill Rig _____ Failing 1500 _____ Truck Mounted Skid Rig _____ Skid Rig _____ Rock Coring Rig _____ Wash Boring Equipment _____ Water Wagon _____ Pump _____ Hose _____ m (ft) _____</p> | <p>8. Bridge Site - Continued Cut Section - m (ft) _____ Fill Section - m (ft) _____ If Stream Crossing: Will Pontoons Be Necessary? _____ Can Pontoons Be Placed in Water Easily? _____ _____</p> <p>Can Cable Be Stretched Across Stream? How Long? _____</p> <p>Is Outboard Motorboat Necessary? _____ Current: Swift _____ Moderate _____ Slow _____ Describe Streambanks scour. If Present Bridge Nearby: Type of Foundation _____ Any Problems Evident in Old Bridge Including Scour _____ (describe on back) Is Water Nearby for Wet Drilling - m (ft) _____ Are Abandoned Foundations in Proposed Alignment? _____</p> <p>9. Ground Water Table Close to Surface - m (ft) _____ nearby Wells - Depth - m (ft) _____ Intermediate Depth - m (ft) _____ Artesian head - m (ft) _____</p> <p>10. Rock Boulders Over Area? Yes _____ No _____ Definite Outcrop? Yes _____ No _____ (show sketch on back) What kind? _____</p> <p>11. Special Equipment Necessary _____</p> <p>12. Remarks on Access (Describe any Problems on Access) _____ _____</p> <p>13. Debris and Sanitary Dumps Stations _____ Remarks _____ _____ _____ _____</p> <p>Reference: Modified from 1978 AASHTO Foundation Investigation Manual</p> |
|---|---|

4.3 GUIDELINES FOR MINIMUM STRUCTURE EXPLORATION PROGRAMS

The cost of a subsurface exploration program is comparatively small in relation to the foundation cost. For example, the cost of one 60 mm (2.4 inch) diameter boring is less than the cost of one 305 mm (12 inch) diameter pile. However, in the absence of adequate boring data, the design engineer must rely on extremely conservative designs with high safety factors. At the same time, the designer assumes enormous risk and uncertainty during the project's construction.

The number of borings required, their spacing, and sampling intervals depend on the uniformity of soil strata and loading conditions. Erratic subsurface conditions require closely spaced borings. Structures sensitive to settlements or subjected to heavy loads require detailed subsurface knowledge. In these cases borings should be closely spaced. Rigid rules for number, spacing, and depth of borings cannot be established. However, the following are general "guidelines" useful in preparing a boring plan.

1. A minimum of one boring with sampling should be performed at each pier or abutment. The boring pattern should be staggered at opposite ends of adjacent footings. Pier and abutment footings over 30 m (100 ft) in length require borings at the extremities of the substructure units.
2. Estimate required boring depths from data gathered in the planning and field reconnaissance phases. Confirmation of boring depth suitability for design purposes should be made by the geotechnical engineer as soon as possible after field crews initiate a boring program. Although less preferred, it may be possible for field crews to adjust boring depths using a resistance criteria such as: "Structure foundation borings shall be terminated when a minimum SPT resistance of 50 blows per 300 mm (1 ft) has been maintained for 7.5 m (25 ft). (This rule is intended for preliminary guidance to drillers. For heavy structures with high capacity piles, the borings must go deeper. A resistance criteria may also be inappropriate in some geologic conditions such as sites with boulder fields.)
3. All borings should extend through unsuitable strata, such as unconsolidated fill, peat, highly organic materials, soft fine grained soils and loose coarse-grained soils to reach hard or dense materials. Where stiff or dense soils are encountered at shallow depths, one or more borings should be extended through this material to a depth where the presence of underlying weaker strata cannot affect stability or settlement of the structure.

4. Standard Penetration Test (SPT) samples should be obtained at 1.5 m (5 ft) intervals or at changes in material with the test data recorded in accordance with AASHTO T206. For spread footing design or embankment evaluations, continuous sampling over the 6 m (20 ft) should be performed. Undisturbed tube samples should be obtained in accordance with AASHTO T207 at sites where cohesive soils are encountered. The location and frequency of undisturbed soil sampling should be based on project requirements.
5. When rock is encountered at shallow depths, additional borings or other investigation methods such as probes, test pits, or geophysical tests may be needed to define the rock profile. When feasible, borings should extend a minimum of 3 m (10 ft) into rock having an average core recovery of 50% or greater with an NX-core barrel providing a 54 mm (2-1/8 inch) diameter core.
6. Drill crews should maintain a field drilling log of boring operations. The field log should include a summary of drilling procedures including SPT hammer type, sample depth and recovery, strata changes, and visual classification of soil samples. The field log should also include pertinent driller's observations such as location of ground water table, boulders, loss of drilling fluids, artesian pressures, *etc.* Disturbed and undisturbed soil samples as well as rock cores should be properly labeled, placed in appropriate storage containers (undisturbed tube samples should be sealed in the field), and properly transported to the soils laboratory.
7. The water level reading in a bore hole should be made during drilling, at completion of the bore hole, and a minimum of 24 hours after completion of the bore hole. Long term readings may require installation of an observation well or piezometer in the bore hole. More than one week may be required to obtain representative water level readings in low permeability cohesive soils or in bore holes stabilized with some drilling muds.
8. All bore holes should be properly backfilled and sealed following completion of the subsurface exploration program, data collection, and analysis. Bore hole sealing is particularly important where groundwater migration may adversely affect the existing groundwater conditions (aquifer contamination) or planned construction (integrity of tremie seals in future cofferdams).

These guidelines should result in subsurface exploration data that clearly identify subsurface stratigraphy and any unusual conditions, allow laboratory assessments of soil strength and compressibility, and document the groundwater table conditions. This information permits a technical evaluation of foundation options and probable costs.

4.4 METHODS OF SUBSURFACE EXPLORATION

The most widely used method of subsurface exploration is drilling holes into the ground from which samples are collected for visual classification and laboratory testing. Table 4-5 summarizes the advantages and disadvantages of four commonly used soil boring methods, as well as rock coring, test pits and geophysical methods.

4.5 SOIL AND ROCK SAMPLING

One of the main purposes of a subsurface exploration program is to obtain **quality** soil and rock samples. Quality samples are important because soil identification and stratification, strength, and compressibility are all evaluated from samples recovered in the exploration program.

Soil samples are divided into two categories, disturbed and undisturbed. Disturbed samples are those which have experienced large structural disturbance during sampling operations and may be used for identification/classification tests. The primary disturbed sampling method is the split barrel sampler used in the Standard Penetration Test (SPT). The penetration resistance values obtained from the Standard Penetration Test are called N values. These N values provide an indication of soil density or consistency and shear strength. The recommended test procedures outlined in AASHTO T206 should be rigidly followed so that consistent, reliable SPT N values are obtained. SPT N values are commonly used for design of pile foundation design in granular soils. **SPT N values are NOT RECOMMENDED for pile design in cohesive soils.**

Undisturbed samples are those in which structural disturbance is kept to an absolute minimum. Undisturbed samples are used for consolidation tests and strength tests such as direct shear, triaxial shear and unconfined compression as well as for determining unit weight. Strength tests provide shear strength design parameters which are used in static analysis methods for pile foundation design. Consolidation tests provide parameters needed to estimate settlements of embankments, spread footings, or pile groups. Unit weight information is used in determining the effective overburden pressure.

Rock cores obtained from borings allow a qualitative evaluation of rock mass and distinguish between boulders and bedrock. Rock Quality Designation (RQD) values determined from cores indicate rock soundness and characteristics and may thereby be useful in estimating the compressive strength of the rock mass. Unconfined compression tests may also be performed on recovered, high quality core samples.

TABLE 4-5 METHODS OF SUBSURFACE EXPLORATIONS*

| Method | Depth | Type of Samples Taken | Advantages | Disadvantages | Remarks |
|--|---|--|--|--|---|
| 1. Seismic 2. Resistivity | Usually less than 30 m.(100 ft) | No samples are taken. | 1. Less expensive than borings. 2. Complements borings. 3. Data obtained very quickly. | 1. Indirect method of exploration, no samples are taken. 2. Interpretation of data is critical and requires substantial experience. | Main uses are described in AASHTO (1988). Additional limitations of seismic methods are: 1. Soil layers must increase in seismic velocities with depth. 2. The layer must be thick. |
| 3. Wash Boring | Depends on the equipment.. Most equipment can drill to depths of 30 m (100 ft) or more. | Disturbed and undisturbed. | 1. Borings of small and large diameter. 2. Equipment is relatively inexpensive. 3. Equipment is light. 4. Washwater provides an indication of change in materials. 5. Method does not interfere with permeability tests. | 1. Slow rate of progress. 2. Not suitable for materials containing stones and boulders. | Hole advanced by a combination of the chopping action of a light bit and jetting action of the water coming through the bit. |
| 4. Rotary Drilling | Depends on the equipment. Most equipment can drill to depths of 60 m (200 ft) or more. | Disturbed and undisturbed. | 1. Suited for borings 100 to 150 mm (4 to 6 inches) in diameter. 2. Most rapid method in most soils and rock. 3. Relatively uniform hole with little disturbance to the soil below the bottom of hole. 4. Experienced driller can detect changes based on rate of progress. | 1. Drilling mud if used does not provide an indication of material change as the washwater does. 2. Use of drilling mud hampers the performance of permeability tests. | Hole advanced by rapid rotation of drilling bit and removal of material by water or drilling mud. Rock coring is performed by rotary drilling. |
| 5. Auger Borings | Depends on the equipment. Most equipment can drill to depths of 30 to 60 m (100 to 200 ft). | Disturbed and undisturbed. | 1. Boring advanced without water or drilling mud. 2. Hollow stem auger acts as a casing. | 1. Difficult to detect change in material. 2. Heavy equipment required. 3. Water level must be maintained in boring equal to or greater than existing water table to prevent sample disturbance. | Hole advanced by rotating and simultaneously pressing an auger into the ground either mechanically or hydraulically. |
| 6. Continuous Sample Method of Advance | Depends on the equipment. | Disturbed and undisturbed. | Almost continuous record of the soil profile can be obtained. | Generally much slower in soils and more expensive than other methods. | Boring advanced by wash method, rotary drilling or auger method and continuous samples are taken. |
| 7. Rock Coring | Rotary drilling equipment is used to drill to depths of 60 m (200 ft) or more. | Continuous rock cores. | Helps differentiate between boulders and bedrock. | Can be slow and fairly expensive. | Several types of core barrels are used including wire line core barrels for deep drilling. |
| 8. Test Pits | Usually less than 6 m (20 ft) . | Disturbed samples and undisturbed block samples. | Least sample disturbance. Valuable in erratic soil deposits such as old fills, landfills, and residual soil deposits. | 1. Limited depth. 2. Slower and expensive. | Power equipment used to excavate the pits. Test pits should be located so as not to disturb bearing stratum if footing foundations are feasible. |

*Excluding in-situ tests.

4.5.1 Disturbed Soil Samplers

The split barrel sampler used in the Standard Penetration Test (SPT) is the primary disturbed soil sampler. The SPT test consists of driving a 51 mm (2 inch) O.D., 35 mm I.D., (1-3/8 inch) split-spoon sampler into the soil with a 64 kg (140 lb) mass dropped 760 mm (30 inches). The sampler is generally driven 450 mm (18 inches), and the blow count for each 150 mm (6 inch) increment is recorded. The number of blows required to advance the sampler from a penetration depth of 150 mm (6 inches) to a penetration depth of 450 mm (18 inches) is the SPT resistance value, N. A schematic of the Standard Penetration Test Procedure is provided in Figure 4.1, SPT hammer types are illustrated in Figure 4.2, and Figure 4.3 contains a picture of the split barrel sampler.

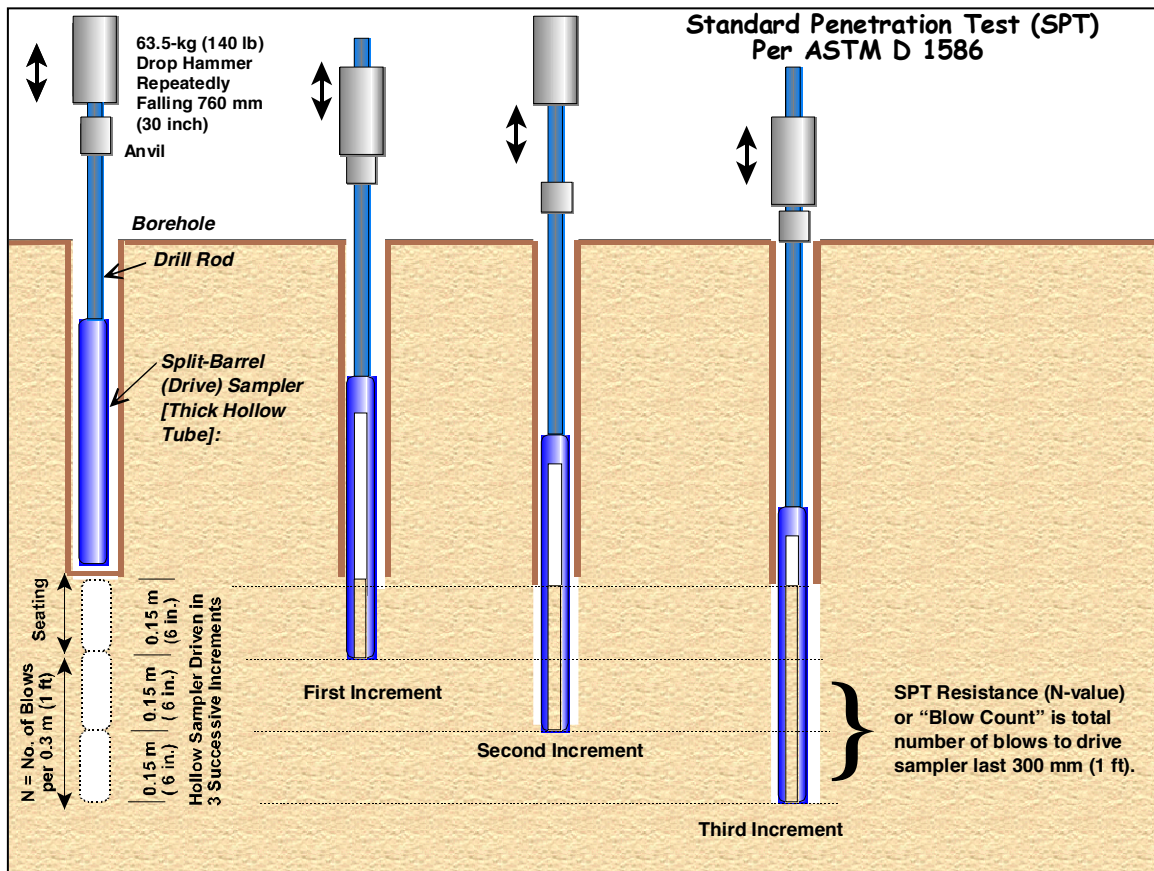


Figure 4.1 SPT Procedure from Mayne et. al., (2002)

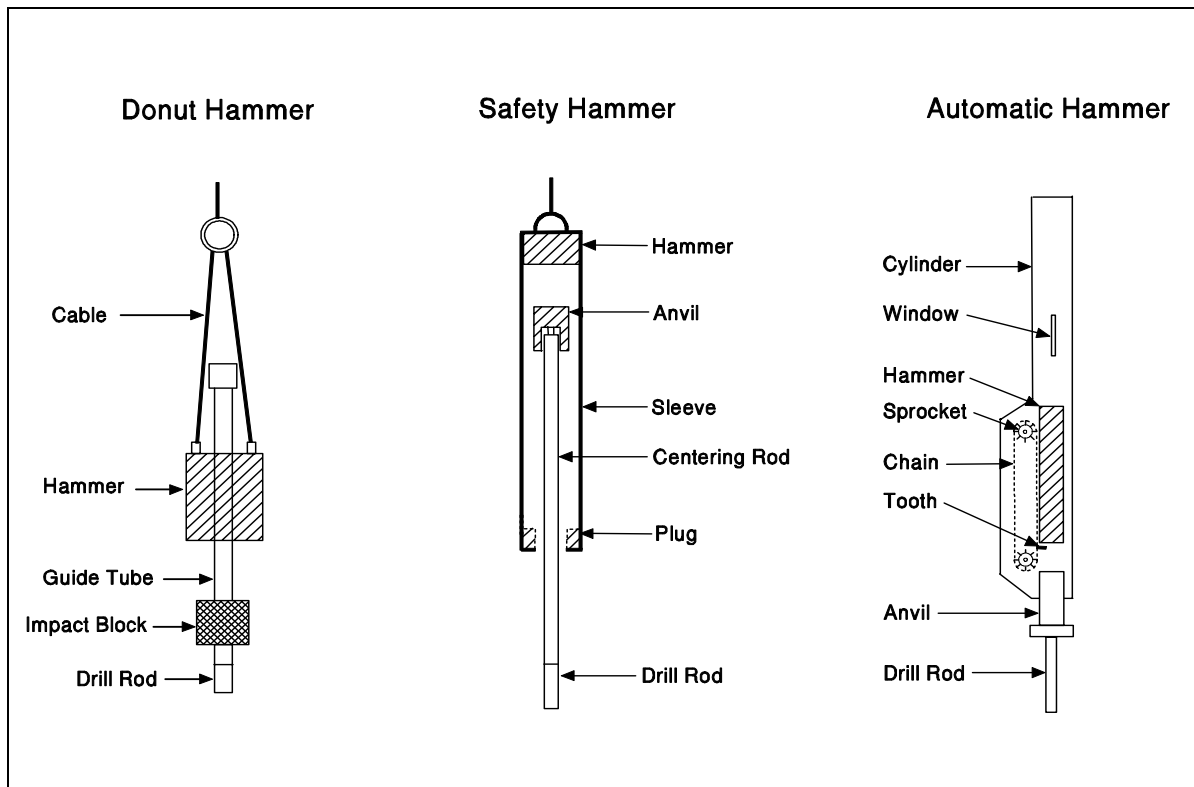


Figure 4.2 SPT Hammer Types



Figure 4.3 Split Barrel Sampler from Mayne et. al., (2002)

The SPT hammer type and operational characteristics have a significant influence on the resulting SPT N values. There are two main hammer types currently in use in the US, the safety hammer and the automatic hammer. A third hammer type, the donut hammer, was used almost exclusively prior to about 1970. However, it is seldom used now due to safety considerations. Figure 4.2 provides illustrations of these SPT hammer types. Numerous measurement studies on SPT energy transfer have been performed. In general, these studies have indicated that the typical energy transfer from donut, safety, and automatic hammers are on the order of 45%, 60%, and 80% of the SPT test potential energy, respectively. It should not be assumed that all SPT hammers of a given type will have the energy transfer values noted above. Energy transfer for a given hammer type can and does vary according to hammer maintenance, hammer manufacturer, driller, and operating procedures. Because of these variations, it is recommended that SPT hammers undergo a yearly calibration in accordance with ASTM D 4633-05 to document hammer performance. It may be particularly advantageous to conduct these calibrations prior to undertaking major projects. A photograph of energy transfer measurements being taken during a SPT sampling event is provide in Figure 4.4.

The pile design charts and methods provided in Chapter 9 that use SPT N values are based on safety hammer correlations, i.e., 60% energy transfer. SPT N values established on the basis on 60% energy transfer are referred to as N_{60} . SPT N values can be converted to N_{60} values based on energy transfer measurements as follows:

$$N_{60} = N (\text{ETR} / 60\%)$$

Where: N = field measured SPT N value

ETR = energy transfer ratio, i.e., transfer energy / potential energy (%)

The significance of the SPT hammer type and energy transfer on N values is apparent in a pile capacity prediction symposium reported by Finno (1989). For this event, two soil borings were drilled less than 10 m (33 ft) apart in a uniform sand soil profile. SPT N values were obtained using a safety hammer in one boring and an automatic hammer in the other boring.

Figure 4.5 presents a plot of the SPT N values versus depth from these two borings. The SPT N values from the safety hammer range from 1.9 to 2.7 times the comparable N value from the automatic hammer. **This significant variation in N values clearly indicates that the type of SPT hammer used should be recorded on all drilling logs.** It is recommended that N values be corrected and reported as N_{60} values whenever possible.

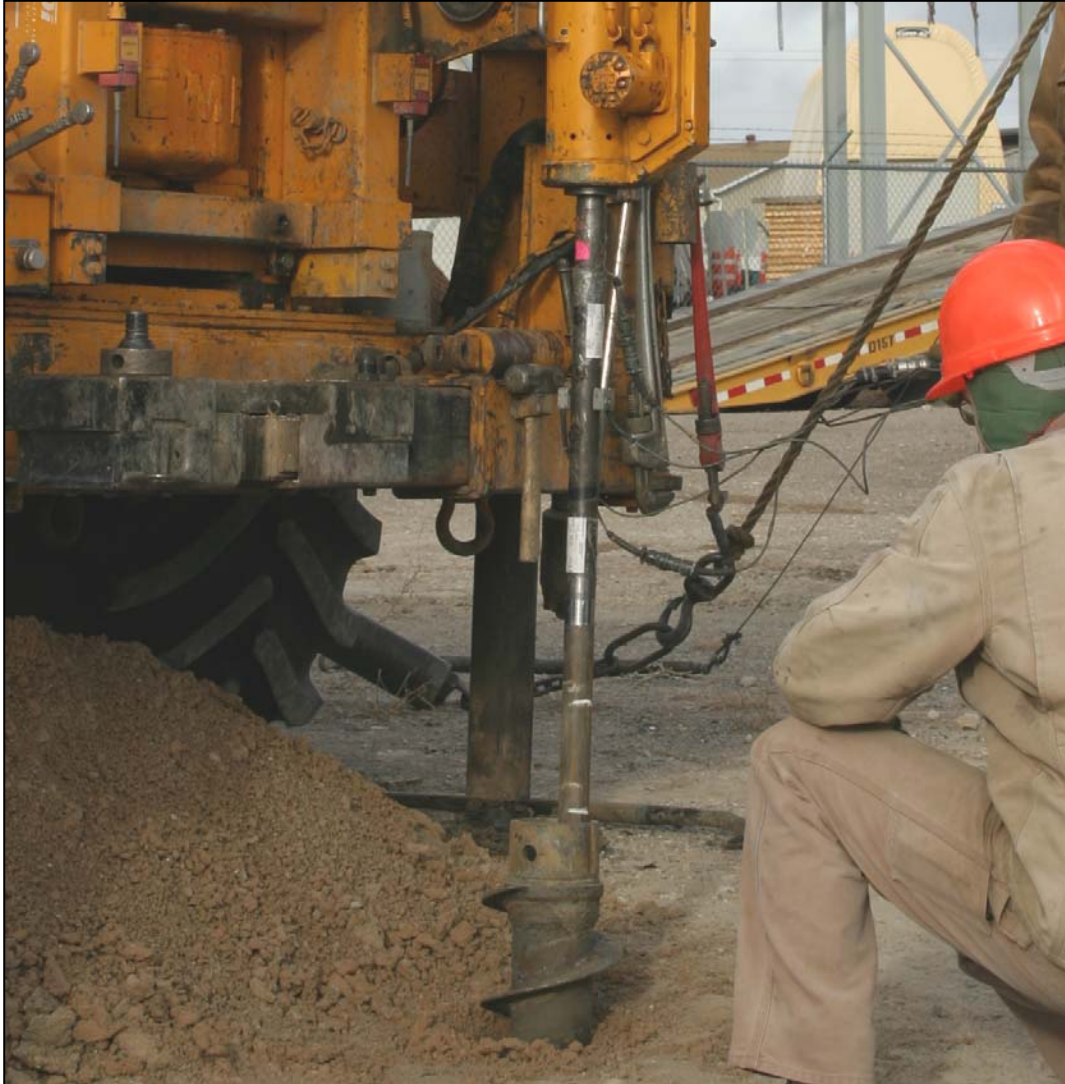


Figure 4.4 Energy Measurements on Automatic SPT Hammer

Cheney and Chassie (2000) list the following common errors that can influence SPT test results:

1. Effect of overburden pressure. Soils of the same density will give smaller SPT N values near the ground surface.
2. Variations in the 760 mm (30 inch) free fall of the drive weight, since this is often done by eye on older equipment using a rope wrapped around a power takeoff (cathead) from the drill motor. Newer automatic hammer equipment does this automatically.

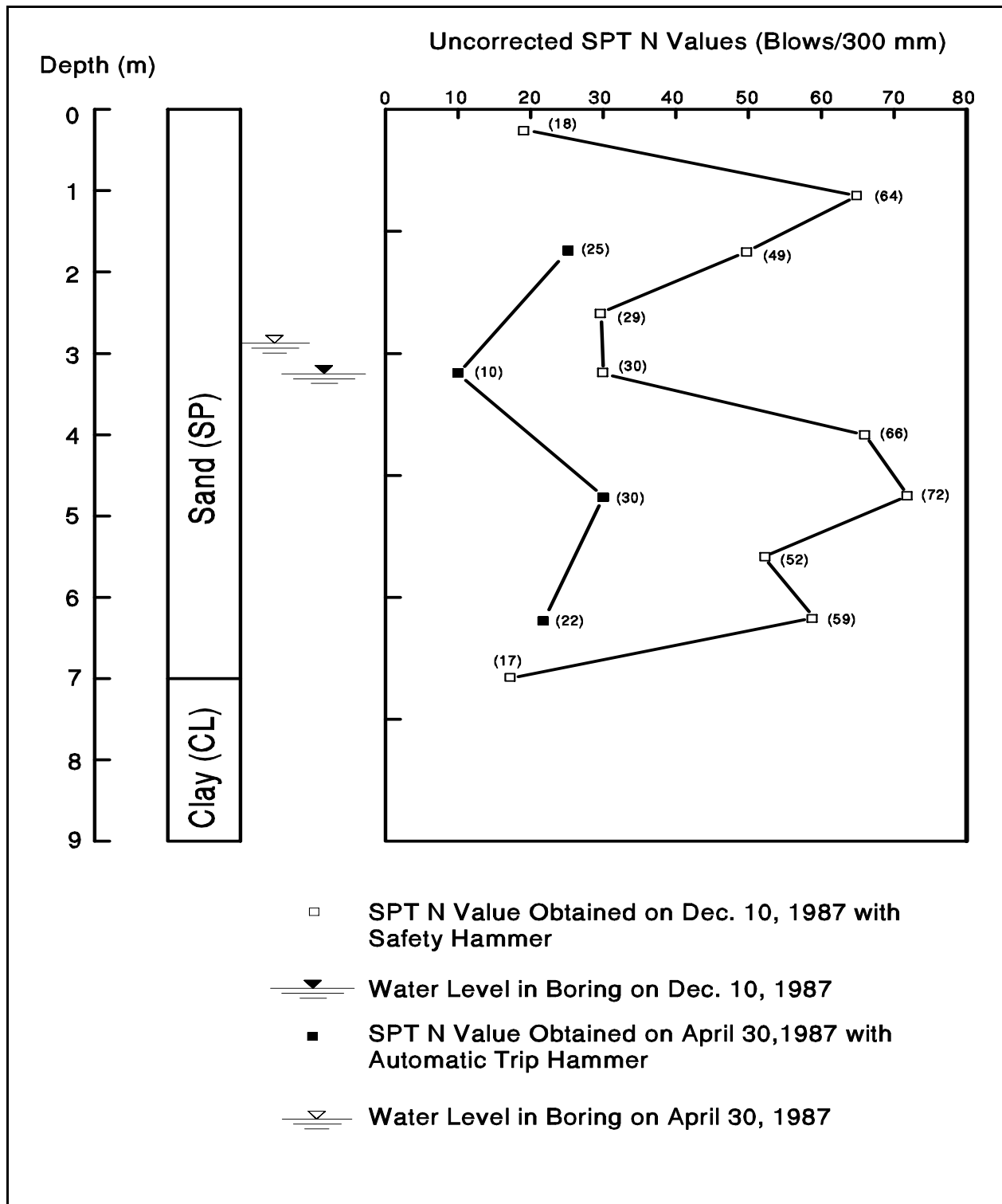
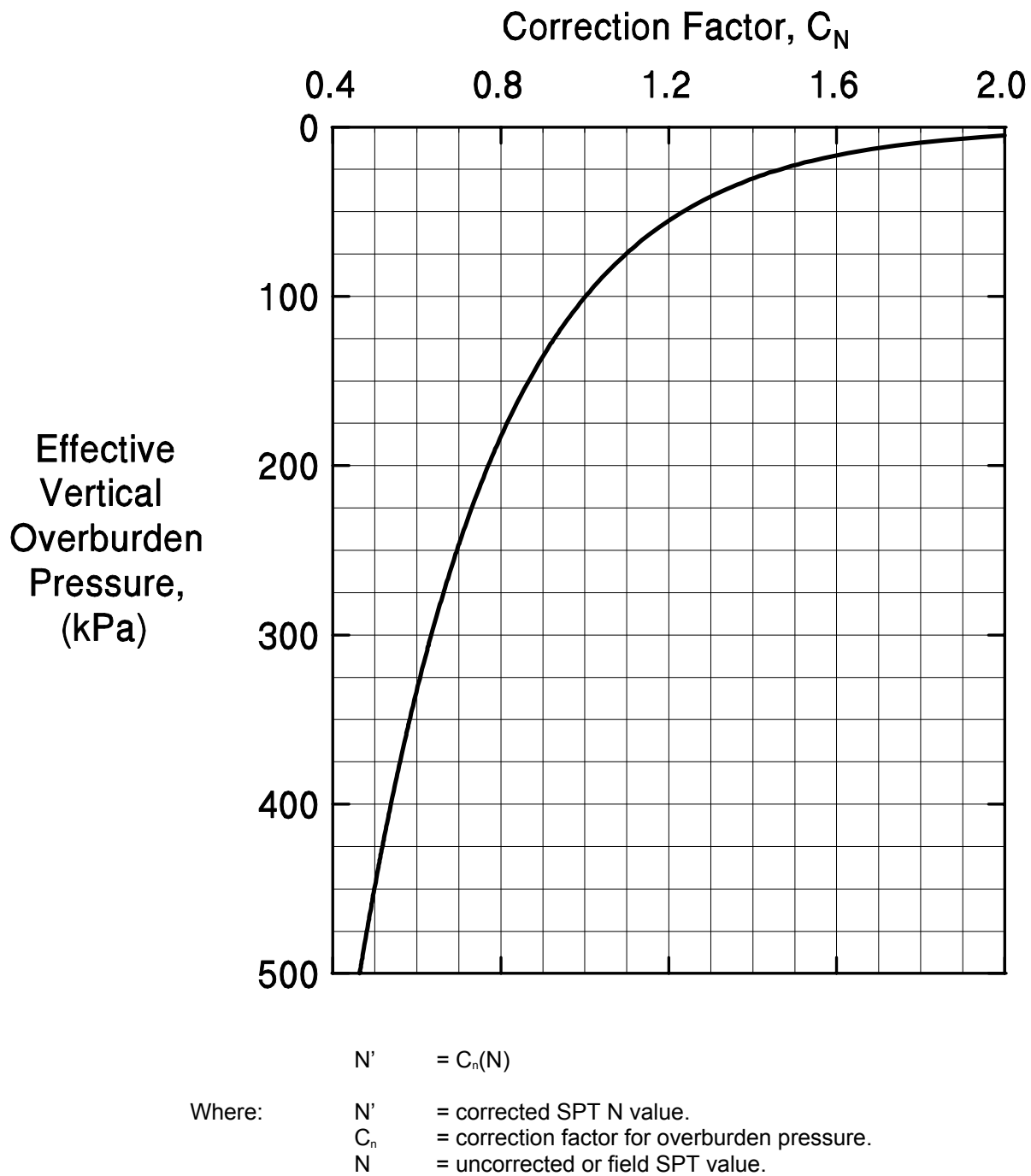


Figure 4.5 SPT Test Results for Safety and Automatic Hammers (after Finno, 1989)

3. Interference with the free fall of the drive weight by the guides or the hoist rope. New equipment eliminates rope interference.
4. Use of a drive shoe that is badly damaged or worn from too many drivings to “refusal” (SPT N values exceeding 100).
5. Failure to properly seat the sampler on undisturbed material at the bottom of the boring.
6. Inadequate cleaning of loosened material from the bottom of the boring.
7. Failure to maintain sufficient hydrostatic pressure in the borehole during drilling or during drill rod extraction. Unbalanced hydrostatic pressures between the borehole drill water and the ground water table can cause the test zone to become "quick". This can happen when using the continuous-flight auger with the end plugged and maintaining a water level in the hollow stem below that in the hole
8. SPT results may not be dependable in gravel. Since the split-spoon inside diameter is 35 mm (1-3/8 inch), gravel sizes larger than 35 mm (1-3/8 inch) will not enter the spoon. Therefore, soil descriptions may not reflect actual gravel content of the deposit. Also, gravel pieces may jam the end of the spoon which may get plugged and cause the SPT blow count to be erroneously high.
9. Samples retrieved from dilatant soils (fine sands, sandy silts) which exhibit unusually high blow count should be examined in the field to determine if the sampler drive shoe is plugged. Poor sample recovery is an indication of plugging.
10. Careless work on the part of the drill crew.

The use of reliable qualified drillers and adherence to recommended sampling practice cannot be overemphasized. State agencies which maintain their own drilling personnel and equipment achieve much more reliable, consistent results than those who routinely let boring contracts to the low bidder.

A correction of field N values is also necessary to account for the effects of overburden pressures when estimating physical properties in cohesionless soils. The corrected N' value is determined by multiplying the field N value by the correction factor obtained from Figure 4.6. All N' values referred to in this manual are the corrected for overburden pressure.



NOTE: Maximum correction factor is 2.0.

100 kPa = 1 TSF

Figure 4.6 Chart for Correction of N-values in Sand for Influence of Effective Overburden Pressure (after Peck *et al.*, 1974)

Correlations of cohesive soil physical properties with N values are crude and, therefore, correction of N values in cohesive soils is not necessary.

The corrected N' values and uncorrected N values (blows / 300 mm) (blows / ft) may be used to estimate the relative density of cohesionless soils and consistency of cohesive soils, respectively. Table 4-6 contains an empirical relationship between N' value, and the relative density, angle of internal friction and unit weight of granular soils. It is emphasized that for soils containing gravel sized particles, this table may yield unreliable results. In those cases, the correlations should be used for rough estimation purposes only. Static analysis procedures to calculate the ultimate capacity of pile foundations in cohesionless soils using SPT N' values are presented in Chapter 9.

Table 4-7 contains an empirical relationship between the uncorrected N value and the unconfined compressive strength and saturated unit weight of cohesive soils. The undrained shear strength is one half of the unconfined compressive strength. Correlation of N values to the undrained shear strength of clays is crude and unreliable for design. It should be used only for preliminary estimating purposes. Undisturbed cohesive samples should be obtained for laboratory determination of accurate shear strength and unit weight.

| TABLE 4-6 EMPIRICAL VALUES FOR ϕ , D_r , AND UNIT WEIGHT OF GRANULAR SOILS BASED ON CORRECTED N' (after Bowles, 1977) | | | | | |
|--|---------------------------|---------------------------|----------------------------|----------------------------|----------------------------|
| Description | Very Loose | Loose | Medium | Dense | Very Dense |
| Relative density D_r | 0 - 0.15 | 0.15 - 0.35 | 0.35 - 0.65 | 0.65 - 0.85 | 0.85 - 1.00 |
| Corrected Standard Penetration N' value | 0 to 4 | 4 to 10 | 10 to 30 | 30 to 50 | 50+ |
| Approximate angle of internal friction ϕ * | 25 - 30° | 27 - 32° | 30 - 35° | 35 - 40° | 38 - 43° |
| Range of approximate moist unit weight γ kN/m^3 (lb/ft^3) | 11.0 - 15.7 (70 - 100) | 14.1 - 18.1 (90 - 115) | 17.3 - 20.4 (110 - 130) | 17.3 - 22.0 (110 - 140) | 20.4 - 23.6 (130 - 150) |

Correlations may be unreliable in soils containing gravel. See Section 9.5. of Chapter 9.

* Use larger values for granular material with 5% or less fine sand and silt.

| TABLE 4-7 EMPIRICAL VALUES FOR UNCONFINED COMPRESSIVE STRENGTH (q_u) AND CONSISTENCY OF COHESIVE SOILS BASED ON UNCORRECTED N (after Bowles, 1977) | | | | | | |
|--|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|----------------------------|
| Consistency | Very Soft | Soft | Medium | Stiff | Very Stiff | Hard |
| q_u , kPa (ksf) | 0 – 24 (0 – 0.5) | 24 – 48 (0.5 – 1.0) | 48 – 96 (1.0 – 2.0) | 96 – 192 (2.0 – 4.0) | 192 – 384 (4.0 – 8.0) | 384+ (8.0+) |
| Standard Penetration N value | 0 - 2 | 2 - 4 | 4 – 8 | 8 - 16 | 16 - 32 | 32+ |
| γ (saturated), kN/m ³ (lb/ft ³) | 15.8 - 18.8 (100 – 120) | 15.8 - 18.8 (100 – 120) | 17.3 - 20.4 (110 – 130) | 18.8 - 22.0 (120 – 140) | 18.8 - 22.0 (120 – 140) | 18.8 - 22.0 (120 – 140) |
| The undrained shear strength is 1/2 of the unconfined compressive strength. | | | | | | |

Correlations are unreliable. Use for preliminary estimates only.

4.5.2 Undisturbed Soil Samplers

Undisturbed samples of cohesive soils should be obtained for accurate shear strength, compressibility, and unit weight determinations. Several types of undisturbed soil samplers are used in conjunction with boring operations.

- Thin wall open tube (Figures 4.7a and 4.7b).
- Piston samplers.
- Pitcher sampler (Figure 4.9)

Thin wall open tube or Shelby tube samplers are the most common method for obtaining relatively undisturbed cohesive soil samples. These tubes have a beveled front cutting edge and are slowly pushed into the soil using a drill rig's hydraulic system. Thin wall open tube samplers are best suited for sampling medium soft to medium stiff cohesive soils. Sample recovery and/or sample disturbance may be unacceptable in very soft soils. Thin wall tube samples also often have difficulty sampling very hard or gravelly soils. Additional details on thin wall tube sampling are described in AASHTO T207 or ASTM D-1587.

Piston samplers were developed to prevent soil from entering the sampling tube before the sample depth and to reduce sample loss during tube extraction. They are basically a thin wall tube sampler with a piston, rod, and a modified sampler head. There are numerous types of piston samplers; free or semi-fixed piston samplers, fixed-piston samplers, and retractable piston samplers. In addition, piston samplers may be mechanically activated

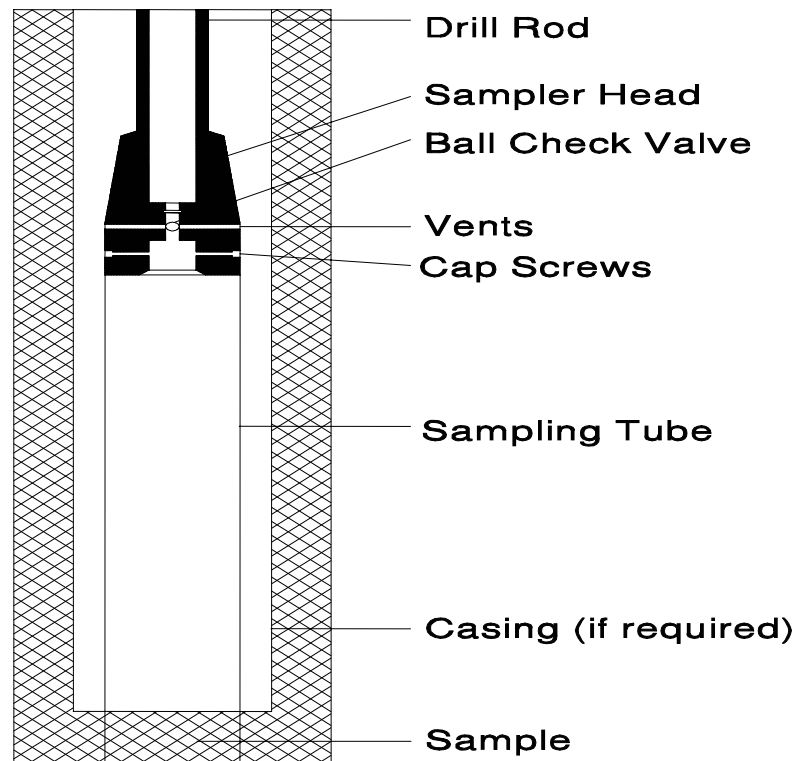


Figure 4.7a Thin Wall Shelby Tube Schematic (after FHWA, 1972)



Figure 4.7b Various Diameter Shelby Tubes from Mayne, et. al., (2002)

such as the Horslev fixed piston sampler, or hydraulically operated such as the Osterberg fixed piston sampler. Free piston samplers are most effective for sampling stiff clays or partially saturated silts and clays. Fixed piston samplers are particularly useful for sampling soft soils where sample recovery is often difficult, and can also be used in stiff clays and silts.

The Pitcher sampler is a core barrel sampler that may be used for sampling a broad range of materials including undisturbed samples of stiff to hard clays, soft rocks and cemented sands. This sampler consists of a rotating outer core barrel with an inner thin walled sampling tube. The sampling tube leads the core barrel when sampling soft soils and the core barrel leads the sampling tube when sampling hard materials. This makes the Pitcher sampler particularly attractive for sampling materials with alternating hard and soft layers. Table 4-8 provides a summary of various undisturbed soil samplers, and their advantages and disadvantages.

Great care is necessary in extraction, handling, and in transporting undisturbed samples to avoid disturbing the natural soil structure. Tubes should be pressed and not hammered. Proper storage and transport should be done with the tube upright and encased in an insulated box with cushioning material. Each tube should be physically separated from adjacent tubes.



Figure 4.8. Pitcher Sampler from Mayne, et. al., (2002)

| TABLE 4-8 UNDISTURBED SOIL SAMPLES | | | | |
|--|---|--|--|--|
| Sampler | Soil Types Suitable for Sampler | Advantages | Disadvantages | Remarks |
| Thin wall open tube sampler Figure 4.5. | Soils having some cohesion unless they are too hard or too gravelly for sampler penetration | <ol style="list-style-type: none"> 1. Small area ratio of tube permits obtaining sample with minimum disturbance. 2. Procedure is simple and requires very little time. | <ol style="list-style-type: none"> 1. Excess or disturbed soil may enter the sampler and cause disturbance. Excess material prevents accurate measurement of recovery length. 2. When using in a bore hole filled with water or drilling fluid, an excess hydrostatic pressure will develop over the sample. 3. Check valve may clog, and may not reduce the hydrostatic pressures. | Not suited for use in boulders, gravels and coarse soils. |
| Samplers with stationary pistons. | Soft soils | <ol style="list-style-type: none"> 1. Disturbed soil is prevented from entering the tube which decreases sample disturbance. 2. Atmospheric and hydrostatic pressures over sample area are reduced, which increases recovery ratio. 3. Any downward movement of the sample creates a partial vacuum over the sample and reduces the danger of losing the sample. 4. Much easier to determine recovery ratio since the length of rods can be easily measured. | <ol style="list-style-type: none"> 1. The apparatus is complicated to use. 2. The insertion, clamping and withdrawal of the rods is time consuming. | When a piston sampler is needed, the fixed piston sampler is preferable to other types of piston samplers to minimize sample disturbance. |
| Samplers with free pistons. | Stiff soils | <ol style="list-style-type: none"> 1. Entrance of disturbed and mixed soil is prevented when the sampler is lowered into position. 2. Recovery ratio is easily determined. 3. The piston is more effective than check valve in reducing pressure over the sample. 4. Easier to operate than the fixed piston. | Additional weight is placed on the soil sample by the weight of the drill rods. | Similar to the fixed piston sampler with the exception that the piston is not fixed when the sample is taken; it is free to ride on top of the sample. |
| Samplers with retracted pistons. | Stiff soils | <ol style="list-style-type: none"> 1. The sampler is simpler in construction and operation than the stationary or free piston sampler as the piston head is held in place by a screw-type connection. 2. The piston prevents the entrance of disturbed soil into the tube when the tube is being placed into position for sampling. | <ol style="list-style-type: none"> 1. The retraction of the piston may cause failure in soft soils as the soil may flow into the sampler. 2. The soil displaced during the positioning of the piston sampler may flow into the sampler when the piston is withdrawn. 3. If there is water leakage into the drill rod, excess hydrostatic pressure will develop over the sample. | Piston is withdrawn just before the beginning of the actual sampling process. |
| Hydraulic piston sampler. | Soft soils | Eliminates need for center rod required to hold piston on a conventional piston-type sampler. This results in less time required to retrieve a sample. | <ol style="list-style-type: none"> 1. There are no means to determine the amount of penetration of the sampling tube into the soil stratum, since there are no visible signs of movement at the top of the hole. 2. Percent recovery is hard to establish, particularly for short pushes which do not fill the sampler. The weight of water in the drill steel causes the sampler to extend to its full length during retrieval from the hole. | The sampling technique is the same as for the stationary piston sampler. The activation of the sampling tube is performed by water pressure applied to the sampler through its attached drill steel. |
| Pitcher. | Stiff to hard clays and soft rocks. Cemented sands. | <ol style="list-style-type: none"> 1. Inner thin wall sampling tube leads outer core barrel in softer soils. 2. Outer core barrel leads sampling tube in hard soils. | <ol style="list-style-type: none"> 1. Sensitive soil samples may be damaged by vibrations of core barrel during sampling. 2. Water sensitive soils may be in continuous contact with drilling fluid. | Well adapted to sampling alternating layers of hard and soft soils. |

4.5.3 Rock Core Samplers

Rock Core Samplers (core barrels) are available in various diameters and length. The most widely used types are:

- a. Single tube.
- b. Double tube, rigid type (Figure 4.9).
- c. Double tube, swivel type (Figure 4.9).
- d. Wire line barrels.

Double tube or wire line core barrels which are capable of recovering rock cores of at least 54 mm in diameter should be used in subsurface exploration for structural projects.

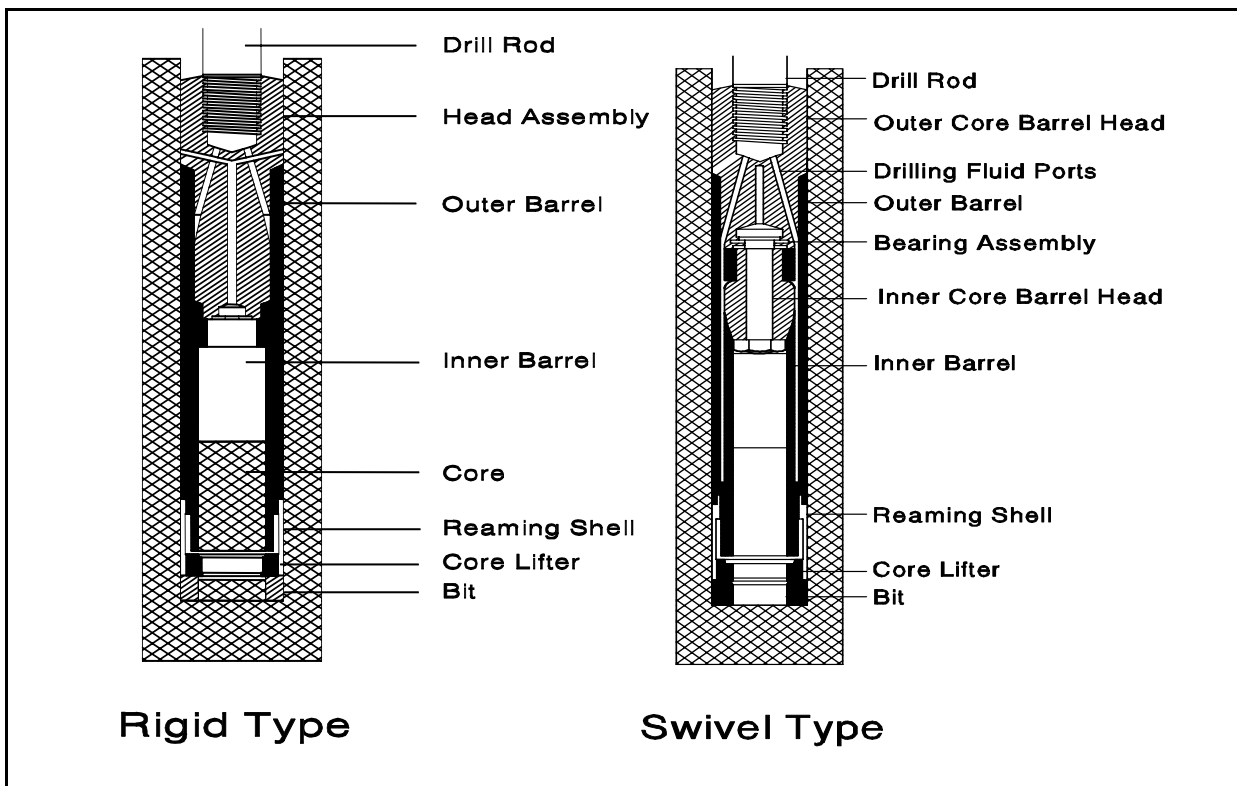


Figure 4.9 Rigid and Swivel Type Double Core Barrels (after FHWA, 1972)

4.6 GROUND WATER MONITORING

Accurate ground water level information is needed for the estimation of soil densities, determination of effective soil pressures and for the preparation of effective stress diagrams. This information is vital for performing foundation design. Water levels will also

indicate the construction difficulties which may be encountered in excavations and the dewatering effort required.

In most structure foundation explorations, water levels should be monitored during drilling of the boring, upon completion of the boring, and 24 hours after the completion of boring. More than one week may be required to obtain representative water level readings in low permeability cohesive soils or in bore holes stabilized with some drilling muds. In these cases, an observation well or piezometer should be installed in a boring to allow long term ground water monitoring. An observation well is typically used to monitor changes in the water level in a select aquifer whereas a piezometer is used to monitor changes in the hydrostatic pressure in a confined aquifer or specific stratum.

An observation well is usually a slotted section of small diameter PVC pipe installed in a bore hole. The bottom section of the slotted PVC pipe is capped and solid PVC sections are used to extend the observation well from the top of the slotted PVC section to a height above grade. The annulus between the slotted section and the sides of the bore hole is backfilled with sand. Once the sand is above the slotted PVC section, a bentonite seal is placed in the annulus sealing off the soil stratum in which the water table fluctuations will be monitored. The annulus above the bentonite seal is usually backfilled with grout or auger cuttings. The water level reading in the observation well will be the highest of the water table in any soil layer that the slotted section penetrates. The top section may be cast into a concrete surface seal that includes a locking removeable cover to prevent damage. The ground surface at the top of the pipe is usually sloped away from the pipe.

Piezometers are generally used to monitor hydrostatic pressure changes in a specific soil stratum. Piezometers may be either pneumatic or vibrating wire diaphragm devices. These piezometers may be installed in a sand pocket with a bentonite seal similar to an observation well. More recently, single and multiple piezometers are being installed in a single bore hole using a cement-bentonite grout. Additional information on piezometers is available in FHWA-NHI-01-031, Subsurface Investigations – Geotechnical Site Characterization by Mayne et.al (2002).

4.7 SUMMARIZATION AND INTERPRETATION OF SUBSURFACE PROFILE

A subsurface profile is a visual representation of subsurface conditions interpreted from subsurface explorations and laboratory testing. A complete subsurface profile should delineate the subsurface stratigraphy; the subsurface material classifications; the shear strength, compressibility, and stress history for each layer; and the ground water table location for foundation design.

A subsurface profile should be developed in stages. First, a rough profile is established from the drillers logs. This helps discover any obvious gaps while the drilling crew is at the site so that additional work can be performed immediately. When borings are completed and laboratory classification and moisture content data is received, the initial soil profile should be revised. Soil stratification and accurate soil descriptions are established at this stage. Overcomplication of a profile by noting minute variations between adjacent soil samples should be avoided. A vertical scale of 10 mm equal to 1 to 3 m (1 inch equals to 10 to 25 ft) a horizontal scale equal to the vertical scale are recommended.

After the soil layer boundaries and descriptions have been established, a determination of the extent and details of additional laboratory testing, such as consolidation and shear strength tests, is made. The final soil profile should include the average physical properties of the soil deposits including unit weight, shear strength, *etc.*, as well as a visual description of each deposit. The observed ground water level and the presence of items such as boulders, voids, and artesian pressures should also be noted. A well developed soil profile is necessary to design a cost-effective foundation. Uncertainties in the development of a subsurface profile usually indicate that additional explorations and/or laboratory testing are required. An example of a subsurface profile is presented in Figure 4.10.

The subsurface conditions presented in a subsurface profile are accurate only at the location of the borings. Interpretation between boring locations as shown in Figure 4.10 is often done for analysis purposes. However, where soil and/or rock profiles vary considerably between boring locations, this interpretation and presentation may be misleading. Interpreted soil profiles, when presented, should clearly note that the soil profile is only accurate at the boring locations, and that the interpreted profile between boring locations cannot be fully relied upon.

4.8 ADDITIONAL SUBSURFACE EXPLORATIONS

During the final design process, additional subsurface explorations may need to be performed to finalize the design soil profile and design soil parameters. Additional subsurface exploration and design soil profile development may be needed for the design of a foundation type not originally considered, due to a design change caused by environmental restrictions, or simply for a cost optimization of the foundation design.

The additional subsurface exploration program may consist of additional soil borings, and/or in-situ testing, and/or geophysical methods to supplement the original information. Additional laboratory tests may also be conducted to delineate soil properties of key strata.

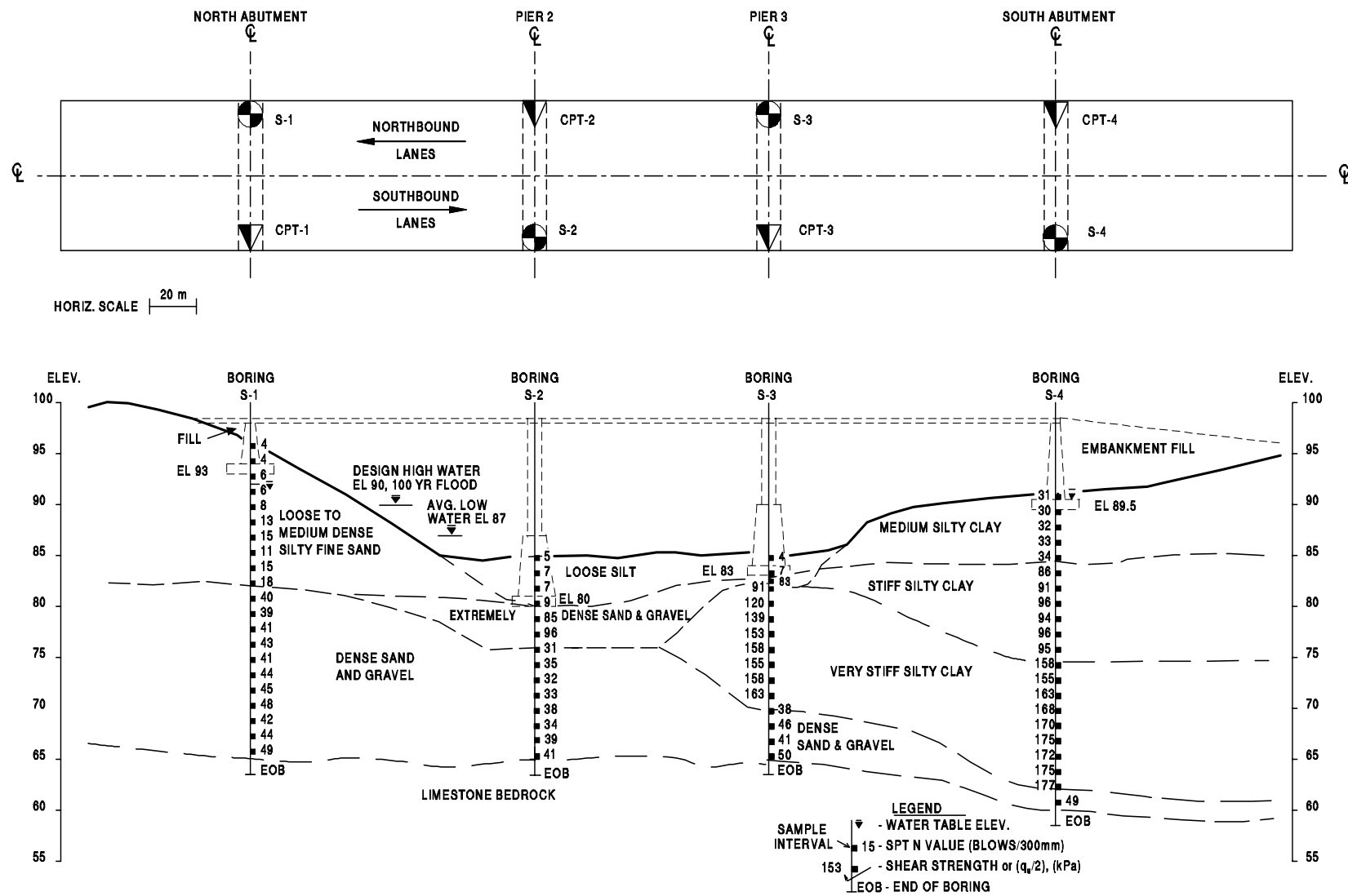


Figure 4.10. Example Subsurface Profile.

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Chapter 5

IN-SITU TESTING

In-situ testing provides soil parameters for the design of structure foundations especially in conditions where standard drilling and sampling methods cannot be used to obtain high quality undisturbed samples. Undisturbed samples from non-cohesive soils are difficult to obtain, trim, and test in the laboratory. Soft saturated clays, saturated sands and intermixed deposits of soil and gravel are also difficult to sample without disturbance. Therefore, representative strength test data is difficult to obtain on these soils in the laboratory. To overcome these difficulties, test methods have been developed to evaluate soil properties, especially strength and compressibility, in-situ.

In-situ testing methods can be particularly effective when used to supplement conventional exploration programs. The speed of in-situ testing in conjunction with no laboratory testing significantly reduces the subsurface exploration program time and cost. In addition, in-situ methods help identify key strata for further conventional sampling and laboratory tests.

Primary in-situ tests that provide data for foundation design are the cone penetration test (CPT), the cone penetration test with pore pressure measurements (CPTu), and the vane shear (VST). Other lesser used in-situ testing devices include the pressuremeter test (PMT), the dilatometer test (DMT), and the dynamic cone penetrometer test. Specific pile design procedures using CPT data are discussed in Chapter 9 of this manual.

The intent of this chapter is to provide a brief summary of in-situ test methods used for deep foundation design. For CPT/CPTu testing a brief summary of the equipment, operation, application, advantages and disadvantages is also provided. The applicability, advantages and disadvantages of all the in-situ testing methods are also briefly summarized in Table 5-1. For a detailed discussion of a particular in-situ testing method, the reader is referred to the publications listed at the end of this chapter. NHI course 132031, Subsurface Investigations – Geotechnical Site Characterization and the accompanying course manual by Mayne, et.al, (2002) provide a thorough coverage of in-situ testing methods.

5.1 CONE PENETRATION TEST (CPT) AND (CPTu)

The cone penetration test (CPT) was first introduced in the U.S. in 1965. By the mid 1970's, the electronic cone began to replace the mechanical cone. In the early 1980's, the

TABLE 5-1 SUMMARY OF IN-SITU TEST METHODS

| Type of Test | Best Suited for | Not Applicable for | Information that can be Obtained for Pile Foundation Design | Advantages | Disadvantages | Remarks |
|--|--------------------------------------|--|---|--|--|---|
| Cone Penetration Test (CPT) | Sand, silt, and clay | Gravel, very dense deposits, rubble fills, and rock. | Continuous evaluation of subsurface stratigraphy. Correlations for determination of in-situ density and friction angle of sands, undrained shear strength of clays, and liquefaction potential. | <ol style="list-style-type: none"> 1. Cone can be considered as a model pile. 2. Quick and simple test. 3. Can reduce number of borings. 4. Relatively operator independent. | <ol style="list-style-type: none"> 1. Does not provide soil samples. 2. Should be used in conjunction with soil borings in an exploration program. 3. Local correlations can be important in data interpretation. | Well suited to the design of axially loaded piles. ASTM D-3441 (mechanical cones) and ASTM D-5778 (electronic cones). |
| Cone Penetration Test with Pore Pressure Measurements (CPTu) | Sand, silt, and clay | Gravel, very dense deposits, and rubble fills. | Finer delineation of continuous subsurface stratigraphy compared to CPT. Correlations for determination of in-situ density and friction angle of sands, undrained shear strength of clays, and liquefaction susceptibility. | <ol style="list-style-type: none"> 1. Same advantages as CPT. 2. Pore pressure measurements can be used to assess soil setup effects. 3. Can help determine if penetration is drained or undrained. | <ol style="list-style-type: none"> 1. Same disadvantages as CPT. 2. Location and saturation of porous filter can influence pore pressure measurements. | Probably best in-situ test method for the design of axially loaded piles. ASTM D-5778. |
| Pressuremeter Test (PMT) | Sand, silt, clay and soft rock. | Organic soils and hard rock. | Bearing capacity from limit pressure and compressibility from pressure meter deformation modulus. | <ol style="list-style-type: none"> 1. Tests can be performed in and below hard strata that may stop other in-situ testing devices. 2. Tests can be made on non-homogenous soil deposits. | <ol style="list-style-type: none"> 1. Bore hole preparation very important. 2. Limited number of tests per day. 3. Limited application for axially loaded pile design. | Good application for laterally loaded pile design. ASTM D-4719. |
| Dilatometer Test (DMT) | Low to medium strength sand and clay | Dense deposits, gravels and rock. | Correlations for soil type, earth pressure at rest, over consolidation ratio, undrained shear strength, and dilatometer modulus. | <ol style="list-style-type: none"> 1. Quick, inexpensive test. 2. Relatively operator independent. | <ol style="list-style-type: none"> 1. Less familiar test method. 2. Intended for soils with particle sizes smaller than fine gravel. 3. Limited application for axially loaded pile design. | May be potentially useful for laterally loaded pile design. ASTM standard in progress. |
| Vane Shear Test | Soft clay | Silt, sand, and gravel | Undrained shear strength. | <ol style="list-style-type: none"> 1. Quick and economical. 2. Compares well with unconfined compression test results at shallow depths. | <ol style="list-style-type: none"> 1. Can be used to depths of only 4 to 6 m (13 to 20 ft) without casing bore hole. | Test should be used with caution in fissured, varved, and highly plastic clays. AASHTO T223. |
| Dynamic Cone Test | Sand and gravel | Clay | Qualitative evaluation of soil density. Qualitative comparison of stratigraphy. | <ol style="list-style-type: none"> 1. Can be useful in soil conditions where static cone (CPT) reaches refusal. | <ol style="list-style-type: none"> 1. An unknown fraction of resistance is due to side friction. 2. Overall use is limited. | Not recommended for final pile design. No AASHTO or ASTM standard. |

piezo-cone or cone penetration test with pore pressure measurements (CPTu) became readily available. Since that time, the CPT/CPTu has developed into one of the most popular in-situ testing devices. Part of this popularity is due to the CPT's ability to provide large quantities of useful data quickly and at an economical cost. Depending upon equipment capability as well as soil conditions, 100 to 350 m (330 to 1150 ft) of penetration testing may be completed in one day

5.1.1 Equipment Description and Operation

Cone penetration testing can be separated into two main categories:

- a. Electronic cones.
- b. Mechanical cones.

Electronic cones are now the dominant cone type used in cone penetration testing. Hence, mechanical cones will not be discussed further in this chapter. Electronic cones may be further divided into two primary types, the standard friction cone (CPT), and the piezo-cone (PCPT or more commonly CPTu).

In the CPT test, a cone with a 1000 mm^2 (1.5 in^2) base and a 60° tip attached to a series of rods is continuously pushed into the ground. Typically, a hydraulic ram with 45 to 180 kN (10 to 40 kips) of thrust capability is used to continuously advance the cone into the ground at a rate of 20 mm (0.8 in/sec). A friction sleeve with a surface area of 15000 mm^2 (22.5 in^2) is located behind the conical tip. Built in load cells are used to continuously measure the cone tip resistance, q_c , and the sleeve friction resistance, f_s . The friction ratio, R_f , is the ratio of f_s/q_c and is commonly used in the interpretation of test results.

The piezo-cone (CPTu), is essentially the same as the standard electronic friction cone and continuously measures the cone tip resistance, q_c , and the sleeve friction resistance, f_s , during penetration. In addition to these values, the piezo-cone includes porous filter piezo-elements that may be located at the cone tip, on the cone face, behind the cone tip, or behind the friction sleeve. These porous filter elements are used to measure pore pressure, u , during penetration. Careful porous element and cavity saturation is essential to obtain reliable pore pressure measurements.

A general schematic and picture of a cone penetrometer is presented in Figures 5.1a and 5.1b. Typical penetration depths for a 45 kN (10 kip) and 180 kN (40 kip) thrust capability

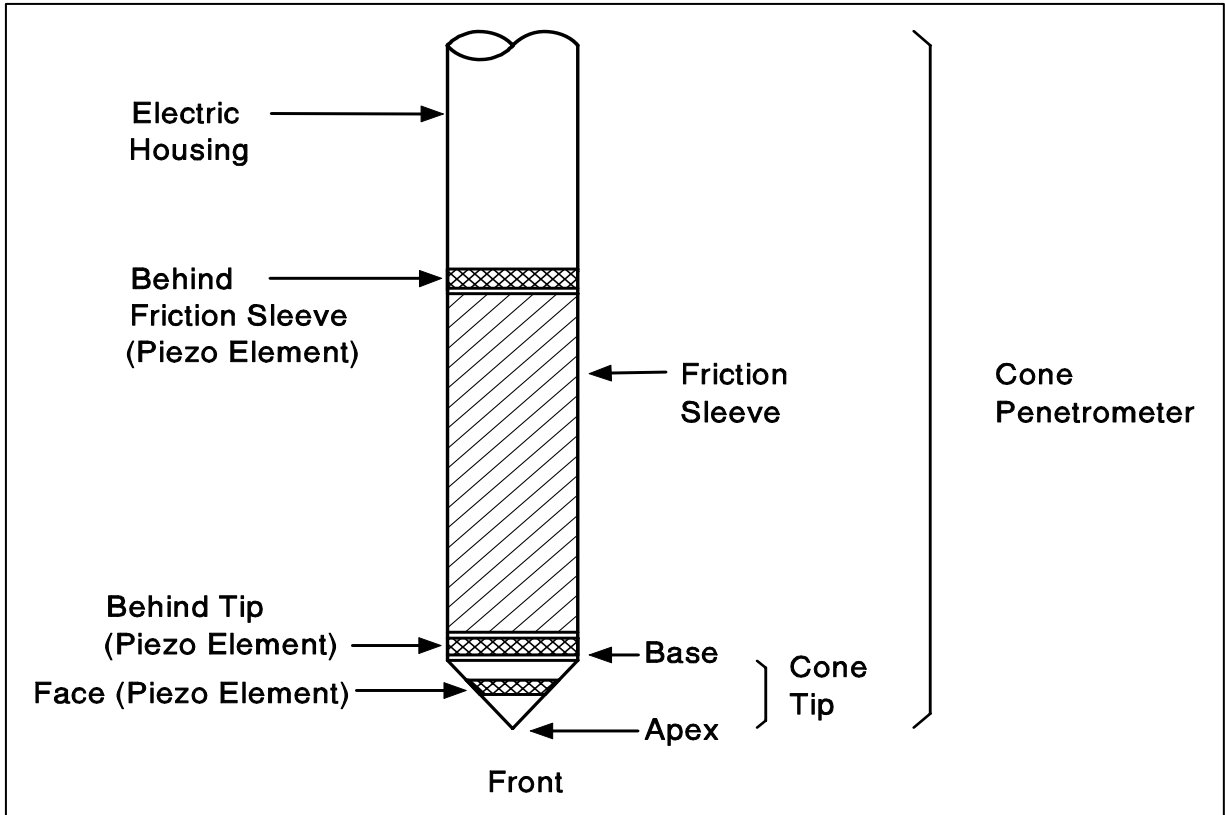


Figure 5.1a Terminology Regarding the Cone Penetrometer (from Robertson and Campanella, 1989)



Figure 5.1b Cone Penetrometers (from Mayne et. al., 2002)

are presented in Tables 5-2 and 5-3, respectively. Additional information on CPT/CPTu testing and analysis may be found in FHWA-SA-91-043, The Cone Penetrometer Test, by Briaud and Miran (1991). Test procedures may be found in ASTM D-3441 for mechanical cones and ASTM D-5778 for electronic cones.

| TABLE 5-2 DRILL RIG WITH 45 kN (10 kip) PUSH CAPACITY | | | | | | |
|---|------|-------|------|-------|--------|-------|
| | Soil | | | | | |
| | Clay | | | Sand | | |
| Depth m (ft) | Soft | Stiff | Hard | Loose | Medium | Dense |
| 1 (3.3) | * | * | * | * | * | |
| 3 (9.8) | * | * | | * | * | |
| 4 (13.1) | * | * | | * | * | |
| 6 (19.7) | * | | | * | * | |
| 9 (29.5) | * | | | * | | |
| 12 (39.4) | * | | | * | | |
| 15 (49.2) | * | | | * | | |
| 18 (59.0) | * | | | | | |
| 21 (68.9) | * | | | | | |
| 24 (78.7) | | | | | | |

| TABLE 5-3 TRUCK WITH 180 kN (40 kip) PUSH CAPACITY | | | | | | |
|--|------|-------|------|-------|--------|-------|
| | Soil | | | | | |
| | Clay | | | Sand | | |
| Depth m (ft) | Soft | Stiff | Hard | Loose | Medium | Dense |
| 4 (13.1) | * | * | * | * | * | * |
| 9 (19.7) | * | * | * | * | * | * |
| 18 (59.0) | * | * | * | * | * | * |
| 27 (88.6) | * | * | | * | * | |
| 36 (118.1) | * | | | * | | |
| 46 (150.9) | * | | | * | | |
| 61 (200.1) | * | | | | | |
| 76 (249.3) | * | | | | | |
| 91 (298.4) | | | | | | |

Tables 5-2 and 5-3 (modified from Briaud and Miran, 1991)

5.1.2 Interpretation of CPT/CPTu Test Results

- a. CPT/CPTu data can provide a continuous profile of the subsurface stratigraphy. A simplified soil classification chart for a standard electronic friction cone is presented in Figure 5.2. Typical CPT test results are presented in Figure 5.3.
- b. From correlations with CPT/CPTu data, evaluations of in-situ relative density, D_r , and friction angle, ϕ , of cohesionless soils as well as the undrained shear strength, c_u , of cohesive soils can be made. Correlations for determination of other soil properties, liquefaction susceptibility, and estimates of SPT values may also be determined. The accuracy of these correlations may vary depending upon geologic conditions. Correlation confirmation with local conditions is therefore important.

5.1.3 Advantages and Disadvantages of CPT/CPTu Tests

The primary advantage of CPT/CPTu testing is the ability to rapidly develop a continuous profile of subsurface conditions more economically than any other subsurface exploration or in-situ testing tools. Determination of in-situ soil strength parameters from correlations with CPT/CPTu data is another advantage. The CPT/CPTu test can also reduce the number of conventional borings needed on a project, or focus attention on discrete zones for detailed soil sampling and testing. Lastly, CPT/CPTu results are relatively operator independent.

Limitations of CPT/CPTu testing include the inability to push the cone in dense or coarse soil deposits. To penetrate dense layers, cones are sometimes pushed in bore holes advanced through the dense strata. Another limitation is that soil samples are not recovered for confirmation of cone stratigraphy. For meaningful pore pressure measurements, careful preparation to ensure saturation of the porous elements and cone cavities is required. Local correlations are also important in data interpretation.

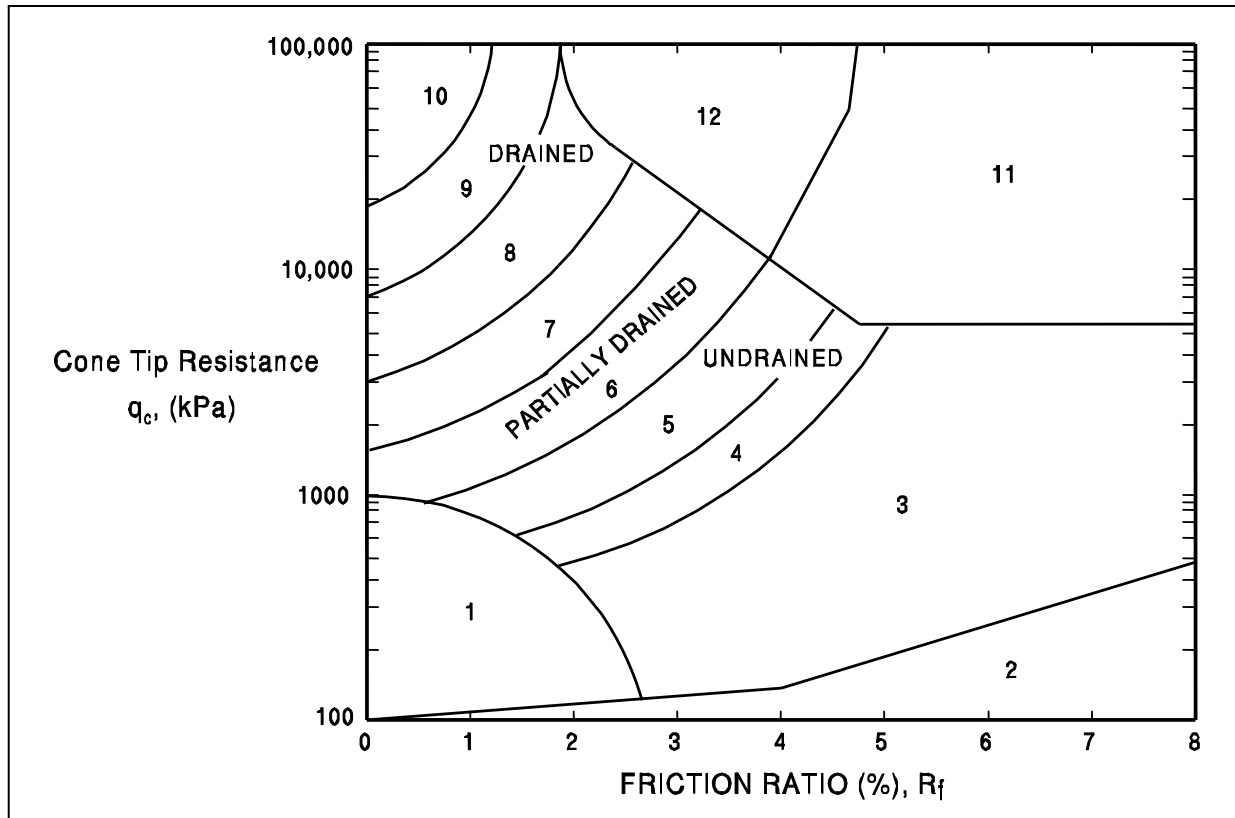


Figure 5.2 Simplified Soil Classification Chart for Standard Electronic Friction Cone (after Robertson et al., 1986)

| Zone | q_c/N | Soil Behavior Type |
|------|---------|---------------------------|
| 1) | 2 | sensitive fine grained |
| 2) | 1 | organic material |
| 3) | 1 | clay |
| 4) | 1.5 | silty clay to clay |
| 5) | 2 | clayey silt to silty clay |
| 6) | 2.5 | sandy silt to clayey silt |
| 7) | 3 | silty sand to sandy silt |
| 8) | 4 | sand to silty sand |
| 9) | 5 | sand |
| 10) | 6 | gravelly sand to sand |
| 11) | 1 | very stiff fine grained |
| 12) | 2 | sand to clayey sand |

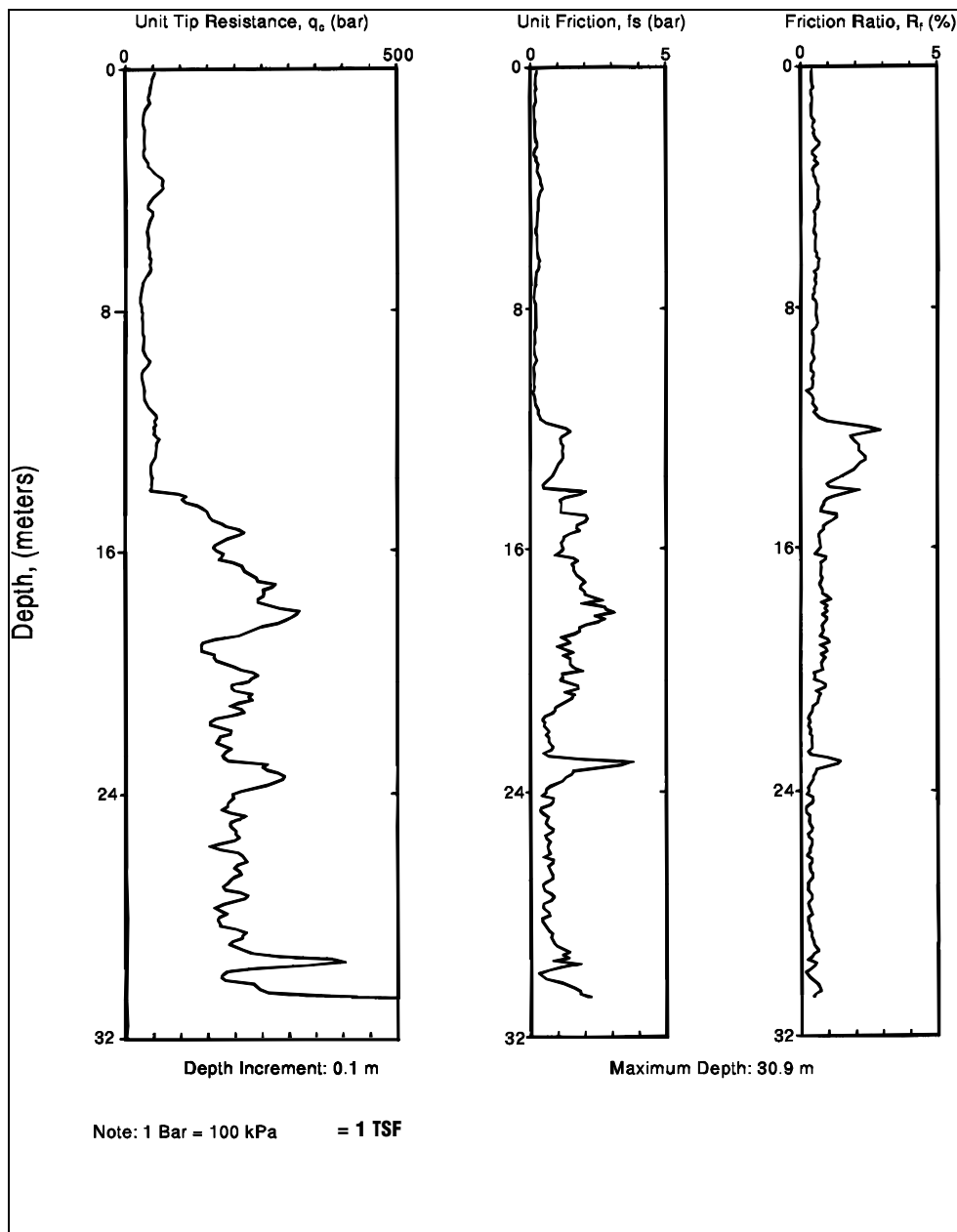


Figure 5.3 Typical CPT Data Presentation

5.2 PRESSUREMETER TEST - (PMT)

The pressuremeter test (PMT) is an in-situ device used to evaluate soil and rock properties. The pressuremeter has been used in Europe for many years and was introduced into the U.S. in the mid 1970's. The pressuremeter imparts lateral pressures to the soil, and the soil shear strength and compressibility are determined by interpretation of a pressure-volume relationship. The test allows a determination of the load-deformation characteristics of soil in axi-symmetric conditions. Deposits such as soft clays, fissured clays, sands, gravels and soft rock can be tested with pressuremeters. A pressuremeter test produces information on the elastic modulus of the soil as well as the at rest horizontal earth pressure, the creep pressure, and the soil limit pressure. A schematic of the pressuremeter test is presented in Figure 5.4.

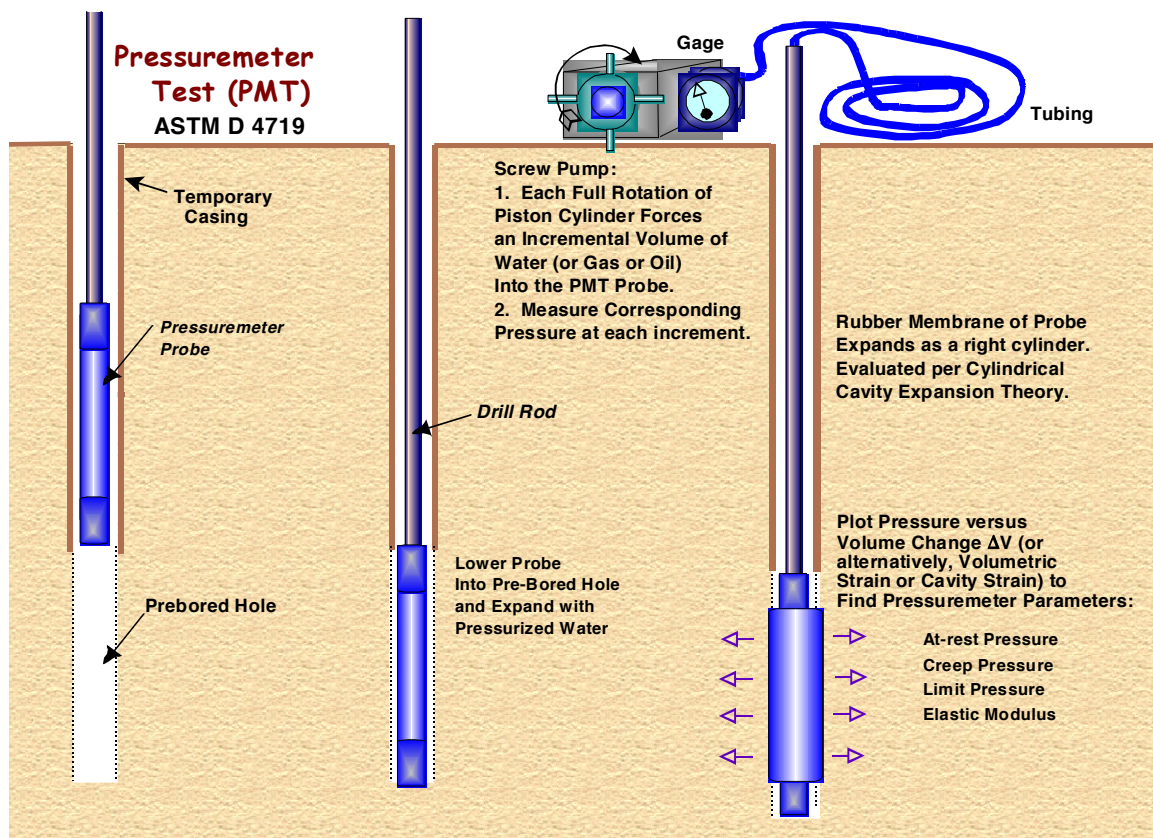


Figure 5.4 Pressuremeter Test Schematic

The utilization of test results is based upon semi-empirical correlations from a large number of tests and observations on actual structures. For piles subjected to lateral loads, the pressuremeter test is a useful design tool and can be used for determination of p-y curves. For design of vertically loaded piles, the pressuremeter test has limited value. Pile design

procedures using pressuremeter data have been developed and may be found in FHWA-IP-89-008, The Pressuremeter Test for Highway Applications, by Briaud (1989). Details on test procedures may be found in ASTM D-4719, Standard Test Method for Pressuremeter Testing in Soils.

5.3 DILATOMETER TEST - (DMT)

The dilatometer test is an in-situ testing device that was developed in Italy in the early 1970's and first introduced in the U.S. in 1979. Like the CPT, the DMT is generally hydraulically pushed into the ground although it may also be driven. When the DMT can be pushed into the ground with tests conducted at 200 mm (8 inch) increments, 30 to 40 m (100 to 130 ft) of DMT sounding may be completed in a day. The primary utilization of the DMT in pile foundation design is the delineation of subsurface stratigraphy and interpreted soil properties. However, it would appear that the CPT/CPTu is generally better suited to this task than the DMT. The DMT may be a potentially useful test for design of piles subjected to lateral loads. Design methods in this area show promise, but are still in the development stage. For design of axially loaded piles, the dilatometer test has limited direct value. A picture of dilatometer test equipment is presented in Figure 5.5.



Figure 5.5 Dilatometer Test Equipment

5.4 VANE SHEAR TEST

The vane shear test is an in-situ test for determining the undrained shear strength of soft to medium clays. Figure 5.6 is a schematic drawing of the essential components and test procedure. The test consists of forcing a four-bladed vane into undisturbed soil and rotating it until the soil shears. Two shear strengths are usually recorded, the peak shearing strength and the remolded shearing strength. These measurements are used to determine the sensitivity of clay. This allows analysis of the soil resistance to be overcome during pile driving in clays which is useful for pile driveability analyses. It is necessary to measure skin friction along the steel connector rods which must be subtracted to determine the actual shear strength. The vane shear test generally provides the most accurate undrained shear strength values for clays with undrained shear strengths less than 50 kPa (1 ksf). The test procedure has been standardized in AASHTO T223-74 and ASTM D-2573.

It should be noted that the sensitivity of a clay determined from a vane shear test provides insight into the set-up potential of the clay deposit. However, the sensitivity value is a qualitative and not a quantitative indicator of soil set-up.

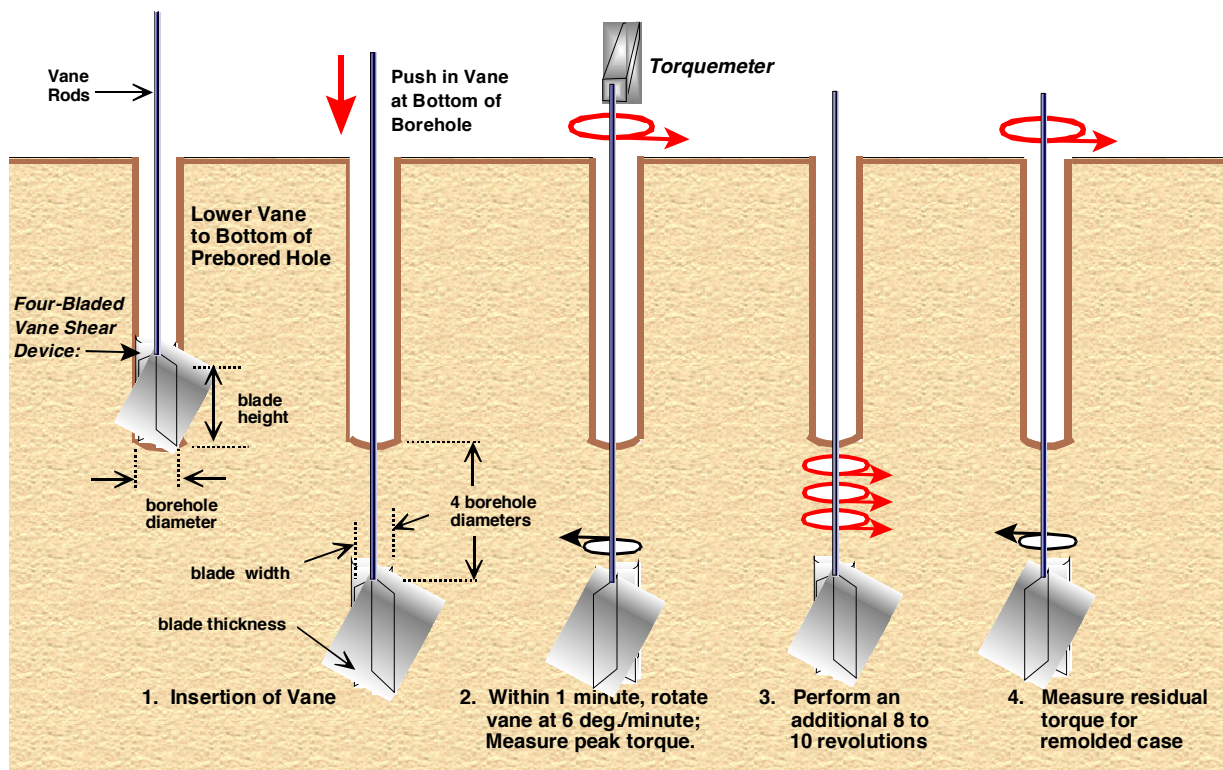


Figure 5.6 Vane Shear Test Equipment and Procedure (after Mayne et al., 2002)

5.5 DYNAMIC CONE TEST

There are two types of dynamic penetrometers with conical points. The dynamic cone type that is most often used has a shaft diameter that is smaller than the cone diameter. Theoretically, due to the cone being larger than the shaft, the penetrometer measures only point resistance. A lesser used cone type has a shaft and cone of the same diameter. This type of dynamic cone penetrometer records both skin friction and point resistance, but the two components cannot be analyzed independently. Equations have been developed for determining bearing capacity of pile foundations by using the dynamic cone test data, but are not used extensively. The dynamic cone penetrometer is not recommended for final foundation design unless specific local correlations with load tests to geotechnical failure have been taken.

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Chapter 6

LABORATORY TESTING

The trend to higher capacity piles and greater pile penetration depths required for special design events reinforces the importance of accurately determining soil shear strength and consolidation properties. For cohesionless materials, the SPT and CPT will be the primary tools for strength and compressibility analysis. These tests should be complemented with appropriate laboratory index tests. For cohesive soils, the use of SPT resistance values for estimation and evaluation of soil shear strength and compressibility cannot be recommended as the basis for a final design. **In cohesive soils, traditional laboratory tests on undisturbed samples yield the best results for evaluation of strength and compressibility properties.**

In laboratory testing, the quality of test results is far more important than the quantity of test results. Inaccurate test results may lead to misjudgments in the design stage and/or problems in the construction stage. Owners and designers of structure foundations have a quality assurance responsibility over activities affecting the quality of laboratory test results. Quality control procedures for in-house or consultant laboratories should be in place for:

- Handling and storage of soil samples.
- Sample preparation for testing.
- Establishment of, and adherence to testing procedures.
- Documentation of equipment calibration and maintenance.
- Training and qualification of laboratory personnel.
- Laboratory test result review and checking.
- Reporting of laboratory test results.

The purpose of this chapter is to present a summary of laboratory tests performed to determine basic soil properties as well as soil shear strength and consolidation properties. For detailed information on laboratory testing, additional references are listed at the end of this chapter.

6.1 TYPES OF TESTS

Laboratory tests can be generally categorized as follows:

1. Soil classification and index tests.
2. Shear strength tests.
3. Consolidation tests.
4. Electro chemical classification tests.

The following subsections briefly describe each type of test. Table 6-1 summarizes the advantages, disadvantages and applications of soil classification, strength and compressibility tests.

6.1.1 Classification and Index Tests

For foundation design, soils are usually classified according to the Unified Soil Classification system. The classification of soil determines the type of material, its general characteristics, and whether any further testing for consolidation and strength properties are needed. The following tests are useful in classifying soils:

- a. Moisture content (AASHTO T265).
- b. Particle size analysis (mechanical and hydrometer analysis) AASHTO T88.
- c. Atterberg limits (liquid and plastic limits) AASHTO T89 and T90.
- d. Unit weight (AASHTO T38).

6.1.2 Shear Strength Tests

The shear strength of a soil is a measure of the soil's ability to resist sliding along internal surfaces within the mass.

TABLE 6-1 LABORATORY TESTS ON SOILS FOR FOUNDATION DESIGN

| Test Category | Test | Classification or Design Parameters Provided by Test | Advantages | Disadvantages | Direct* Applications | Standard Test Procedure | Soil Types best suited for |
|--|---|--|--|--|---|-------------------------|--------------------------------------|
| Classification and Index Tests (both disturbed and undisturbed samples used unless noted) | Liquid limit | Liquid limit | Assists in correct soil classification. | ---- | Classification | AASHTO T89-68 | Cohesive soils and silts |
| | Plastic limit | Plastic limit | Assists in correct soil classification. | ---- | Classification | AASHTO T90-70 | Cohesive soils and silts |
| | Moisture content | Moisture content | Can assist in soil shear strength judgements and water table determination. | ---- | Classification | AASHTO T265-79 | Cohesive soils and silts |
| | Particle size analysis (mechanical and hydrometer analysis) | Grain size curves | Assists in soil classification. | --- | Classification | AASHTO T88-72 | Cohesive and cohesionless soils |
| | Unit weight (Undisturbed samples only) | Dry density | Can assist in soil shear strength judgements. | ---- | Effective stress computations. | AASHTO T38 | Cohesive soils |
| Shear strength (undisturbed samples used) | Triaxial compression test (UU, CU, or CD tests **) | Cohesion c or c' ; Angle of internal friction ϕ or ϕ' . (In terms of total or effective stresses). | 1. Models in-situ conditions better than other two tests. 2. Drainage control 3. Pore water pressure can be measured. 4. More accurate than other two methods. | 1. Expensive. 2. Complicated test procedure. 3. Difficult to use for sands and silts. | Static capacity calculations for deep foundations. | AASHTO T234-70 | Cohesive soils |
| | Direct shear test | Cohesion, c' ; Angle of internal friction, ϕ' . (In terms of effective stresses). | Simple and quick test. | 1. Predetermined failure plane. 2. Poor drainage control. | Static capacity calculations for deep foundations. | AASHTO T236-72 | Cohesionless soils (sands and silts) |
| | Unconfined compression test | Unconfined compression strength and shear strength. | 1. Simple, quick, inexpensive test to measure strength of cohesive soils. 2. More uniform stresses and strains on sample than direct shear test. 3. Failure surface tends to develop at weakest portion of samples unlike the forced shear plane of direct shear test. | 1. No lateral confining pressure during test. 2. Pore water pressures and saturation cannot be controlled. 3. Test results, especially with depth, are conservative and misleading due to release of confining stress when sample is removed from below ground and tested. | Static capacity calculations for deep foundations. | AASHTO T208-70 | Cohesive soils |
| Consolidation (undisturbed samples used) | Consolidation | Compression index. Recompression index. Coefficient of secondary compression. Coefficient of consolidation. Preconsolidation pressure. Swelling index. | ---- | ---- | Computation of foundation settlement and time rate of settlement. | AASHTO T216-74 | Cohesive soils |

* - All test results permit empirical and engineering judgement guidance with regard to pile installation and construction monitoring.

** - UU = Unconsolidated Undrained, CU = Consolidated Undrained, and CD= Consolidated Drained

For the design of foundations, a knowledge of the soil shear strength is essential. Shear tests on soil are performed to determine the cohesion, c , and the angle of internal friction, ϕ . Cohesion is the interparticle attraction effect and is independent of the normal stress, σ , but considerably dependent on water content and strain rate. The internal friction angle depends on the interlocking of soil grains and the resistance to sliding between the grains.

Internal friction depends on the roughness of grains and normal stress. The shear strength of a soil is defined as follows:

$$\tau = c + \sigma \tan \phi$$

For pile foundation design, the resistance along the pile shaft and at the pile toe are a function of τ , c and ϕ parameters.

Effective stress, σ' , is defined as the soil grain to soil grain pressure and is equal to the total overburden pressure, σ , minus the pore water pressure (neutral pressure), u . This may be expressed in equation form as:

$$\sigma' = \sigma - u$$

The pore water has no shear strength and is incompressible. Only the intergranular stress (effective stress) is effective in resisting shear or limiting compression of the soil. When pore water drains from soil during consolidation, the decrease in water pressure increases the level of effective stress. Effective stress is important in both laboratory testing and in design, since it correlates directly with soil behavior. An increase in effective stress causes densification and an increase in shear strength.

Three test methods are commonly used to measure shear strength in the laboratory. In order of increasing cost and test sophistication they are as follows:

- a. Unconfined compression test (AASHTO T208).
- b. Direct shear test (AASHTO T236).
- c. Triaxial compression test (AASHTO T234).

The unconfined compression test is the most widely used laboratory test to evaluate soil shear strength. In the unconfined compression test, an axial load is applied on a cylindrical soil sample while maintaining a zero lateral or confining pressure. The axial loading is

increased to failure and the shear strength is then considered to be one half the axial stress at failure. Unconfined compression tests are performed only on cohesive soil samples.

Unconfined compression tests on cohesive samples recovered from large depths or samples with a secondary structure, such as sand seams, fissures, or slickensides, can give misleadingly low shear strengths. This is due to the removal of the in-situ confining stress normally present. Triaxial compression tests provide better information on soil shear strength in these cases.

The direct shear test is performed by placing a sample of soil into a shear box which is split into two parts at mid-height. A normal load is then applied to the top of the sample and one half of the shear box is pulled or pushed horizontally past the other half. The shear stress is calculated from the horizontal force divided by the sample area and is plotted versus horizontal deformation. A plot of at least three normal stresses and their corresponding maximum shear stresses provides the shear strength parameters c and ϕ . Bowles (1977) notes that the ϕ values determined from plain strain direct shear tests are approximately 1.1 times the ϕ values determined from triaxial tests. Direct shear tests are primarily performed on recompacted granular soils. Direct shear tests are generally not recommended for cohesive soils due to limitations on drainage control during shear.

The most versatile shear strength test is the triaxial compression test. The triaxial test allows a soil sample to be subjected to three principal stresses under controlled conditions. A cylindrical test specimen is encased in a rubber membrane and is then subjected to a confining pressure. Drainage from the sample is controlled through its two ends. The shearing force is applied axially and increased to failure. A plot of normal stress versus shear stress is developed and parameters c and ϕ are determined. In triaxial tests where full drainage is allowed during shear, or in undrained tests with pore pressure measurements during shear, the effective stress parameters c' and ϕ' can be determined. In shear testing, the drainage, consolidation, and loading conditions are selected to simulate field conditions. Triaxial compression tests are classified according to the consolidation and drainage conditions allowed during testing. The three test types normally conducted are unconsolidated undrained (UU), consolidated undrained (CU) and consolidated drained (CD). The unconfined compression test may theoretically be considered a UU test performed with no confining pressure. Direct shear tests are usually consolidated under a normal stress then sheared either very slowly to model drained conditions, or rapidly to model undrained conditions.

Total stress and effective stress pile design methods are presented in Chapter 9. The total stress methods use undrained shear strengths. Effective stress design methods use drained shear strength data. Therefore, selection of the shear strength tests to be performed should consider the analysis method(s) that will be used.

6.1.3 Consolidation Tests

To estimate the amount and rate at which a cohesive soil deposit will consolidate under an applied load of a structure, a one dimensional consolidation test (AASHTO T216) is usually performed. In this test, a saturated soil sample is constrained laterally while being compressed vertically. The vertical compression is measured and related to the void ratio of the soil. Loading the sample results in an increased pore water pressure within the voids of the sample. Over a period of time, as the water is squeezed from the soil, this excess water pressure will dissipate resulting in the soil grains (or skeleton) supporting the load. The amount of water squeezed from the sample is a function of load magnitude and compressibility of soil skeleton. The rate of pressure dissipation is a function of the permeability of the soil.

The results from the test are used to plot void ratio, e , versus pressure, p , on a semi-log scale to determine the preconsolidation pressure, p_c , and compression index, C_c . An illustration of a typical e -log p curve is presented in Figure 9.61. A plot of log time versus sample compression is used to determine coefficient of consolidation. Consolidation test results can be used to estimate magnitude and settlement rate of pile foundations in cohesive soils. A settlement design example using consolidation test data is presented in Chapter 9.

6.1.4 Electro Chemical Classification Tests

The soil and groundwater can contain constituents detrimental to pile materials. Electro chemical classification tests can be used to determine the aggressiveness of the subsurface conditions and the potential for pile deterioration. These electro chemical tests include:

- a. pH (AASHTO T289).
- b. Resistivity (AASHTO T288).
- c. Sulfate ion content (AASHTO T290).

- d. Chloride ion content (AASHTO T291).

Additional discussion of the influence of environmental conditions on pile selection are presented in Section 8.8 of Chapter 8.

6.2 LABORATORY TESTING FOR PILE DRIVEABILITY CONSIDERATIONS

As noted earlier in this chapter, pile foundations are increasingly being driven to greater depths and greater capacities. Laboratory tests to determine the remolded shear strength of cohesive soils and the gradation and fine content of cohesionless soils are important in assessing the pile driveability and the potential soil setup effects (changes in pile capacity with time).

Remolded Shear Strength of Cohesive Soils

Cohesive soils may lose a significant portion of their shear strength when disturbed or remolded, as during the pile driving process. The ability to estimate the soil strength at the time of driving and the resulting strength gain with time or soil set-up is a key component of economical pile design in cohesive soils. Soil-set-up is discussed further in Section 9.10.1.1. **The sensitivity of a cohesive soil can provide a qualitative but not quantitative indication of potential soil set-up.** Sensitivity determined in-situ with a vane shear device as described in Section 5.4 of Chapter 5 provides the best assessment of cohesive soil sensitivity. However, the sensitivity of a cohesive soil can also be determined from laboratory tests on undisturbed and remolded samples.

The sensitivity of a cohesive soil, S_t , is defined as:

$$S_t = (q_u \text{ undisturbed}) / (q_u \text{ remolded})$$

Table 6-2 contains typical values of sensitivity as reported by Sowers (1979) which may be useful for preliminary estimates of remolded shear strength. Terzaghi and Peck, (1967) noted that clays with sensitivities less than 16 generally regain a portion to all of their original shear strength with elapsed time. Based upon typical sensitivity values reported by Terzaghi and Peck as well as by Sowers, the remolded shear strength of many cohesive soils during pile driving would be expected to range from about 1/3 to 1/2 the undisturbed shear strength.

| TABLE 6-2 TYPICAL VALUES OF SENSITIVITY FROM SOWERS (1979) | |
|--|-------|
| Clay of medium plasticity, normally consolidated | 2-8 |
| Highly flocculent, marine clays | 10-80 |
| Clays of low to medium plasticity, overconsolidated | 1-4 |
| Fissured clays, clays with sand seams | 0.5-2 |

To determine site specific soil sensitivity from laboratory data, remolded soil specimens having the same moisture content as the undisturbed specimen should be tested in unconfined compression.

Gradation of Cohesionless Soils

The gradation and fine content of cohesionless soils provide useful information in assessing pile driveability. Soils with a high fine content generally have lower angles of internal friction than lower fine content soils of similar density. A high fine content can also affect soil drainage and pore pressures during shear, and thus, the effective stresses acting on a pile during driving. Depending upon soil density, cohesionless soils with high fine contents are also more likely to demonstrate soil set-up than cohesionless soils with little or no fines. The gradation and angularity of the soil grains also influences the angle of internal friction.

Routine laboratory grain size analyses (mechanical and hydrometer) can quantify gradation and fine content. With this information, better engineering assessments of pile driveability and soil setup potential in cohesionless soils can be made.

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Chapter 7

FOUNDATION DESIGN PROCEDURE

A foundation is the interfacing element between the superstructure and the underlying soil or rock. The loads transmitted by the foundation to the underlying soil must not cause soil shear failure or damaging deformations of the superstructure. It is essential to systematically consider various foundation types and to select the optimum alternative based on the superstructure requirements, the subsurface conditions, and foundation cost.

Foundation types may include shallow foundations consisting of spread footing or mat foundations with or without ground improvement; or deep foundations consisting of driven piles, micropiles, or drilled shafts.

Subsequent chapters of this manual provide guidance on pile foundation design and construction. Guidance for other foundation solutions is contained in the following documents:

| | | |
|--------------------|--|---|
| Spread Footings | FHWA-SA-02-054 FHWA-NHI-01-023 FHWA- RD-86-185 | Kimmerling (2002) Munfakh et al. (2001) Gifford et al. (1987) |
| Ground Improvement | FHWA-NHI-04-001 | Elias et. al (2004) |
| Micropiles | FHWA-NHI-05-039 FHWA-RD-96-016 to 019 | Sabatini et al. (2005) Bruce and Juran (1997) |
| Drilled Shafts | FHWA-IF-99-025 | O'Neil and Reese (1999) |
| Auger Cast Piles | GEC 8 | Brown and Dapp (2006) |

Complete references for the above design manuals are provided at the end of this chapter. Information on the availability of these documents is provided at www.fhwa.dot.gov/bridge/geopub.htm

7.1 FOUNDATION DESIGN APPROACH

The following design approach is recommended to determine the optimum foundation alternative.

1. Determine the foundation loads to be supported, structure layout, and special requirements such as limits on total and differential settlements, lateral deformations, lateral loads, scour, seismic performance, and time constraints on construction. **This step is often partially overlooked or vaguely addressed. A complete knowledge of these issues is of paramount importance.**
2. Evaluate the subsurface exploration and the laboratory testing data. Ideally, the subsurface exploration and laboratory testing programs were performed with knowledge of the loads to be transmitted to, and supported by the soil and/or rock materials.
3. Prepare a final soil profile and critical cross sections. Determine soil layers suitable or unsuitable for spread footings, pile foundations, or drilled shafts. Also consider if ground improvement techniques could modify unsuitable layers into suitable support layers.
4. Consider and prepare alternative designs.

Shallow Foundations: a. Spread footings.
(without ground improvement) b. Mat foundations.

Shallow Foundations: a. Spread footings.
(with ground improvement) b. Mat foundations.

Deep Foundations: a. Pile foundations.
 i. Candidate pile types
 ii. Viable pile sections
 b. Drilled shafts.
 c. Micropile.

Table 7-1 summarizes shallow and deep foundation types and uses, as well as applicable and non-applicable subsurface conditions.

5. Prepare cost estimates for feasible alternative foundation designs including all associated substructure costs. The cost estimates should be developed using the concept of foundation support cost that was introduced in Chapter 2. The foundation support cost should include all associated substructure costs required for foundation construction such as sheeting or cofferdam requirements, cap requirement and size, and the effect of environmental or construction limitations such as noise restrictions or abatement procedures, bubble nets, etc.

6. Select the optimum foundation alternative. Generally the most economical alternative (lowest foundation support cost) should be selected and recommended. However, the ability of the local construction force as well as the availability of materials and equipment should also be considered.

For major projects, if the estimated costs of feasible foundation alternatives (during the design stage) are within 15 percent of each other, then alternate foundation designs should be considered for inclusion in the contract documents. The most economical foundation design will then be determined by construction demand and material pricing rather than subtleties in the design estimate.

| TABLE 7-1 FOUNDATION TYPES AND TYPICAL USES* | | | |
|---|--|--|--|
| Foundation Type | Use | Applicable Soil Conditions | Non-suitable or Difficult Soil Conditions |
| Spread footing, wall footings. | Individual columns, walls, bridge piers. | Any conditions where bearing capacity is adequate for applied load. May use on single stratum; firm layer over soft layer, or weaker layer over firm layer. Check immediate, differential and consolidation settlements. | Any conditions where foundations are supported on soils subject to scour or liquefaction. Bearing layer located below ground water table. |
| Mat foundation. | Same as spread and wall footings. Very heavy column loads. Usually reduces differential settlements and total settlements. | Generally soil bearing value is less than for spread footings. Over one-half area of structure covered by individual footings. Check settlements. | Same as footings. |
| Pile foundations (shaft resistance, toe resistance or combination). | In groups to transfer heavy column and bridge loads to suitable soil layers. Also to resist uplift and/or lateral loads. | Poor surface and near surface soils. Soils suitable of load support 5 to 90 m (15 to 300 ft) below ground surface. Check settlement of pile groups. | Shallow depth to hard stratum. Sites where pile driving vibrations or heave may adversely impact adjacent facilities. Boulder fields. |
| Drilled shafts (shaft resistance, toe resistance or combination). | Larger column loads than for piles. Cap sometimes eliminated by using drilled shafts as column extension. | Poor surface and near surface soils. Soils and/or rock of suitable load support located 8 to 90 m (25 to 300 ft) below ground surface. | Deep deposits of soft clays and loose water bearing granular soils. Caving formations difficult to stabilize. Artesian conditions. Boulder fields. |
| Micropiles. | Often used for seismic retrofitting, underpinning, and in low head room situations. | Any soil, rock, or fill conditions including areas with rubble fill, boulders, and karstic conditions. | High slenderness ratio may present buckling problems from loss of lateral support in liquefaction susceptible soils. |

* Modified from Bowles (1977).

7.2 CONSIDERATION OF SPREAD FOOTING FOUNDATION

The feasibility of using spread footings for foundation support should be considered in any foundation selection process. Spread footings are generally more economical than deep foundations (piles and drilled shafts); spread footings in conjunction with ground improvement techniques should also be considered. **Deep foundations should not be used indiscriminately for all subsurface conditions and for all structures.** There are subsurface conditions where pile foundations are very difficult and costly to install, and other conditions when they may not be necessary.

7.3 ESTABLISHMENT OF A NEED FOR A DEEP FOUNDATION

The first difficult problem facing the foundation designer is to establish whether or not the site conditions dictate that a deep foundation must be used. Vesic (1977) summarized typical situations in which piles may be needed. These typical situations as well as additional uses of deep foundations are shown in Figure 7.1.

Figure 7.1(a) shows the most common case in which the upper soil strata are too compressible or too weak to support heavy vertical loads. In this case, deep foundations transfer loads to a deeper dense stratum and act as toe bearing foundations. In the absence of a dense stratum within a reasonable depth, the loads must be gradually transferred, mainly through soil resistance along shaft, Figure 7.1(b). An important point to remember is that deep foundations transfer load through unsuitable layers to suitable layers. The foundation designer must define at what depth suitable soil layers begin in the soil profile.

Deep foundations are frequently needed because of the relative inability of shallow footings to resist inclined, lateral, or uplift loads and overturning moments. Deep foundations resist uplift loads by shaft resistance, Figure 7.1(c). Lateral loads are resisted either by vertical deep foundations in bending, Figure 7.1(d), or by groups of vertical and battered foundations, which combine the axial and lateral resistances of all deep foundations in the group, Figure 7.1(e). Lateral loads from overhead highway signs and noise walls may also be resisted by groups of deep foundations, Figure 7.1(f).

Deep foundations are often required when scour around footings could cause loss of bearing capacity at shallow depths, Figure 7.1(g). In this case the deep foundations must extend below the depth of scour and develop the full capacity in the support zone below the level of expected scour. FHWA scour guidelines by Richardson and Davis (2001) require the geotechnical analysis of bridge foundations to be performed on the basis that all stream bed materials in the scour prism have been removed and are not available for bearing or lateral support. Costly damage and the need for future underpinning can be avoided by properly designing for scour conditions.

Soils subject to liquefaction in a seismic event may also dictate that a deep foundation be used, Figure 7.1(h). Seismic events can induce significant lateral loads to deep foundations. During a seismic event, liquefaction susceptible soils offer less lateral resistance as well as reduced shaft resistance to a deep foundation. Liquefaction effects on deep foundation performance must be considered for deep foundations in seismic areas.

Deep foundations are often used as fender systems to protect bridge piers from vessel impact, Figure 7.1(i). Fender system sizes and group configurations vary depending upon the magnitude of vessel impact forces to be resisted. In some cases, vessel impact loads must be resisted by the bridge pier foundation elements. Single deep foundations may also be used to support navigation aids.

In urban areas, deep foundations may occasionally be needed to support structures adjacent to locations where future excavations are planned or could occur, Figure 7.1(j). Use of shallow foundations in these situations could require future underpinning in conjunction with adjacent construction.

Deep foundations are used in areas of expansive or collapsible soils to resist undesirable seasonal movements of the foundations. Deep foundations under such conditions are designed to transfer foundation loads, including uplift or down-drag, to a level unaffected by seasonal moisture movements, Figure 7.1(k).

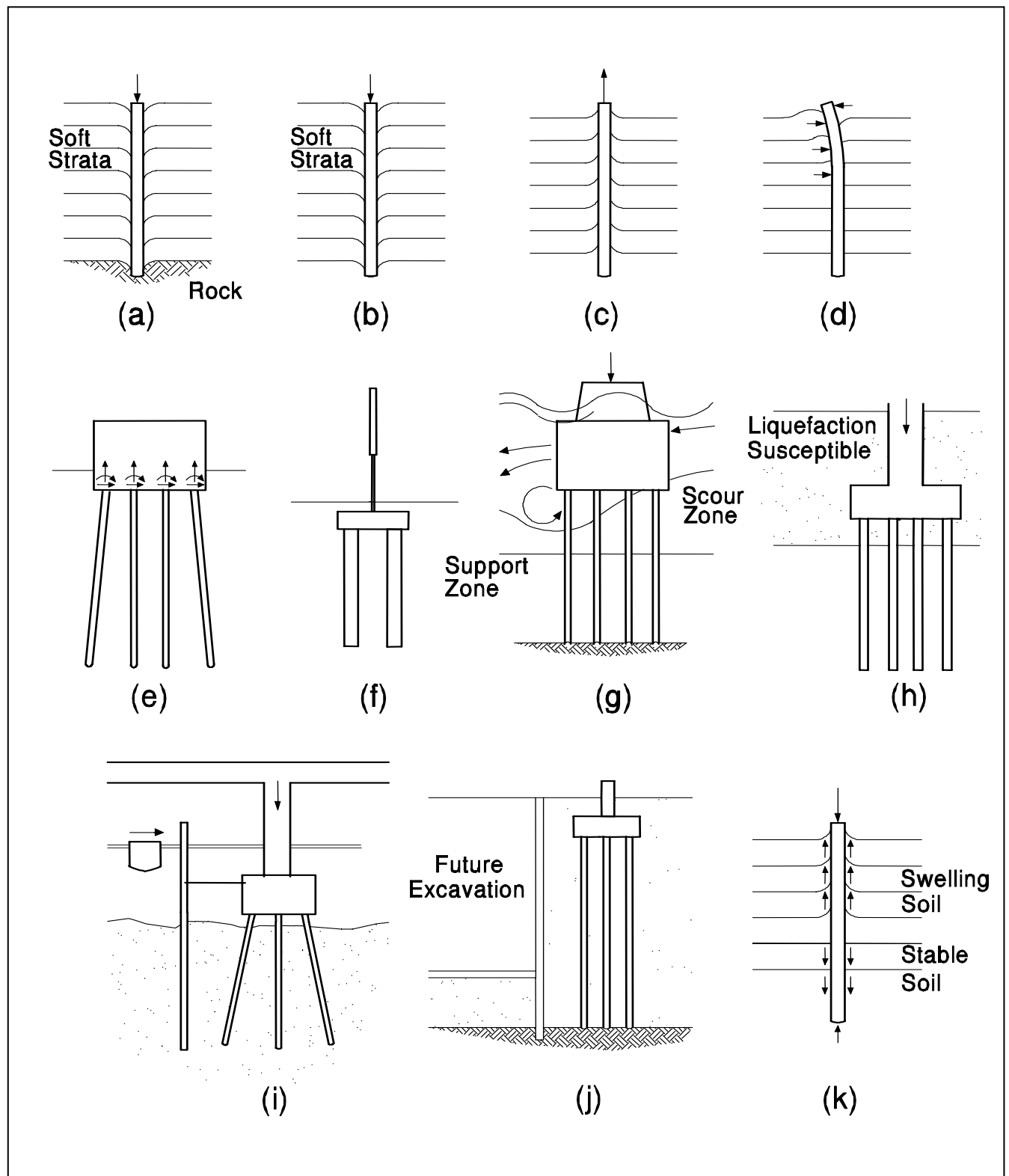


Figure 7.1 Situations in which Deep Foundations may be Needed (modified from Vesic, 1977)

In many instances either a shallow or deep foundation alternative is technically feasible. Under these circumstances, an evaluation of the shallow foundation should include; (1) the dimensions and depth of shallow footings based on allowable bearing capacity, (2) the magnitude and time-rate of settlement under anticipated loads, and (3) detailed cost analysis including such factors as need for cofferdams, overall substructure cost, dewatering and foundation seals, construction time, construction risk and claims potential. A comparative analysis of feasible deep foundation alternatives should also be made. The cost analyses of feasible alternatives should have a significant role in final selection of the foundation type.

Because this manual deals only with driven pile foundations, other types of foundations will not be discussed further.

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Chapter 8

PILE TYPES FOR FURTHER EVALUATION

The economic selection of a pile foundation type and section for a structure should be based on the specific soil conditions as well as the foundation loading requirements, final performance criteria, construction limitations and time, as well as the foundation support cost. This chapter focuses on the characteristics of driven pile foundation types typically used for highway structures. Design data useful in the selection and design of specific pile types is included in Appendices C-1 (SI units) and C-2 (US units). Additional details on pile splices and toe protection devices are presented in Chapter 22.

8.1 OVERVIEW OF TYPICAL PILE TYPES

Piles can be broadly categorized in two main types: foundation piles for support of structural loads and sheet piles for earth retention systems. Discussion of sheet piles is outside the scope of this manual.

There are numerous types of foundation piles. Figure 8.1 shows a pile classification system based on type of material, configuration, installation technique and equipment used for installation. Foundation piles can also be classified on the basis of their method of load transfer from the pile to the surrounding soil mass. Load transfer can be by shaft resistance, toe bearing resistance or a combination of both.

Table 8-1 modified from NAVFAC (1982) summarizes characteristics and uses of common pile types. The table is for preliminary guidance only, and should be confirmed by local practice. In addition, the design load should be determined by geotechnical engineering principles, limiting stresses in the pile material, and type and function of structure. Uncased cast-in-place concrete piles, although outside the scope of this driven pile manual, are included in this chapter because all feasible pile types should be considered in any selection process.

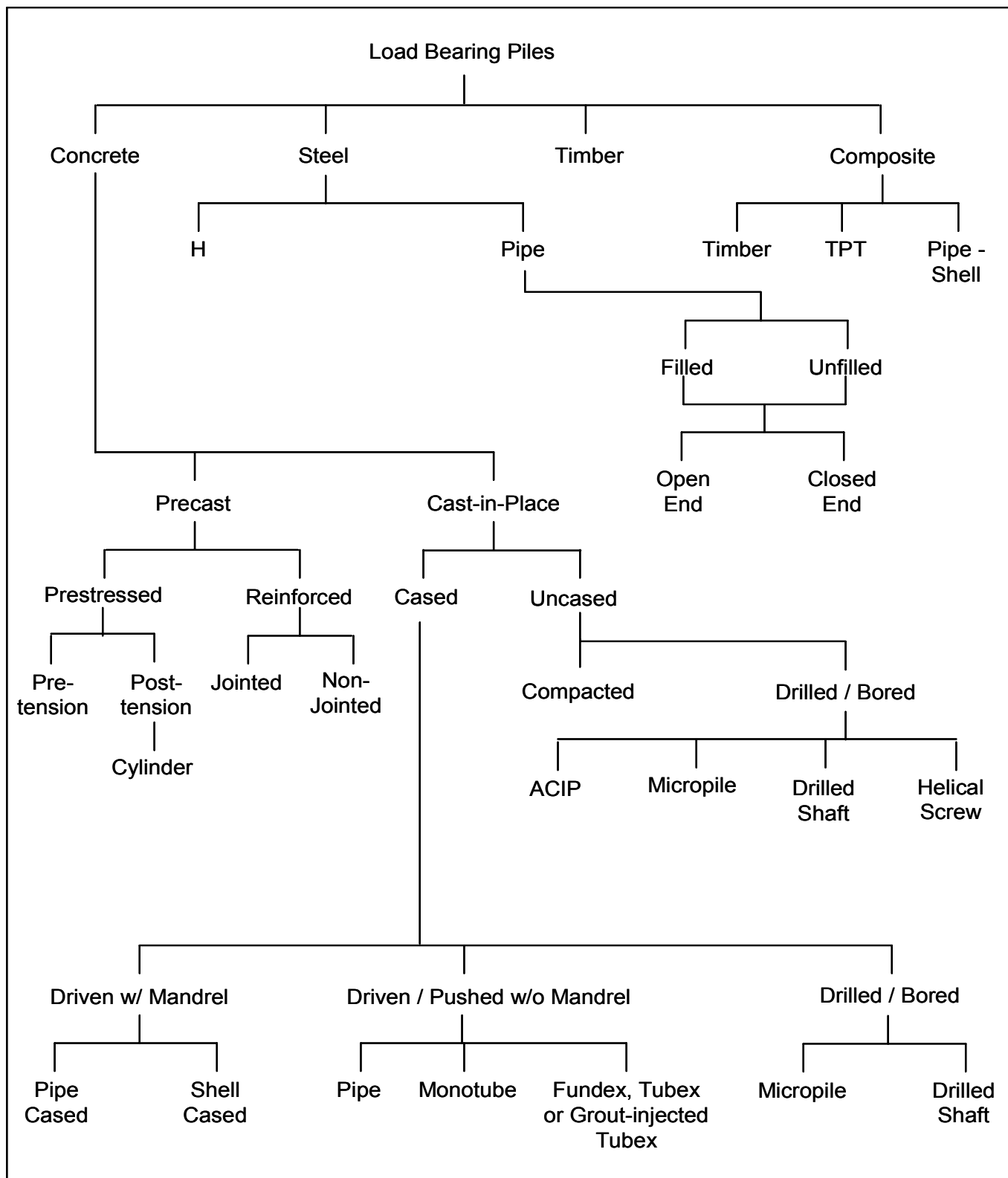
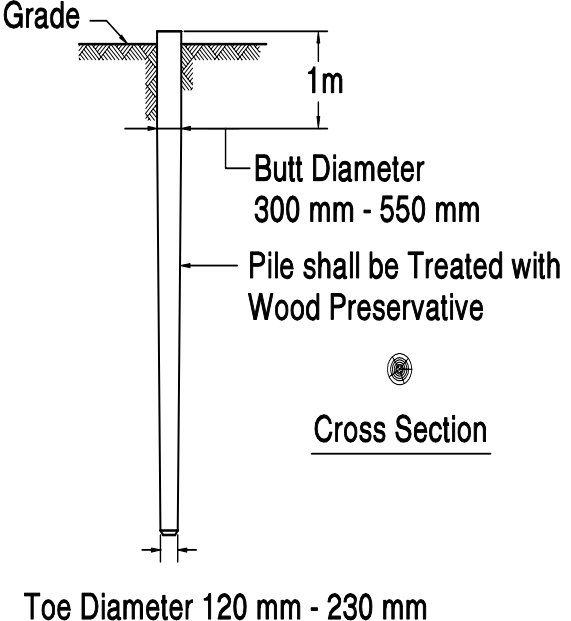

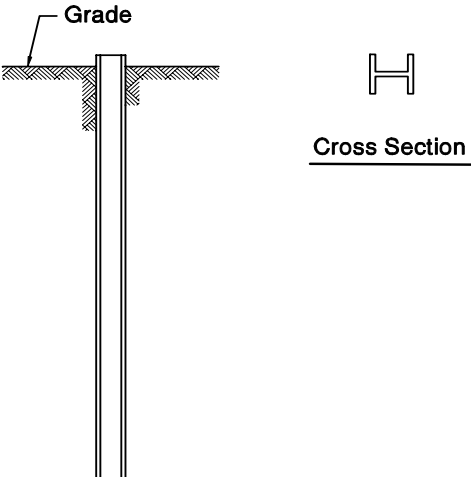


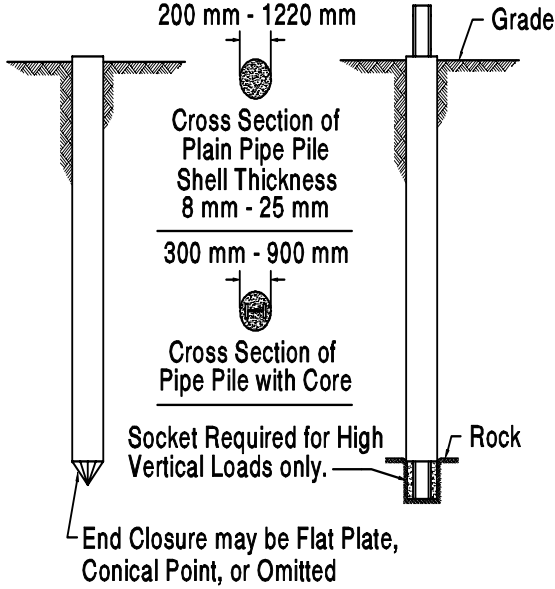
Figure 8.1 Pile Classification Chart

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* | | |
|---------------------------------------|---|---|
| PILE TYPE | TIMBER | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 5 m - 23 m (15 – 75 ft) Southern Pine 5 m - 37 m (15 – 120 ft) Douglas Fir |  <p>Grade</p> <p>1m</p> <p>Butt Diameter 300 mm - 550 mm</p> <p>Pile shall be Treated with Wood Preservative</p> <p> Cross Section</p> <p>Toe Diameter 120 mm - 230 mm</p> |
| MATERIAL SPECIFICATIONS | ASTM-D25 AWPA UC4A, UC4B UC4C, UC5A, UC5B and UC5C. | |
| MAXIMUM STRESSES | See Chapter 10. | |
| TYPICAL AXIAL DESIGN LOADS | 100 kN - 500 kN (20 – 110 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Difficult to splice. • Vulnerable to damage in hard driving; both pile head and toe may need protection. • Intermittently submerged piles are vulnerable to decay unless treated. | |
| ADVANTAGES | <ul style="list-style-type: none"> • Comparatively low in initial cost. • Permanently submerged piles are resistant to decay. • Easy to handle. | |
| REMARKS | <ul style="list-style-type: none"> • Best suited for friction piles in granular material. | |

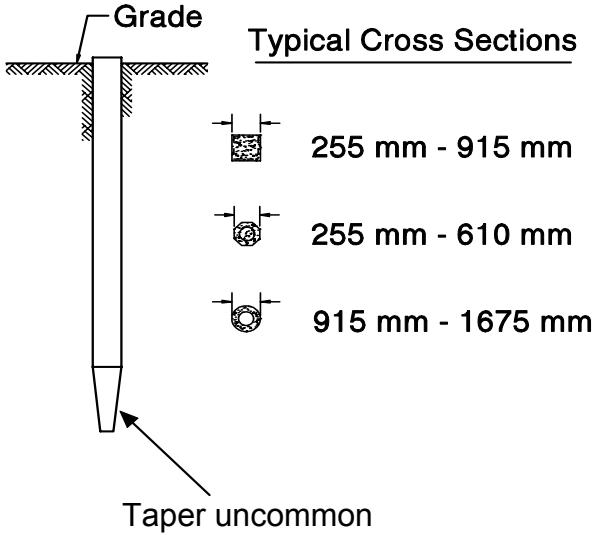
* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|---|--|
| PILE TYPE | STEEL - H SECTIONS | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 5 m - 40 m (15 – 130 ft) |  |
| MATERIAL SPECIFICATIONS | ASTM - A572, A588, or A690 Grade 50 (A36 steel is no longer produced) | |
| MAXIMUM STRESS | See Chapter 10. | |
| TYPICAL AXIAL DESIGN LOADS | 600 kN - 2,500 kN (130 – 560 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Vulnerable to corrosion where exposed HP section may be damaged or deflected by major obstructions. | |
| ADVANTAGES | <ul style="list-style-type: none"> • Available in various lengths and sizes. • High capacity. • Small soil displacement. • Easy to splice. • Able to penetrate through light obstructions. • Pile toe protection will assist penetration through harder layers and some obstructions. | |
| REMARKS | <ul style="list-style-type: none"> • Best suited for toe bearing on rock. • Allowable capacity should be reduced in corrosive environments. • Use as a friction pile in granular materials often results in cost overruns. | |

* Table modified and reproduced from NAVFAC DM 7.2 (198

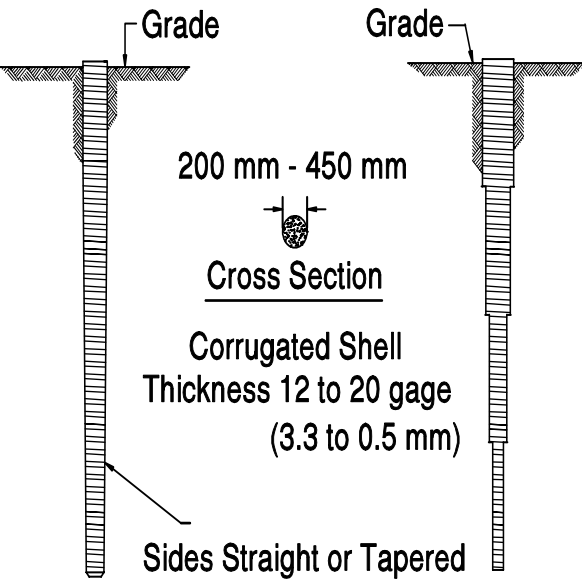
| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|---|---|
| PILE TYPE | STEEL PIPE PILES | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 5 m - 40 m (15 - 130 ft) |  <p>The illustration shows two vertical steel pipe piles. The left pile is a 'Plain Pipe Pile' with a cross-section showing a shell thickness of 8 mm - 25 mm and an outer diameter of 200 mm - 1220 mm. The right pile is a 'Pipe Pile with Core' with a cross-section showing an outer diameter of 300 mm - 900 mm. Both piles are shown extending from 'Grade' down to 'Rock'. A note indicates that a 'Socket Required for High Vertical Loads only' is needed at the bottom. Another note states 'End Closure may be Flat Plate, Conical Point, or Omitted'.</p> |
| MATERIAL SPECIFICATIONS | ASTM A252, Grade 2 or 3 - for pipe. ACI 318 - for concrete (if filled). ASTM A572 - for core (if used). | |
| MAXIMUM STRESSES | See Chapter 10. | |
| TYPICAL AXIAL DESIGN LOADS | 800 kN - 2,500 kN (180 - 560 kips) with or without concrete fill and without cores. 2,500 kN - 15,000 kN (560 - 3400 kips) concrete filled with cores. | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Soil displacement for closed end pipe. | |
| ADVANTAGES | <ul style="list-style-type: none"> • Closed end pipe can be internally inspected after driving. • Low soil displacement for open end installation. • Open end pipe with cutting shoe can be used against obstructions. • Open end pipe can be cleaned out and driven further. • High load capacities. • Easy to splice. | |
| REMARKS | <ul style="list-style-type: none"> • Provides high bending resistance where unsupported length is loaded laterally. • Open end not recommended as a friction pile in granular material. | |

* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|--|--|
| PILE TYPE | PRESTRESSED/PRECAST CONCRETE | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 15 m - 40 m (50 – 130 ft) for prestressed. 10 m - 15 m (30 - 50 ft) for reinforced. |  <p>The illustration shows a vertical pile with a cross-section at the top labeled 'Grade'. To the right, under the heading 'Typical Cross Sections', are three circular cross-sections with their dimensions: 255 mm - 915 mm, 255 mm - 610 mm, and 915 mm - 1675 mm. An arrow points to the bottom of the pile with the text 'Taper uncommon'.</p> |
| MATERIAL SPECIFICATIONS | ACI 318 - for concrete. ASTM - A82, A615, A722, and A884 - for reinforcing steel. ASTM - A416, A421, and A882 - for prestressing. | |
| MAXIMUM STRESSES | See Chapter 10. | |
| TYPICAL AXIAL DESIGN LOADS | 400 kN - 4,500 kN (90 – 1000 kips) for prestressed. 400 kN - 1,000 kN (90 – 225 kips) for reinforced. | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Unless prestressed, vulnerable to handling damage. • Relatively high breakage rate, especially when piles are to be spliced. • Considerable displacement. • Difficult to splice when insufficient length ordered. | |
| ADVANTAGES | <ul style="list-style-type: none"> • High load capacities. • Corrosion resistance obtainable. • Hard driving possible. | |
| REMARKS | <ul style="list-style-type: none"> • Cylinder piles are well suited for bending resistance. | |

Note: Reinforcing may be Prestressed

* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | | |
|---|--|--|--|
| PILE TYPE | CAST-IN-PLACE CONCRETE (MANDREL DRIVEN SHELL) | TYPICAL ILLUSTRATION | |
| TYPICAL LENGTHS | 3 m - 40 m (10 – 130 ft), but typically in the 15 m - 25 m (50 – 80 ft) range. |  | |
| MATERIAL SPECIFICATIONS | ACI 318 - for concrete. | | |
| MAXIMUM STRESSES | 33% of 28-day strength of concrete, with increase to 40% of 28-day strength provided: <ul style="list-style-type: none"> • Casing is a minimum of 12 gage thickness. • Casing is seamless or with welded seams. • Ratio of steel yield strength to concrete is not less than 6. • Pile diameter not greater than 450 mm (18 in). | | |
| TYPICAL AXIAL DESIGN LOADS | Designed for a wide loading range but generally in the 400-1400 kN (90 – 315 kip) range. | | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Difficult to splice after concreting. • Redriving not recommended. • Thin shell vulnerable during driving to excessive earth pressure or impact. • Considerable displacement. | | |
| ADVANTAGES | <ul style="list-style-type: none"> • Initial economy. • Tapered sections provide higher resistance in granular soil than uniform piles. • Can be inspected after driving. • Relatively less waste of steel. • Can be designed as toe bearing or friction pile. | | |
| REMARKS | <ul style="list-style-type: none"> • Best suited as friction pile in granular materials. | | |

* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|---|----------------------|
| PILE TYPE | CAST-IN-PLACE CONCRETE (SHELLS DRIVEN WITHOUT A MANDREL) | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 5 m - 25 m (15 – 80 ft) | |
| MATERIAL SPECIFICATIONS | ACI 318 - for concrete. ASTM A252 - for steel pipe. | |
| MAXIMUM STRESSES | See Chapter 10. | |
| TYPICAL AXIAL DESIGN LOADS | 500 kN - 1350 kN (110 – 300 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Difficult to splice after concreting. • Considerable displacement. | |
| ADVANTAGES | <ul style="list-style-type: none"> • Can be redriven. • Shell not easily damaged if fluted. | |
| REMARKS | <ul style="list-style-type: none"> • Best suited for friction piles of medium length. | |

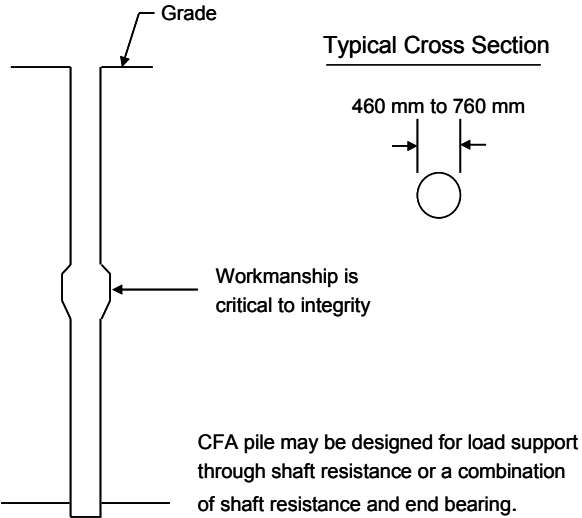
* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|---|--|
| PILE TYPE | COMPOSITE PILES | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 15 m - 65 m (50 – 210 ft) | <p style="text-align: center;"><u>Typical Combinations</u></p> <p>The diagram illustrates four typical pile combinations across a ground line. Top-left: A pile with 'Precast Concrete' above ground and 'HP Section' below ground. Top-right: A pile with 'Cased or Uncased Concrete' above ground and 'Timber' below ground. Bottom-left: A pile with 'Concrete Filled Steel Shell' above ground and 'Steel Pipe Concrete Filled' below ground. Bottom-right: A pile with 'Steel Pipe Concrete Filled' above ground and 'HP Section' below ground.</p> |
| MATERIAL SPECIFICATIONS | ASTM A572 - for HP section. ASTM A252 - for steel pipe. ASTM D25 - for timber. ACI 318 - for concrete. | |
| MAXIMUM STRESSES | 33% of 28-day strength of concrete. 62 MPa (9 ksi) for structural and pipe sections if thickness is greater than 4 mm (0.16 inches). | |
| TYPICAL AXIAL DESIGN LOADS | 300 kN - 1,800 kN (70 – 400 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> Difficult to attain good joints between two materials except for concrete H or pipe composite piles. | |
| ADVANTAGES | <ul style="list-style-type: none"> Considerable length can be provided at comparatively low cost for wood composite piles. High capacity for some composite piles. Internal inspection for pipe composite piles. | |
| REMARKS | <ul style="list-style-type: none"> The weakest of any material used shall govern allowable stresses and capacity. | |

* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|--|----------------------|
| PILE TYPE | DRILLED SHAFTS | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 5 m to 65 m or more (15 – 200 ft) | |
| MATERIAL SPECIFICATIONS | ACI 318 - for concrete. ASTM A82, A615, A722, and A884 for reinforcing steel. | |
| MAXIMUM STRESSES | 33% of 28-day strength of concrete. | |
| TYPICAL AXIAL DESIGN LOADS | 1,500 kN - 20,000 kN (330 – 4500 kips) or more. | |
| DISADVANTAGES | <ul style="list-style-type: none"> Requires relatively more extensive inspection. Construction procedures are critical to quality. Boulders can be a serious problem, especially in small diameter shafts. Mobilization of end bearing on a long shaft can require substantial displacement of shaft head. | |
| ADVANTAGES | <ul style="list-style-type: none"> Length variations easily accommodated. High bearing capacity and bending resistance. Availability of several construction methods. Can be continued above ground as a column. | |
| REMARKS | <ul style="list-style-type: none"> No driving observations (blow count) available to aid in assessing capacity. Not recommended in soft clays and loose sands. | |

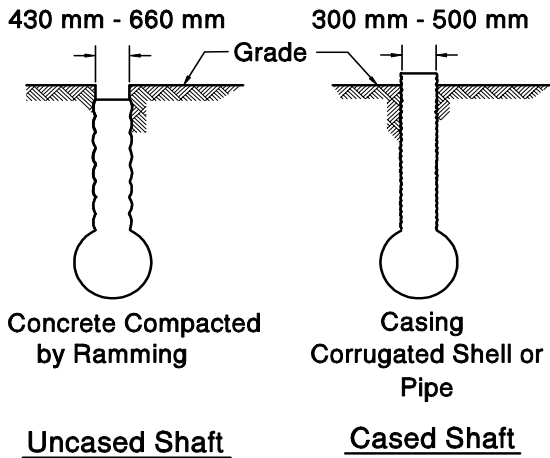
* Table modified and reproduced from NAVFAC DM 7.2 (1982)

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|--|--|
| PILE TYPE | AUGER PLACED, PRESSURE INJECTED CONCRETE PILES (CFA PILES) | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 5 m - 25 m (15 – 80 ft) |  <p>Grade</p> <p>Typical Cross Section</p> <p>460 mm to 760 mm</p> <p>Workmanship is critical to integrity</p> <p>CFA pile may be designed for load support through shaft resistance or a combination of shaft resistance and end bearing.</p> |
| MATERIAL SPECIFICATIONS | ACI 318 - for concrete. ASTM A82, A615, A722, & A884 - for reinforcing steel. | |
| MAXIMUM STRESSES | 33% of 28-day strength of concrete. | |
| TYPICAL AXIAL DESIGN LOADS | 260 kN - 875 kN (60 – 200 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Greater dependence on quality workmanship. • Not suitable through peat or similar highly compressible material. • Requires more extensive subsurface exploration. • No driving observation (blow count) to aid in assessing capacity. | |
| ADVANTAGES | <ul style="list-style-type: none"> • Economy. • Zero displacement. • Minimal vibration to endanger adjacent structures. • High shaft resistance. • Good contact on rock for end bearing. • Visual inspection of augured material. | |
| REMARKS | <ul style="list-style-type: none"> • Best suited as a friction pile in granular material. | |

* Table modified and reproduced from NAVFAC DM 7.2 (1982)

TABLE 8-1 TECHNICAL SUMMARY OF PILES (CONTINUED)

| PILE TYPE | MICROPILES | TYPICAL ILLUSTRATION |
|----------------------------|---|--|
| TYPICAL LENGTHS | 12 m - 25 m (40 – 100 ft) | <p>Cross Section</p> <p>130 - 230 mm</p> <p>150 - 230 mm</p> <p>Grout</p> <p>Steel Reinforcing Bar</p> <p>Steel Pipe (typically 100 - 180 mm)</p> |
| MATERIAL SPECIFICATIONS | ASTM C150 - for Portland cement. ASTM C595 - for blended hydraulic cement. ASTM A615 - for reinforcing steel. | |
| TYPICAL AXIAL DESIGN LOADS | 300 kN - 1100 kN (70 – 250 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> • Cost | |
| ADVANTAGES | <ul style="list-style-type: none"> • Low noise and vibrations. • Small amount of spoil. • Excellent for sites with low headroom and restricted access. • Applicability to soil containing rubble and boulders, karstic areas. | |
| REMARKS | <ul style="list-style-type: none"> • Can be used for any soil, rock or fill condition. | |

| TABLE 8-1 TECHNICAL SUMMARY OF PILES* (CONTINUED) | | |
|---|--|--|
| PILE TYPE | PRESSURE INJECTED FOOTINGS | TYPICAL ILLUSTRATION |
| TYPICAL LENGTHS | 3 m - 15 m (10 – 50 ft) |  <p>430 mm - 660 mm 300 mm - 500 mm</p> <p>Grade</p> <p>Concrete Compacted by Ramming Casing Corrugated Shell or Pipe</p> <p><u>Uncased Shaft</u> <u>Cased Shaft</u></p> |
| MATERIAL SPECIFICATIONS | ACI 318 - for concrete. ASTM A252 for steel pipe. | |
| MAXIMUM STRESSES | 33% of 28-day strength of concrete. 62 MPa (9 ksi) for pipe shell if thickness is greater than 4 mm (0.16 inches). | |
| TYPICAL AXIAL DESIGN LOADS | 600 kN - 1,200 kN (135 – 270 kips) | |
| DISADVANTAGES | <ul style="list-style-type: none"> Base of footing cannot be made in clay or when hard spots (e.g., rock ledges) are present in soil. When clay layers must be penetrated to reach suitable material, special precautions are required for shafts in groups. | |
| ADVANTAGES | <ul style="list-style-type: none"> Provides means for placing high capacity footings on bearing stratum without necessity for excavation or dewatering. High blow energy available for overcoming obstructions. Great uplift resistance if suitably reinforced. | |
| REMARKS | <ul style="list-style-type: none"> Best suited for granular soils where bearing is achieved through compaction around base. Minimum spacing 1.5 m (5 ft) on center. | |

* Table modified and reproduced from NAVFAC DM 7.2 (1982)

8.2 TIMBER PILES

Timber piles are usually of round, tapered cross section made from tree trunks of Southern Pine or Douglas Fir driven with the small end down. Southern Pine timber piles can be found to lengths up to 23 meters (75 ft), and some west coast Douglas Fir may be up to 37 meters (120 ft) in length. Oak and other timber types have also been used for piles, but that is infrequent today. ASTM D25, Standard Specification for Round Timber Piles, presents guidelines on minimum timber pile dimensions, straightness, knot sizes, *etc.* AWWA C3, Piles, Preservative Treatment by Pressure Process, contains penetration and retention values for the various preservatives. Figure 8.2 presents a photograph of timber piles.



Figure 8.2 Timber Piles

Timber piles are best suited for modest loads when used as friction piles in sands, silts and clays. The taper of timber piles is effective in increasing the shaft resistance, particularly in loose sands. They are not recommended as piles to be driven through dense gravel, boulders, or till, or for toe bearing piles on rock since they are vulnerable to damage at the pile head and toe in hard driving. Overdriving of timber piles can result in the crushing of fibers or brooming at the pile head. This can be controlled by using a helmet with cushion material and/or metal strapping around the head of the pile. In hard driving situations, a metal shoe should be

attached to the pile toe. Timber piles are favored for the construction of bridge fender systems and small jetties due to the good energy absorption properties of wood.

Timber pile splices are difficult and generally undesirable. However, splice details are discussed in Chapter 22.

Durability is generally not a design consideration if a timber pile is below the permanent water table. However, when a timber pile is subjected to alternate wetting and drying cycles or located above the water table, damage and decay by insects may result. Such damage reduces the service life of timber piles significantly unless the pile is treated with a wood preservative. The most common treatments for timber piling are Creosote, Chromated Copper Arsenate (CCA) for Southern Pine, and Ammoniacal Copper Zinc Arsenate (ACZA) for Douglas Fir. Creosote cannot be used alone in southern waters because of attack by *limnoria tripundtata*, but should be used as part of a dual treatment with CCA or ACZA. If cracking of the pile shaft or head occurs and extends below the prescribed pile cut-off level, the initial preservative treatment will not be effective, and the trimmed end of the pile should be treated a second time.

According to Graham (1995), the durability of round timber piling is a function of site-specific conditions:

1. Foundation piles permanently submerged in ground water will typically last indefinitely.
2. Fully embedded, treated foundation piles partially above the ground water with a concrete cap will typically last on the order of 100 years or longer.
3. Treated trestle piles over land will generally last as long as utility poles in the area, *i.e.*, about 75 years in northern areas and about 40 years in southern areas of the United States.
4. Treated piles in fresh water will typically last about five to ten years less than land trestle piles in the same area.
5. For treated piles in brackish water, the longevity should be determined by the experience in the area.

6. Treated marine piles will typically last about 50 years in northern climates and 25 years in southern climates of the United States.

8.3 STEEL H-PILES

Steel H-piles consist of rolled wide flange sections that have flange widths approximately equal the section depth. In most H-pile sections, the flange and web thicknesses are the same. They are manufactured in standard sizes ranging from 200 to 360 mm (8 to 14 inches). In some cases, W-sections are also used for piles. Figure 8.3 contains a photograph of H-piles with driving shoes. A summary of standard H-pile sections including properties needed for design is provided in Appendix C.



Figure 8.3 H-piles with Driving Shoes

H-piles produced today typically meet the requirements of ASTM A572, Grade 50 steel. ASTM A36 steel H-piles are no longer readily available. Steel sections

meeting the requirements of ASTM A588 and ASTM A690 are also available. These steels are high strength, low alloy steels developed for improved corrosion resistance in atmospheric (ASTM A588) and marine (ASTM A690) environments. However, ASTM A588 and A690 steels are typically hard to obtain, and long lead times may be necessary if they are specified. ASTM A572, A588 and A690 steels are all Grade 50 steels. Therefore, it is possible to use the higher strength of the Grade 50 steel if the pile can be installed to sufficient capacity as limited by the soil. Steel H-Piles are very effective when driven into soft rock. They can be driven very hard with modern high impact velocity hammers with little likelihood of pile toe damage.

H-piles are suitable for use as toe bearing piles, and as combination shaft resistance and toe bearing piles. Since H-piles generally displace a minimum amount of soil, they can be driven more easily through dense granular layers and very stiff clays than displacement piles. In addition, the problems associated with soil heave during foundation installation are often reduced by using H-piles. However, sometimes H-piles will "plug". That is, the soil being penetrated will adhere to the web and the inside flange surfaces creating a closed-end, solid section. The pile will then drive as if it were a displacement pile below the depth of plug formation. Plugging can have a substantial effect on both the soil resistance during driving and the ultimate static pile capacity.

Experience indicates that corrosion is not a practical problem for steel piles driven in natural soil, due primarily to the absence of oxygen in the soil. However, in fill materials at or above the water table, moderate corrosion may occur and protection may be needed. As noted above, high strength, low alloy steels are available for improved corrosion resistance. Another common protection method requires the application of pile coatings before and after driving. Coal-tar epoxies, fusion bonded epoxies, metallized zinc, metallized aluminum and phenolic mastics are some of the pile coatings available. Encasement by cast-in-place concrete, precast concrete jackets, or cathodic protection can also provide protection for piles extending above the water table. Another design option for piles subject to corrosion is to select a heavier section than that required by the design loads, anticipating the loss of material caused by corrosion. Corrosion losses can be estimated using the information provided in Section 8.8.1.

One advantage of H-piles is the ease of extension or reduction in pile length. This makes them suitable for nonhomogeneous soils with layers of hard strata or natural

obstructions. Splices are commonly made by full penetration groove welds so that the splice is as strong as the pile in both compression and bending. The welding should always be done by properly qualified welders. Proprietary splices are also commonly used for splicing H-piles. Chapter 22 presents information on typical splices. A steel load transfer cap is not required by AASHTO if the pile head is embedded 305 mm (12 inches) into the concrete pile cap. Pile toe reinforcement using commercially manufactured cast pile shoes is recommended for H-piles driven through or into very dense soil or soil containing boulders or other obstructions. Pile shoes are also used for penetration into sloping rock surfaces. Chapter 22 provides details on available driving shoes.

The disadvantages of H-piles include a tendency to deviate when natural obstructions are encountered. Field capacity verification of H-piles used as friction piles in granular soils based on the penetration resistance (blow count) can also be problematic, and can result in significant length overruns. An H-pile in a granular profile will often not plug during the dynamic loading of pile installation but may plug under the slower static loading condition. Length for length, steel piles tend to be more expensive than concrete piles. On the other hand, steel's high design load for a given weight can reduce pile driving costs.

8.4 STEEL PIPE PILES

Pipe piles consist of seamless, welded or spiral welded steel pipes in diameters typically ranging from 200 to 1220 mm (8 to 48 inches). Still larger sizes are available, but they are not commonly used in land or nearshore applications. Typical wall thicknesses range from 4.5 to 25 mm (0.188 to 1 inch) with wall thicknesses of up to 64 mm (2.5 inches) possible. Open end pipe piles as large as 1830 to 3050 mm (72 to 120 inches) have been used on large projects with significant vessel impact and/or seismic design considerations. Pipe piles should be specified by grade with reference to ASTM A252. In some situations, a contractor may propose to supply used pipe not produced under ASTM standards. Pipe piles not meeting ASTM standards must be evaluated by an engineer for general condition, driveability, and weldability prior to approval. Figure 8.4 contains a picture of a typical smaller diameter closed-end pipe pile and Figure 8.5 presents a photograph of a large open end pipe pile. Appendix C includes a table of dimensions and design properties for pipe piles.



Figure 8.4 Typical Closed-End Pipe Pile



Figure 8.5 Large Diameter Open End Pipe Piles

Steel pipe piles can be used in friction, toe bearing, a combination of both, or as rock socketed piles. They are commonly used where variable pile lengths are required since splicing is relatively easy. Common offshore or nearshore applications of pipe piles include their use as bridge foundation piles, fender systems, and large diameter mooring dolphins. With the increased ductility requirements for earthquake resistant design, pipe piles are being used extensively in seismic areas.

Pipe piles may be driven either open or closed end. If the capacity from the full pile toe area is required, the pile toe should be closed with a flat plate or a conical tip. Pipe piles may be left open or filled with concrete, and they can also have a structural shape such as an H-section inserted into the concrete. Open end pipe piles can be socketed into bedrock (rock socketed piles). In driving through dense materials, open end piles may form a soil plug. The plug makes the pile act like a closed end pile and can significantly increase the pile toe resistance. Plugging is discussed in greater detail in Section 9.10.5. The plug should not be removed unless the pile is to be filled with concrete. Most often, pipe piles are driven from the pile head. However, closed end pipe piles can also be bottom driven using a mandrel.

A closed end pipe pile is generally formed by welding a 12 to 25 mm (0.5 to 1 inch) thick flat steel plate or a conical point to the pile toe. When pipe piles are driven to weathered rock or through boulders, a cruciform end plate or a conical point with rounded nose is often used to prevent distortion of the pile toe. Open ended piles can also be reinforced with steel cutting shoes to provide protection from damage.

Typically, pipe piles are spliced using full penetration groove welds. Proprietary splicing sleeves are available and should be used only if the splice can provide full strength in bending (unless the splice will be located at a distance below ground where bending moments are small). Typical pile splices are described in Chapter 22. The discussion presented under H-piles on corrosion is also applicable to steel pipe piles.

The spin fin pile, Figure 8.6, is a variation of a pipe pile recently introduced along the west coast. It is a pipe pile with an outside thread made of fins that gradually wind around the lower portion of the pile. During driving the pile rotates, but in response to uplift the pile is prevented from twisting. This results in a plugging effect that increases the pile's uplift capacity.



Figure 8.6 760 mm (30 inch) Diameter Spin Fin Pile

8.5 PRECAST CONCRETE PILES

This general classification covers both conventionally reinforced concrete and prestressed concrete piles. Both types can be manufactured by various methods and can be produced in a number of different cross sections. However, precast reinforced concrete piles are rarely used in the U.S. Concrete piles are sometimes cast with a hollow core. The hollow core may be used for a jet pipe (if continuous), for reducing section weight, for placing instrumentation during construction, or for determining pile damage. Precast concrete piles are usually of constant cross section but can also include a tapered section near the pile toe.

Precast concrete piles are suitable for use as friction piles when driven in sand, gravel, or clays. In boulder conditions, a short piece of structural H-section or

"stinger" may be cast into or attached to the pile toe for penetrating through the zone of cobbles and boulders. A rock shoe or "Oslo point" cast into the pile toe can assist seating of concrete piles into a rock surface. Precast concrete piles are capable of high capacities when used as toe bearing piles.

Concrete piles are considered resistant to corrosion but can be damaged by direct chemical attack (from organic soil, industrial wastes or organic fills), electrolytic action (chemical or stray direct currents), or oxidation. There have been cases where concrete piles exhibited serious corrosion problems in sea water. It is desirable in this case that the concrete be as dense as possible. Concrete can be protected from chemical attack by use of special cements and by special coatings as discussed in Section 8.8.

A necessary consideration when dealing with hollow core precast concrete piles driven in water includes the evaluation of internal pressures within the cylinder which can reach bursting pressures and cause vertical cracks during driving. Another concern for piles driven through water is water jet cracking. If a pile is under high tension stresses during driving, small cracks can open and close during each hammer blow. If the cracks are large enough, water can enter the cracks and subsequently be expelled at high velocities. Water jet pressures will often cause concrete deterioration near the cracks. This process can also be accelerated by the high impact compressive forces induced by driving. A high prestressing force in concrete piles can help reduce this danger by resisting tension stresses during driving and thereby reducing the risk of crack development.

8.5.1 Prestressed Concrete Piles

Prestressed concrete piles consist of a configuration similar to a conventional reinforced concrete pile except that the longitudinal reinforcing steel is replaced by the prestressing steel. The prestressing steel may be in the form of strands or wires which are enclosed in a conventional steel spiral and placed in tension. Prestressing steel must conform to ASTM A416, A421, and A882. Due to the effects of prestressing, these piles can usually be made lighter and longer than reinforced concrete piles of the same size.

In cases of extreme environmental conditions epoxy coating has been used on prestressing strand. If this coating is used it should be dusted with sand before the

epoxy sets. Then the strand will have sufficient bond strength to carry the prestress development bond stresses. If an epoxy coating has been used on the strand it should also be used on the tie or spiral reinforcement. However, epoxy coating should not be necessary for prestressed piles since the prestressing force will keep the concrete in compression making deterioration less likely.

Prestressed sections vary from the most common solid square section to a solid octagonal section. In addition, large sections are available but often these sections have internal circular voids.

Prestressed piles can either be pretensioned or post-tensioned. Pretensioned piles are usually cast to their full length in permanent casting beds. Post-tensioned piles are usually manufactured in sections, most commonly cylindrical, and assembled and prestressed to the required pile lengths at the manufacturing plant or on the job site. Figure 8.7 shows typical prestressed concrete pile sections and a square prestressed concrete pile is shown in Figure 8.8. Design data for typical prestressed concrete pile sections is presented in Appendix C

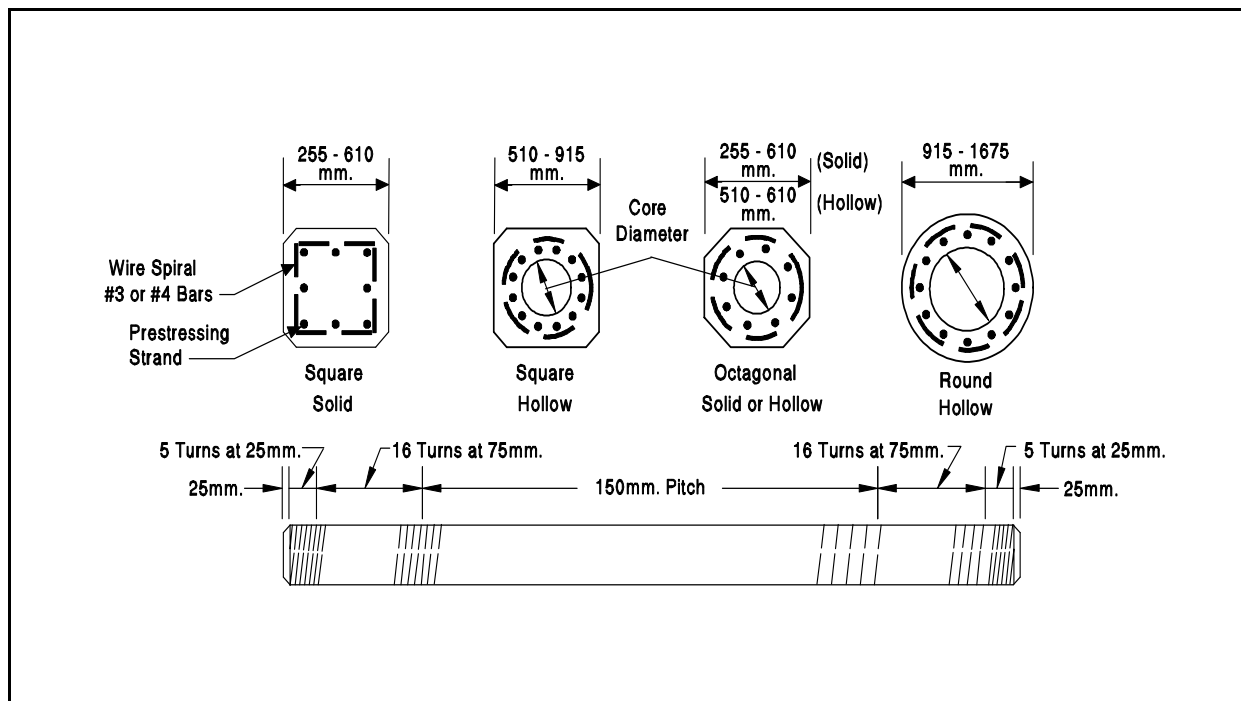


Figure 8.7 Typical Prestressed Concrete Piles (after PCI, 1993)



Figure 8.8 Square Prestressed Concrete Pile

The primary advantage of prestressed concrete piles compared to conventional reinforced concrete piles is durability. Since the concrete is under continuous compression, hairline cracks are kept tightly closed and thus prestressed piles are usually more resistant to weathering and corrosion than conventionally reinforced piles. This characteristic of prestressed concrete removes the need for special steel coatings since corrosion is not as serious a problem as for reinforced concrete. Another advantage of prestressing is that the tensile stresses which can develop in the concrete under certain driving and handling conditions are less critical.

Prestressed concrete piles are more vulnerable to damage from striking hard layers of soil or obstructions during driving than reinforced concrete piles. This is due to the decrease in axial compression capacity which results from the application of the prestressing force. When driven in soft soils, care must also be used since large tension stresses can be generated in easy driving.

Prestressed concrete piles cutoff and splicing problems are considered much more serious by contractors that drive them infrequently than by those that drive only this pile type. Special reinforcement required at the pile head in seismic areas can pose

problems if actual lengths vary significantly from the planned length. In these cases, a splice detail must be included so that the seismic reinforcement is extended into the pile cap.

8.5.2 Reinforced Concrete Piles

These piles are manufactured from concrete and have reinforcement consisting of a steel cage made up of several longitudinal bars and lateral or tie steel in the form of individual hoops or a spiral. Steel reinforcing for reinforced concrete piles is governed by ASTM A82, A615, and A884. High yield strength steel reinforcement must conform to ASTM A722 and may be used to resist uplift loads. Figure 8.9 shows a typical reinforced concrete pile.

Reinforced concrete piles as compared to prestressed piles are more susceptible to damage during handling and driving because of tensile stresses. Advantages of reinforced concrete piles include their lower net compressive stresses during driving and under service loads, and a reduced danger of pile head cracking. In addition, these piles are easier to splice than prestressed piles and thus may be used when variable pile lengths are needed. To avoid corrosion of the reinforced concrete joints, splices should be located below the ground surface, or if under water, the mudline. Segmental pile sections can be used to produce piles with varied lengths to accommodate variable soil conditions, and are easily transported to job sites.

The most common type of jointed pile is a square cross section made of high density concrete with each successive unit of shorter length. Typical pile cross sections range from 250 to 400 mm (10 to 16 inches), but sizes above and below this range are produced. Joints between these pile sections can be of the mechanical type, including bayonet fittings or wedges. The joints must be well aligned or energy will be lost during driving and bending stresses may be introduced due to an eccentric connection. These piles are best suited for friction piles in sand, gravel and clay.

Another jointed reinforced concrete pile type utilizes a hexagonal section. The advantages of this cross sectional shape are an improved stress distribution over the pile section and an improved resistance to torsional loading.

Special precautions should be taken when placing piles during cold weather. If piles are driven through ice and water before reaching soil, the air and concrete

may be at low temperatures relative to the soil and water. Such temperature gradients can cause concrete to crack due to non-uniform shrinkage and expansion. Although most reinforced concrete piles are jointed, there are occasions when non-jointed piles are more economical due to the cost of pile segments. Often for a very large job when thousands of piles will be used, piles can be economically cast on site. Most non-jointed piles have a square cross section and are difficult to change

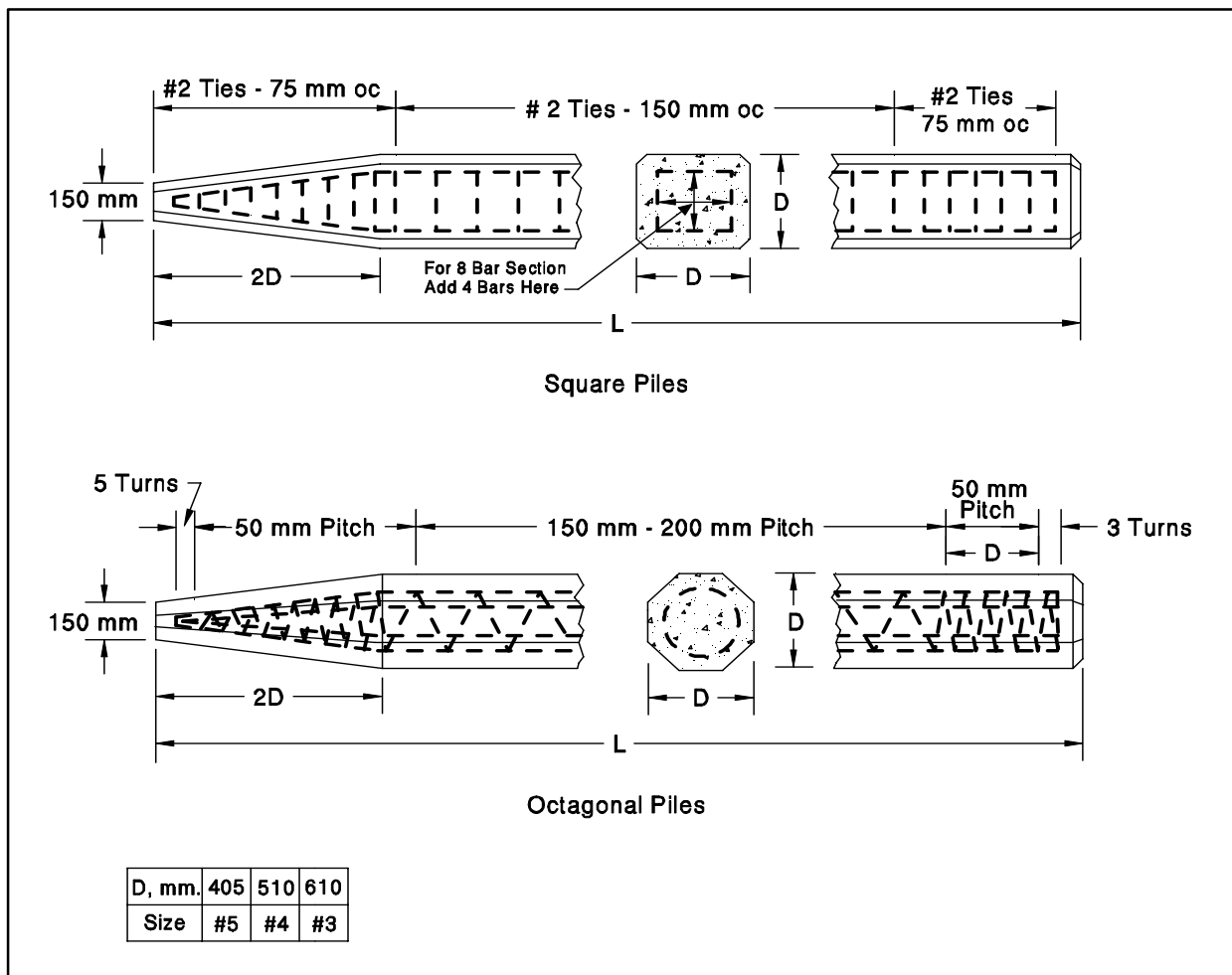


Figure 8.9 Typical Conventionally Reinforced Concrete Pile Details (after PCA, 1951)

in length. Only a few splicing procedures exist if a situation arises where a reinforced concrete pile must be lengthened. The first method of pile lengthening involves the breakdown of the projecting pile head to provide a suitable lap for reinforcing steel. Concrete is cast to form a joint. A second option is to butt the two piles together within a steel sleeve, and use an epoxy cement to join the two piles. The last lengthening method involves the use of dowel bars to be inserted into drilled holes with epoxy cement to form the joint. If piles are lengthened, the connecting pile sections must be carefully aligned, since excessive bending

stresses may result if any eccentricity exists. Splicing problems tend to become less severe or even non-existent when contractors develop experience and techniques. Special reinforcement required at the pile head in seismic areas can pose problems if actual lengths vary significantly from the planned length. In these cases, a splice detail must be included so that the seismic reinforcement is extended into the pile cap.

Reinforced concrete piles are used infrequently in the United States. However, in Europe, Australia, and many Asian countries reinforced concrete piles are used routinely based on economic considerations.

8.5.3 Spun-Cast Concrete Cylinder Piles

Concrete cylinder piles are post-tensioned, hollow concrete piles which are cast in sections, bonded with a plastic joint compound, and then post tensioned in lengths containing several segments. Special concrete is cast by a process unique to cylinder piles which achieves high density and low porosity. The pile is spun centrifugally in the casting process to obtain the high density. The pile is virtually impervious to moisture. Results of chloride ion penetration and permeability tests on prestressed cylinder piles indicate that the spun cylinder piles have excellent resistance to chloride intrusion. Figure 8.10 shows the typical configuration of a cylinder pile. A photograph of a concrete cylinder piles is presented in Figure 8.11. Appendix C provides appropriate engineering design data.

Not all cylinder piles are centrifugally cast. There is now a system where the pile is cast in a bed with forms. These piles are produced to the required length in a single piece and are pretensioned instead of being post tensioned like the spun-cast piles. These piles will not have the high density low porosity concrete that is characteristic of spun-cast cylinder piles and will therefore not have the same resistance to chloride intrusion.

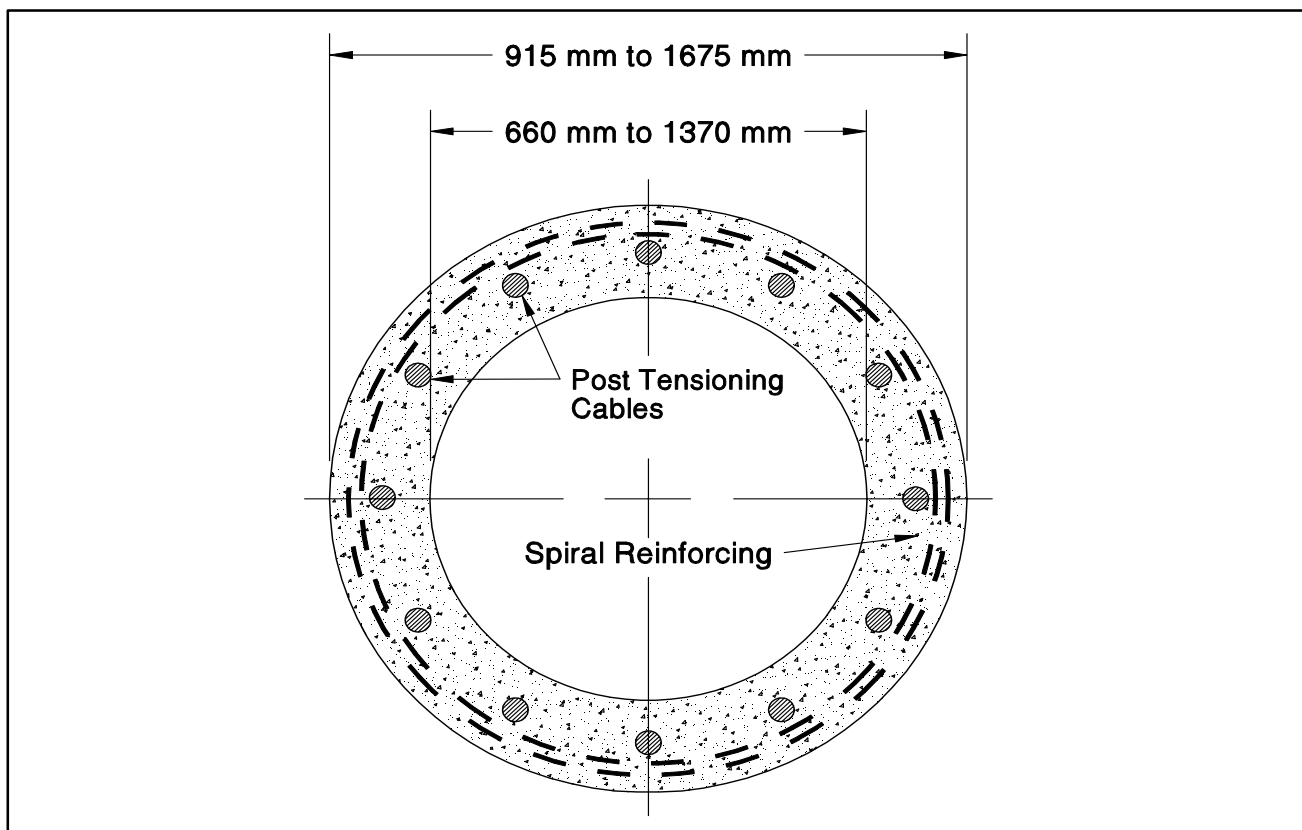


Figure 8.10 Typical Spun-Cast Concrete Cylinder Pile Section



Figure 8.11 Concrete Cylinder Pile

Generally spun-cast cylinder piles are used for marine structures or land trestles and have high resistance to corrosion. In freeze-thaw conditions however, the long term resistance of cylindrical piles is required. The piles typically extend above ground and are designed to resist a combination of axial loads and bending moments. They are available in diameters of 915 to 1675 mm (36 to 66 inches).

Cylinder piles are sometimes quite difficult to drive. However, they usually extend directly to the superstructure support level avoiding the need for a pile cap, which can result in substantial cost savings. Jetting is often used to install cylinder piles to the desired depth. When used, jetting must be controlled to minimize degradation of the lateral soil resistance.

8.6 CAST-IN-PLACE CONCRETE PILES

Cast-in-place concrete piles are installed by placing concrete in a steel shell that has been driven or inserted into a bored hole in the ground. The steel shell or casing may be left in place or withdrawn after the concrete is placed. Concrete is also placed in predrilled holes that are uncased. Predetermination of pile lengths is not as critical as for precast concrete piling.

8.6.1 Cased Driven Shell Concrete Piles

The cased driven shell concrete pile is the most widely used type of cast-in-place concrete pile. There are two principal types of cased piles. One type is driven without a mandrel and the other is driven with a mandrel. A mandrel is usually a heavy tubular steel section inserted into the pile that greatly improves the pile driveability. After driving, the mandrel is removed. Shells driven without mandrels have thicknesses in the range of 3 to 64 mm (0.12 to 2.5 inches). Shells driven with mandrels are much thinner, often 10 to 24 gage or 3.3 to 0.5 mm (0.13 to 0.02 inches) thick. The mandrel driven shells are usually corrugated circumferentially. This results in excellent frictional characteristics and increased collapse strength prior to concrete placement.

After driving, a shell pile is inspected internally along its full length before concrete is placed. Reinforcing steel is required only when the concrete in the pile may be under tension from such conditions as uplift, high lateral loads, or for unsupported

pile lengths. Reinforcing steel may also be used to provide additional axial load capacity.

a. Mandrel Driven Shell Concrete Piles

Mandrel driven shells can be used in most soil conditions except where obstacles such as cobbles and boulders are present that could damage the thin shells during driving. In addition, these thin shells are susceptible to collapse under hydrostatic pressure prior to concrete placement. They are best suited for friction piles in granular material.

The pile shells for mandrel driven piles are often produced from sections of corrugated steel and can be of constant diameter, steadily decreasing in diameter from the pile head to the pile toe, or diameter decreasing in discrete steps over the pile length. Typical tapers are on the order of 25 mm (1 inch) per 2.5 meter (8 ft) length. It is also possible to have different lengths for each section. Separate shell sections are usually screw-connected and waterproofed with an O-ring gasket. The Step Taper, Armco Hel-Cor, Republic Corwel and Guild pile are among the piles driven with mandrels.

The properties of the reusable mandrels dictate the driveability of these shell pile sections. This can result in a significant cost advantage for a mandrel driven shell pile since the mandrels result in improved pile driveability and load capacity at low material costs. Construction control of mandrel driven piles should include a wave equation analysis that accounts for the improved pile driveability from the mandrel. A dynamic formula should not be used for construction control of mandrel driven piles. Mandrel driven piles may be costly if it is necessary to drive piles to an unanticipated depth that exceeds the mandrel length available at the job site.

b. Monotube - Cased Concrete Piles

The Monotube pile, shown in Figure 8.12, is a proprietary pile driven without a mandrel. Monotubes are longitudinally fluted and are tapered over the lower pile length. These piles are available in 3 to 9 gage shell thicknesses or roughly 6 mm to 4 mm (0.23 to 0.15 inches). The fluted and tapered design of Monotube piles has several functional advantages. The flutes add

stiffness necessary for handling and driving lightweight piles. The flutes also increase the surface area while the tapered section improves the capacity per unit length in compression loading. The flutes are formed by cold working when the pile is manufactured. The cold working increases the yield point of the steel to more than 345 MPa (50 ksi), further improving the pile driveability. Monotube sections are spliced by a frictional connection and a fillet weld between a non-tapered extension and the lower pile section into which it is inserted. The manufacturer's recommended splicing detail should be followed. Additional design data for the Monotube pile is included in Appendix C.

c. Pipe - Cased Concrete Piles

Another variation of the cased, cast-in-place pile is the concrete filled pipe pile. These pipe piles can be driven either open or closed end. Closed end piles can be driven conventionally from the pile head, can be bottom driven with a mandrel, or by a mandrel engaged at both the pile head and toe. Open end piles are usually driven from the pile head. Piles that are driven open ended, may require internal clean out if the pile will be concrete filled to some distance below grade. Before concrete placement, steel reinforcement and uplift resisting dowels can be added, as necessary. Open end pipe piles are seldom cleaned out full length unless a rock socket is planned or short pile lengths are used.

d. Fundex Tubex or Grout-Injected Tubex Piles

The Fundex pile is a unique form of a pipe-cased, cast-in-place concrete pile. Instead of the pile being driven into the ground with a hammer, it is screwed into the ground with a special iron drill point which is welded to the end of the first section of pipe. A drill table then forces the pile into the ground utilizing a constant vertical load and torque. When the first pipe section reaches a depth providing sufficient headroom for the attachment of a second pipe section, the second section is welded to the first and drilling is resumed. Depending on the soil conditions, the pipe casing can be installed either grouted or non-grouted. Grouting can be used along the entire pile length or only in the bearing layer of the soil. The grout shell is created by pressure-injecting cement grout throughout the specified pile depth. Once the pile reaches its final design penetration, grouting is

stopped and steel reinforcement is placed. The drill point is left in place at the toe of the pile, providing a waterproof pile toe for concrete filling of the pipe casing.



Figure 8.12 Tapered Monotube Section With Add-on Sections

Some of the advantages of the Fundex Tubex piles include vibrationless and quiet installation, drilling equipment that can be used in confined spaces, and a removable mast that allows installation with only 6 meters (20 ft) of overhead clearance. In addition, the grout-injected Tubex pile can make use of a bentonite-water slurry to lessen frictional drag during installation when grout is not being injected into the soil surrounding the pile wall.

e. Driven and Drilled-In Caisson Piles

The Drilled-In Caisson is a special type of high capacity, cased, cast-in-place pile used for large engineering structures. The casing of this pile is usually a heavy-walled pipe fitted with a drive shoe which is driven to bedrock and sealed off within the rock. Once the casing reaches bedrock, it is cleaned out and a socket is drilled into the rock with rotary drilling

equipment. Next the rock socket is cleaned, and a steel H-shaped core or reinforcing cage is placed before filling the rock socket and cased pipe with concrete.

8.6.2 Uncased Concrete Piles

There are several types of cast-in-place piles that can be classified as uncased piles. Two principal types of uncased piles are bored piles and compacted concrete piles.

a. Bored Piles

Bored piles are installed by drilling or augering a hole in the ground and filling it with concrete. Bored pile installations should be performed carefully by an experienced contractor and with experienced inspection. Bored piles are susceptible to problems such as necking (smaller pile diameter at some locations along their length), grout contamination by soil, or bore hole collapse. Bored, uncased piles have a high degree of risk for structural integrity. There are several types of bored piles and they do not have the advantage of capacity determination from driving observations.

- (1) Auger Cast-in-Place (ACIP) piles are usually installed by turning a continuous-flight hollow-stem auger into the ground to the required depth. As the auger is withdrawn, grout or concrete is pumped under pressure through the hollow stem, filling the hole from the bottom up. Vertical reinforcing steel is pushed down into the grout or concrete shaft before it hardens. Uplift tension reinforcing can be installed by placing a single high strength steel bar through the hollow stem of the auger before grouting. After reinforcing steel is placed, the pile head is cleaned of any lumps of soil which may have fallen from the auger. Then the pile head is formed with a temporary steel sleeve to protect the fresh grout from contamination, or it is formed to the ground surface above the cutoff grade and later trimmed off to the cutoff elevation.
- (2) Drilled shafts are installed by mechanically drilling a hole to the required depth and filling the hole with concrete. Sometimes an

enlarged base is formed mechanically to increase the toe bearing area. Drilling slurry or a temporary liner can be used when the sides of the hole are unstable. Reinforcing steel is installed as a cage inserted prior to concrete placement. Drilled shafts are often used where large toe bearing capacities can be achieved, such as on rock or in glacial tills. They are also used where support is primarily developed through shaft resistance in granular and cohesive soils, and rock. Drilled shafts are sometimes designed with a permanent steel casing.

- (3) Drilled and grouted piles (micropiles) are installed by rotating a casing with a cutting edge into the soil or by percussion methods. Soil cuttings are removed with circulating drilling fluid. Reinforcing steel is then inserted and a sand-cement grout is pumped through a tremie. The bored hole is filled from the bottom up while the casing is withdrawn. These piles are principally used for underpinning work, seismic retrofitting and landslide stabilization. Several types of micropiles leave the casing in place for added bending resistance and axial capacity.
- (4) Helical Screw cast-in-place piles are formed using the Atlas Piling System. The helical piles are displacement piles formed using a single-start auger head with a short flight. The auger head is carried on a hollow stem which transmits a large torque and compressive force as it is screwed into the ground to the required depth. After reinforcement is placed, concrete is poured through the end of the hollow auger and the auger is slowly unscrewed and removed. This process leaves behind a screw-threaded cast-in-place pile with large threads which provide increased surface area for improved shaft resistance. In fact, for a given pile size and volume of concrete, pile capacities are greater than for traditionally constructed bored piles. The disadvantage of this pile type is that the restricted diameter of the reinforcement cage limits the bending capacity.

b. Compacted Concrete Pile

The compacted concrete pile is installed by bottom driving a temporary steel casing into the ground using a drop weight driving on a zero slump concrete plug at the bottom of the casing. When the required depth has been

reached, the steel casing is restrained from above and the concrete plug is driven out the bottom of the tube. An enlarged base is formed by adding and driving out small batches of zero slump concrete.

Steel reinforcing is then installed prior to adding more concrete to the shaft. It is suggested that widely spaced bars be used to allow the low workability mix to penetrate to the exterior of the piles. After the base is formed and reinforcement is placed, concrete continues to be added and the uncased shaft is formed by compacting the concrete with a drop weight in short lifts as the casing is being withdrawn. Alternatively, if a high workability mix is used to complete the pile, a vibrator can be clamped to the top of the tube and used to compact the concrete into place as the casing is withdrawn.

This type of driven, cast-in-place pile is often referred to as a Franki pile or pressure injected footing. The best site conditions for these piles are loose to medium dense granular soils.

8.7 COMPOSITE PILES

In general, a composite pile is made up of two or more sections of different materials or different pile types. Depending upon the soil conditions, various composite sections may be used. The upper pile section is often precast concrete, steel pipe, or corrugated shell. The lower pile section may consist of steel H, steel pipe, or timber pile. Composite piles have limited application and are generally used only under special conditions.

8.7.1 Precast Concrete - Steel Piles

One of the more commonly used composite piles consists of a lower section of steel H, or pipe pile embedded in an upper pile section of precast concrete. These composite sections are often used when uplift requirements dictate penetration depths that a displacement pile cannot achieve, or in waterfront construction where surficial soil layers have high corrosion potential. A photograph of a composite square concrete pile with H-pile stinger is presented in Figure 8.13.

8.7.2 Wood Composite Piles

Timber-steel or timber-concrete composite sections are sometimes used as foundation piles. It is common to have a timber section below the groundwater level with either a concrete or corrosion protected steel upper section. In the case of the composite timber-concrete pile, an untreated timber pile is first driven below the permanent ground water level, then a corrugated steel shell is connected to the pile head of the timber section with a wedge ring driven into the wood. After driving, the shell is filled with concrete to the cutoff elevation and the pile is complete.



Figure 8.13 Square Concrete Pile With Embedded H-pile Section at Pile Toe

8.7.3 Tapertube Pile

Another composite pile type is the Tapertube pile, Figure 8.14. This pile consists of a tapered, 12 sided polygon over the lower section with conventional steel pipe pile material as the upper add-on sections. The 4.6 to 9.1 m (15 to 30 ft) long tapered section steel is available with pile toe diameters ranging from 203 to 356 mm (8 to

14 in) and pile head diameters of 305 to 610 mm. The tapered tube section has a yield strength of 345 MPa (50 ksi), and the upper pipe sections conform to ASTM A252 Grade 3 steel. The tapered and pipe sections are connected using a full penetration weld.



Figure 8.14 Tapered Tube Pile

8.7.4 Pipe - Corrugated Shell Piles

This composite pile consists of a pipe pile for the lower section and a corrugated shell for the upper portion of the pile. A variety of pipe and shell diameters can be used to accommodate a range of loading conditions. The pipe-shell pile is mandrel driven. The mandrel provides a guide for alignment of the two pile sections provided it extends to the pipe pile head or partially into the pipe pile. Possible pile joints include; a sleeve joint, a welded joint, and a drive-sleeve joint. Once the pipe and shell are driven and connected, they are filled with concrete to cutoff grade and any excess shell is removed.

8.7.5 Composite Tapered Precast Tip - (TPT)

The most common form of this composite pile consists of a round, tapered, precast concrete tip, attached at the bottom of a pile shaft. The pile shaft may consist of pipe pile or thin corrugated shell. The precast tip is driven to its designed depth with a mandrel, then the pile shaft is socketed into the precast tip and filled with concrete. Enlarged tip piles can be particularly effective if downdrag forces are present. In addition to the reduced shaft resistance created by driving the enlarged tip, the shaft can be coated or wrapped with a material to further resist downdrag. The enlarged tip provides significant toe bearing capacity.

8.8 DESIGN CONSIDERATIONS IN AGGRESSIVE SUBSURFACE ENVIRONMENTS

In every design, consideration should be given to the possible deterioration of the pile over its design life due to the surrounding environment. This section will address design considerations in aggressive subsurface environments where corrosion, chemical attack, abrasion, and other factors can adversely affect pile durability after installation. An assessment of the in-situ soil conditions, fill materials, and groundwater properties is necessary to completely categorize an aggressive subsurface condition.

An aggressive environment can generally be identified by soil resistivity and pH tests. If either the pH or soil resistivity tests indicate the subsurface conditions are aggressive, then the pile selection and foundation design should be based on an aggressive subsurface environment. The design of pile foundations in an aggressive environment is a developing field. Therefore, a corrosion/degradation specialist should be retained for major projects with pile foundations in aggressive environments.

Whenever the pH value is 4.5 or less, the foundation design should be based on an aggressive subsurface environment. Alternatively, if the resistivity is less than 2000 ohms-cm the site should also be treated as aggressive. When the soil resistivity test results are between 2000 and 5000 ohms-cm then chloride ion content and sulfate ion content tests should be performed. If these test results indicate a chloride ion content greater than 100 parts per million (ppm) or a sulfate ion content greater than 200 ppm, then the foundation design should be based on an

aggressive subsurface environment. Resistivity values greater than 5000 ohms-cm are considered non-aggressive environments. Electro chemical classification tests for aggressive environments are described in Chapter 6.

Contaminated soil and groundwater can cause significant damage to foundation piles in direct contact with the aggressive chemicals. Acidic groundwater is common at sites with either organic soils or industrial contamination. The subsurface exploration program should indicate if the soil or groundwater is contaminated. If industrial contamination is found, the maximum likely concentrations should be determined as well as an estimate of the lateral and vertical extent of the contamination.

8.8.1 Corrosion of Steel Piles

Steel piles driven through contaminated soil and groundwater conditions may be subject to high corrosion rates and should be designed appropriately. Corrosion of steel or steel reinforced piles may also occur if piles are driven into disturbed ground or fill, if piles are located in a marine environment, or if piles are subject to alternate wetting and drying from tidal action. Corrosion rates are a function of the ambient temperature, pH, access to oxygen, and chemistry of the aqueous environment surrounding the steel member.

For steel piles buried in fill or disturbed natural soils, a conservative estimate of the corrosion rate is 0.08 mm per year (0.003 inches per year). Morley (1979) reported corrosion rates of 0.05 mm per year (0.002 inches per year) for steel piles immersed in fresh water, except at the waterline in canals where the rate was as high as 0.34 mm per year (0.013 inches per year). The high rate at the water line was attributed to debris abrasion and/or cell action between other parts of the structure.

AASHTO Standard R 27-01 (2004) provides a recommended assessment procedure for evaluating corrosion of steel piling in non-marine applications. This recommended procedure consists of a Phase I and Phase II assessment. In the Phase I assessment, information on the location of the pile cap relative to the groundwater table, the soil characteristics, and soil contaminants is obtained. This information is used to determine if a Phase II assessment is required.

If the pile cap is at or above the water table, a Phase II assessment is performed to evaluate the corrosivity of the site. The Phase II assessment consists of collecting continuous soil samples to a depth of 1 meter below the water table and conducting

laboratory tests on the recovered samples. The site sampling and testing protocol is outlined in Figure 8.15. After collecting the necessary information, the possibility of uniform or macrocell corrosion is evaluated using the flow chart presented in Figure 8.16. The final step in the evaluation process includes determining the necessity for electrochemical testing, corrosion monitoring, and mitigation techniques. A flow chart of this process is presented in Figure 8.17.

It should be noted that the flow charts do not cover all possibilities for corrosion of steel piling at a site. Factors not covered include chemical contamination, stray DC currents, and the presence of high concentrations of microbes. When these conditions are present on a project, a corrosion specialist should be consulted.

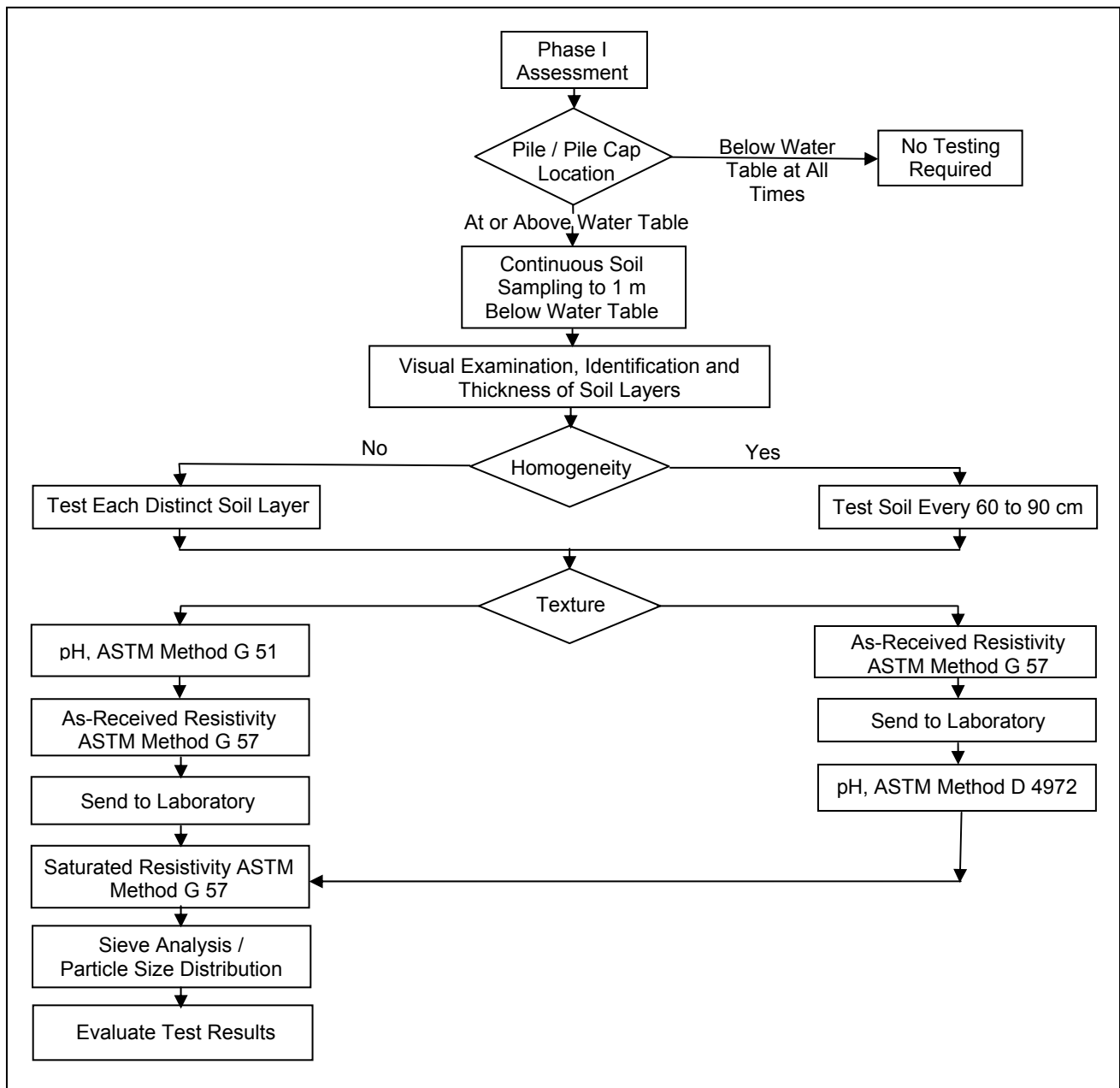


Figure 8.15 Soil Sampling and Testing Protocol for Corrosion Assessment of Steel Piles in Non-Marine Applications

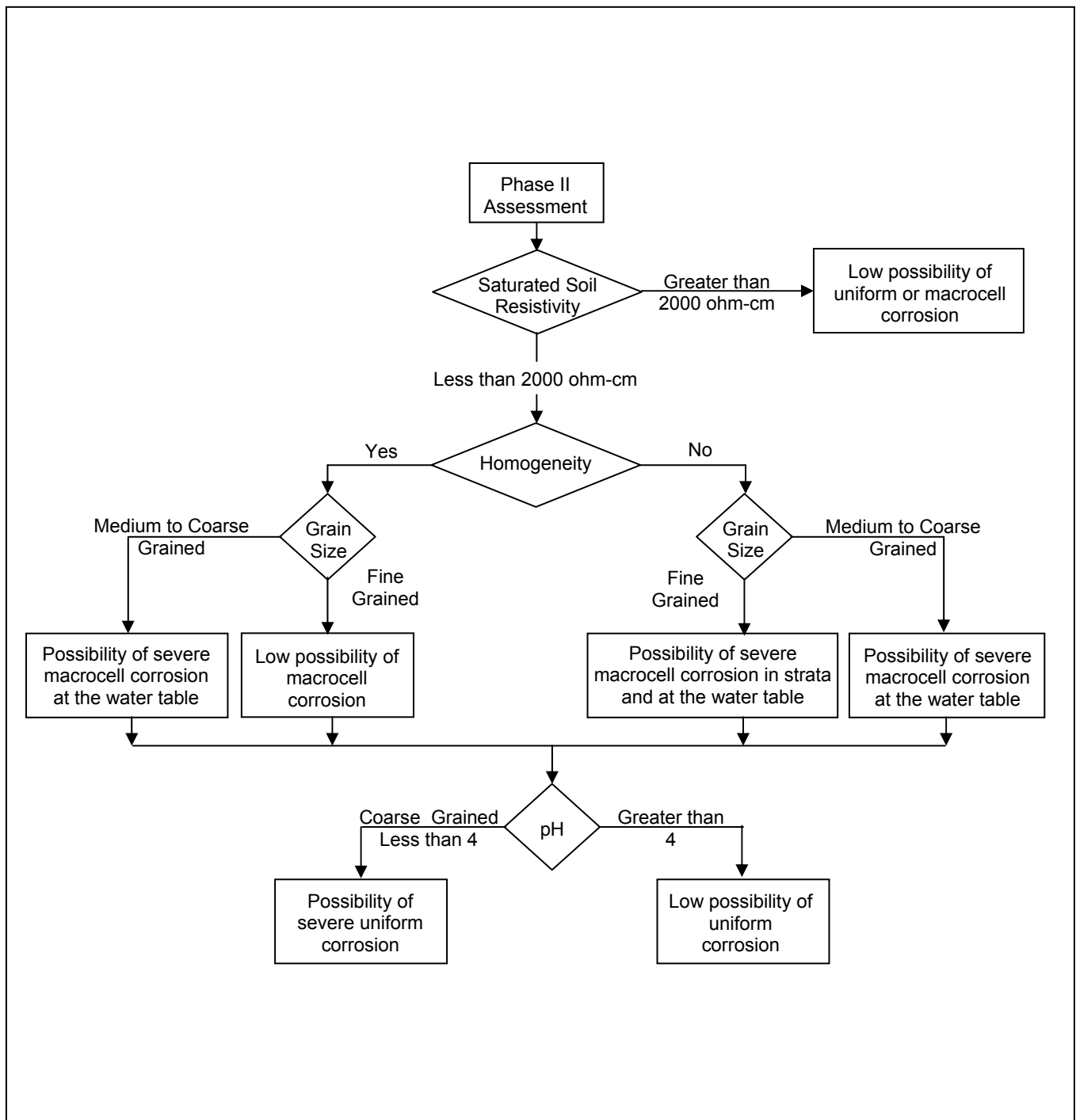


Figure 8.16 Procedure for Uniform or Macrocell Corrosion Assessment of Steel Piles in Non-Marine Applications

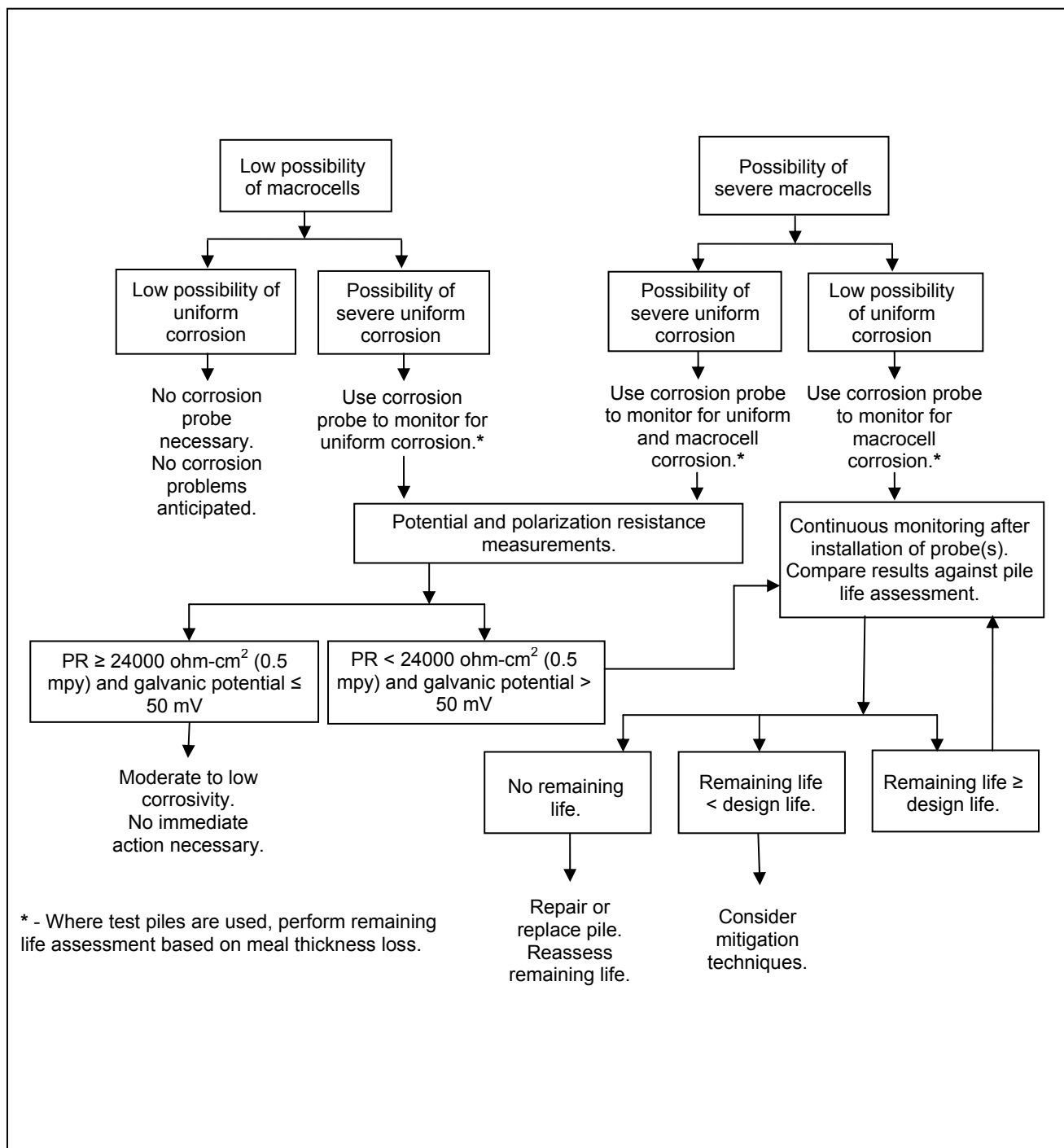


Figure 8.17 Procedure for Determination of Electrochemical Testing, Corrosion Monitoring and Corrosion Mitigation Techniques

ASHTO Standard R 27-01 (2004) should be consulted for a detailed step by step procedure of corrosion evaluation process and estimation of remaining service life. Additional insight into the corrosion of steel piles in non-marine environments is also presented in NCHRP Report 408 by Beavers and Dunn (1998).

For steel piles in marine environments (salt water), separate zones, each with a different corrosion rate, are present along the length of the pile. Tomlinson (1994) identifies these zones as follows:

1. Atmospheric zone: exposed to the damp atmospheric conditions above the highest water level but subject to airborne spray.
2. Splash zone: above the mean high tide, but exposed to waves, spray, and from passing ships.
3. Intertidal zone: between mean high and low tides.
4. Continuous immersion zone: below lowest low tide.
5. Underground zone: below the mudline.

Figure 8.18, after Morley and Bruce (1983), summarizes average and maximum probable marine corrosion rates in these zones as well as in the low water zone.

In corrosive environments, the designer should apply one of the design options for piles in corrosive environments discussed in Section 8.8.4.

8.8.2 Sulfate and Chloride Attack on Concrete Piles

Attack on precast and cast-in-place concrete occurs in soils with high sulfate or chloride concentrations. Factors influencing the rate of attack of sulfates or chlorides on concrete piles include the pH of the soil, the solubility of the sulfate or chloride, the movement of the groundwater relative to the piles, and the density of the pile concrete.

The reaction between concrete and sulfate begins with sulfate ions in solution. Once the sulfate ions in the groundwater come in contact with portland cement, an

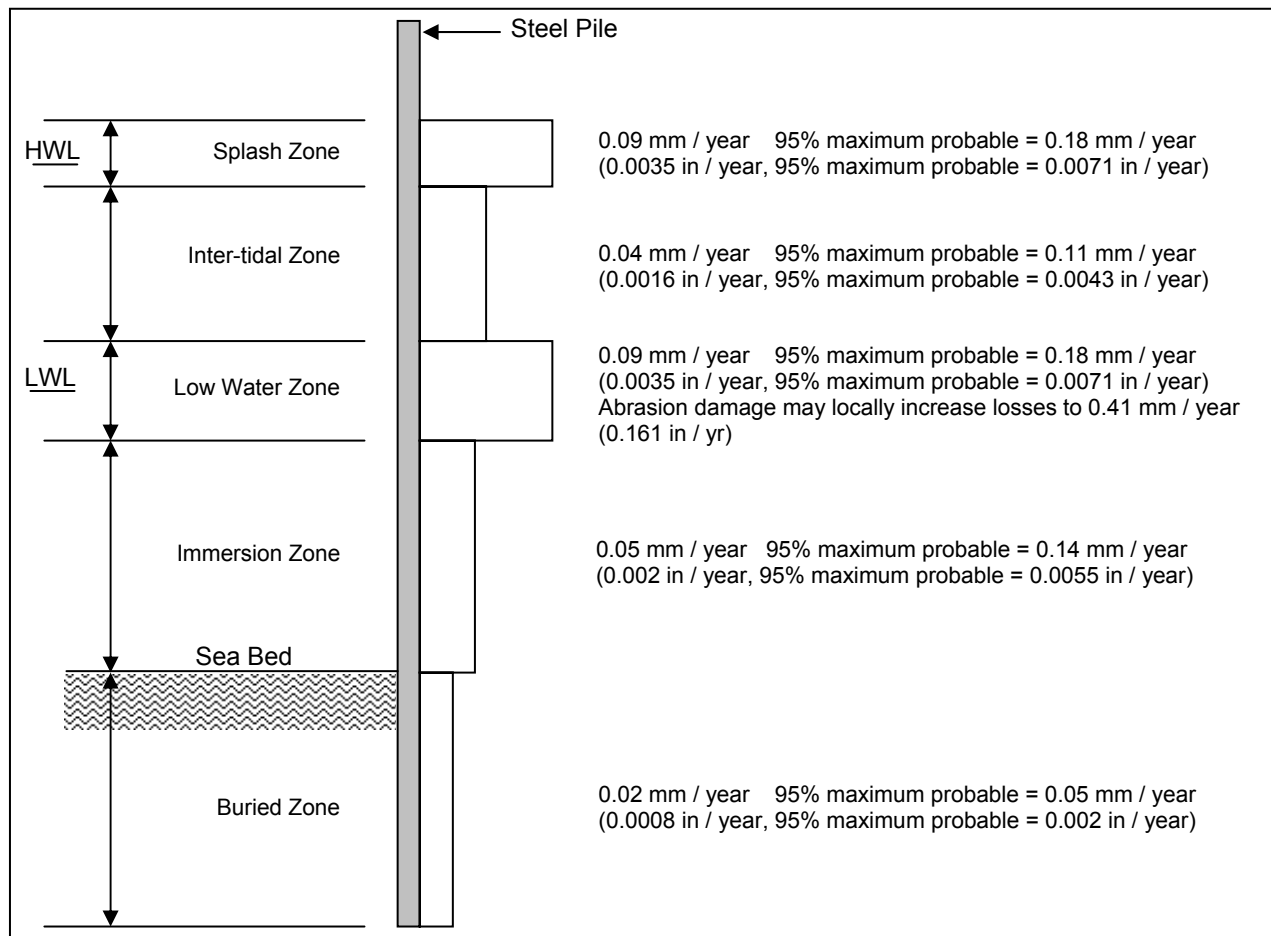


Figure 8.18 Loss of Thickness by Corrosion for Steel Piles in Seawater (after Morley and Bruce, 1983)

expansive chemical reaction takes place. Expansion of concrete often leads to cracking and spalling which can significantly reduce the available structural capacity of a pile foundation.

One method of reducing sulfate attack is to use a dense concrete which is less permeable to sulfate ions. Other possible deterrents include using sulfate-resisting cement, using cement with 25% pozzolanic material, or creating a physical barrier between the concrete and the groundwater with some sort of pile sleeve.

Chlorides are commonly found in soils, groundwater, or industrial wastes. Instead of attacking concrete, chlorides cause corrosion of reinforcement steel with consequential expansion and bursting of concrete as the products of steel corrosion are formed. Once corrosion begins, it continues at an accelerated rate. This can lead to a loss of bond between steel and concrete and extreme reduction of pile

capacity. Protective measures which can reduce corrosion include increased concrete cover around the reinforcing steel, and the use of galvanized, or epoxy coated reinforcement.

8.8.3 Insects and Marine Borers Attack on Timber Piles

Timber piles are subject to insect attack on land by termites and beetles, or in water by marine borers. Incidences of marine borer attack on timber piles have reemerged in some areas as previously polluted water has improved. As mentioned in Section 8.2, arsenate and creosote pressure treatments are the most effective means of protecting timber piles from premature deterioration. In southern waters, creosote must be combined with other preservative treatments because of attack by limnoria tripundata. Table 8-2 provides a summary of AWPI recommended preservative treatments depending upon foundation use, preservative, and wood

| TABLE 8-2 Preservative Assay Retention Requirements (AWPI, 2002) | | | | |
|---|-------------------|-------------|-----------------------------------|---------------------|
| Use Category | Creosote (pcf) | | Waterborne (CCA or ACZA) (pcf) | |
| | Southern Pine | Douglas Fir | Southern Pine CCA | Douglas Fir ACZA |
| Foundation | 12 | 17 | 0.8 | 1.0 |
| Land & Fresh Water | 12 | 17 | 0.8 | 1.0 |
| Marine (Saltwater) N. of Delaware ¹ or San Francisco ¹ | 16 | 16 | 1.5 | 1.5 |
| S. of New Jersey ² or San Francisco ² | 20 | 20 | 2.5 | 2.5 |
| Dual Treatment ³ | 20 | 20 | 1.0 | 1.0 |
| Comments: 1. Where Teredo is expected and Limnoria tripunctata is not expected, creosote or creosote solutions provide adequate protection. 2. Where Teredo and Limnoria tripunctata are expected and where pholad attack is not expected, either dual treatment, or high retentions of CCA for Southern Pine or ACZA for Douglas Fir provide maximum protection. 3. In those areas where Limnoria tripunctata and pholad attack is expected or known, dual treatment provides the maximum protection. | | | | |

species. Environmental damage from pressure treatments must be a consideration when selecting protection methods.

When designing with timber piles, the wood species is usually not specified unless a specific species of wood is more suitable for design loads and/or environmental conditions. Certain species are not suitable for preservative treatment, while others may provide increased durability. As expected, ASTM standards for timber piles vary with geologic region, as land and fresh water piles have less stringent preservative treatment requirements than piles used in marine environments.

If timber piles are installed in other aggressive environments such as environments containing chemical wastes, a timber pile specialist should be consulted in determining the appropriate preservative treatment.

8.8.4 Design Options for Piles Subject to Degradation or Abrasion

When a pile must be installed in an aggressive or abrasive environment, several design options can be considered. These design options include:

- a. A heavier steel section than required can be used to provide extra thickness (H and pipe sections). This method is not effective in running water with active bedload to scour the corroded surface.
- b. Cathodic protection of steel piles in soil below the water table or in marine environments. Note that this method of protection tends to be a costly solution and requires periodic anode replacement.
- c. Concrete encasement of steel piles above the mud line. This method may alter the impact absorbing properties of the pile.
- d. Use of copper-bearing steel is effective against atmospheric corrosion but cost is greater than conventional steel.
- e. Sleeving or encapsulating of reinforced, cast-in-place piles through use of metal casings or polymer or fiberglass jackets isolates contaminants from concrete.

- f. Use of a low water/cement ratio, resistant aggregate, and minimum air content consistent with the environment to improve abrasion resistance of precast concrete piles
- g. Use of a protective metallic or epoxy paint (isocyanate-cured) or fusion bonded epoxy coating on exposed sections of the pile. This method has the same limitations as (b) in running water.
- h. Use of coal-tar epoxies for corrosion protection in marine environments.

Protective coatings cannot be replaced after a pile is driven. Therefore, if a protective coating is used, the coating should be designed to be durable enough to remain undamaged during pile transportation, handling, and placement in the leads for driving as well as resistant to the abrasion resulting from pile driving. The designer should also note that the shaft resistance on a coated pile may be significantly different than on an uncoated pile, depending on the coating.

8.9 SELECTION OF PILE TYPE AND SIZE FOR FURTHER EVALUATION

The selection of appropriate pile types for any project involves the consideration of several design and installation factors including pile characteristics, subsurface conditions and performance criteria. This selection of elimination process should consider the factors listed in Tables 8-1, 8-3 and 8-4. Table 8-1 summarizes typical pile characteristics and uses. Table 8-3 provides pile type recommendations for various subsurface conditions. Table 8-4 presents the placement effects of pile shape characteristics.

In addition to the considerations provided in the tables, the problems posed by the specific project location and topography must be considered in any pile selection process. Following are some of the usually encountered problems:

1. Vibrations from driven pile installation may affect pile type selection, use of installation, and special techniques such as predrilling and/or vibration monitoring of adjacent structures.
2. Remote areas may restrict driving equipment size and, therefore, pile size.

3. Local availability of certain materials and capability of contractors may have decisive effects on pile selection.
4. Waterborne operations may dictate use of shorter pile sections due to pile handling limitations.
5. Steep terrain may make the use of certain pile equipment costly or impossible.

Often several different pile types meet all the requirements for a particular structure. In such cases, the final choice should be made on the basis of a cost analysis that assesses the over-all cost of the foundation alternatives. This requires that candidate pile types be carried forward in the design process for determination of the pile section requirements for design loads and constructability. The cost analysis should also include uncertainties in execution, time delays, cost of load testing programs, as well as the differences in the cost of pile caps and other elements of the structure that may differ among alternatives. For major projects, alternate foundation designs should be considered for inclusion in the contract documents if there is a potential for cost savings.

| TABLE 8-3* PILE TYPE SELECTION BASED ON SUBSURFACE AND HYDRAULIC CONDITIONS | |
|---|--|
| TYPICAL PROBLEM | RECOMMENDATIONS |
| Boulders overlying bearing stratum | Use heavy nondisplacement pile with a point and include contingent predrilling item in contract. |
| Loose cohesionless soil | Use tapered pile to develop maximum skin friction. |
| Negative shaft resistance | Use smooth steel pile to minimize drag adhesion. Use bitumen coating or plastic wrap (if feasible) as pile-soil bond breaker or increase design stress. Avoid use of batter piles. |
| Deep soft clay | Use rough concrete piles to increase adhesion and rate of pore water dissipation. |
| Artesian pressure | Use solid prestressed concrete pile, tapered piles with sufficient collapse strength or thick wall closed end pipe with flush boot plate depending upon local practice. H-piles without driving shoes may also be viable selection. Do not use mandrel driven thin-wall shells, as generated hydrostatic pressure may cause shell collapse. Pile heave also common to closed-end pile. |
| Scour | Use uniform section pile with sufficient structural strength to act as a column through scour zone. Do not use tapered piles unless a large part of the taper extends well below scour depth; design permanent pile capacity to mobilize soil resistance below scour depth. |
| Coarse gravel deposits | Use prestressed concrete piles where hard driving is expected. In coarse soils use of H-piles and open end pipe piles often results in excessive pile lengths. |

* Table modified and reproduced (Cheney and Chassie, 1993).

| TABLE 8-4* PILE TYPE SELECTION PILE SHAPE EFFECTS | | |
|---|--|--|
| SHAPE CHARACTERISTICS | PILE TYPE | PLACEMENT EFFECT |
| Displacement | Closed end steel pipe | Increase lateral ground stress. |
| | Precast concrete | Densifies cohesionless soils, remolds and weakens cohesive soils temporarily. Setup time for large pile groups in sensitive clays may be up to six months. |
| Nondisplacement | Steel H | Minimal disturbance to soil. |
| | Open end steel pipe | Not suited for friction piles in coarse granular soils. Piles often have low driving resistances in these deposits making field capacity verification difficult thereby often resulting in excessive pile lengths. |
| Tapered | Timber Monotube Tapertube Thin-wall shell | Increased densification of soil, high capacity for short length in granular soils. |

* Table modified and reproduced (Cheney and Chassie, 1993).

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Chapter 9

STATIC ANALYSIS METHODS

Static analysis methods can be categorized as analytical methods that use soil strength and compressibility properties to determine pile capacity and performance. This chapter will focus on analysis methods for determining compression, uplift, and lateral load capacity of single piles and pile groups. Important considerations are as follows:

1. Static analysis methods are an integral part of the design process. Static analysis methods are necessary to determine the most cost effective pile type and to estimate the number of piles and the required pile lengths for the design of substructure elements. The foundation designer must have knowledge of the design loads and the structure performance criteria in order to perform the appropriate static analyses.
2. Many static analysis methods are available. The methods presented in this chapter are relatively simple methods that have proven to provide reasonable agreement with full scale field results. Other more sophisticated analysis methods may be used and in some cases may provide better results. Regardless of the method used, it is important to continually apply experience gained from past field performance of the analysis method.
3. Designers should fully understand the basis for, the limitations of, and the applicability of a chosen method. A selected method should also have a proven agreement with full scale field results.

Construction procedures can have a significant influence on the behavior of pile foundations. The analysis methods described in this chapter lead to successful designs of deep foundations only if adequate construction techniques are used. Construction inspection should be an integral part of the design and construction of any foundation. Static load tests, wave equation analysis or dynamic monitoring for construction control should, whenever possible, be used to confirm the results of a static design method. These items are discussed in greater detail in subsequent chapters.

The first few sections of this chapter will briefly cover background information. Static analysis procedures for piles subject to compression, uplift and lateral loads will be covered, as well as pile group settlement. The influence of special design events on static design will be discussed. Limited guidance on design in liquefaction susceptible soils will be provided. However, seismic design is a special design event beyond the scope of this

manual. Last, the chapter will address construction issues pertinent to static analysis methods and foundation design.

9.1 BASICS OF STATIC ANALYSIS

There are four general types of static analyses covered in this chapter. Static analyses are performed to determine:

1. Ultimate axial compression capacity of a pile or pile group. These calculations are performed to determine the long term capacity of a foundation as well as to determine the soil resistance provided from soil layers subject to scour, liquefaction, or that are otherwise unsuitable for long term support. Static analyses are used to establish minimum pile penetration requirements, pile lengths for bid quantities, as well as to estimate the ultimate soil resistance at the time of driving (SRD).
2. Ultimate uplift capacity of a pile or pile group. These calculations are performed to determine the soil resistance to uplift or tensile loading which, in some cases, may also determine the minimum pile penetration requirements.
3. Ultimate lateral resistance of a pile or pile group. These soil-structure interaction analysis methods consider the soil strength and deformation behavior as well as the pile structural properties and are used in pile section selection.
4. Settlement of a pile group. These calculations are performed to estimate the foundation deformation under load the structure loads.

The static capacity of a pile can be defined as the sum of soil/rock resistances along the pile shaft and at the pile toe available to support the imposed loads on the pile. As noted above, static analyses are performed to determine the ultimate capacity of an individual pile and of a pile group as well as the deformation response of a pile group to the applied loads.

The ultimate capacity of an individual pile and of a pile group is the smaller of: (1) the capacity of surrounding soil/rock medium to support the loads transferred from the pile(s) or, (2) the structural capacity of the pile(s). Soil-structure interaction analysis methods are used to determine the deformation response of piles and pile groups to lateral loads. The results from these analyses as well as the results of static analysis of pile group settlement are compared to the performance criteria established for the structure.

The static pile capacity from the sum of the soil/rock resistances along the pile shaft and at the pile toe can be estimated from geotechnical engineering analysis using

1. Laboratory determined shear strength parameters of the soil and rock surrounding the pile.
2. Standard Penetration Test data.
3. In-situ test data (*i.e.*, CPT/CPTU).

On many projects, multiple static analyses are required for a design. First, a static analysis is necessary to determine the number and length of piles necessary to support the structure loads. A second static analysis may also be required to determine the total soil resistance the pile will encounter during installation. This second analysis enables the design engineer to determine the necessary capability of the driving equipment. Figures 9.1 and 9.2 illustrate situations that require two static analyses.

Figure 9.1 shows a situation where piles are to be driven for a bridge pier. In this case, the first static analysis performed should neglect the soil resistance in the soil zone subject to scour, since this resistance may not be available for long term support. The number of piles and pile lengths determined from this analysis will then be representative of the long term conditions in the event of scour. At the time of pile driving however, the scour zone soil will provide resistance to pile penetration. Therefore, a second static analysis is required to estimate the total resistance encountered by the pile during driving to the embedment depth determined in the first analysis. The second static analysis includes the soil resistance in the materials above the scour depth as well as the underlying strata.

Figure 9.2 shows another frequently encountered situation in which piles are driven through loose uncompacted fill material into the natural ground. The loose fill material offers unreliable resistance and is usually neglected in determining the number of piles and the pile lengths required. A second static analysis is then performed to determine total resistance encountered by the pile during driving, which includes the resistance in the fill material. In both examples, the soil resistance to be overcome during driving will be substantially greater than the required ultimate pile capacity.

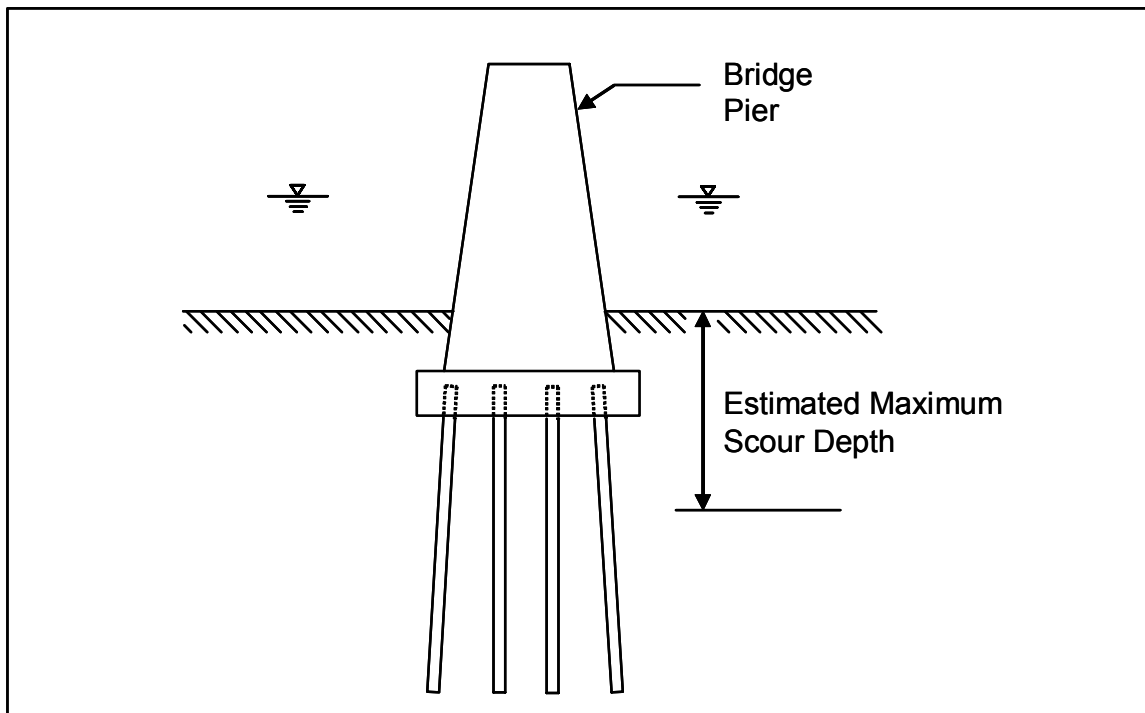


Figure 9.1 Situation Where Two Static Analyses are Necessary – Due to Scour

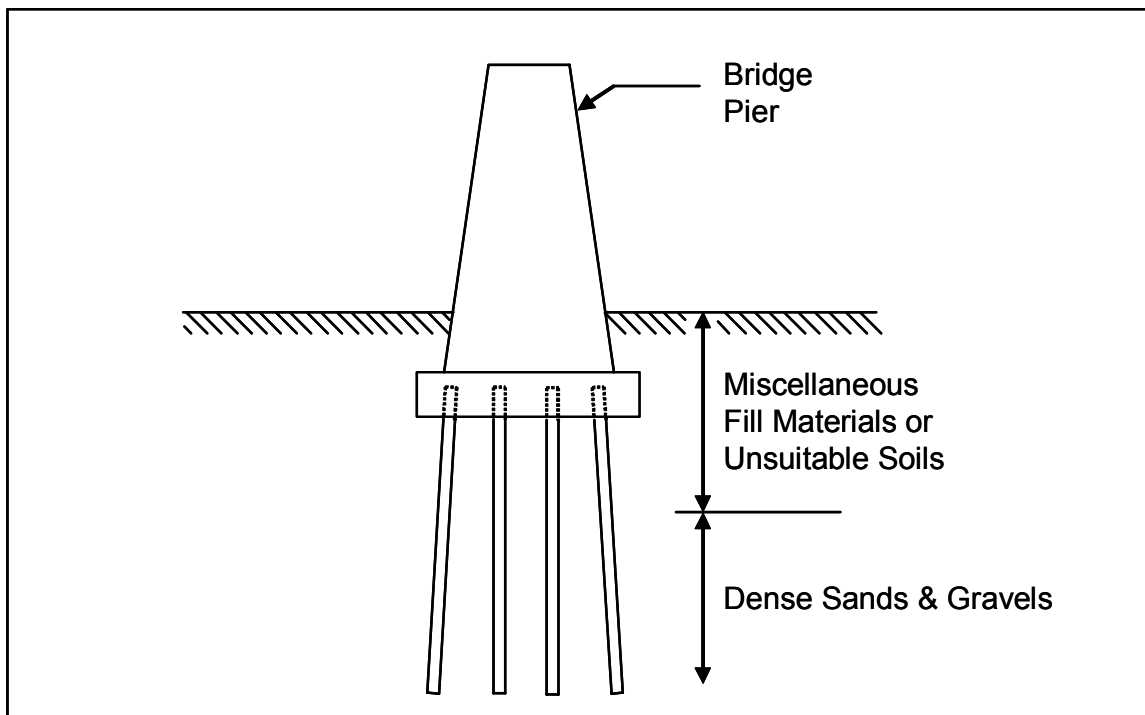


Figure 9.2 Situation Where Two Static Analyses are Necessary – Due to Fill Materials

The results of multiple static analyses should be considered in the development of project plans and specifications. For example, consider a case where scour, uplift loading, or some other special design event dictates that a greater pile penetration depth be achieved than that required for support of the axial compressive loads. The static analyses indicate that 2000 kN (450 kips) of soil resistance must be overcome to obtain the minimum penetration depth for a 1400 kN (315 kip) ultimate capacity pile. This information should be conveyed in the construction documents so that the driving equipment can be properly sized and so that the intent of the design is clearly and correctly interpreted by the contractor and construction personnel. Specifying only a 1400 kN (315 kip) ultimate capacity pile, without including a minimum penetration requirement and the soil resistance to be overcome, can lead to construction claims.

Prior to discussing static design methods for estimating pile capacity in detail, it is desirable to review events that occur in the pile-soil system during and after pile driving as well as basic load-transfer mechanisms.

9.2 EVENTS DURING AND AFTER PILE DRIVING

The soil in which a pile foundation is installed is almost always disturbed. Several factors influence the degree of disturbance. These include the soil type and density, the pile type (displacement, non-displacement), and the method of pile installation (driven, drilled, jetted). **For driven piles, substantial soil disturbance and remolding is unavoidable.**

9.2.1 Cohesionless Soils

The capacity of piles driven into cohesionless soil depends primarily on the relative density of the soil. During driving, the relative density of loose to medium dense cohesionless soil is increased close to the pile due to vibrations and lateral displacement of soil. This effect is most pronounced in the immediate vicinity of displacement piles. Broms (1966) and more recent studies found the zone of densification extends as far as 3 to 5.5 diameters away from the pile shaft and 3 to 5 diameters below the pile toe as depicted in Figure 9.3.

The increase in relative density increases the capacity of single piles and pile groups. The pile type selection also affects the amount of change in relative density. Piles with large displacement characteristics such as closed-end pipe and precast concrete increase the relative density of cohesionless material more than low displacement open-end pipe or steel H-piles.

The increase in horizontal ground stress, which occurs adjacent to the pile during the driving process, can be lost by relaxation in dense sand and gravels. The relaxation phenomenon occurs as the negative pore pressures generated during driving are dissipated. The negative pore pressures occur because of volume change and dilation of dense sand. The phenomena can be explained by considering the following effective stress shear strength equation.

$$\tau = c + (\sigma - u) \tan \phi$$

Where: τ = Shear strength of soil.
 c = Cohesion.
 σ = Vertical (normal) pressure.
 u = Pore water pressure.
 ϕ = Angle of internal friction.

Negative pore pressures temporarily increase the soil shear strength, and therefore pile capacity, by changing the $(\sigma - u) \tan \phi$ component of shear strength to $(\sigma + u) \tan \phi$. As negative pore pressures dissipate, the shear strength and pile capacity decrease.

The pile driving process can also generate high positive pore water pressures in saturated cohesionless silts and loose to medium dense fine sands. Positive pore pressures temporarily reduce the soil shear strength and the pile capacity. This phenomena is identical to the one described below for cohesive soils. The gain in capacity with time or soil set-up is generally quicker for sands and silts than for clays because the pore pressures dissipate more rapidly in cohesionless soils than in cohesive soils.

9.2.2 Cohesive Soils

When piles are driven into saturated cohesive materials, the soil near the piles is disturbed and radially compressed. For soft or normally consolidated clays, the zone of disturbance is generally within one pile diameter around the pile. For piles driven into saturated stiff clays, there are also significant changes in secondary soil structure (closing of fissures) with remolding and loss of previous stress history effects in the immediate vicinity of pile. Figure 9.4 illustrates the disturbance zone for piles driven in cohesive soils as observed by Broms (1966). This figure also notes the ground heave that can accompany driving displacement piles in cohesive soils.

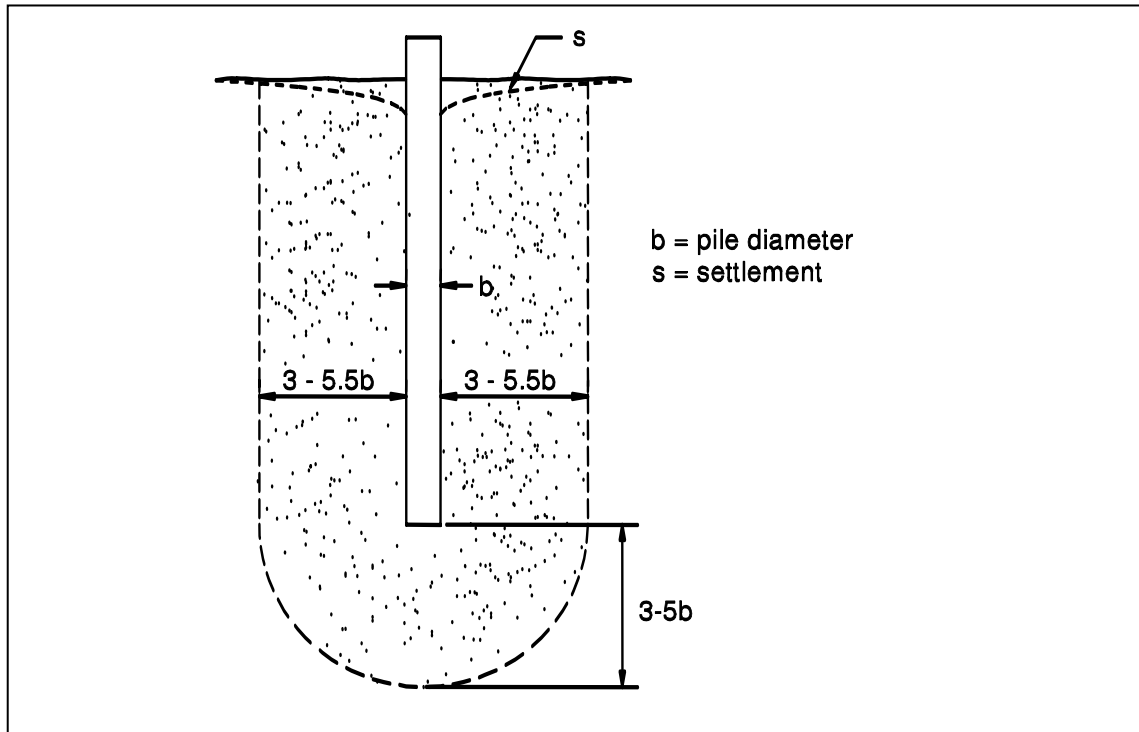


Figure 9.3 Compaction of Cohesionless Soils During Driving of Piles (Broms, 1966)

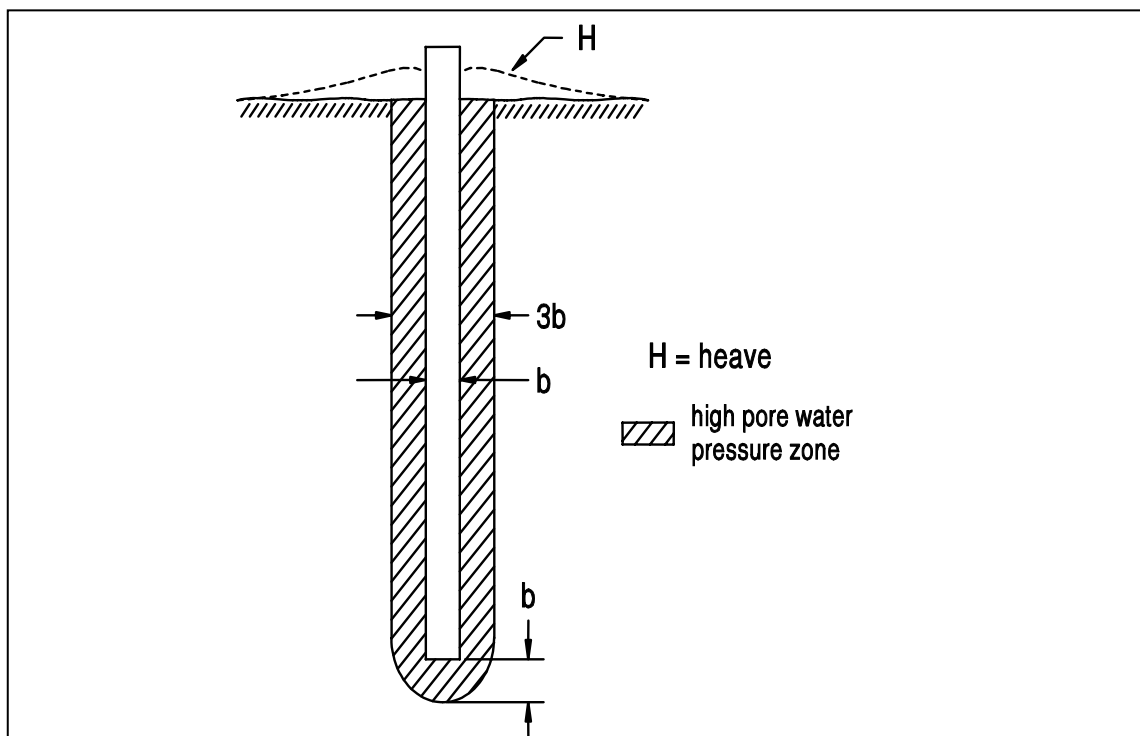


Figure 9.4 Disturbance of Cohesive Soils During Driving of Piles (Broms, 1966)

The disturbance and radial compression generate high pore pressures (positive pore pressures) which temporarily reduce soil shear strength, and therefore the load capacity of the pile. As reconsolidation of clay around the pile occurs, the high pore pressures are diminished, which leads to an increase in shear strength and pile capacity (setup). This phenomenon is opposite to "relaxation" described for cohesionless soils. The zone and magnitude of soil disturbance are dependent on the soil properties of soil sensitivity, driving method, and the pile foundation geometry. Limited data available for partially saturated cohesive soils indicates that pile driving does not generate high pore pressures and hence significant soil setup does not occur.

9.3 LOAD TRANSFER

The ultimate pile capacity, Q_u , of a pile in homogeneous soil may be expressed by the sum of the shaft resistance R_s and toe resistance R_t , or

$$Q_u = R_s + R_t$$

This may also be expressed in the form

$$Q_u = f_s A_s + q_t A_t$$

where f_s is the unit shaft resistance over the shaft surface area, A_s , and q_t is the unit toe resistance over the pile toe area, A_t . The above equations for pile bearing capacity assume that both the pile toe and the pile shaft have moved sufficiently with respect to the adjacent soil to simultaneously develop the ultimate shaft and toe resistances. Generally, the displacement needed to mobilize the shaft resistance is smaller than that required to mobilize the toe resistance. This simple rational approach has been commonly used for all piles except very large diameter piles.

Figure 9.5 illustrates typical load transfer profiles for a single pile. The load transfer distribution can be obtained from a static load test where strain gages or telltale rods are attached to a pile at different depths along the pile shaft. Figure 9.5 shows the measured axial load, Q_u , in the pile plotted against depth. The shaft resistance transferred to the soil is represented by R_s , and R_t represents the resistance at the pile toe. In Figure 9.5(a), the load transfer distribution for a pile with no shaft resistance is illustrated. In this case the full axial load at the pile head is transferred to the pile toe. In Figure 9.5(b), the axial load

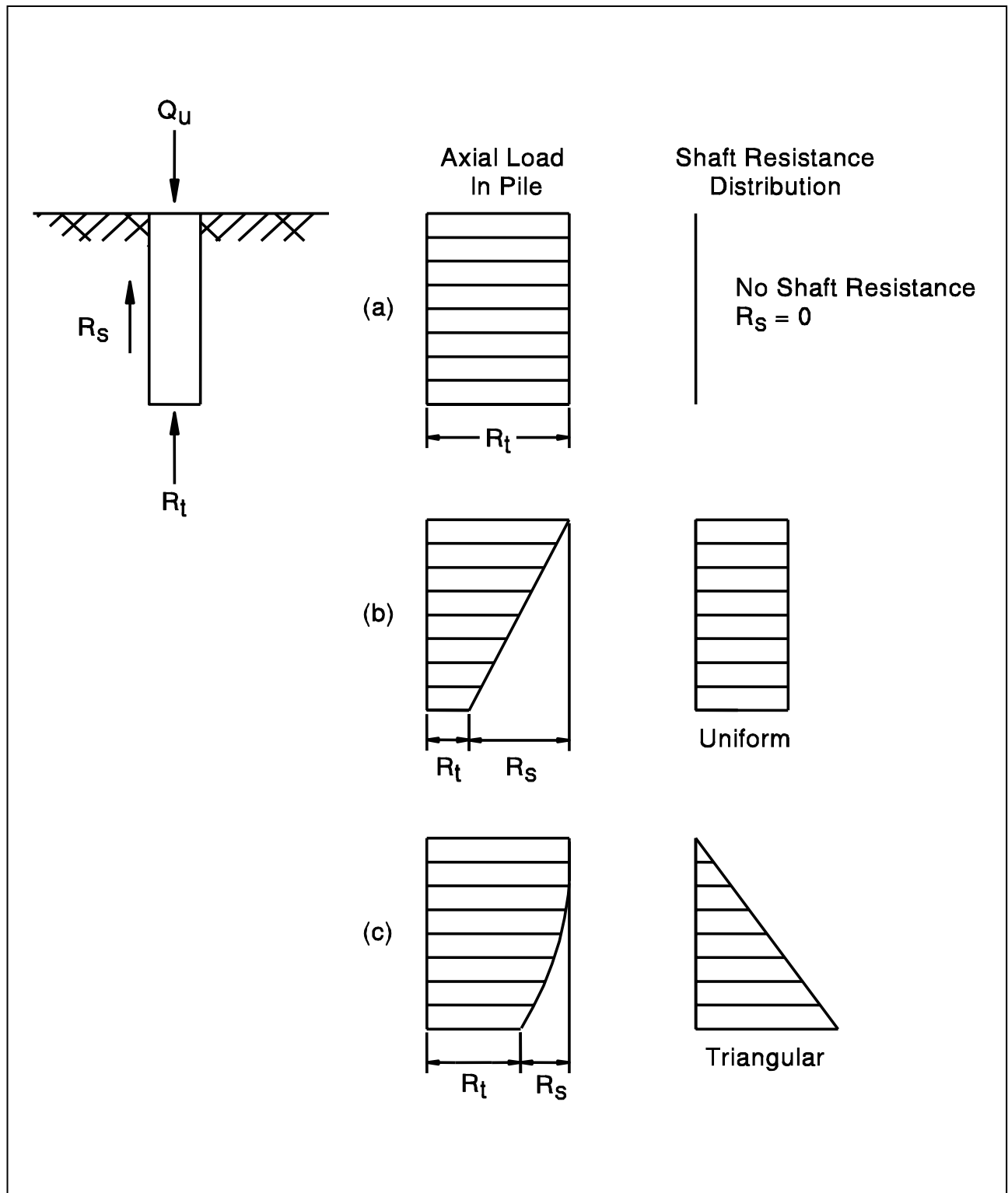


Figure 9.5 Typical Load Transfer Profiles

versus depth for a uniform shaft resistance distribution typical of a cohesive soil is illustrated. Figure 9.5(c) presents the axial load in the pile versus depth for a triangular shaft resistance distribution typical of cohesionless soils.

9.4 EFFECTIVE OVERBURDEN PRESSURE

The effective overburden pressure at a given depth below ground surface is the vertical stress at that depth due to the weight of the overlying soils. A plot of effective overburden pressure versus depth is called a " p_o Diagram" and is used in many static pile capacity and settlement calculations. Therefore, an understanding of how to construct and use a p_o Diagram is important.

Information needed to construct a p_o Diagram includes the total unit weight and thickness of each soil layer as well as the depth of the water table. The soil layer thickness and depth of the water table should be available from the project boring logs. The total unit weight of each soil layer may be obtained from density tests on undisturbed cohesive samples or estimated from Standard Penetration Test (SPT) N values in conjunction with the soil visual classification.

The first step in constructing a p_o Diagram is to calculate the total overburden pressure, p_t , versus depth. This is done by summing the product of the total unit weight times the layer thickness versus depth. Similarly, the pore water pressure, u , is summed versus depth by multiplying the unit weight of water, γ_w , of 9.8 kN/m^3 (62.4 lbs/ft^3), times the water height. The effective overburden pressure, p_o , at any depth is then the total overburden pressure minus the pore water pressure at that depth.

The effective overburden pressure at any depth is determined by summing the weights of all layers above that depth as follows:

1. For soil deposits above the static water table:

$$p_o = (\text{total soil unit weight, } \gamma)(\text{thickness of soil layer above the desired depth}).$$

2. For soil deposits below the static water table:

$$p_o = (\text{total soil unit weight, } \gamma)(\text{depth}) - (\text{unit weight of water, } \gamma_w)(\text{height of water}).$$

This may also be expressed as the buoyant or effective unit weight, γ' , ($\gamma' = \gamma - \gamma_w$):
 $p_o = (\text{buoyant unit weight, } \gamma') (\text{depth})$.

Figures 9.6 and 9.7 present examples of p_o diagrams for cases where the water table is above and below the ground surface level.

9.5 CONSIDERATIONS IN SELECTION OF DESIGN SOIL STRENGTH PARAMETERS

Most of the static analysis methods in cohesionless soils directly or indirectly utilize the soil friction angle, ϕ , in calculation of pile capacity. The soil friction angle may be determined from laboratory tests as described in Chapter 6, or may be estimated using corrected Standard Penetration Test (SPT) N values and the empirical values in Table 4-6. The designer should be aware of the many factors that can influence SPT N values discussed in Section 4.5.1 of Chapter 4 when selecting a design friction angle based on SPT values.

In coarse granular deposits, the selection of the design friction angle should be done conservatively. A comparison of ultimate pile capacities from static load test results with static analysis predictions indicates that static analyses often overpredict the shaft resistance in these deposits. This is particularly true for coarse granular deposits comprised of uniform sized or rounded particles. Cheney and Chassie (1993) recommend limiting the shearing resistance by neglecting particle interlock forces. For shaft resistance calculations in gravel deposits, this results in a maximum ϕ angle of 32° for gravels comprised of soft rounded particles, and in a maximum ϕ angle of 36° for hard angular gravel deposits. The ϕ angle used to calculate the toe resistance is determined using normal procedures.

Static analysis methods used for design of pile foundations in cohesive soils require accurate assessment of the soil shear strength and consolidation properties. This information should be obtained from laboratory tests on undisturbed samples as described in Chapter 6 and/or from in-situ testing as described in Chapter 5. Designs based solely on strength and compressibility information estimated from SPT N values from disturbed soil samples should be avoided.

Additional guidance on the selection of design soil strength parameters may be found in Geotechnical Engineering Circular 5 by Sabatini *et al.* (2002).

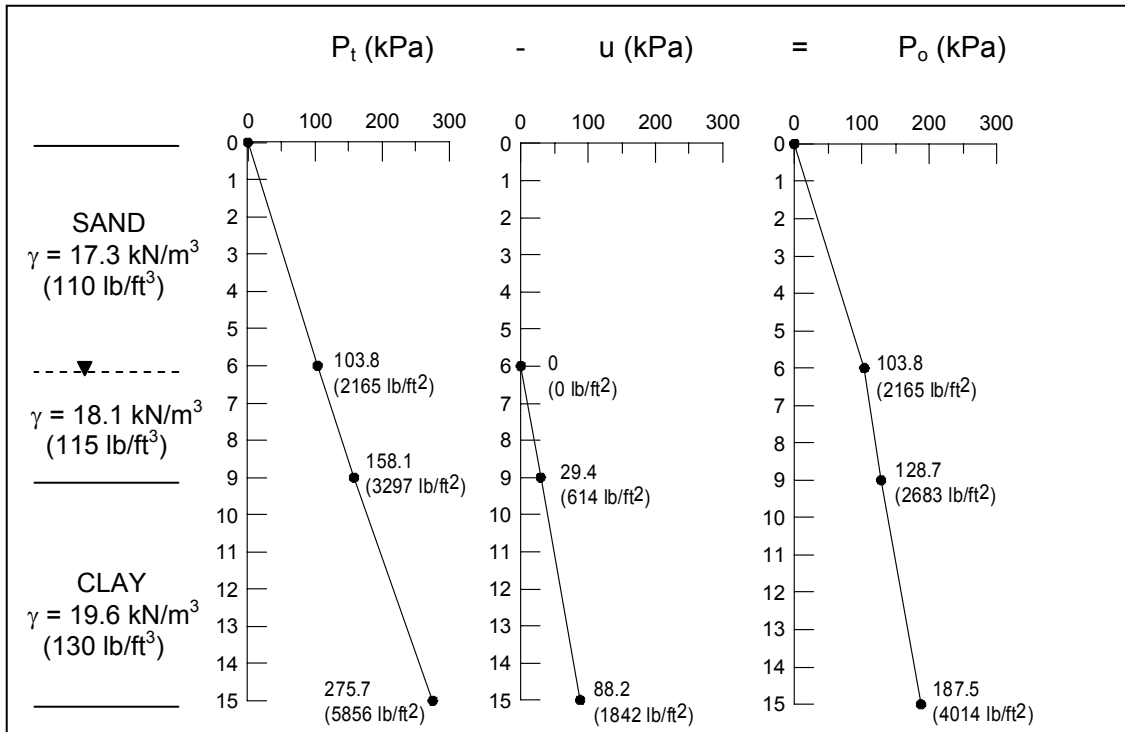


Figure 9.6 Effective Overburden Pressure Diagram – Water Table Below Ground Surface

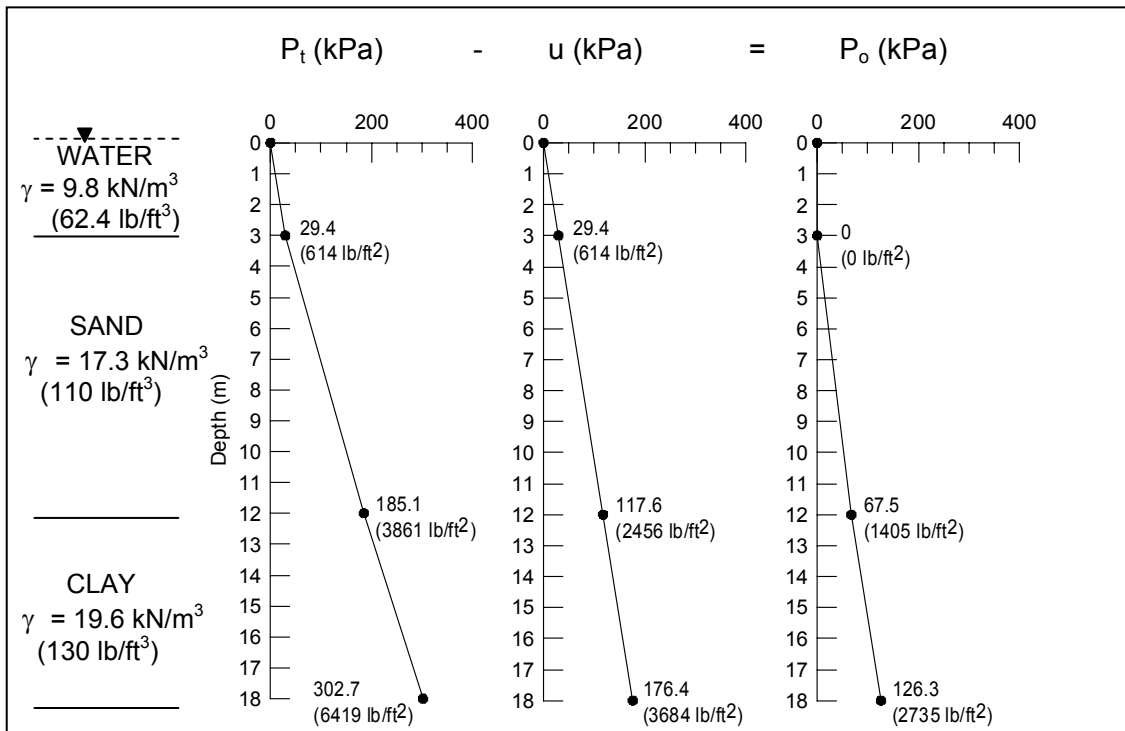


Figure 9.7 Effective Overburden Pressure Diagram – Water Table Above Ground Surface

The capacity of a pile when driven in many soil formations is not the same as the long term pile capacity. This is due to the soil disturbance created during installation as described in Section 9.2 of this chapter. For design in cohesive soils, the sensitivity of the cohesive soils should be determined as discussed in Section 6.2 of Chapter 6. Knowledge of the soil sensitivity allows a more accurate static analysis of the driving resistance in cohesive soils.

Increases and decreases on pile capacity with time are known as soil setup and relaxation, respectively. These time effects are discussed in greater detail in Section 9.10.1. For a cost effective foundation design with any static analysis method, it is of paramount importance that the foundation designer logically select the soil strength parameters and include consideration of time dependent soil strength changes.

9.6 FACTORS OF SAFETY

Static analysis results yield an ultimate pile capacity or soil resistance. The allowable soil resistance (pile design load) is selected by dividing the ultimate pile capacity in suitable soil support layers by a factor of safety. The range in the factor of safety has primarily depended upon the reliability of the particular static analysis method with consideration of the following items.

1. The level of confidence in the input parameters. (This is a function of the type and extent of the subsurface exploration and laboratory testing of soil and rock materials.)
2. Variability of the soil and rock.
3. Method of static analysis.
4. Effects of and consistency of the proposed pile installation method.
5. Level of construction monitoring (static load test, dynamic analysis, wave equation analysis, Gates dynamic formula).

A large number of static analysis methods are documented in the literature with specific recommendations on the factor of safety to be used with each method. These recommended factors of safety have routinely disregarded the influence of the construction control method used to complement the static analysis computation. As part of the overall design process, it is important that the foundation designer qualitatively assess the validity of the chosen design analysis method and the reliability of the geotechnical design parameters.

While the range in static analysis factors of safety was from 2 to 4, most of the static analysis methods recommended a factor of safety of 3. As foundation design loads have increased over time, the use of high factors of safety has often resulted in pile installation problems. In addition, experience has shown that construction control methods have a significant influence on pile capacity. Therefore, the factor of safety used in a static analysis calculation should be based upon the construction control method specified. Provided that the procedures recommended in this manual are used for the subsurface exploration and analysis, the factors of safety in Table 9-1 are recommended, based on the specified construction control method. These factors of safety are discussed in greater detail in Chapter 14. The factor of safety for other test methods not included in Table 9-1 should be determined by the individual designer.

| Table 9-1 Recommended Factor of Safety Based on Construction Control Method | |
|---|------------------|
| Construction Control Method | Factor of Safety |
| Static load test (ASTM D-1143) with wave equation analysis | 2.00 |
| Dynamic testing (ASTM D-4945) with wave equation analysis | 2.25 |
| Indicator piles with wave equation analysis | 2.50 |
| Wave equation analysis | 2.75 |
| Gates dynamic formula | 3.50 |

The pile design load should be supported by soil resistance developed only in soil layers that contribute to long term load support. The soil resistance from soils subject to scour, or from soil layers above soft compressible soils should not be considered. The following example problem will be used to clarify the use of the factor of safety in static pile capacity calculations for determination of the pile design load as well as for determination of the soil resistance to pile driving.

Consider a pile to be driven through the soil profile described in Figure 9.8. The proposed pile type penetrates through a sand layer subject to scour in the 100 year flood overlying a very soft clay layer unsuitable for long term support and into competent support materials. Hence the soil resistances from the scour susceptible and soft clay layers do not contribute to long term load support and should not be included in the soil resistance for support of the design load. In this example, static load testing with wave equation analysis will be used for construction control. Therefore a factor of safety of 2.0 should be applied to the soil resistance calculated in suitable support layers in the static analysis. It should be noted

that this approach is for scour conditions under the 100 year or overtopping flood events and that a different approach would apply for the superflood or 500 year event. Additional discussion on scour considerations is provided in Section 9.9.4 of this chapter.

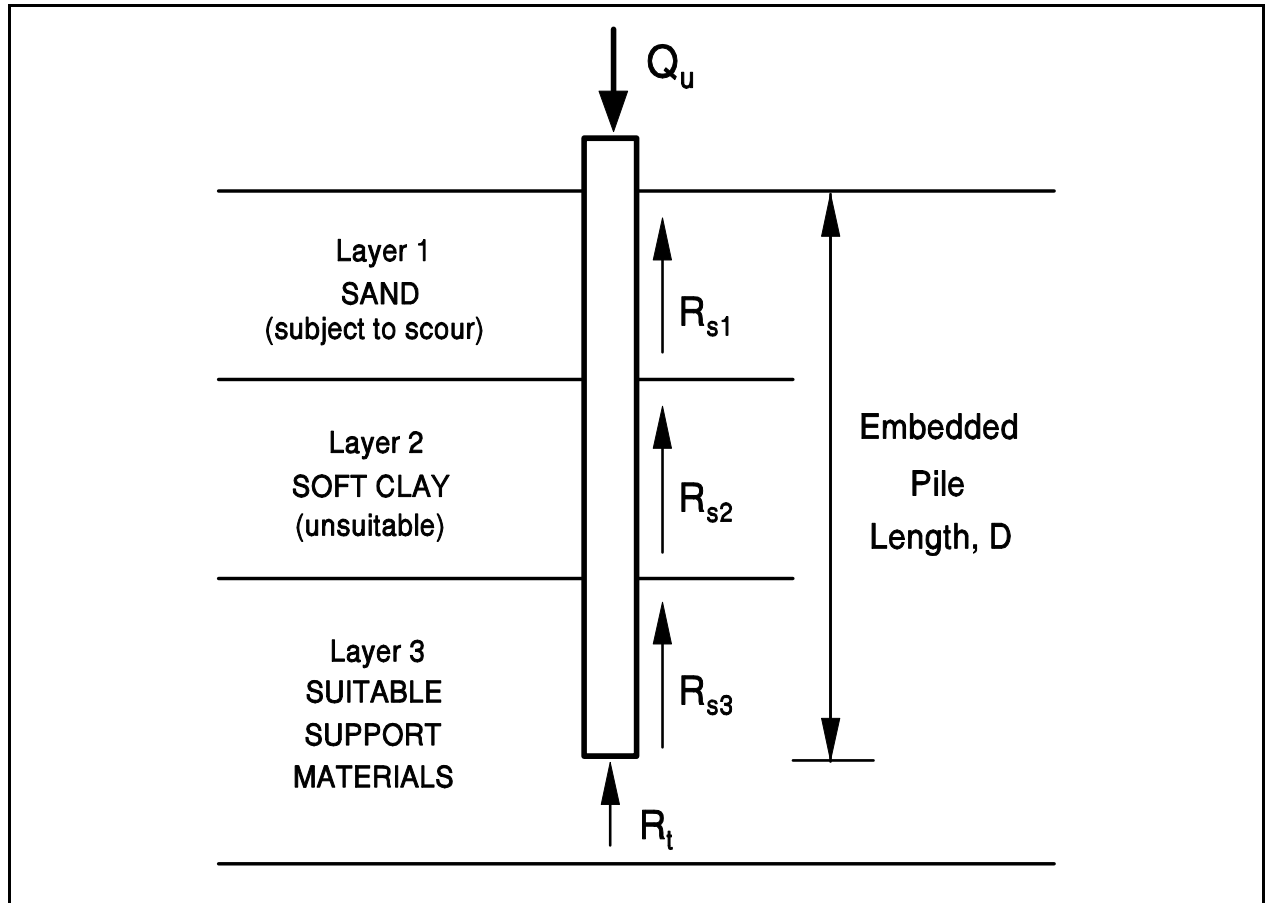


Figure 9.8 Soil Profile for Factor of Safety Discussion

In the static analysis, a trial pile penetration depth is chosen and an ultimate pile capacity, Q_u , is calculated. This ultimate capacity includes the soil resistance calculated from all soil layers including the shaft resistance in the scour susceptible layer, R_{s1} , the shaft resistance in the unsuitable soft clay layer, R_{s2} as well as the resistance in suitable support materials along the pile shaft, R_{s3} , and at the pile toe resistance, R_t .

$$Q_u = R_{s1} + R_{s2} + R_{s3} + R_t$$

The design load, Q_a , is the sum of the soil resistances from the suitable support materials divided by a factor of safety, FS. As noted earlier, a factor of safety of 2.0 is used in the equation below because of the planned construction control with static load testing.

$$Q_a = (R_{s3} + R_t) / (FS=2)$$

The design load may also be expressed as the sum of the ultimate capacity minus the calculated soil resistances from the scour susceptible and unsuitable layers divided by the factor of safety.

$$Q_a = (Q_u - R_{s1} - R_{s2}) / (FS=2)$$

The result of the static analysis is then the estimated pile penetration depth, D , the design load for that penetration depth, Q_a , and the calculated ultimate capacity, Q_u .

For preparation of construction plans and specifications, the calculated ultimate capacity, Q_u , is specified. Note that if the construction control method changes after the design stage, the required ultimate capacity and the required pile penetration depth for the ultimate capacity will also change. This is apparent when the previous equation for the design load is expressed in terms of the ultimate capacity as follows:

$$Q_u = R_{s1} + R_{s2} + (Q_a)(FS=2)$$

A static analysis should also be used to calculate the soil resistance to driving, SRD, that must be overcome to reach the estimated pile penetration depth necessary to develop the ultimate capacity. This information is necessary for the designer to select a pile section with the driveability to overcome the anticipated soil resistance and for the contractor to properly size equipment. Driveability aspects of design are discussed in Section 9.10.7.

In the soil resistance to driving calculation, a factor of safety is not used. The soil resistance to driving is the sum of the soil resistances from the scour susceptible and unsuitable layers plus the soil resistance in the suitable support materials to the estimated penetration depth.

$$SRD = R_{s1} + R_{s2} + R_{s3} + R_t$$

Soil resistances in this calculation should be the resistance at the time of driving. Hence time dependent changes in soil strengths due to soil setup or relaxation should be considered. For the example presented in Figure 9.8, the driving resistance from the unsuitable clay layer would be reduced by the sensitivity of the clay. Therefore, R_{s2} would

be $R_{s2} / 2$ for a clay with a sensitivity of 2. The soil resistance to driving to depth D would then be as follows

$$SRD = R_{s1} + R_{s2}/2 + R_{s3} + R_t$$

This example problem considers only the driving resistance at the final pile penetration depth. In cases where piles are driven through hard or dense layers above the estimated pile penetration depth, the soil resistance to penetrate these layers should also be calculated. Additional information on the calculation of time dependent soil strength changes is provided in Section 9.10.1 of this chapter.

9.7 DESIGN OF SINGLE PILES

9.7.1 Ultimate Capacity of Single Piles

Numerous static analysis methods are available for calculating the ultimate capacity of a single pile. The following sections of this chapter will detail analysis methods for piles in cohesionless, cohesive, and layered soil profiles using readily available SPT or laboratory test information. Additional methods based on cone penetration test results are also presented. As noted earlier, designers should fully understand the basis for, the limitations of, and the applicability of a chosen method. The selected method should also have a proven agreement with full scale field results in soil conditions similar to the project being designed, with the pile type being evaluated, and the pile installation conditions (impact driving, vibratory driving, etc.) to be used.

9.7.1.1 Bearing Capacity of Piles in Cohesionless Soils

The ultimate bearing capacity of a single pile in a cohesionless soil is the sum of shaft and toe resistances ($Q_u = R_s + R_t$). The calculation assumes that the shaft resistance and toe bearing resistance can be determined separately and that these two factors do not affect each other. Many analytical and empirical methods have been developed for estimating pile capacity in cohesionless materials. Table 9-2 describes some of the available methods. Each of the methods presented in Table 9-2 is also discussed in subsequent subsections.

9.7.1.1a Meyerhof Method Based on Standard Penetration Test (SPT) Data

Existing empirical correlations between Standard Penetration Test (SPT) results and static pile load tests can be used for preliminary estimates of static pile capacity for cohesionless soils. These correlations are based on the analyses of numerous pile load tests in a variety of cohesionless soil deposits. The Meyerhof (1976) method is quick and is easy to use. However, because the method is based on SPT test data which can be influenced by numerous factors, this method should only be used for preliminary estimates and not for final design.

Meyerhof (1976) reported that the average unit shaft resistance, f_s , of driven displacement piles, such as closed-end pipe piles and precast concrete piles, in kPa is:

$$f_s = 2\bar{N}' \leq 100 \text{ kPa}$$

The average unit shaft resistance of driven nondisplacement piles, such as H-piles, in kPa is:

$$f_s = \bar{N}' \leq 100 \text{ kPa}$$

where \bar{N}' is the average corrected SPT resistance value, in blows per 300 mm (1 ft), along the embedded length of pile. Typically, the soil profile is delineated into 3 to 6 m (10 to 20 ft) thick layers, and the average unit shaft resistance is calculated for each soil layer.

TABLE 9-2 METHODS OF STATIC ANALYSIS FOR PILES IN COHESIONLESS SOILS

| Method | Approach | Method of Obtaining Design Parameters | Advantages | Disadvantages | Remarks |
|--|----------------|---|--|---|---|
| Meyerhof Method | Empirical | Results of SPT tests. | Widespread use of SPT test and input data availability. Simple method to use. | Non reproducibility of N values. Not as reliable as the other methods presented in this chapter. | Due to non reproducibility of N values and simplifying assumptions, use should be limited to preliminary estimating purposes. |
| Brown Method | Empirical | Results of SPT tests based on N_{60} values. | Widespread use of SPT test and input data availability. Simple method to use. | N_{60} values not always available. | Simple method based on correlations with 71 static load test results. Details provided in Section 9.7.1.1b. |
| Nordlund Method. | Semi-empirical | Charts provided by Nordlund. Estimate of soil friction angle is needed. | Allows for increased shaft resistance of tapered piles and includes effects of pile-soil friction coefficient for different pile materials. | No limiting value on unit shaft resistance is recommended by Nordlund. Soil friction angle often estimated from SPT data. | Good approach to design that is widely used. Method is based on field observations. Details provided in Section 9.7.1.1c. |
| Effective Stress Method. | Semi-empirical | Soil classification and estimated friction angle for β and N_t selection. | β value considers pile-soil friction coefficient for different pile materials. Soil resistance related to effective overburden pressure. | Results effected by range in β values and in particular by range in N_t chosen. | Good approach for design. Details provided in Section 9.7.1.3. |
| Methods based on Cone Penetration Test (CPT) data. | Empirical | Results of CPT tests. | Testing analogy between CPT and pile. Reliable correlations and reproducible test data. | Limitations on pushing cone into dense strata. | Good approach for design. Details provided in Section 9.7.1.7. |

Meyerhof (1976) recommended that the unit toe resistance, q_t , in kPa for piles driven into sands and gravels may be approximated by:

$$q_t = 400\bar{N}'_o + \frac{(40\bar{N}'_B - 40\bar{N}'_o)D_B}{b} \leq 400\bar{N}'_B$$

Where: \bar{N}'_o = Average corrected SPT N' value for the stratum overlying the bearing stratum.

\bar{N}'_B = Average corrected SPT N' value of the bearing stratum.

D_B = Pile embedment depth into the bearing stratum in meters.

b = Pile diameter in meters.

The limiting value of $400\bar{N}'_B$ is reached when the embedment depth into the bearing stratum reaches 10 pile diameters. The above equation applies when the pile toe is located near the interface of two strata with a weaker stratum overlying the bearing stratum. For piles driven in a uniform cohesionless stratum, the unit toe resistance can be calculated as follows:

$$q_t = \frac{40\bar{N}'_B D_B}{b} \leq 400\bar{N}'_B$$

It is recommended that the average corrected SPT N' value, \bar{N}'_B , be calculated by averaging N' values within the zone extending 3 diameters below the pile toe. For piles driven into non-plastic silts, Meyerhof recommended the unit toe resistance, q_t , be limited to $300\bar{N}'_B$ instead of the $400\bar{N}'_B$ given in the above equation.

STEP BY STEP PROCEDURE FOR USING METHOD BASED ON SPT DATA

STEP 1 Correct SPT field N values for overburden pressure.

Use correction factors from Figure 4.6 to obtain corrected SPT N' values.

STEP 2 Compute the average corrected SPT N' value, \bar{N}' , for each soil layer. Along the embedded length of pile, delineate the soil profile into layers based on soil density indicated by N' . The individual soil layers should be selected between 3 and 6 m (10 to 20 ft) thick.

STEP 3 Compute unit shaft resistance, f_s (kPa) for driven, displacement piles from:

$$f_s = 2\bar{N}' \leq 100 \text{ kPa}$$

for driven, non-displacement piles such as H-piles, use:

$$f_s = \bar{N}' \leq 100 \text{ kPa}$$

STEP 4 Compute ultimate shaft resistance, R_s (kN).

$$R_s = f_s A_s$$

Where: A_s = Pile shaft surface area.
= (pile perimeter)(embedded length).

For H-piles in cohesionless soils, the "box" area should generally be used for shaft resistance calculations. Additional discussion on the behavior of open pile sections is presented in Section 9.10.5.

STEP 5 Compute average corrected SPT N' values, \bar{N}'_O and \bar{N}'_B , near pile toe.

In cases where the pile toe is situated near the interface of a weaker stratum overlying the bearing stratum, compute the average corrected SPT N' value for the stratum overlying the bearing stratum, \bar{N}'_O , and the average corrected SPT N' value for the bearing stratum, \bar{N}'_B .

In uniform cohesionless soils, compute the average corrected SPT N' value by averaging N' values within the zone extending 3 diameters below the pile toe.

STEP 6 Compute unit toe resistance, q_t (kPa).

For weaker stratum overlying the bearing stratum compute q_t from:

$$q_t = 400\bar{N}'_o + \frac{(40\bar{N}'_B - 40\bar{N}'_o)D_B}{b} \leq 400\bar{N}'_B$$

For piles in a uniform cohesionless deposit compute q_t from:

$$q_t = \frac{40\bar{N}'_B D_B}{b} \leq 400\bar{N}'_B$$

For piles driven into non-plastic silts, the unit toe resistance, q_t , should be limited to $300\bar{N}'_B$ instead of $400\bar{N}'_B$.

STEP 7 Compute ultimate toe resistance, R_t (kN).

$$R_t = q_t A_t$$

Where: A_t = Pile toe area.

For steel H and unfilled open end pipe piles, use only steel cross section area at pile toe unless there is reasonable assurance and previous experience that a soil plug will form at the pile toe. Additional discussion on plug formation in open pile sections is presented in Section 9.10.5. The assumption of a soil plug would allow the use of a box area at H pile toe and total pipe cross section area for open end pipe pile.

STEP 8 Compute ultimate pile capacity, Q_u (kN).

$$Q_u = R_s + R_t$$

STEP 9 Compute allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}}$$

Use Factor of Safety based on the construction control method as detailed in Section 9.6.

In using the Meyerhof method, it should be remembered that it is intended to be used only for preliminary capacity and length estimates. Limiting values often apply for the unit shaft and toe resistances and they should be used. It should also be remembered that the Standard Penetration Test is subject to many errors. Thus, judgment must be exercised when performing capacity calculations based on SPT results.

9.7.1.1b Brown Method

The Brown Method (2001) is a simple empirical method that uses Standard Penetration Test N_{60} values for calculating unit shaft resistance and unit end bearing values. The Brown Method was based on capacity correlations with 71 static load tests from Caltrans projects in a wide variety of soil types. The pile types included closed end pipe, open end pipe, H-piles, and precast concrete piles. The method considers compression and uplift loading as well as pile installation method (impact driving and partial vibratory installation).

Brown reported that the average unit shaft resistance, f_s , is:

$$f_s = F_{vs} (A_b + B_b N_{60})$$

N_{60} is the SPT N value corrected for 60% energy transfer and F_{vs} is a reduction factor for vibratory installed piles. A_b and B_b were determined from regression analyses on the data base and depend upon the soil type as noted in Table 9-3. Limits on the value of N_{60} were also recommended. If N_{60} is greater than 50, a value of 50 should be used and if N_{60} is less than 3, use 3. Brown recommended that the shaft resistance for H-piles be calculated using the “box” perimeter rather than the actual pile/soil contact area and for open end pipe piles Brown recommended using only the external surface area. The shaft resistance, R_s , is then:

$$R_s = f_s A_s$$

Where A_s is the pile shaft surface area (recommended pile perimeter noted above multiplied by length).

| TABLE 9-3 INPUT FACTORS FOR BROWN'S METHOD | | | | | | | |
|--|---------------------|---------------------------|----------|-------|-------|---------|-----------|
| Loading Condition | Installation Method | Soil Type | F_{vs} | A_b | | B_b | |
| | | | | kPa | (ksf) | kPa/bpf | (ksf/bpf) |
| Compression | Impact | Clay to Sand | 1.0 | 26.6 | 0.555 | 1.92 | 0.040 |
| " | " | Gravelly Sand to Boulders | 1.0 | 42.6 | 0.888 | 42.6 | 0.888 |
| " | " | Rock | 1.0 | 138.0 | 2.89 | 138.0 | 2.89 |
| Tension | Impact | Clay to Sand | 1.0 | 25.0 | 0.522 | 1.8 | 0.0376 |
| " | " | Gravelly Sand to Boulders | 1.0 | 40.0 | 0.835 | 0.0 | 0.0 |
| " | " | Rock | 1.0 | 130 | 2.71 | 0.0 | 0.0 |
| " | Vibratory | Clay to Sand | 0.68 | 25.0 | 0.522 | 1.8 | 0.0376 |
| " | " | Gravelly Sand to Boulders | 0.68 | 40.0 | 0.835 | 0.0 | 0.0 |
| " | " | Rock | 0.68 | 130.0 | 2.71 | 0.0 | 0.0 |

Brown (2001) recommended that the unit toe resistance, q_t , for impact driven piles in MPa be calculated as:

$$q_t = 0.17 N_{60}$$

In US units, the unit toe resistance, q_t , in ksf is calculated:

$$q_t = 3.55 N_{60}$$

For vibratory installed piles this unit toe resistance should then be multiplied by 0.56. The pile toe resistance, R_t , is then calculated as follows:

$$R_t = q_t (A_t + A_{tp} F_p)$$

Brown recommended the actual steel area at the pile toe be used for A_t on H-piles and open end pipe piles. On these open end sections, the resistance on the soil plug is

calculated from the unit toe resistance multiplied by the soil plug area at the pile toe, A_{tp} , and a plug mobilization factor, F_p , of 0.42 for open end pipe piles or 0.67 for H-piles.

While the simplicity of Brown's method is attractive, it is recommended that the method be used only for preliminary length estimates until a greater experience base is obtained with the method results. Caltrans continues to study and expand on Brown's work as reported by Olson and Shantz (2004).

9.7.1.1c Nordlund Method

The Nordlund Method (1963) is based on field observations and considers the shape of pile taper and its soil displacement in calculating the shaft resistance. The method also accounts for the differences in soil-pile coefficient of friction for different pile materials. The method is based on the results of several load test programs in cohesionless soils. Several pile types were used in these test programs including timber, H, closed end pipe, Monotubes and Raymond step taper piles. These piles, which were used to develop the method's design curves, had pile widths generally in the range of 250 to 500 mm (10 to 20 inches). The Nordlund Method tends to overpredict pile capacity for piles with widths larger than 600 mm (24 inches).

According to the Nordlund Method, the ultimate capacity, Q_u , of a pile in cohesionless soil is the sum of the shaft resistance, R_s and the toe resistance, R_t . Nordlund suggests the shaft resistance is a function of the following variables:

1. The friction angle of the soil.
2. The friction angle on the sliding surface.
3. The taper of the pile.
4. The effective unit weight of the soil.
5. The pile length.
6. The minimum pile perimeter.
7. The volume of soil displaced.

These factors are considered in the Nordlund equation as illustrated in Figure 9.9.

The Nordlund Method equation for computing the ultimate capacity of a pile is as follows:

$$Q_u = \sum_{d=0}^{d=D} K_{\delta} C_F p_d \frac{\sin(\delta + \omega)}{\cos \omega} C_d \Delta d + \alpha_t N'_q A_t p_t$$

Where:

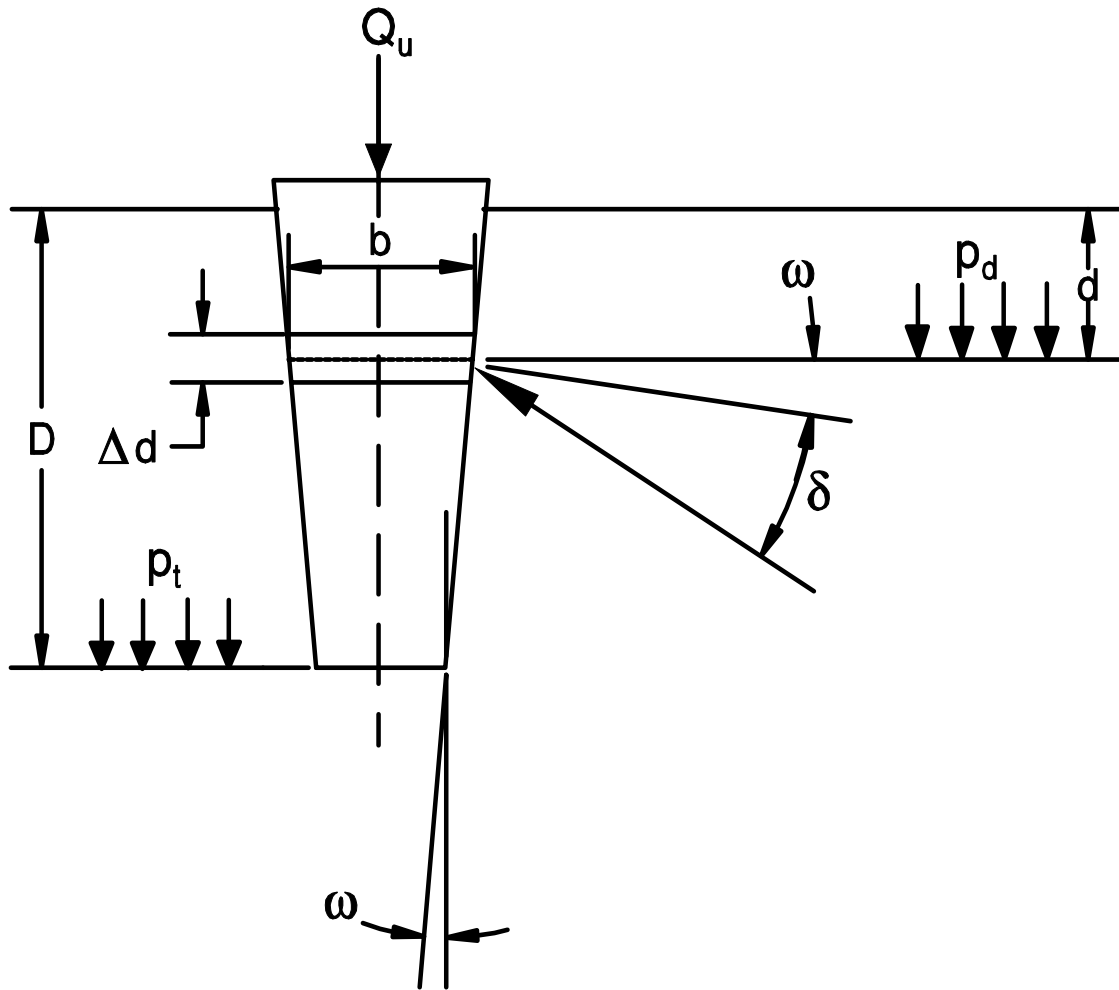
- d = Depth.
- D = Embedded pile length.
- K_{δ} = Coefficient of lateral earth pressure at depth d .
- C_F = Correction factor for K_{δ} when $\delta \neq \phi$.
- p_d = Effective overburden pressure at the center of depth increment d .
- δ = Friction angle between pile and soil.
- ω = Angle of pile taper from vertical.
- ϕ = Soil friction angle.
- C_d = Pile perimeter at depth d .
- Δd = Length of pile segment.
- α_t = Dimensionless factor (dependent on pile depth-width relationship).
- N'_q = Bearing capacity factor.
- A_t = Pile toe area.
- p_t = Effective overburden pressure at the pile toe.

For a pile of uniform cross section ($\omega=0$) and embedded length D , driven in soil layers of the same effective unit weight and friction angle, the Nordlund equation becomes:

$$Q_u = (K_{\delta} C_F p_d \sin \delta C_d D) + (\alpha_t N'_q A_t p_t)$$

The soil friction angle ϕ influences most of the calculations in the Nordlund method. In the absence of laboratory test data, ϕ can be estimated from corrected SPT N' values. Therefore, Figure 4.6 in Chapter 4 should be used for correcting field N values. The corrected SPT N' values may then be used in Table 4-6 of Chapter 4 to estimate the soil friction angle, ϕ .

Nordlund developed this method in 1963 and updated it in 1979 and has not placed a limiting value on the shaft resistance. However, Nordlund has recommended that the effective overburden pressure, p_t , used for computing the pile toe resistance be limited to 150 kPa (3 ksf).



$$Q_u = \sum_{d=0}^{d=D} K_{\delta} C_F p_d \frac{\sin(\delta + \omega)}{\cos \omega} C_d \Delta d + \alpha_t N'_q A_t p_t$$

Figure 9.9 Nordlund's General Equation for Ultimate Pile Capacity

STEP BY STEP PROCEDURE FOR USING NORDLUND METHOD

Steps 1 through 6 are for computing the shaft resistance and steps 7 through 9 are for computing the pile toe resistance.

- STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer.
- Construct p_o diagram using procedure described in Section 9.4.
 - Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values. Delineate soil profile into layers based on corrected SPT N' values.
 - Determine ϕ angle for each layer from laboratory tests or in-situ data.
 - In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, \bar{N}' , for each soil layer and estimate ϕ angle from Table 4-6 in Chapter 4.
- STEP 2 Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .
- Compute volume of soil displaced per unit length of pile, V .
 - Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.
 - Calculate δ from δ/ϕ ratio.
- STEP 3 Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.
- Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.
 - If the displaced volume is 0.0093, 0.093, or 0.930 m^3/m (0.1, 1.0 or 10.0 ft^3/ft) which correspond to one of the curves provided in Figures 9.11 through 9.14

and the ϕ angle is one of those provided, K_δ can be determined directly from the appropriate figure.

- c. If the displaced volume is 0.0093, 0.093, or 0.930 m³/m (0.1, 1.0 or 10.0 ft³/ft) which correspond to one of the curves provided in Figures 9.11 through 9.14 but the ϕ angle is different from those provided, use linear interpolation to determine K_δ for the required ϕ angle. Tables 9-4a and 9-4b also provide interpolated K_δ values at selected displaced volumes versus ϕ angle for uniform piles ($\omega = 0$).
- d. If the displaced volume is other than 0.0093, 0.093, or 0.930 m³/m (0.1, 1.0 or 10.0 ft³/ft) which correspond to one of the curves provided in Figures 9.11 through 9.14 but the ϕ angle corresponds to one of those provided, use log linear interpolation to determine K_δ for the required displaced volume. An example of this procedure may be found in Appendix F.2.1.2. Tables 9-4a and 9-4b also provide interpolated K_δ values at selected displaced volumes versus ϕ angle for uniform piles ($\omega = 0$).
- e. If the displaced volume is other than 0.0093, 0.093, or 0.930 m³/m (0.1, 1.0 or 10.0 ft³/ft) which correspond to one of the curves provided in Figures 9.11 through 9.14 and the ϕ angle does not correspond to one of those provided, first use linear interpolation to determine K_δ for the required ϕ angle at the displaced volume curves provided for 0.0093, 0.093, or 0.930 m³/m (0.1, 1.0 or 10.0 ft³/ft). Then use log linear interpolation to determine K_δ for the required displaced volume. An example of this procedure may be found in Appendix F.2.1.2. Tables 9-4a and 9-4b also provide interpolated K_δ values at selected displaced volumes versus ϕ angle for uniform piles ($\omega = 0$).

STEP 4 Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and δ/ϕ value to determine C_F .

STEP 5 Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa).

Note: A limiting value is not applied to p_d .

- STEP 6 Compute the shaft resistance in each soil layer. Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$R_s = K_\delta C_F p_d \sin \delta C_d D$$

(for uniform pile cross section)

For H-piles in cohesionless soils, the "box" area should generally be used for shaft resistance calculations. Additional discussion on the behavior of open pile sections is presented in Section 9.10.5.

- STEP 7 Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

- Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.
- Enter Figure 9.16(b) with ϕ angle near pile toe to determine, N'_q .
- If ϕ angle is estimated from SPT data, compute the average corrected SPT N' value over the zone from the pile toe to 3 diameters below the pile toe. Use this average corrected SPT N' value to estimate ϕ angle near pile toe from Table 4-5.

- STEP 8 Compute the effective overburden pressure at the pile toe, p_t (kPa).

Note: The limiting value of p_t is 150 kPa (3 ksf).

- STEP 9 Compute the ultimate toe resistance, R_t (kN).

- $R_t = \alpha_t N'_q A_t p_t$
- limiting $R_t = q_L A_t$

q_L value is obtained from:

1. Entering Figure 9.17 with ϕ angle near pile toe determined from laboratory or in-situ test data.
 2. Entering Figure 9.17 with ϕ angle near the pile toe estimated from Table 4-6 and the average corrected SPT N' near toe as described in Step 7.
- c. Use lesser of the two R_t values obtained in steps a and b.

For steel H and unfilled open end pipe piles, use only steel cross section area at pile toe unless there is reasonable assurance and previous experience that a soil plug will form at the pile toe. Additional discussion on plug formation in open pile sections is presented in Section 9.10.5. The assumption of a soil plug would allow the use of a box area at H pile toe and total pipe cross section area for open end pipe pile.

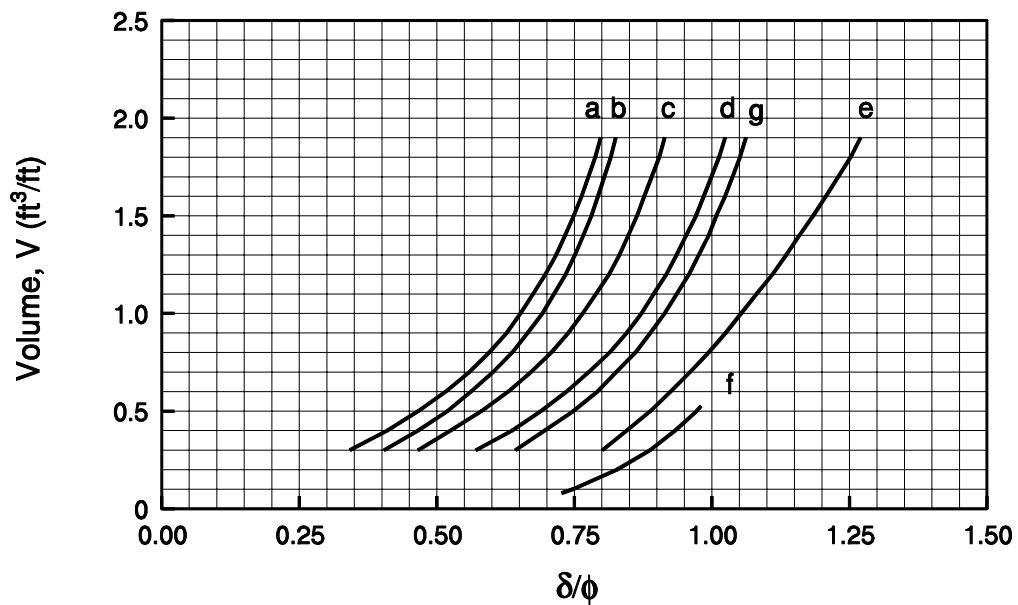
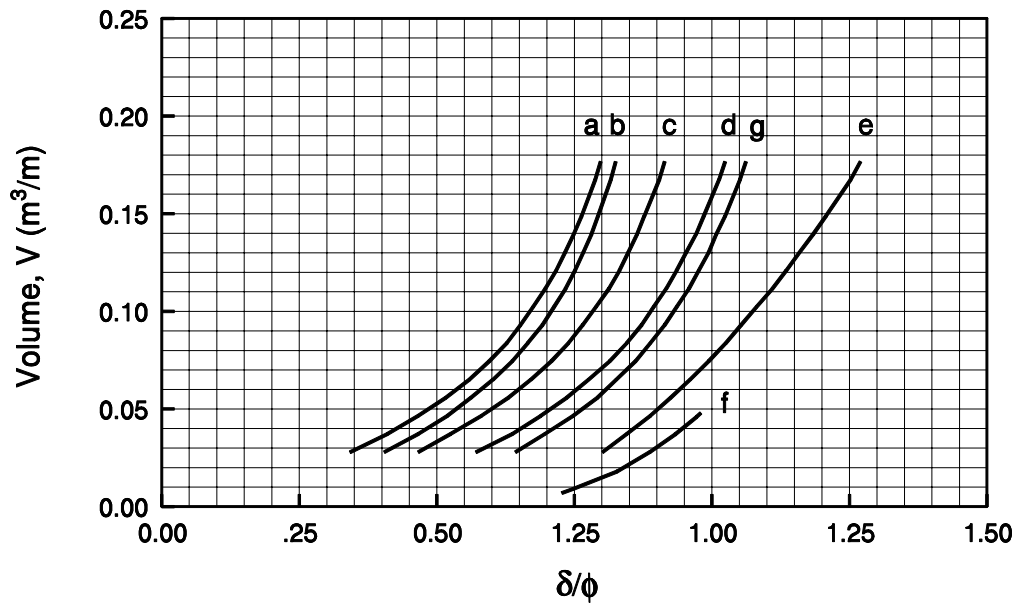
STEP 10 Compute the ultimate pile capacity, Q_u (kN).

$$Q_u = R_s + R_t$$

STEP 11 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}}$$

The factor of safety used in the calculation should be based upon the construction control method to be specified. Recommended factors of safety were described in Section 9.6.



- a. Closed end pipe and non-tapered portion of monotube piles
- b. Timber piles
- c. Precast concrete piles
- d. Raymond step-taper piles
- e. Raymond uniform taper piles
- f. H-piles
- g. Tapered portion of monotube piles

Figure 9.10 Relationship of δ/ϕ and Pile Soil Displacement, V , for Various Types of Piles (after Nordlund, 1979)

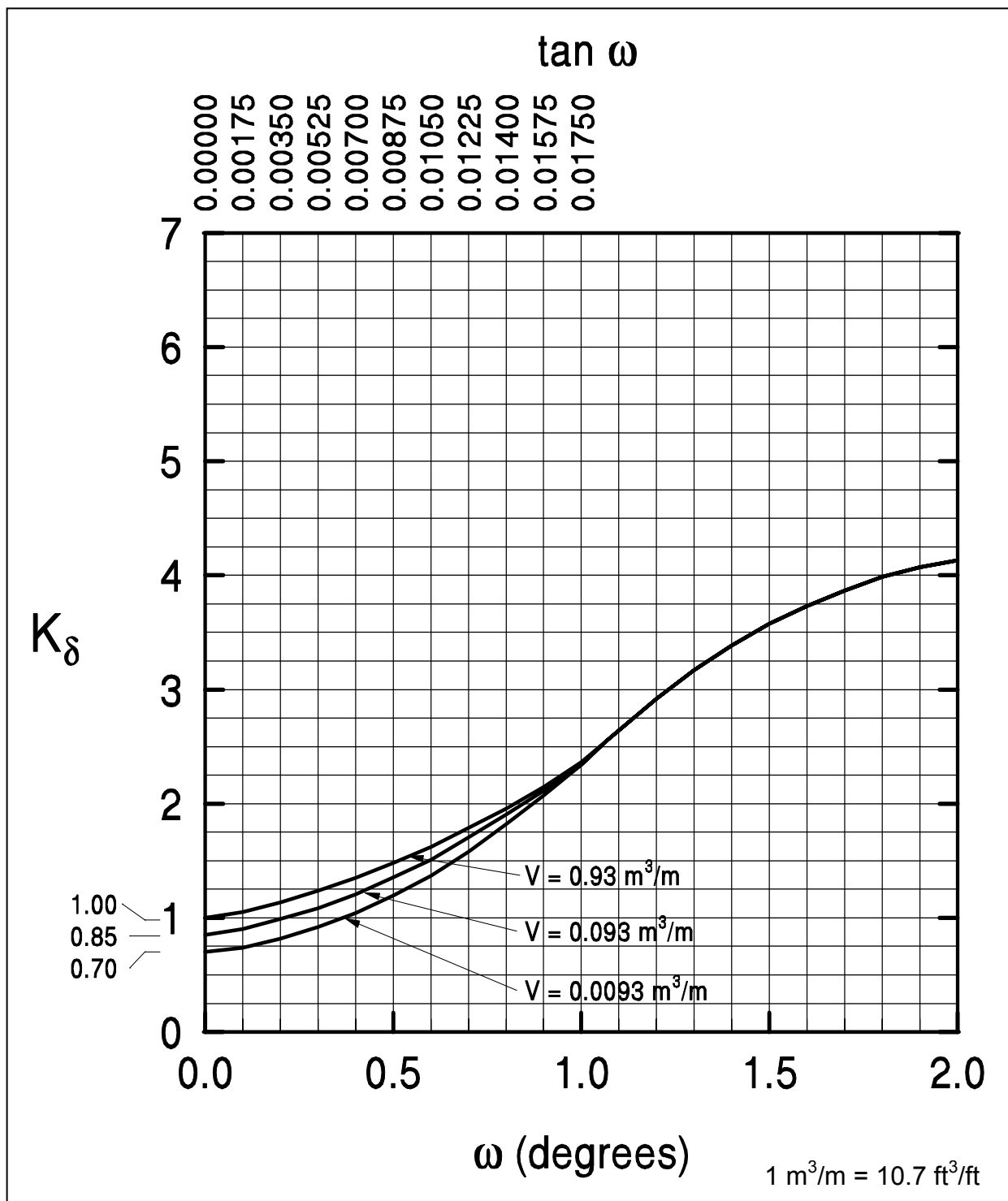


Figure 9.11 Design Curve for Evaluating K_δ for Piles when $\phi = 25^\circ$ (after Nordlund, 1979)

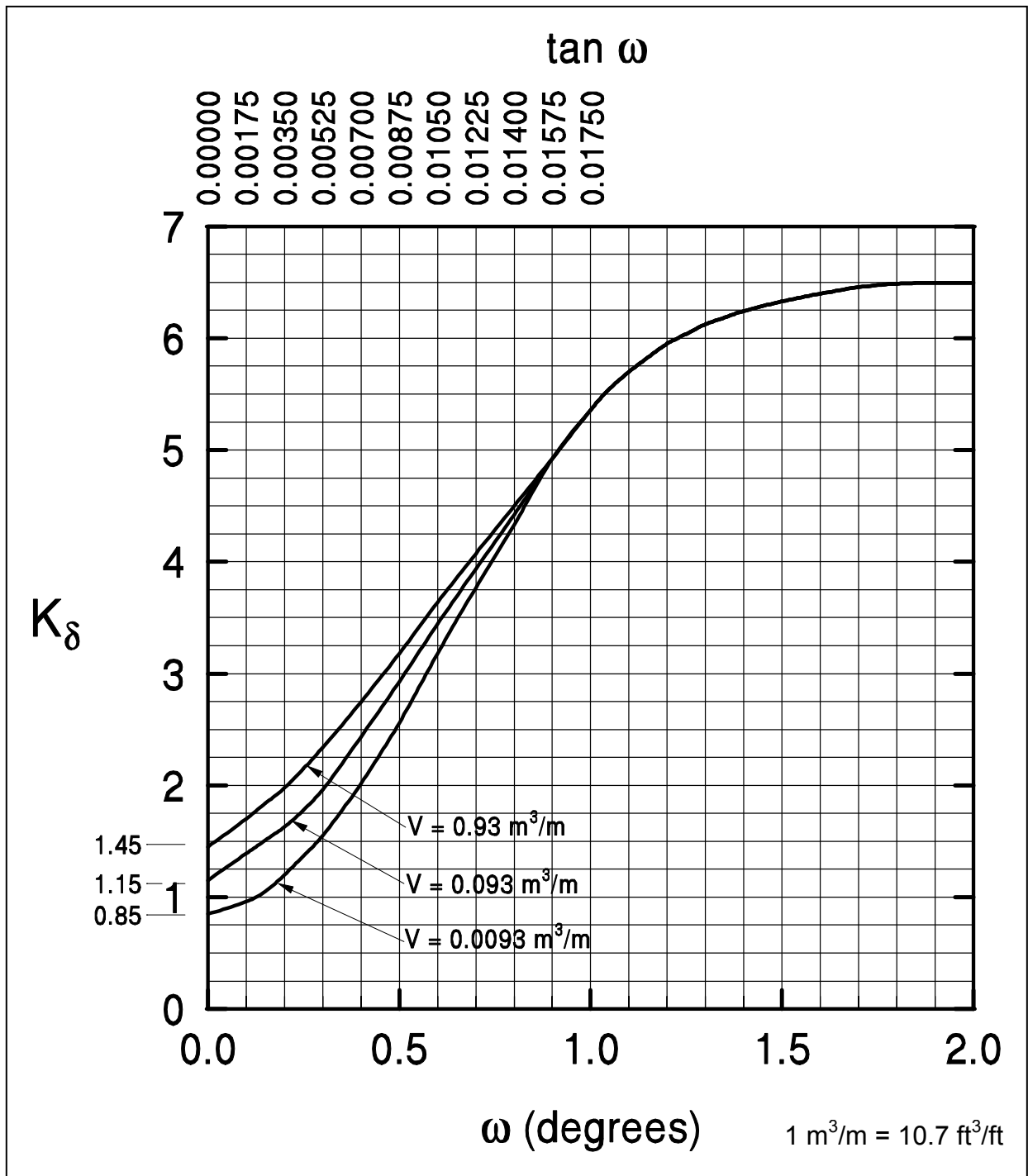


Figure 9.12 Design Curve for Evaluating K_δ for Piles when $\phi = 30^\circ$ (after Nordlund, 1979)

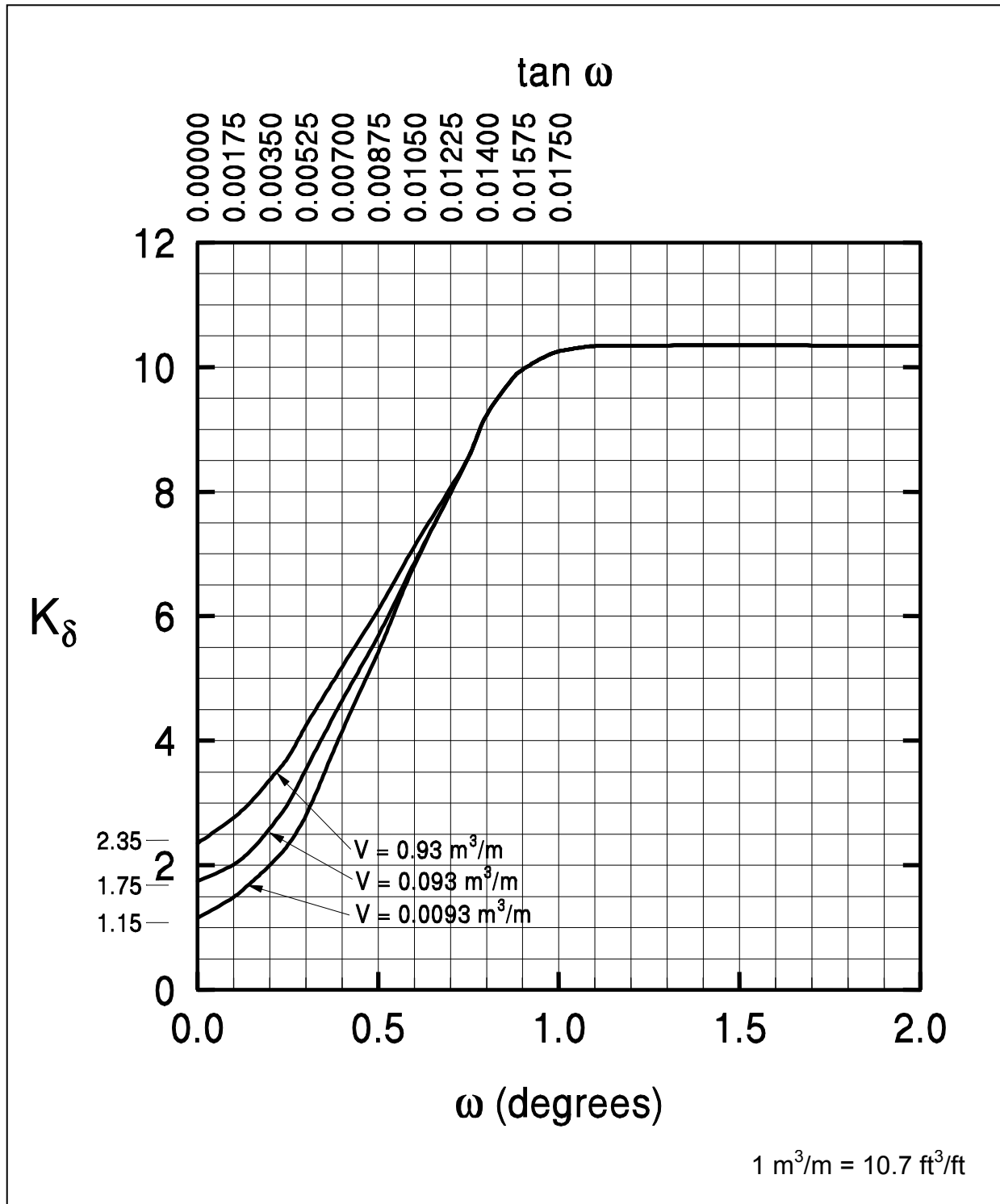


Figure 9.13 Design Curve for Evaluating K_δ for Piles when $\phi = 35^\circ$ (after Nordlund, 1979)

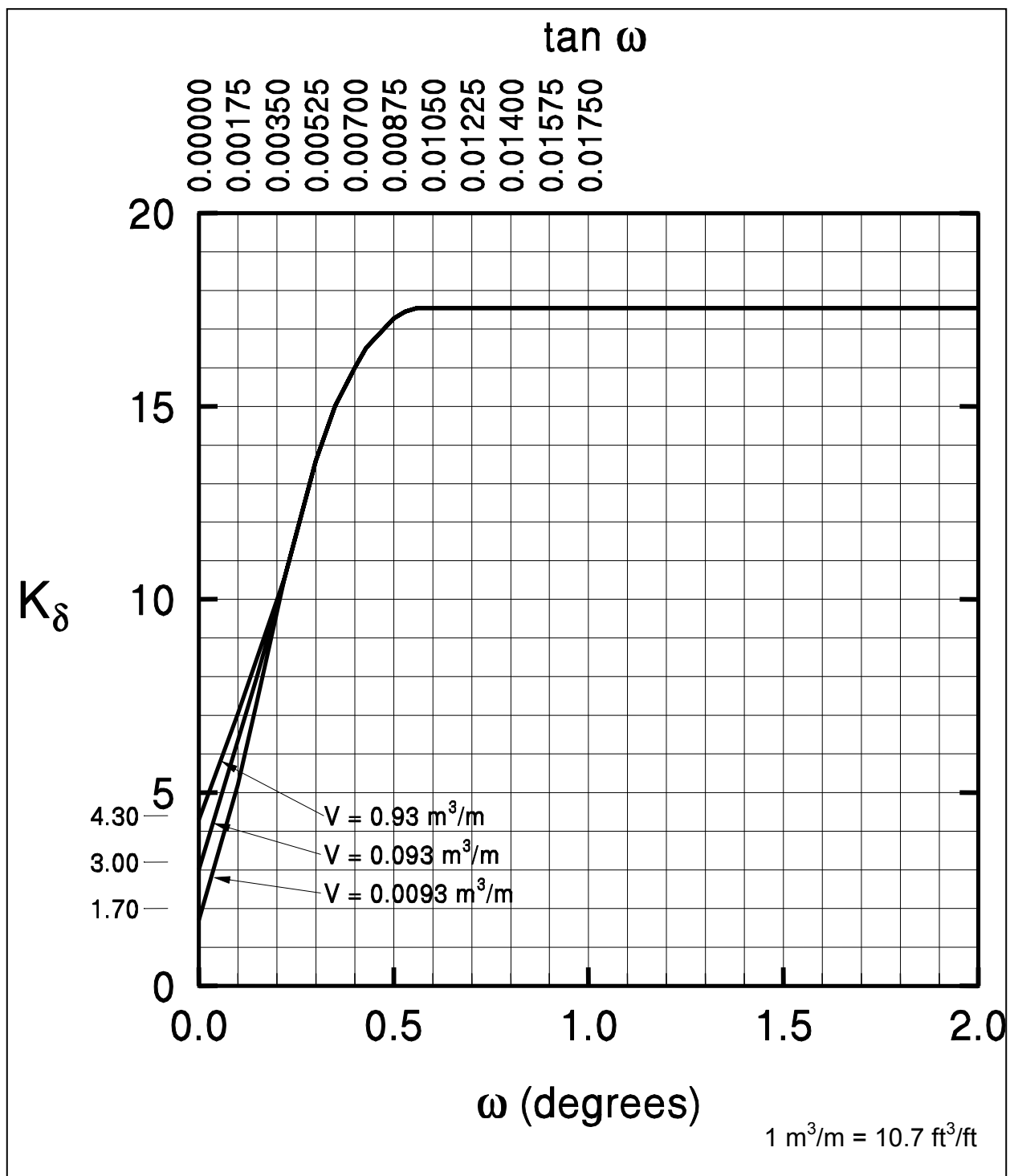


Figure 9.14 Design Curve for Evaluating K_δ for Piles when $\phi = 40^\circ$ (after Nordlund, 1979)

Table 9-4(a) Design Table for Evaluating K_δ for Piles when $\omega = 0^\circ$ and $V = 0.0093$ to $0.0930 \text{ m}^3/\text{m}$ (0.10 to $1.00 \text{ ft}^3/\text{ft}$)

| ϕ | Displaced Volume -V, m^3/m , (ft^3/ft) | | | | | | | | | |
|--------|--|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|------------------|
| | 0.0093 (0.10) | 0.0186 (0.20) | 0.0279 (0.30) | 0.0372 (0.40) | 0.0465 (0.50) | 0.0558 (0.60) | 0.0651 (0.70) | 0.0744 (0.80) | 0.0837 (0.90) | 0.0930 (1.00) |
| 25 | 0.70 | 0.75 | 0.77 | 0.79 | 0.80 | 0.82 | 0.83 | 0.84 | 0.84 | 0.85 |
| 26 | 0.73 | 0.78 | 0.82 | 0.84 | 0.86 | 0.87 | 0.88 | 0.89 | 0.90 | 0.91 |
| 27 | 0.76 | 0.82 | 0.86 | 0.89 | 0.91 | 0.92 | 0.94 | 0.95 | 0.96 | 0.97 |
| 28 | 0.79 | 0.86 | 0.90 | 0.93 | 0.96 | 0.98 | 0.99 | 1.01 | 1.02 | 1.03 |
| 29 | 0.82 | 0.90 | 0.95 | 0.98 | 1.01 | 1.03 | 1.05 | 1.06 | 1.08 | 1.09 |
| 30 | 0.85 | 0.94 | 0.99 | 1.03 | 1.06 | 1.08 | 1.10 | 1.12 | 1.14 | 1.15 |
| 31 | 0.91 | 1.02 | 1.08 | 1.13 | 1.16 | 1.19 | 1.21 | 1.24 | 1.25 | 1.27 |
| 32 | 0.97 | 1.10 | 1.17 | 1.22 | 1.26 | 1.30 | 1.32 | 1.35 | 1.37 | 1.39 |
| 33 | 1.03 | 1.17 | 1.26 | 1.32 | 1.37 | 1.40 | 1.44 | 1.46 | 1.49 | 1.51 |
| 34 | 1.09 | 1.25 | 1.35 | 1.42 | 1.47 | 1.51 | 1.55 | 1.58 | 1.61 | 1.63 |
| 35 | 1.15 | 1.33 | 1.44 | 1.51 | 1.57 | 1.62 | 1.66 | 1.69 | 1.72 | 1.75 |
| 36 | 1.26 | 1.48 | 1.61 | 1.71 | 1.78 | 1.84 | 1.89 | 1.93 | 1.97 | 2.00 |
| 37 | 1.37 | 1.63 | 1.79 | 1.90 | 1.99 | 2.05 | 2.11 | 2.16 | 2.21 | 2.25 |
| 38 | 1.48 | 1.79 | 1.97 | 2.09 | 2.19 | 2.27 | 2.34 | 2.40 | 2.45 | 2.50 |
| 39 | 1.59 | 1.94 | 2.14 | 2.29 | 2.40 | 2.49 | 2.57 | 2.64 | 2.70 | 2.75 |
| 40 | 1.70 | 2.09 | 2.32 | 2.48 | 2.61 | 2.71 | 2.80 | 2.87 | 2.94 | 3.0 |

Table 9-4(b) Design Table for Evaluating K_δ for Piles when $\omega = 0^\circ$ and $V = 0.093$ to $0.930 \text{ m}^3/\text{m}$ (1.0 to $10.0 \text{ ft}^3/\text{ft}$)

| ϕ | Displaced Volume -V, m^3/m (ft^3/ft) | | | | | | | | | |
|--------|--|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|-----------------|
| | 0.093 (1.0) | 0.186 (2.0) | 0.279 (3.0) | 0.372 (4.0) | 0.465 (5.0) | 0.558 (6.0) | 0.651 (7.0) | 0.744 (8.0) | 0.837 (9.0) | 0.930 (10.0) |
| 25 | 0.85 | 0.90 | 0.92 | 0.94 | 0.95 | 0.97 | 0.98 | 0.99 | 0.99 | 1.00 |
| 26 | 0.91 | 0.96 | 1.00 | 1.02 | 1.04 | 1.05 | 1.06 | 1.07 | 1.08 | 1.09 |
| 27 | 0.97 | 1.03 | 1.07 | 1.10 | 1.12 | 1.13 | 1.15 | 1.16 | 1.17 | 1.18 |
| 28 | 1.03 | 1.10 | 1.14 | 1.17 | 1.20 | 1.22 | 1.23 | 1.25 | 1.26 | 1.27 |
| 29 | 1.09 | 1.17 | 1.22 | 1.25 | 1.28 | 1.30 | 1.32 | 1.33 | 1.35 | 1.36 |
| 30 | 1.15 | 1.24 | 1.29 | 1.33 | 1.36 | 1.38 | 1.40 | 1.42 | 1.44 | 1.45 |
| 31 | 1.27 | 1.38 | 1.44 | 1.49 | 1.52 | 1.55 | 1.57 | 1.60 | 1.61 | 1.63 |
| 32 | 1.39 | 1.52 | 1.59 | 1.64 | 1.68 | 1.72 | 1.74 | 1.77 | 1.79 | 1.81 |
| 33 | 1.51 | 1.65 | 1.74 | 1.80 | 1.85 | 1.88 | 1.92 | 1.94 | 1.97 | 1.99 |
| 34 | 1.63 | 1.79 | 1.89 | 1.96 | 2.01 | 2.05 | 2.09 | 2.12 | 2.15 | 2.17 |
| 35 | 1.75 | 1.93 | 2.04 | 2.11 | 2.17 | 2.22 | 2.26 | 2.29 | 2.32 | 2.35 |
| 36 | 2.00 | 2.22 | 2.35 | 2.45 | 2.52 | 2.58 | 2.63 | 2.67 | 2.71 | 2.74 |
| 37 | 2.25 | 2.51 | 2.67 | 2.78 | 2.87 | 2.93 | 2.99 | 3.04 | 3.09 | 3.13 |
| 38 | 2.50 | 2.81 | 2.99 | 3.11 | 3.21 | 3.29 | 3.36 | 3.42 | 3.47 | 3.52 |
| 39 | 2.75 | 3.10 | 3.30 | 3.45 | 3.56 | 3.65 | 3.73 | 3.80 | 3.86 | 3.91 |
| 40 | 3.00 | 3.39 | 3.62 | 3.78 | 3.91 | 4.01 | 4.10 | 4.17 | 4.24 | 4.30 |

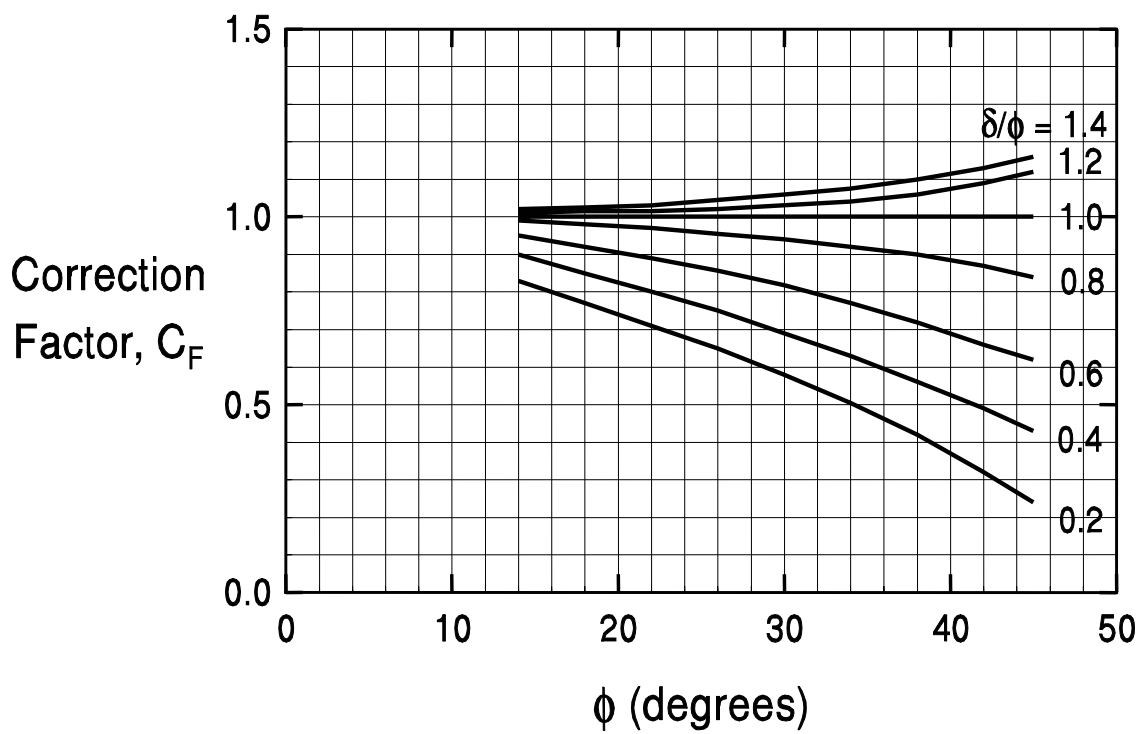


Figure 9.15 Correction Factor for K_δ when $\delta \neq \phi$ (after Nordlund, 1979)

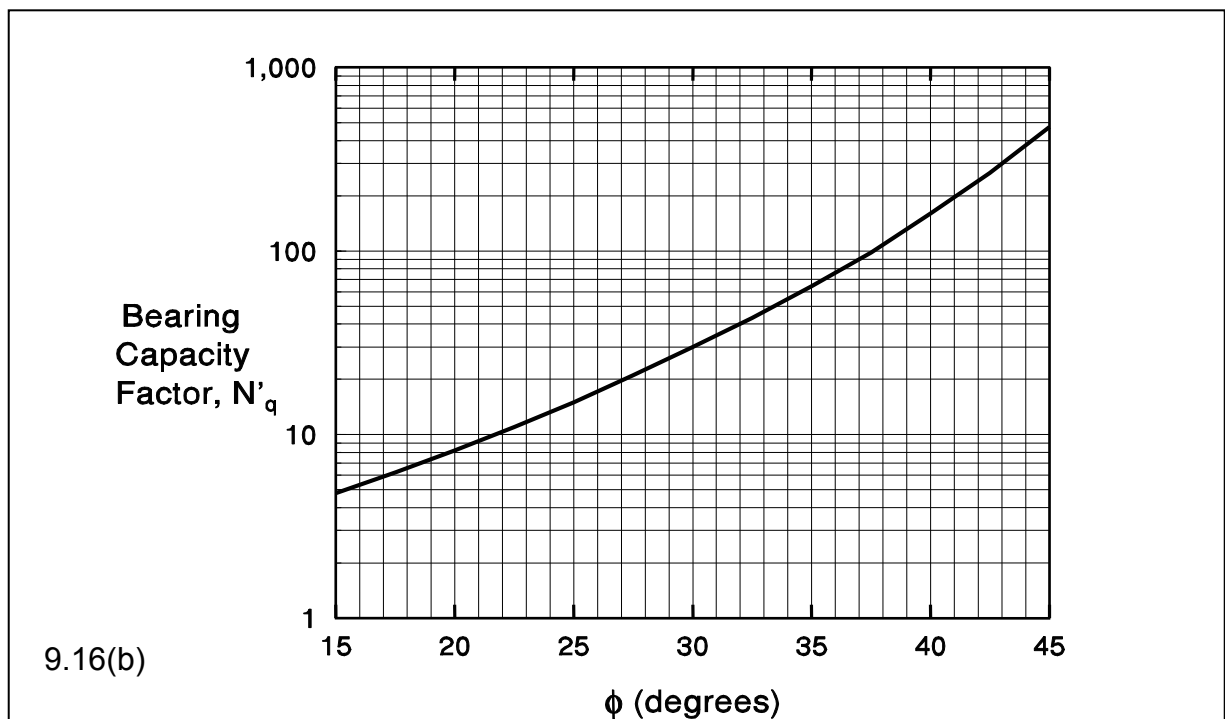
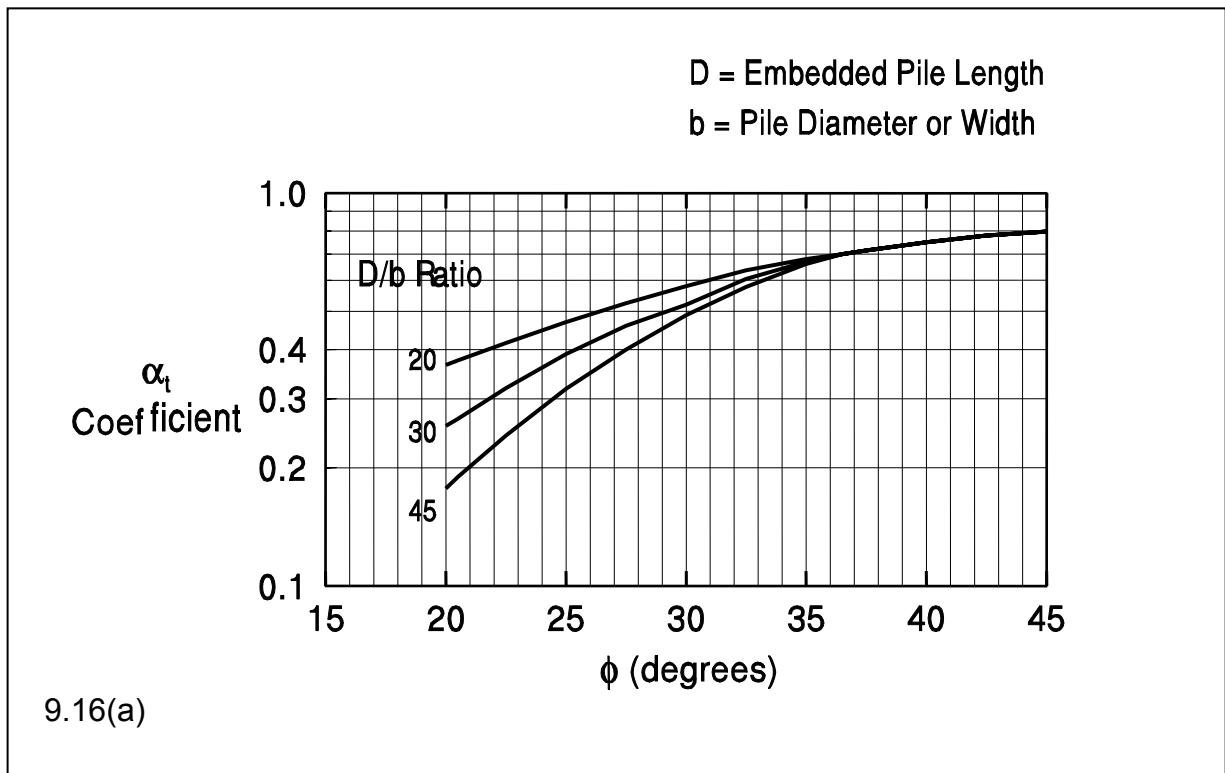


Figure 9.16 Chart for Estimating α_t Coefficient and Bearing Capacity Factor N'_q (Chart modified from Bowles, 1977)

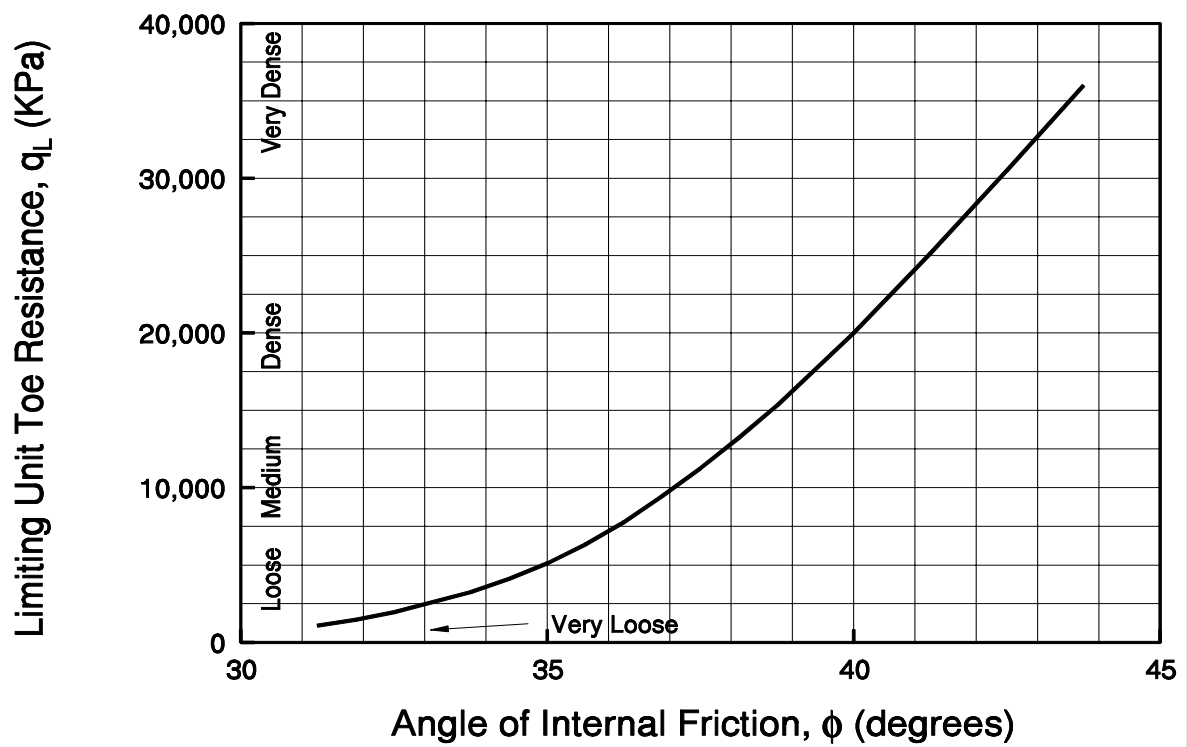
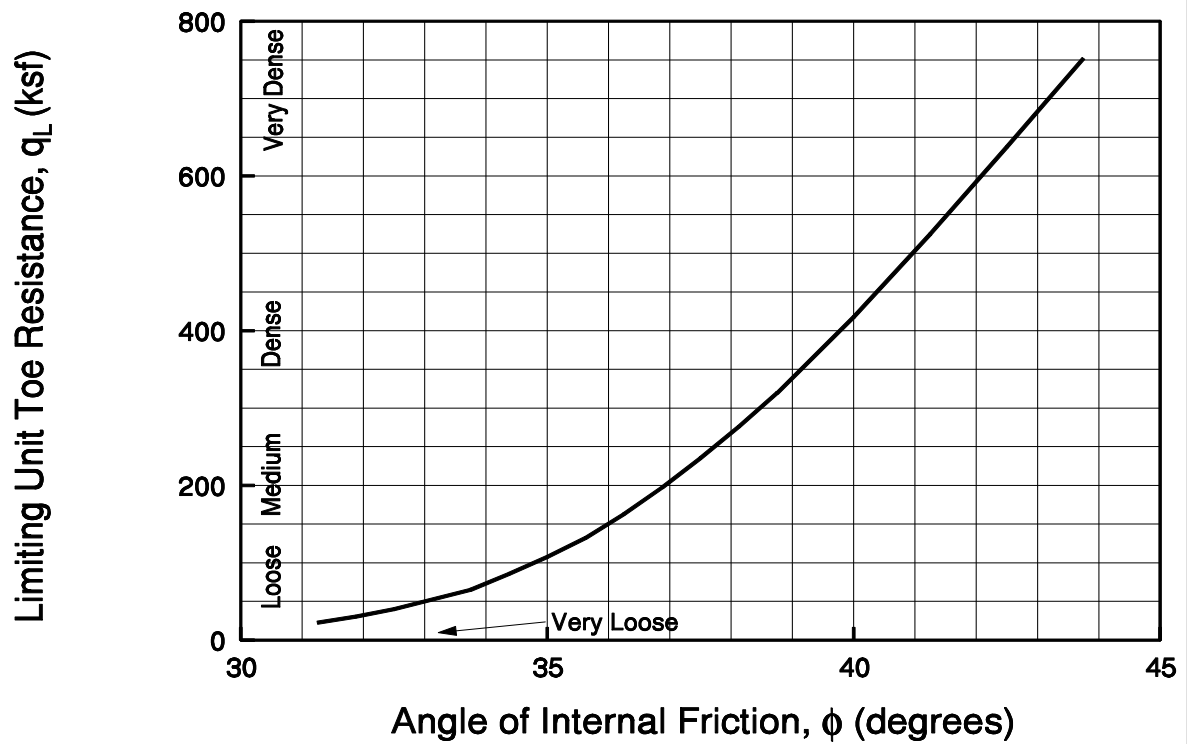


Figure 9.17 Relationship Between Maximum Unit Pile Toe Resistance and Friction Angle for Cohesionless soils (after Meyerhof, 1976)

9.7.1.2 Ultimate Capacity of Piles in Cohesive Soils

The ultimate capacity of a pile in cohesive soil may also be expressed as the sum of the shaft and toe resistances or $Q_u = R_s + R_t$. The shaft and toe resistances can be calculated from static analysis methods using soil boring and laboratory test data in either total stress or effective stress methods. The α -Method is a total stress method that uses undrained soil shear strength parameters for calculating static pile capacity in cohesive soil. The α -Method will be presented in Section 9.7.1.2a. The effective stress method uses drained soil strength parameters for capacity calculations. Since the effective stress method may be used for calculating static pile capacity in cohesive as well as cohesionless soils, this method will be presented in Section 9.7.1.3. Alternatively, in-situ CPT test results can also be used to calculate pile capacity in cohesive soils from cone sleeve friction and cone tip resistance values. CPT based methods are discussed in Section 9.7.1.7. An overview of design methods for cohesive soils is presented in Table 9-5.

The shaft resistance of piles driven into cohesive soils is frequently as much as 80 to 90% of the total capacity. Therefore, it is important that the shaft resistance of piles in cohesive soils be estimated as accurately as possible.

9.7.1.2a Total Stress - α -Method

For piles in clay, a total stress analysis is often used where ultimate capacity is calculated from the undrained shear strength of the soil. This approach assumes that the shaft resistance is independent of the effective overburden pressure and that the unit shaft resistance can be expressed in terms of an empirical adhesion factor times the undrained shear strength.

The unit shaft resistance, f_s , is equal to the adhesion, c_a , which is the shear stress between the pile and soil at failure. This may be expressed in equation form as:

$$f_s = c_a = \alpha c_u$$

in which α is an empirical adhesion factor for reduction of the average undrained shear strength, c_u , of undisturbed clay along the embedded length of the pile. The coefficient α depends on the nature and strength of the clay, pile dimension, method of pile installation, and time effects. The values of α vary within wide limits and decrease rapidly with increasing shear strength.

| TABLE 9-5 METHODS OF STATIC ANALYSIS FOR PILES IN COHESIVE SOILS | | | | | |
|--|---|--|--|---|--|
| Method | Approach | Method of Obtaining Design Parameters | Advantages | Disadvantages | Remarks |
| α -Method (Tomlinson Method). | Empirical, total stress analysis. | Undrained shear strength estimate of soil is needed. Adhesion calculated from Figures 9.18 and 9.19. | Simple calculation from laboratory undrained shear strength values to adhesion. | Wide scatter in adhesion versus undrained shear strengths in literature. | Widely used method described in Section 9.7.1.2a. |
| Effective Stress Method. | Semi-Empirical, based on effective stress at failure. | β and N_t values are selected from Table 9-6 based on drained soil strength estimates. | Ranges in β and N_t values for most cohesive soils are relatively small. | Range in N_t values for hard cohesive soils such as glacial tills can be large. | Good design approach theoretically better than undrained analysis. Details in Section 9.7.1.3. |
| Methods based on Cone Penetration Test data. | Empirical. | Results of CPT tests. | Testing analogy between CPT and pile. Reproducible test data. | Cone can be difficult to advance in very hard cohesive soils such as glacial tills. | Good approach for design. Details in Section 9.7.1.7. |

It is recommended that Figure 9.18 generally be used for adhesion calculations, unless one of the special soil stratigraphy cases identified in Figure 9.19 is present at a site. In cases where either Figures 9.18 or 9.19 could be used, the inexperienced user should select and use the smaller value obtained from either figure. All users should confirm the applicability of a selected design chart in a given soil condition with local correlations between static capacity calculations and static load tests results.

In Figure 9.18, the adhesion, c_a , is expressed as a function of the undrained shear strength, c_u , with consideration of both the pile type and the embedded pile length, D , to pile diameter, b , ratio. The embedded pile length used in Figure 9.18 should be the minimum value of the length from the ground surface to the bottom of the clay layer, or the length from the ground surface to the pile toe.

Figures 9.19a and 9.19b present the adhesion factor, α , versus the undrained shear strength of the soil in kPa and ksf, respectively, as a function of unique soil stratigraphy and pile embedment. The adhesion factor from these soil stratigraphy cases should be used only for determining the adhesion in a stiff clay layer in that specific condition. For a soil profile consisting of clay layers of significantly different consistencies such as soft clays over stiff clays, adhesion factors should be determined for each individual clay layer.

The top graph in Figures 9.19a and 9.19b may be used to select the adhesion factor when piles are driven through a sand or sandy gravel layer and into an underlying stiff clay stratum. This case results in the highest adhesion factors as granular material is dragged into the underlying clays. The greater the pile penetration into the clay stratum, the less influence the overlying granular stratum has on the adhesion factor. Therefore, for the same undrained shear strength, the adhesion factor decreases with increased pile penetration into the clay stratum.

The middle graph in Figures 9.19a and 9.19b should be used to select the adhesion factor when piles are driven through a soft clay layer overlying a stiff clay layer. In this case, the soft clay is dragged into the underlying stiff clay stratum thereby reducing the adhesion factor of the underlying stiff clay soils. The greater the pile penetration into the underlying stiff clay soils, the less the influence the overlying soft clays have on the stiff clay adhesion factor. Therefore, the stiff clay adhesion factor increases with increasing pile penetration into the stiff clay soils.

Last, the bottom graph in Figures 9.19a and 9.19b may be used to select the adhesion factor for piles driven in stiff clays without any different overlying strata. In stiff clays, a gap often forms between the pile and the soil along the upper portion of the pile shaft. In this case, the shallower the pile penetration into a stiff clay stratum the greater the effect the gap has on the shaft resistance that develops. Hence, the adhesion factor for a given shear strength is reduced at shallow pile penetration depths and increased at deeper pile penetration depths.

In highly overconsolidated clays, undrained shear strengths may exceed the upper limits of Figures 9.18 and 9.19. In these cases, it is recommended that adhesion factor, α , be calculated according to API Recommended Practice 2A (1993). API recommends the adhesion factor be computed using the following equations based on Ψ , the ratio of the undrained shear strength of the soil, c_u , divided by the effective overburden pressure, p_o' .

$$\alpha = 0.5 \Psi^{-0.5} \quad \text{for } \Psi \leq 1.0$$

$$\alpha = 0.5 \Psi^{-0.25} \quad \text{for } \Psi > 1.0$$

API stipulates that α be ≤ 1.0 . In addition, API recommends the above equations be applied with care in soils with high c_u / p_o' ratios as limited load test data is available for soils with c_u / p_o' ratios greater than 3.

In the case of H piles in cohesive soils, the shaft resistance should not be calculated from the surface area of the pile, but rather from the "box" area of the four sides. The shaft resistance for H-piles in cohesive soils consists of the sum of the adhesion, c_a , times the flange surface area along the exterior of the two flanges, plus the undrained shear strength of the soil, c_u , times the area of the two remaining sides of the "box", due to soil-to-soil shear along these faces. This computation can be approximated by determining the adhesion using the appropriate corrugated pile curve in Figure 9.18 and multiplying the adhesion by the H-pile "box" area. Additional information on the behavior of open pile sections is presented in Section 9.10.5.

In clays with large shrink-swell potential, static capacity calculations should ignore the shaft resistance from the adhesion in the shrink-swell zone. During dry times, shrinkage will create a gap between the clay and the pile in this zone and therefore the shaft resistance should not be relied upon for long term support.

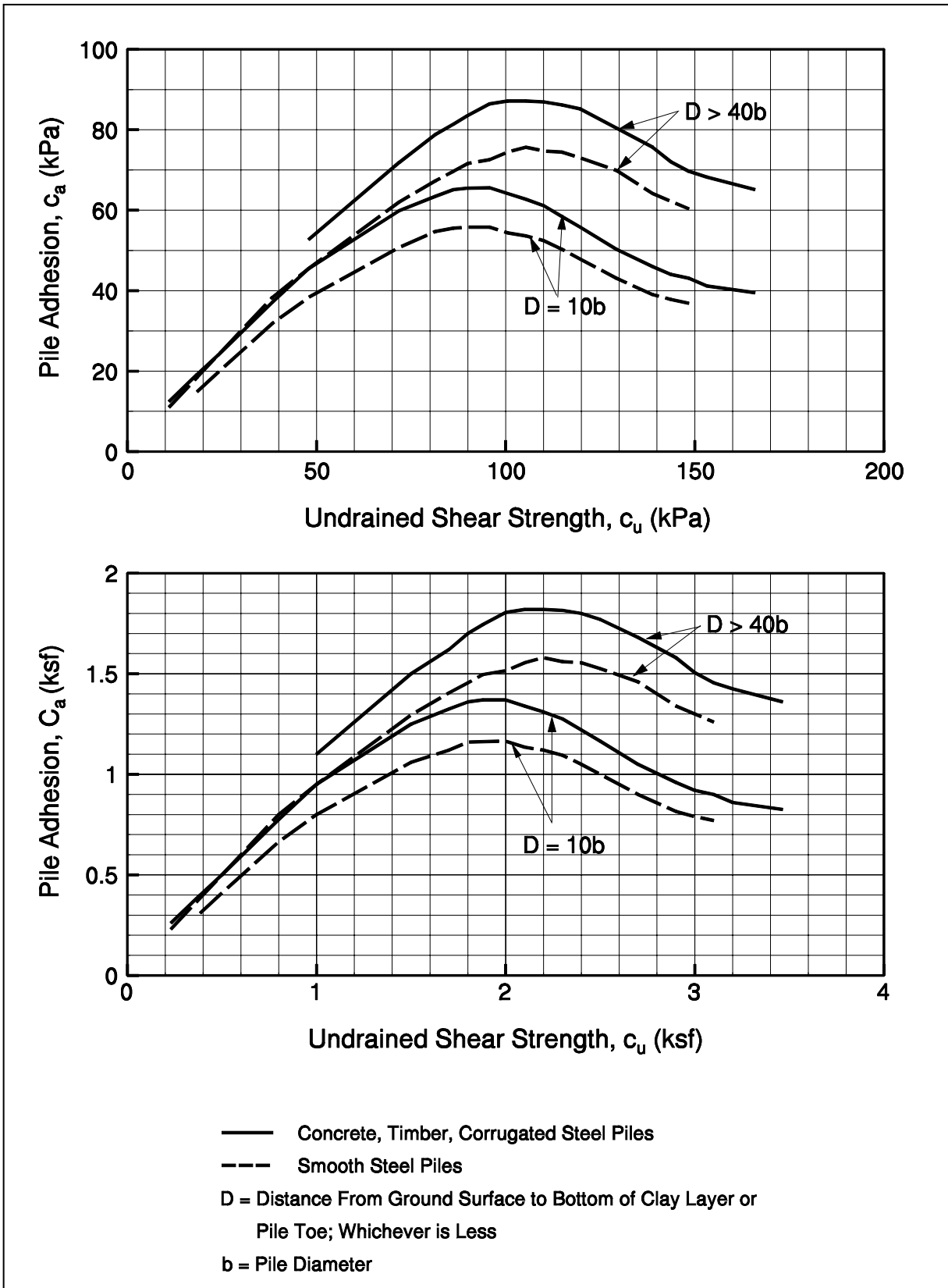


Figure 9.18 Adhesion Values for Piles in Cohesive Soils (after Tomlinson, 1979)

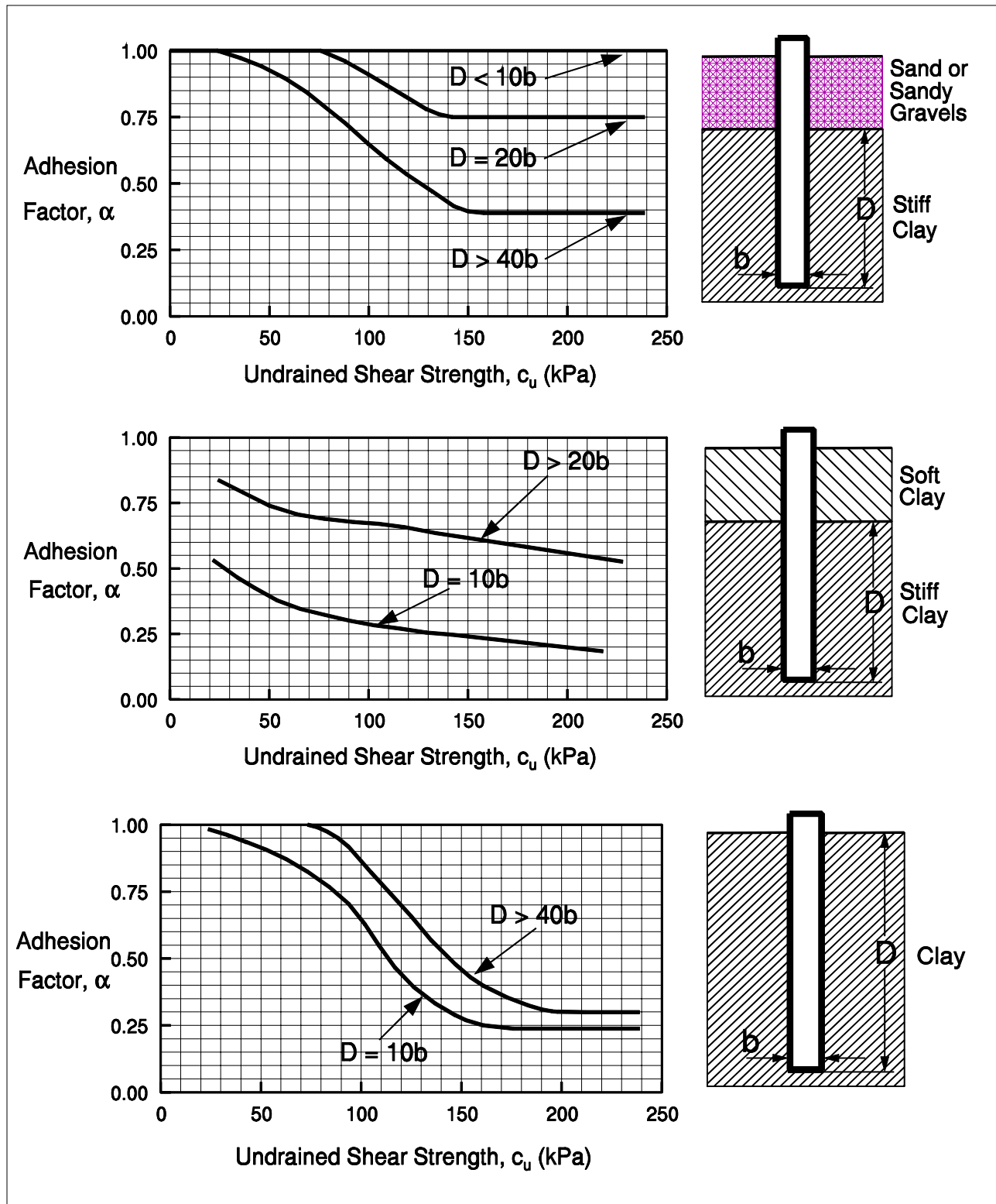


Figure 9.19(a) Adhesion Factors for Driven Piles in Clay –SI Units (Tomlinson, 1980)

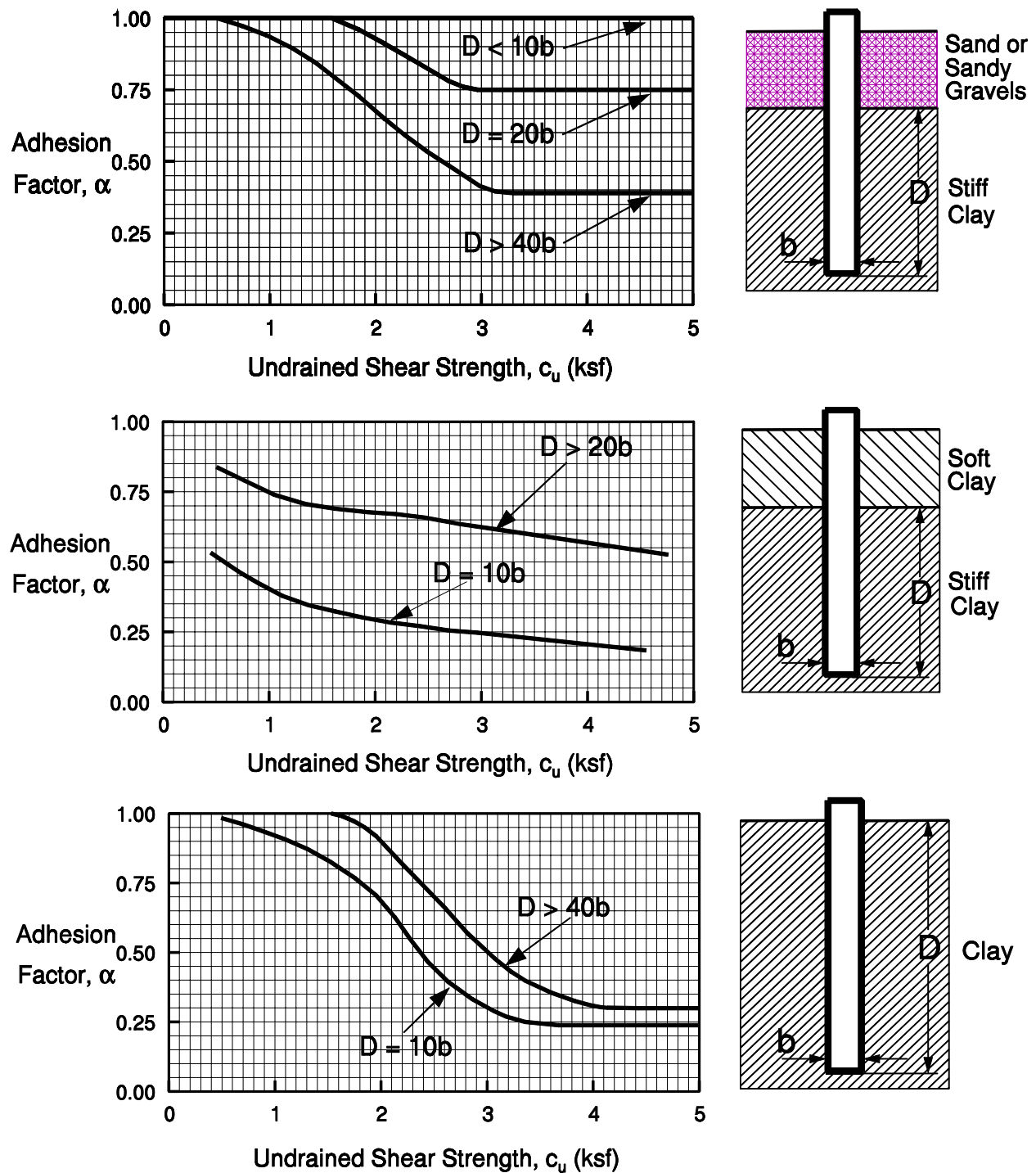


Figure 9.19(b) Adhesion Factors for Driven Piles in Clay - US Units (Tomlinson, 1980)

The unit toe resistance in a total stress analysis for homogeneous cohesive soil can be expressed as:

$$q_t = c_u N_c$$

The term N_c is a dimensionless bearing capacity factor which depends on the pile diameter and the depth of embedment. The bearing capacity factor, N_c , is usually taken as 9 for deep foundations.

It should be remembered that the movement required to mobilize the toe resistance is several times greater than that required to mobilize the shaft resistance. At the movement required to fully mobilize the toe resistance, the shaft resistance may have decreased to a residual value. Therefore, the toe resistance contribution to the ultimate pile capacity in cohesive soils is sometimes ignored except in hard cohesive deposits such as glacial tills.

STEP BY STEP PROCEDURE FOR - "α-METHOD"

- STEP 1 Delineate the soil profile into layers and determine the adhesion, c_a , from Figure 9.18 or adhesion factor, α , from Figure 9.19a or 9.19b for each layer.

Enter appropriate figure with the undrained shear strength of the soil, c_u , and determine adhesion or adhesion factor based on the embedded pile length in clay, D , and pile diameter ratio, b . Use the curve for the appropriate soil and embedment condition.

- STEP 2 For each soil layer, compute the unit shaft resistance, f_s in kPa (ksf).

$$f_s = c_a = \alpha c_u$$

Where: c_a = Adhesion.

- STEP 3 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s , in kN (kips), from the sum of the shaft resistance from each layer.

$$R_s = f_s A_s$$

Where: A_s = Pile-soil surface area in m^2 (ft^2) from (pile perimeter) (length).
A discussion on the behavior of open pile sections in cohesive soils is presented in Section 9.10.5.

STEP 4 Compute the unit toe resistance, q_t in kPa (ksf).

$$q_t = 9 c_u$$

Where: c_u = Undrained shear strength of soil at the pile toe.
in kPa (ksf)

STEP 5 Compute the ultimate toe resistance, R_t in kN (kips).

$$R_t = q_t A_t$$

Where: A_t = Area of pile toe in m^2 (ft^2).

For open pile sections, refer to the discussion of pile plugging presented in Section 9.10.5.

STEP 6 Compute the ultimate pile capacity, Q_u in kN (kips).

$$Q_u = R_s + R_t$$

STEP 7 Compute the allowable design load, Q_a in kN (kips).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}}$$

The factor of safety in this static calculation should be based on the specified construction control method as described in Section 9.6 of this chapter.

9.7.1.3 Effective Stress Method

Static capacity calculations in cohesionless, cohesive, and layered soils can also be performed using an effective stress based method. Effective stress based methods were developed to model the long term drained shear strength conditions. Therefore, the effective soil friction angle, ϕ' , should be used in parameter selection.

In an effective stress analysis, the unit shaft resistance is calculated from the following expression:

$$f_s = \beta \bar{p}_o$$

Where: β = Bjerrum-Burland beta coefficient = $K_s \tan \delta$.
 \bar{p}_o = Average effective overburden pressure along the pile shaft, in kPa (ksf).
 K_s = Earth pressure coefficient.
 δ = Friction angle between pile and soil.

The unit toe resistance is calculated from:

$$q_t = N_t p_t$$

Where: N_t = Toe bearing capacity coefficient.
 p_t = Effective overburden pressure at the pile toe in kPa (ksf).

Recommended ranges of β and N_t coefficients as a function of soil type and ϕ' angle from Fellenius (1991) are presented in Table 9-6. Fellenius notes that factors affecting the β and N_t coefficients consist of the soil composition including the grain size distribution, angularity and mineralogical origin of the soil grains, the original soil density and density due to the pile installation technique, the soil strength, as well as other factors. Even so, β coefficients are generally within the ranges provided and seldom exceed 1.0.

For sedimentary cohesionless deposits, Fellenius states N_t ranges from about 30 to a high of 120. In very dense non-sedimentary deposits such as glacial tills, N_t can be much higher, but can also approach the lower bound value of 30. In clays, Fellenius notes that the toe resistance calculated using an N_t of 3 is similar to the toe resistance calculated from a traditional analysis using undrained shear strength. Therefore, the use of a relatively low N_t coefficient in clays is recommended unless local correlations suggest higher values are appropriate.

Graphs of the ranges in β and N_t coefficients versus the range in ϕ' angle as suggested by Fellenius are presented in Figure 9.20 and 9.21, respectively. These graphs may be helpful in selection of β or N_t . The inexperienced user should select conservative β and N_t coefficients. As with any design method, the user should also confirm the appropriateness of a selected β or N_t coefficient in a given soil condition with local correlations between static capacity calculations and static load tests results.

It should be noted that the effective stress method places no limiting values on either the shaft or toe resistance.

STEP BY STEP PROCEDURE FOR THE EFFECTIVE STRESS METHOD

STEP 1 Delineate the soil profile into layers and determine ϕ' angle for each layer.

- a. Construct p_o diagram using previously described procedure in Section 9.4.
- b. Divide soil profile throughout the pile penetration depth into layers and determine the effective overburden pressure, p_o , in kPa (ksf) at the midpoint of each layer.
- c. Determine the ϕ' angle for each soil layer from laboratory or in-situ test data.
- d. In the absence of laboratory or in-situ data for cohesionless layers, determine the average corrected SPT N' value for each layer and estimate ϕ' angle from Table 4-6 in Chapter 4.

STEP 2 Select the β coefficient for each soil layer.

- a. Use local experience to select β coefficient for each layer.
- b. In the absence of local experience, use Table 9-6 or Figure 9.20 to estimate β coefficient from ϕ' angle for each layer.

STEP 3 For each soil layer compute the unit shaft resistance, f_s in kPa (ksf).

$$f_s = \beta p_o$$

| TABLE 9-6 APPROXIMATE RANGE OF β AND N_t COEFFICIENTS (Fellenius, 1991) | | | |
|--|---------|-------------|----------|
| Soil Type | ϕ' | B | N_t |
| Clay | 25 - 30 | 0.23 - 0.40 | 3 - 30 |
| Silt | 28 - 34 | 0.27 - 0.50 | 20 - 40 |
| Sand | 32 - 40 | 0.30 - 0.60 | 30 - 150 |
| Gravel | 35 - 45 | 0.35 - 0.80 | 60 - 300 |

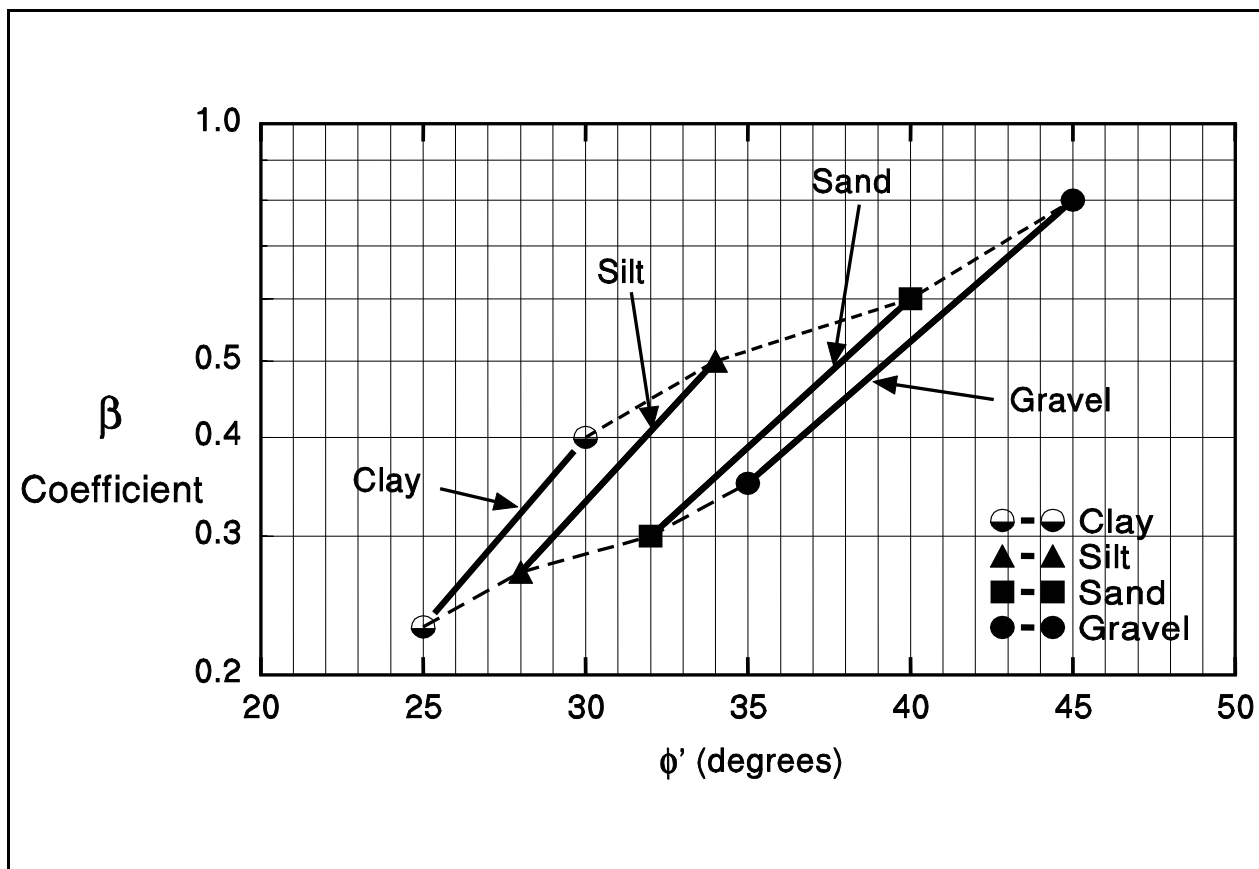


Figure 9.20 Chart for Estimating β Coefficient versus Soil Type ϕ' (after Fellenius, 1991)

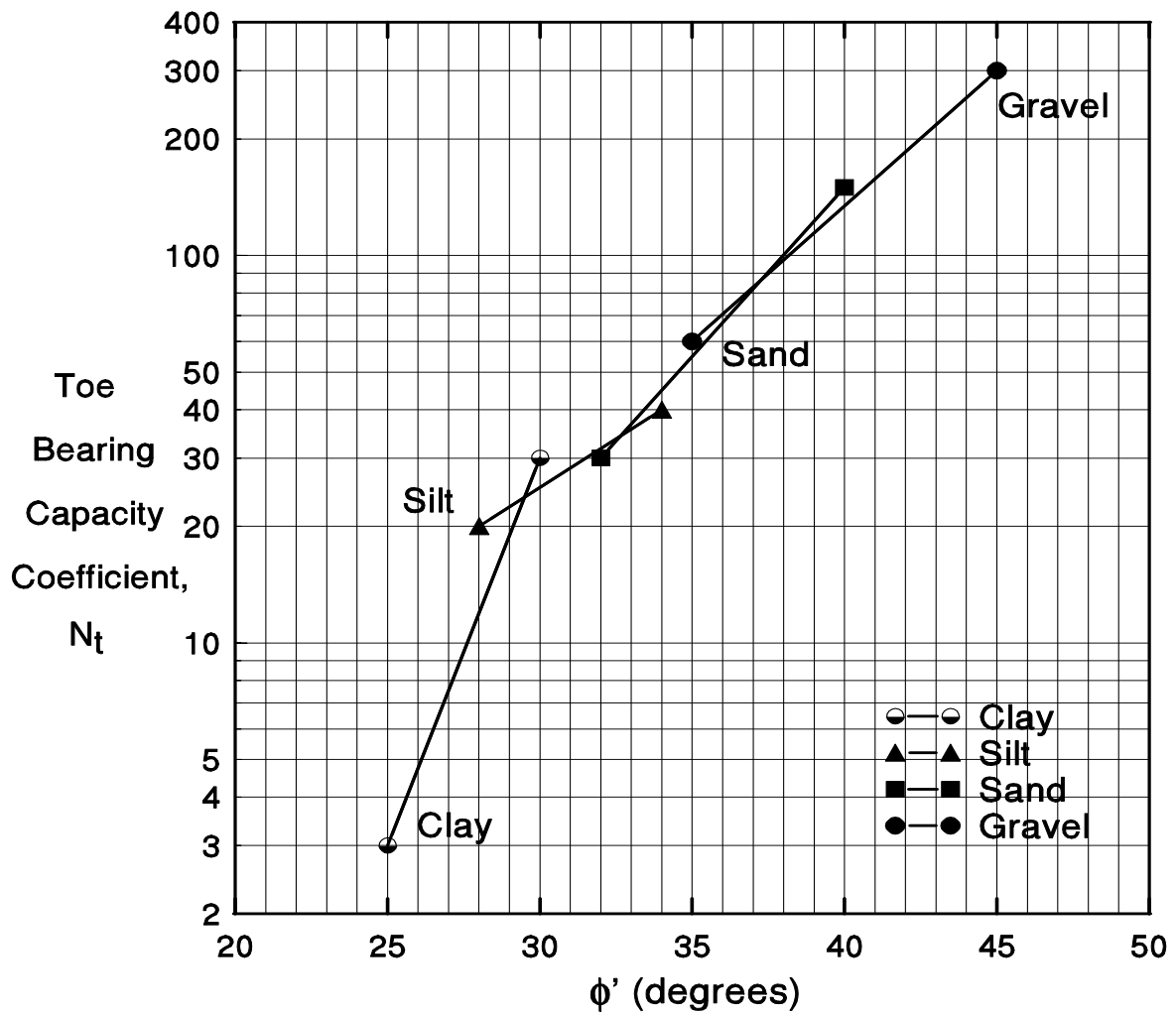


Figure 9.21 Chart for estimating N_t Coefficients versus Soil Type ϕ' Angle (after Fellenius, 1991)

STEP 4 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s in kN (kips) from the sum of the shaft resistance from each soil layer.

$$R_s = f_s A_s$$

Where: A_s = Pile-soil surface area in m^2 (ft^2) from (pile perimeter) (length).

Refer to Section 9.10.5 for additional information on the behavior of open pile sections.

STEP 5 Compute the unit toe resistance, q_t in kPa (ksf).

$$q_t = N_t p_t$$

- Use local experience to select N_t coefficient.
- In the absence of local experience, estimate N_t from Table 9-6 or Figure 9.21 based on ϕ' angle.
- Calculate the effective overburden pressure at the pile toe, p_t in kPa (ksf).

STEP 6 Compute the ultimate toe resistance, R_t in kN (kips).

$$R_t = q_t A_t$$

Where: A_t = Area of the pile toe in m^2 (ft^2).

For open pile sections, refer to the additional information on pile plugging presented in Section 9.10.5.

STEP 7 Compute the ultimate pile capacity, Q_u in kN (kips).

$$Q_u = R_s + R_t$$

STEP 8 Compute the allowable design load, Q_a in kN (kips).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}}$$

The factor of safety in this static calculation should be based on the specified construction control method as described in Section 9.6 of this chapter.

9.7.1.4 Ultimate Capacity of Piles in Layered Soils

The ultimate capacity of piles in layered soils can be calculated by combining the methods previously described for cohesionless and cohesive soils. For example, a hand calculation combining the Nordlund method from Section 9.7.1.1b for cohesionless soil layers with the α -method from Section 9.7.1.2a for cohesive soil layers could be used. The effective stress method as described in Section 9.7.1.3 could also be used for layered soil profiles. Last, the CPT based methods presented in Section 9.7.1.7 could be used in a layered soil profile.

9.7.1.5 The DRIVEN Computer Program

The FHWA developed the computer program DRIVEN in 1998 for calculation of static pile capacity. The DRIVEN program can be used to calculate the capacity of open and closed end pipe piles, H-piles, circular or square solid concrete piles, timber piles, and Monotube piles. The program results can be displayed in both tabular and graphical form. Analyses may be performed in either SI or English units and can be switched between units during analyses. The DRIVEN Program User's Manual by Mathias and Cribbs (1998) is provided in FHWA-SA-98-074. The DRIVEN manual and software Version 1.2, released in March 2001, can be downloaded from: www.fhwa.dot.gov/bridge/geosoft.htm.

In the DRIVEN program, the user inputs the soil profile consisting of the soil unit weights and strength parameters including the percentage strength loss during driving. For the selected pile type, the program calculates the pile capacity versus depth for the entire soil profile using the Nordlund and α -methods in cohesionless and cohesive layers, respectively. Using the user input soil strength losses, the program calculates the ultimate pile capacity at the time of driving as well as during restrike.

The DRIVEN program includes several analysis options that facilitate pile design. These options include:

- Soft compressible soils: The shaft resistance from unsuitable soil layers defined by the user is subtracted from the ultimate pile capacity calculation.

| | |
|------------------|---|
| Scourable soils: | Based on a user input depth, the calculated shaft resistance from scourable soils due to local scour is subtracted from the ultimate pile capacity calculation. In the case of channel degradation scour, the reduction in pile capacity from the loss of shaft resistance in the scour zone as well as the influence of the reduced effective overburden pressure from soil removal on the capacity calculated in the underlying layers is considered. |
| Pile Plugging: | DRIVEN handles pile plugging based on the recommendations presented in Section 9.10.5 of this manual. |

The initial DRIVEN program screen is the project description screen illustrated in Figure 9.22. In this screen the user inputs the project information as well as identifies the number of soil layers. Inputs for three water table elevations are provided. The water table at the time of drilling is used for correction of SPT N values for overburden pressure if that option is selected by the user. The water table at the time of restrike / driving affects the effective overburden pressure in the static capacity calculations at those times. The static calculation at the time of driving includes soil strength losses and the restrike static calculations would include the long term soil strength. The water table at the ultimate condition is used in the effective overburden pressure for the static capacity calculation under an extreme event.

The soil profile screen for a two layer soil profile is shown in Figure 9.23 for a cohesive soil. A mouse click on the select graph option will result in the cohesive soil layer properties screen shown in Figure 9.24 to appear. The user can then select how the adhesion is calculated. The general adhesion option uses the Tomlinson data presented in Figure 9.18. The three underlying options correspond to the Tomlinson data presented in Figures 9.19a, 9.19b, and 9.19c, respectively. The bottom option allows the user to enter an adhesion value of their choice.

The soil profile screen for a two layer profile with cohesionless soil properties is presented in Figure 9.25. The user can input the same or different soil friction angles to be used in the shaft resistance and end bearing calculations in the layer. The user can also user to input SPT N values and let the program compute the soil friction angle using a correlation developed by Peck, Hanson and Thornburn in 1974 as shown in Figure 9.26. However, it is recommended that the user manually select the soil friction angle rather than use this program option as factors influencing the N value - ϕ angle correlation such as SPT hammer type and sample recovery are not considered by the program.

Project Definition

Client Information

Client: FHWA Pile Manual

Project Name: Student Exercise #4

Project Manager: CED

Date: 02/19/2005

Computed By: PJH

Soil Layers

Soil Layers: 2

Water Tables

Depth at top of boring: 0.0

Depth at Time of Drilling: 1.000 m

Depth for Restrike/Driving: 1.000 m

Depth for Ultimate: 1.000 m

Unit System

☒ SI ☐ English View

Optional Design Considerations

☐ Soft Compressible Soils Overlying the Bearing Strata Edit

☐ Scourable Soil Overlying the Bearing Strata Edit

OK Cancel Help

Figure 9.22 DRIVEN Project Definition Screen

Soil Profile

Soil Layer Profile

Soil Layer #1

Layer General Data

Depth to bottom of layer: 14.000 m

Total unit weight of soil: 19.800 kN/m³

Driving strength loss: 43.000 %

Layer Soil Type

☒ Cohesive ☐ Cohesionless

Undrained Shear Strength: 130.000 kPa

Select Graph

Pile Type: Pipe Pile - Closed End Edit

Split Layer Delete Layer Calculator OK Cancel Help

Figure 9.23 DRIVEN Soil Profile Screen – Cohesive Soil

Cohesive Soil Layer Properties

Soil Layer #1

Adhesion Type

- ☒ General Adhesion for Cohesive Soils (Tomlinson 1979)
- ☐ Piles Driven Through Overlying Sands or Sandy Gravels (Tomlinson 1980)
- ☐ Piles Driven Through Soft Clay (Tomlinson 1980)
- ☐ Piles Without Different Overlying Strata (Tomlinson 1980)
- ☐ User Defined Adhesion

Figure 9.24 DRIVEN Cohesive Soil Layer Properties Screen

Soil Profile

Soil Layer Profile

Soil Layer #2

Layer General Data

Depth to bottom of layer m

Total unit weight of soil kN/m³

Driving strength loss %

Layer Soil Type

☐ Cohesive ☒ Cohesionless

Internal Friction Angle Skin Friction degrees

☐ Use SPT 'N' Values

Internal Friction Angle End Bearing degrees

☐ Use SPT 'N' Values

Pile Type

Figure 9.25 DRIVEN Soil Profile Screen – Cohessionless Soil

Cohesionless Soil Layer Prop...

Soil Layer #2

Correct the N - values for the influence
of the effective overburden pressure

☒ Yes ☐ No

Number of SPT "N" values (5 are allowed) 5

Depth of Top of Layer 14.000 m

Depth of Bottom of Layer 20.000 m

| Depth | N | Depth | N |
|---|---|---|---|
| 14 m | 35 | 18.5 m | 42 |
| 15.5 m | 33 | 20 m | 45 |
| 17 m | 31 | | |

The program uses the relationship between standard
penetration test values and angle of internal friction of the
soil as presented by Peck, Hanson and Thornburn (1974)

OK
Cancel
Help

Figure 9.26 DRIVEN Cohesionless Soil Layer Properties Screen

Soil Profile

Soil Layer Profile

Split Layer
Delete Layer
Calculator

Soil Layer #2

Layer General Data

Depth to bottom of layer 20.000 m

Total unit weight of soil 18.800 kN/m³

Driving strength loss 0.000 %

Layer Soil Type

☐ Cohesive ☒ Cohesionless

Internal Friction Angle 35. degrees

Skin Friction

☐ Use SPT 'N' Values Edit

Internal Friction Angle 35.00 degrees

End Bearing

☐ Use SPT 'N' Values Edit

Pile Type Pipe Pile - Closed End Edit

Pipe Pile - Closed End
 Pipe Pile - Open End
 Timber Pile
 Concrete Pile
 Raymond Uniform Taper Pile
 H Pile
 Monotube Pile

Pipe Pile - Closed End

Depth of Top of Pile 1 m

Diameter of Pile 324 mm

OK
Cancel

Figure 9.27 Driven Pile Selection Drop Down Menu and Pile Detail Screen

Both cohesive and cohesionless soil profile screens request the user to provide the percentage strength loss of the soil type during driving. This is sometimes difficult for the program user to quantify. Insight into appropriate driving strength loss values can be gathered from the soil setup factors presented in Table 9-19 of Section 9.10.1.1. The percent driving strength loss needed for input into DRIVEN can be then be calculated from:

$$\% \text{ Driving Strength Loss} = 1 - [1 / \text{setup factor}]$$

After the soil input has been entered, the user must select a pile type from a drop down menu. A pile detail screen will appear for the pile type selected requesting additional information on the depth to the top of the pile and the pile properties. These DRIVEN screens are presented in Figure 9.27.

Once all soil and pile information is entered, the user can review the static capacity calculations in tabular or graphical form by a mouse click on the appropriate icon in the program toolbar. The icons for tabular and graphical output are identified in Figure 9.28. The tabular output screen is shown in Figure 9.29. A summary of the analysis input and results will be printed if the user clicks on the report button. Analysis output can also be presented graphically as shown in Figures 9.30 and 9.31 for driving and restrike static analyses, respectively. The ultimate capacity versus depth from shaft resistance, toe resistance, and the combined shaft and toe resistance can be displayed by clicking on “skin friction”, “end bearing”, and “total capacity”. Capacity changes with time or from extreme events can be reviewed by clicking on “restrike”, “driving”, and “ultimate” in the plot set area.

The program also generates the soil input file required for a driveability study in the GRLWEAP wave equation program. The GRLWEAP file created by DRIVEN is compatible with the Windows versions of GRLWEAP. However, the DRIVEN file must be identified as a pre 2002 input file in the current version of GRLWEAP.

Additional DRIVEN program capabilities are described in the DRIVEN Program User’s Manual by Mathias and Cribbs (1998).

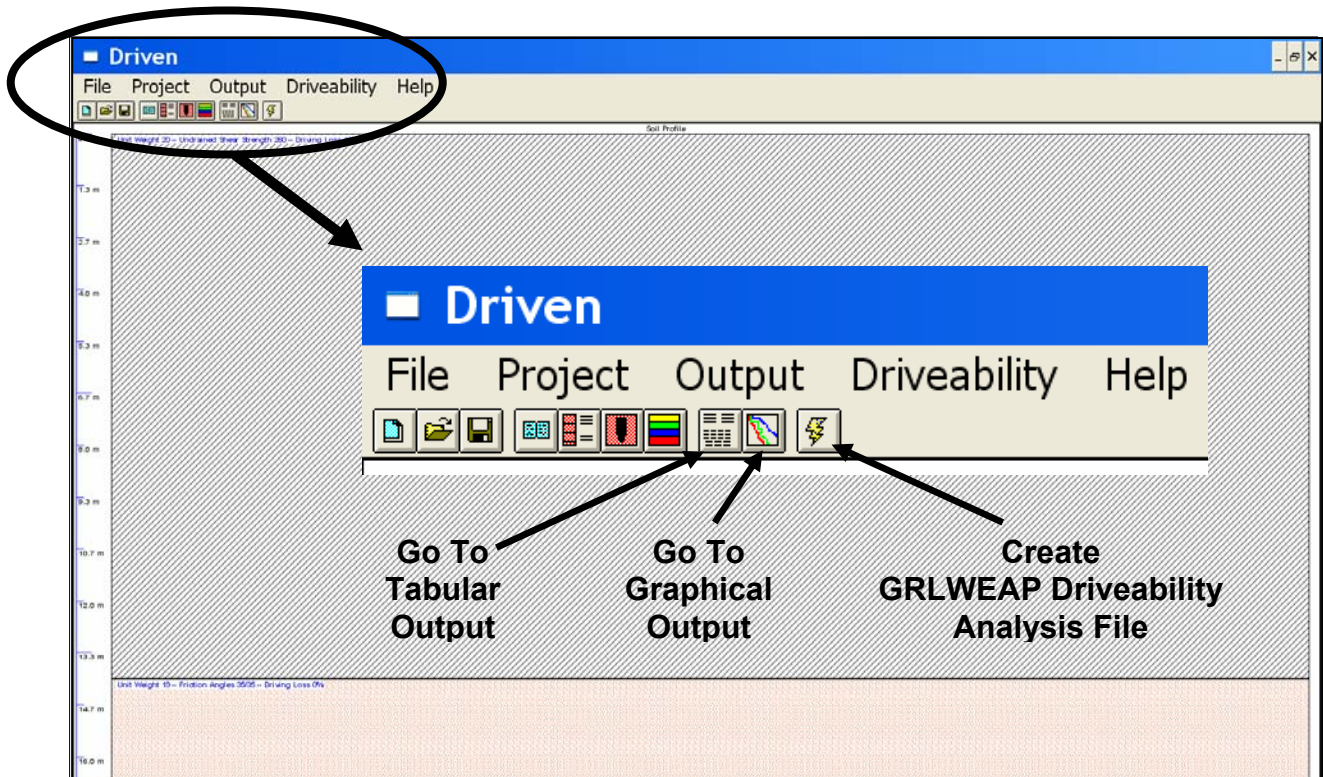


Figure 9.28 DRIVEN Toolbar Output and Analysis Options

Output - Tabular

Pile Type: **Pipe Pile - Closed End**

CONTRIBUTION

| Depth | Soil Type | Effective Stress | Sliding Friction Angle | Adhesion |
|---------|--------------|------------------|------------------------|-----------|
| 9.01 m | Cohesive | N/A | N/A | 55.88 kPa |
| 12.01 m | Cohesive | N/A | N/A | 64.12 kPa |
| 13.99 m | Cohesive | N/A | N/A | 69.47 kPa |
| 14.01 m | Cohesionless | 149.83 kPa | 21.80° | N/A |
| 17.01 m | Cohesionless | 163.33 kPa | 21.80° | N/A |

☒ Skin ☐ End ☒ Restrike ☐ Driving ☐ Ultimate

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 12.01 m | 718.51 kN | 96.46 kN | 814.97 kN |
| 13.99 m | 918.51 kN | 96.46 kN | 1014.97 kN |
| 14.01 m | 919.97 kN | 424.74 kN | 1344.72 kN |
| 17.01 m | 1166.84 kN | 424.74 kN | 1591.59 kN |
| 19.99 m | 1452.56 kN | 424.74 kN | 1877.30 kN |

Figure 9.29 DRIVEN Tabular Output Screen

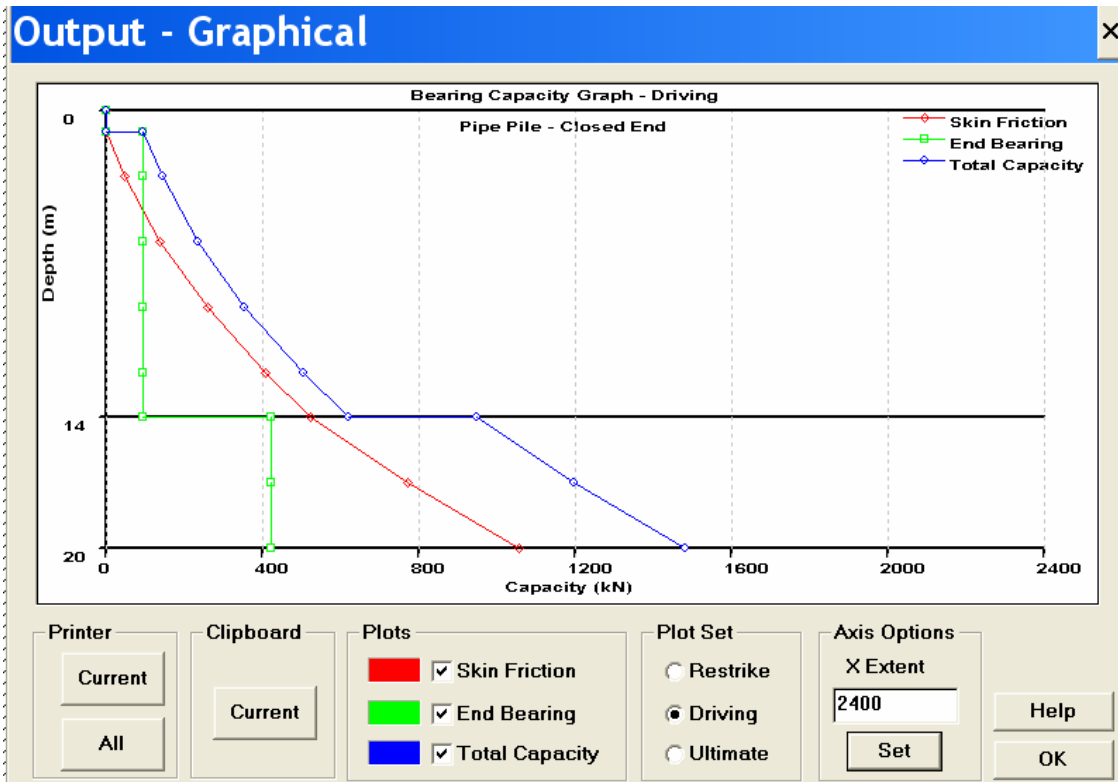


Figure 9.30 DRIVEN Graphical Output for End of Driving

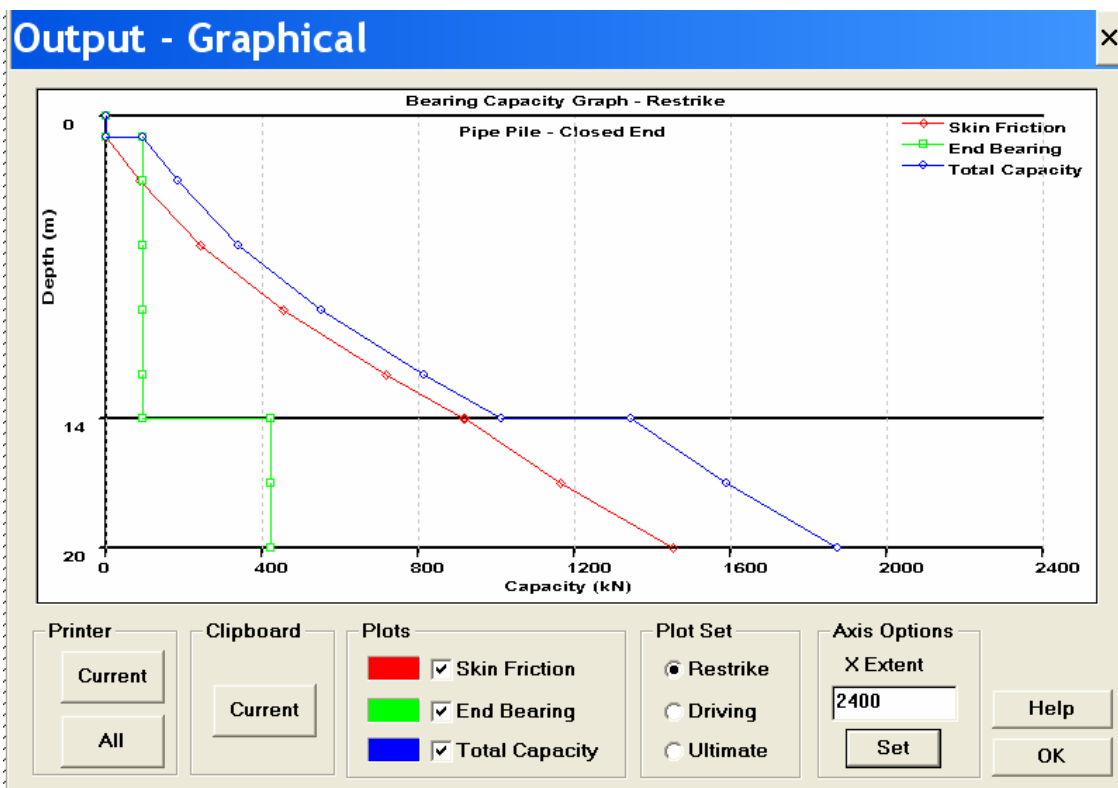


Figure 9.31 DRIVEN Graphical Output for Restrike.

9.7.1.6 Ultimate Capacity of Piles on Rock

Pile foundations on rock are normally designed to carry large loads. For pile foundations driven to rock, which include steel H-piles, pipe piles or precast concrete piles, the exact area in contact with the rock, the depth of penetration into rock, as well as the quality of rock are largely unknown. Therefore, the determination of load capacity of driven piles on rock should be made on the basis of driving observations, local experience and load tests.

Rock Quality Designation (RQD) Values can provide a qualitative assessment of rock mass as shown in Table 9-7. The RQD is only for NX size or larger core samples (double tube core barrel) and is computed by summing the length of all pieces of core equal to or longer than 102 mm (4 inches) and dividing by the total length of the coring run. The result is multiplied by 100 to get RQD in percent. Fresh, irregular breaks should be ignored and the pieces counted as intact lengths.

| TABLE 9-7 ENGINEERING CLASSIFICATION FOR IN-SITU ROCK QUALITY | |
|---|-------------------|
| RQD % | Rock Mass Quality |
| 90-100 | Excellent |
| 75-90 | Good |
| 50-75 | Fair |
| 25-50 | Poor |
| 0-25 | Very Poor |

Except for soft weathered rock, the structural capacity of the pile will generally be lower than the capacity of rock to support loads for toe bearing piles on rock of fair to excellent quality as described in Table 9-7. The structural capacity, which is based on the allowable design stress for the pile material, will therefore govern the pile capacity in many cases.

Small diameter piles supported on fair to excellent quality rock may be loaded to their allowable structural capacity as described in Chapter 10. Piles supported on soft weathered rock, such as shale or other types of very poor or poor quality, should be designed based on the results of pile load tests.

9.7.1.7 Methods Based on Cone Penetration Test (CPT) Data

When subsurface exploration programs include in-situ testing with a static cone penetrometer test (CPT), the CPT data can be used to estimate static capacity of single piles under axial loading. The CPT provides especially useful data as a "model pile" pushed into the strata expected to contribute resistance for a driven pile. The cone penetration resistance often correlates well with that of a driven full-sized pile under static loading conditions.

At sites where the cone soundings satisfactorily penetrate to the depths contemplated for driven piles, the CPT results can provide valuable information for estimating static pile capacities. At locations where a shallow stratum causes "refusal" conditions for the CPT device, it is likely that pile driveability problems could develop in the same stratum.

There are two main approaches for using CPT data to pile design, indirect methods and direct methods. Indirect methods use CPT derived soil parameters such as soil friction angle and undrained shear strength along with bearing capacity and / or cavity expansion theories. Direct methods use cone resistance values to determine unit shaft and toe resistances. Eslami and Fellenius (1997) consider indirect methods less suitable for pile capacity evaluations than direct methods. They also note that there are five direct methods currently used for pile capacity evaluations in North America. These methods include the Nottingham and Schmertmann method, the Laboratoire des Ponts et Chaussées or LPC Method, the DeRuiter and Beringen method, the Meyerhof method, and the Tumay and Fakhroo method. However, all of these methods have limitations. Eslami and Fellenius (1997) identify the following difficulties associated with the current direct methods.

1. The five CPT methods are over a decade old and the method calibration was made with older cone than the modern cones now available.
2. The methods do not include a means of identify soil type from the CPT data.
3. All five methods specify extreme values be eliminated or filtered out potentially biasing the results.
4. The methods were developed prior to the piezocone and therefore neglect the pore pressure acting on the cone shoulder.
5. The CPT methods use total stress rather than effective stress values.

6. The methods were developed based on pile types and soil conditions in a local area and may therefore not perform as well outside of that locality.
7. All five methods require judgment in selecting the coefficient applied to the average cone resistance to determine unit toe resistance.

Elsami and Fellenius (1997) note several other specific limitations of particular methods. The methods presented in this the following sections of this manual include a new direct method based on CPTu measurements proposed Elsami and Fellenius, as well as the Nottingham and Schmertmann Method and the LPC Method. Additional information on the two older direct CPT methods may be found in FHWA publication FHWA-SA-91-043, "The Cone Penetrometer Test", by Briaud and Miran (1991). The UNICONE computer program performs ultimate pile capacity calculations for all five CPT and the one CPTu direct methods.

9.7.1.7a Elsami and Fellenius Method

In the Elsami and Fellenius method, the unit shaft resistance is correlated to the average effective cone tip resistance with a shaft correlation coefficient applied based on the soil profile. The unit shaft resistance is calculated from:

$$f_s = C_{sc} q_E$$

Where: C_{sc} = is the shaft correlation coefficient from Table 9-8.
 q_E = the cone tip resistance after correction for pore pressure on the cone shoulder and adjustment to effective stress.

The shaft resistance in a given soil layer is then:

$$R_s = f_s A_s$$

Where: A_s = Pile shaft surface area.
 = (pile perimeter)(embedded length).

The unit toe resistance is computed using a geometric averaging of the cone tip resistance over the influence zone at the pile toe after the cone tip resistances have been corrected

| TABLE 9-8 C_{sc} VALUES FOR ELSAMI AND FELLENIUS METHOD | |
|---|--------------|
| Soil Type | C_{sc} (%) |
| Soft sensitive soil | 8.0 |
| Clay | 5.0 |
| Stiff clay and mixtures of clay and silt | 2.5 |
| Mixture of silt and sand | 1.0 |
| Sand | 0.4 |

for pore pressure on the cone shoulder and effective stress. The zone of influence at the pile toe is based on the pile diameter, b , and ranges from $4b$ below the pile toe to $8b$ above the pile toe when the pile is installed through a weak zone overlying a dense zone. When a pile is driven through a dense soil into a weak soil, the zone of influence is from $4b$ below the pile toe to $2b$ above the pile toe. The unit toe resistance is calculated from:

$$q_t = C_{tc} q_{Eg}$$

Where: C_{tc} = toe correction coefficient equal to 1.0 in most cases.
 q_{Eg} = geometric average of the cone tip resistance over the influence zone after correction for pore pressure on the cone shoulder and adjustment to effective stress.

The toe correction coefficient is a function of the pile size since larger piles require greater movement to mobilize the pile toe resistance. For pile diameters, b , greater than 400 mm (16 inches), the toe correction coefficient should be calculated as follows:

SI units $C_{tc} = 1 / 3b$ (b in meters)

US Units $C_{tc} = 12 / b$ (b in inches)

The pile toe resistance is then computed from:

$$R_t = q_t A_t$$

Where: A_t = Pile toe area.

The ultimate pile capacity, Q_u , using the Elsami and Fellenius method is obtained by summing the shaft resistance from each soil layer plus the toe resistance or:

$$Q_u = R_s + R_t$$

9.7.1.7b Nottingham and Schmertmann Method

One empirical procedure used in U.S. practice was derived from work originally published by Nottingham and Schmertmann (1975), and summarized in publication FHWA-TS-78-209, "Guidelines for Cone Penetration Test, Performance and Design" by Schmertmann (1978). The ultimate shaft resistance, R_s , in cohesionless soils may be derived from unit sleeve friction of the CPT using the following expression:

$$R_s = K \left[\frac{1}{2} (\bar{f}_s A_s)_{0 \text{ to } 8b} + (\bar{f}_s A_s)_{8b \text{ to } D} \right]$$

Where: K = Ratio of unit pile shaft resistance to unit cone sleeve friction from Figure 9.32 as a function of the full penetration depth, D .

\bar{f}_s = Average unit sleeve friction over the depth interval indicated by subscript.

A_s = Pile-soil surface area over f_s depth interval.

b = Pile width or diameter.

D = Embedded pile length.

$0 \text{ to } 8b$ = Range of depths for segment from ground surface to a depth of $8b$.

$8b \text{ to } D$ = Range of depths for segment from a depth equal to $8b$ to the pile toe.

The transfer function K , relating pile shaft resistance to CPT sleeve friction, varies as a function of total pile penetration (depth of embedment/pile diameter), pile material type, and type of cone penetrometer used. No limit was imposed on sleeve friction values in the procedure originally proposed by Nottingham and Schmertmann (1975).

If cone sleeve friction data is not available, R_s can be determined from the cone tip resistance as follows:

$$R_s = C_f \sum q_c A_s$$

Where: C_f is obtained from Table 9-9 and
 q_c = Average cone tip resistance along the pile length.
 A_s = Pile-soil surface area from (pile perimeter) (length).

| TABLE 9-9 CPT C_f VALUES | |
|----------------------------|-------|
| Type of Piles | C_f |
| Precast Concrete | 0.012 |
| Timber | 0.018 |
| Steel Displacement | 0.012 |
| Open End Steel Pipe | 0.008 |

For shaft resistance in cohesive soils, the ultimate shaft resistance, R_s , is obtained from the sleeve friction values using the following expression:

$$R_s = \alpha' \bar{f}_s A_s$$

Where: α' = Ratio of pile shaft resistance to cone sleeve friction, patterned after Tomlinson's α -method.

The value of α' varies as a function of sleeve friction, f_s , value as shown in Figure 9.33. It is expected that this method of calculating pile shaft resistance is less appropriate in sensitive soils as the friction sleeve of the cone encounters severely disturbed soils behind the cone tip.

The estimation of pile toe ultimate capacity is described in Figure 9.34. In essence an elaborate averaging scheme is used to weight the cone tip resistance values, from 8 pile diameters above the pile toe, to as much as 3.75 pile diameters below the pile toe, favoring the lower cone tip resistance, q_c , values within the depth range. The authors make reference to a "limit" value of q_c between 5000 to 15000 kPa, that should be applied to the ultimate unit pile toe resistance, q_t , unless local experience warrants use of higher values. In the case of mechanical cone soundings in cohesive soils, the q_t value is reduced by 40 percent to account for end bearing effects on the base of the friction sleeve. As discussed in Section 9.10.5, careful consideration of soil plugging phenomena is needed in choosing the cross-sectional area over which q_t is applied for low displacement open ended pipe and H-piles.

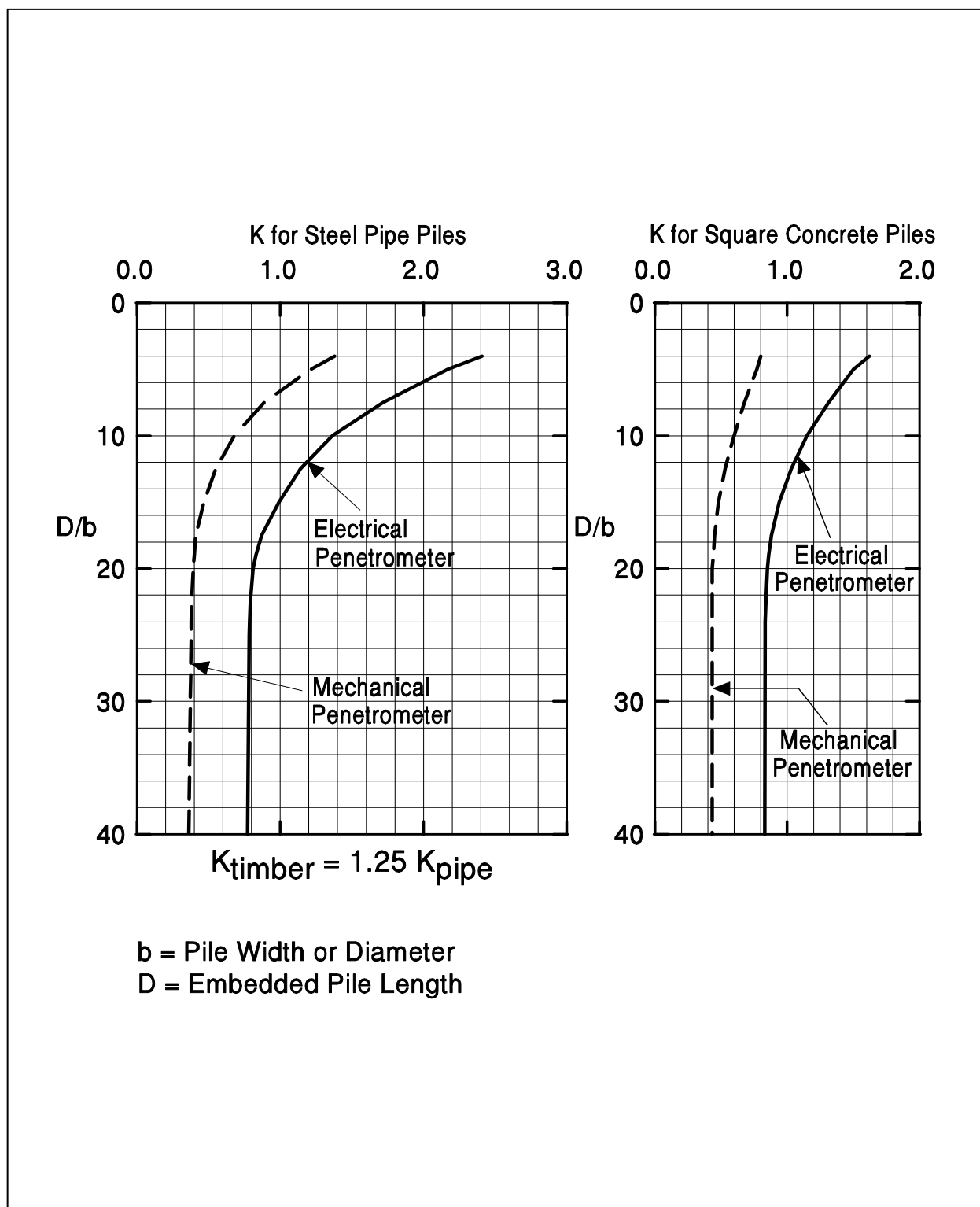


Figure 9.32 Penetrometer Design Curves for Pile Side Friction in Sand (after FHWA Implementation Package, FHWA-TS-78-209)

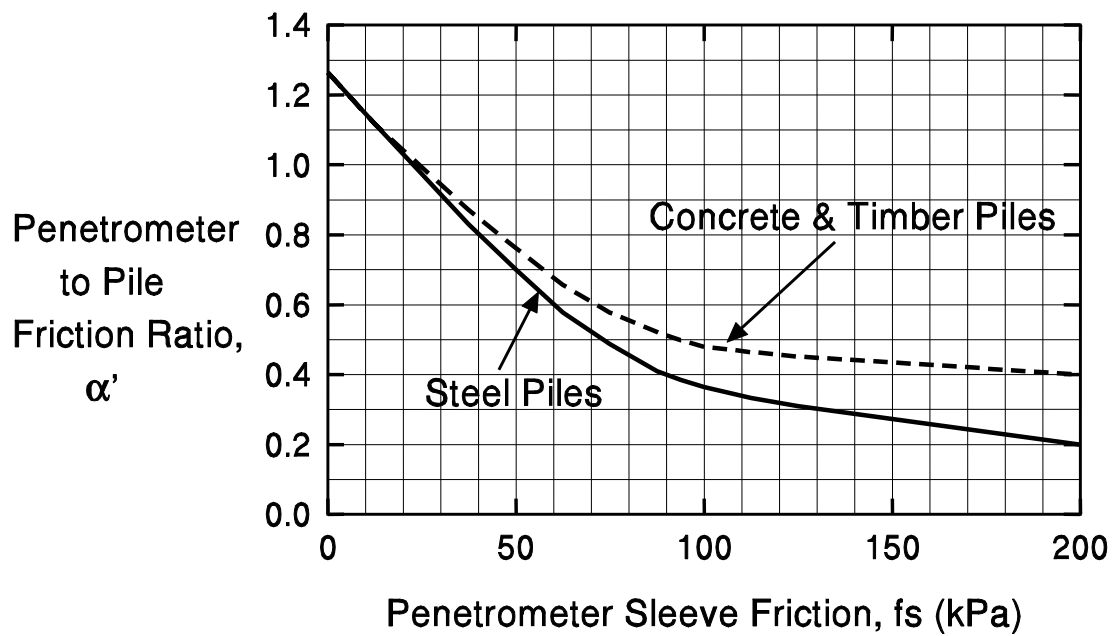


Figure 9.33 Design Curve for Pile Side Friction in Clay (after Schmertmann, 1978)

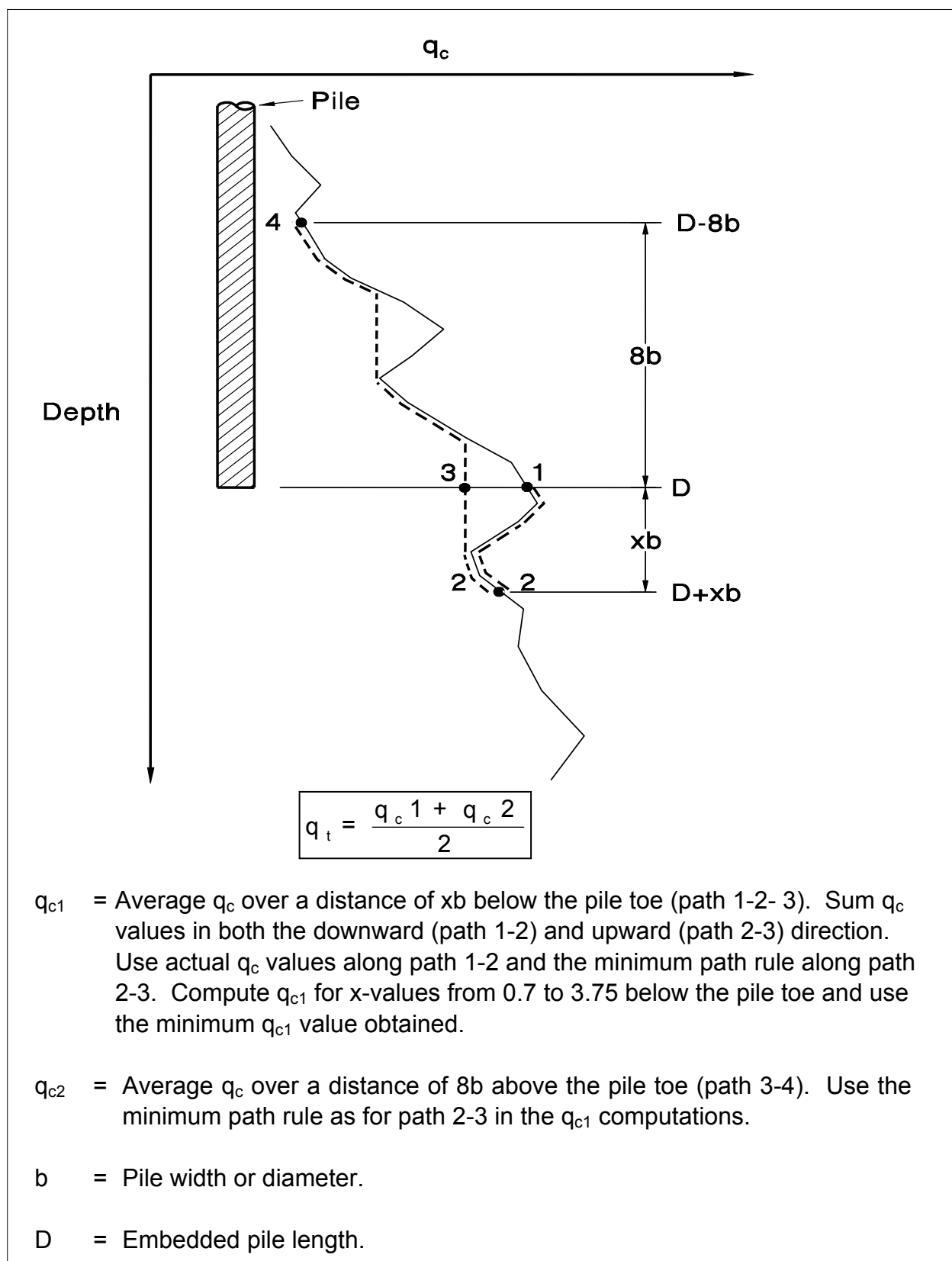


Figure 9.34 Illustration of Nottingham and Schmertmann Procedure for Estimating Pile Toe Capacity (FHWA-TS-78-209)

STEP BY STEP PROCEDURE FOR THE NOTTINGHAM AND SCHMERTMANN METHOD

STEP 1 Delineate the soil profile into layers using the cone tip resistance, q_t , and sleeve friction, f_s , values.

STEP 2 Compute the shaft resistance for each soil layer, R_s (kN).

- a. For piles in cohesionless soils, compute ultimate shaft resistance, R_s , using the average sleeve friction value for the layer, \bar{f}_s , and the K value. Note that K should be determined using the full pile penetration depth to diameter ratio from Figure 9.32, and not the penetration depth for the layer. Conversely, the depth d corresponds to the pile toe depth, or the depth to the bottom of the layer, whichever is less. For H-piles in cohesionless soils, the pile-soil surface area A_s , should be the "box" area.

$$R_s = K \left[\frac{1}{2} (\bar{f}_s A_s)_{0 \text{ to } 8b} + (\bar{f}_s A_s)_{8b \text{ to } d} \right]$$

For cohesionless layers below a depth of $8b$, the above equation for shaft resistance in a layer reduces to:

$$R_s = K \bar{f}_s A_s$$

For piles in cohesionless soils without sleeve friction data, compute the ultimate shaft resistance from:

$$R_s = C_f \sum q_c A_s$$

Where: C_f is obtained from Table 9-9 and

q_c = Average cone tip resistance along the pile length.

- b. For piles in cohesive soils, compute the ultimate shaft resistance using the average sleeve friction value for the layer from:

$$R_s = \alpha' \bar{f}_s A_s$$

Where: α' determined from Figure 9.33.

STEP 3 Calculate the total pile shaft resistance from the sum of the shaft resistances from each soil layer.

STEP 4 Compute the unit pile toe resistance, q_t (kPa).

$$q_t = \frac{q_{c1} + q_{c2}}{2}$$

Where: q_{c1} and q_{c2} = Unit cone tip resistance.

Use procedure shown in Figure 9.24 to determine q_t .

STEP 5 Determine the ultimate toe resistance, R_t (kN).

$$R_t = q_t A_t$$

Where: A_t = Pile toe area.

For steel H and unfilled open ended pipe piles, use only the steel cross section area at the pile toe unless there is reasonable assurance and previous experience that a soil plug would form. For a plugged condition use the "box" area of the H pile and the full cross section area for pipe pile. Additional information on the plugging of open pile sections is presented in Section 9.10.5.

STEP 6 Determine ultimate pile capacity, Q_u (kN).

$$Q_u = R_s + R_t$$

STEP 7 Determine allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}}$$

The factor of safety in this static calculation should be based on the specified construction control method as described in Section 9.6 of this chapter.

9.7.1.7c Laboratoire des Ponts et Chaussees (LPC)

The LPC method was developed and presented by Bustamante and GIANESSELLI (1983), based on empirical criteria taking into consideration soil type, pile type, and level of cone tip resistance. The approach considers only cone tip resistance, q_c , and factors soil type, pile type, installation method, and q_c , into determination of ultimate shaft resistance along the pile, contributed layer-by-layer, based on a family of prescribed curves. The resistance at the pile toe is calculated as the product of q_c and a cone bearing factor, K_c , that varies by soil type and pile installation method.

In the LPC method, the pile is categorized based on pile type and installation procedure as indicated in Table 9-10. Next Tables 9-11(a) and 9-11(b) are used to determine the shaft resistance design curve in Figures 9.35(a) or 9.35(b) to be used for each soil layer, based on the soil type, pile category and cone tip resistance. In Table 9-11(a), the method provides no guidance on whether to use design curve 1 or 2 when q_c is between 700 and 1200 kPa (15 and 25 ksf). Therefore it is recommended to interpolate between curves 1 or 2 when q_c is between 700 and 1200 kPa (15 and 25 ksf) to determine the unit shaft resistance, f_s .

The unit toe resistance is calculated from the cone bearing capacity factor, K_c , obtained in Table 9-12, times the average cone resistance, q_c , within one pile diameter below the pile toe. This may be expressed in equation from as:

$$q_t = K_c q_c$$

In order to apply the CPT design procedures, it is necessary to characterize the subsurface materials as cohesive or cohesionless. The usual approach is to identify the "soil behavior" type as a function of cone tip resistance, q_c , and friction ratio, R_f . The friction ratio is the cone sleeve friction, f_s , divided by the cone tip resistance, or f_s/q_c . The soil classification chart presented in Figure 5.2 can then be used to characterize the soil as cohesive or cohesionless.

| TABLE 9-10 DRIVEN PILE TYPE CATEGORIES FOR LPC METHOD | | |
|---|---|--|
| Pile Type | Pile Description | Pile Installation Procedure |
| A | Driven prefabricated concrete piles. | Reinforced or prestressed concrete pile installed by driving or vibro-driving |
| B | Driven steel piles. | Pile made of steel only and driven in place: H pile, pipe pile or any shape obtained by welding sheet-pile sections. |
| C | Driven prestressed concrete tube piles. | Made of hollow cylinder elements of lightly reinforced concrete assembled together by prestressing before driving. Each element is generally 1.5 to 3 m (5 to 10 ft) long and 0.7 to 0.9 m (2.3 to 3 ft) in diameter; the thickness is approximately 0.15 m (0.5 ft). The piles are driven open-ended. |

| TABLE 9-11(a) CURVE SELECTION BASED ON PILE TYPE AND INSERTION PROCEDURES FOR CLAY AND SILT | | | |
|---|--------------------|---------------------------|--|
| Curve No. | q_c in kPa (ksf) | Pile Type (see Table 9-9) | Comments on Insertion Procedure |
| 1 | <700 (<15 ksf) | A, B, C | |
| 2 | >1200 (>25 ksf) | A, B, C | For all steel piles, experience shows that, in plastic soils, f_s is often as low as curve 1. Therefore, use curve 1 in plastic soils when no previous load test data is available. For all driven concrete piles use curve 3 in low plasticity soils with sand or sand and gravel layers or containing boulders, and when $q_c > 2500$ kPa (52 ksf). |
| 3 | > 1200 (>25 ksf) | A | For all driven concrete piles in low plasticity soils with sand or sand and gravel layers or containing boulders, and when $q_c > 2500$ kPa (52 ksf). |

| TABLE 9-11(b) CURVE SELECTION BASED ON PILE TYPE AND INSERTION PROCEDURES FOR SAND AND GRAVEL | | | |
|---|--------------------|---------------------------|---|
| Curve No. | q_c in kPa (ksf) | Pile Type (see Table 9-9) | Comments on Insertion Procedure |
| 1 | <3500 (<74 ksf) | A, B, C | |
| 2 | >3500 (>74 ksf) | A, B, C | For fine sands. Since steel piles can lead to very small values of f_s in such soils, use curve 1 unless higher values can be based on load test results. For concrete piles, use curve 2 for fine sands of $q_c > 7500$ kPa (157 ksf). |
| 3 | >7500 (>157 ksf) | A, B | For coarse gravelly sand or gravel only. For concrete piles, use curve 4 if it can be justified by a load test. |
| 4 | >7500 (>157 ksf) | A | Only for coarse gravelly sand and gravel and, if justified, by load test. |

| TABLE 9-12 CONE BEARING CAPACITY FACTORS FOR LPC METHOD | |
|---|----------------------------|
| Type of Soil | Cone Bearing Factor, K_c |
| Clay-silt | 0.600 |
| Sand-gravel | 0.375 |

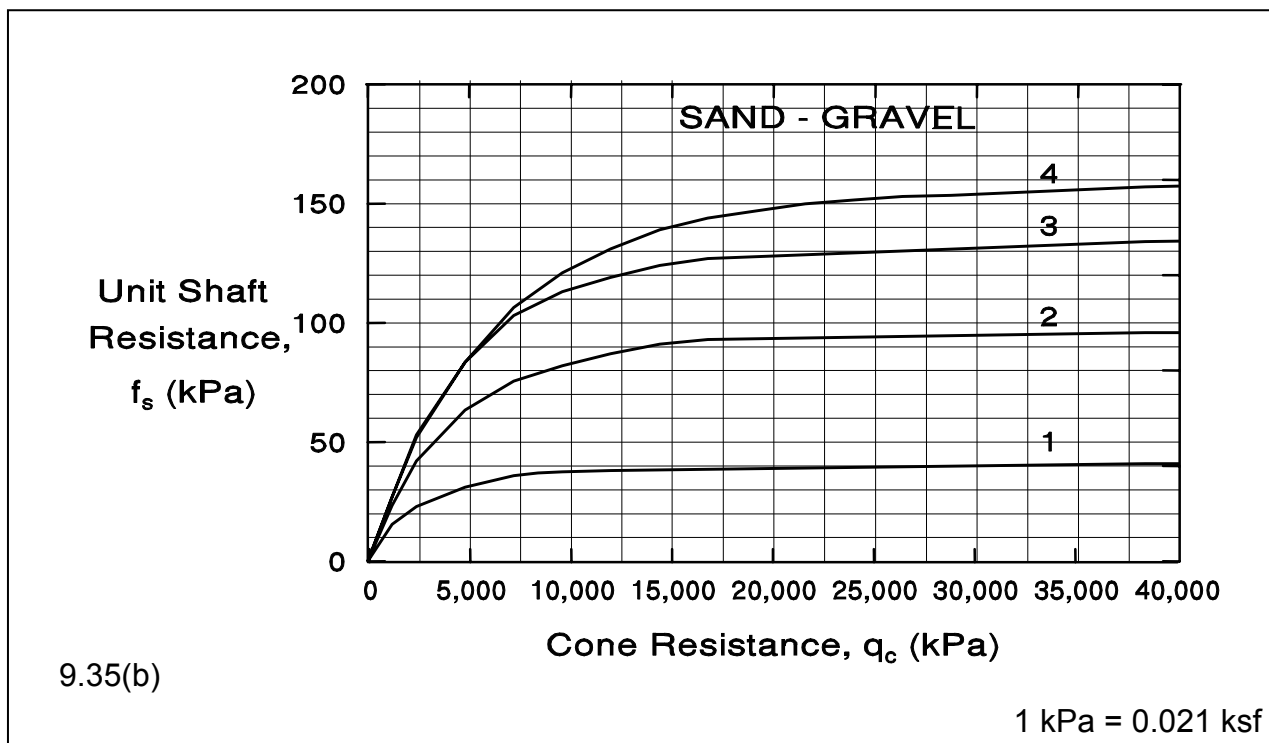
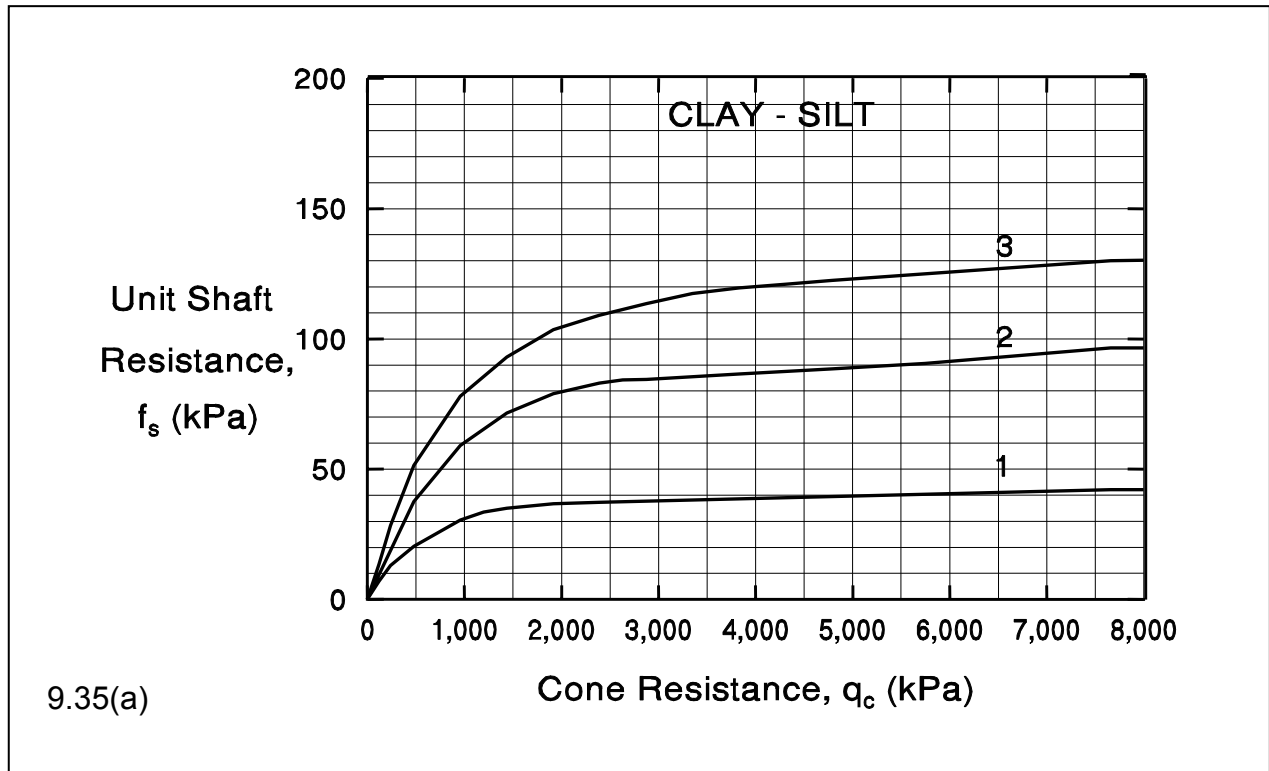


Figure 9.35 Maximum Unit Shaft Resistance Curves for LPC Method

STEP BY STEP PROCEDURE FOR THE LPC METHOD

STEP 1 Delineate the soil profile into layers using the cone tip resistance, q_c , and friction ratio, R_f , values.

Use Figure 5.2 to characterize each layer as cohesive or cohesionless.

STEP 2 Determine unit shaft resistance values for each soil layer, f_s (kPa).

a. Determine the average q_c value for each layer.

b. Use Table 9-11(a) or 9-11(b) to determine appropriate friction design curve in Figure 9.35(a), or Figure 9.35(b) based on pile type from Table 9-9 and soil characterization.

c. Enter Figures 9.35(a) or 9.35(b) with cone tip resistance, q_c , to determine layer unit shaft resistance, f_s (kPa).

STEP 3 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s (kN), from the sum of the shaft resistance from each soil layer.

$$R_s = f_s A_s$$

Where: A_s = Pile-soil surface area from pile perimeter and length.
For H-piles, the "box" area should be used.

STEP 4 Compute the unit pile toe resistance, q_t (kPa).

a. Average q_c value from pile toe to one diameter below pile toe.

b. Obtain cone bearing capacity factor, K_c , from Table 9-12.

c. Compute unit pile toe resistance from following equation.

$$q_t = K_c q_c$$

STEP 5 Compute the ultimate toe resistance, R_t in kN (kips).

$$R_t = q_t A_t$$

Where: A_t = Pile toe area in m^2 (ft^2).

Note: For steel H and unfilled open ended pipe piles, use only the steel cross section area at the pile toe unless there is reasonable assurance and previous experience that a soil plug would form. For a plugged condition use the "box" area of the H pile and the full cross section area for pipe pile. Additional discussion on plugging of open pile sections is presented in 9.10.5.

STEP 6 Compute the ultimate pile capacity, Q_u in kN (kips).

$$Q_u = R_s + R_t$$

STEP 7 Determine allowable design load, Q_a in kN (kips).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}}$$

The factor of safety in this static calculation should be based on the specified construction control method as described in Section 9.6 of this chapter.

9.7.2 Uplift Capacity of Single Piles

The design of piles for uplift loading conditions has become increasingly important for structures subject to seismic loading. In some cases, the pile uplift capacity determines the minimum pile penetration requirements. Nicola and Randolph (1993) note that in fine grained cohesive soils, where loading is assumed to occur under undrained conditions, the shaft resistance is generally considered equal in compression and in uplift.

In noncohesive or free draining soils, the uplift capacity of a pile has been more controversial. Nicola and Randolph (1993) state that it has been customary to assume that the shaft resistance in uplift is approximately 70% of the shaft resistance in compression. Based upon a finite difference parametric study, they concluded that a reduction in shaft resistance for uplift in free draining soils should be used, and that piles have lower uplift capacity than their compression shaft resistance. Conversely, the American Petroleum Institute's (1993) recommended design practice considers the pile shaft resistance to be equal in uplift and compression loading. Likewise, Altaee, *et al.*, (1992) presented a case of an instrumented pile in sand where the shaft resistance was approximately equal in compression and uplift when residual stresses were considered.

Tomlinson (1994) notes that the shaft resistance under cyclic loading is influenced by the rate of application of load as well as the degree of degradation of soil particles at the soil-pile interface. Under cyclic or sustained uplift loading in clays, the uplift resistance can decrease from the peak value to a residual value. In sands, particle degradation or reorientation can also result in decrease in uplift capacity under cyclic or sustained uplift loading. Therefore, the designer should consider what effect, if any, sustained or cyclic uplift loading will have on soil strength degradation.

Based on the above issues, the design uplift capacity of a single pile should be taken as $\frac{1}{3}$ of the ultimate shaft resistance calculated from any of the static analysis methods presented in this chapter except for the Meyerhof (SPT) method which should not be used. If a tensile load test is done for design confirmation, the design uplift capacity may be increased to $\frac{1}{2}$ of the tensile load test failure load as defined in Chapter 18. Selection of the design uplift capacity should also consider the potential for soil strength degradation due to the duration or frequency of uplift loading, which may not influence the load test results.

The uplift capacity of pile groups is discussed in Section 9.8.3. Tensile load test procedures are described by Kyfor *et al.* (1992) in FHWA-SA-91-042 and in Chapter 18.

9.7.3 Ultimate Lateral Capacity of Single Piles

In addition to axial compression and uplift loads, piles are routinely subjected to lateral loads. Potential sources of lateral loads on bridge structures include vehicle acceleration and braking forces, wind loads, wave and current forces, debris loading, ice forces, vessel impact loads, construction procedures, thermal expansion and contraction, earth pressures on the backs of abutment walls, slope movements, and seismic events. These lateral loads can be of the same magnitude as axial compressive loads and therefore warrant careful consideration during design. The foundation deformation under lateral loading must also be within the established performance criterion for the structure.

Historically, designers often used prescription values for the lateral load capacity of vertical piles, or added batter piles to increase a pile group's lateral capacity when it was believed that vertical piles could not provide the needed lateral resistance. However, vertical piles can be designed to withstand significant lateral loads. Modern analysis methods should be employed in the selection of the pile type and pile section.

Coduto (1994) notes that a foundation system consisting of only vertical piles designed to resist both axial and lateral loads is more flexible, and thus more effective at resisting dynamic loads, as well as less expensive to build. Bollmann (1993) reported that the Florida Department of Transportation often uses only vertical piles to resist lateral loads, including ship impact loads because vertical piles are often less expensive than batter piles.

In areas where seismic lateral shaking is a serious concern, batter piles can deliver excessively large horizontal forces to the structure during the earthquake event. This phenomenon was observed during the Loma Prieta earthquake of 1989 in California and discussed in greater detail by Hadjian *et al.* (1992). In earthquake areas, lateral loads should be resisted by ductile vertical piles, and batter piles should be avoided whenever possible.

Modern analysis methods are now readily available that allow the lateral load-deflection behavior of piles to be rationally evaluated. Lateral loads and moments on a vertical pile are resisted by the flexural stiffness of the pile and mobilization of resistance in the surrounding soil as the pile deflects. The flexural stiffness of a pile is defined by the pile's modulus of elasticity, E , and moment of inertia, I . The soil resistance to an applied lateral load is a combination of soil compression and shear resistance, as shown in Figure 9.36.

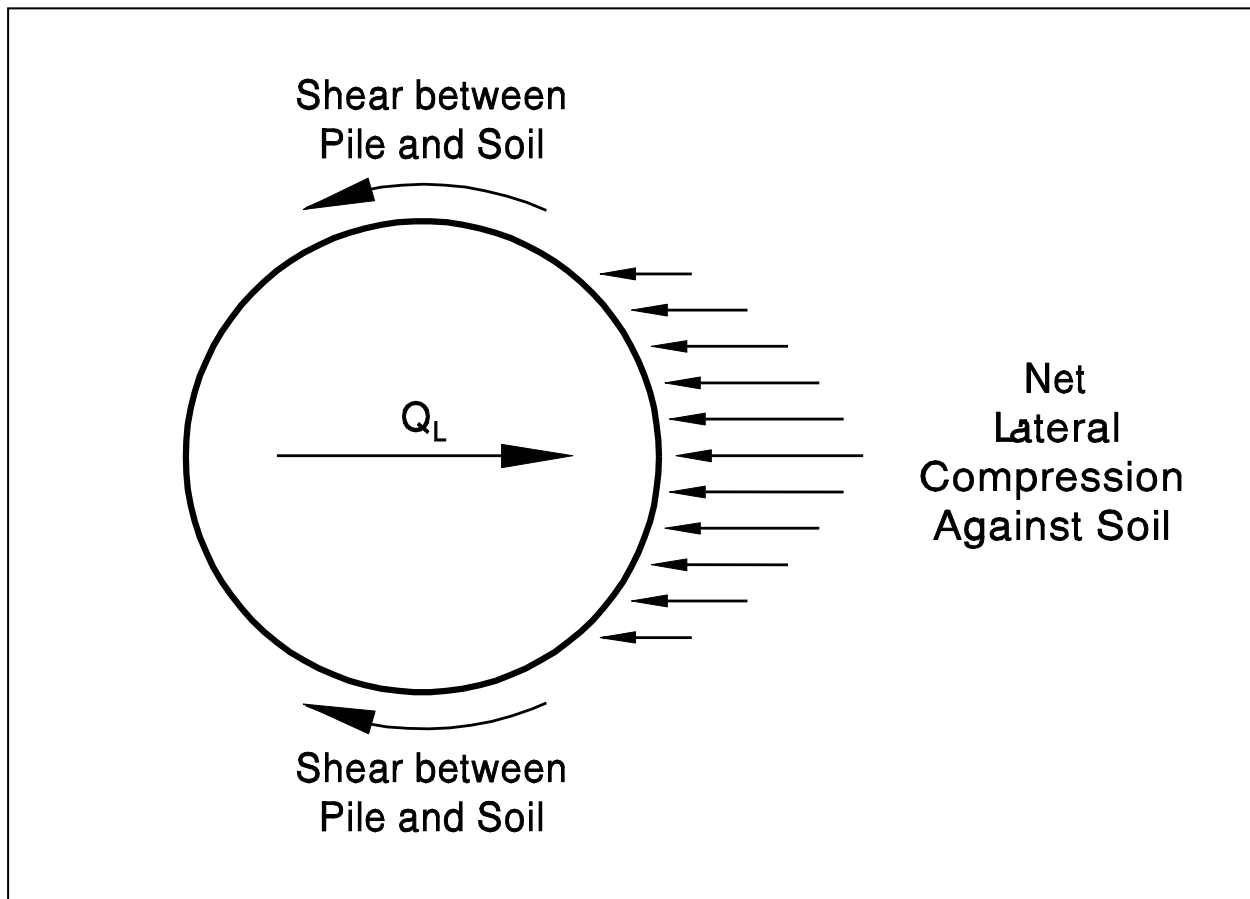


Figure 9.36 Soil Resistance to a Lateral Pile Load (adapted from Smith, 1989)

The design of laterally loaded piles must evaluate both the pile structural response and soil deformation to lateral loads. The factor of safety against both soil failure and pile structural failure must be determined. In addition, the pile deformation under the design loading conditions must be calculated and compared to foundation performance criteria.

The design of laterally loaded piles requires the combined skills of the geotechnical and structural engineer. It is inappropriate for the geotechnical engineer to analyze a laterally loaded pile without a full understanding of pile-structure interaction. Likewise it is inappropriate for the structural engineer to complete a laterally loaded pile design without a full understanding of how pile section or spacing changes may alter the soil response. Because of the interaction of pile structural and geotechnical considerations, the economical solution of lateral pile loading problems requires communication between the structural and geotechnical engineer.

Soil, pile, and load parameters have significant effects on the lateral load capacity of piles. The factors influencing these parameters are as follows:

1. Soil Parameters

- a. Soil type and physical properties such as shear strength, friction angle, density, groundwater level, and moisture content.
- b. Coefficient of horizontal subgrade reaction in kN/m^3 (lbs/in^3). This coefficient is defined as the ratio between a horizontal pressure per unit area of vertical surface in kN/m^2 (lbs/in^2) and the corresponding horizontal displacement in meters (inches). For a given deformation, the greater the coefficient, the greater the lateral load resistance.

2. Pile Parameters

- a. Physical properties such as shape, material, and dimensions.
- b. Pile head conditions (rotational constraint, if any).
- c. Method of pile placement such as driving, jetting, *etc.*
- d. Group action.

3. Lateral Load Parameters

- a. Static (monotonic or cyclic) or dynamic.
- b. Eccentricity (moment coupled with shear force).

9.7.3.1 Lateral Capacity Design Methods

The basic design approaches for lateral pile capacity analysis of vertical piles consist of lateral load tests or analytical methods. Both of these approaches are described in greater detail in the following sections.

1. Lateral Load Tests

Full scale lateral load tests can be conducted at a site during either the design or construction stage. The load-deformation data obtained is used to finalize or confirm the design for the particular site. Factors such as loading rate, cyclic (single or multi-directional) versus monotonic application of design forces, and magnitude of axial load should be considered in developing appropriate field testing procedures. These tests may be time-consuming, costly, and cannot be justified on all projects. Chapter 19 provides additional details on lateral load test procedures and interpretation.

2. Analytical Methods

The analytical methods are based on theory and empirical data and permit the rational consideration of various site parameters. Two common approaches are Broms' (1964a, 1964b) hand calculation method and Reese's (1984) computer solution. Both approaches consider the pile to be analogous to a beam on an elastic foundation. FHWA publication FHWA-IP-84-11 by Reese (1984) presents details of both methods.

Broms' method provides a relatively easy hand calculation procedure to determine lateral loads and pile deflections at the ground surface. Broms' method ignores the axial load on the pile. For small projects, Broms' method may be used. However, when there are definitive limits on the allowable pile movements, a more detailed load-deformation analysis may still be required.

Reese's method is a more rigorous computer analysis that now uses the LPILE computer program. Reese's method permits the inclusion of more complete modeling parameters of a specific problem. The program output provides distributions versus depth of moment, shear, soil and pile moduli, and soil resistance for the entire length of pile, including moments and shears in above ground sections.

For the design of all major pile foundation projects, Reese's more rigorous computer method should be used. The LPILE program is described in more detail in Section 9.7.3.3. Additional information on the LPILE program may be found in the program technical manual by Reese et al. (2000).

9.7.3.2 Broms' Method

The Broms' method is a straight forward hand calculation method for lateral load analysis of a single pile. The method calculates the ultimate soil resistance to lateral load as well as the maximum moment induced in the pile. Broms' method can be used to evaluate fixed or free head conditions in either purely cohesive or purely cohesionless soil profiles. The method is not conducive to lateral load analyses in mixed cohesive and cohesionless soil profiles. For long fixed head piles in sands, the method can also overpredict lateral load capacities (Long, 1996). Therefore, for mixed profiles and for long fixed head piles in sands, the LPILE program should be used. A step by step procedure developed by the New York State Department of Transportation (1977) on the application of Broms' method is provided below.

STEP BY STEP PROCEDURE FOR BROMS' METHOD

STEP 1 Determine the general soil type (*i.e.*, cohesive or cohesionless) within the critical depth below the ground surface (about 4 or 5 pile diameters).

STEP 2 Determine the coefficient of horizontal subgrade reaction, K_h , within the critical depth for cohesive or cohesionless soils.

a. Cohesive Soils:
$$K_h = \frac{n_1 n_2 80 q_u}{b}$$

Where: q_u = Unconfined compressive strength in kPa (lbs/ft²).

b = Width or diameter of pile in meters (ft).

n_1 and n_2 = Empirical coefficients taken from Table 9-13.

b. Cohesionless Soils:

Choose K_h from the Table 9-14. (The values of K_h given in Table 9-14 were determined by Terzaghi.)

| TABLE 9-13 VALUES OF COEFFICIENTS n_1 AND n_2 FOR COHESIVE SOILS | |
|---|-------|
| Unconfined Compressive Strength, q_u , in kPa (lbs/ft ²) | N_1 |
| Less than 48 kPa (1000 lbs/ft ²) | 0.32 |
| 48 to 191 kPa (1000 to 4000 lbs/ft ²) | 0.36 |
| More than 191 kPa (4000 lbs/ft ²) | 0.40 |
| Pile Material | N_2 |
| Steel | 1.00 |
| Concrete | 1.15 |
| Wood | 1.30 |

| TABLE 9-14 VALUES OF K_h FOR COHESIONLESS SOILS | | |
|---|--|--------------------|
| Soil Density | K_h , in kN/m ³ (lbs/in ³) | |
| | Above Ground Water | Below Ground Water |
| Loose | 1900 (7) | 1086 (4) |
| Medium | 8143 (30) | 5429 (20) |
| Dense | 17644 (65) | 10857 (40) |

STEP 3 Adjust K_h for loading and soil conditions.

a. Cyclic loading (for earthquake loading) in cohesionless soil:

1. $K_h = \frac{1}{2} K_h$ from Step 2 for medium to dense soil.
2. $K_h = \frac{1}{4} K_h$ from Step 2 for loose soil.

b. Static loads resulting in soil creep (cohesive soils):

1. Soft and very soft normally consolidated clays
 $K_h = (\frac{1}{3} \text{ to } \frac{1}{6}) K_h$ from Step 2.
2. Stiff to very stiff clays
 $K_h = (\frac{1}{4} \text{ to } \frac{1}{2}) K_h$ from Step 2.

STEP 4 Determine pile parameters.

- a. Modulus of elasticity, E , in MPa (lbs/in²).
- b. Moment of inertia, I , in meter⁴ (inches⁴).
- c. Section modulus, S , in meter³ (inches³) about an axis perpendicular to the load plane.
- d. Yield stress of pile material, f_y , in MPa (lb/in²) for steel or ultimate compression strength, f'_c , in MPa (lb/in²) for concrete.
- e. Embedded pile length, D , in meters (inches).
- f. Diameter or width, b , in meters (inches).
- g. Eccentricity of applied load e_c for free-headed piles - *i.e.*, vertical distance between ground surface and lateral load in meters (inches).
- h. Dimensionless shape factor C_s (for steel piles only):
 - 1. Use 1.3 for piles with circular cross section.
 - 2. Use 1.1 for H-section piles when the applied lateral load is in the direction of the pile's maximum resisting moment (normal to the pile flanges).
 - 3. Use 1.5 for H-section piles when the applied lateral load is in the direction of the pile's minimum resisting moment (parallel to the pile flanges).
- i. M_y , the resisting moment of the pile.
 - 1. $M_y = C_s f_y S$ in kN-m (in-lb) for steel piles.
 - 2. $M_y = f'_c S$ in kN-m (in-lb) for concrete piles.

STEP 5 Determine β_h for cohesive soils or η for cohesionless soils.

a. $\beta_h = \sqrt[4]{K_h b / 4EI}$ for cohesive soil, or

b. $\eta = \sqrt[5]{K_h / EI}$ for cohesionless soil.

STEP 6 Determine the dimensionless length factor.

a. $\beta_h D$ for cohesive soil, or

b. ηD for cohesionless soil.

STEP 7 Determine if the pile is long or short.

a. Cohesive soil:

1. $\beta_h D > 2.25$ (long pile).

2. $\beta_h D < 2.25$ (short pile).

Note: It is suggested that for $\beta_h D$ values between 2.0 and 2.5, both long and short pile criteria should be considered in Step 9, and then the smaller value should be used.

b. Cohesionless soil:

1. $\eta D > 4.0$ (long pile).

2. $\eta D < 2.0$ (short pile).

3. $2.0 < \eta D < 4.0$ (intermediate pile).

STEP 8 Determine other soil parameters over the embedded length of pile.

- a. The Rankine passive pressure coefficient for cohesionless soil, K_p .
 $K_p = \tan^2 (45 + \phi/2)$ where ϕ = angle of internal friction.
- b. The average effective unit weight of soil, γ' in kN/m^3 (lbs/in^3).
- c. The cohesion, c_u , in kPa (lbs/in^2).
 $c_u = 1/2$ the unconfined compressive strength, q_u .

STEP 9 Determine the ultimate lateral load for a single pile, Q_u .

- a. Short Free or Fixed-Headed Pile in Cohesive Soil.

Using D/b (and e_c/b for the free-headed case), enter Figure 9.37, select the corresponding value of $Q_u/c_u b^2$, and solve for Q_u in kN (lbs).

- b. Long Free or Fixed-Headed Pile in Cohesive Soil.

Using $M_y/c_u b^3$ (and e_c/b for the free headed case), enter Figure 9.38, select the corresponding value of $Q_u/c_u b^2$, and solve for Q_u in kN (lbs).

- c. Short Free or Fixed-Headed Pile in Cohesionless Soil.

Using D/b (and e_c/D for the free-headed case), enter Figure 9.39, select the corresponding value of $Q_u/K_p b^3 \gamma$ and solve for Q_u in kN (lbs).

- d. Long Free or Fixed-Headed Pile in Cohesionless Soil.

Using $M_y/b^4 \gamma K_p$, (and e_c/b for the free headed case), enter Figure 9.40, select the corresponding value of $Q_u/K_p b^3 \gamma$ and solve for Q_u in kN (lbs).

- e. Intermediate Free or Fixed-Headed Pile in Cohesionless Soil.

Calculate Q_u in kN (lbs) for both a short pile (Step 9c) and long pile (Step 9d) and use the smaller value.

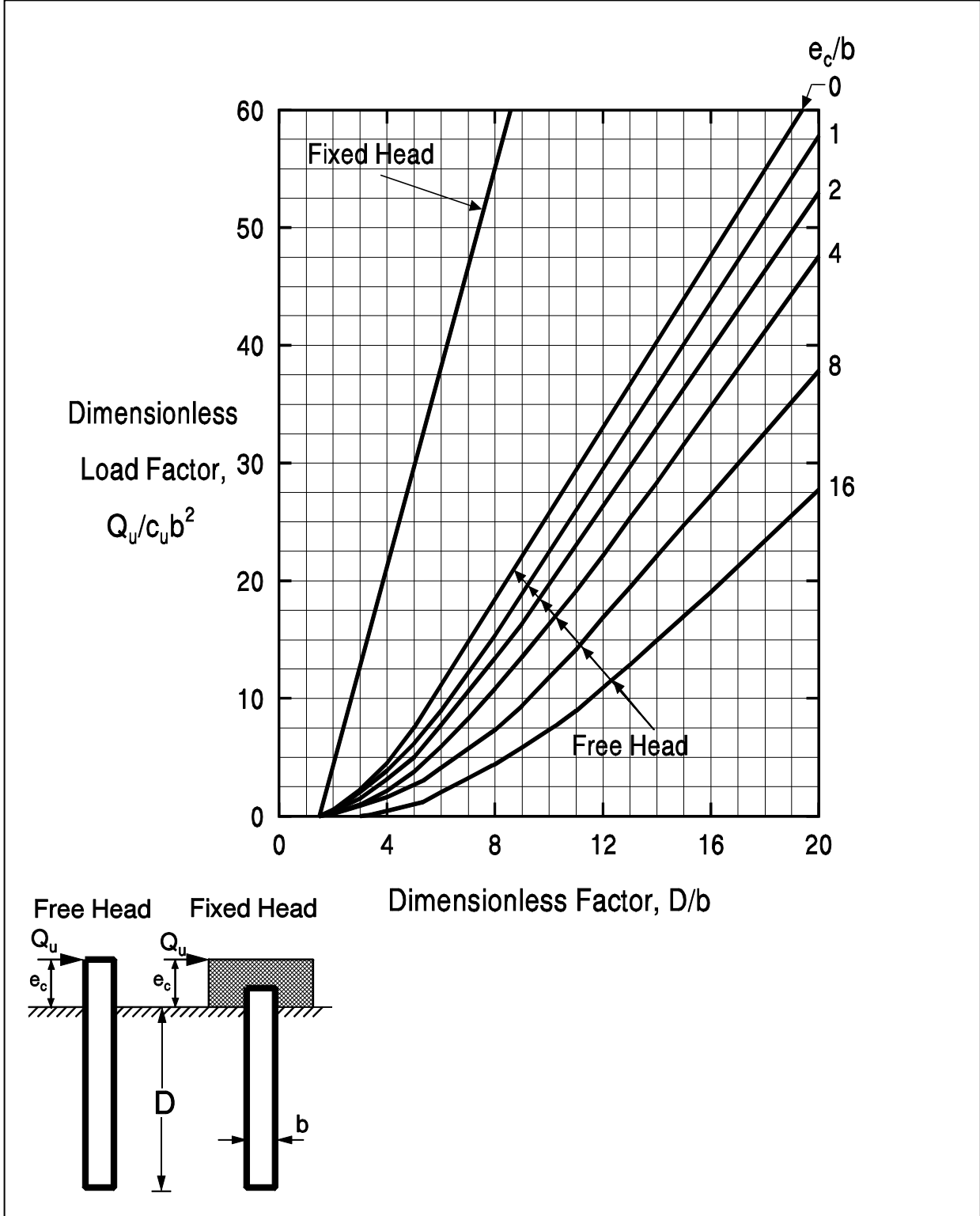


Figure 9.37 Ultimate Lateral Load Capacity of Short Piles in Cohesive Soils

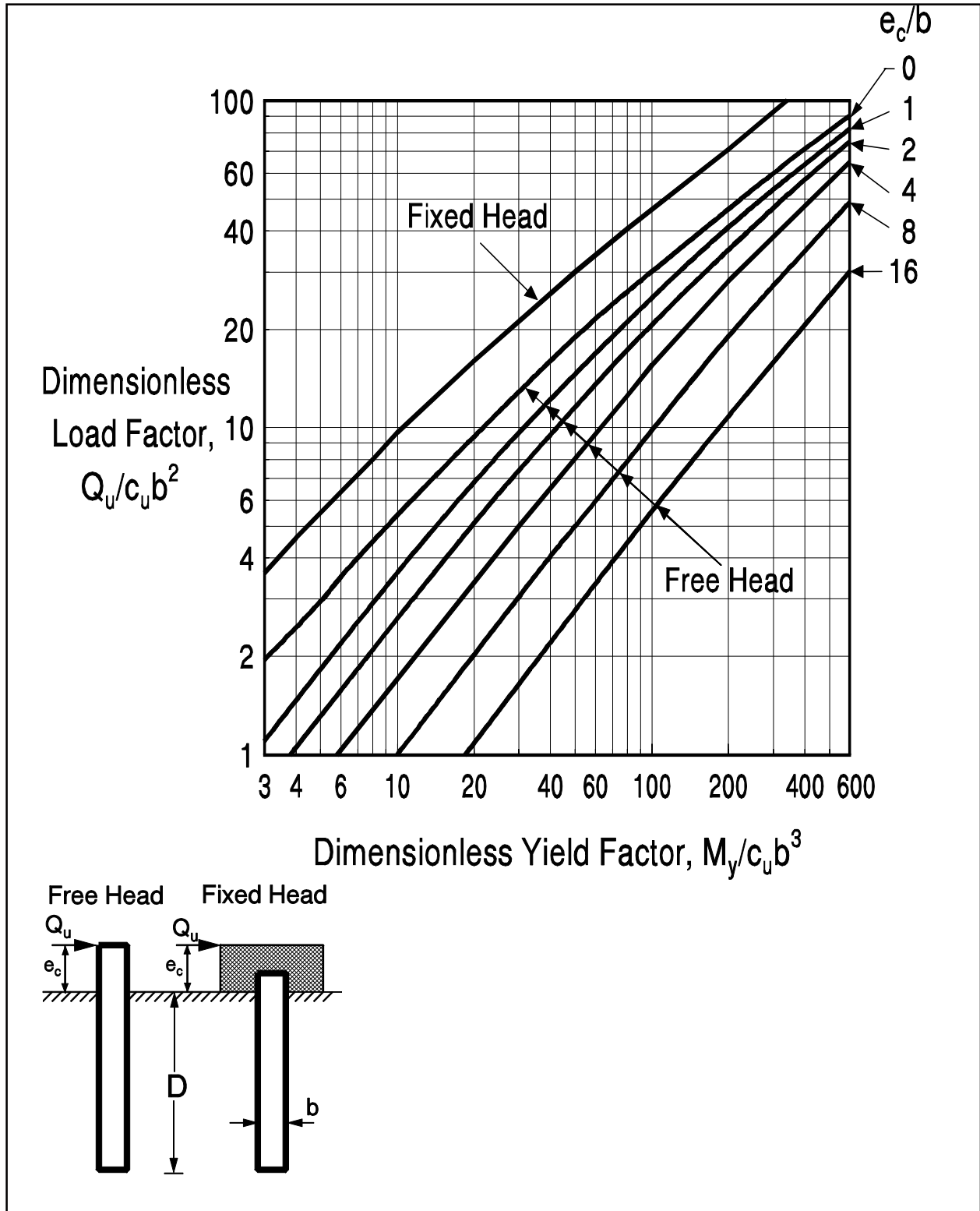


Figure 9.38 Ultimate Lateral Load Capacity of Long Piles in Cohesive Soils

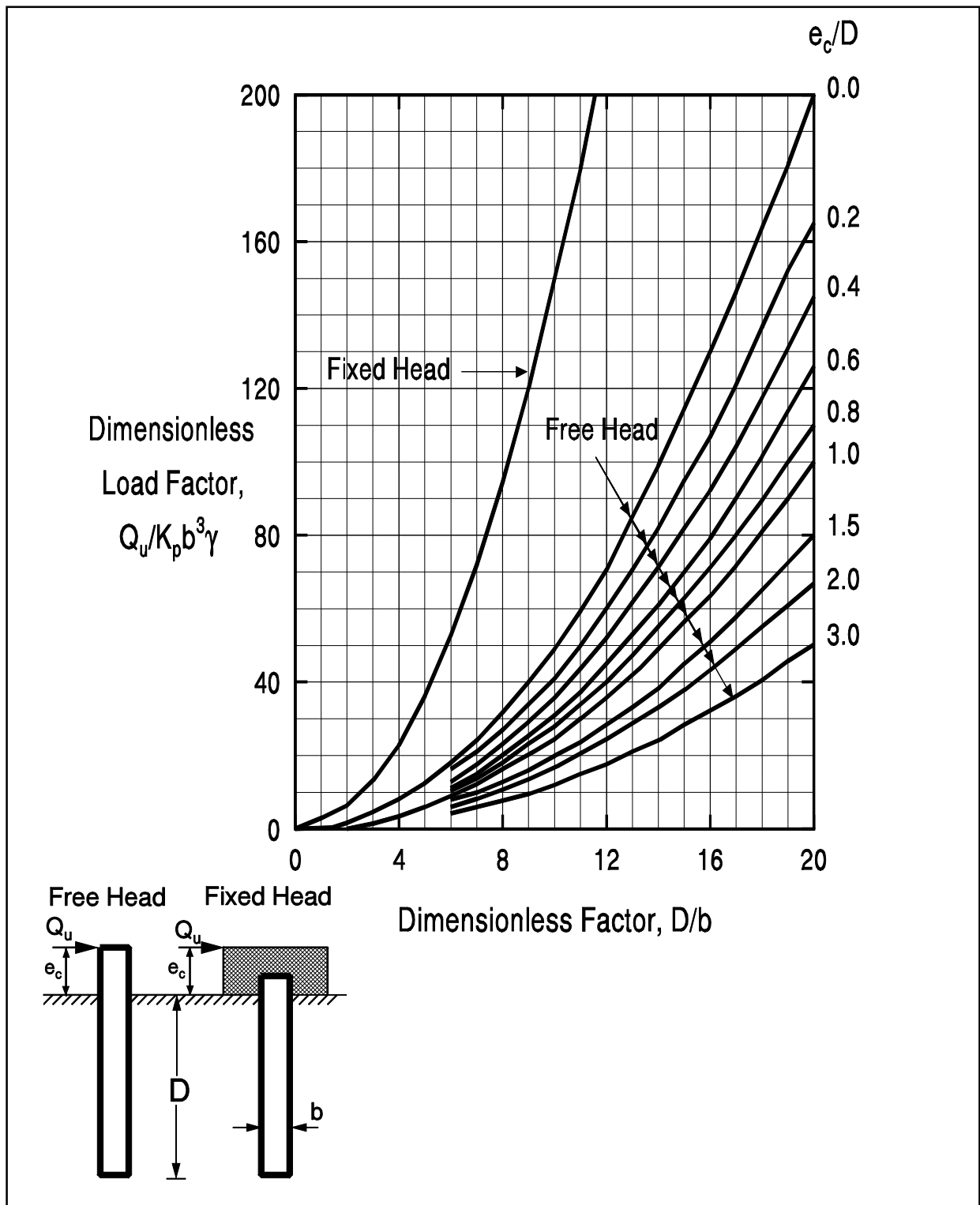


Figure 9.39 Ultimate Lateral Load Capacity of Short Piles in Cohesionless Soils

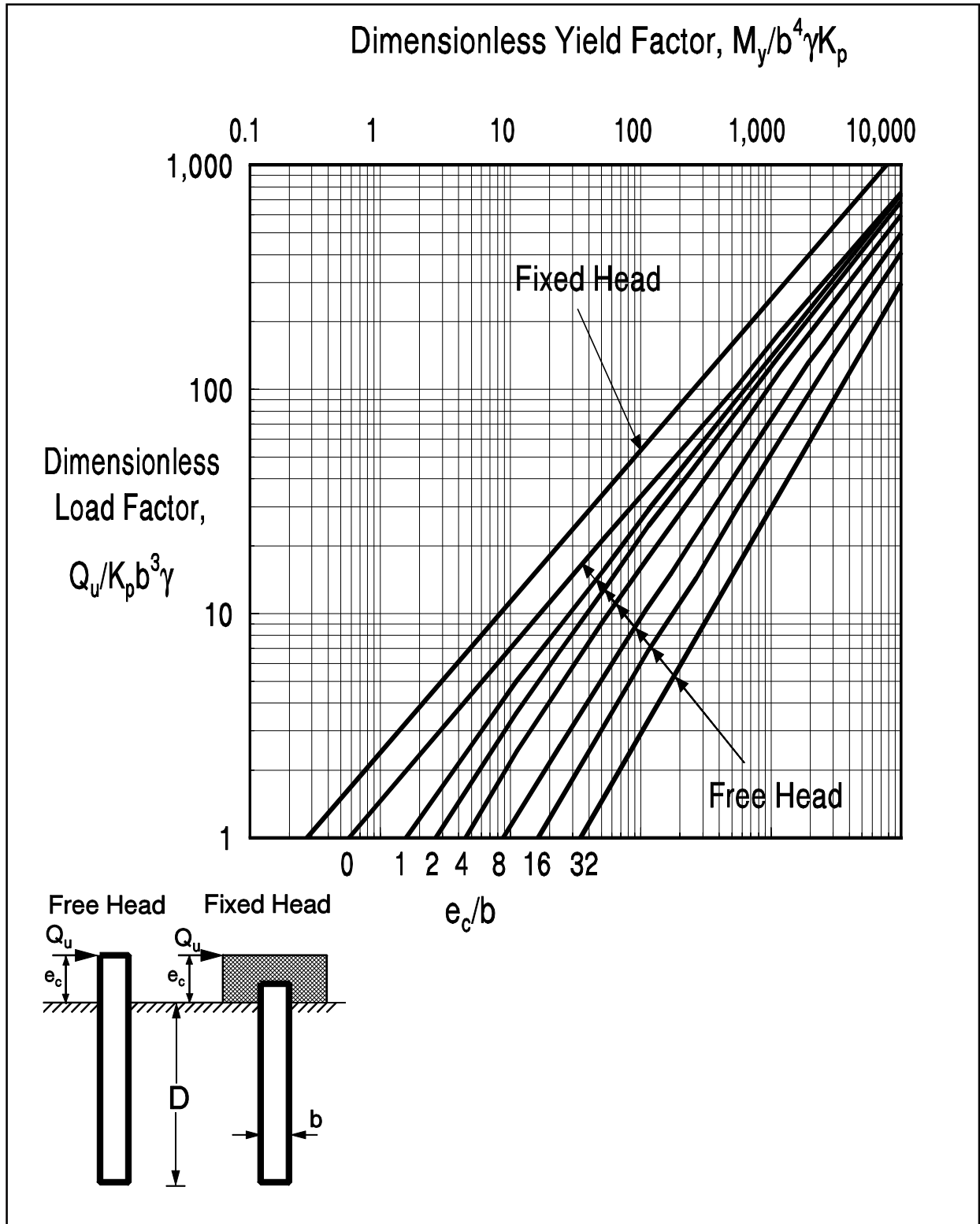


Figure 9.40 Ultimate Lateral Load Capacity of Long Piles in Cohesionless Soils

STEP 10 Calculate the maximum allowable working load for a single pile Q_m .

Calculate Q_m in kN (lbs) from the ultimate load Q_u in kN (lbs) determined in Step 9 as shown in Figure 9.41.

$$Q_m = \frac{Q_u}{2.5}$$

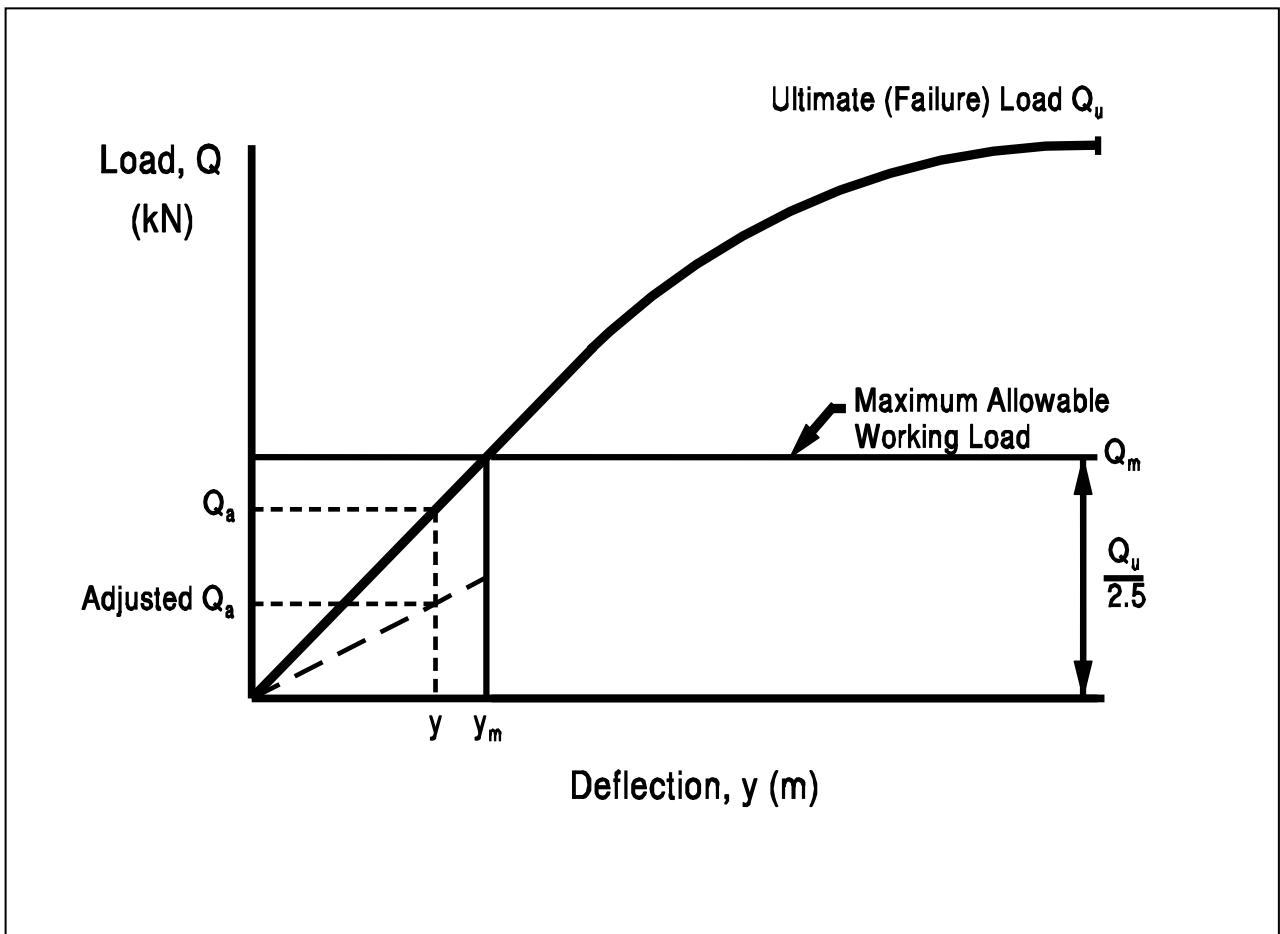


Figure 9.41 Load Deflection Relationship Used in Determination of Broms' Maximum Working Load

STEP 11 Calculate the working load for a single pile, Q_a in kN (lbs).

Calculate Q_a corresponding to a given design deflection at the ground surface, y , in meters (inches) or the deflection corresponding to a given design load. If Q_a and y are not given, substitute the value of Q_m in kN (lbs) from Step 10 for Q_a in the following cases and solve for y_m in meters (inches):

a. Free or Fixed-Headed Pile in Cohesive Soil.

Using $\beta_h D$ (and e_c/D for the free-headed case), enter Figure 9.42, select the corresponding value of $yK_h bD/Q_a$, and solve for Q_a in kN (lbs) or y in meters (inches).

b. Free or Fixed-Headed Pile in Cohesionless Soil.

Using ηD (and e_c/D for the free-headed case), enter Figure 9.43, select the corresponding value of $y(EI)^{3/5} K_h^{2/5}/Q_a D$, and solve for Q_a in kN (lbs) or y in meters (inches).

STEP 12 Compare Q_a to Q_m .

If $Q_a > Q_m$, use Q_m and calculate y_m (Step 11).

If $Q_a < Q_m$ use Q_a and y .

If Q_a and y are not given, use Q_m and y_m .

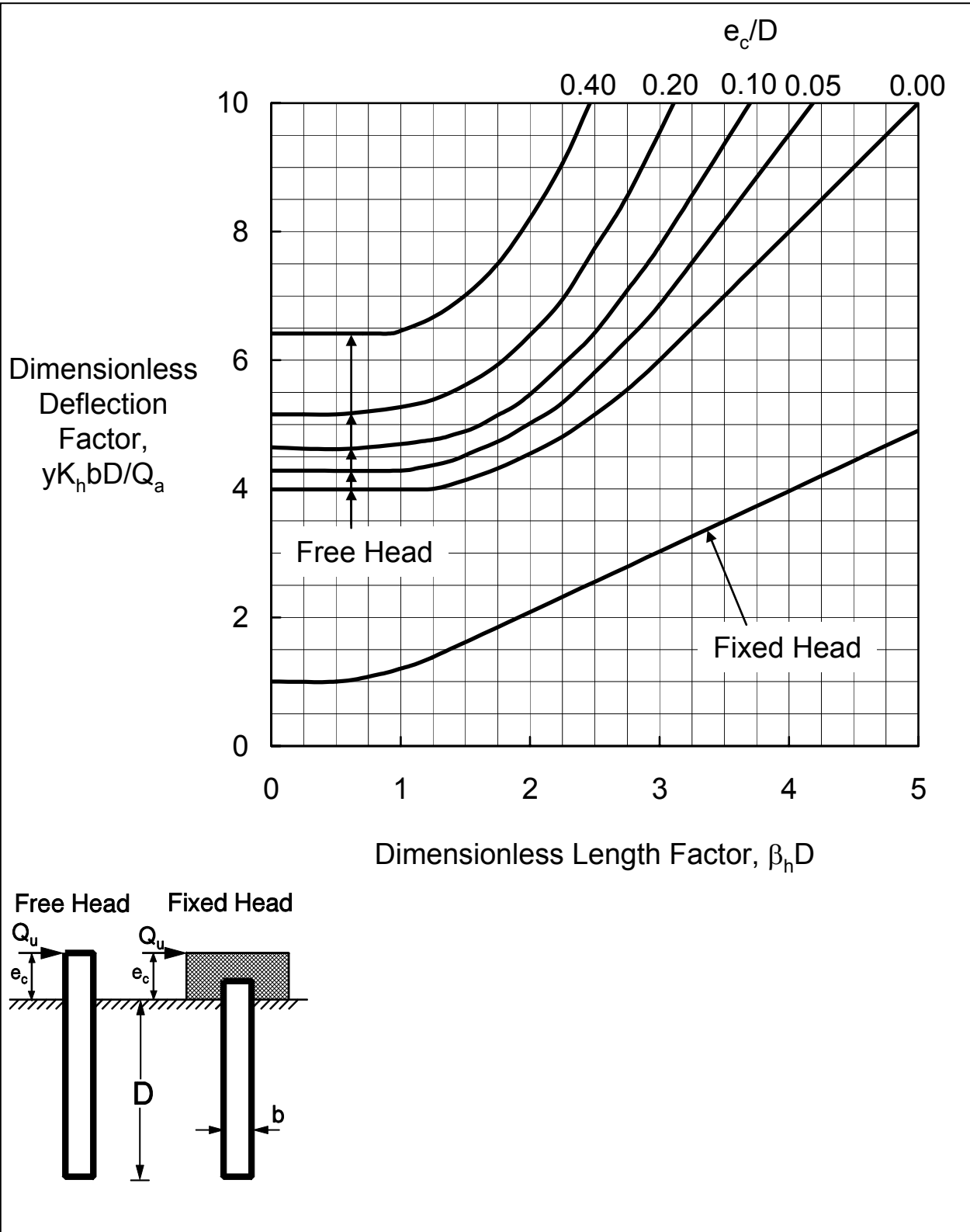


Figure 9.42 Lateral Deflection at Ground Surface of Piles in Cohesive Soils

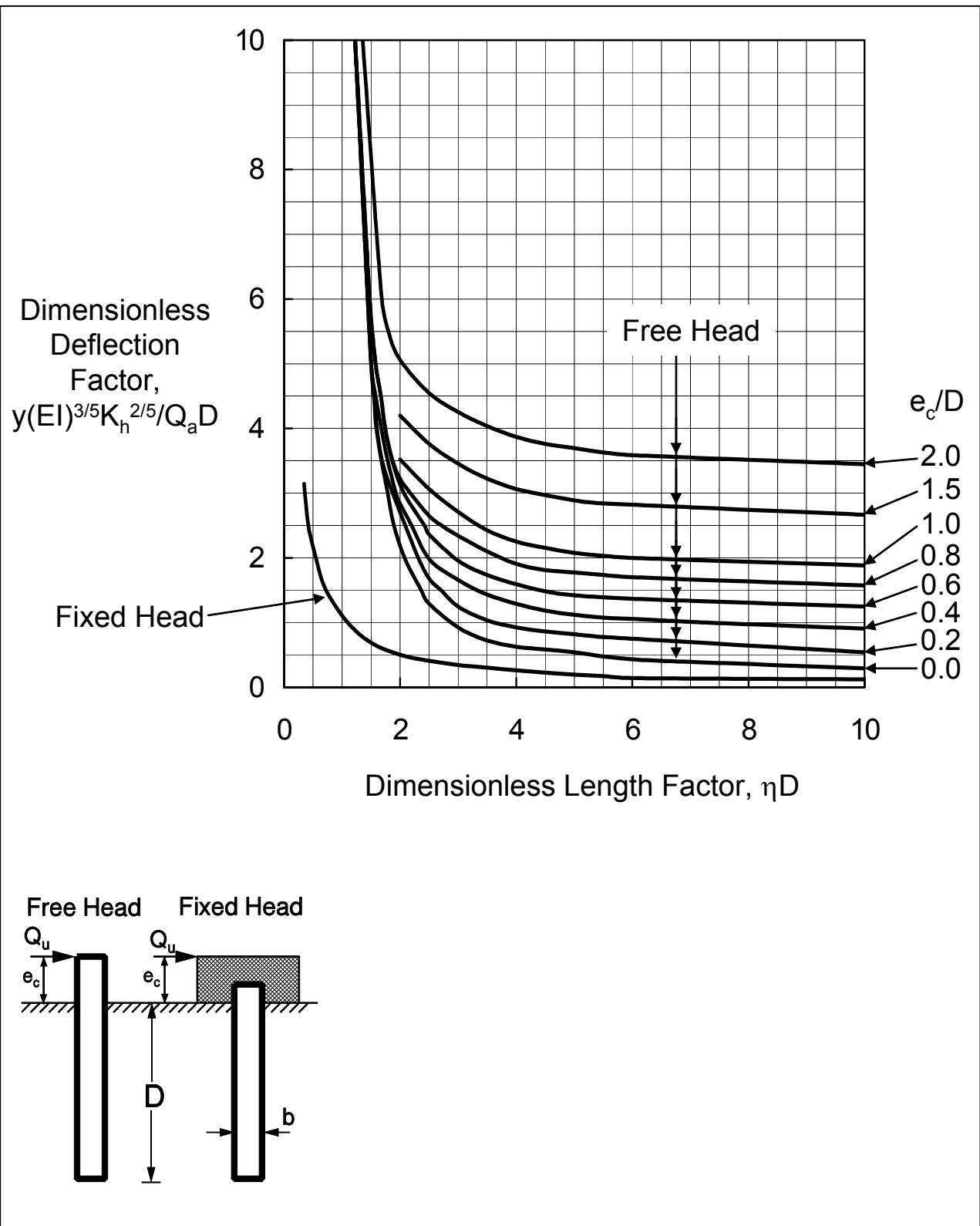
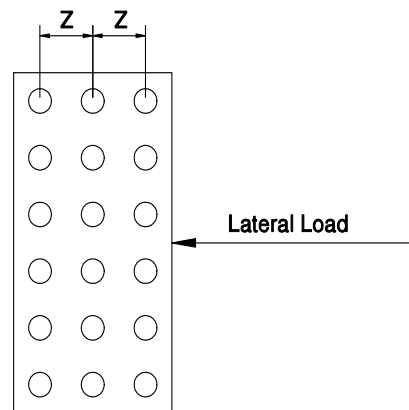


Figure 9.43 Lateral Deflection at Ground Surface of Piles in Cohesionless Soils

STEP 13 Reduce the allowable load from Step 12 for pile group effects and the method of pile installation.

- a. Group reduction factor determined by the center to center pile spacing, z , in the direction of load.

| z | Reduction Factor |
|-----|------------------|
| 8b | 1.0 |
| 6b | 0.8 |
| 4b | 0.5 |
| 3b | 0.4 |



- b. Method of installation reduction factor.

1. For driven piles use no reduction.
2. For jetted piles use 0.75 of the value from Step 13a.

STEP 14 Determine pile group lateral capacity.

The total lateral load capacity of the pile group equals the adjusted allowable load per pile from Step 13b times the number of piles. The deflection of the pile group is the value selected in Step 12. It should be noted that no provision has been made to include the lateral resistance offered by the soil surrounding an embedded pile cap.

Special Note

Inspection of Figures 9.39 and 9.40 for cohesionless soils indicates that the ultimate load Q_u is directly proportional to the effective soil unit weight, γ . As a result, the ultimate load for short piles in submerged cohesionless soils will be about 50 percent of **the value** for the same soil in a dry state. For long **piles**, the reduction in Q_u is somewhat less than 50 percent due to the partially offsetting effect that the reduction in γ has on the dimensionless yield factor. In addition to these considerations, it should be noted that the coefficient of horizontal subgrade reaction K_h is less for the submerged case (Table 9-14) and thus the deflection will be greater than for the dry state.

9.7.3.3 Reese's LPILE Method

The interaction of a pile-soil system subjected to lateral load has long been recognized as a complex function of nonlinear response characteristics of both pile and soil. The most widely used nonlinear analysis method is the p-y method, where p is the soil resistance per unit pile length and y is the lateral soil or pile deflection. This method, illustrated in Figure 9.44, models the soil resistance to lateral load as a series of nonlinear springs.

Reese (1984, 1986) has presented procedures for describing the soil response surrounding a laterally loaded pile for various soil conditions by using a family of p-y curves. The procedures for constructing these curves are based on experiments using full-sized, instrumented piles and theories for the behavior of soil under stress.

The soil modulus E_s is defined as follows:

$$E_s = -\frac{p}{y}$$

The negative sign indicates that the soil resistance opposes pile deflection. The soil modulus, E_s , is the secant modulus of the p-y curve and is not constant except over a small range of deflections. Typical p-y curves are shown in Figure 9.45. Ductile p-y curves, such as curve A, are typical of the response of soft clays under static loading and sands. Brittle p-y curves, such as curve B, can be found in some stiff clays under dynamic loading conditions.

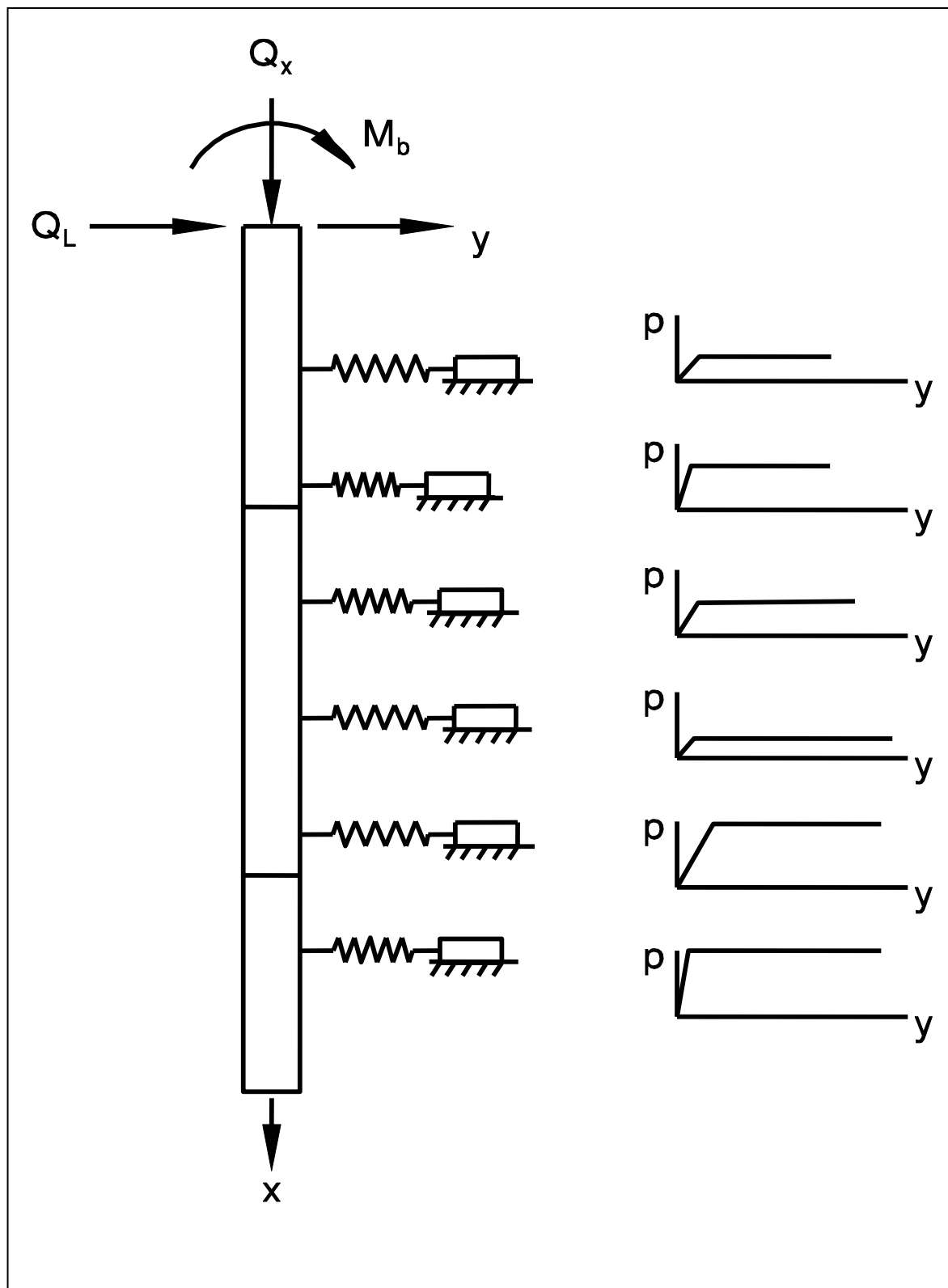


Figure 9.44 LPILE Pile-Soil Model

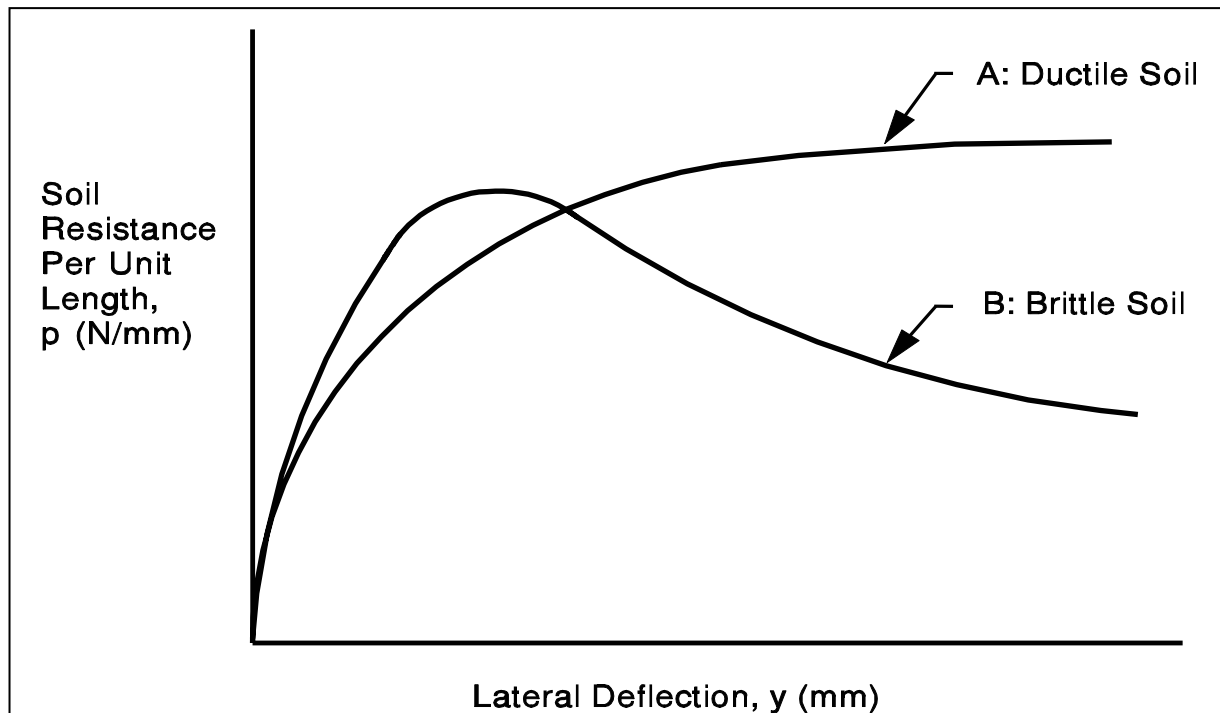


Figure 9.45 Typical p-y Curves for Ductile and Brittle Soil (after Coduto, 1994)

The factor most influencing the shape of the p-y curve is the soil properties. However, the p-y curves also depend upon depth, soil stress-strain relationships, pile width, water table location, and loading conditions (static or cyclic). Procedures for constructing p-y curves for various soil and water table conditions as well as static or cyclic loading conditions are provided in the LPILE program documentation by Reese et al., (2000).

Procedures for p-y curve development cover the following soil and water table conditions:

1. Soft clays below the water table.
2. Stiff clays below the water table.
3. Stiff clays above the water table.
4. Sands above or below the water table.

The LPILE program solves the nonlinear differential equations representing the behavior of the pile-soil system to lateral (shear and moment) loading conditions in a finite difference formulation using Reese's p-y method of analysis. The strongly nonlinear reaction of the surrounding soil to pile-soil deflection is represented by the p-y curve prescribed to act on each discrete element of the embedded pile. For each set of applied boundary (static)

loads the program performs an iterative solution which satisfies static equilibrium and achieves an acceptable compatibility between force and deflection (p and y) in every element.

The shape and discrete parameters defining each individual p - y curve may be input by the user or generated by the program. Layered soil systems are characterized by conventional geotechnical data including soil type, shear strength, density, depth, and stiffness parameters, and whether the loading conditions are monotonic or cyclic in nature.

In LPILE, the influence of applied loads (axial, lateral and moment) at each element can be modeled with flexural rigidity varying as a function of applied moment. In this manner, progressive flexural damage such as cracking in a reinforced concrete pile can be treated more rigorously. The LPILE program code includes a subroutine which calculates the value of flexural rigidity at each element under the boundary conditions and resultant pile-soil interaction conditions.

LPILE problem data is input through a series of menu-driven screens. Detailed information concerning the software can be found in the LPILE program user's manual by Reese et al. (2000). The user's manual includes useful guidelines for integrating LPILE analyses into the overall design process for laterally loaded deep foundations, and example problems.

The LPILE computer printout file summarizes the input information and the analysis results. The input data summarized includes the pile geometry and properties, and soil strength data. Output information includes the generated p - y curves at various depths below the pile head and the computed pile deflections, bending moments, stresses and soil moduli as functions of depth below the pile head. This information allows an analysis of the pile's structural capacity. Internally generated (or input) values of flexural rigidity for cracked or damaged pile sections are also output. Graphical presentations versus depth include the computed deflection, slope, moment, and shear in the pile, and soil reaction forces similar to those illustrated in Figure 9.46.

The LPILE analyses characterize the behavior of a single pile under lateral loading conditions. A detailed view is obtained of the load transfer and structural response mechanisms to design conditions. Considerable care is required in extrapolating the results to the behavior of pile groups (pile-soil-pile interaction, *etc.*), and accounting for the effects of different construction processes such as predrilling or jetting.

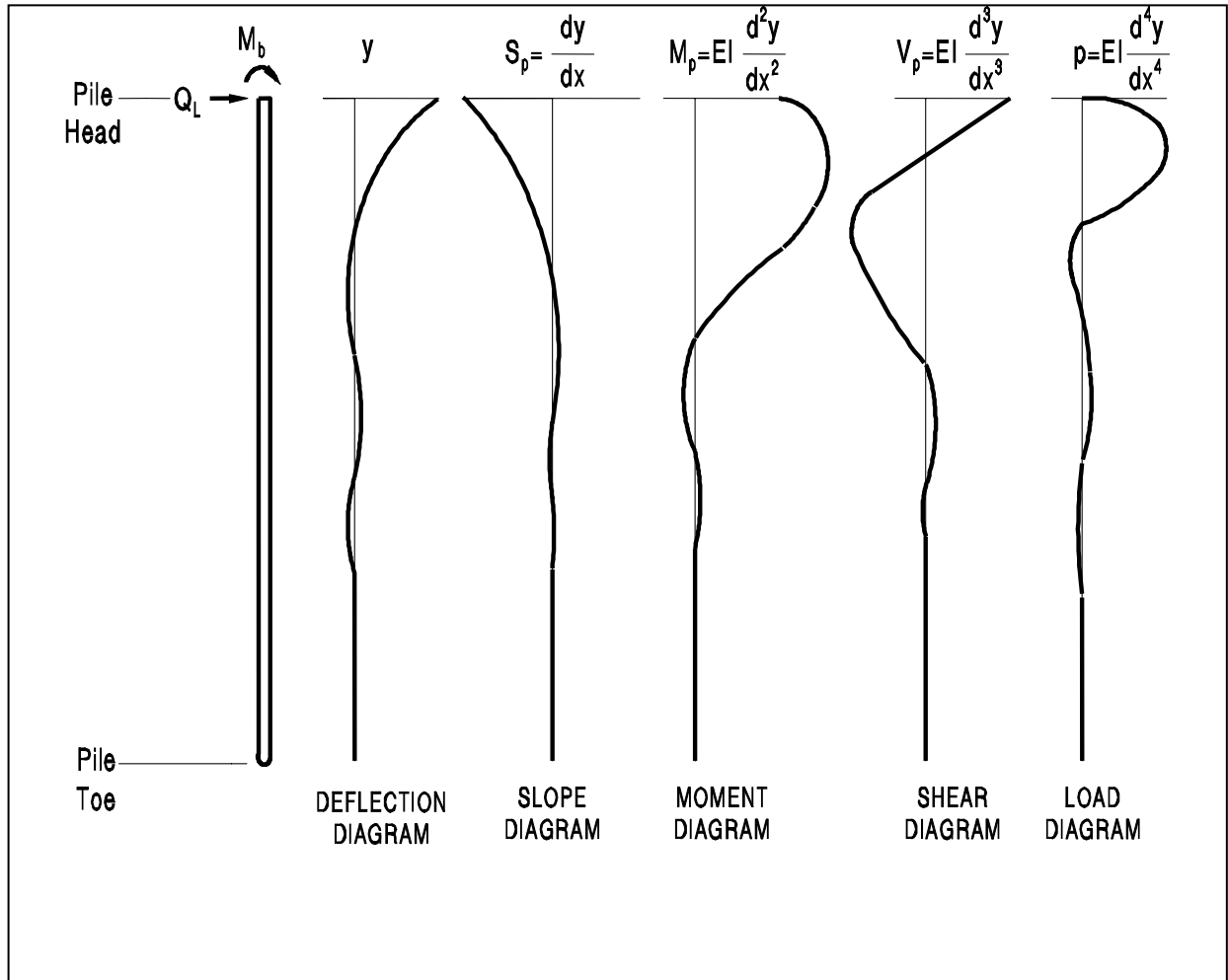


Figure 9.46 Graphical Presentation of LPILE Results (Reese, *et al.* 2000)

In any lateral analysis case, the analyst should verify that the intent of the modeling assumptions, all elastic behavior for example, is borne out in the analysis results. When a lateral load test is performed, the measured load-deflection results versus depth should be plotted and compared with the LPILE predicted behavior so that an evaluation of the validity of the p-y curves used for design can be made. Figure 9.47 illustrates a comparison between the measured load-deflection curve and one predicted by COM624P, the predecessor to the LPILE program

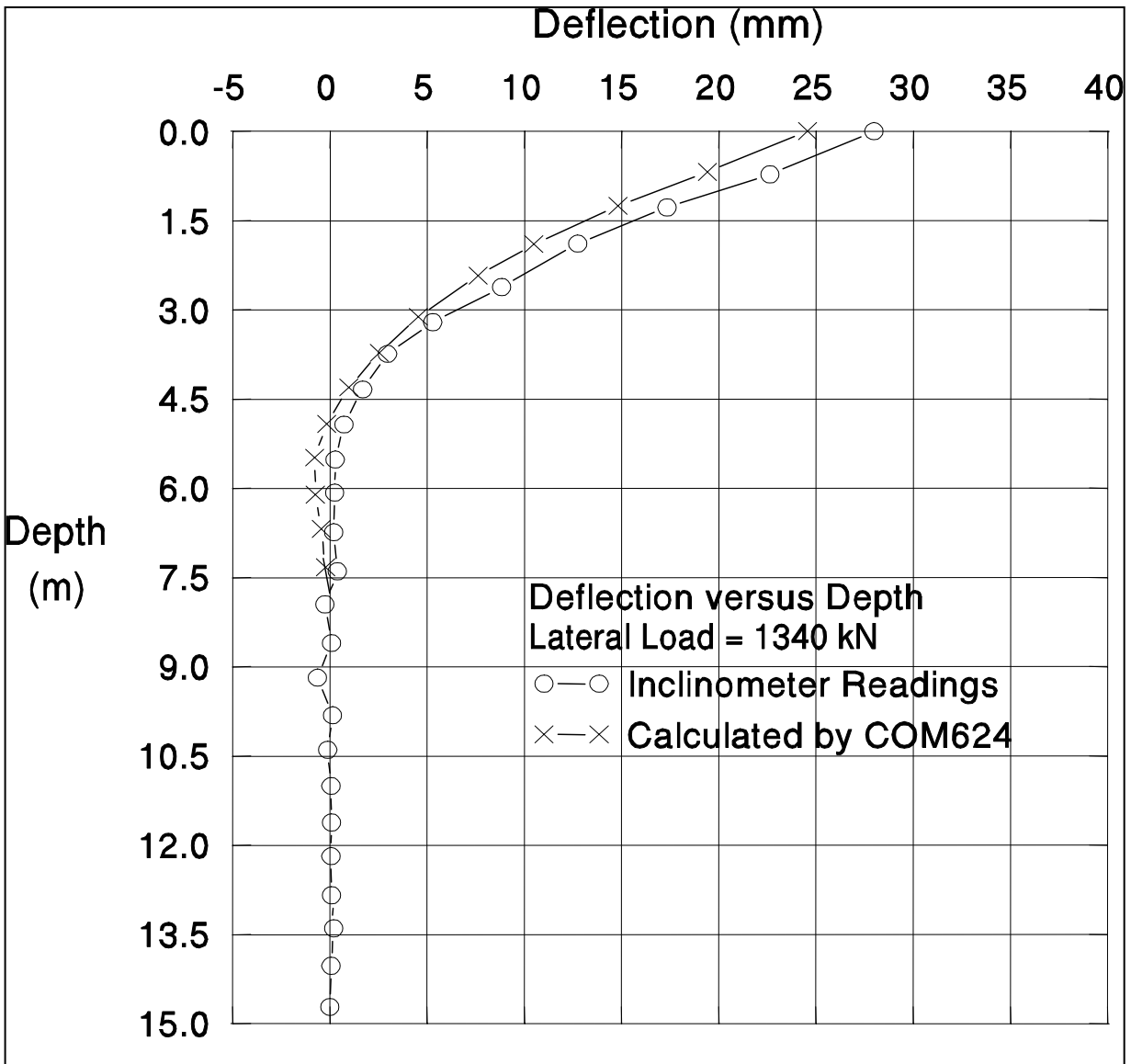


Figure 9.47 Comparison of Measured and COM624P Predicted Load-Deflection Behavior versus Depth (after Kyfor *et al.* 1992)

The opening LPILE program screen is presented in Figure 9.48. The main basic menu choices include; File, Data, Options, Computation, and Graphic. Clicking on the File menu allows the user to choice between a opening a new or existing file. File saving is also under the File menu options. A step by step procedure follows for performing a new LPILE analysis. The program user should also consult the LPILE technical and user's manuals by Reese *et al.* (2000).

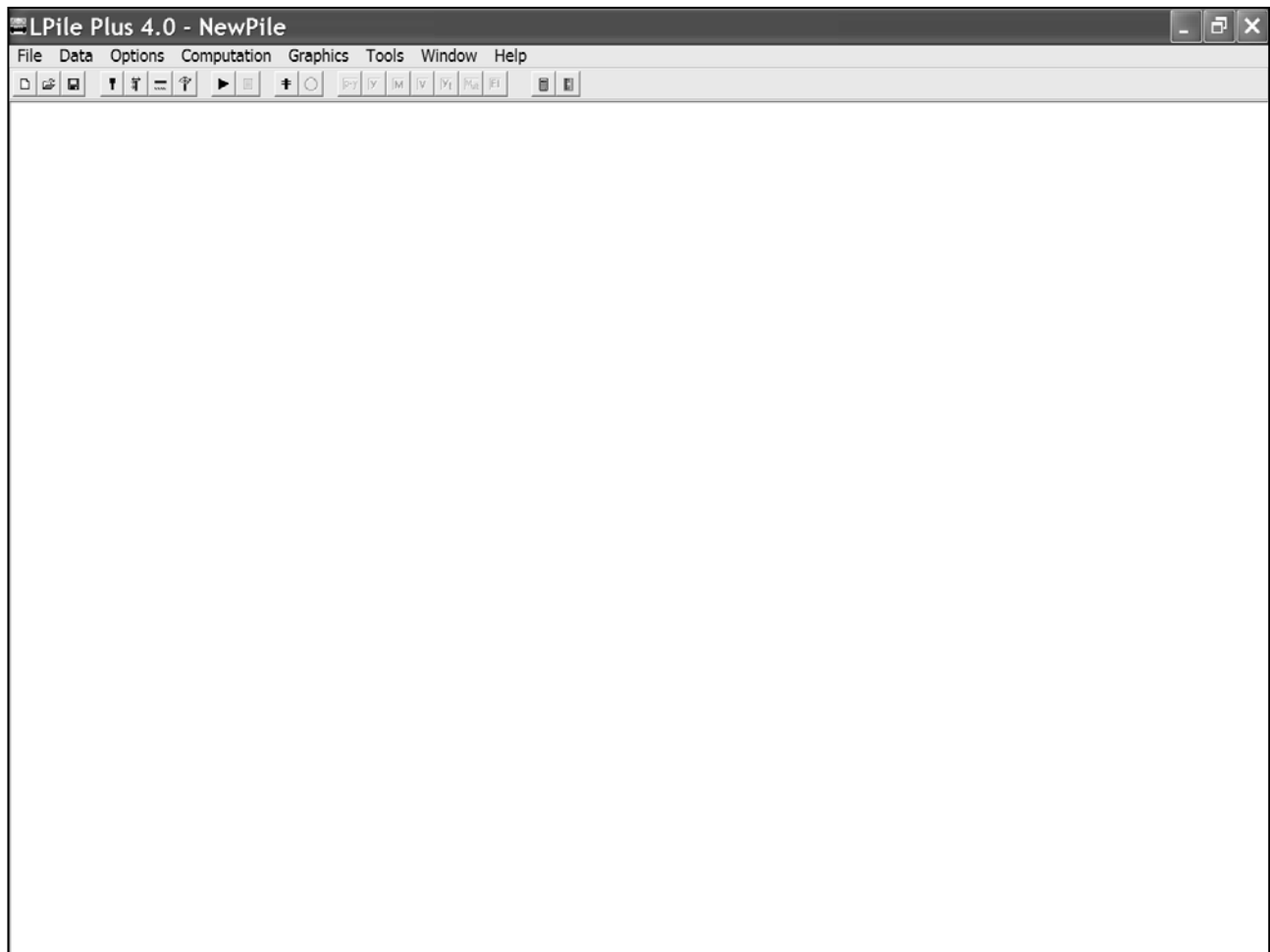


Figure 9.48 LPILE Main Screen

STEP BY STEP PROCEDURE FOR A BASIC LPILE ANALYSIS

- STEP 1 Click on the Options menu. A submenu will open to the right allowing the unit system for the analysis to be selected.
- STEP 2 Click on the Data menu to start data entry.
- STEP 3 Click on Title in the drop down window. The project title window will then appear as shown in Figure 9.49. A single line of text can then be entered to describe the project. After entering analysis description, click on the X to close the box.
- STEP 4 Next click on Pile Properties in the drop down window. The pile properties window will appear as shown in Figure 9.50.

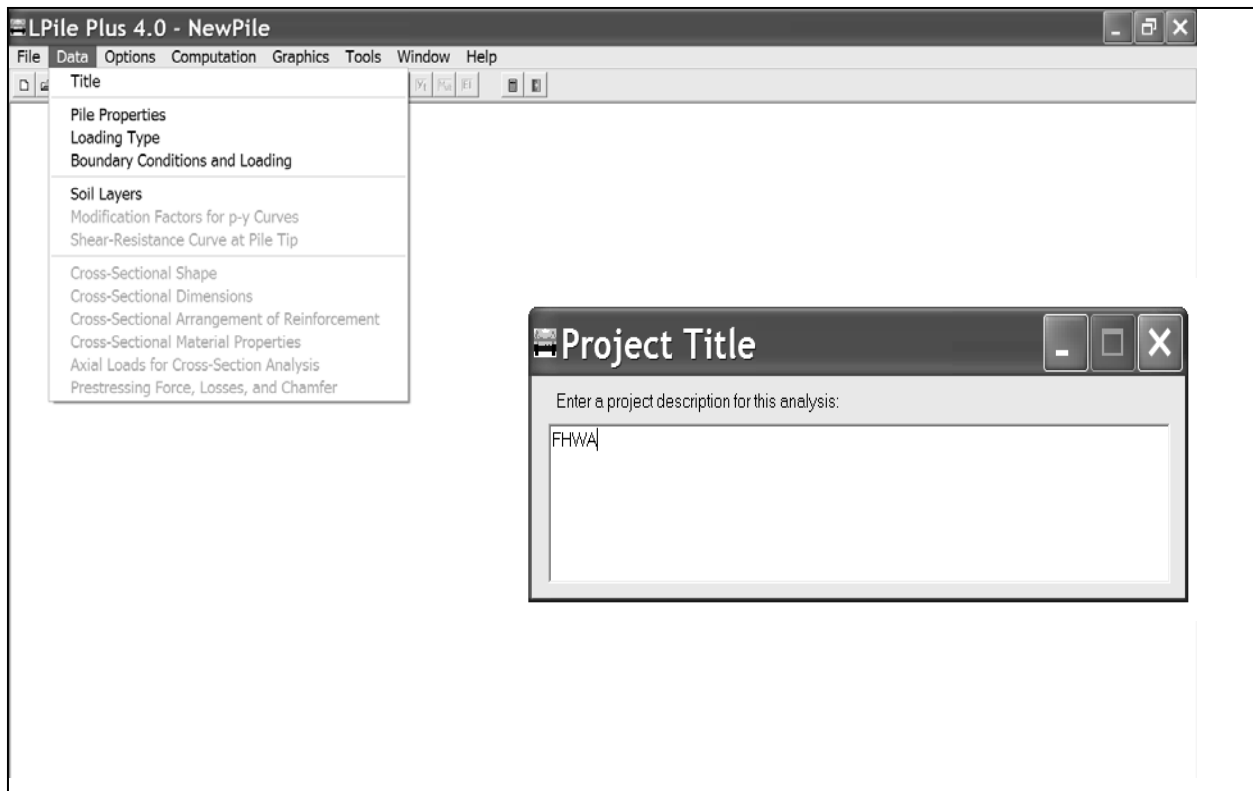


Figure 9.49 LPILE Data Menu and Project Title Window

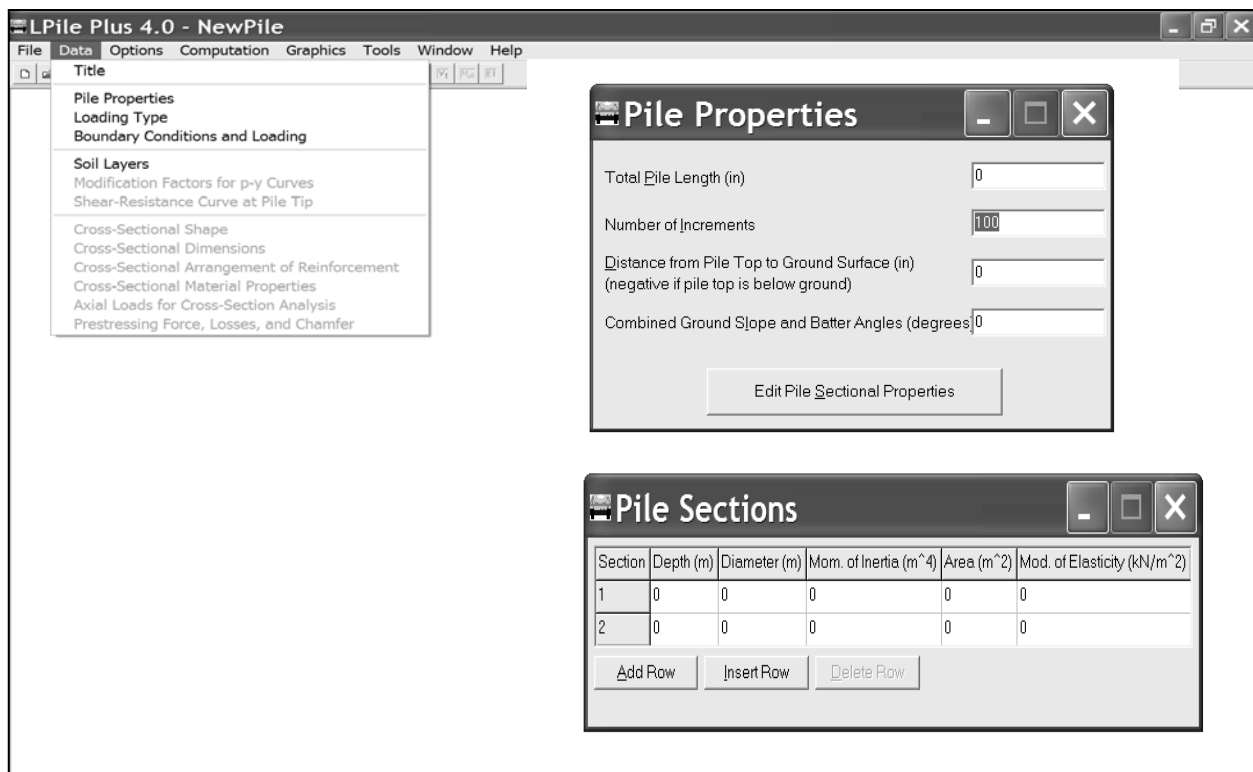


Figure 9.50 LPILE Data Menu and Pile Property and Pile Section Windows

- a. Enter the total pile length in meters (inches)
- b. Select the number of increments. The maximum number of increments a pile can be divided into is 300. Except for short piles, the number of increments is generally chosen between 80 and 200.
- c. Enter the distance from the pile head to the ground surface in meters (inches). Use a negative number if the pile head is below ground surface.
- d. If applicable, enter the combined ground slope and pile batter angle in degrees. The ground slope is defined as the angle between the sloping ground surface and a horizontal surface. The angle is positive if the pile moves downhill under the applied load and negative if the pile moves uphill. The pile batter angle from vertical is handled similarly. The batter angle is positive if the load is applied against the batter direction and negative if the load is applied with the batter direction.
- e. Click on the Edit Pile Sectional Properties box and the Pile Sections window will appear. Enter pile section information consisting of depth, diameter, moment of inertia, cross sectional area, and modulus of elasticity. For non-uniform piles, up to 10 rows of data can be entered by clicking on the Add Row box as necessary. Cross sectional area and moment of inertia data for most pile sections may be found in Appendix C.

STEP 5 Click on Loading Type in the Data menu. The Loading Type window will appear as shown in Figure 9.51.

- a. For each critical set of loading combinations, determine the axial loads, lateral loads, and bending moments to be analyzed. Load information should be supplied by the structural engineers.
- b. Select the type of loading, cyclic or static. If cyclic loading is selected, enter the number of cycles to be analyzed between 2 and 5000.
- c. If distributed lateral loads are to be analyzed, click on the "Include Distributed Lateral Loads" checkbox. This will activate a window that allows up to 10 combinations of depth and lateral load to be input. Depth entries must be in increasing order of depth.

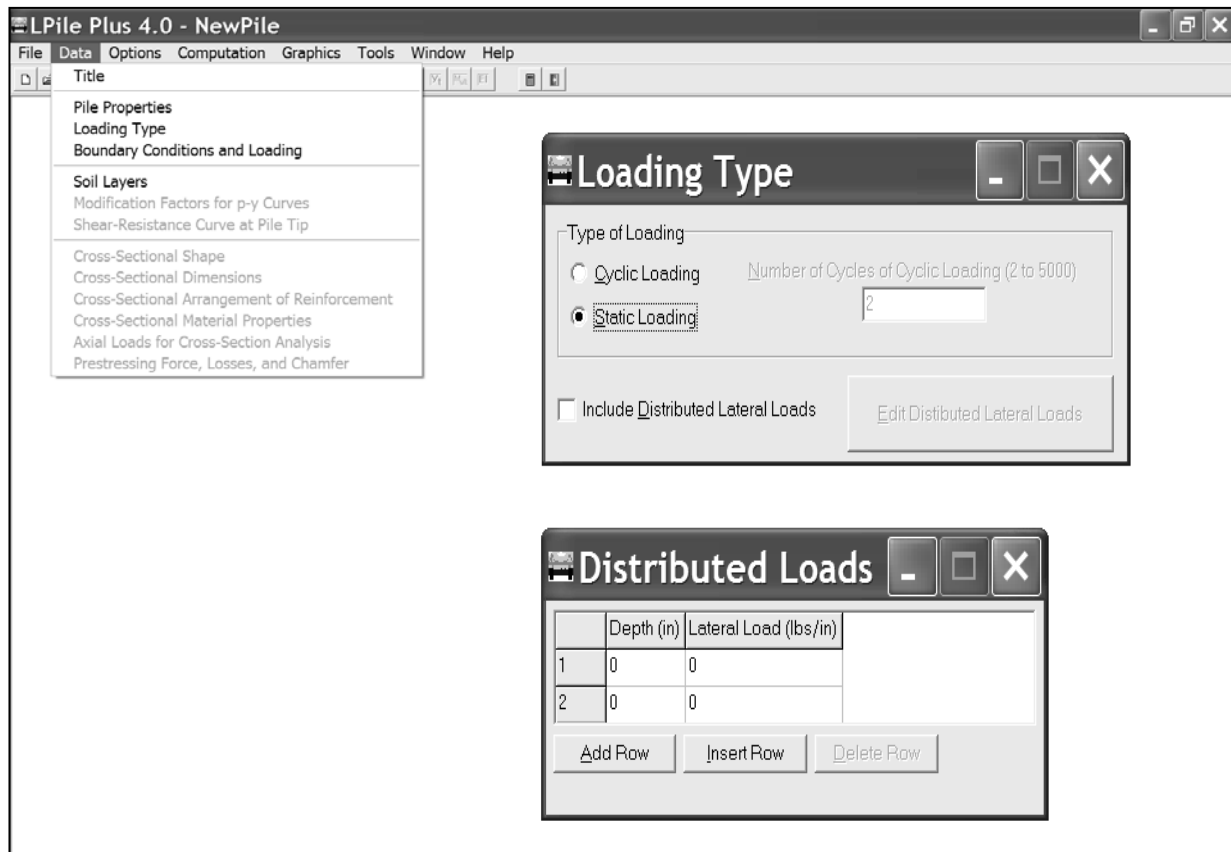


Figure 9.51 LPILE Loading Type and Distributed Loads Input Screens

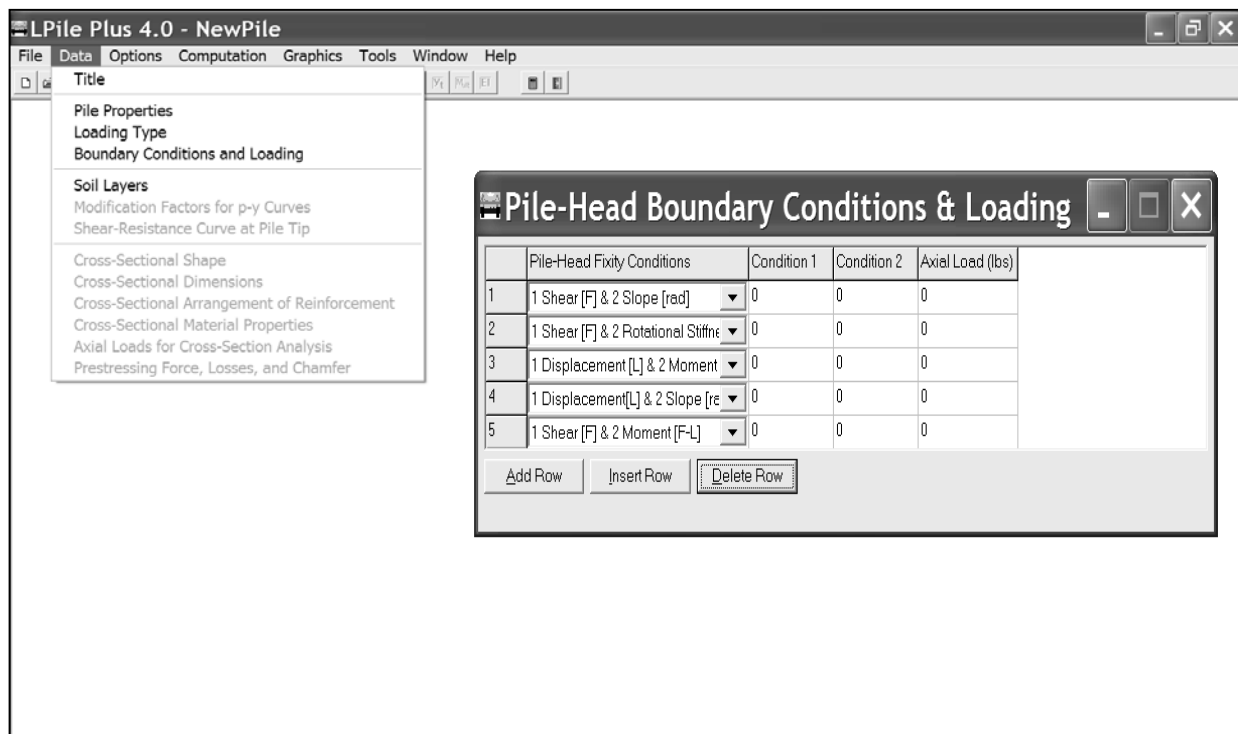


Figure 9.52 LPILE Pile Head Boundary Conditions and Loading Input Screen

STEP 6 Click on Boundary Conditions and Loading in the Data menu. The Pile Head Boundary Conditions window will appear as shown in Figure 9.52. The five available boundary condition options are depicted.

- a. Select the desired boundary condition from the dropdown list of choices. LPILE allows up to 10 rows of input boundary conditions to be analyzed. The boundary conditions are as follows:

The shear and moment case is selected to input values of applied load and applied moment at the pile head. This case is for a pile head that is free to rotate and move laterally.

The shear and slope case is selected to input values of applied lateral load and the slope of the applied load. A fixed head condition can be modeled by inputting a zero slope.

The shear and rotational stiffness case is selected to input the applied lateral load and the rotational stiffness at the pile head. A fixed head condition can be modeled by using a large rotational stiffness value. This boundary condition models an elastically restrained pile head.

The displacement and moment case is selected to input values of lateral displacement and moment at the pile head.

The displacement and slope case is selected to model lateral displacement and slope at the pile head.

- b. Enter the appropriate values for Condition 1 (first boundary condition, i.e. shear, displacement, etc.) and Condition 2 (second boundary condition, i.e. slope, rotational stiffness, etc.) along with the axial pile load. The axial pile load is used to evaluate secondary moments resulting from pile deflection.

STEP 7 Click on Soil Conditions in the Data menu. The soil layers window will then appear as shown in Figure 9.53. The nine available soil type selections are depicted and correspond to the p-y model that will be assigned to the layer.



Figure 9.53 LPILE Soil Layers and Individual Soil Property Input Screens

- For each soil layer, select the soil type and values for the top and bottom of each soil layer. Then click on data for soil properties line corresponding to the layer.
- For each soil type, a second soil property input window will appear. The user must input values for the effective unit weight and depending upon the soil type selected, values for the cohesive strength, the soil strain ϵ_{50} , the p-y modulus, the friction angle, the uniaxial compressive strength and Young's Modulus.

Values for ϵ_{50} , can be obtained from triaxial tests or an assumed value from Table 9-15 can be selected. Values for the p-y modulus, k, can be measured from laboratory or in-situ test data or assumed value from Table 9-16 can be chosen.

- c. After inputting the required soil information for the selected soil type, close the soil property box and return to the soil layer window. Add rows as appropriate for the soil model and repeat steps a and b for each layer

| TABLE 9-15 REPRESENTATIVE VALUES OF ϵ_{50} FOR CLAYS | | |
|---|--|-----------------|
| Clay Consistency | Average Undrained Shear Strength, c_u in kPa (ksf) | ϵ_{50} |
| Soft Clay | 12 – 24 (0.25 – 0.50) | 0.02 |
| Medium Clay | 24 – 48 (0.50 - 1.0) | 0.01 |
| Stiff Clay | 48 – 96 (1.0 – 2.0) | 0.007 |
| Very Stiff Clay | 96 – 192 (2.0 – 4.0) | 0.005 |
| Hard Clay | 192 – 383 (4.0 – 8.0) | 0.004 |

STEP 8 Click on the Analysis Type in the Options menu. The Analysis Type window will then appear as shown in Figure 9.54. The four analysis type options available are as follows:

Type 1 – Computations of Pile Response with User Specified, Constant EI (Basic Modeling). This analysis uses the modulus of elasticity, E, and moment of inertia, I, that were input in the pile properties section.

Type 2 -- Computations of Ultimate Bending Moment of Cross Section (Section Design). Selection of this analysis method activates additional Data menu input screens (not described herein) on the pile cross sectional shape, the pile cross sectional dimensions, the rebar arrangement, the cross sectional material properties and the axial loads for the cross section analysis. This analysis option computes the ultimate bending moment and the nonlinear variation of flexural stiffness with applied moment.

| TABLE 9-16 REPRESENTATIVE p-y MODULUS VALUES, k, FOR CLAYS AND SANDS | | | | |
|--|---|--|---|---|
| Soil Type | Avg. Undrained Shear Strength, c_u in kPa (ksf) | Soil Condition Relative to Water Table | k - Static Loading in kN/m^3 (lb/in ³) | k - Cyclic Loading in kN/m^3 (lb/in ³) |
| Soft Clay | 12 – 24 (0.25-0.50) | --- | 8,140 (30) | |
| Medium Clay | 24 – 48 (0.50 -1.0) | --- | 27,150 (100) | |
| Stiff Clay | 48 – 96 (1.0 – 2.0) | --- | 136,000 (500) | 54,300 (200) |
| Very Stiff Clay | 96 – 192 (2.0 – 4.0) | --- | 271,000 (1000) | 108,500 (400) |
| Hard Clay | 192 – 383 (4.0 – 8.0) | --- | 543,000 (2000) | 217,000 (1000) |
| Loose Sand | --- | Submerged | 5,430 (20) | 5,430 (20) |
| Loose Sand | --- | Above | 6,790 (25) | 6,790 (25) |
| Medium Dense Sand | --- | Submerged | 16,300 (60) | 16,300 (60) |
| Medium Dense Sand | --- | Above | 24,430 (90) | 24,430 (90) |
| Dense Sand | --- | Submerged | 33,900 (125) | 33,900 (125) |
| Dense Sand | --- | Above | 61,000 (225) | 61,000 (225) |

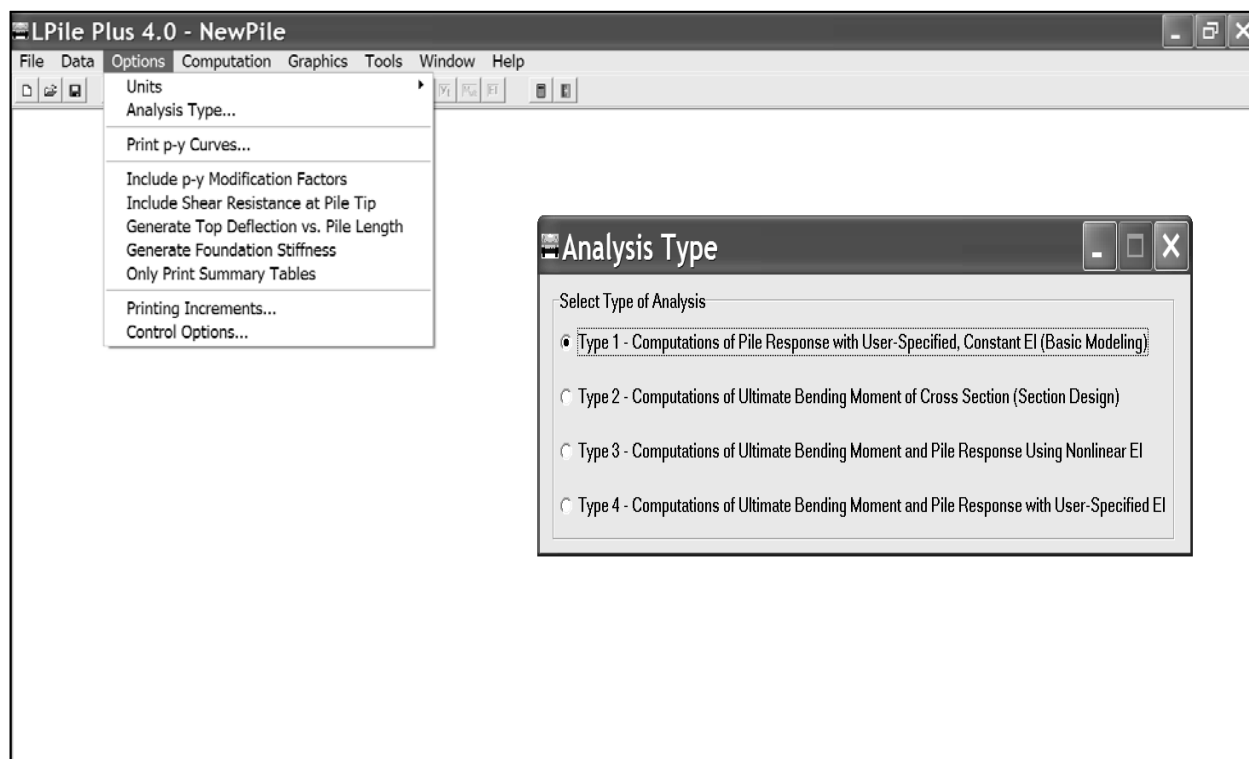


Figure 9.54 LPILE Analysis Type Input Screen

Type 3 – Computations of Ultimate Bending Moment and Pile Response Using Nonlinear EI. This analysis type, the pile cross section is analyzed to determine the ultimate bending moment and the variation of flexural stiffness with applied bending moment. LPILE then analyzes the laterally loaded pile using the nonlinear flexural stiffness values determined in the analysis of the cross section.

Type 4 – Computations of Ultimate Bending Moment and Pile Response with User-Specified EI. By selecting this analysis type, LPILE first analyses the pile cross section to determine the ultimate bending moment and the variation of flexural stiffness with applied bending moment. LPILE then analyzes the laterally loaded pile using the flexural stiffness computed by the user specified modulus of elasticity, E , and moment of inertia, I .

STEP 9 Click on Run Analysis in the Computations menu. After the analysis is completed, click on View Output Text File to review results. Results can also be printed after they are displayed on the screen. The LPILE Computation menu options are displayed in Figure 9.55.

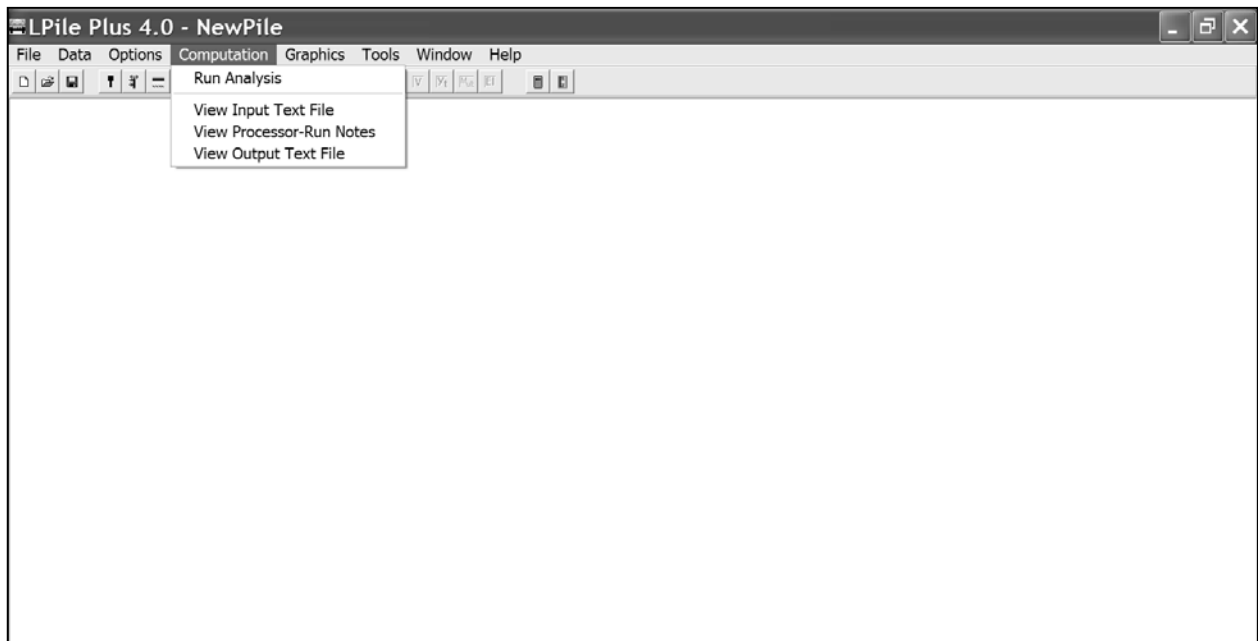


Figure 9.55 LPILE Computation Menu Screen

STEP 10 Review output to determine the pile structural acceptability by finding the ultimate lateral load that produces a plastic hinge (ultimate bending moment).

- a. In this step the lateral, axial and bending moments used in the analysis should be ultimate values.
- b. For concrete piles, the value of I for a cracked section can be determined directly by LPILE for each loading step. Alternatively, variations in E and I can be entered as a function of depth along the pile.

STEP 11 Determine pile acceptability based on deflection under service loads.

- a. Use design loading conditions and not ultimate values for lateral and axial loads and bending moments.
- b. Compare LPILE predicted movement with performance criteria.

STEP 12 Optimize required pile section and pile penetration depth for lateral loading conditions to meet performance criteria as necessary.

After a basic LPILE analysis is performed, additional analyses can be used to refine the lateral pile design. Evaluation of pile group performance is discussed in Section 9.8.4.

9.8 DESIGN OF PILE GROUPS

The previous sections of this chapter dealt with design procedures for single piles. However piles for almost all highway structures are installed in groups, due to the heavy foundation loads. The next sections of this chapter will address the foundation design procedures for evaluating the axial compression capacity of pile groups as well as the settlement of pile groups under axial compression loads. The axial compression capacity and settlement of pile groups are interrelated and are therefore presented in sequence. Sections covering the design of pile groups for uplift and lateral load capacity will be presented following the axial compression capacity and settlement of pile group sections. At the present time, pile group design computations are primarily performed using computer programs designed for this purpose such as FB-Pier or Group 6.0 rather than the simple hand calculations presented in this manual.

The efficiency of a pile group in supporting the foundation load is defined as the ratio of the ultimate capacity of the group to the sum of the ultimate capacities of the individual piles comprising the group. This may be expressed in equation form as:

$$\eta_g = \frac{Q_{ug}}{nQ_u}$$

Where: η_g = Pile group efficiency.
 Q_{ug} = Ultimate capacity of the pile group.
 n = Number of piles in the pile group.
 Q_u = Ultimate capacity of each individual pile in the pile group.

If piles are driven into compressible cohesive soil or in dense cohesionless material underlain by compressible soil, then the ultimate axial compression capacity of a pile group may be less than that of the sum of the ultimate axial compression capacities of the individual piles. In this case, the pile group has a group efficiency of less than 1. In cohesionless soils, the ultimate axial compression capacity of a pile group is generally greater than the sum of the ultimate axial compression capacities of the individual piles comprising the group. In this case, the pile group has a group efficiency greater than 1.

The settlement of a pile group is likely to be many times greater than the settlement of an individual pile carrying the same load per pile as each pile in the pile group. Figure 9.56(a) illustrates that for a single pile, only a small zone of soil around and below the pile toe is subjected to vertical stress. Figure 9.56(b) illustrates that for a pile group, a considerable depth of soil around and below the pile group is stressed. The settlement of the pile group may be large, depending on the compressibility of the soils within the stressed zone.

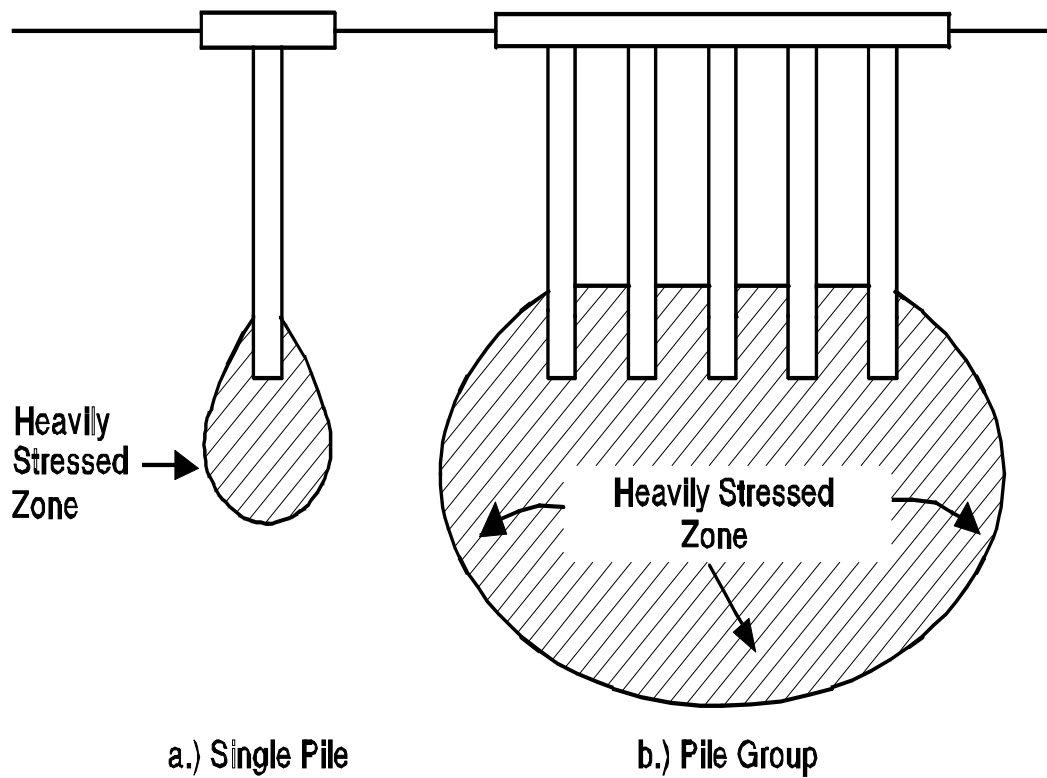


Figure 9.56 Stress Zone from Single Pile and Pile Group (after Tomlinson, 1994)

The soil medium supporting a pile group is also subject to overlapping stress zones from individual piles in the group. The overlapping effect of stress zones for a pile group supported by shaft resistance is illustrated in Figure 9.57.

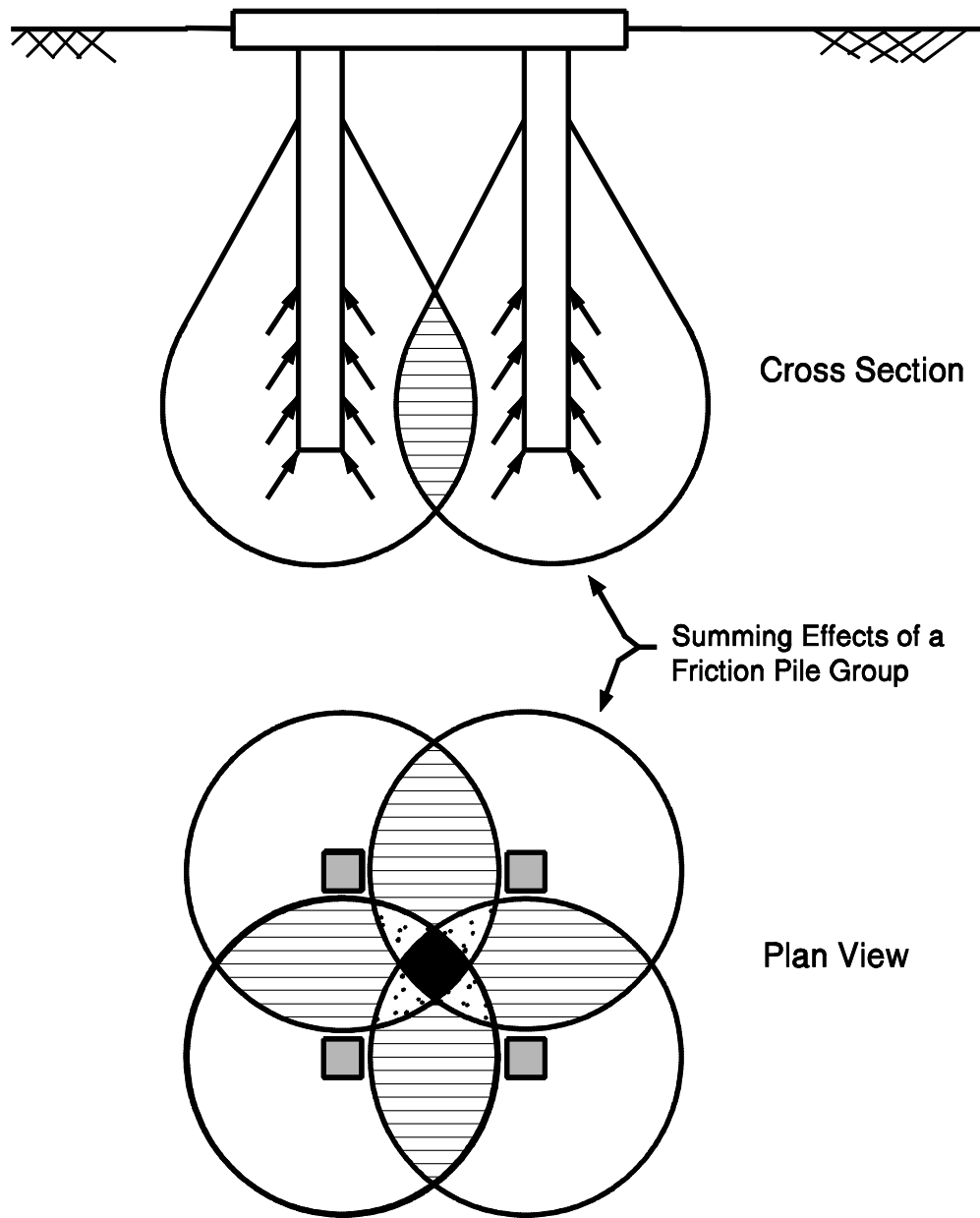
9.8.1 Axial Compression Capacity of Pile Groups

9.8.1.1 Pile Group Capacity in Cohesionless Soils

In cohesionless soils, the ultimate group capacity of driven piles with a center to center spacing of less than 3 pile diameters is greater than the sum of the ultimate capacity of the individual piles. The greater group capacity is due to the overlap of individual soil compaction zones around each pile which increases the shaft resistance due to soil densification. Piles in groups at center to center spacings greater than three times the average pile diameter generally act as individual piles.

Design recommendations for estimating group capacity for driven piles in cohesionless soil are as follows:

1. The ultimate group capacity for driven piles in cohesionless soils not underlain by a weak deposit may be taken as the sum of the individual ultimate pile capacities, provided jetting or predrilling was not used in the pile installation process. Jetting or predrilling can result in group efficiencies less than 1. Therefore, jetting or predrilling should be avoided whenever possible and controlled by detailed specifications when necessary.
2. If a pile group founded in a firm bearing stratum of limited thickness is underlain by a weak deposit, then the ultimate group capacity is the smaller value of either the sum of the ultimate capacities of the individual piles, or the group capacity against block failure of an equivalent pier, consisting of the pile group and enclosed soil mass punching through the firm stratum into the underlying weak soil. From a practical standpoint, block failure in cohesionless soils can only occur when the center to center pile spacing is less than 2 pile diameters, which is less than the minimum center to center spacing of 2.5 diameters allowed by AASHTO code (2002). The method shown for cohesive soils in the Section 9.8.1.3 may be used to evaluate the possibility of a block failure.
3. Piles in groups should not be installed at center to center spacings less than 3 times the average pile diameter. A minimum center to center spacing of 3 diameters is recommended to optimize group capacity and minimize installation problems.








-  **Pile Locations**
-  **2 Piles Contributing to Stress**
-  **3 Piles Contributing to Stress**
-  **3 Piles Contributing to Stress**
-  **4 Piles Contributing to Stress**

Figure 9.57 Overlap of Stress Zones for Friction Pile Group (after Bowles 1988)

9.8.1.2 Pile Group Capacity in Cohesive Soils

In the absence of negative shaft resistance, the group capacity in cohesive soil is usually governed by the sum of the ultimate capacities of the individual piles, with some reduction due to overlapping zones of shear deformation in the surrounding soil. Negative shaft resistance is described in section 9.9.1 and often occurs when soil settlement transfers load to the pile. AASHTO (2002) code states that the group capacity is influenced by whether the pile cap is in firm contact with the ground. If the pile cap is in firm contact with the ground, the soil between the piles and the pile group act as a unit.

The following design recommendations are for estimating ultimate pile group capacity in cohesive soils. The lesser of the ultimate pile group capacity, calculated from Steps 1 to 4, should be used.

1. For pile groups driven in clays with undrained shear strengths of less than 95 kPa (2 ksf) and the pile cap not in firm contact with the ground, a group efficiency of 0.7 should be used for center to center pile spacings of 3 times the average pile diameter. If the center to center pile spacing is greater than 6 times the average pile diameter, then a group efficiency of 1.0 may be used. Linear interpolation should be used for intermediate center to center pile spacings.
2. For piles in clays with undrained shear strengths less than 95 kPa (2 ksf), and the pile cap in firm contact with the ground, a group efficiency of 1.0 may be used.
3. For pile groups in clays with undrained shear strength in excess of 95 kPa (2 ksf), a group efficiency of 1.0 may be used regardless of the pile cap - ground contact.
4. Calculate the ultimate pile group capacity against block failure using the procedure described in Section 9.8.1.3.
5. Piles in cohesive soils should not be installed at center to center pile spacings less than 3.0 times the average pile diameter and not less than 1 meter (3.3 ft).

It is important to note that the driving of pile groups in cohesive soils can generate large excess pore water pressures. This can result in short term (1 to 2 months after installation) group efficiencies on the order of 0.4 to 0.8. As these excess pore pressures dissipate, the pile group efficiency will increase. Figure 9.58 presents observations on the dissipation of excess pore water pressure versus time for pile

groups driven in cohesive soils. Depending upon the group size, the excess pressures typically dissipate within 1 to 2 months after driving. However, in very large groups, full pore pressure dissipation may take up to a year.

If a pile group will experience the full group load shortly after construction, the foundation designer must evaluate the reduced group capacity that may be available for load support. In these cases, piezometers should be installed to monitor pore pressure dissipation with time. Effective stress capacity calculations can then be used to determine if the increase in pile group capacity versus time during construction meets the load support requirements.

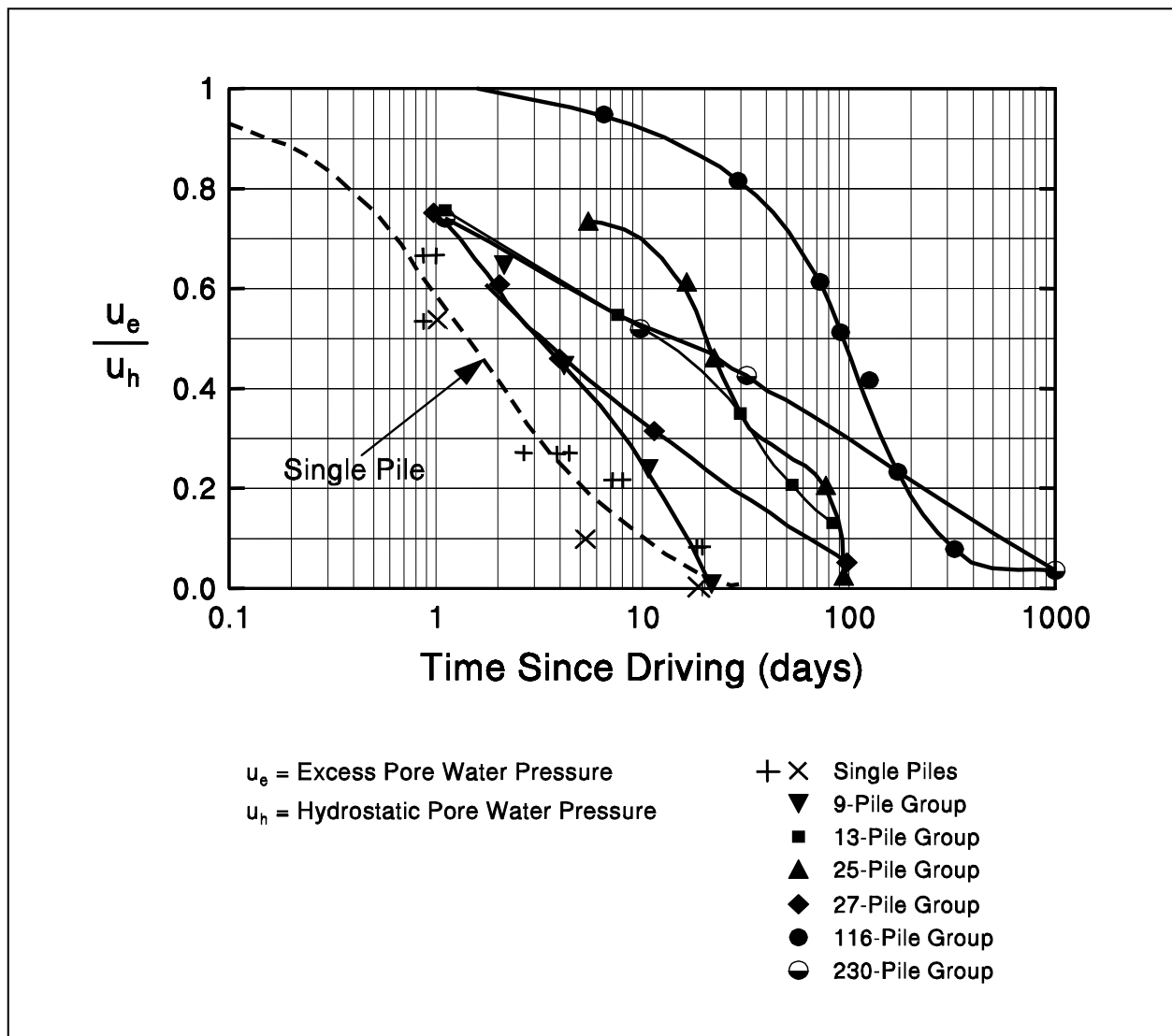


Figure 9.58 Measured Dissipation of Excess Pore Water Pressure in Soil Surrounding Full Scale Pile Groups (after O'Neill, 1983)

9.8.1.3 Block Failure of Pile Groups

Block failure of pile groups is generally only a design consideration for pile groups in soft cohesive soils or in cohesionless soils underlain by a weak cohesive layer. For a pile group in cohesive soil as shown in Figure 9.59, the ultimate capacity of the pile group against a block failure is provided by the following expression:

$$Q_{ug} = 2D (B + Z) c_{u1} + B Z c_{u2} N_c$$

Where:

- Q_{ug} = Ultimate group capacity against block failure.
- D = Embedded length of piles.
- B = Width of pile group.
- Z = Length of pile group.
- c_{u1} = Weighted average of the undrained shear strength over the depth of pile embedment for the cohesive soils along the pile group perimeter.
- c_{u2} = Average undrained shear strength of the cohesive soils at the base of the pile group to a depth of $2B$ below pile toe level.
- N_c = Bearing capacity factor.

If a pile group will experience the full group load shortly after construction, the ultimate group capacity against block failure should be calculated using the remolded or a reduced shear strength rather than the average undrained shear strength for c_{u1} .

The bearing capacity factor, N_c , for a rectangular pile group is generally 9. However, for pile groups with small pile embedment depths and/or large widths, N_c should be calculated from the following equation.

$$N_c = 5 \left[1 + \frac{D}{5B} \right] \left[1 + \frac{B}{5Z} \right] \leq 9$$

When evaluating possible block failure of pile groups in cohesionless soils underlain by a weak cohesive deposit, the weighted average unit shaft resistance for the cohesionless soils should be substituted for c_{u1} in calculating the ultimate group capacity. The pile group base strength determined from the second part of the ultimate group capacity equation should be calculated using the strength of the underlying weaker layer.

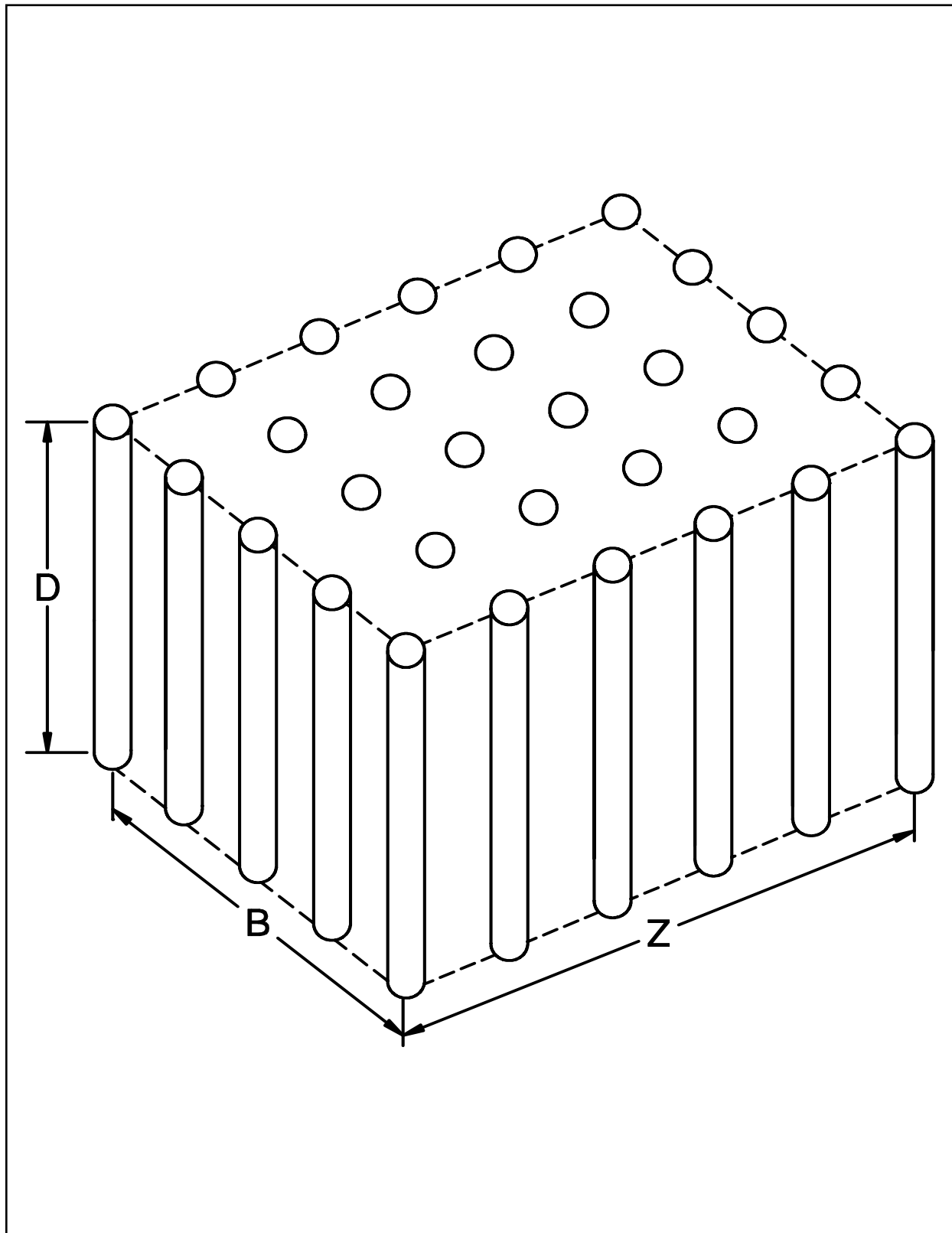


Figure 9.59 Three Dimensional Pile Group Configuration (after Tomlinson, 1994)

9.8.2 Settlement of Pile Groups

Pile groups supported in and underlain by cohesionless soils will produce only immediate settlements. This means the settlements will occur immediately as the pile group is loaded. Pile groups supported in and underlain by cohesive soils may produce both immediate settlements and consolidation settlements that occur over a period of time. In highly over- consolidated clays, the majority of the foundation settlement will occur immediately. Consolidation settlements will generally be the major source of foundation settlement in normally consolidated clays.

Methods for estimating settlement of pile groups are provided in the following sections. Methods for estimating single pile settlements are not provided because piles are usually installed in groups.

9.8.2.1 Elastic Compression of Piles

The pile group settlement methods discussed in the following sections only consider soil settlements and do not include the settlement caused by elastic compression of pile material due to the imposed axial load. Therefore, the elastic compression should also be computed and this settlement added to the group settlement estimates of soil settlement. The elastic compression can be computed by the following expression:

$$\Delta = \frac{Q_a L}{A E}$$

Where: Δ = Elastic compression of pile material in mm (in).
 Q_a = Design axial load in pile in kN (kips).
 L = Length of pile in mm (in).
 A = Pile cross sectional area in m^2 (in^2).
 E = Modulus of elasticity of pile material in kPa (ksi).

The modulus of elasticity for steel piles is 207,000 MPa (30,000 ksi). For concrete piles, the modulus of elasticity varies with concrete compressive strength and is generally on the order of 27800 MPa (4030 ksi). The elastic compression of short piles is usually quite small and can often be neglected in design.

9.8.2.2 Settlements of Pile Groups in Cohesionless Soils

9.8.2.2a Method Based on SPT Test Data

Meyerhof (1976) recommended that the settlement of a pile group in a homogeneous sand deposit not underlain by a more compressible soil at a greater depth may be conservatively estimated by the following expression:

$$s = \frac{0.96 p_f \sqrt{B} I_f}{\bar{N}'} \quad (\text{SI units}) \quad \text{or} \quad s = \frac{4 p_f \sqrt{B} I_f}{\bar{N}'} \quad (\text{US units})$$

For silty sand, use:
$$s = \frac{1.92 p_f \sqrt{B} I_f}{\bar{N}'} \quad (\text{SI units}) \quad \text{or} \quad s = \frac{8 p_f \sqrt{B} I_f}{\bar{N}'} \quad (\text{US units})$$

Where:

- s = Estimated total settlement in mm (in).
- p_f = Design foundation pressure in kPa (ksf). Group design load divided by group area.
- B = Width of pile group in m (ft).
- \bar{N}' = Average corrected SPT N' value within a depth B below pile toe.
- D = Pile embedment depth in m (ft).
- I_f = Influence factor for group embedment = $1 - [D / 8B] \geq 0.5$.

For piles in cohesionless soils underlain by cohesive deposits, the method presented in Sections 9.8.2.4 should be used.

9.8.2.2b Method Based on CPT Test Data

Meyerhof (1976) recommended the following relationship to estimate maximum settlements using cone penetration test results for saturated cohesionless soils.

$$(\text{SI units}) \quad s = \frac{42 p_f B I_f}{\bar{q}_c} \quad (\text{US units}) \quad s = \frac{p_f B I_f}{2 \bar{q}_c}$$

Where: s , p_f , B , and I_f are as defined in the previous method, and

- \bar{q}_c = Average static cone tip resistance in kPa (ksf) within a depth of B below the pile toe level.

9.8.2.3 Settlement of Pile Groups in Cohesive Soils

Terzaghi and Peck (1967) proposed that pile group settlements could be evaluated using an equivalent footing situated at a depth of $1/3 D$ above the pile toe. This concept is illustrated in Figure 9.60. For a pile group consisting of only vertical piles, the equivalent footing has a plan area $(B)(Z)$ that corresponds to the perimeter dimensions of the pile group as shown in Figure 9.59. The pile group load over this plan area is then the bearing pressure transferred to the soil through the equivalent footing. The load is assumed to spread within the frustum of a pyramid of side slopes at 30° and to cause uniform additional vertical pressure at lower levels. The pressure at any level is equal to the load carried by the group divided by the plan area of the base of the frustum at that level. Consolidation settlements are calculated based on the pressure increase in the underlying layers.

Consolidation settlements of cohesive soils are usually computed on the basis of laboratory tests. A typical plot of consolidation test results illustrating the relationships of the compression indices C_c and C_{cr} to void ratio, e , and pressure, p , are shown in Figure 9.61. For pressure increases less than the preconsolidation pressure, p_c , settlement is computed using a value of the compression index representing recompression, C_{cr} . For pressure increases greater than the preconsolidation pressure, settlement is computed using the compression index, C_c .

The following three equations are used to calculate settlements of cohesive soils depending upon the pressure increase and whether the soil is overconsolidated or normally consolidated. The terms used in these equations are as follows:

- s = Total settlement in mm (in).
- H = Original thickness of stratum in mm (in).
- C_{cr} = Recompression index.
- e_0 = Initial void ratio.
- p_o = Effective overburden pressure at midpoint of compressible stratum prior to pressure increase in kPa (ksf).
- p_c = Estimated preconsolidation pressure in kPa (ksf).
- C_c = Compression index.
- Δp = Average change in pressure in the compressible stratum in kPa (ksf).

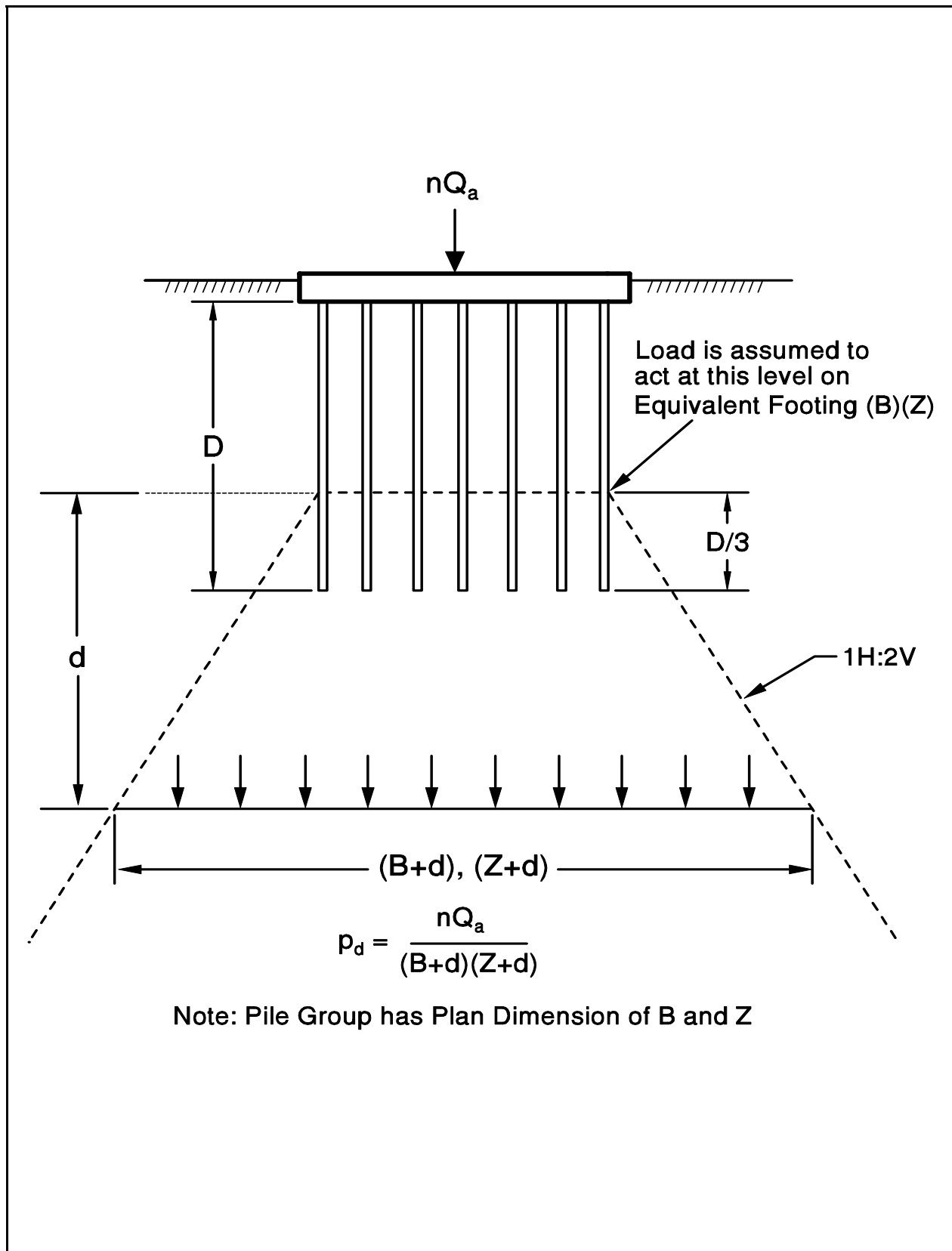


Figure 9.60 Equivalent Footing Concept

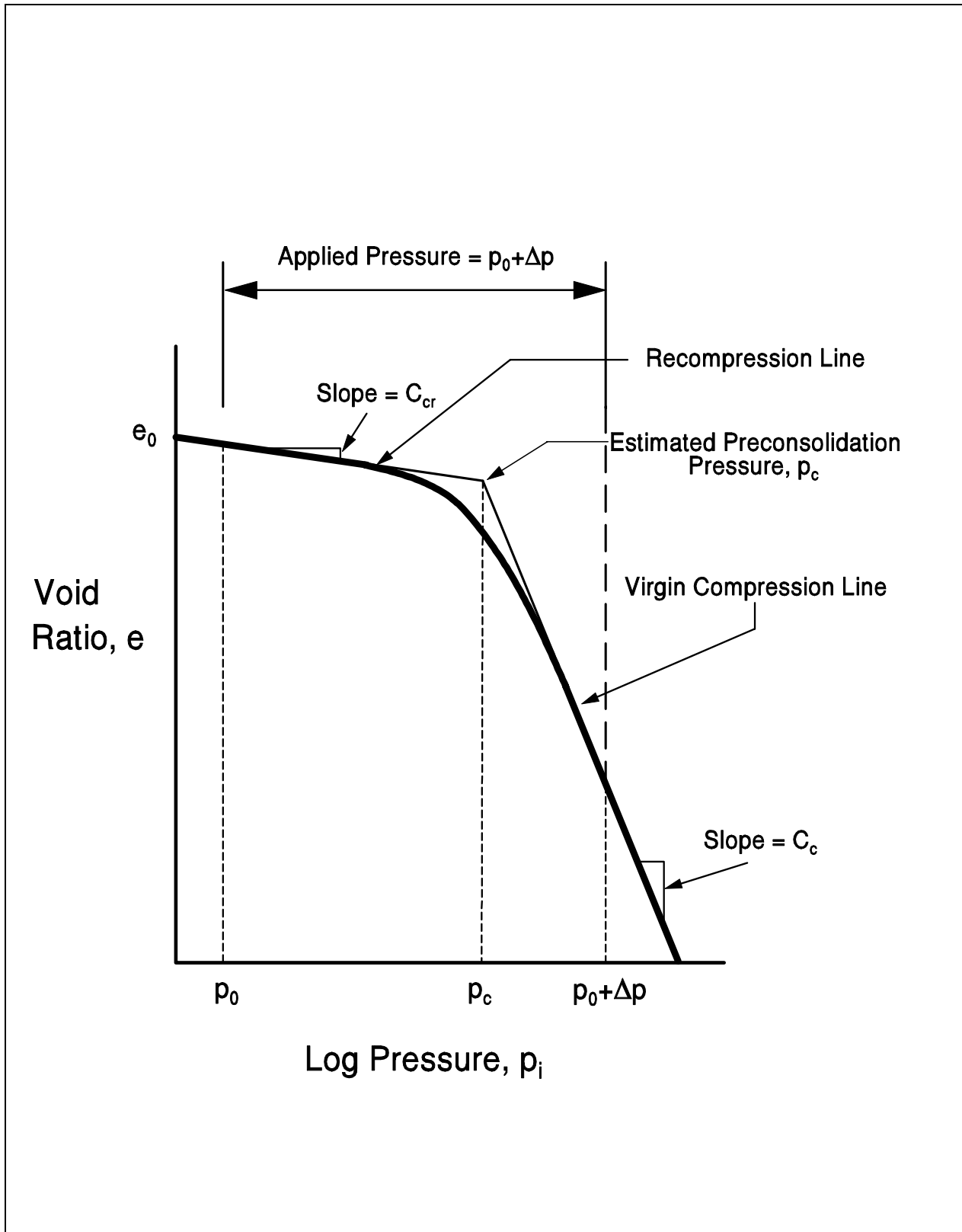


Figure 9.61 Typical e -log p Curve from Laboratory Consolidation Test

For overconsolidated cohesive soils where the pressure after the foundation pressure increase is greater than the soil preconsolidation pressure, settlements may be computed as follows:

$$s = H \left[\frac{C_{cr}}{1 + e_0} \log \frac{p_c}{p_o} \right] + H \left[\frac{C_c}{1 + e_0} \log \frac{p_o + \Delta p}{p_c} \right]$$

For overconsolidated cohesive soils where the pressure after the foundation pressure increase is less than the soil preconsolidation pressure, settlements should be computed using the following equation:

$$s = H \left[\frac{C_{cr}}{1 + e_0} \log \frac{p_o + \Delta p}{p_o} \right]$$

For normally consolidated cohesive soils, settlements should be computed from:

$$s = H \left[\frac{C_c}{1 + e_0} \log \frac{p_o + \Delta p}{p_o} \right]$$

Rather than fixing the equivalent footing at a depth of $\frac{1}{3} D$ above the pile toe for all soil conditions, the depth of the equivalent footing should be adjusted based upon soil stratigraphy and load transfer mechanism to the soil. Figure 9.62 presents the recommended location of the equivalent footing for the following load transfer and soil resistance conditions:

- a) toe bearing piles in hard clay or sand underlain by soft clay
- b) piles supported by shaft resistance in clay
- c) piles supported in shaft resistance in sand underlain by clay
- d) piles supported by shaft and toe resistance in layered soil profile

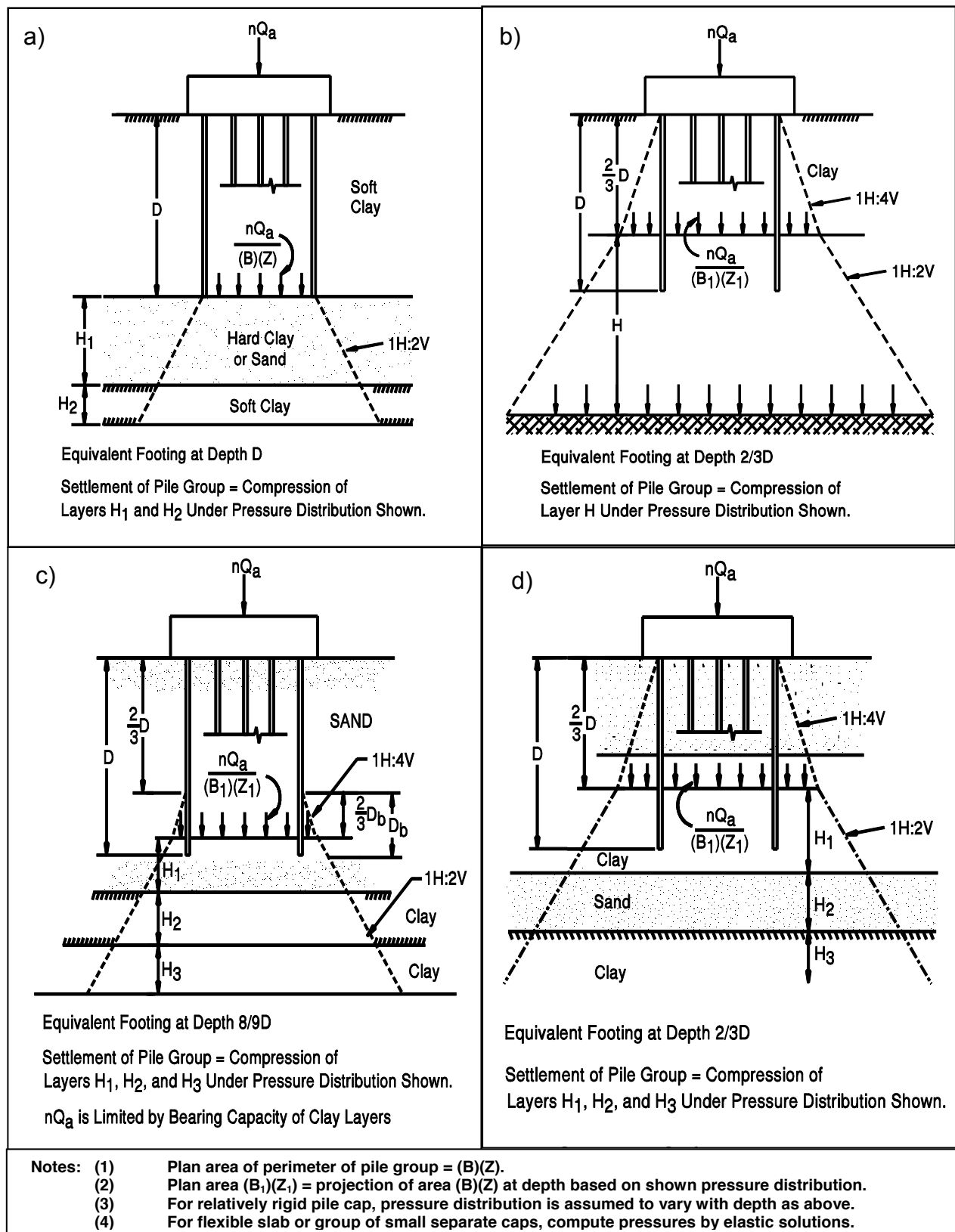


Figure 9.62 Pressure Distribution Below Equivalent Footing for a Pile Group (adapted from Cheney and Chassie, 1993)

STEP BY STEP PROCEDURE FOR PILE GROUP SETTLEMENT IN COHESIVE SOILS

STEP 1 Determine the new load imposed on soil by the pile group.

- a. Determine the location of the equivalent footing. For pile groups supported primarily by toe resistance, the equivalent footing is placed at the pile toe as illustrated in Figure 9.62(a). For pile groups supported primarily by shaft resistance, the equivalent footing is placed at a depth of $\frac{2}{3} D$ as shown in Figure 9.62(b).
- b. Determine the dimensions of the equivalent footing. For pile groups consisting only of vertical piles, the equivalent footing (unless modified for load transfer as in Figure 9.62(b)) has the same dimensions as the length and width of the pile group from Figure 9.59. For pile groups supported primarily by shaft resistance that include batter piles, the plan area of the footing should be calculated from the dimensions of the pile group at depth $\frac{2}{3} D$, including the plan area increase due to the pile batter. For toe bearing groups with batter piles, the equivalent footing area should be the dimensions of the pile group at depth D , including the area increase due to pile batter.
- c. Determine the pressure distribution to soil layers below the equivalent footing up to the depth at which the pressure increase from the equivalent footing is less than 10% of existing effective overburden pressure at that depth. Remember that the equivalent footing size may be increased and the footing pressure correspondingly reduced as a result of load transfer above the footing location or in groups with batter piles. The depth at which the pressure increase is less than 10% will provide the total thickness of cohesive soil layer or layers to be used in performing settlement computations. Note that the group design load should be used in determining the pressure distribution for settlement computations, and not the ultimate group load.

- d. Divide the cohesive soil layers in the affected pressure increase zone into several thinner layers of 1.5 to 3 meter (5 to 10 ft) thickness. The thickness of each layer is the thickness H for the settlement computation for that layer.
- e. Determine the existing effective overburden pressure, p_o , at midpoint of each layer.
- f. Determine the imposed pressure increase, Δp , at midpoint of each affected soil layer based on the appropriate pressure distribution.

STEP 2 Determine consolidation test parameters.

Plot results of consolidation test(s) as shown in Figure 9.61. Determine p_c , e_o , C_{cr} and C_c values from the consolidation test data.

STEP 3 Compute settlements.

Using the appropriate settlement equation, compute the settlement of each affected soil layer. Sum the settlements of all layers to obtain the total estimated soil settlement from the pile group. Add the elastic compression of the pile under the design load to obtain the total estimated pile group settlement.

9.8.2.4 Time Rate of Settlement in Cohesive Soils

Settlement analyses in cohesive soils should also evaluate the time required for the anticipated settlement to occur. In time rate computations, the time for 90% consolidation to occur is usually used to determine the total time required for primary settlement. The time rate of settlement of a cohesive soil deposit can be calculated from:

$$t = \frac{TH_v^2}{C_v}$$

Where: t = time for settlement to occur in days

T = theoretical time factor for percentage of primary consolidation to occur from Table 9-17

H_v = the maximum vertical drainage path in the cohesive layer in m (ft)

C_v = the coefficient of consolidation in m^2/day (ft^2/day) from laboratory consolidation tests

The term H_v should not be confused with the term H used in the settlement equations for cohesive soils. H_v is the maximum distance water must travel from the compressible cohesive deposit to a more permeable layer. In the case of a cohesive layer overlain and underlain by a permeable granular layer, H_v would be $\frac{1}{2}$ the cohesive layer thickness. However if the cohesive layer were overlain by a permeable granular layer and underlain by a non-permeable rock layer, H_v would be the full thickness of the cohesive deposit. Additional discussion on time rate of consolidation can be found in the Soils and Foundation Workshop Manual, Report No. HI-88-009, Cheney and Chassie (2002).

| TABLE 9-17 TIME FACTOR (T) | |
|----------------------------|-----------------|
| Percent Primary Settlement | Time Factor (T) |
| 10 | 0.008 |
| 20 | 0.031 |
| 30 | 0.071 |
| 40 | 0.126 |
| 50 | 0.197 |
| 60 | 0.287 |
| 70 | 0.403 |
| 80 | 0.567 |
| 90 | 0.848 |

9.8.2.5 Settlement of Pile Groups in Layered Soils

Piles are often installed in a layered soil profile consisting of cohesionless and cohesive soils or in soil profiles where an underlying soil stratum of different consistency is affected by the pile group loading. In these cases, group settlement will be influenced by the pressure increase in and compressibility of the affected layers. Figures 9.62(a), 9.62(c) and 9.62(d) may be used to determine the location of the equivalent footing and to evaluate the resulting pressure increase in a soil layer. The settlement of each layer

is then calculated using the appropriate settlement equation presented in Section 9.8.2.3 for cohesive layers and from the following equation for cohesionless layers.

$$s = H \left[\frac{1}{C'} \log \frac{p_o + \Delta p}{p_o} \right]$$

Where:

| | | |
|----------------|---|---|
| s | = | Total layer settlement in mm (in). |
| H | = | Original thickness of layer in mm (in). |
| C' | = | Dimensionless bearing capacity index from Figure 9.63, determined from average corrected SPT N' value N, for layer with consideration of SPT hammer type. |
| p _o | = | Effective overburden pressure at midpoint of layer prior to pressure increase in kPa (ksf). |
| Δp | = | Average change in pressure in the layer in kPa (ksf). |

Cheney and Chassie (2002) report that FHWA experience with this method indicates the method is usually conservative and can overestimate settlements by a factor of 2. This conservatism is attributed to the use of the original bearing capacity index chart from Hough (1959) which was based upon SPT donut hammer data. Based upon average energy variations between SPT donut and safety hammers reported in technical literature, Figure 9.63 now includes a correlation between SPT N values from a safety hammer and bearing capacity index. The safety hammer values are considered N₆₀ values. This modification should improve the accuracy of settlement estimates with this method.

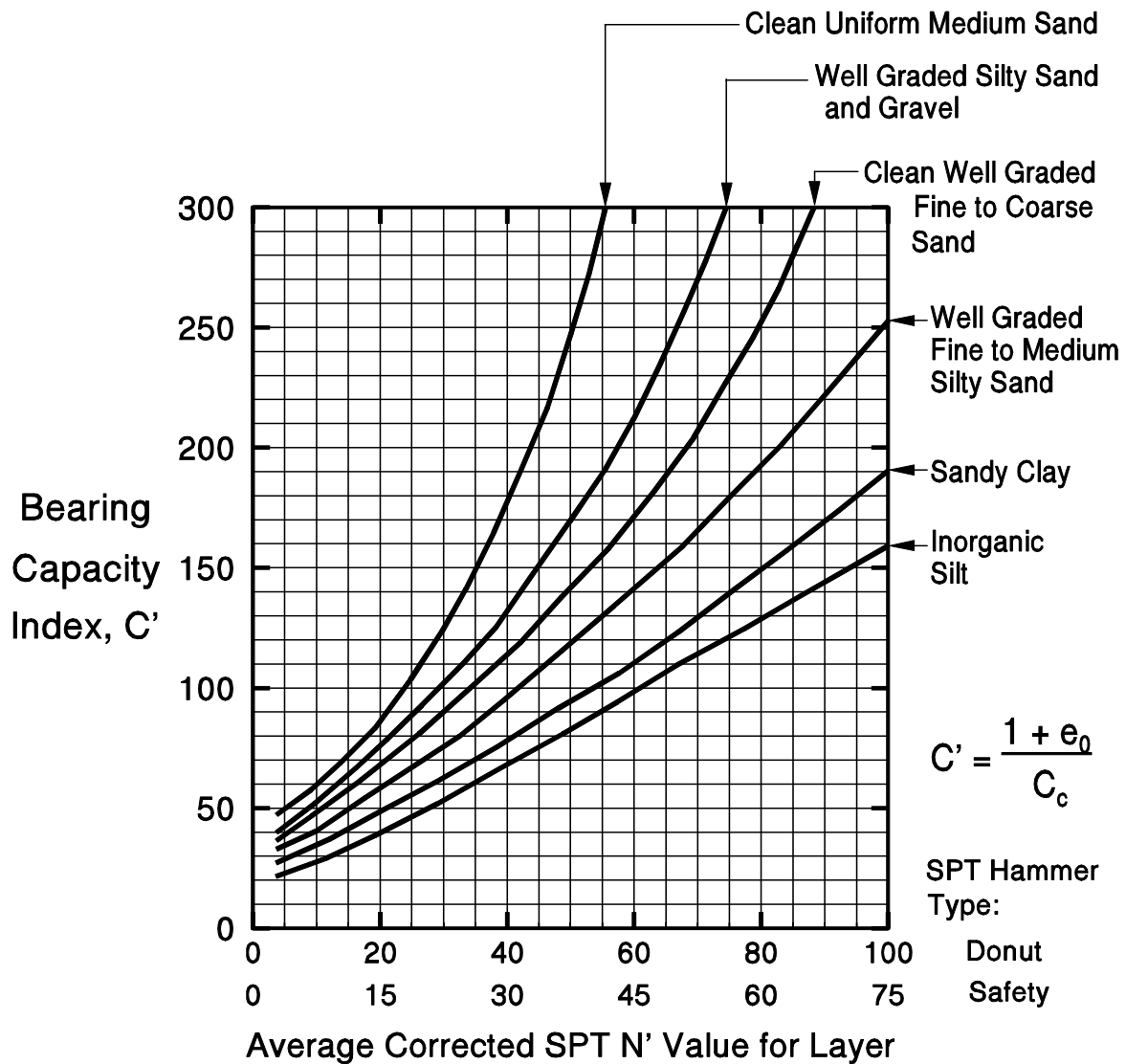


Figure 9.63 Values of the Bearing Capacity Index, C' , for Granular Soil (modified after Cheney and Chassie, 1993)

STEP BY STEP PROCEDURE FOR GROUP SETTLEMENT IN LAYERED SOIL PROFILES

STEP 1 Determine the new load imposed on soil by the pile group.

- a. Determine the location of the equivalent footing. For pile groups supported primarily by toe resistance, the equivalent footing is placed at the pile toe as illustrated in Figure 9.62(a). For pile groups supported primarily by shaft resistance in sands underlain by cohesive soils, the equivalent footing is placed at a depth of $8/9 D$ as shown in Figure 9.62(c). For pile groups in layered soils supported by a combination of shaft and toe resistance, the equivalent footing is placed at $2/3 D$ as shown in Figure 9.62(d).
- b. Determine the dimensions of the equivalent footing. For pile groups consisting only of vertical piles, the equivalent footing (unless modified for load transfer as in Figures 9.62(c) and 9.62(d)) has the same dimensions as the length and width of the pile group from Figure 9.59. For pile groups supported primarily by shaft resistance that include batter piles, the plan area of the footing should be calculated from the dimensions of the pile group at the equivalent footing depth that includes the plan area increase due to the pile batter. For toe bearing groups with batter piles, the equivalent footing area should be calculated from the dimensions of the pile group at depth D , including the plan area increase due to the pile batter.
- c. Determine the pressure distribution to soil layers below the equivalent footing up to the depth at which the pressure increase from the equivalent footing is less than 10% of existing effective overburden pressure at that depth. Remember that the equivalent footing size may be increased and the footing pressure correspondingly reduced as a result of load transfer above the footing location or in groups with batter piles. The depth at which the pressure increase is less than 10% will provide the total thickness of soil to be evaluated in the settlement computations. Note that the group design load should be used in determining the pressure distribution for settlement computations, and not the ultimate group capacity.

- d. Divide the soil layers in the affected pressure increase zone into several thinner layers of 1.5 to 3 meter (5 to 10 ft) thickness. The thickness of each layer is the thickness H for the settlement computation for that layer.
- e. Determine the existing effective overburden pressure, p_o , at midpoint of each soil layer.
- f. Determine the imposed pressure increase, Δp , at midpoint of each affected soil layer based on the appropriate pressure distribution.

STEP 2 Determine consolidation test parameters for each cohesive layer.

Plot results of consolidation test(s) as shown in Figure 9.61. Determine p_c , e_o , C_{cr} and C_c values from the consolidation test data.

STEP 3 Determine bearing capacity index for each cohesionless layer.

Determine the average corrected SPT N' value, \bar{N}' , for each cohesionless layer. Use N' or the appropriate SPT hammer type in Figure 9.63 to obtain the bearing capacity index for each layer. The safety hammer N values in Figure 9.63 are considered representative of N_{60} values.

STEP 4 Compute settlements.

Using the appropriate settlement equation, compute the settlement of each affected soil layer. Sum the settlements of all layers to obtain the total estimated soil settlement from the pile group. Add the elastic compression of the pile under the design load to obtain the total estimated pile group settlement.

9.8.2.6 Settlement of Pile Groups Using the Janbu Tangent Modulus Approach

The previous methods of group settlement analyses assume a linear relationship between induced stress and soil strain. However in most soils, a non-linear relationship exists between stress and strain. Figure 9.64 illustrates that a stress increase at a small original stress will result in a larger strain than the same stress increase applied at a greater original stress.

Janbu (1963, 1965) proposed a tangent modulus approach that is referenced in the Canadian Foundation Engineering Manual (1985). In this method, the stress strain relationship of soils is expressed in terms of a dimensionless modulus number, m , and a stress exponent, j . Values of the modulus number can be determined from conventional laboratory triaxial or oedometer tests. The stress exponent, j , can generally be taken as 0.5 for cohesionless soils and 0 for cohesive soils.

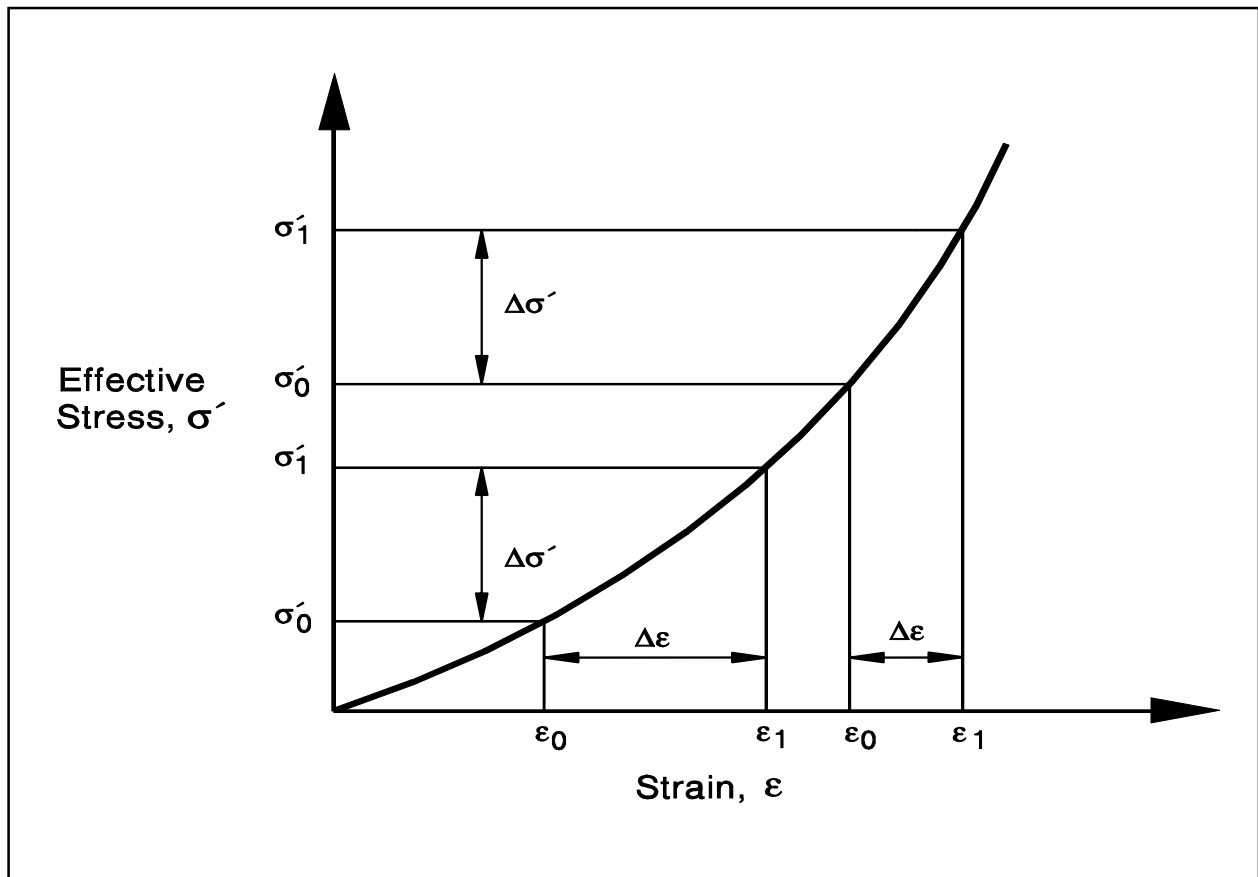


Figure 9.64 The Non-Linear Relation Between Stress and Strain in Soil (after Fellenius, 1990)

The following four equations are used to calculate the strain for normally and over consolidated, cohesionless and cohesive soils. The terms used in these four equations are as follows:

- ε = Strain from the increase in effective stress.
- m_n = Dimensionless modulus number.
- m_{nr} = Dimensionless recompression modulus number.
- j = Stress exponent.
- σ'_{1} = New effective stress after stress increase, (kPa).
- σ'_{0} = Original effective stress prior to stress increase, (kPa).
- σ'_p = Preconsolidation stress, (kPa).
- σ_r = Constant reference stress = 100 kPa.

For normally consolidated cohesionless soils, the strain induced by an increase in effective stress may be expressed as follows:

$$\varepsilon = \frac{1}{m_n j} \left[\left(\frac{\sigma'_{1}}{\sigma_r} \right)^j - \left(\frac{\sigma'_{0}}{\sigma_r} \right)^j \right]$$

For over consolidated cohesionless soils, the following equation should be used to calculate the strain induced by an increase in effective stress:

$$\varepsilon = \frac{1}{m_n j} \left[\left(\frac{\sigma'_{1}}{\sigma_r} \right)^j - \left(\frac{\sigma'_p}{\sigma_r} \right)^j \right] + \frac{1}{m_{nr} j} \left[\left(\frac{\sigma'_p}{\sigma_r} \right)^j - \left(\frac{\sigma'_{0}}{\sigma_r} \right)^j \right]$$

For cohesive soils, the stress exponent is zero, $j=0$. The strain induced by an increase in effective stress in a normally consolidated cohesive soil is then as follows:

$$\varepsilon = \frac{1}{m_n} \ln \left[\left(\frac{\sigma'_{1}}{\sigma'_{0}} \right) \right]$$

For over consolidated cohesive soils, the following equation should be used to calculate the strain induced by an increase in effective stress:

$$\varepsilon = \frac{1}{m_{nr}} \ln \left[\left(\frac{\sigma'_p}{\sigma'_{0'}} \right) \right] + \frac{1}{m_n} \ln \left[\left(\frac{\sigma'_{1'}}{\sigma_p} \right) \right]$$

In cohesionless soils, the modulus number can be calculated from the soil modulus of elasticity, E_s (kPa), and the previously described terms using the following equation:

$$m_n = \frac{E_s}{5[\sqrt{\sigma'_1} + \sqrt{\sigma'_{0'}}]}$$

In cohesive soils, the modulus number, m_n , or recompression modulus number, m_{nr} , can be calculated from the initial void ratio, e_0 , and the compression index, C_c , or recompression index, C_{cr} . The modulus number is calculated from:

$$m_n = 2.30 \left[\frac{1 + e_0}{C_c} \right]$$

The recompression modulus number, m_{nr} , is calculated by substituting the recompression index, C_{cr} , for the compression index, C_c , in the above equation.

The Janbu tangent modulus approach is quite adaptable to calculating pile group settlements in any soil profile. For reference purposes, typical and normally conservative modulus number and stress exponent values from the Canadian Foundation Engineering Manual (1985) are presented in Table 9-18. These values may be useful for preliminary settlement estimates. A step by step procedure for this method follows.

| TABLE 9-18 TYPICAL MODULUS AND STRESS EXPONENT VALUES | | | |
|---|---------------------|--------------------------------|----------------------|
| Soil Type | Consistency | Range in Modulus Number, m_n | Stress Exponent, j |
| Glacial Till | Very Dense to Dense | 1000 - 300 | 1.0 |
| Gravel | --- | 400 - 40 | 0.5 |
| Sand | Dense | 400 - 250 | 0.5 |
| Sand | Medium Dense | 250 - 150 | 0.5 |
| Sand | Loose | 150 - 100 | 0.5 |
| Silt | Dense | 200 - 80 | 0.5 |
| Silt | Medium Dense | 80 - 60 | 0.5 |
| Silt | Loose | 60 - 40 | 0.5 |
| Silty Clay & Clayey Silt | Hard - Stiff | 60 - 20 | 0 |
| Silty Clay & Clayey Silt | Stiff - Firm | 20 - 10 | 0 |
| Silty Clay & Clayey Silt | Soft | 10 - 5 | 0 |
| Marine Clay | Soft | 20 - 5 | 0 |
| Organic Clay | Soft | 20 - 5 | 0 |
| Peat | --- | 5 - 1 | 0 |

STEP BY STEP PROCEDURE FOR PILE GROUP SETTLEMENT BY JANBU METHOD

STEP 1 Determine the new load imposed on soil by the pile group.

- a. Determine the location of the equivalent footing. For pile groups supported primarily by toe resistance, the equivalent footing is placed at the pile toe as illustrated in Figure 9.62(a). For pile groups supported primarily by shaft resistance in sands underlain by cohesive soils, the equivalent footing is placed at a depth of $\frac{8}{9} D$ as shown in Figure 9.62(c). For pile groups in layered soils supported by a combination of shaft and toe resistance, the equivalent footing is placed at $\frac{2}{3} D$ as shown in Figure 9.62(d).
- b. Determine the dimensions of the equivalent footing. For pile groups consisting only of vertical piles, the equivalent footing (unless modified for load transfer as in Figures 9.62(c) and 9.62(d) has the same dimensions as the length and width of the pile group from Figure 9.59. For pile groups supported primarily by shaft resistance that include batter piles, the plan area of the footing should be calculated from the dimensions of the pile group at the equivalent footing depth that includes the plan area increase due to the pile batter. For toe bearing groups with batter piles, the equivalent footing area should be calculated from the dimensions of the pile group at depth D , including the plan area increase due to the pile batter.
- c. Determine the pressure distribution to soil layers below the equivalent footing up to the depth at which the pressure increase from the equivalent footing is less than 10% of existing effective overburden pressure at that depth. Remember that the equivalent footing size may be increased, and the footing pressure correspondingly reduced, as a result of load transfer above the footing location, or in groups with batter piles. The depth at which the pressure increase is less than 10% will provide the total thickness of the soil to be analyzed and the number of soil layers for settlement calculations. Note that the group design load should be used in determining the pressure distribution for settlement computations, and not the ultimate group capacity.

- d. Divide the soil layers in the affected pressure increase zone into several thinner layers of 1.5 to 3 (5 to 10 ft) meter thickness. The thickness of each layer is the thickness H for the settlement computation for that layer.
- e. Determine the existing effective stress, σ'_o , at midpoint of each soil layer.
- f. Determine the preconsolidation stress, σ'_p , at the midpoint of each soil layer and whether the soil layer is overconsolidated or normally consolidated.
- g. Determine the new effective stress, σ'_1 , at midpoint of each affected soil layer based on the equivalent footing pressure distribution.

STEP 2 Determine modulus number and stress exponent for each soil layer.

Use laboratory test data to compute modulus number for each layer. Preliminary settlement estimates can be made by using assumed modulus numbers based on soil type as indicated in Table 9-18.

STEP 3 Select the appropriate strain computation equation for each layer.

Select the strain equation applicable to each layer depending upon whether the soil layer is cohesive or cohesionless, and overconsolidated or normally consolidated.

STEP 4 Compute settlements.

Using the appropriate strain computation equation, compute the settlement, s , of each affected soil layer of thickness, H from: $s=(\varepsilon)(H)$. Sum the settlements of all layers to obtain the total estimated soil settlement from the pile group. Add the elastic compression of the pile under the design load to obtain the total estimated pile group settlement.

9.8.2.7 Settlement of Pile Groups Using the Neutral Plane Method

As the previous sections demonstrate, most of the group settlement methods select the depth of the equivalent footing based upon the assumed load transfer behavior. A preferred solution is to determine the depth of the neutral plane, and place the equivalent footing at or below the neutral plane location. The neutral plane occurs at the depth where the group dead load plus the load from negative shaft resistance is equal to the positive shaft resistance plus the toe resistance. The design should aim to locate the neutral plane in competent soils. When this is done, group settlements are usually well within acceptable limits.

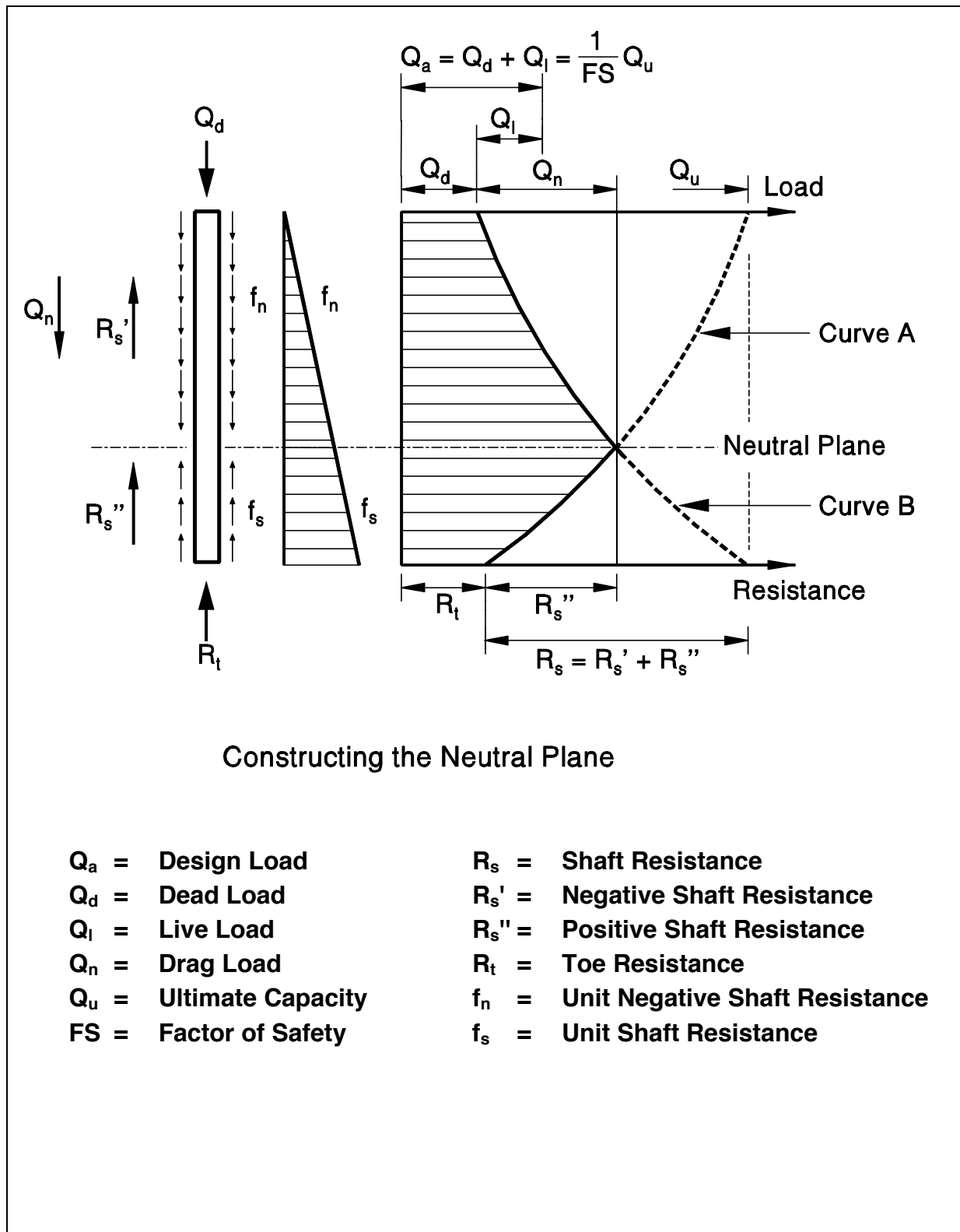
The position of the neutral plane and the resulting negative shaft resistance can be determined from a static calculation. As previously stated, the neutral plane is the depth at which the sum of dead load on the pile plus the negative shaft resistance is equal to the positive shaft plus the toe resistance. Above the neutral plane, the settlement of the soil is greater than the settlement of the pile. Any shaft resistance above the neutral plane is negative shaft resistance, since by definition the soil settlement is greater than the pile settlement. Therefore, the soil settlement transfers load to the pile. Below the neutral plane, the settlement of the soil is less than the settlement of the pile and load is transferred from the pile to the soil. Therefore, pile settlement is controlled by the soil compressibility below the neutral plane.

The following step by step procedure adapted from Goudreault and Fellenius (1994) is recommended for determination of the neutral plane.

STEP BY STEP PROCEDURE FOR DETERMINING THE NEUTRAL PLANE DEPTH

STEP 1 Perform a static capacity calculation.

- a. Determine the ultimate pile capacity, Q_u , from a static capacity calculation.
- b. Plot the load transfer versus depth by subtracting the shaft resistance at a given depth from the ultimate capacity. This computation is identified as Curve A in Figure 9.65.



Constructing the Neutral Plane

| | |
|---------------------------|--|
| Q_a = Design Load | R_s = Shaft Resistance |
| Q_d = Dead Load | R_s' = Negative Shaft Resistance |
| Q_l = Live Load | R_s'' = Positive Shaft Resistance |
| Q_n = Drag Load | R_t = Toe Resistance |
| Q_u = Ultimate Capacity | f_n = Unit Negative Shaft Resistance |
| FS = Factor of Safety | f_s = Unit Shaft Resistance |

Figure 9.65 Neutral Plane (after Goudreault and Fellenius, 1994)

STEP 2 Determine the load transfer to the pile above the neutral plane.

- a. Determine the pile dead load, Q_d .
- b. Plot the load transfer to the pile versus depth by adding the shaft resistance at a given depth to the dead load. This computation is labeled as Curve B in Figure 9.65.

STEP 3 Determine the depth of the neutral plane.

- a. The depth where Curves A and B intersect is the depth of the neutral plane.
- b. The location of the neutral plane will move if the dead load is changed or the soil resistance versus depth is altered. Hence, design or construction decisions altering the dead load, or soil resistance versus depth, will require reevaluation of the neutral plane location under the changed conditions. Preaugering, jetting, use of bitumen coatings, *etc.* are but a few of the factors that can change the soil resistance versus depth and thus the neutral plane location.

Goudreault and Fellenius (1994) note that the magnitude of group settlement between the neutral plane and the pile toe level is generally small. This is because the piles below the neutral plane act as reinforcing elements and the compression of the pile-reinforced soil is small. Therefore, for most cases they recommend calculating the pile group settlements based on locating the neutral plane at the pile toe.

The group load is distributed below the neutral plane at a slope of 1H:2V. As in the previous methods, the soil materials below the equivalent footing at the neutral plane and the depth where the pressure increase is less than 10% should be evaluated for settlement. Group settlements are generally calculated based upon the pressure increase and the resulting strain as presented for the Janbu method in Section 9.8.2.6. However, the methods presented for layered soils in Section 9.8.2.5 could also be used.

9.8.3 Uplift Capacity of Pile Groups

The uplift capacity of a pile group is often a significant factor in determining the minimum pile penetration requirements and in some cases can control the foundation design. A few common conditions where group uplift capacity may significantly influence the foundation design include cofferdam seals that create large buoyancy forces, cantilever segmental bridge construction, and seismic, vessel impact, or debris loading. When piles with uplift loads are driven to a relatively shallow bearing stratum, uplift capacity may control the foundation design. Current AASHTO specifications (2002) for the determination of group uplift capacity are presented in Section 9.8.3.1. The AASHTO specifications for group uplift capacity are considered relatively conservative, particularly in cohesionless soils.

In cohesionless soils, Tomlinson's method presented in Section 9.8.3.2 will yield higher group uplift capacities than AASHTO specifications, and the Tomlinson method is recommended for design. Both AASHTO specifications and Tomlinson's method limit the group uplift capacity to the uplift capacity of an individual pile times the number of piles in the group. In the event this limit controls the group uplift capacity, an uplift load test may be cost effective and should be considered. With an uplift load test, a reduced safety factor is used to determine the uplift capacity. This should result in higher individual and group uplift capacities.

In cohesive soils, Tomlinson's method will yield similar results to AASHTO specifications. In the event the uplift capacity of an individual pile times the number of piles in the group limits the group uplift capacity, an uplift load test may again be cost effective and should be considered since an increase in the group uplift capacity would likely result.

9.8.3.1 Group Uplift Capacity by AASHTO Code

AASHTO specifications (2002) for service load design limit the uplift capacity of a pile group to the lesser value determined from any of the following:

1. The design uplift capacity of a single pile times the number of piles in a pile group. The design uplift capacity of a single pile is specified as $\frac{1}{3}$ the ultimate shaft resistance calculated in a static analysis method, or $\frac{1}{2}$ the failure load determined from an uplift load test.
2. $\frac{2}{3}$ the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the piles.

3. $\frac{1}{2}$ the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded pile length plus $\frac{1}{2}$ the total soil shear resistance on the peripheral surface of the pile group.

9.8.3.2 Tomlinson Group Uplift Method

Tomlinson (1994) states that the ultimate uplift capacity of a pile group in cohesionless soils may be conservatively taken as the effective weight of the block of soil extending upward from the pile toe level at a slope of 1H:4V, as shown in Figure 9.66. For simplicity in performing the calculation, the weight of the piles within the soil block are considered equal to the weight of the soil. Tomlinson states that a factor of safety of 1 is acceptable in this calculation since the shear resistance around the perimeter of the group is ignored in the calculation. Tomlinson also recommended that the ultimate group uplift capacity determined from this calculation not exceed the sum of the ultimate uplift capacities of the individual piles comprising the pile group divided by an appropriate safety factor. It is recommended that a factor of safety of 2 be used if the ultimate uplift capacity of an individual pile is determined from an uplift load test and a factor of safety of 3 be used if based on the shaft resistance from a static calculation.

For pile groups in cohesive soils as shown in Figure 9.67, Tomlinson recommends the group uplift capacity be calculated based upon the undrained shear resistance of the block of soil enclosed by the group plus the effective weight of the pile cap and pile-soil block. This may be expressed in equation form as:

$$Q_{ug} = 2D (B + Z) C_{u1} + W_g$$

Where:

- Q_{ug} = Ultimate group capacity against block failure in uplift in kN (kips).
- D = Embedded length of piles in m (ft).
- B = Width of pile group in m (ft).
- Z = Length of pile group in m (ft).
- C_{u1} = Weighted average of the undrained shear strength over the depth of pile embedment along the pile group perimeter in kPa (ksf).
- W_g = Effective weight the pile/soil block including the pile cap weight in kN (kips).

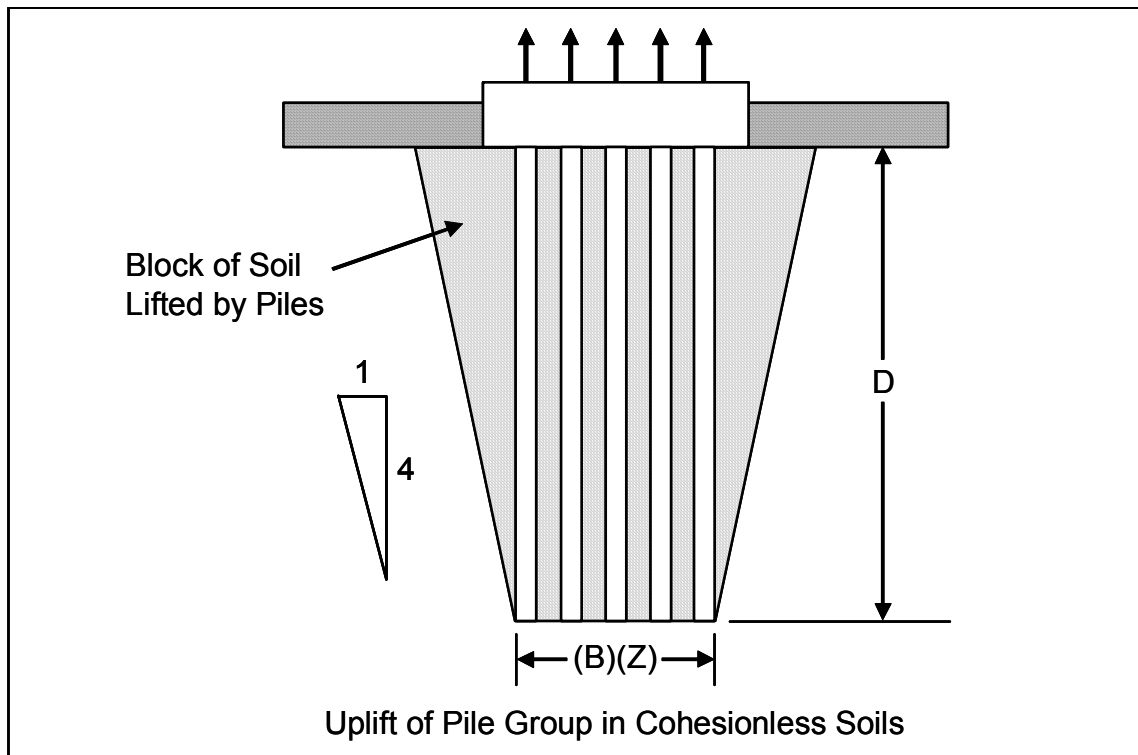


Figure 9.66 Uplift of Pile Group in Cohesionless Soil (after Tomlinson, 1994)

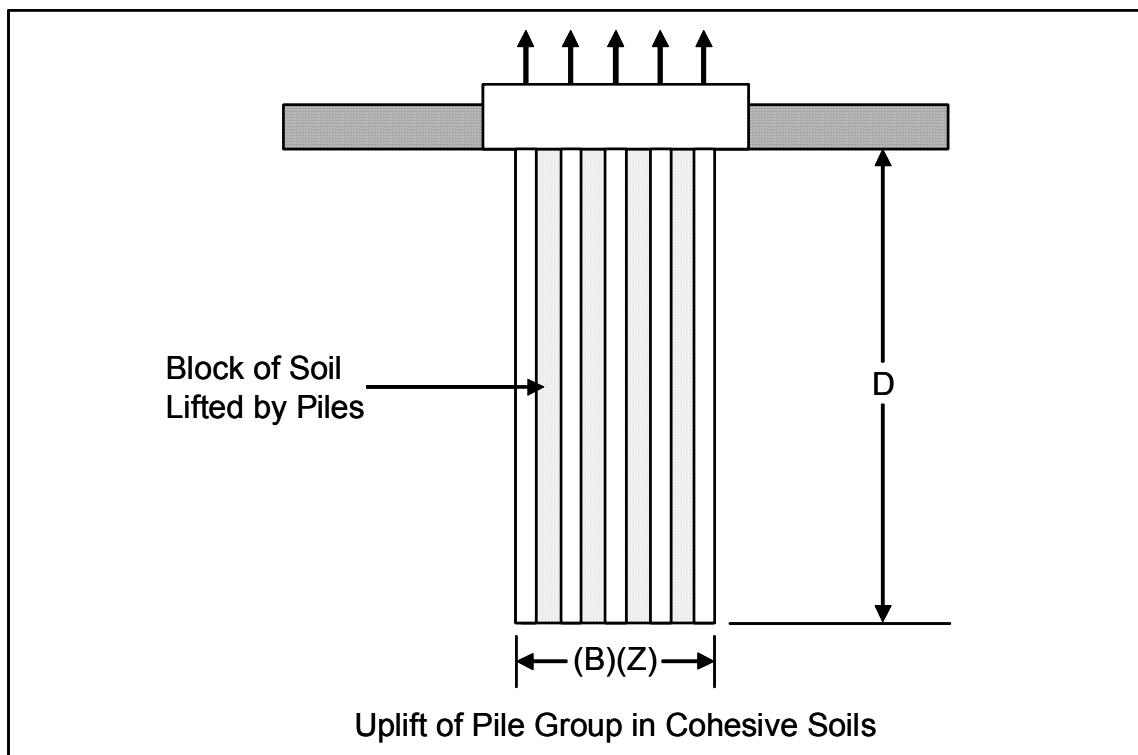


Figure 9.67 Uplift of Pile Group in Cohesive Soils (after Tomlinson, 1994)

Tomlinson states that a factor of safety of 2 should be used with this calculation to allow for possible weakening of the soil around the pile group as a result of the pile group installation. If long term sustained uplift loading is anticipated, a factor of safety of 2.5 to 3 is recommended. Tomlinson also recommends that the ultimate group uplift capacity determined from this calculation not exceed the sum of the ultimate uplift capacities of the individual piles comprising the pile group divided by an appropriate factor of safety. It is recommended that a factor of safety of 2 be used if the ultimate uplift capacity of an individual pile is determined from an uplift load test, and a factor of safety of 3 be used if based on the shaft resistance from a static calculation.

9.8.4 Lateral Capacity of Pile Groups

The ability of a pile group to resist lateral loads from vessel impact, debris, wind, or wave loading, seismic events, and other sources is a significant design issue. The deflection of a pile group under a lateral load is typically 2 to 3 times larger than the deflection of a single pile loaded to the same intensity. Holloway *et al.* (1981), and Brown *et al.* (1988) reported that piles in trailing rows of pile groups have significantly less resistance to a lateral load than piles in the lead row, and therefore exhibit greater deflections. This is due to the pile-soil-pile interaction that takes place in a pile group. The pile-soil-pile interaction results in the lateral capacity of a pile group being less than the sum of the lateral capacities of the individual piles comprising the group. Hence, laterally loaded pile groups have a group efficiency of less than 1.

The lateral capacity of an individual pile in a pile group is a function of its position in the group and the center to center pile spacing. Brown *et al.* (1988) proposed a p-multiplier, P_m , be used to modify the p-y curve of an individual pile based upon the piles row position. An illustration of the p-multiplier concept is presented in Figure 9.68. For piles in a given row, the same P_m value is applied to all p-y curves along the length of the pile. In a lateral load test of a 3 by 3 pile group in very dense sand with a center to center pile spacing of $3b$, Brown found the leading row of piles had a P_m of 0.8 times that of an individual pile. The P_m values for the middle and back row of the group were 0.4 and 0.3, respectively.

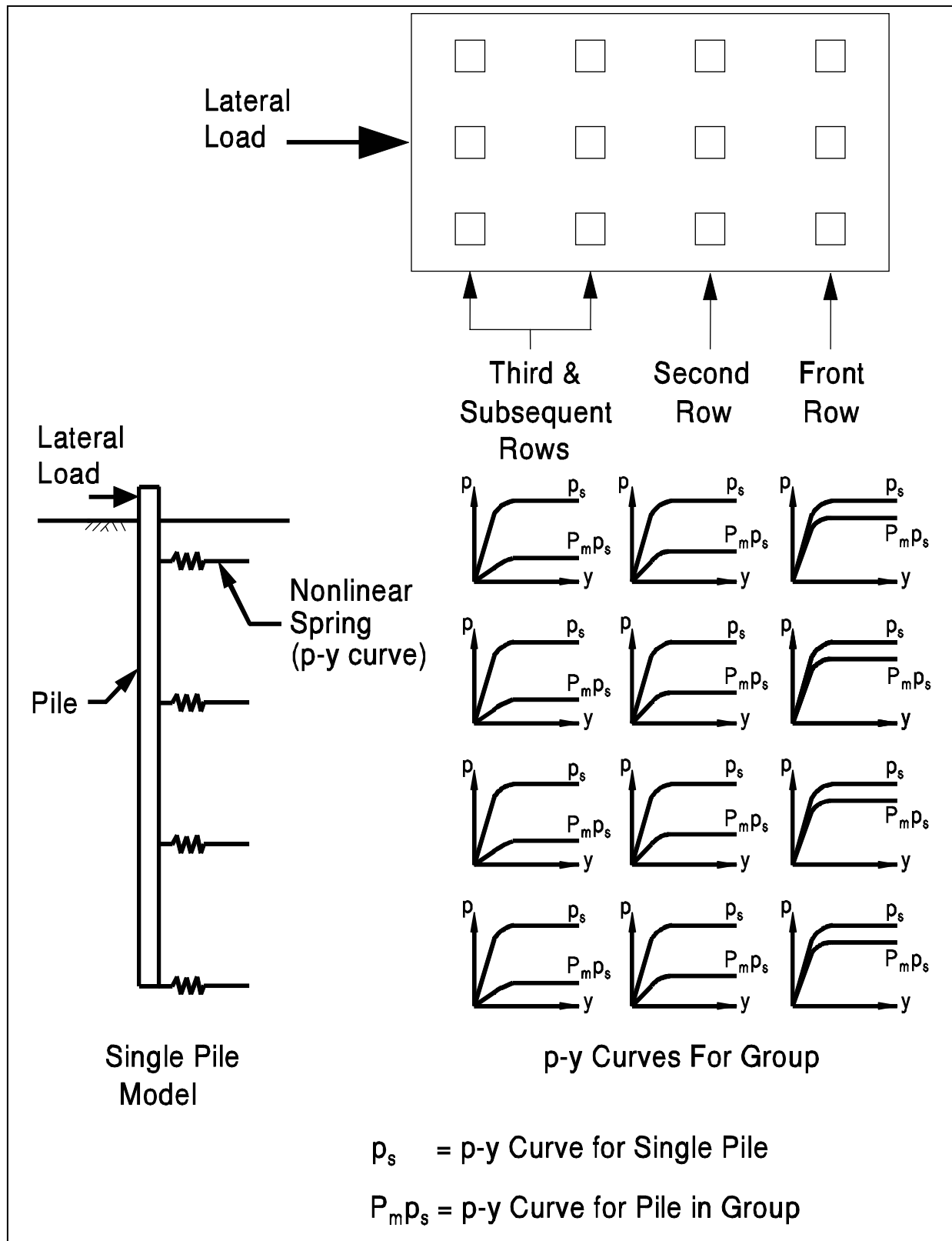


Figure 9.68 Illustration of p-multiplier Concept for Lateral Group Analysis

McVay, *et al.* (1995) performed centrifuge model tests on a 3 by 3 pile group having center to center pile spacings of 3b and 5b. A dense and loose sand condition were simulated in the centrifuge model tests. For the dense sand case at a center to center spacing of 3b, the centrifuge model test results were similar to Brown's field results. However, McVay also found that the P_m values were influenced by soil density and the center to center spacing. The P_m results from McVay's centrifuge tests as well as other recent results for vertical piles in 3 x 3 pile groups are summarized in Table 9-19. McVay's centrifuge tests indicated lateral load group efficiencies in sands on the order of 0.74 for a center to center pile of 3b and 0.93 for a center to center spacing of 5b. Field studies in cohesive soils have also shown that pile-soil-pile interaction occurs. Brown *et al.* (1987) reported P_m values of 0.7, 0.5, and 0.4 for the lead, second, and third row of a laterally loaded pile group in stiff clays.

The most recent work on this topic has included full scale lateral load testing of a 16 pile group in loose sand by Ruesta and Townsend (1997), and a 9 pile group in clayey silt by Rollins *et al.* (1998). A scaled model study of a cyclically laterally loaded pile group in medium clay has also been reported by Moss (1997). The center to center pile spacing, P_m results, and pile head deflections reported in these studies are included in Table 9-19. NCHRP Project 24-09 entitled "Static and Dynamic Lateral Loading of Pile Groups" was also recently completed Brown, *et al.* (2001). The objective of this study was to develop and validate an improved design method for pile groups subjected to static and dynamic lateral loads.

Brown and Bollman (1993) proposed a p-multiplier procedure for the design of laterally loaded pile groups. It is recommended that this approach, outlined in the step by step procedure that follows, be used for the design of laterally loaded pile groups. This procedure can be performed using multiple individual analyses with the LPILE program as illustrated in Appendix F.8. The analyses can also be performed with less effort using the FB-Pier or Group 6.0 computer programs.

The computer program FB-Pier was developed with FHWA support as the primary design tool for analysis of pile groups under axial and lateral loads. This program, which is a successor of the LPGSTAN program by Hoit and McVay (1994) is a non-linear, finite element analysis, soil structure interaction program. FB-Pier uses a p-multiplier approach in evaluation of laterally loaded pile groups under axial, lateral, and combined axial and lateral loads. The program is capable of analyzing driven pile and drilled shaft foundation supported sound walls, retaining walls, signs and high mast lighting. Additional information on FB-Pier program capabilities can be found at <http://bsi-web.ce.ufi.edu>.

| TABLE 9-19 LATERALLY LOADED PILE GROUPS STUDIES | | | | | |
|---|--------------------------|-------------------------------|---|------------------------|-------------------------------|
| Soil Type | Test Type | Center to Center Pile Spacing | Calculated p-Multipliers, P_m For Rows 1, 2, & 3+ | Deflection in mm (in) | Reference |
| Stiff Clay | Field Study | 3b | .70, .50, .40 | 51 (2) | Brown <i>et al</i> , (1987) |
| Stiff Clay | Field Study | 3b | .70, .60, .50, | 30 (1.2) | Brown <i>et al</i> , (1987) |
| Medium Clay | Scale Model- Cyclic Load | 3b | .60, .45, .40 | 600 at 50 cycles (2.4) | Moss (1997) |
| Clayey Silt | Field Study | 3b | .60, .40, .40 | 25-60 (1.0 - 2.4) | Rollins <i>et al</i> , (1998) |
| V. Dense Sand | Field Study | 3b | .80, .40, .30 | 25 (1) | Brown <i>et al</i> , (1988) |
| M. Dense Sand | Centrifuge Model | 3b | .80, .40, .30 | 76 (3) | McVay <i>et al</i> , (1995) |
| M. Dense Sand | Centrifuge Model | 5b | 1.0, .85, .70 | 76 (3) | McVay <i>et al</i> , (1995) |
| Loose M. Sand | Centrifuge Model | 3b | .65, .45, .35 | 76 (3) | McVay <i>et al</i> , (1995) |
| Loose M. Sand | Centrifuge Model | 5b | 1.0, .85, .70 | 76 (3) | McVay <i>et al</i> , (1995) |
| Loose F. Sand | Field Study | 3b | .80, .70, .30 | 25-75 (1-3) | Ruesta <i>et al</i> , (1997) |

STEP BY STEP DESIGN PROCEDURE FOR LATERALLY LOADED PILE GROUPS USING LPILE

STEP 1: Obtain Lateral Loads.

STEP 2: Develop p-y curves for single pile.

- a. Obtain site specific single pile p-y curves from instrumented lateral pile load test at site.
- b. Use p-y curves based on published correlations with soil properties.
- c. Develop site specific p-y curves based on in-situ test data.

STEP 3: Perform LPILE analyses.

- a. Perform LPILE analyses using the P_m value for each row position to develop load-deflection and load-moment data.
- b. Based on current data, it is suggested that P_m values of 0.8 be used for the lead row, 0.4 for the second row, and 0.3 for the third and subsequent rows. These recommendations are considered reasonable for center to center pile spacing of $3b$ and pile deflections at the ground surface of .10 to .15 b . For larger center to center spacings or smaller deflections, these P_m values should be conservative.
- c. Determine shear load versus deflection behavior for piles in each row. Plot load versus pile head deflection results similar to as shown in Figure 9.69(a).

STEP 4: Estimate group deflection under lateral load.

- a. Average the load for a given deflection from all piles in the group (i.e., each of the four rows) to determine the average group response to a lateral load as shown in Figure 9.69(a).

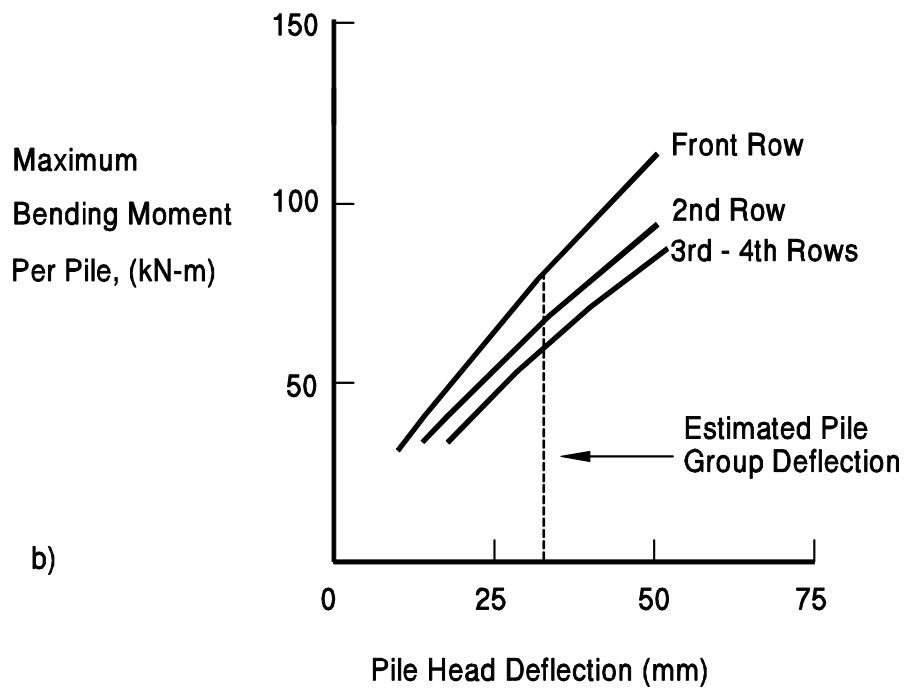
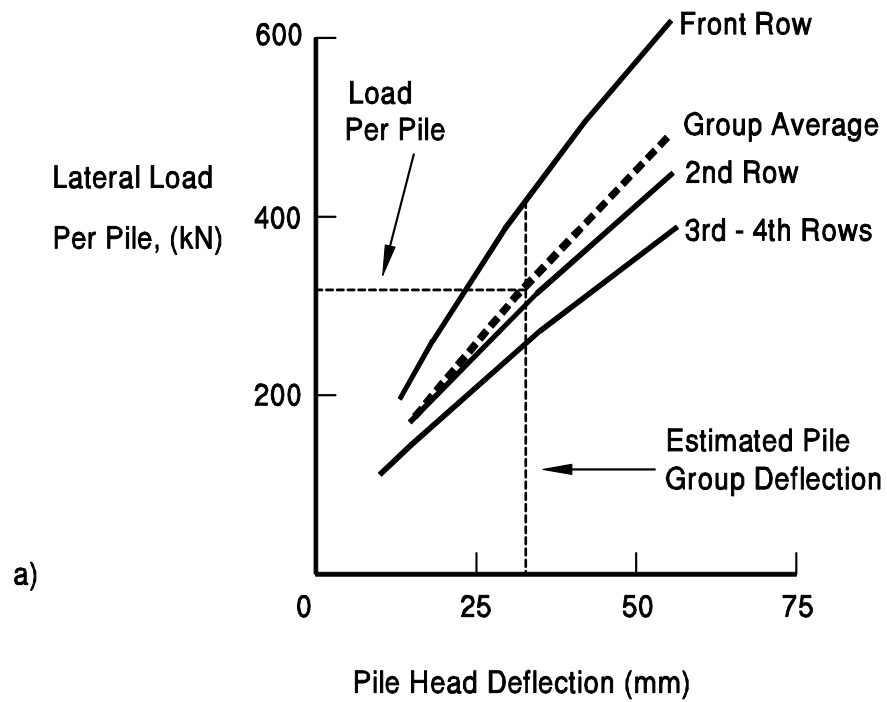


Figure 9.69 Typical Plots of Load versus Deflection and Bending Moment versus Deflection for Pile Group Analysis (adapted from Brown and Bollman, 1993)

Divide the lateral load to be resisted by the pile group by the number of piles in the group to determine the average lateral load resisted per pile.

Enter load-deflection graph similar to Figure 9.69(a) with the average load per pile to estimate group deflection using the group average load deflection curve.

STEP 5: Evaluate pile structural acceptability.

- a. Plot the maximum bending moment determined from LPILE analyses versus deflection for each row of piles as illustrated in Figure 9.69(b).
- b. Check the pile structural adequacy for each row of piles. Use the estimated group deflection under the lateral load per pile to determine the maximum bending moment for an individual pile in each row.
- c. Determine maximum pile stress from LPILE output associated with the maximum bending moment.
- d. Compare maximum pile stress with pile yield stress.

STEP 6: Perform refined pile group evaluation that considers superstructure substructure interaction.

9.9 SPECIAL DESIGN CONSIDERATIONS

In certain situations, additional design problems exist that must be analyzed. These special design considerations include negative shaft resistance, vertical ground movements from swelling soils, lateral squeeze of foundation soils, scour effects on pile capacity, pile heave, and seismic considerations.

9.9.1 Negative Shaft Resistance or Downdrag

When piles are installed through a soil deposit undergoing consolidation, the resulting relative downward movement of the soil around piles induces "downdrag" forces on the piles. These "downdrag" forces are also called negative shaft resistance. Negative

shaft resistance is the reverse of the usual positive shaft resistance developed along the pile surface. The downdrag force increases the axial load on the pile and can be especially significant on long piles driven through compressible soils. Therefore, the potential for negative shaft resistance must be considered in pile design. Batter piles should be avoided in soil conditions where large soil settlements are expected because of the additional bending forces imposed on the piles, which can result in pile deformation and damage.

Settlement computations should be performed to determine the amount of settlement the soil surrounding the piles is expected to undergo after the piles are installed. The amount of relative settlement between soil and pile that is necessary to mobilize negative shaft resistance is about 10 to 12 mm (0.4 to 0.5 in). At that movement, the maximum value of negative shaft resistance is equal to the soil-pile adhesion. The negative shaft resistance can not exceed this value because slip of the soil along the pile shaft occurs at this value. It is particularly important in the design of friction piles to determine the depth at which the pile will be unaffected by negative shaft resistance. Only below that depth can positive shaft resistance forces provide support to resist vertical loads.

The most common situation where large negative shaft resistance develops occurs when fill is placed over a compressible layer immediately prior to, or after piles are driven. This condition is shown in Figure 9.70(a). Negative shaft resistance can also develop whenever the effective overburden pressure is increased on a compressible layer through which a pile is driven; due to lowering of the ground water table as illustrated in Figure 9.70(b), for example.

Briaud and Tucker (1993) presented the following criteria for identifying when negative shaft resistance may occur. If any one of these criteria is met, negative shaft resistance should be considered in the design. The criteria are:

1. The total settlement of the ground surface will be larger than 100 mm (4 in).
2. The settlement of the ground surface after the piles are driven will be larger than 10 mm (0.4 in).
3. The height of the embankment to be placed on the ground surface exceeds 2 m (6.5 ft).
4. The thickness of the soft compressible layer is larger than 10 m (33 ft).

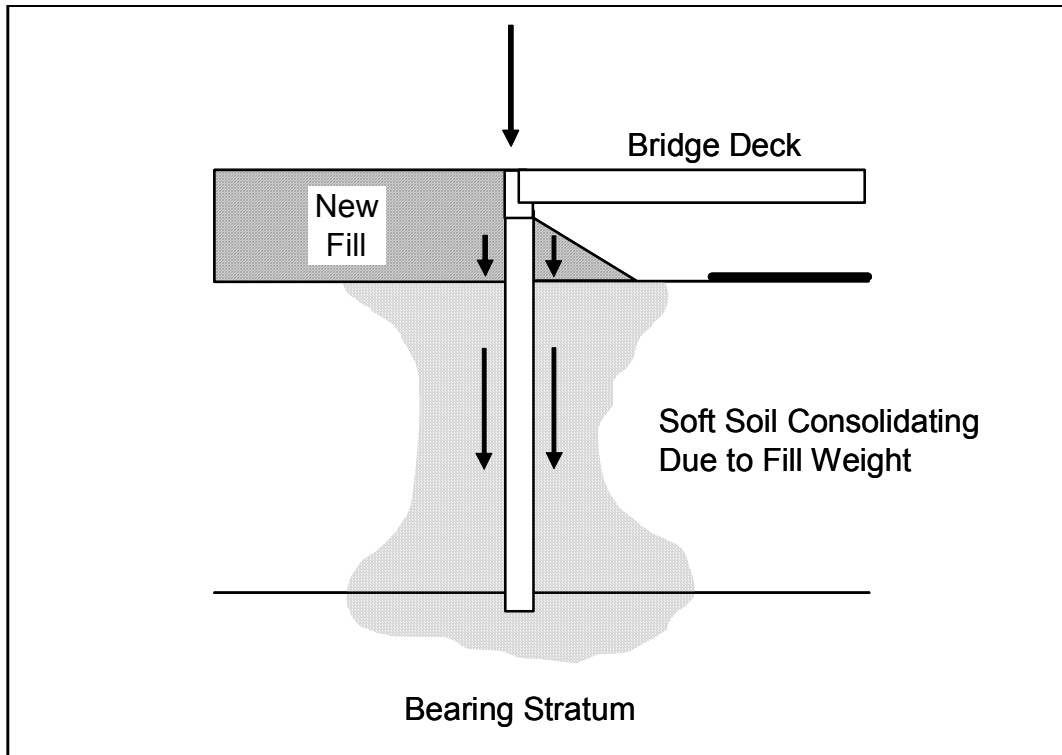


Figure 9.70(a) Common Downdrag Situation Due to Fill Weight

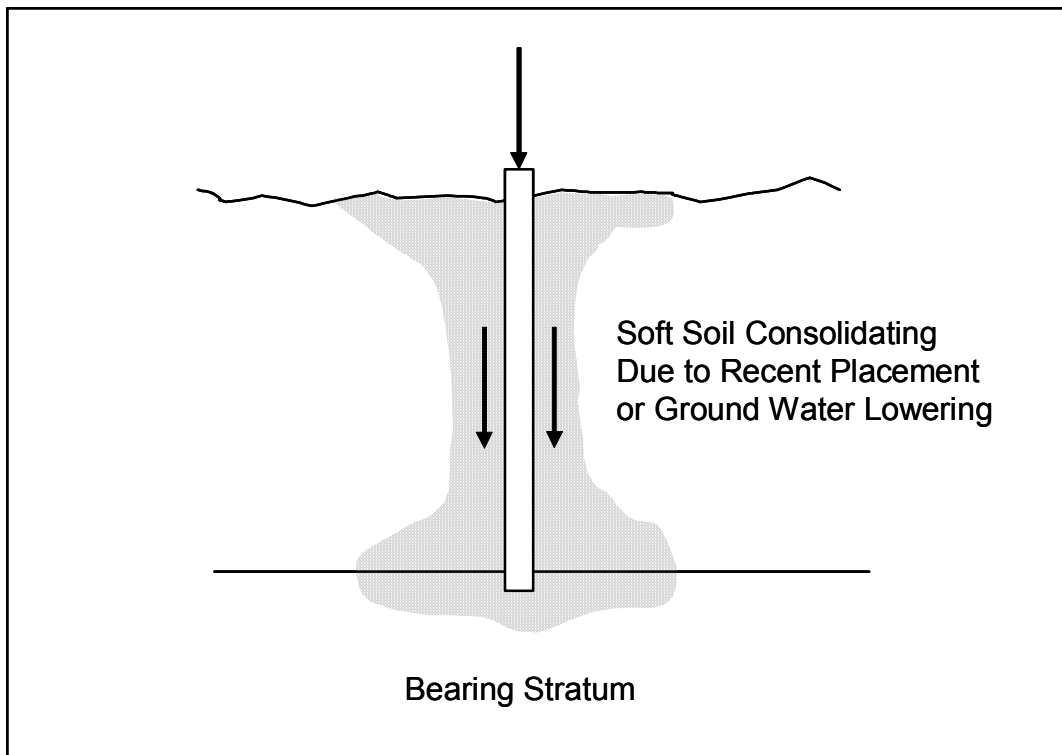


Figure 9.70(b) Common Downdrag Situation Due to Ground Water Lowering

5. The water table will be lowered by more than 4 m (13 ft).
6. The piles will be longer than 25 m (82 ft).

9.9.1.1 Methods for Determining Negative Shaft Resistance

Negative shaft resistance is similar to positive shaft resistance, except the direction of force is opposite. Two design approaches have been used for the design of pile foundations subject to negative shaft resistance. The traditional method has been to calculate the shaft resistance from the soil layers above the zone of consolidating soils, and add this resistance as a load the pile supports. In this approach, any of the previously discussed methods for computing positive pile shaft resistance in cohesive and cohesionless soils can be used. Newer methods of determining negative shaft resistance loads are based on the interrelationship between pile movement and the developed negative shaft resistance load, such as used in the NCHRP study entitled “Downdrag on Bitumen-Coated Piles” by Briaud and Tucker (1993).

9.9.1.1a Traditional Approach to Negative Shaft Resistance

The total stress α -method presented in Section 9.7.1.3 is often used for computing the negative shaft resistance or drag load in cohesive soils. In this approach, the adhesion calculated from the undrained shear strength of the soil times the pile perimeter is equated to the drag load from the consolidating soil layers. Similarly, the drag load from cohesionless layers above a consolidating soil layer is calculated from the shaft resistance in the cohesionless layers.

When selecting the undrained shear strength for calculation of the negative shaft resistance adhesion in the α -method, it is important to remember that the consolidating cohesive soil will have a higher undrained shear strength with time. The adhesion should be calculated using either the higher adhesion value, determined from the undrained shear strength at the time of the soil borings, or the estimated undrained shear strength of the soil after consolidation. Drag loads equal to 100% of the undrained shear strength of a soft clay, ie $\alpha = 1$, have been reported by Johansesen and Bjerrum (1965) for toe bearing piles driven to a relatively unyielding bearing layer. Engineering judgement should be exercised in determining drag loads so that the drag load is not grossly overestimated, resulting in an expensive foundation design, nor underestimated, resulting in a overloaded foundation.

STEP BY STEP DESIGN PROCEDURE FOR ANALYSIS OF DOWNDRAG LOADING

STEP 1 Establish the simplified soil profile and soil properties for computing settlement.

STEP 2 Determine the overburden pressure increase, Δp , versus depth due to the approach embankment fill.

The overburden pressure increase, Δp , is equal to the pressure coefficient, K_f , determined from the pressure distribution chart presented in Figure 9.71, multiplied by the height of fill, h_f , and the unit weight of fill, γ_f . The pressure distribution chart provides the pressure coefficient, K_f , at various depths below the bottom of the fill (x_{bf}), and also at various distances from the centerline of the fill. The depth below the bottom of the fill is given as a multiple of " b_f ", where b_f is the distance from the centerline of the fill to the midpoint of the fill side slope, as shown in Figure 9.71.

Alternatively, the FoSSA computer program (2005) could be used to determine the stress distribution and settlements from the embankment.

For downdrag loading settlement calculations, the overburden pressure increase, Δp , at various depths beneath the centerline of the fill needs to be calculated over the embedded pile length.

- STEP 3 Perform settlement computations for the soil layers along the embedded pile length.
- Determine consolidation test parameters for each soil layer from laboratory consolidation test results.
 - Compute settlement of each soil layer using the appropriate settlement equation provided in Section 9.8.2.3 for cohesive layers or Section 9.8.2.5 for cohesionless layers.
 - Compute the total settlement over the embedded pile length which is equal to the sum of the settlement from each soil layer. Do not include soil settlements below the pile toe level in this computation.

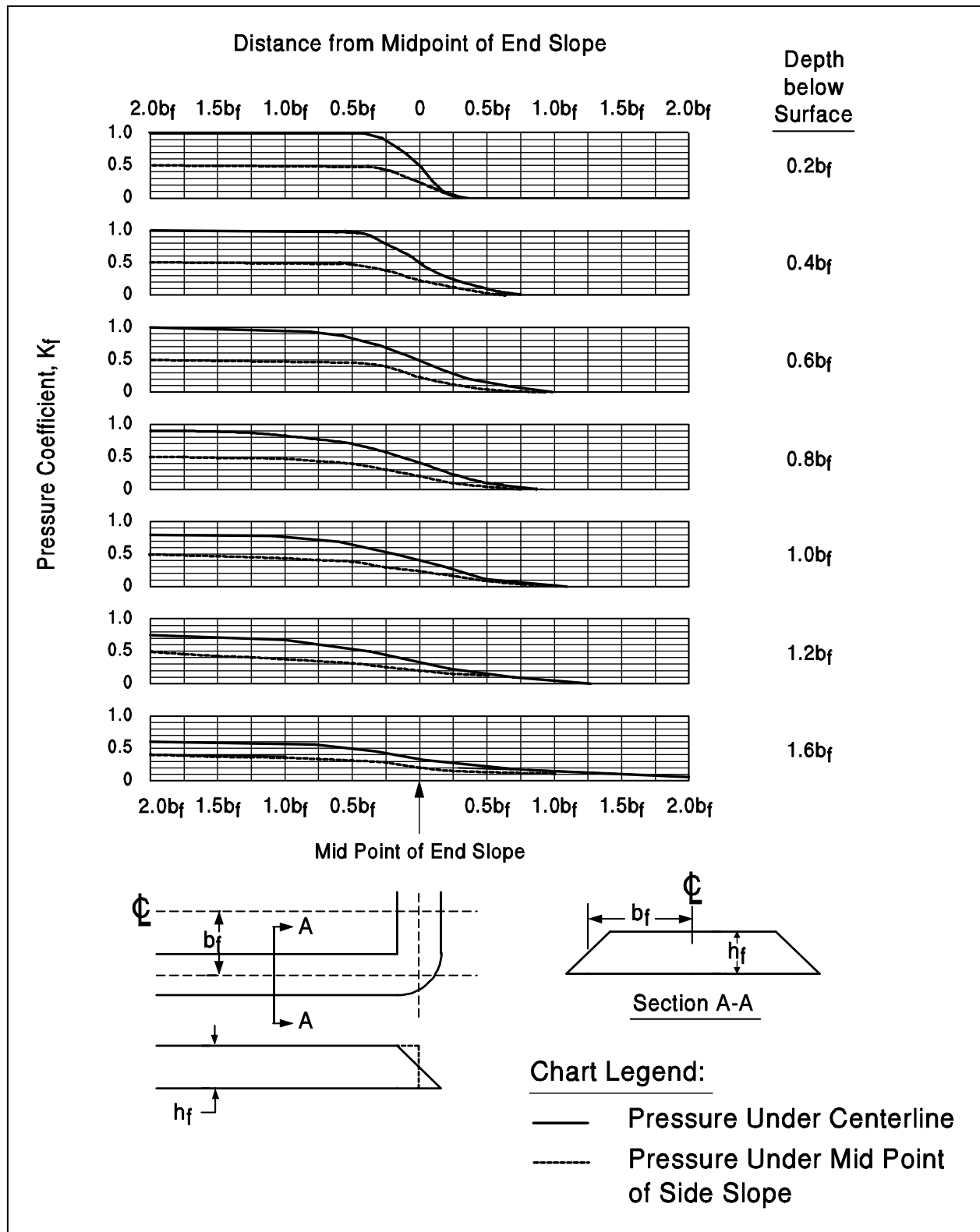


Figure 9.71 Pressure Distribution Chart Beneath the End of a Fill (after Cheney and Chassie, 1993)

STEP 4 Determine the pile length that will experience negative shaft resistance.

Negative shaft resistance occurs due to the settlement between soil and pile. The amount of settlement between soil and pile necessary to mobilize the negative shaft resistance is about 10 mm (0.4 in). Therefore, negative shaft resistance will occur on the pile shaft in each soil layer or portion of a soil layer with a settlement greater than 10 mm (0.4 in).

STEP 5 Determine magnitude of negative shaft resistance, Q_s^- .

The method used to calculate the ultimate negative shaft resistance over the pile length determined in Step 4 should be the same method used to calculate the ultimate positive shaft resistance, except that it will act in the opposite direction.

STEP 6 Calculate the ultimate pile capacity provided by the positive shaft resistance and the toe resistance, Q_u^+ .

Positive shaft and toe resistances will develop below the depth where the relative pile-soil movements are less than 10 mm (0.4 in). The positive soil resistances can be calculated on the pile length remaining below the negative shaft resistance depth from Step 4 using an appropriate static analysis method for the soil type as described in this chapter.

STEP 7 Calculate the net ultimate pile capacity, Q_u^{NET} , available to resist imposed loads.

$$Q_u^{NET} = Q_u^+ - Q_s^-$$

STEP 8 Consider alternatives to obtain higher net ultimate pile capacity.

Alternatives are described in Section 9.9.1.2 and include use of preloading or wick drains to reduce settlements prior to pile installation, use of lightweight fills to reduce settlements that cause downdrag loads, use of friction reducers to reduce downdrag loads, use of higher allowable material stress, and isolation of pile from consolidating soil.

An example calculation using this step by step procedure is included in Appendix F.6.

9.9.1.1b Alternative Approach to Negative Shaft Resistance

Dumas (2000) recommended an alternative approach for analysis and design of deep foundations subject to negative shaft resistance for highway structures. Dumas noted that design for negative shaft resistance can be a complex and time consuming process. In addition, the level of effort frequently employed in a detailed approach does not result in any appreciable economic advantage in foundation costs. Dumas recommended the design protocol presented below.

STEP 1 Determine ultimate deadload (DL_{Ult}) and live load (LL_{Ult}) per pile.

STEP 2 Determine the magnitude of negative shaft resistance, Q_s^- .

Assume an initial neutral plane (NP) at the soft to dense/stiff soil interface or at the top of the layer with approximately zero settlement.

STEP 3 Evaluate structural adequacy of pile.

The pile stress should not exceed the AASHTO recommended values (Chapter 10). It is important that this step be performed before soil resistance and pile toe estimations are performed. Extensive effort could be expended on these calculations, only to result in a structurally inadequate system.

$Q_{AllowStrc}$ = Maximum allowable ASD Stresses as per AASHTO.

$Q_{ReqAllowStrc}$ = maximum applied ASD stress demand on the pile. This will be the larger of two loading conditions:

LL + DL. Maximum stress will occur at the pile head.

DL + Q_{neg} . Maximum stress will occur at the NP.

If $Q_{AllowStrc} < Q_{ReqAllowStrc}$, then consider:

- a. Using higher strength materials. High performance concrete and high strength steel are commonly available.
- b. Using higher allowable stresses. For steel piles, AASHTO allows for considerable flexibility.
- c. Using a larger pile section without increasing the DL or LL, repeat Steps 2-3.

- d. Decreasing the DL and/or LL by adding more piles and repeat Steps 1-3. When evaluating this option, it is essential to consider the increased pile cap costs in the economic evaluation.
- e. Refining the location of the neutral plane. Refer to Steps R-1 to R-5. Repeat Steps 2-3.
- f. Specifying a construction sequence where primary consolidation settlement is completed prior to pile installation. For this approach to be effective, the iterative procedure for locating the neutral plane must be employed.
- g. Reducing the overall Q_s^- forces by using a bitumen coatings or other bond breaker.
- h. Reducing the overall settlement of the upper compressible soil (thereby decreasing Q_s^-) by a reducing the overburden load and/or by using light weight fill materials.

STEP 4 Determine the applied / required ultimate soil resistance (Q_{ReqUlt}).

The applied / required ultimate soil resistance (Q_{ReqUlt}):

If $(LL * FS_{AASHTO}) < (2 * Q_s^- * FS_{Neg})$, then

$$Q_{ReqUlt} = (DL * FS_{AASHTO}) + (Q_s^- * FS_{Neg})$$

otherwise

$$Q_{ReqUlt} = (DL + LL) * FS_{AASHTO}$$

STEP 5 Select an estimated minimum pile tip elevation for Q_{ReqUlt} calculated in Step 4.

STEP 6 Evaluate the adequacy of lateral resistance. It is recommended that LPILE p-y curve, or equivalent, be used.

STEP 7 Evaluate driveability and constructability. Determine if the pile can be driven without damage.

STEP 8 Calculate the cost associated with resisting the downdrag load (additional pile length, size, numbers, strength, lightweight fills, etc.) required to achieve acceptable soil or structural capacity. If costs are considered excessive, then consider items a through h of Step 3.

Iterative Procedure for Locating the Neutral Plane STEP R-1 to R-5

STEP R-1 Calculate and/or plot the soil settlement from the top of the bearing strata to the top of the pile.

STEP R-2 Calculate and/or plot pile settlements (W_n). Using the Q_{ReqUlt} from Step 4, and the estimated tip elevation from Step 5, calculate pile settlements (W_n). Remember, the initial neutral plane has been assumed to be located at the soft to dense/stiff soil interface--top of the layer with approximately zero settlement. W_n is the sum of pile toe movement and elastic shortening. If a linear curve is selected for load transfer in the base resistance and fully plastic curves are selected for load transfer in shaft resistance, a hand solution can be made without difficulty. More sophisticated t-z approaches incorporated in computer programs may be appropriate if the economic analysis in Step 8 warrants it.

STEP R-3 Determine the distance of the new neutral plane from the soft/dense soil interface (Z_n) graphically or by calculation. If the soft compressible layer is homogenous, the settlement can be considered linear (zero at the interface, and its maximum value at the pile top), and the following equation can be used.

$$Z_n = W_n / (\text{soil settlement at the pile top/depth of the soft layer})$$

STEP R-4 Using the new neutral plane, recalculate Q_s^- (Step 2), Q_{ReqUlt} (Step 4), the estimated pile toe elevation (Step 5), and Z_n (Steps R-2 & R-3).

STEP R-5. Repeat Step R-4 until reasonable convergence is achieved. Typically, 2 to 3 iterations.

9.9.1.2 Methods for Reducing Negative Shaft Resistance Forces

In situations where the negative shaft resistance on piles is large and a reduction in the pile design load is impractical, negative shaft resistance forces can be handled or reduced by using one or more of the following techniques:

a. Reduce soil settlement

Preconsolidation of compressible soils can be achieved by preloading and consolidating the soils **prior** to pile installation. This approach is often used for bridge foundations in fill sections. Wick drains are often used in conjunction with preloading in order to shorten the time required for consolidation. Additional information on wick drains is available in "Prefabricated Vertical Drains", FHWA RD 86/168 by Rixner *et al.* (1986) and in "Ground Improvement Methods" manual by Elias *et al.* (2004).

b. Use lightweight fill material

Construct structural fills using lightweight fill material to reduce the downdrag loads. Lightweight fill materials often used, depending upon regional availability, include geofoam, foamed concrete, wood chips, blast furnace slag, and expanded shales. Additional information on lightweight fills is available in Elias *et al.* (2004). Geofoam blocks being placed for embankment construction are shown in Figure 9.72.

c. Use a friction reducer

Bitumen coating and plastic wrap are two methods commonly used to reduce the friction at the pile-soil interface. Bitumen coatings should only be applied to the portion of the pile which will be embedded in the negative shaft resistance zone. Case histories on bitumen coatings have reported reductions in negative shaft resistance from as little as 47% to as much as 90%. Goudreault and Fellenius (1994) suggest that the reduction effect of bitumen may be analyzed by using an upper limit of 10 kPa (0.2 ksf) as the pile-soil shear resistance or adhesion in the bitumen coated zone.

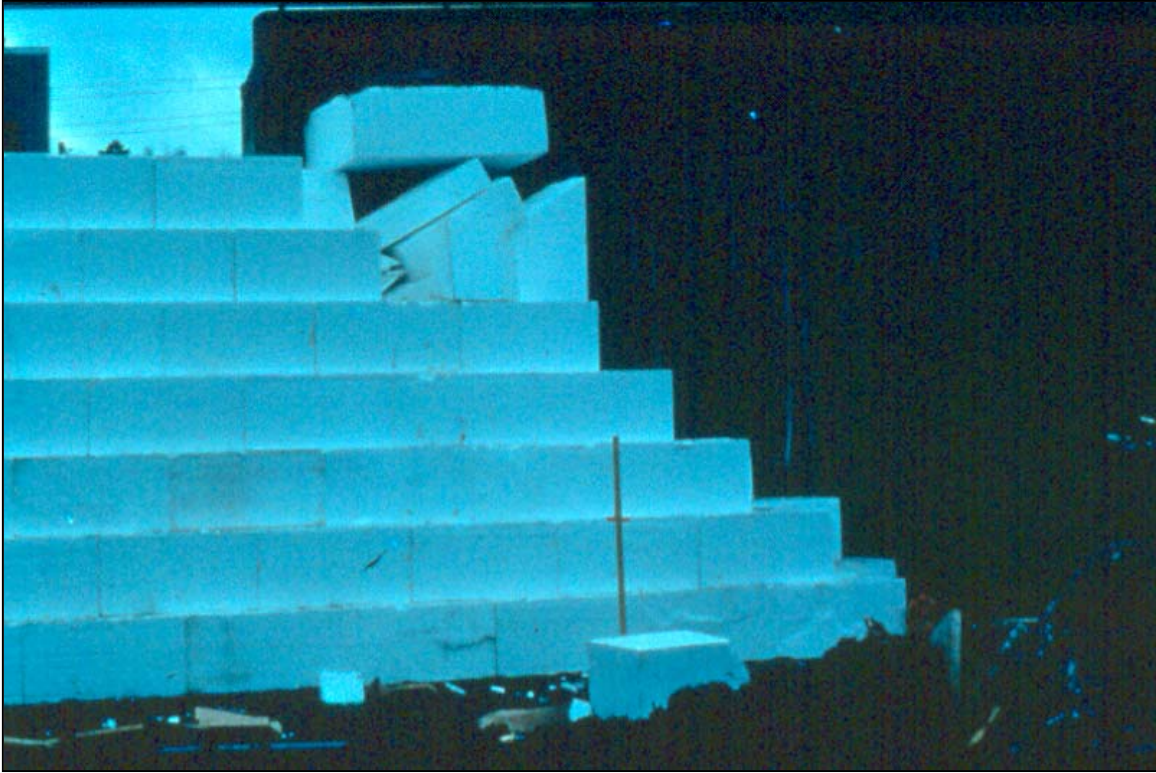


Figure 9.72 Geofoam Blocks for Embankment Construction

One of the major problems with bitumen coatings is protecting the coating during pile installation, especially when driving through coarse soils. An inexpensive solution to this problem is to weld an over-sized collar around the pile where the bitumen ends. The collar opens an adequate size hole to permit passage of the bitumen for moderate pile lengths in fine grained soils. Figure 9.73 presents a photograph on an over-sized collar between the uncoated lower pile section and white washed bitumen coating on the upper pile section.

Bitumen coatings can also present additional construction problems associated with field coating and handling. The bitumen coating used must have relatively low viscosity to permit slippage during soil consolidation, yet high enough viscosity and adherence to insure the coating will stick to the pile surface during storage and driving. The bitumen must also have sufficient ductility to prevent cracking and spalling of the bitumen during handling and driving. Therefore, the climate at the time of pile installation should be considered in selection of the proper bitumen coating. The use of bitumen coatings can be quite successful provided proper construction control methods are followed. However, Bitumen coatings should not be casually specified as the solution to downdrag loading.

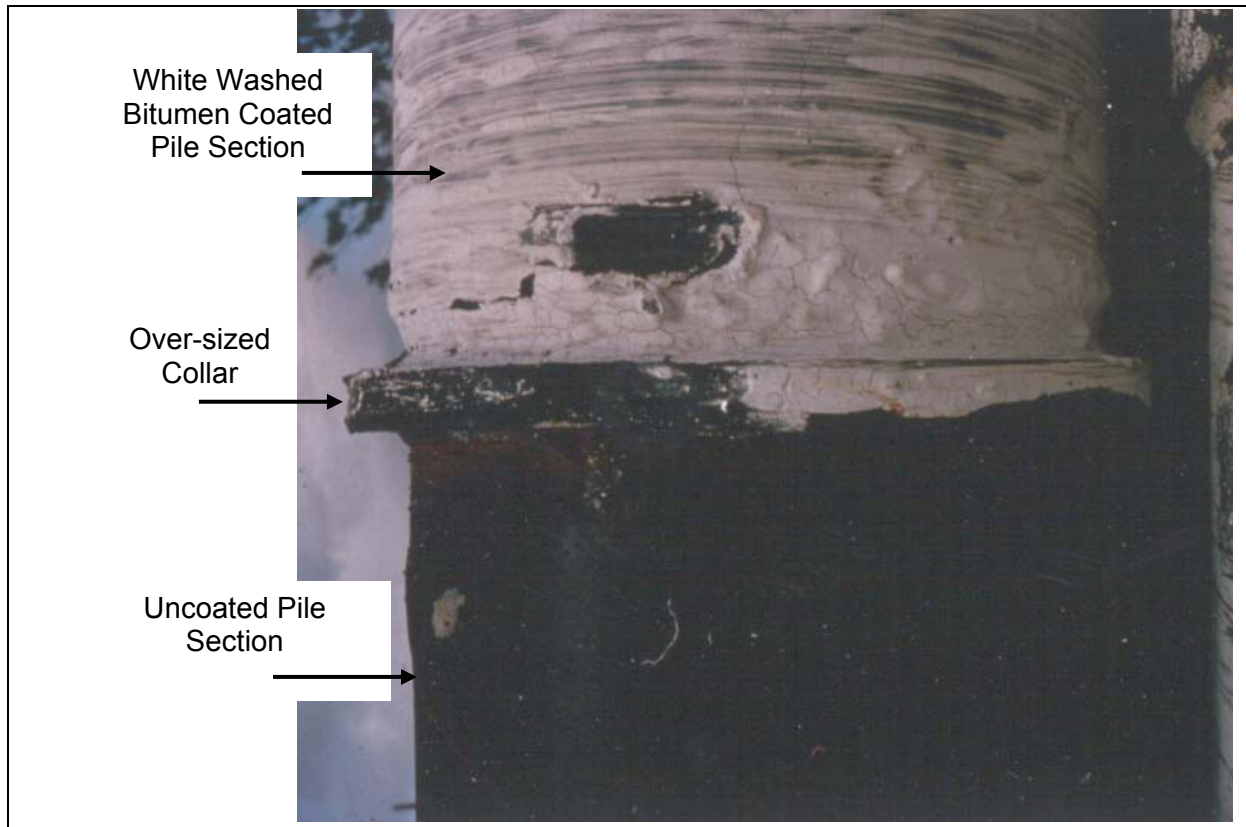


Figure 9.73 Over-sized Collar for Bitumen Coating Protection

Plastic wrap has proven to be an economically attractive friction reducer, particularly for abutment piles driven behind and before construction of MSE walls. Tawfig (1994) performed laboratory tests on 0.15 mm (0.006 in) thick polyethylene sheets used as a friction reducer. The laboratory test results indicated plastic wraps reduced the pile-soil shear resistance from between 78% for a one wrap layer to 98% for a two layer wrap with mineral oil lubricant of the pile-soil shear resistance. The laboratory test data indicated the pile-soil shear resistance of a one wrap layer was about 10 kPa (0.2 ksf) and only 1 kPa (0.02 ksf) for the lubricated two wrap system.

d. Increase allowable-pile stress

In piles where the allowable pile material strength has not been fully utilized, the pile design stress can be increased to offset the negative shaft resistance load. Increased structural capacity can also be obtained by using higher strength pile materials, or in the case of pipe piles, by using an increased wall thickness. Foundation settlement at the increased loading should be computed and checked against the foundation performance criteria.

- e. Prevent direct contact between soil and pile

Pile sleeves are sometimes used to eliminate direct contact between pile and soil. Bentonite slurry has been used in the past to achieve the same purpose. These methods are generally more expensive.

9.9.2 Vertical Ground Movements from Swelling Soils

Detrimental vertical ground movements can also occur in swelling soils subject to seasonal moisture changes, such as expansive clays. In this case, the swell pressures can induce uplift forces on the pile. For piles driven in swelling soils, bitumen coatings on the pile shaft through the swelling soil zone is effective in reducing the uplift forces.

9.9.3 Lateral Squeeze of Foundation Soil

Bridge abutments supported on piles driven through soft compressible cohesive soils may tilt forward or backward depending on the geometry of the backfill and the abutment. This problem is illustrated in Figure 9.74. Large horizontal movements may cause damage to the structure. The unbalanced fill loads shown in Figure 9.74 displace the soil laterally. This lateral displacement may bend the piles, causing the abutment to tilt toward or away from the fill.

The following rules of thumb are recommended for determining whether tilting will occur, as well as estimating the magnitude of horizontal movement.

1. Lateral squeeze and abutment tilting can occur if:

(SI Units)

$$[\gamma \text{ fill in kN/m}^3] [\text{fill height in m}] > 3 [\text{undrained shear strength of soft soil in kPa}]$$

(US Units)

$$[\gamma \text{ fill in lb/ft}^3] [\text{fill height in ft}] > 3 [\text{undrained shear strength of soft soil in psf}]$$

2. If abutment tilting can occur, the magnitude of the horizontal movement can be estimated by the following formula:

Horizontal Abutment Movement in mm (in) = 0.25 Vertical Fill Settlement in mm (in)

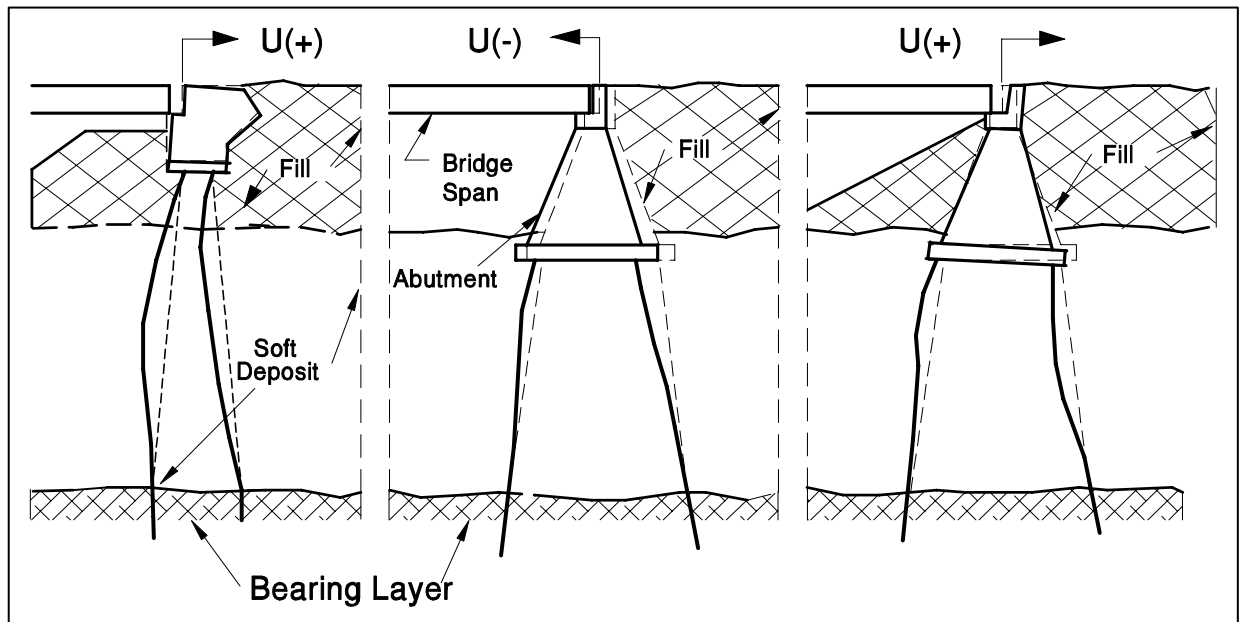


Figure 9.74 Examples of Abutment Tilting Due to Lateral Squeeze

9.9.3.1 Solutions to Prevent Tilting

- Delay installation of abutment piling until after fill settlement has stabilized (best solution).
- Provide expansion shoes large enough to accommodate the movement.
- Use steel H-piles to provide high tensile strength in flexure.
- Use lightweight fill to reduce driving forces.

9.9.4 Ultimate Capacity of Piles in Soils Subject to Scour

Scour is defined as the erosion of soil materials from the streambed and/or stream banks due to flowing water. Though often considered as being localized, scour may consist of multiple components including long term aggradation and degradation, local scour, contraction scour, and general scour. Aggradation and degradation involve the long term streambed elevation changes due to an abundance or deficit, respectively, in upstream sediment supply. Local scour involves the removal of material from the immediate vicinity of a substructure unit and can be either clear-water, free of disturbed upstream sediment, or live-bed scour, complicated by the transport of upstream sediment into the scour hole. In contrast, contraction scour and general scour involve erosion across all or most of the channel width and relate directly with the stream stratigraphy at the scour location. Contraction scour results from a contraction of flow, while general scour encompasses other short-term, non-localized lowering of the streambed.

Different materials, subject to any of the abovementioned types of scour, erode at different rates. In a flood event, loose granular soils can be eroded away in a few hours. Cohesive or cemented soils typically erode more gradually and over several cycles of flooding but can experience the same ultimate scour depths as those of cohesionless deposits. As noted earlier in this chapter, the ultimate capacity of a driven pile is due to soil resistance along the pile shaft and at the pile toe. Therefore, the erosion of the soil materials providing pile support can have significant detrimental effects on pile capacity and must clearly be evaluated during the design stage.

Depending on the type of scour and the scour susceptibility of the streambed soils, multiple static capacity calculations may be required to evaluate the ultimate capacity of a pile and toe establish pile penetration requirements. In the case of local scour, the soil in the scour zone provides resistance at the time of driving that cannot be counted on for long term support. Hence, shaft resistance in the scour zone, although included for driveability considerations, is ignored for design purposes. However, because the erosion is localized, pile capacity calculations should assume that the effective overburden pressure is unchanged. The effects of non-localized scour on long term pile capacity are more severe. In all of degradation, contraction scour, and general scour, a reduction in both the scour zone soil resistance and the effective overburden is applied to long term capacity calculations, due to the widespread removal of the streambed materials. This added reduction in effective stresses can have a significant effect on the calculated shaft and toe resistances. Figure 9.75 provides an illustration of localized and non-localized scour.

The FHWA publication FHWA NHI-01-001, "Evaluating Scour at Bridges" by Richardson and Davis (2001), more commonly known as HEC-18, recommends that the following pile design issues also be considered at bridge sites subject to scour.

1. For pile supported substructures subjected to scour, a reevaluation of the foundation design may require a change in the pile length, number, cross-sectional dimension and type based on the loading and performance requirements and site-specific conditions.
2. Piling should be designed for additional lateral restraint and column action because of the increase in unsupported pile length after scour. The unsupported pile length is discussed in Chapter 10.
3. Local scour holes at piers and abutments may overlap one another in some instances. If local scour holes do overlap, the scour is indeterminate and may be deeper. The topwidth of a local scour hole on each side of the pier ranges from 1.0 to 2.8 times the depth of local scour. A topwidth value of 2.0 times the depth of local scour on each side of a pier is suggested for practical applications.
4. Perform the bridge foundation analysis on the basis that all streambed material in the scour prism above the total scour line has been removed and is not available for pile capacity or lateral support. In areas where the local scour is confined to the proximity of the footing, the lateral ground stresses on the pile length which remains embedded may not be significantly reduced from the pre-local scour conditions.
5. Placing the top of the footing or pile cap below the streambed a depth equal to the estimated long term degradation and contraction scour depth will minimize obstruction to flood flows and resulting local scour. Even lower footing elevations may be desirable for pile supported footings when the piles could be damaged by erosion and corrosion from exposure to river or tidal currents. However, in deep water situations, it may be more cost effective to situate the pile cap above the mudline and design the foundation accordingly.
6. Stub abutments positioned in the embankment should be founded on piling driven below the elevation of the thalweg including long term degradation and contraction scour in the bridge waterway to assure structural integrity in the event the thalweg shifts and the bed material around the piling scours to the thalweg elevation.

The design event dictates the recommended design procedure for scour. For scour depths associated with earlier the 100-year flood event or the overtopping flood, the procedure illustrated in Section 9.6 should be followed where the factor of safety is linked to the construction control. For the superflood, or 500-year event, HEC-18 specifies a minimum factor of safety of 1.0. This minimum factor of safety is determined by dividing the maximum pile load by the sum of the shaft and toe resistances available below the scour depth. The shaft and toe resistances should be determined from an appropriate static analysis calculation as detailed earlier in this chapter.

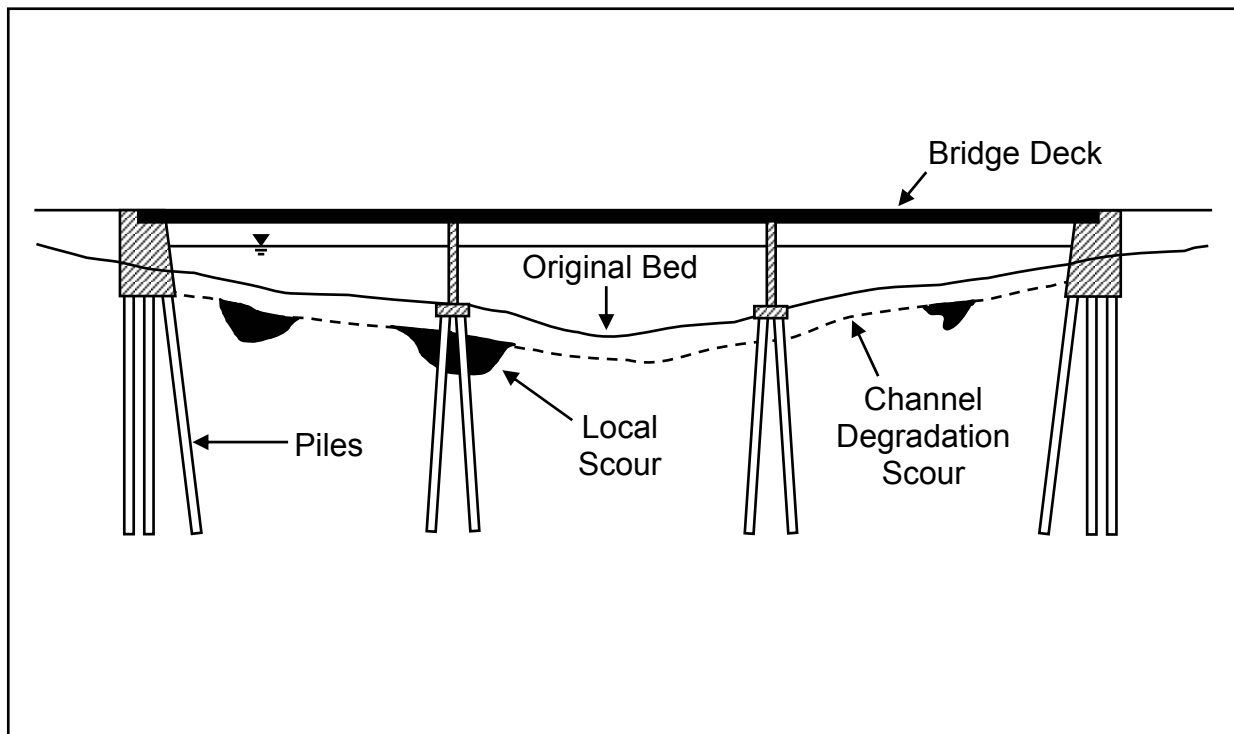


Figure 9.75 Local and Channel Degradation Scour

9.9.5 Soil and Pile Heave

As noted by Hagerty and Peck (1971), whenever piles are driven, soil is displaced. This can result in both upward movement (pile heave) and lateral movements of previously driven piles. These soil movements can be detrimental to the capacity of previously driven piles as well as to adjacent facilities. Obviously, the greater the volume of soil displaced by pile driving, the greater the potential for undesirable movements of previously driven piles, or damage to adjacent structures. Heave of toe bearing piles is particularly troublesome since the pile may be lifted from the bearing stratum, thereby greatly reducing the pile capacity and increasing the foundation settlement when

loaded. Haggerty and Peck noted that saturated, insensitive clays behave incompressibly during pile driving and have the greatest heave potential.

When piles are to be installed in cohesive soils, it is recommended that the potential magnitude of vertical and lateral soil movements be considered in the design stage. If calculations indicate that movements may be significant, use of an alternate low displacement pile, or specifying a modified installation procedure (such as predrilling to reduce the volume of displaced soil) should be evaluated. A step by step procedure adapted from Haggerty and Peck for estimating soil and pile heave in a saturated insensitive clay follows. The procedure assumes a regular pile driving sequence and a level foundation surface. The paper by Haggerty and Peck should be consulted for modifications to the recommended procedure for conditions other than those stated.

STEP BY STEP PROCEDURE FOR ESTIMATING SOIL AND PILE HEAVE

STEP 1 Calculate the estimated soil heave at the ground surface.

- a. Divide the volume of inserted piles by the volume of soil enclosed by the pile foundation to obtain the volumetric displacement ratio.
- b. Estimate the normalized soil heave (soil heave / pile length) from $\frac{1}{2}$ the volumetric displacement ratio calculated in Step 1a.
- c. Calculate the soil heave at the ground surface by multiplying the normalized soil heave in Step 1b by the average length of piles.

STEP 2 Determine the depth of no pile-soil movement.

- a. Figure 9.76 illustrates that a depth, d , exists where the potential upward pushing and downward resisting forces on the pile shaft are equal.
- b. Calculate the pile-soil adhesion along the entire pile shaft using the α -method described in Section 9.7.1.2a.
- c. Through multiple iterations determine the depth, d , where the adhesion from the upward pushing force equals the adhesion from the downward resisting force. Remember only shaft resistance is considered in calculating the downward resisting force.

STEP 3 Calculate the estimated pile heave.

- a. Calculate the percentage of pile length subject to heave from $(D-d) / D$ where D is the embedded pile length, and d is the equilibrium depth from Step 2c.
- b. Calculate the estimated pile heave by multiplying the estimated soil heave from Step 1c by the percentage of pile length subject to heave from Step 3a.

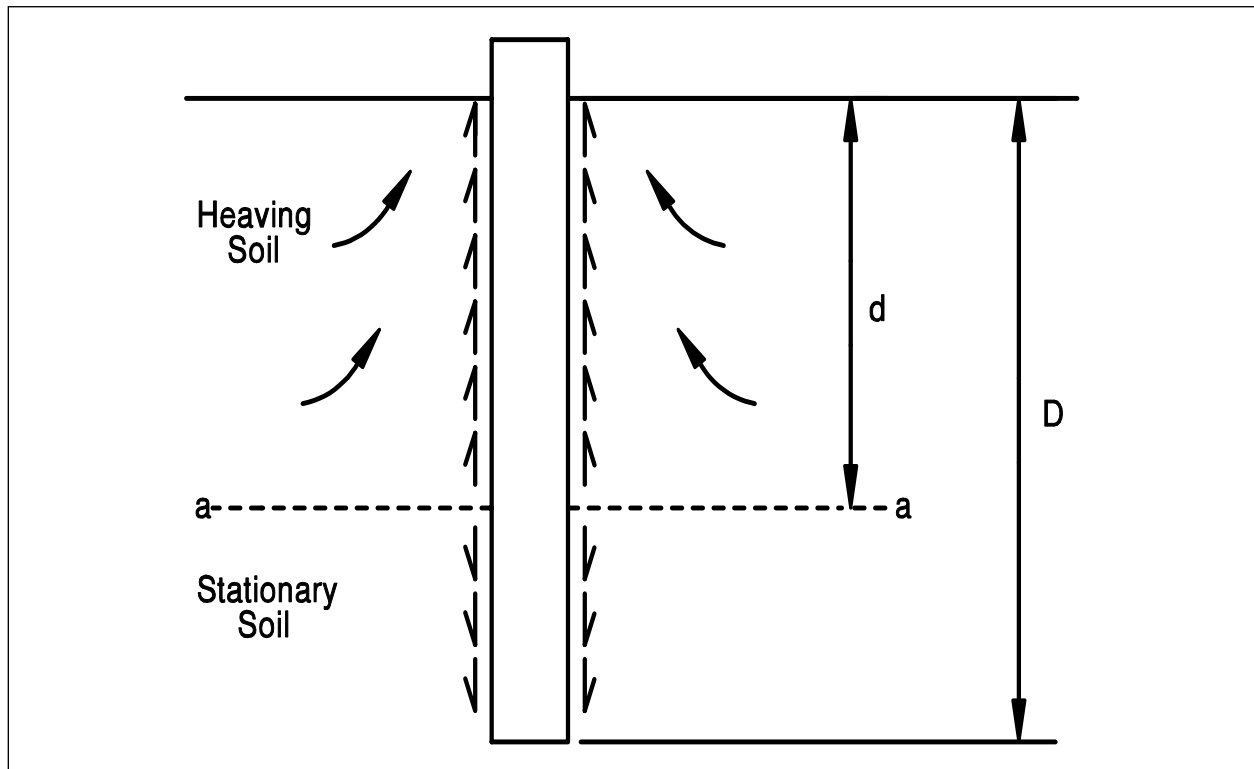


Figure 9.76 Balance of Forces on Pile Subject to Heave (after Haggerty and Peck, 1971)

9.9.6 Seismic Considerations

The design issues associated with pile foundation design for seismic events are significant and are beyond the scope of this manual. Other publications such as FHWA RD-86/102, Seismic Design of Highway Bridge Foundations by Lam and Martin (1986), and Division 1A - Seismic Design of AASHTO Standard Specification (1992) should be consulted for design guidance in seismically active areas. Geotechnical Engineering Circular No. 3 by Kavazanjian, *et al.*, (1997) provides additional guidance on geotechnical earthquake engineering. Pile foundation design issues in seismic events include liquefaction effects on pile capacity, ground movements, seismic induced foundation loads, and seismic

induced drag loads. This manual will therefore only briefly address the identification of liquefiable soils and the consequences of liquefaction on pile foundation design.

Soil types most susceptible to liquefaction can be described as saturated, very loose to medium dense, fine to medium grained sands and non-plastic silts. However, liquefaction has also occurred in saturated, very loose to medium dense gravels and certain clayey soils.

In seismically active areas where peak earthquake acceleration will be greater than 0.1g, the soil susceptibility to liquefaction should be evaluated. A commonly used procedure for identification of liquefaction susceptible soils was proposed by Seed *et al.* (1983). This liquefaction evaluation approach is detailed in the Commentary for Section 6, Division 1A of the AASHTO Standard Specifications (2002) as well as Lam and Martin (1986). If the soils are found to liquefy during the design event, the pile foundation must be designed to accommodate the loss of frictional resistance, seismic induced loads, as well as the anticipated vertical and horizontal displacements. Alternatively, the liquefaction potential may be mitigated through ground improvement techniques.

Pile foundations in liquefiable soils must penetrate through the zone of liquefaction and develop adequate capacity in the underlying soils. Evaluation of compression and uplift capacities during the seismic event can be made by assigning residual strength properties to the liquefiable layers. Residual strengths of sands and silty sands can be approximated from SPT resistance values using a correlation proposed by Seed (1987) and updated by Seed and Harder (1990).

Following a seismic event that induces soil liquefaction, the liquefied layer will consolidate. The soil resistance in and above the liquified layer will then become additional drag load that the pile must support. The pile foundation must be structurally capable of supporting this drag load and the foundation settlement resulting from the drag load must be within the structure's performance criteria.

Liquefaction induced lateral spread can impose significant bending moments in piles driven through liquefiable soils. Therefore, piles in liquefiable soils should be flexible and ductile in order to accommodate lateral loads. The maximum bending moment of piles in liquefiable soils is often evaluated in a LPILE analysis by assigning Reese's soft clay p-y curve with low residual shear strengths and high ϵ_{50} values to the liquefiable layer.

9.10 ADDITIONAL DESIGN AND CONSTRUCTION CONSIDERATIONS

The previous sections of this chapter addressed routine and special event static analysis procedures for pile foundation design. However, the designer should be aware of additional design and construction considerations that can influence the reliability of static analysis procedures in estimating pile capacity. These issues include the influence of time, predrilling or jetting, construction dewatering, soil densification, and the plugging of open pile sections on pile capacity. Pile driving induced vibrations can also influence the final design and static calculation results if potential vibration levels dictate changes in pile type or installation procedures. The closing section of this chapter focuses on pile driveability. Evaluation of pile driveability is a fitting final topic of this design chapter since all the previously described analyses are meaningless if the pile cannot be driven to the required depth and capacity without damage.

9.10.1 Time Effects on Pile Capacity

As noted in Section 9.2, the soil is greatly disturbed when a pile is driven into the soil. As the soil surrounding the pile recovers from the installation disturbance, a time dependent change in pile capacity often occurs. Frequently piles driven in saturated clays, and loose to medium dense silts or fine sands gain capacity after driving has been completed. This phenomenon is called soil setup. Occasionally piles driven into dense saturated fine sands, dense silts, or weak laminated rocks such as shale, will exhibit a decrease in capacity after the driving has been completed. This phenomenon is called relaxation. Case history discussions on soil setup and relaxation may be found in Fellenius *et al.* (1989), and Thompson and Thompson (1985), respectively.

9.10.1.1 Soil Setup

When saturated cohesive soils are compressed and disturbed due to pile driving, large excess pore pressures develop. These excess pore pressures are generated partly from the shearing and remolding of the soil and partly from radial compression as the pile displaces the soil. The excess pore pressures cause a reduction in the effective stresses acting on the pile, and thus a reduction in the soil shear strength. This results in a reduced pile capacity during, and for a period of time after, driving.

After driving, the excess pore pressures will dissipate primarily through radial flow of the pore water away from the pile. With the dissipation of pore pressures, the soil reconsolidates and increases in shear strength. This increase in soil shear strength results in an increase in the static pile capacity and is called soil setup. A similar decrease in

resistance to pile penetration with subsequent soil setup may occur in loose to medium dense, saturated, fine grained sands or silts. The magnitude of the gain in capacity depends on soil characteristics, pile material and pile dimensions.

Because the pile capacity may increase after the end of driving, pile capacity assessments should be made from static load testing or retapping performed **after** equilibrium conditions in the soil have been re-established. The time for the return of equilibrium conditions is highly variable and depends on soil type and degree of soil disturbance. Piezometers installed within three diameters of the pile can be used to monitor pore pressure dissipation with time. Effective stress static pile capacity calculation methods can be used to evaluate the increase in capacity with time once pore pressures are quantified.

Static load testing or restrike testing of piles in fine grained soils should not be conducted until after pore pressures dissipate and return to equilibrium. In the absence of site specific pore pressure data from piezometers, it is suggested that static load testing or retapping of piles in clays and other predominantly fine grained soils be delayed for at least two weeks after driving and preferably for a longer period. In sandy silts and fine sands, pore pressures generally dissipate more rapidly. In these more granular deposits, five days to a week is often a sufficient time delay.

Rausche, *et al.* (1996) calculated general soil setup factors based on the predominant soil type along the pile shaft. The soil setup factor was defined as the static load test failure load divided by the end-of-drive wave equation capacity. These results are presented in Table 9-20. The data base for this study was comprised of 99 test piles from 46 sites. The number of sites and the percentage of the data base in a given soil condition is included in the table. While these soil set-up factors may be useful for preliminary estimates, soil setup is better estimated based on site specific data gathered from pile retapping, dynamic measurements, static load testing, and local experience.

Komurka *et.al.*, (2003) summarized the current practice in estimating and measuring soil setup in a report to the Wisconsin Highway Research Program. This report summarizes the mechanisms associated with soil setup development and reviews several empirical relationships for estimating set-up.

| TABLE 9-20 SOIL SETUP FACTORS (after Rausche <i>et al.</i> , 1996) | | | |
|---|-----------------------------|----------------------------------|---|
| Predominant Soil Type Along Pile Shaft | Range in Soil Set-up Factor | Recommended Soil Set-up Factors* | Number of Sites and (Percentage of Data Base) |
| Clay | 1.2 - 5.5 | 2.0 | 7 (15%) |
| Silt - Clay | 1.0 - 2.0 | 1.0 | 10 (22%) |
| Silt | 1.5 - 5.0 | 1.5 | 2 (4%) |
| Sand - Clay | 1.0 - 6.0 | 1.5 | 13 (28%) |
| Sand - Silt | 1.2 - 2.0 | 1.2 | 8 (18%) |
| Fine Sand | 1.2 - 2.0 | 1.2 | 2 (4%) |
| Sand | 0.8 - 2.0 | 1.0 | 3 (7%) |
| Sand - Gravel | 1.2 - 2.0 | 1.0 | 1 (2%) |

* Confirmation with Local Experience Recommended

9.10.1.2 Relaxation

The ultimate capacity of driven piles can also decrease with time following driving. This is known as relaxation and it has been observed in dense, saturated, fine grained soils such as non-cohesive silts and fine sands, as well as in some shales. In these cases, the driving process is believed to cause the dense soil near the pile toe to dilate (tendency for volume increase), thereby generating negative pore pressures (suction). The negative pore pressures temporarily increase the effective stresses acting on the pile, resulting in a temporarily higher soil strength and driving resistance. When these pore pressures dissipate, the effective stresses acting on the pile decrease, as does the pile capacity. Relaxation in weak laminated rocks has been attributed to a release of locked in horizontal stresses, Thompson and Thompson (1985).

Because the pile capacity may decrease (relaxation) after the end of driving, pile capacity assessments from static load testing or retapping should be made after equilibrium conditions in the soil have been re-established. In the absence of site specific pore pressure data from piezometers, it is suggested that static load testing or retapping of piles in dense silts and fine sands be delayed for five days to a week after driving, or longer if possible. In relaxation prone shales, it is suggested that static load testing or restrike testing be delayed a minimum of two weeks after driving.

Published cases of the relaxation magnitude of various soil types are quite limited. However, data from Thompson and Thompson (1985) as well as Hussein *et al.* (1993) suggest relaxation factors for piles founded in some shales can range from 0.5 to 0.9. The relaxation factor is defined as the static load test failure load divided by the pile capacity at the end of initial driving. Relaxation factors of 0.5 and 0.8 have also been observed in two cases where piles were founded in dense sands and extremely dense silts, respectively. The importance of evaluating time dependent decreases in pile capacity for piles founded in these materials cannot be over emphasized.

9.10.1.3 Estimation of Pore Pressures During Driving

According to Lo and Stermac (1965), the maximum pore pressure induced from pile driving may be estimated from the following equation.

$$\Delta u_m = \left[(1 - K_0) + \left(\frac{\Delta u}{p} \right)_m \right] p_i$$

Where: Δu_m = Maximum excess pore pressure in kPa (ksf).
 K_0 = Coefficient of earth pressure at-rest.
 $(\Delta u/p)_m$ = Maximum value of the pore pressure ratio, $\Delta u/p$, measured in a CU triaxial test with pore pressure measurements.
 p_i = Initial effective overburden pressure prior to pile driving in kPa (ksf).

Ismael and Klym (1979) presented a case history where the above procedure was used. They reported good agreement between measured excess pore pressures with estimates from the Lo and Stermac procedure.

Poulos and Davis (1980) summarized measurements of excess pore pressures due to pile driving from several case histories. In this compilation, the reported excess pore pressure measurements divided by the effective overburden pressure were plotted versus the radial

distance from the pile surface divided by the pile radius. These results are presented in Figure 9.77 and indicate that the excess pore pressure at the pile-soil interface can approach 1.4 to 1.9 times the effective overburden pressure, depending upon the clay sensitivity.

The foundation designer should evaluate the potential change in pile capacity with time. Once pore pressures are measured or estimated, effective stress static pile capacity calculation methods can be used to quantify the probable change in pile capacity with time.

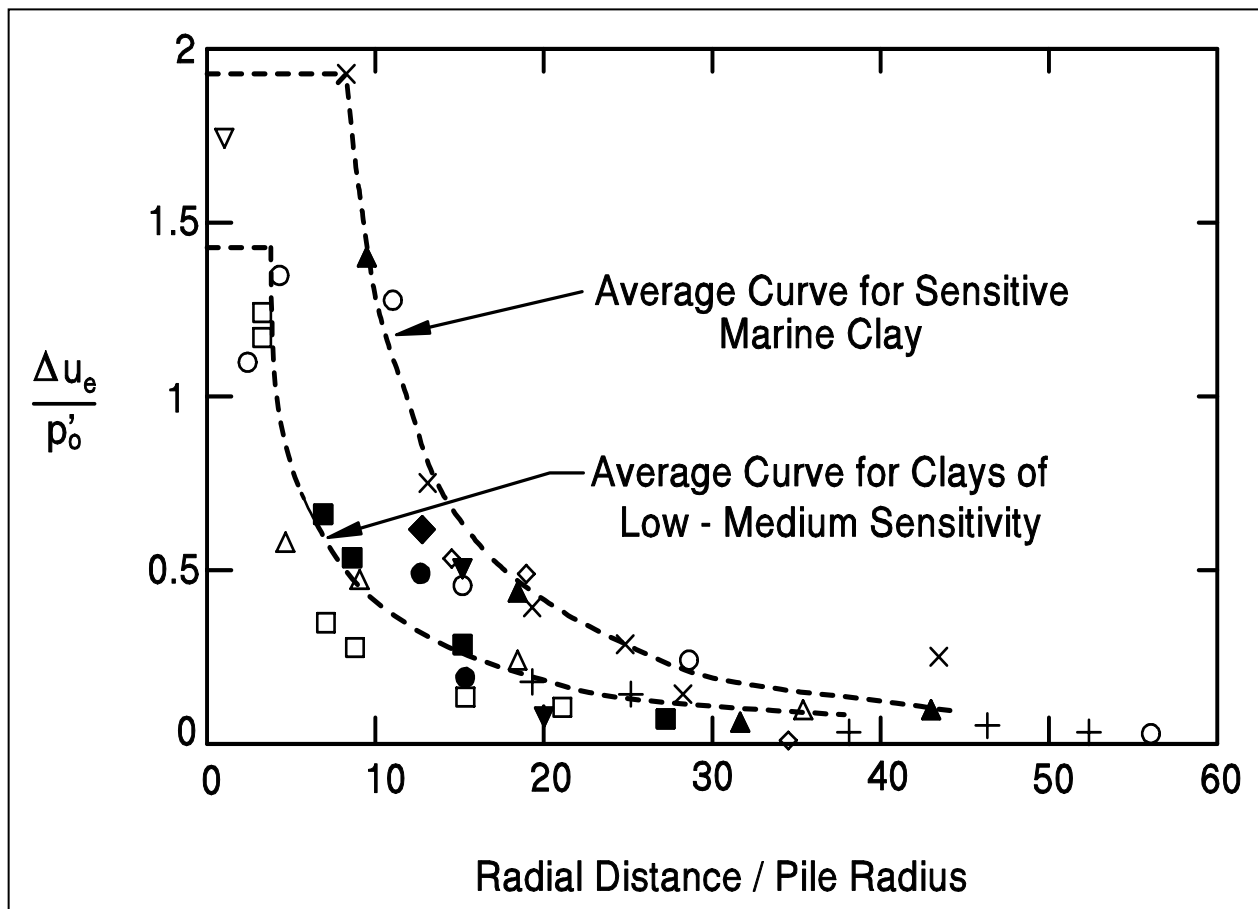


Figure 9.77 Excess Pore Water Pressure due to Pile Driving (after Poulos and Davis, 1980)

9.10.2 Effects of Predrilling, Jetting and Vibratory Installation on Pile Capacity

Piles are sometimes predrilled or jetted to a prescribed depth in order to attain the pile penetration depths required, as well as to reduce other foundation installation concerns, such as ground vibrations. Jetting is usually performed in cohesionless soils that can be freely eroded by water jets. Jetting, which can be very effective in sands, is usually ineffective in cohesive soils. For clays, and other drillable materials, such as thin layers of rock, predrilling the pile locations is more effective. The predrilled hole can be slightly smaller, equal to, or slightly larger than the pile diameter.

The use of predrilling or jetting will result in greater soil disturbance than considered in standard static pile capacity calculations. Therefore, when predrilling or jetting is contemplated, the effect of either of these construction procedures on calculated compression, uplift, and lateral pile capacity should be considered. Poulos and Davis (1980) report that the ultimate shaft resistance should be reduced by 50% of the originally calculated capacity in the jetted zone if the pile is jetted and then driven to the final penetration. McClelland *et al.* (1969) reported that a decrease in shaft resistance over a predrilled depth can range from 50 to 85% of that calculated without predrilling, depending upon the size of the predrilled hole. Hence, the probable reduction in compression, uplift, and lateral capacity from jetting or predrilling should be evaluated whenever predrilling or jetting is being considered.

Agencies are often requested to allow pile installation with a vibratory pile hammer instead of an impact hammer. Mosher (1987) summarized the results from five sites where piles were installed by both impact and vibratory hammers. This study concluded that for a significant majority of the cases, piles installed in sand with a vibratory hammer had a lower ultimate capacity than impact driven piles at the same site. Mosher also concluded that time dependent soil strength changes occurred equally for both installation methods. Hence, the capacity of the vibratory installed piles did not increase to the capacity of the impact driven piles with time. However, it was also observed that impact driving a vibratory installed pile would increase the capacity of the vibratory installed pile to that of an impact driven pile.

O'Neill and Vipulanandan (1989) performed a laboratory evaluation of piles installed with vibratory hammers. This laboratory study found impact driven piles had a 25% greater unit shaft resistance and a 15 to 20% higher unit toe resistance than vibratory installed piles in medium dense to dense, uniform, fine sand. However, in very dense, uniform, fine sand, the impact driven pile had a 20 to 30% lower unit shaft resistance and approximately a 30% lower unit toe resistance than the vibratory installed pile.

These two studies indicate use of vibratory pile installation rather than impact driving will affect the ultimate pile capacity that can be achieved at a given pile penetration depth. Therefore, communication between design and construction personnel should occur, and the influence of vibratory pile installation be evaluated when it is proposed. Impact driving a specific final depth of vibratory installed piles may provide a foundation that meets the engineer's performance requirements at reduced installation cost.

9.10.3 Effects of Site Dewatering on Pile Capacity and Adjacent Structures

When a site is dewatered during construction, a temporary increase in effective stresses will occur. This causes a corresponding temporary increase in soil shear strength that will result in piles driven in a dewatered site to develop a greater capacity at a shallower pile penetration depth as compared to the non-dewatered condition. The soil resistance to be overcome to reach a specified penetration depth will also be greater than in the non-dewatered condition. If not considered in the design stage, the selected pile type may not be driveable to the required penetration depth in the dewatered construction condition. When dewatering is terminated, the effective stresses acting on the pile will decrease as the water table rises. This will result in a decrease in the soil shear strength and a decrease in long term pile capacity. Hence piles driven to the ultimate capacity in the dewatered condition would have less than the required ultimate capacity once dewatering was terminated.

For projects where significant dewatering is required, the effects of the dewatering on pile capacity and pile driveability should be evaluated. In these cases, multiple static analyses should be performed to determine the pile capacity and driveability requirements under the short term dewatered condition, as well as the long term pile capacity after dewatering has been terminated.

Dewatering can also have negative impacts on nearby structures supported on deep and shallow foundations. The increase in effective stress can cause or increase negative shaft resistance loads on deep foundations or cause consolidation settlements that affect the performance of deep and shallow foundations systems. The potential dewatering effects on adjacent structures should be evaluated during the design phase.

9.10.4 Densification Effects on Pile Capacity and Installation Conditions

As illustrated in Figure 9.3, driving a pile in cohesionless soil influences the surrounding soils to a distance of about 3 to 5 pile diameters away from the pile. The soil displacement and vibrations resulting from driving pile groups in cohesionless soils can further densify cohesionless materials. The use of displacement piles also intensifies group densification effects in cohesionless soils.

Densification can result in the pile capacity as well as the resistance to pile penetration being significantly higher than that calculated for a single pile in the static capacity calculations. The added confinement provided by cofferdams or the sequence of pile installation can further aggravate a group densification problem. Piles should be installed from the center of the group outward in order to reduce group densification effects due to installation sequence. Densification can cause significant construction problems if scour, seismic, or other considerations require pile penetration depths that cannot be achieved.

Potential densification effects should be considered in the design stage. Studies by Meyerhof (1959) and Kishida (1967) indicate that an increase in the soil friction angle of up to 4 degrees would not be uncommon for piles in loose to medium dense sands. It is expected that the increase in soil friction angle would be less for dense sands or cohesionless soils with a significant fine content. Densification affects the soil resistance to be overcome during driving and should be evaluated through static analyses performed using higher soil strength parameters than used for design. Results from these static analyses may indicate that a low displacement pile should be used, the pile spacing should be increased, or that a pile installation aid should be specified in order to obtain the required pile penetration depth.

9.10.5 Plugging of Open Pile Sections

Open pile sections include open end pipe piles and H-piles. The use of open pile sections has increased, particularly where special design events dictate large pile penetration depths. When open pile sections are driven, they may behave as low displacement piles and "cookie cut" through the soil, or act as displacement piles if a soil plug forms near the pile toe. It is generally desired that open sections remain unplugged during driving and plugged under static loading conditions.

Stevens (1988) reported that plugging of pipe piles in clays does not occur during driving if pile accelerations (along the plug zone) are greater than 22g's. Holloway and Beddard (1995) reported that hammer blow size (impact force and energy) influenced the dynamic response of the soil plug. With a large hammer blow, the plug "slipped" under the dynamic event whereas under a lesser hammer blow the pile encountered toe resistance typically of a plugged condition. From a design perspective, these cases indicate that pile penetration of open sections can be facilitated if the pile section is designed to accommodate a large pile hammer. Wave equation analyses can provide calculated accelerations at selected pile segments.

Static pile capacity calculations must determine whether an open pile section will exhibit plugged or unplugged behavior. Studies by O'Neill and Raines (1991), Raines *et al.* (1992), as well as Paikowsky and Whitman (1990) suggest that plugging of open pipe piles in medium dense to dense sands generally begins at a pile penetration to pile diameter ratio of 20, but can be as high as 35. For pipe piles in soft to stiff clays, Paikowsky and Whitman (1990) reported plugging occurs at penetration-to-pile diameter ratios of 10 to 20.

The above studies suggest that plugging in any soil material is probable under static loading conditions once the penetration to pile diameter ratio exceeds 20 in dense sands and clays, or 20 to 30 in medium sands. An illustration of the difference in the soil resistance mechanism that develops on a pipe pile with an open and plugged toe condition is presented in Figure 9.78. Paikowsky and Whitman (1990) recommend that the static capacity of an open end pipe pile be calculated from the lesser of the following equations:

Plugged Condition:
$$Q_u = f_{so} A_s + q_t A_t$$

Unplugged Condition:
$$Q_u = f_{so} A_s + f_{si} A_{si} + q_t A_p - w_p$$

Where:

- Q_u = Ultimate pile capacity in kN (kips).
- f_{so} = Exterior unit shaft resistance in kPa (ksf).
- A_s = Pile exterior surface area in m^2 (ft^2).
- f_{si} = Interior unit shaft resistance in kPa (ksf).
- A_{si} = Pile interior surface area in m^2 (ft^2).
- q_t = Unit toe resistance in kPa (ksf).
- A_t = Toe area of a plugged pile in m^2 (ft^2).
- A_p = Pile cross sectional area of an unplugged pile in m^2 (ft^2).
- w_p = Weight of the plug kN (kips).

The soil stresses and displacements induced by driving an open pile section and a displacement pile section are not the same. Hence, a lower unit toe resistance, q_t , should be used for calculating the toe capacity of open end pipe piles compared to a typical closed end condition. The value of the interior unit shaft resistance in an open end pipe pile is typically on the order of 1/3 to 1/2 the exterior unit shaft resistance, and is influenced by soil type, pile diameter, and pile shoe configuration. These factors will also influence the length of soil plug that may develop.

For open end pipe piles in cohesionless soils, Tomlinson (1994) recommends that the static pile capacity be calculated using a limiting value of 5000 kPa (105 ksf) for the unit toe resistance, regardless of the pile size or soil density. Tomlinson states that higher unit toe resistances do not develop, because yielding of the soil plug rather than bearing capacity failure of the soil below the plug governs the capacity.

For open end pipe piles driven in stiff clays, Tomlinson (1994) recommends that the static pile capacity be calculated as follows when field measurements confirm a plug is formed and carried down with the pile:

$$Q_u = 0.8 c_a A_s + 4.5 c_u A_t$$

Where: Q_u = Ultimate pile capacity in kN (kips).
 c_a = Pile adhesion from Figure 9.18 in kPa (ksf).
 A_s = Pile-soil surface area in m^2 (ft^2).
 c_u = Average undrained shear strength at the pile toe in kPa (ksf).
 A_t = Toe area of a plugged pile in m^2 (ft^2).

Static pile capacity calculations for open end pipe piles in cohesionless soils should be performed using the Paikowsky and Whitman equations. Toe resistance should be calculated using the Tomlinson limiting unit toe resistance of 5000 kPa (105 ksf), once Meyerhof's limiting unit toe resistance, determined from Figure 9.17, exceeds 5000 kPa (105 ksf). For open end pipe piles in predominantly cohesive soils, the Tomlinson equation should be used.

The plugging phenomenon in H-piles can be equally difficult to analyze. However, the distance between flanges of an H-pile is smaller than the inside diameter of most open end pipe piles. Therefore, it can usually be assumed that an H-pile will be plugged under static

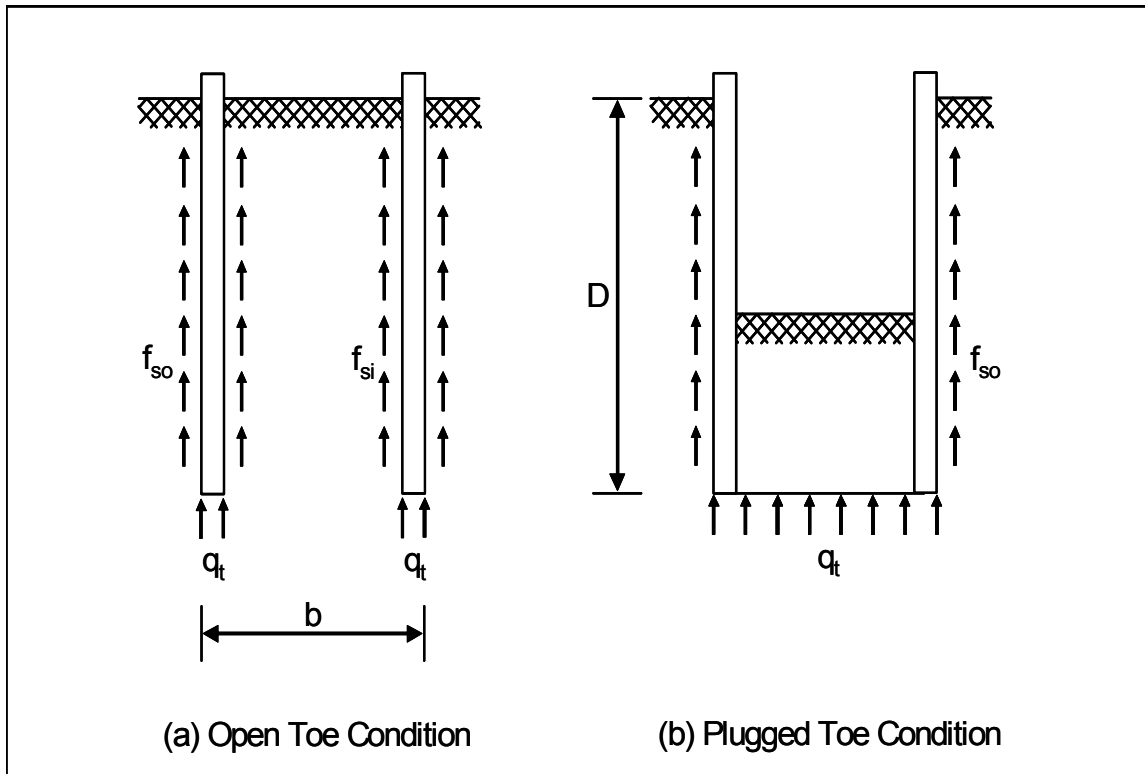


Figure 9.78 Plugging of Open End Pipe Piles (after Paikowsky and Whitman, 1990)

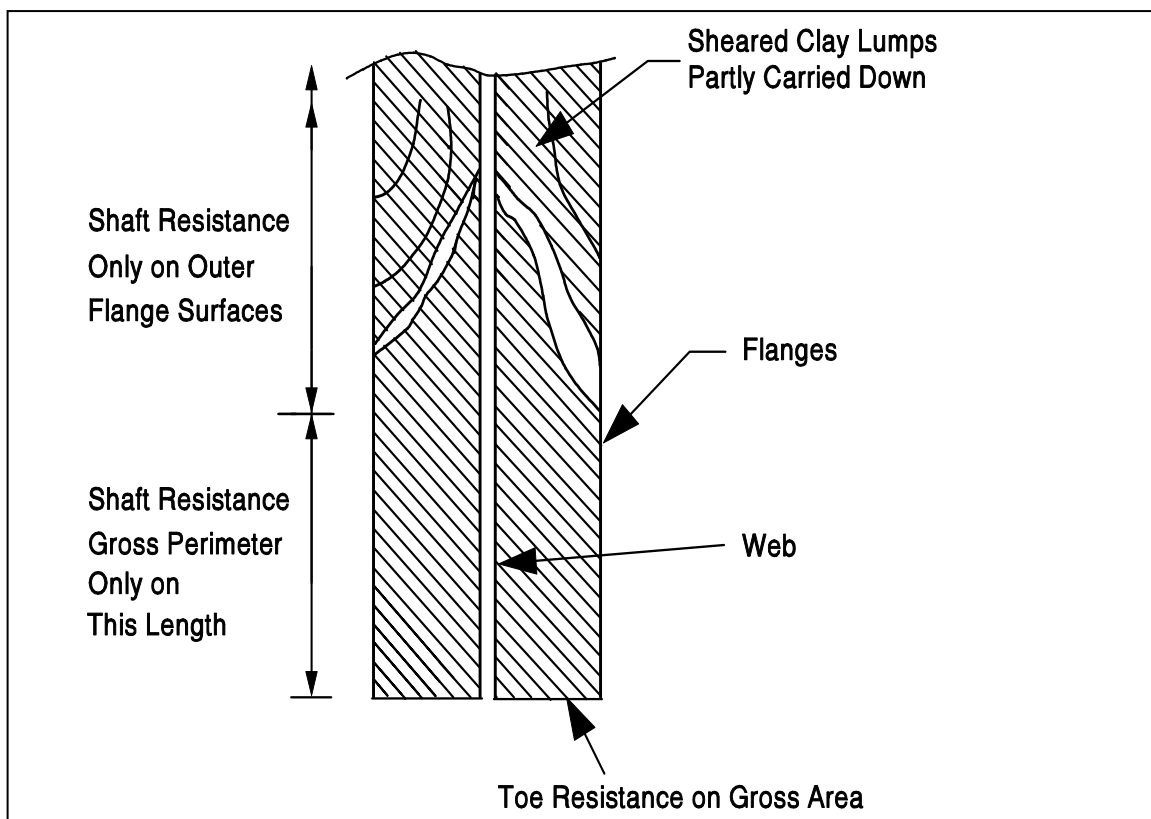


Figure 9.79 Plugging of H-Piles (after Tomlinson, 1994)

loading conditions and the “box” area of the pile toe can be used for static calculation of the toe capacity in cohesionless and cohesive soils. The toe capacity for H-piles driven to rock is usually governed by the pile structural strength, calculated based on the steel cross sectional area, and should not include the area of a soil plug, if any.

For H-piles in cohesionless soils, arching between the flanges can usually be assumed, and the “box” perimeter can be used for shaft resistance calculations. In most cohesive soils, the shaft resistance is calculated from the sum of the adhesion, c_a , along the exterior of the two flanges plus the undrained shear strength of the soil, c_u , times the surface area of the two remaining sides of the “box” due to soil-to-soil shear along these two faces. Figure 9.79 illustrates that calculation of H-piles in stiff clays can still be problematic. Sheared clay lumps can develop above the plug zone, in which case the shaft resistance may only develop along the exterior surfaces of the flanges in the sheared lump zone.

The above discussions highlight the point that a higher degree of uncertainty often exists for static pile capacity calculations of open pile sections than for displacement piles. Soil plug formation and plug response is often different under static and dynamic loading. This can complicate pile capacity evaluations of open pile sections with all dynamic methods (wave equation, dynamic testing, and dynamic formulas). Therefore, for large diameter open end pipe piles, greater than 450 mm (18 in), or for H-piles designed due carry their load primarily in shaft resistance, a static load test is recommended for capacity verification.

9.10.6 Design Considerations Due to Pile Driving Induced Vibrations

Since piles are driven by impact or vibratory hammers, ground vibrations of some magnitude are almost always induced into the surrounding soils during pile installation. Damage to nearby structures can result from two mechanisms:

- 1) Vibrations induced soil densification and settlement,
- 2) The effects of vibrations on the structure itself.

The ground vibration level where vibration induced soil densification and settlement or structural damage from direct vibrations occur depends upon the vibration magnitude and frequency as well as the type and condition of the existing structure or facility. The vibrations created by pile driving depend on the soil type, pile type and section, pile hammer, pile installation techniques, pile penetration resistance, the pile toe penetration depth, and the distance from the pile. Therefore, the distance from a pile driving operation

where these variables combine to potentially cause structure damage varies. For pile driving projects having structures or facilities within a potential damage zone, careful evaluation of the pile driving procedures and/or monitoring of ground vibrations during pile installations should be performed by personnel with vibration monitoring and mitigation experience.

Lacy and Gould (1985) found that vibration induced soil densification settlements and resulting structural damage can occur at peak particle velocities much less than 50 mm per second (2 inches per second) and that soil gradation is an important factor in this phenomenon. They reported that significant vibration induced settlements occurred at some sites with peak particle velocities measured on the ground surface as low as 2.5 to 5.1 mm per second (0.1 to 0.2 inches per second). Sands particularly susceptible to vibration induced densification were late Pleistocene deposits with uniformity coefficients of up to 4 or 5 and relative densities of up to 50 or 55%.

Wiss (1981) reported "safe" levels of ground vibration for structures have typically been recommended between 12 and 100 mm per second (0.5 and 4 inches per second). In many codes, such as NFPA 495 (2006), the maximum allowable particle velocity to prevent the onset or propagation of hairline cracks in plaster or drywall is a function of the vibration frequency. For example, a particle velocity of 25 mm per second (1 inch per second) at 30 Hz would be below NFPA 495 code limits but would be above code limits if the vibration frequency were 10 Hz.

Bay (2003) summarized relationships between peak particle velocity and the distance from the pile as a function of rated hammer energy. These results were plotted against typical damage thresholds for various types of structures. Charts for Class II and Class III soils were provided and are reproduced in Figures 9.80 top and bottom, respectively. Class II soils were defined as competent soils with Standard Penetration test N values of 5 to 15 blows per 0.3 m (ft). Class III soils are hard soils with SPT N values of 15 to 50 blows per 0.3 m (ft). Bay noted that stiff soil crusts near the ground surface can significantly increase the vibration levels from those noted in the charts. Bay noted other factors that can influence the vibration levels include nearby deep excavations, rock outcrops, and shallow bedrock. Soil-structure interaction should also be considered in assessing vibration levels and damage potential. Therefore, while informative, these charts should not be used to eliminate vibration monitoring.

If the potential for damaging ground vibrations is high, pile installation techniques should be specified to reduce vibration levels. Specifications could require predrilling or jetting as well

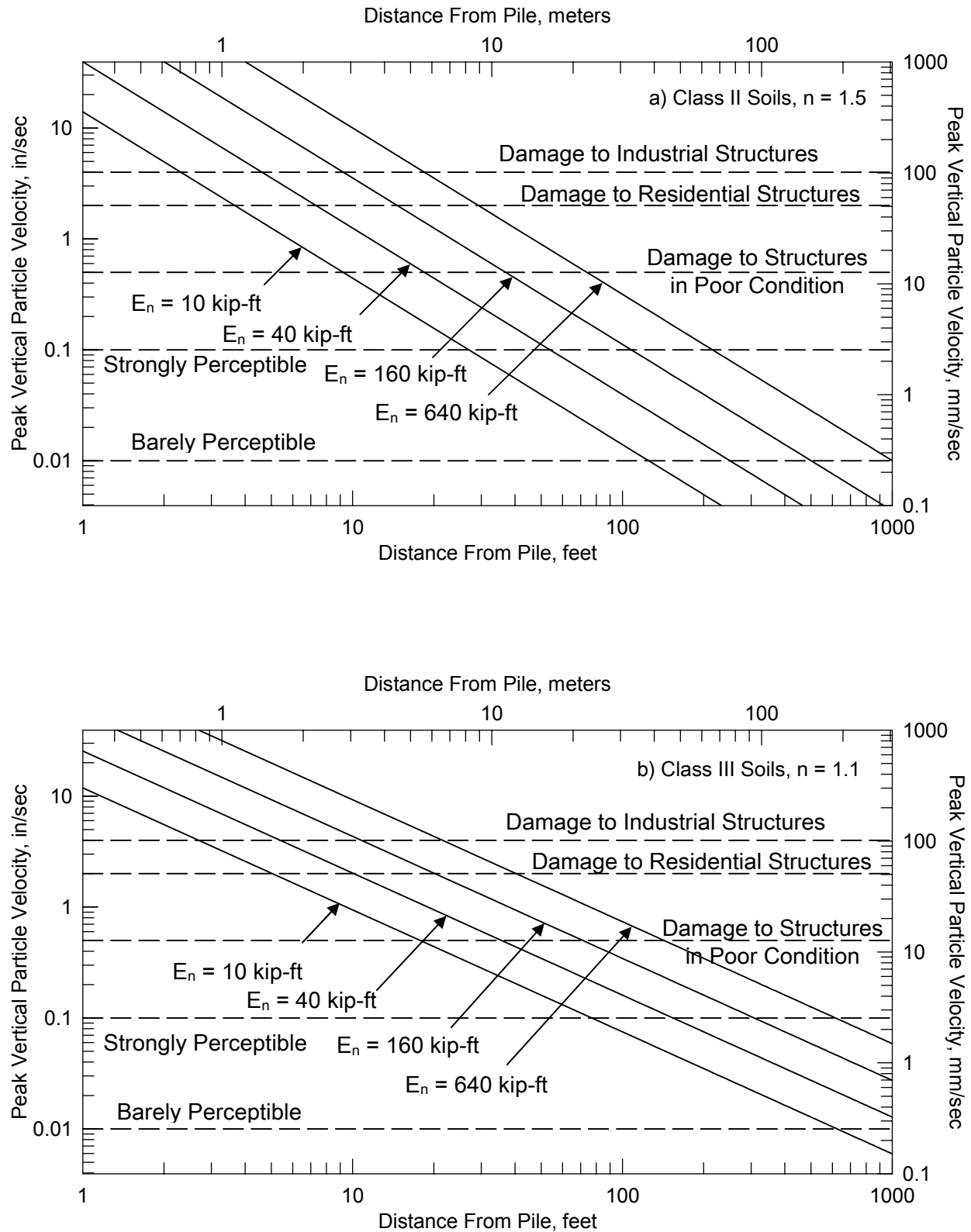


Figure 9.80 Predicted Vibration Levels for Class II and Class III Soils (after Bay, 2003)

as use of a different pile type or use of a specific type of pile hammer. Since predrilling and jetting influence compression, uplift, and lateral pile capacities, a determination of probable vibration levels and remediation measures should be evaluated in the design stage. A case history illustrating how a change in pile installation procedures reduced vibration induced soil densification and off-site settlement damage was reported by Lukas and Gill (1990).

NCHRP Project 20-5, Dynamic Effects of Pile Installations on Adjacent Structures, by Woods (1997), provides a synthesis of pile driving induced vibrations and typical mitigation practices. This synthesis noted that vibration problem management is the key to minimizing vibration damage, delays and claims. Two important elements in vibration management are a vibration specification with limits on the maximum peak particle velocity and a predriving survey of surrounding structures. An example vibration specification that details the requirements of a preconstruction survey as well as particle velocity controls is included in the NCHRP synthesis. The predriving survey needs to document conditions within the potential effected area. Woods reported that vibration damage a distance greater than on pile length away from driving is relatively uncommon but settlement damage in loose clean sands can occur up to 400 meters (1300 ft) away. Woods also concluded that piles with low impedances, EA/C , tend to transmit the hammer energy to the soils along the pile shaft and thus increase ground vibrations, whereas piles with higher impedances tend to more effectively transmit the hammer energy to the pile toe resulting in lower ground vibration levels. Hence, selection of a stiffer pile section at sites where vibrations are a concern may reduce vibration problems.

The Pile Driving Contractors Association (2006) is currently compiling a national pile driving noise and vibration database. The goal of this database is to allow contractors and designers to make reasonable assessments of the potential vibration effects from driven pile installations.

9.10.7 Design Considerations Due to Pile Driving Noise

Driven piles are installed by impact hammers. Noise levels associated with typical impact pile driving activities depend upon the hammer and pile type used. Noise from impact pile driving operations typically ranges from around 80 to 135 dBa. If local ordinances dictate allowable noise levels at or below this level, some driving equipment may not meet these requirements. Manufacturers of a few diesel and hydraulic hammers can provide optional noise suppression devices that may reduce the pile driving generated noise by about 10

dBa. Independently manufactured devices are also available. Additional information on noise suppression equipment is presented in Chapter 22.

In noise sensitive areas, the foundation designer should review any noise ordinances to determine if pile driving noise suppression devices would be necessary and if so, the impact this may have on the contractor's equipment selection and productivity. If limits on work hours, pile equipment type, or noise suppression equipment are required, costs associated with these limitations should be considered in the foundation selection process.

9.10.8 Pile Driveability

Greater pile penetration depths are increasingly being required to satisfy performance criteria in special design events such as scour, vessel impact, ice and debris loading, and seismic events. Therefore, the ability of a pile to be driven to the required penetration depth has become increasingly more important and must be evaluated in the design stage. Pile driveability refers to the ability of a pile to be driven to a desired penetration depth and/or capacity. All of the previously described static analysis methods are meaningless if the pile cannot be driven to the required design depth and ultimate capacity without sustaining damage. The limit of pile driveability is the maximum soil resistance a pile can be driven against without sustaining damage or a refusal driving resistance with a properly sized driving system.

Primary factors controlling the ultimate geotechnical capacity of a pile are the pile type and length, the soil conditions, and the method of installation. Since the pile type, length and method of installation can be specified, it is often erroneously assumed that the pile can be installed as designed to the estimated penetration depth. However, the pile must have sufficient driveability to overcome the soil resistance encountered during driving to reach the estimated or specified pile penetration depth. If a pile section does not have a driveability limit in excess of the soil resistance to be overcome during driving, it will not be driveable to the desired pile penetration depth. The failure to adequately evaluate pile driveability is one of the most common deficiencies in driven pile design practice.

In evaluating the driveability of a pile, the soil disturbance during installation and the time dependent soil strength changes should be considered. Both soil setup and relaxation have been described earlier in this chapter. For economical pile design, the foundation designer must match the soil resistance to be overcome at the time of driving with the pile impedance, the pile material strength, and the pile driving equipment.

9.10.8.1 Factors Affecting Driveability

A pile must satisfy two aspects of driveability. First, the pile must have sufficient stiffness to transmit driving forces large enough to overcome soil resistance. Second, the pile must have sufficient structural strength to withstand the driving forces without damage.

The primary controlling factor on pile driveability is the pile impedance, EA/C . Once the pile material is selected, and thus the pile modulus of elasticity, E , and the pile wave speed, C , only increasing the pile cross sectional area, A , will improve the pile driveability. For steel H-piles, the designer can improve pile driveability by increasing the H-pile section without increasing the H-pile size. The driveability of steel pipe piles can be improved by increasing the pipe wall thickness. For open ended pipe piles, an inside-fitting cutting shoe can improve driveability by delaying the formation of a soil plug and thereby reducing the soil resistance to be overcome. Most concrete piles are solid cross sections. Therefore, increasing the pile area to improve driveability is usually accompanied by an increase in the soil resistance to driving.

A lesser factor influencing pile driveability is the pile material strength. The influence of pile material strength on driveability is limited, since strength does not alter the pile impedance. However, a pile with a higher pile material strength can tolerate higher driving stresses that may allow a larger pile hammer to be used. This may allow a slightly higher capacity to be obtained before refusal driving conditions or pile damage occur.

Other factors that may affect pile driveability include the driving system characteristics such as ram weight, stroke, and speed, as well as the actual system performance in the field. The dynamic soil response can also affect pile driveability. Soils may have higher damping characteristics or elasticity than assumed, both of which can reduce pile driveability. Dynamic soil response is discussed in greater detail in Chapters 16 and 17.

Even if the pile structural capacity and geotechnical capacity both indicate a high pile capacity could be used, a high pile capacity may still not be obtainable because driving stresses may exceed allowable driving stress limits. A pile cannot be driven to an ultimate static capacity that is as high as the structural capacity of the pile because of the additional dynamic resistance or damping forces generated during pile driving. The allowable static design stresses in pile materials by various codes generally represent the static stress levels (pile capacity) which can be consistently developed with normal pile driving equipment and methods. Maximum allowable design and driving stresses are presented in Chapter 10.

9.10.8.2 Methods for Determining Pile Driveability

There are three available methods for predicting and/or checking pile driveability. As design tools, all of the methods have advantages and disadvantages and are therefore presented in order of increasing cost and reliability.

1. Wave Equation Analysis

This method, Goble and Rausche (1986), accounts for pile impedance and predicts driving stresses as well as the relationship of pile driving resistance versus ultimate pile capacity. Wave equation analyses performed in the design stage require assumptions on the hammer type and performance level, the drive system components, as well as the soil response during driving. These shortcomings are reflected in variations between predicted and actual field behavior. Even with these shortcomings, the wave equation is a powerful design tool that can and should be used to check driveability in the design stage, to design an appropriate pile section, or to specify driving equipment characteristics. Additional information on the wave equation, including its use as a construction control tool, is presented in Chapter 16.

2. Dynamic Testing and Analysis

Dynamic measurements can be made during pile installation to calculate driving stresses and to estimate static pile capacity at the time of driving. Time dependent changes in pile capacity can be evaluated if measurements are made during restrike tests. Additional signal matching analysis can also provide soil parameters for refined wave equation analysis. A shortcoming of this method as a design tool is that it must be performed during pile driving. Therefore, in order to use dynamic testing information to confirm driveability or to refine a design, a test program is required during the design stage. Additional details on dynamic testing and analysis, including its use as a construction control tool, is presented in Chapter 17.

3. Static Load Tests

Static load tests, Kyfor *et al.* (1992), are useful for checking driveability and confirming pile capacity prior to production pile driving. Test piles are normally driven to estimated lengths and load tested. The confirmation of pile driveability through static load testing is the most accurate method of confirming driveability and pile capacity since a pile is actually driven and load tested. However, this advantage also illustrates one of its shortcomings as a design tool, in that a test program is required during the design stage.

Other shortcomings associated with static load tests for determining driveability include:

- a. cost and time delay that limit their suitability to certain projects.
- b. assessment of driving stresses and extent of pile damage, if any, sustained by the pile is not provided by the test.
- c. can be misleading on projects where soil conditions are highly variable.

Additional details on static load testing, including its use as a construction control tool, is presented in Chapter 18. The Osterberg cell and the Statnamic test can also be used to evaluate pile capacity. These methods are discussed in Chapters 19 and 20, respectively.

As design and construction control tools, methods 1 and 2 offer additional information and complement static load tests. Used properly, methods 1 and 2 can yield significant savings in material costs or reduction of construction delays. These methods can be used to reduce the number of static load tests and also allow evaluation of increases in the maximum allowable design stresses. A determination of the increase (soil setup) or decrease (relaxation) in pile capacity with time can also be made if piles are retapped after initial driving.

9.10.8.3 Driveability Versus Pile Type

Driveability should be checked during the design stage of all driven piles. It is particularly important for closed end steel pipe piles where the impedance of the steel casing may limit pile driveability. Although the designer may attempt to specify a thin-wall pipe in order to save material cost, a thin wall pile may lack the driveability to develop the required ultimate capacity or to achieve the necessary pile penetration depth. Wave equation analyses should be performed in the design stage to select the pile section and wall thickness.

Steel H-piles and open pipe piles, prestressed concrete piles, and timber piles are also subject to driveability limitations. This is particularly true as allowable design stresses increase and as special design events require increased pile penetration depths. The driveability of long prestressed concrete piles can be limited by the pile's tensile strength.

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Chapter 10

STRUCTURAL ASPECTS OF DRIVEN PILE FOUNDATIONS

The structural design of driven piles as a specific topic has not been emphasized extensively in the past. But, during last decade the structural design of piles has become more critical because lateral loads have been considered more carefully. An increased emphasis has been placed on the analysis of the effects of vessel impact, scour, and earthquake events in bridge design making the pile structural analysis more critical. Sometimes, these events will control the foundation design and the structural failure modes can govern the design. In such cases, the foundation design cannot be finalized by geotechnical considerations only so the foundation specialist needs an understanding of the structural aspects of driven pile design where substantial lateral loads are present.

This chapter deals with the static and dynamic structural pile capacity in terms of allowable stresses for pile materials. A driven pile has to remain within structural limits (stress and buckling) under static loading conditions during its service life as well as under dynamic, driving induced loads. Therefore, the material stress limits are placed on:

1. The maximum allowable driving stresses.
2. The maximum allowable design stress during the service life.

Driving stress limits, group layout, cap preliminary design, in-service stress limits, and buckling of piles are addressed in this chapter.

10.1 DRIVING STRESSES

In almost all cases, the highest stress levels occur in a pile during driving. High driving stresses are necessary to cause pile penetration. The pile must be stressed to overcome the ultimate soil resistance, plus any dynamic resistance forces, in order to be driven to support the pile design load. The high strain rate and temporary nature of the loading during pile driving allow a substantially higher driving stress limitation than for the static design case. Wave equation analyses can be used for predicting driving stresses prior to installation. During installation, dynamic testing can be used to monitor driving stresses.

10.2 FACTORS AFFECTING ALLOWABLE DESIGN STRESSES

Traditionally, the allowable design stress was determined by dividing the ultimate stress of the pile material by a factor of safety. The factor of safety was based on experience and included consideration of load and structural resistance variations. The allowable design stresses in this chapter are in conformance with AASHTO (2002) Standard Specification.

Allowable design stresses for piles, given in Article 4.5.7.3 of the AASHTO Standard Specification, are a function of the following variables:

1. Average section strength from an acceptance test such as:
 - a. f_y (yield strength) for steel piles.
 - b. f'_c (unit ultimate strength from 28-day cylinder test for concrete).
 - c. Wood crushing strengths.
2. Reduction for defects such as knots in timber.
3. Reduction for section treatment such as preservation treatment of wood.
4. ϕ - factor which allows for variations in materials, construction dimensions, and calculation approximations. These items are partially under the engineer's control.
5. Factor of safety to account for the possibility that design service loads may be exceeded.
 - a. Among other causes, increase in load may occur due to overloads permitted on a bridge, pile mislocation, differential settlement and unaccounted negative shaft resistance or downdrag load.
 - b. Decrease in resistance offered by the pile may occur due to variability in pile material properties, corrosion, heave, or undetected driving induced damage.

10.3 AASTHO ALLOWABLE DESIGN AND DRIVING STRESSES

The limitations on maximum allowable static design stresses for driven piles in various codes generally represent the static capacity which can be consistently developed with traditional driving equipment and methods.

The pile material ultimate strength must be greater than the ultimate pile-soil resistance. In order that this is achieved, a factor of safety is applied to the material strength to obtain an allowable stress. The recommended AASHTO limits for maximum pile design stresses will generally keep the driving stresses within recommended limits. Allowable design stresses are covered in Article 4.5.7.3 of the AASHTO Standard Specification for Highway Bridges (2002) and driving stresses limits are presented in AASHTO Article 4.5.11.

10.3.1 Steel H-piles

a. Design Stresses

Table 10-1 contains the AASHTO recommended design and driving stresses for axially loaded steel H-piles in terms of the steel yield stress, f_y . AASHTO limits the maximum allowable design stress to $0.25 f_y$. In conditions where pile damage is unlikely, AASHTO allows the design stress to be increased to a maximum of $0.33 f_y$ provided static and/or dynamic load tests confirming satisfactory results are performed. As noted in Chapter 8, new H-piles now meet the requirements of ASTM A-572 steel with a yield strength of 345 MPa (50 ksi), and are no longer produced in A-36 steel. Design stresses of 86 to 114 MPa (12.5 to 16.5 ksi) are possible on these higher strength steel H-piles at 0.25 and $0.33 f_y$. For older A-36 steel with a yield stress of 248 MPa (36 ksi), a design stress of 0.25 to $0.33 f_y$ correspond to a design stress of 62 to 82 MPa (9.0 to 11.9 ksi).

b. Driving Stresses

AASHTO limits the maximum compression and tension driving stresses to $0.9 f_y$. For A-572 steel, this results in a maximum driving stress of 310 MPa (45 ksi) and, for older A-36 steel, this results in a maximum driving stress of 223 MPa (32.4 ksi).

| TABLE 10-1 MAXIMUM ALLOWABLE STRESSES FOR STEEL H-PILES | |
|---|--|
| | AASHTO (2002) Standard Specification Articles 4.5.7.3 and 4.5.11 |
| Design Stresses | $0.25 f_y$ $0.33 f_y$ If damage is unlikely, and confirming static and/or dynamic load tests are performed and evaluated by engineer. |
| Driving Stresses | $0.9 f_y$ 223 MPa (32.4 ksi) for ASTM A-36 ($f_y = 248$ MPa; 36 ksi) 310 MPa (45.0 ksi) for ASTM A-572 or A-690, ($f_y = 345$ MPa; 50 ksi) |

10.3.2 Steel Pipe Piles (unfilled)

a. Design Stresses

Table 10-2 summarizes the AASHTO recommended design and driving stresses for axially loaded unfilled steel pipe piles in terms of the steel yield stress, f_y . The maximum AASHTO allowable design stress is limited to $0.25 f_y$. For ASTM A-252, Grade 2 steel with a yield stress of 241 MPa (35 ksi), this results in a maximum design stress of 60 MPa (8.75 ksi) and for Grade 3 steel with a yield stress of 310 MPa (45 ksi) this results in a design stress of 78 MPa (11.25 ksi). AASHTO allows the design stress to be increased to a maximum of $0.33 f_y$ in conditions where pile damage is unlikely. However, static and/or dynamic load tests confirming satisfactory results should be performed for design at this stress level. For ASTM A-252, Grade 2 steel, a design stress of $0.33 f_y$ corresponds to a design stress of 79 MPa (11.55 ksi) and for Grade 3 steel this corresponds to a design stress of 102 MPa (14.85 ksi).

b. Driving Stresses

AASHTO specifications limit the maximum allowable driving stresses to $0.9 f_y$. For A-252 Grade 2 steel, this results in a maximum driving stress of 217 MPa (31.5 ksi), and for Grade 3 steel, this corresponds to a maximum allowable driving stress of 279 MPa (40.5 ksi) .

| TABLE 10-2 MAXIMUM ALLOWABLE STRESSES FOR UNFILLED STEEL PIPE PILES | |
|---|--|
| | AASHTO (2002) Standard Specification Articles 4.5.7.3 and 4.5.11 |
| Design Stresses | $0.25 f_y$ $0.33 f_y$ If damage is unlikely, and confirming static and/or dynamic load tests are performed and evaluated by engineer. |
| Driving Stresses | $0.9 f_y$ 186 MPa (27.0 ksi) for ASTM A-252, Grade 1 ($f_y = 207$ MPa; 30 ksi) 217 MPa (31.5 ksi) for ASTM A-252, Grade 2 ($f_y = 241$ MPa; 35 ksi) 279 MPa (40.5 ksi) for ASTM A-252, Grade 3 ($f_y = 310$ MPa; 45 ksi) |

10.3.3 Steel Pipe Piles (top driven and concrete filled)

a. Design Stresses

Table 10-3 summarizes AASHTO (2002) recommended design and driving stresses for axially loaded, top driven and concrete filled pipe piles in terms of the steel yield strength, f_y , and the concrete compressive strength, f'_c . These requirements are also applicable to Monotube piles. AASHTO limits the maximum allowable design stress to the sum of $0.25 f_y$ on the steel cross sectional area plus $0.40 f'_c$ on the concrete cross sectional area.

b. Driving Stresses

Concrete filled pipe piles are generally unfilled when driven. Hence, the AASHTO recommended driving stress for unfilled steel pipe piles apply.

| TABLE 10-3 MAXIMUM ALLOWABLE STRESSES FOR TOP DRIVEN, CONCRETE FILLED, STEEL PIPE PILES | |
|--|--|
| | AASHTO (2002) Standard Specification Articles 4.5.7.3 and 4.5.11 |
| Design Stresses | 0.25 f_y (on steel area) <i>plus</i> 0.40 f'_c (on concrete area) |
| Driving Stresses | 0.9 f_y 186 MPa (27.0 ksi) for ASTM A-252, Grade 1 (f_y = 207 MPa; 30 ksi) 217 MPa (31.5 ksi) for ASTM A-252, Grade 2 (f_y = 241 MPa; 35 ksi) 279 MPa (40.5 ksi) for ASTM A-252, Grade 3 (f_y = 310 MPa; 45 ksi) |

10.3.4 Precast, Prestressed Concrete Piles

a. Design Stresses

Table 10-4 summarizes the AASHTO recommended design and driving stresses for axially loaded prestressed concrete piles in terms of the concrete compression strength, f'_c , and the effective prestress after losses, f_{pe} . Prestressed concrete piles fully embedded in soils providing lateral support are limited to a maximum design stress of $0.33 f'_c - 0.27 f_{pe}$ on the gross cross sectional area of the concrete. The concrete must have a minimum 28 day compression strength of 34.5 MPa (5.0 ksi)

b. Driving Stresses

AASHTO specifications limit the maximum allowable compression driving stress to 0.85 times the concrete compressive strength, f'_c , minus the effective prestress after losses, f_{pe} . In normal environments, tension driving stresses are limited to 0.25 times the square root of the concrete compressive strength plus the effective prestress after losses in SI units or 3 times the square root of the concrete compressive strength plus the effective prestress after losses in US units. In severe corrosive environments, maximum allowable tension stresses

are limited to the effective prestress after losses in both SI and US units. For calculating tension driving stresses, both f'_c and f_{pe} must be in MPa when using SI units or in psi when using US units. The driving stress limits are on the gross concrete area.

Control of driving stresses is particularly important when driving prestressed concrete piles at high driving stress levels while penetrating through dense soil layers into underlying weaker soils. When the pile breaks through the dense layer with the hammer operating at a large stroke, the reduced pile toe resistance can cause a large tension stress to be reflected up the pile.

| TABLE 10-4 MAXIMUM ALLOWABLE STRESSES FOR PRECAST, PRESTRESSED, CONCRETE PILES | |
|--|--|
| | AASHTO (2002) Standard Specification Articles 4.5.7.3 and 4.5.11 |
| Design Stresses | $0.33 f'_c - 0.27 f_{pe}$ (on gross concrete area) f'_c minimum of 34.5 MPa (5.0 ksi) f_{pe} generally > 5 MPa (0.7 ksi) |
| Driving Stresses | Compression Limit $< 0.85 f'_c - f_{pe}$ (on gross concrete area) Tension Limit (1) $< 0.25 (f'_c)^{1/2} + f_{pe}$ (on gross concrete area) <u>SI Units</u> * $< 3 (f'_c)^{1/2} + f_{pe}$ (on gross concrete area) <u>US Units</u> * Tension Limit (2) $< f_{pe}$ (on gross concrete area) (1) - Normal Environments (2) - Severe Corrosive Environments * Note: f'_c and f_{pe} must be in MPa for SI Unit equation and in psi for US Unit equation. |

10.3.5 Conventionally Reinforced Concrete Piles

a. Design Stresses

Table 10-5 summarizes the AASHTO recommended design and driving stresses for axially loaded reinforced concrete piles in terms of the concrete compression strength, f'_c , and the yield strength of the reinforcing steel, f_y . The recommended maximum allowable design stress is limited to $0.33 f'_c$ on the gross cross sectional area of the concrete. The concrete must have a minimum 28 day compression strength of 34.5 MPa (5.0 ksi).

b. Driving Stresses

AASHTO specifications limit the maximum allowable compression driving stress to $0.85 f'_c$ and the maximum tension driving stress to $0.70 f_y$.

Control of driving stresses is particularly important when driving reinforced concrete piles at high driving stress levels while penetrating through dense soil layers into underlying weaker soils. When the pile breaks through the dense layer with the hammer operating at a large stroke, the reduced pile toe resistance can cause a large tension stress to be reflected up the pile.

| TABLE 10-5 MAXIMUM ALLOWABLE STRESSES FOR CONVENTIONALLY REINFORCED CONCRETE PILES | |
|--|--|
| | AASHTO (2002) Standard Specification Articles 4.5.7.3 and 4.5.11 |
| Design Stresses | $0.33 f'_c$ (on gross concrete area) f'_c minimum of 34.5 MPa (5.0 ksi) |
| Driving Stresses | Compression Limit $< 0.85 f'_c$ Tension Limit $< 0.70 f_y$ (of steel reinforcement) |

10.3.6 Timber Piles

a. Design Stresses

Table 10-6 summarizes AASHTO recommended design and driving stresses for axially loaded timber piles in terms of the maximum allowable design stress in compression parallel to the grain, σ_a . This value varies depending upon the timber species, and for the common species listed in the table below ranges from about 5.5 MPa to 8.3 MPa (0.8 to 1.2 ksi) The resulting maximum design load is based upon the allowable design stress times the pile toe area.

The engineer can specify species of timber piles but can seldom specify subspecies which have a wide range of strengths. There is a large natural variability of clear wood strength and natural growth imperfections which can also significantly affect wood strength. Therefore, while a high design stress may be allowed, engineering judgment must also be used, taking into account the above factors as well as the installation conditions.

b. Driving Stresses

AASHTO specifications limit maximum allowable compression and tension driving stresses to 3 times the allowable design stress from Table 10-6.

| TABLE 10-6 MAXIMUM ALLOWABLE STRESSES FOR TIMBER PILES | |
|--|---|
| | AASHTO (2002) Standard Specification Articles 4.5.7.3 and 4.5.11 |
| Design Stresses | <p>5.5 to 8.3 MPa (0.8 to 1.2 ksi) (for pile toe area depending upon species)</p> <p>Southern Pine $\sigma_a = 8.3$ MPa (1.2 ksi) Douglas Fir $\sigma_a = 8.3$ MPa (1.2 ksi) Red Oak $\sigma_a = 7.6$ MPa (1.1 ksi) Eastern Hemlock $\sigma_a = 5.5$ MPa (0.8 ksi)</p> |
| Driving Stresses | <p>Compression Limit $< 3 \sigma_a$</p> <p>Tension Limit $< 3 \sigma_a$</p> <p>σ_a - AASHTO allowable working stress</p> |

10.4 GEOTECHNICAL AND STRUCTURAL LOADS

The problem of the design of a pile group subjected to a general set of loads is illustrated in Figure 10.1. The requirements that must be satisfied are:

1. The axial geotechnical capacity of the piles must be satisfactory in both compression and tension. Since moments are applied to the pile cap the individual pile loads will vary across the group. Bear in mind that a large number of load combinations can be present.
2. The lateral displacement of the pile group under service loads must not be excessive.
3. The structural strength of the piles under the effect of combined axial and lateral loads must be satisfactory. Since there are several load combinations it will usually not be obvious which pile in the group is critical in the structural case.

The first and second requirements will be satisfied in the geotechnical design process. However, it should be noted that several trial designs may be necessary to achieve a satisfactory and efficient design. In general, it can be seen from Figure 10.1 that it may be necessary to modify both pile capacity and pile spacing to obtain the best design. The larger the moments on the pile group the more complex the design process becomes. If the pile row spacing is larger the lateral load carried by the second and other rows is increased (see Table 9-19). On the other hand the pile cap cost will increase.

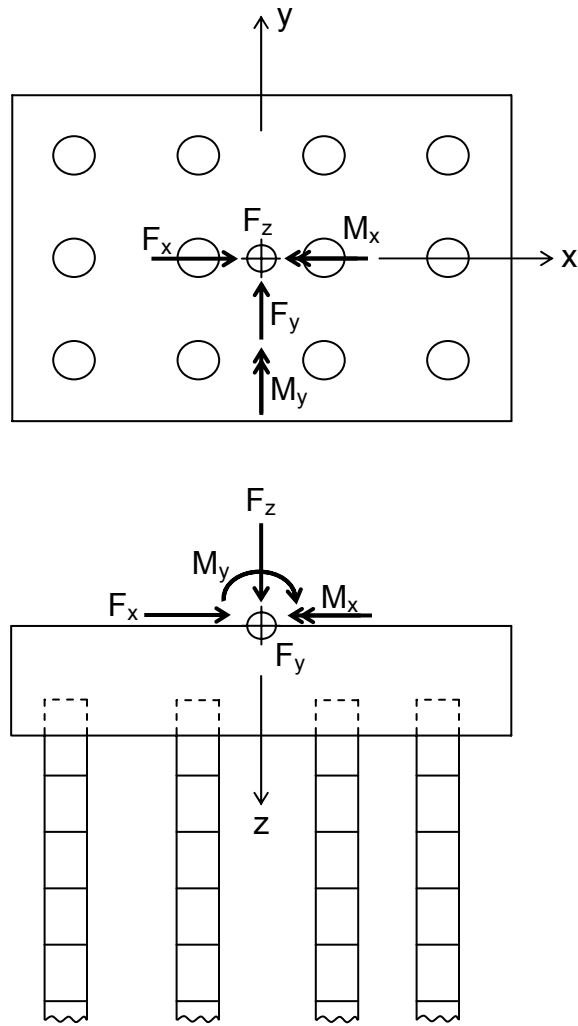


Figure 10.1. Pile Group with General Loads

10.5 LAYOUT OF PILE GROUPS

A group of piles is typically required to support large structural loads. An initial group layout must be determined to perform in-service stress checks. The possible loads are illustrated in Figure 10.1. The various load combinations, as given in Article 3.22 of the 2002 AASHTO Standard Specification, should be investigated to determine the pile stress conditions.

An initial, or trial, group layout may be computed dividing the factored axial load acting on the pile cap/group by the allowable capacity of a single pile, and then rounding the number up (say, by 15% or more, depending upon magnitude of the moments and lateral loads) to a constructible pile layout. Therefore, the number of piles is estimated as:

$$\frac{F_z}{Q_A} \cong \text{Number of piles (round-up)} \Rightarrow n$$

where:

| | | |
|-------|---|--|
| F_z | = | largest factored, axial load of the superstructure |
| Q_A | = | allowable (geotechnical) axial load on a single pile |
| n | = | number of piles in group |

Develop a trial configuration for the group of piles with this rounded-up number with a minimum center-to-center pile spacing of 0.75 m (2.5 ft) or 2.5 pile diameters, which ever is greater per AASHTO Article 4.5.15. Example pile group layouts can be found in CRSI Design Handbook (2002) and other sources.

This trial configuration should then be checked for single pile axial capacity adequacy under the combined superstructure axial loads and moments. The various factored load combinations, and not just the combination with the largest axial load, should be checked to determine the critical loading case. The maximum single pile axial load, q_s , may be computed as:

$$q_s = \frac{F_z + W_c + W_s}{n} \pm \frac{M_x y}{\sum y^2} \pm \frac{M_y x}{\sum x^2}$$

where:

| | | |
|-------|---|---|
| F_z | = | factored, axial load of the superstructure acting upon the pile cap |
| W_c | = | estimated weight of pile cap |

| | | |
|-------|---|---|
| W_s | = | estimated weight of soil above pile cap, if applicable |
| n | = | number of piles in the group |
| M_x | = | factored, moment about the x axis acting on the pile cap |
| M_y | = | factored, moment about the y axis acting on the pile cap |
| x | = | distance along x-axis from the center of the column to each pile center |
| y | = | distance along y-axis from the center of the column to each pile center |

Add one, or more, piles to the group or increase the pile spacing if $q_s > Q_A$ and recompute the maximum single pile axial load (q_s). If the moments in one direction are substantially larger than the other it may be desirable to make the cap unsymmetric.

10.6 PRELIMINARY DESIGN OF PILE CAPS

The purpose of this section is to provide guidelines to develop a preliminary size of a pile cap for the purposes of cost estimating. Information for complete, comprehensive structural design is beyond the scope of this manual, and not presented here.

The design and size of the pile cap is dependent on the pile group layout, pile loads, and superstructure loads. Thus, an iterative design is required to optimize overall economics. The horizontal dimensions of the pile cap for the trial pile group configuration may be estimated by using the minimum center-to-center pile spacing and, per AASTHO Article 4.5.15, a minimum edge of cap to pile distance of 230 mm (9 inches). Maximum width and/or length of pile cap may be dictated by project constraints.

The thickness of the pile cap is a sum of the pile embedment into the cap, clear space between the cap reinforcing steel and the top of (embedded) piles, and thickness required for structural support. Per AASHTO Article 4.5.15.1.2, the piles shall project not less than 300 mm (12 inches) into the cap after damaged pile material has been removed, though in special cases it may be reduced to 150 mm (6 inches). The reinforced concrete must be designed with consideration of flexure and shear, for the factored loads. Potential shear failures include punching about a single pile, punching about a pair of piles, punching of the (superstructure) column, and across the widths of the cap.

An initial, trial total (including pile embedment and 75 mm (3 inches) clear space between top of piles and reinforcing steel) thickness of the pile cap may be estimated from experience, agency guidelines or standards, or with the following equation.

$$t_{\text{cap}} (\text{mm}) \approx \frac{Q_A (\text{kN})}{2} + 750$$

$$t_{\text{cap}} (\text{inches}) \approx \frac{Q_A (\text{tons})}{6} + 30$$

This initial, trial thickness should be refined by examining punching shear, beam shear, and bending in the reinforced concrete pile cap. Equations for these preliminary calculation steps are shown below.

1. Determine dimensions for computations

a. Select a trial total thickness of cap, D.

b. Determine effective depth to concrete reinforcement, d.

$$d = D - \text{pile embedment} - \text{clear space} - \text{distance to center of steel}$$

i. assume pile embedment distance into cap = 300 mm (12 inches).
The pile embedment is suggested to be 12 inches. However, it can be as little as 150 mm (6 inches)

ii. assume clear space between top of pile and concrete reinforcement = 75 mm (3 inches)

iii. assume distance up to center of steel reinforcement = $1\frac{1}{2}$ x bar diameter

c. Determine critical punching shear perimeter, b_o , around the column. The shear force applied the shear perimeter is the load acting outside that perimeter.

i. For square columns

$$b_o = 4 (c + d)$$

ii. For rectangular columns

$$b_o = 2(c_1 + c_2 + 2d)$$

iii. For circular column

$$b_o = (c_o + d)$$

with c = column side for square columns

c_1 = small column side for rectangular columns

c_2 = large column side for rectangular columns

c_o = column diameter

2. Check punching shear at $d/2$ from column

a. $v \leq v_c$ per AASHTO Article 8.15.5.6

b. compute total applied design shear stress at critical section, v

$$v = \frac{n_o Q_A}{b_o d}$$

c. nominal shear strength of concrete, per AASHTO Article 8.15.5.6.3

$$v_c = [0.8 + 2 / \beta_c] \sqrt{f'_c} \leq 1.8 \sqrt{f'_c}$$

where: β_c = the ratio of the long side to the short side of the loaded area.

v = design shear stress

v_c = nominal shear strength of concrete

n_o = number of piles whose center lie outside of b_o

3. Check beam shear, per AASHTO Article 8.15.5.6.1

a. Determine beam shear distance from center of the column to the critical section, per AASHTO Article 4.4.11.3.2

$$\text{Beam Shear } D = \frac{c}{2} + \frac{d}{2}$$

for circular columns, use an equivalent area square section and c

b. For each direction of pile cap, check number of piles that lie outside of the critical section. Where the critical section passes through the pile cross

section, the applied load is proportioned based on the amount of pile section within the critical section as per AASHTO Article 4.4.11.3.2.

c. $v \leq v_c$ per AASHTO Article 8.15.5.6

d. Shear load and stress

$$V = n_c \times Q_A$$

$$v = \frac{n_c Q_A}{w d}$$

e. nominal shear strength of concrete subject to shear and bending, per AASHTO Article 8.15.5.2.1

$$v_c = 0.95 \sqrt{f'_c}$$

where:

- V = design shear load
- v = design shear stress
- v_c = nominal shear strength of concrete
- n_c = no. of piles whose center lie outside critical shear line plus the percentage of load from the piles that intersect the critical shear plane.
- w = width of pile cap (in applicable direction)

4. Check bending

a. Compute bending moment, for each direction of pile cap, from piles to edge of column.

$$M_u = \sum Q_A \text{ arm}$$

The term arm refers to the distance from the edge of the column to each pile.

The moment capacity of a reinforced concrete beam is determined based on the assumption of a rectangular distribution of the compression stress in the concrete at failure. The design must fail by yield in the tension steel to assure

ductility. The area of steel required per AASHTO Article 8.16.3.2 can be computed with the following equations:

$$M_u = \phi M_n = \phi \left[A_s f_y \left(d - \frac{a}{2} \right) \right]$$

where a is the depth of the rectangular compression stress block

$$a = \frac{A_s f_y}{0.85 f'_c b}$$

The equation for moment strength, M_n , can be solved for the area of steel, A_s . However, $a/2$ is small compared with d so an approximate value can be assumed for $a/2$, A_s can be calculated and the steel area adjusted to arrive at a satisfactory A_s . If $d - a/2$ is assumed to be $0.9d$, A_s will be quite close and it will be satisfactory for preliminary design. If an improved A_s is desired it can be obtained made by determining an improved a with a knowledge of the preliminary A_s and with the new a the next cycle of A_s can be determined and it will probably be final.

A_s/bd is called the reinforcement ratio, ρ . The case where failure occurs in the steel at the same time as in the concrete is called balanced design and the associated reinforcement ratio is ρ_b . Failure in the concrete is assumed to take place at 0.003 strain. The reinforcement ratio must be less than $0.75\rho_b$ to assure that the bending failure takes place by yielding in the steel. ρ_b can be determined from

$$\rho_b = [0.85\beta_1 f'_c]/f_y [87,000/(87,000 + f_y)]$$

where β_1 is 0.85 for concrete strengths up to and including 4,000 psi. For concrete strengths above 4,000 psi it shall be reduced at a rate of 0.05 for each 1,000 psi but not less than 0.65. Values for ρ_b are available in concrete design textbooks or design manuals.

Per AASHTO Article 8.17.1.2, the minimum reinforcement should be at least one-third greater than that required by analysis to waive requirements of 8.17.2.1. Therefore, increase minimum area of steel to:

$$A_s = \frac{4}{3} (A_{s-\text{initial}})$$

The final, structural design of pile caps is beyond the scope of this manual. See AASHTO (2002), ACI (1997), etc. for guidance on detailed structural design.

10.7 STRUCTURAL PROPERTIES OF PILES

The largest stresses in piles occur at the greatest distance from the neutral axis. This is at the outer edge(s) of a single pile and at the outer edge of the outermost piles of a group. Under combined axial and bending loading, the pile area (A), the stiffness or moment of inertia (I), and distance from neutral axis to the edge of the section (c) must be defined to check maximum stress.

The moment of inertia for various shapes may be computed with the following equations.

for solid, circular sections:

$$I = \frac{\pi (O.D.)^4}{64}$$

for (circular) pipe sections:

$$I = \frac{\pi [(O.D.)^4 - (I.D.)^4]}{64}$$

where : O.D. = outside diameter
 I.D. = inside diameter

for solid, square sections:

$$I = \frac{d^4}{12}$$

where : d = width/height of square

It is also convenient to compute the elastic section modulus (S) for the structural analysis. S is simply the moment of inertia divided by the distance to the outermost element, so

$$S = \frac{I}{c}$$

where : c = distance from centroid to outer edge

The structural properties of common pile sections are presented in Appendix C.

10.8 DESIGN OF PILES FOR COMBINED AXIAL AND LATERAL LOADS

10.8.1 Structural Design of Driven Piles for Axial Loads by ASD

Consider first the traditional limits that have been used historically for allowable stress design of piles. Code limitations were placed on the allowable axial pile stress under design load. Little if any emphasis was placed on geotechnical limitations and the allowable axial pile stress was based on an extended experience with the axial driving stresses. These limits were selected primarily to assure that the pile could be driven to a required capacity without damage. The resulting allowable stresses were misunderstood to be limits on the stresses that could be safely applied to the pile material from a structural point of view. This is not true. For example, the allowable stress that was commonly permitted on steel piles was $0.25 f_y$ but it is obvious that much higher design stresses could be applied to the steel before structural failure occurred. A commonly used allowable stress for laterally supported compression member is $0.6 f_y$. Even when a driveability analysis by wave equation was required these allowable stresses continued to be specified.

The actual explanation for the use of this allowable stress comes from the practice several decades ago of the use of 248 MPa (36 ksi) yield point steel with the traditional air hammer and a pile driving formula such as Engineering News. With the typical stroke of three feet for these hammers and an efficiency of about 65 percent, the effective, transmitted impact velocity will be about 3.0 to 3.7 meters/second (10 to 12 feet/second). This impact velocity will deliver a peak impact stress to the pile top of about 124 to 138 MPa (18 to 20 ksi). If a factor of safety of about 2.0 is assumed this produces a design stress of about 62 MPa (9 ksi) or $0.25 f_y$ for A36 steel with its 248 MPa (36 ksi) yield point. If a larger capacity is desired a higher impact stress is required and the common air hammers of forty years ago could not be depended on to achieve

that. This rather crude description will not cover all cases of pile driving but it, rather generally, defines how the limitation came about and these limitations were arrived at by experience not a rational analysis. With an allowable stress of this magnitude driving to a blow count defined by a dynamic formula with an air hammer, pile damage did not usually occur.

Today, many modern diesel or hydraulic hammers will deliver much higher impact velocities. But, some of the old traditional approaches are still with us. The AASHTO Standard Specification (2002) contains an allowable design stress of $0.25 f_y$ (Article 4.5.7.3). However, it also allows design stresses up to $0.33 f_y$ “in conditions where pile damage is unlikely.” With the advent of 345 MPa (50 ksi) steel, an allowable stress of about 83 MPa (12 ksi) becomes possible and $0.33 f_y$ gives a much larger allowable of 110 MPa (16 ksi). With a factor of safety of 2.0 the associated ultimate stress is 220 MPa (32 ksi). To achieve this ultimate stress a driving stress near the limiting value that can be achieved by a high impact velocity hammer will be required.

The allowable axial compression stresses for all pile types are given in Article 4.5.7.3 of the AASHTO Standard Specification. The allowable load on concrete filled steel pipe piles is $0.25 f_y A_s + 0.40 f'_c A_c$. Prestressed concrete piles have an allowable load of $0.33 f'_c A_c - 0.27 f_{pe} A_{ps}$. Allowable stresses for timber piles are given in Table 4.5.7.3A. And of course, the allowable steel stresses are limited to $0.25 f_y$ and $0.33 f_y$ as discussed above. This specification also specifies factors of safety on the geotechnical axial strength in Table 4.5.6.2A.

In addition to the allowable pile material stresses, the AASHTO Standard Specification states in Article 4.5.9 that the Engineer “should” evaluate “constructability” of a pile foundation using a wave equation analysis. Allowable maximum driving stresses are given in Article 4.5.11. It may be concluded that the limiting material design stresses are redundant except for the case where the geotechnical capacity is established by the use of a driving formula.

The Allowable Stress Design loads and load combinations to be used in design are specified in the first part of Table 3.22.1A. A total of 11 different load combinations are given and all of them must be satisfied. The details and definitions of the loads and their application are discussed in Section 3 of the AASHTO Standard Specification.

Consider a very brief summary of the structural design process for axial loads only that is implied by the AASHTO Standard Specification, Allowable Stress Design provisions.

1. A pile type and design load is selected for a pile.
2. The method of capacity determination is selected and, with that, the factor of safety is determined from the AASHTO Standard Specification, Table 4.5.6.2A.
3. The allowable stress for the pile material is obtained from the AASHTO Specification Article 4.5.7.3 and the pile cross section is selected to carry the required design load.
4. The pile length required to carry the ultimate axial load determined with the factor of safety applied to the specified design loads is determined from geotechnical considerations.
5. Driveability is then evaluated by wave equation analysis. It is possible that the limiting driving stresses can not be satisfied and a larger pile section or a smaller design load may have to be selected but this is unlikely. Thus, it can be seen that there is redundancy in specifying allowable pile stresses and also driveability limits. But, the driveability limits must be included.

10.8.2 Structural Design of Driven Piles for Combined Axial and Lateral Loads by ASD

In Article 4.5.6.5 of the AASHTO Standard Specification a lateral load analysis is specified to determine the horizontal displacement. Reference is made to an analysis to evaluate structural strength and deflection with a reference to the work of Reese (1984). References are also made to the approximate methods of Broms (1964) and Singh et al (1971). However, the statement is made that the strength analysis based on Broms or Singh is only appropriate in a preliminary analysis.

Over the past two decades it has become common to perform a structural analysis for lateral loads and extensive software has been developed to perform the analysis as referenced in Chapter 9 of this manual. Section 9.7.3.3 of Chapter 9 discusses the LPILE computer program for the analysis of single piles. The geotechnical design of pile groups is discussed in detail in Section 9.8 of Chapter 9. When designing pile groups for both axial and lateral loads the designer should be aware of the FB-Pier program developed at the University of Florida for the Florida DOT. This program can perform a general analysis of pile foundations and can include pile cap, pier and superstructure. A single pile analysis can be used and the pile group analyses can be

assembled from the single pile analysis. The lateral soil resistance will be affected by the shading from multiple rows of piles as discussed in Section 9.8.4 of Chapter 9.

The behavior of a single pile under the action of a lateral load is illustrated in Figure 9.44. The geotechnical engineer must represent the lateral soil resistance response using the soil model shown. Both the nonlinear soil response of the individual springs and the distribution of the resistance along the pile length must be defined. An additional consideration that must be established is the fixity condition at the pile head. In many cases of single piles the pile head may be free to rotate. However, if the pile head is embedded in a pile cap it is likely that the pile head will be fixed. The assumed pile head condition can radically affect the maximum moment in the pile. If the pile head is assumed fixed the maximum moment will be at the pile head while if the pile head is pinned the maximum moment will be at some point along the pile below the pile head. The pinned condition will produce a much smaller maximum moment in the pile than does the fixed head condition.

An approach to the structural design of pile groups subjected to a general set of loads will be discussed. As noted above, the AASHTO Standard Specification, Section 4, Foundations makes only a very general reference to this problem. Current practice will be covered using the requirements from the AASHTO Standard Specification Sections on the particular structural material. The limitations given in AASHTO Sections 8, 9, 10 and 13 provide guidance that can be used to govern driven pile structural design

The central problem becomes the analysis of an individual pile in the group for the combined bending and axial loads applied to that particular pile in the group.

10.8.2.1 Timber Piles

Consider first the analysis of a timber pile group. The structural design of timber piles is not covered specifically in the AASHTO Standard Specification. The stress in the pile can be calculated from the expression:

$$f_c = \frac{P}{A} \pm \frac{M_y}{S} \pm \frac{M_x}{S} \quad \text{Equation 10-1}$$

where P is the applied axial load on the pile, A is the pile cross sectional area, M_x and M_y are the moments about the x and y axes of the pile, respectively, and S is the section modulus of the pile cross section. The values for P are found by the analysis of

the pile group response to the vertical and moment loads on the pile cap shown in Figure 1. The values of M_x and M_y are determined by the lateral pile analysis discussed in Section 9.7.3 of Chapter 9 of this manual. Since the cross section is assumed circular the section modulus is independent of the reference axes. The allowable stress for timber is given in Article 13.7.3.2 of the AASHTO Standard Specification and is specified to be:

$$F'_c = F_c C_D C_P \quad \text{Equation 10-2}$$

where F_c is the allowable compression stress given in Table 13.5.2A for the wet service condition, C_D is the load duration factor given in Table 13.5.5A and C_P is the column stability factor given in Article 13.7.3.3.

10.8.2.2 Steel Piles

The structural design of steel piles is not discussed specifically in the AASHTO Standard Specification. The cross section design of compression members is discussed in AASHTO Article 10.35.2. (There are a number of limitations on plate thicknesses that must be satisfied.) Steel piles are designed for capacity to satisfy the requirements of AASHTO Article 10.36, Combined Stresses. These limitations are based on an allowable steel stress including the effect of combined bending and axial loads. The conditions that must be dealt with are as described for timber piles including the problem of dealing with a number of load combinations for a typical pile group shown in Figure 10.1. The three conditions presented above for timber piles in Equation 10-1 must also be satisfied for steel piles that are fully embedded in the ground.

For pipe piles:

$$f_c = \frac{P}{A} \pm \frac{M_y}{S} \pm \frac{M_x}{S} \quad \text{Equation 10-1}$$

For H-Piles:

$$f_c = \frac{P}{A} \pm \frac{M_y}{S_y} \pm \frac{M_x}{S_x} \quad \text{Equation 10-1a}$$

The determination of the structural capacity of a partially unsupported steel pile as specified in AASHTO Article 10.36 will be summarized here. Two interaction requirements must be satisfied as follows

$$\frac{f_a}{F_a} + \frac{C_{mx} f_{bx}}{\left(1 - \frac{f_a}{F'_e}\right) F_{bx}} + \frac{C_{my} f_{by}}{\left(1 - \frac{f_a}{F'_e}\right) F_{by}} \leq 1.0 \quad \text{Equation 10-3}$$

and

$$\frac{f_a}{0.472 F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \text{ (at points of support)} \quad \text{Equation 10-4}$$

where

$$F'_e = \frac{\pi^2 E}{F.S. (K_b L_b / r_b)^2} \quad \text{Equation 10-5}$$

- f_a = computed axial stress;
- f_{bx} or f_{by} = computed compressive bending stress about the x axis and y axis, respectively;
- F_a = axial stress that would be permitted if axial force alone existed, regardless of the plane of bending;
- F_{bx}, F_{by} = compressive bending stress that would be permitted if bending moment alone existed about the x axis and the y axis, respectively, as evaluated according to AASHTO Table 10.32.1A
- F'_e = Euler buckling stress divided by a factor of safety;
- E = modulus of elasticity of steel;
- K_b = effective length factor in the plane of bending from AASHTO Appendix C;
- L_b = actual unbraced length in the plane of bending; The unbraced length must include the effect of the lateral soil resistance for the embedded length of the pile.
- r_b = Radius of gyration in the plane of bending;
- C_{mx}, C_{my} = coefficient about the x axis and y axis, respectively, whose value is taken from AASHTO Table 10.36A;
- $F.S.$ = Factor of safety = 2.12.

In most cases of driven pile design, the pile will be fully embedded so Equation 10-1 will govern.

The above limitations are familiar to the structural designer from their use in steel column design. The allowable stresses are given in Table 10.32.1A of the AASHTO Standard Specification (2002).

10.8.2.3 Prestressed Concrete Piles

The structural design of prestressed concrete piles is not discussed in the AASHTO Standard Specification. AASHTO contains two major Sections dealing with concrete structures – Sections 8 and 9. AASHTO Section 9 deals specifically with the design of prestressed concrete structures. However, it makes no mention of the design of either piles or prestressed concrete compression members, probably because prestressed concrete columns are not commonly used in bridge structures or any other structure for that matter. AASHTO Section 8 is titled Reinforced Concrete. It also does not deal specifically with piles but it does have a clear treatment of reinforced concrete compression members. The methods specified will be reviewed.

Allowable Stress Design is called Service Load Design in the AASHTO Standard Specification and it is covered in AASHTO Article 8.15. AASHTO Article 8.15.4, Compression Members, states, “The combined flexural and axial load capacity of compression members shall be taken as 35 percent of that computed in accordance the provisions of Article 8.16.4.” All of reinforced concrete performance is now analyzed on a strength basis so calculated stresses are not determined. To use the calculated strengths in the ASD format they are reduced to 35 percent of the ultimate values and compared with the working loads determined by ASD. Other provisions are also contained in this Article. The fundamental problem is that an elastic analysis of concrete compression members produces very poor results due to the substantial time dependent deformations that occur in concrete members loaded in compression. If the loads introduce both axial and bending forces the problems are particularly difficult.

In order to apply AASHTO Article 8.16.4 to prestressed concrete piles subjected to combined bending and axial loads some suggestions are offered. The design axial strength at zero eccentricity specified in AASHTO Equation (8-31) could be replaced by

$$P_0 = 0.85 f'_c (A_g - A^*_s) - A^*_s f_{se} \qquad \text{Equation 10-6}$$

where f'_c is the concrete cylinder strength, A_g is the area of the gross concrete section, A^*_{st} is the area of the prestressing steel and f_{se} is the effective prestress. In this strength estimate, the effective prestress force is subtracted from the axial compression strength of the concrete. In the extreme compression load case, the effective prestress would have been reduced by the compression deformations but probably there would still be prestress force active at the concrete compression failure. Therefore, this strength estimate should be conservative since the full effective prestress is subtracted from the capacity. The design axial strength at balanced conditions, P_b , given in AASHTO Equation (8-32) can be replaced by

$$P_b = 0.85 f'_c b a_b - A^*_{st} f_{se} \quad \text{Equation 10-7}$$

where b is the pile width, a_b is the distance from the extreme compression fiber to the bottom of the compression block and A^*_{st} is that portion of the prestressing steel that will act in tension in the balanced failure condition. The value of a_b can be estimated from

$$a_b = \frac{87,000}{(87,000 + f_{se})} \quad \text{Equation 10-8}$$

This estimate of a_b has been generated by Goble (2005). It should provide a conservative value of a_b . The expression for balanced moment can be estimated from

$$M_b = 0.85 f'_c b a_b (d - d'' - a_b/2) + A^*_{st} f_{se} d'' \quad \text{Equation 10-9}$$

where d is the distance from the extreme compression fiber to the tension prestressing steel, d'' is the distance from the tension prestressing steel to the centroid of the gross section and A^*_{st} is the area of the prestressing steel that acts in tension to resist the balanced moment.

With the above quantities determined the combined bending and axial capacity can be determined from the interaction expressions given in AASHTO Article 8.16.4.3. When the three values described above have been calculated it is a reasonably simple task to determine the allowable capacity. However, the analysis of a large pile group with a number of load combinations would be a time consuming task. Alternatively, the use of computer software such as FB Pier can give a much more reliable answer with considerably less effort.

10.8.2.3.1 Concrete Pile Interaction Analysis

In the general case, a pile cap will be loaded at its center with a vertical load, two orthogonal lateral loads and two orthogonal bending moments as shown in Figure 10.1. Actually, the loads may be applied at the column top but they can be transferred to the pile cap or the total structure can be analyzed. Horizontal soil resistance forces will be mobilized on the piles and may also act on the faces of the pile cap. Figure 10.1 illustrates this condition for a 12 pile group.

A numerical analysis can be performed by discretizing the piles into elements of finite length as shown in Figure 10.1. Soil resistance forces are prescribed along the pile lengths in the form of a response resistance-displacement relationship. The analysis process applies the forces to the pile cap incrementally and the displacements and member forces are determined in the analysis. Since the soil response will be nonlinear the loads must be applied incrementally until the maximum load is reached or failure occurs.

The analysis of the prestressed concrete section response to a combination of an axial load and two orthogonal moments is complex. A successful and practical approach to the analysis of the pile cross section is offered by the FB-Pier Program. The concrete and the prestressing steel stress strain relationships are assumed. An example is illustrated in Figure 10.2. For concrete, the FB-Pier program assumes a maximum concrete strength of $0.85f_c$ to include loading time effects on the concrete strength and all points on the stress strain curve are reduced to 85 percent of the short time values.

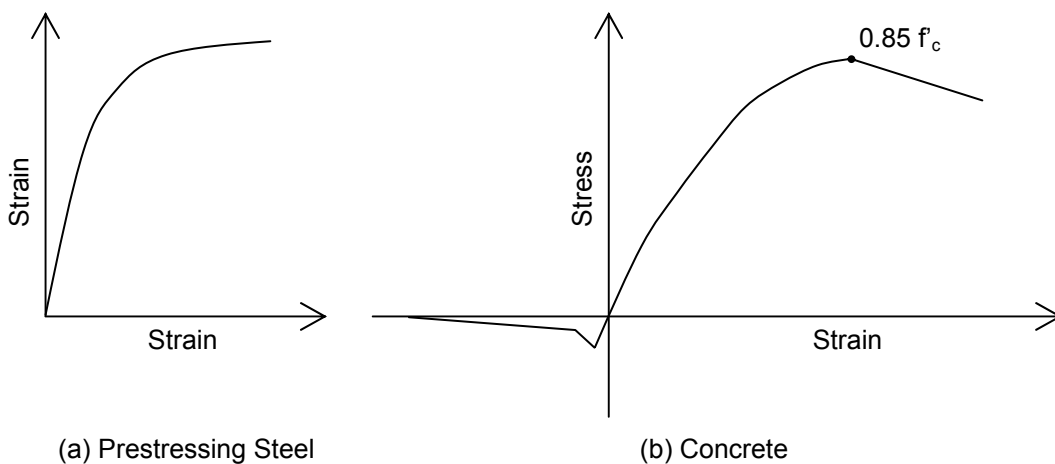


Figure 10.2 Assumed Material Stress Strain Curves

Bi-axial interaction diagrams are determined for each of an increasing set of axial loads up to the maximum axial strength condition. An illustration of one of these interaction diagrams for a particular axial load is shown in Figure 10.3. These diagrams are determined for the entire range of axial loads up to the axial failure case. With increasing axial load the maximum moment strength becomes smaller. A three dimensional interaction diagram can then be constructed with the axial load on the vertical axis and a particular interaction diagram at each level of axial load. Imagine a stack of these interaction diagrams. Thus, a three dimensional failure surface is defined. The equation of the failure surface can be generated by fitting a surface through the interaction diagrams at each level.

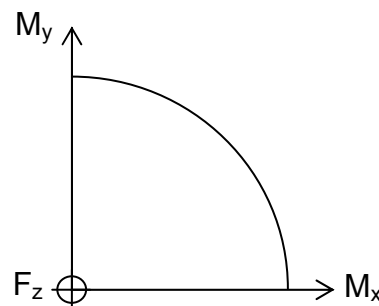


Figure 10.3 Pile Interaction Diagram

When the necessary failure surfaces are available the analysis at a particular load level can be checked by examining whether the vector of the forces on the section (axial, M_x and M_y) falls within or outside the failure envelope. The deformations associated with the three applied forces make it possible to determine the displacements associated with the various load levels. This elegant and powerful analysis algorithm produces excellent results. Well-designed graphics make it is possible for the foundation specialist to easily evaluate the results.

The analysis has been discussed for prestressed concrete piles and they are probably the most challenging to deal with. FB-Pier can also analyze steel piles and concrete filled pipes using the same concepts described above.

10.9 UNSUPPORTED LENGTH AND BUCKLING

A pile or a pile group may have a portion of its length that is laterally unsupported. Examples of this are piles in water, piles after scour has occurred, and piles in very weak soil not capable of providing adequate lateral support to prevent buckling.

Potential buckling of the unsupported length of the pile, i.e., column length, must be checked. In these cases, the maximum supportable pile load may be controlled by buckling, and not by unit stress. The unbraced length must include the effect of the lateral soil resistance for the embedded length of the pile. A procedure for determining the effective length was proposed by Davisson and Robinson (1965).

Per Article 4.5.7.2 of AASHTO, the structural design provisions for compression members of AASHTO Sections 8, 9, 10, and 13 apply, except: timber piles shall be designed in accordance with Article 13.5 using the allowable unit stresses given in Article 13.2 and Table 4.5.7.3.A.

10.9.1 Timber Piles

For timber piles with unsupported length, the maximum allowable compression stress should be reduced by the column stability factor, C_P , of Equation 10-2. The formula for calculating the column stability factor is provided in AASHTO code Article 13.7.3.3.5.

10.9.2 Steel Piles

The maximum unsupported length for steel piles should be determined by satisfying the requirements of Equation 10-5, the Euler buckling stress formula.

10.9.3 Prestressed Concrete Piles

For prestressed concrete pile, it is recommended that maximum design stress computed from Table 10-4 be limited to L/r values of 60 where L is the unsupported length and r is the radius of gyration. For piles fully fixed at both ends, L may be taken as 0.5 times the length between the assumed points of fixity. For piles fully fixed at one end and hinged at the other, it is recommended that L be taken as 0.7 times the length between the hinge and assumed point of fixity.

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Chapter 11

CONTRACT DOCUMENTS

11.1 OVERVIEW OF PLAN AND SPECIFICATION REQUIREMENTS

Pile foundations generally cannot be inspected after installation. Therefore, construction specifications and control are of prime importance for a successful pile foundation. Preparation of the contract plan details and construction specifications related to piling issues are the responsibility of the foundation designer in cooperation with materials and construction personnel. Project plans should include:

- Location of piles.
- Designation to identify piles.
- Pile cut off elevation.
- Estimated pile toe elevation.
- Minimum pile toe elevation.
- Required pile batter and direction.
- Orientation of H-piles.
- Ultimate pile capacity.
- Location of soil borings.
- Results of subsurface exploration.

It is the designer's responsibility to confirm that plans and specifications have been prepared using compatible language. This is particularly true in defining the required pile capacity, which is an important component of any driven pile specification. Problems can arise when modern dynamic methods, which use ultimate pile capacity, are mixed with specifications written for a dynamic formula that uses allowable pile capacity. For example, plans stating "piles shall be driven to a safe bearing of 1000 kN (225 kips)" may have been suitably worded when construction control was performed with the Engineering News formula, which uses the allowable design load. However, this type of wording with modern dynamic methods creates confusion and could result in piles being driven to only the design load, or to a claim for overdriving. Construction plans should therefore indicate the ultimate pile capacity. This ultimate capacity should include an appropriate factor of safety on the design load as well as the resistances from any unsuitable support layers.

This chapter includes a generic pile specification that was developed with input from State and Federal bridge and geotechnical engineers. The generic specification, originally released in 1985 as FHWA Geotechnical Guideline 13, has been slightly modified and updated as necessary. AASHTO (2002) contains similar specifications without commentary.

The intent of the attached generic specification is to provide designers and highway agencies with a comprehensive driven pile specification. Commentary sections are included where appropriate to explain the reasons behind development of particular sections of the specification and the relationship of the specification requirements to necessary pile design or construction activities. Note that only driven piles are covered by the specification. Other deep foundation types such as drilled shafts require completely different construction controls and should not be included in a driven pile specification.

A good driven pile specification should include the following basic components:

- | | |
|--------------------------------|---|
| 1. Pile Material Details | <ul style="list-style-type: none">- Material type and section.- Material grade and strength.- Splice details.- Toe protection requirement.- Coating details.- Transportation and handling. |
| 2. Driving System Requirements | <ul style="list-style-type: none">- Hammer.- Hammer and pile cushions.- Helmet and inserts.- Pile leads. |
| 3. Installation Issues | <ul style="list-style-type: none">- Driving sequence.- Pile location tolerances.- Pile alignment tolerances.- Pile cutoff.- Use of followers.- Use of jetting.- Use of spudding.- Predrilling.- Pile heave. |

- Pile cap connection.
 - Pile rejection criteria
4. Capacity Verification
- Static load testing.
 - Dynamic testing.
 - Wave equation analysis.
 - Dynamic formulas.
5. Basis of Payment
- Method of measurement.
 - Payment items.

11.2 BACKGROUND AND REASONS FOR SPECIFICATION IMPROVEMENT

Older pile specifications placed the major responsibilities for pile capacity determination on the field staff. Little analysis was done in the design stage to provide accurate estimates of the required pile length to safely support the design load. Nor did many design analyses account for the actual soil resistance which had to be overcome to drive the pile to the estimated length, or the stresses generated in the pile during driving. Older specifications frequently placed the responsibility for determining what pile length to order on the contractor. Delays for reordering additional lengths or splices to reach final penetration requirements were considered incidental to the price bid for the item. This resulted in higher bid prices due to the unknown risks associated with the pile item.

Procedures, equipment, and analysis methods now exist to permit the designer to accurately establish pile section and length for any driving condition. Basic foundation design procedures are routinely followed by nearly all public agencies. Much of this design information is neither reflected in the pile specification of the agency nor utilized by the agencies construction staff. Many agencies perform detailed static analyses to determine pile length, but control the pile length actually installed in the field with the unreliable Engineering News formula. Changes are required in pile specifications to permit the cost effective use of modern construction control methods. The five areas of major change are briefly explained below as well as in commentary sections of the attached driven pile specification.

1. **Ordered Length Replaces Estimated Length:** Public highway agencies should assume responsibility for determining and placing in the contract documents the pile

length necessary to safely support the design load. Costs associated with overruns or underruns due to inaccurate length determination should not be borne by the contractor. The attached specification is based on the highway agency performing an adequate subsurface exploration and design analyses to rationally establish pile lengths during the design phase.

2. **Ultimate Pile Capacity Replaces Design Load:** Installation of piling to a predetermined length involves overcoming the design soil resistance, multiplied by the safety factor in suitable pile supporting layers, plus the resistance in any overlying layers unsuitable for long term support. The use of procedures involving design load, such as the Engineering News formula, should be replaced with ultimate load based methods. The ultimate pile load should be based on both the actual resistance to be overcome to reach the required penetration depth and the confidence in the method of construction control to be used. The attached specification is written in terms of ultimate load.
3. **Increased Emphasis on Approval of Driving Equipment:** The use of properly sized pile driving equipment will practically insure a successful installation of properly designed piles. Conversely, improperly sized pile driving equipment insures a pile project fraught with problems, regardless of how well the pile design was done. Too small a pile hammer results in extremely difficult, time consuming driving. Too large a pile hammer increases the risk of pile damage. The attached specification places great emphasis on a formal approval procedure for the hammer and driving system. This approval procedure is the most significant change to current specifications.
4. **Pile Capacity Control by Modern Methods Instead of Dynamic Formulas:** Good piling practice dictates use of the wave equation and dynamic pile testing to replace the use of dynamic formulas to monitor pile driving on all projects. Continued use of the Engineering News formula can only result in unreliable, costly pile foundations.

Highway agencies need to utilize modern methods in both design and construction control of pile foundations. The wave equation uses ultimate soil resistances, basic soil properties, and calculated pile lengths in conjunction with driving equipment characteristics to determine the necessary pile penetration resistance for the ultimate capacity, as well as the maximum pile stresses during driving. Dynamic pile testing provides a quick, reliable field test supplement and/or alternate to static load testing, as well as a supplement to wave equation analysis. Both methods are detailed in the attached specification, with commentary containing recommended safety factors applied to the pile design load based on the method of construction control selected.

5. **Separation of Payment into Fixed and Variable Cost Items Instead of Lump Sum**

Costs: Fair compensation for work performed in pile driving can only be accomplished by recognizing and providing bid items for contract costs which are fixed and contract costs which are variable. The currently popular payment methods used by highway agencies involve lumping fixed and variable costs into a single item. Such lump sum items, with variable contingencies, are recognized as high risk items by contractors who, to avoid a monetary loss, increase the price bid to cover the risk. The attached specification contains a list of bid items which separate the major fixed and variable costs to permit contractors to develop a low risk bid.

11.3 GENERIC DRIVEN PILE SPECIFICATION

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SECTION XXX.01 DESCRIPTION

This item shall consist of furnishing and driving foundation piles of the type and dimensions designated, including cutting off or building up foundation piles when required. Piling shall conform to and be installed in accordance with these specifications, and at the location, and to the elevation, penetration and/or capacity shown on the plans, or as directed by the Engineer.

The Contractor shall furnish the piles in accordance with an itemized order list which will be furnished by the Engineer, showing the number and length of all piles. When test piles are required, the pile lengths shown on the plans are for estimating purposes only and the actual lengths to be furnished for production piles will be determined by the Engineer after the test piles have been driven. The lengths given in the order list will be based on the lengths which are assumed after cutoff to remain in the completed structure. The Contractor shall, without added compensation, increase the lengths to provide for fresh heading and for such additional length as may be necessary to suit the Contractor's method of operation.

Commentary: *The objective of this specification is to provide criteria by which the Owner can assure that designated piles are properly installed and the Contractor can expect equitable compensation for work performed. The Owner's responsibility is to estimate the pile lengths required to safely support the design load. Pile lengths should be estimated based on subsurface explorations, testing and analysis which are completed during the design phase. Pile contractors who enter contractual agreements to install piles for an owner should not be held accountable or indirectly penalized for inaccuracies in estimated lengths. The Contractor's responsibility is to provide and install designated piles, undamaged, to the lengths specified by the Owner. This work is usually accomplished within an established framework of restrictions necessary to insure a "good" pile foundation. The price bid for this item of work will reflect the Contractor's estimate of both actual cost to perform the work and perceived risk.*

A. Pile Installation Plan

A Pile Driving Installation Plan shall be prepared by the Contractor and submitted to the Engineer no later than 30 days before driving the first pile. The Pile Driving Installation

Plan shall include the following:

1. List and size of proposed equipment including cranes, barges, driving equipment, jetting equipment, compressors, and predrilling equipment. Include manufacturer's data sheets on hammers.
2. Methods to determine hammer energy in the field for determination of pile capacity. Include in the submittal necessary charts and recent calibrations for any pressure measuring equipment.
3. Detailed drawings of any proposed followers.
4. Detailed drawings of any templates.
5. Details of proposed load test equipment and procedures, including recent calibrations of jacks and required load cells.
6. Sequence of driving of piles for each different configuration of pile layout.
7. Proposed schedule for test pile program and production pile driving.
8. Details of proposed features and procedures for protection of existing structures.
9. Required shop drawings for piles, cofferdams, etc.
10. Methods and equipment proposed to prevent displacement of piles during placement and compaction of fill within 4.5 m (15 ft) of the piles.
11. Methods to prevent deflection of battered piles due to their own weight and to maintain their as-driven position until casting of the pile cap is complete.
12. Proposed pile splice locations and details of any proprietary splices anticipated to be used.

SECTION XXX.02 MATERIALS

Materials shall meet the requirements in the following Subsections of Section XXX - Materials:

- Portland Cement Concrete
- Reinforcing Steel
- Structural Steel
- Castings for Pile Shoes
- Steel Shells for Cast in Place Piles
- Timber Piles
- Paint / Coatings
- Timber Preservative and Treatment

Commentary: *The appropriate sections of each agency's standard specifications should be included under the XXX.02 Materials Section. A generic materials section cannot be provided herein, considering the vast combinations of materials used in piling operations and the varying control methods used by individual highway departments. The above list contains the common material components. Additions or deletions may be required to this list based on the content of individual agency standard specifications and the pile type specified.*

SECTION XXX.03. EQUIPMENT FOR DRIVING PILES

A. Pile Hammers. Piles may be driven with air, steam, diesel, or hydraulic hammers. Gravity hammers, if specifically permitted in the contract, shall only be used to drive timber piles. When gravity hammers are permitted, the ram shall weigh between 900 and 1600 kg (2 and 3.5 kips) and the height of drop shall not exceed 4 m (13 ft). In no case shall the weight of gravity hammers be less than the combined weight of helmet and pile. All gravity hammers shall be equipped with hammer guides to insure concentric impact on the helmet.

Air/steam hammers shall be operated and maintained within the manufacturer's specified ranges. The plant and equipment furnished for air/steam hammers shall have sufficient capacity to maintain at the hammer, under working conditions, the volume and pressure specified by the manufacturer. The plant and equipment shall

be equipped with accurate pressure gauges which are easily accessible to the Engineer. The weight of the striking parts of air and steam hammers shall not be less than one third the weight of helmet and pile being driven, and in no case shall the striking parts weigh less than 1250 kg (2.75 kips).

Open end (single acting) diesel hammers shall be equipped with a device such as rings on the ram to permit the Engineer to visually determine hammer stroke at all times during pile driving operations. Also, the Contractor shall provide the Engineer a chart from the hammer manufacturer equating stroke and blows per minute for the open-end diesel hammer to be used. For open end diesel hammers, the contractor shall provide and maintain in working order for the Engineer's use, an approved device to automatically determine and display ram stroke.

Closed end (double acting) diesel hammers shall be equipped with a bounce chamber pressure gauge, in good working order, mounted near ground level so as to be easily read by the Engineer. Also, the Contractor shall provide the Engineer a chart, calibrated to actual hammer performance within 90 days of use, equating bounce chamber pressure to either equivalent energy or stroke for the closed-end diesel hammer to be used.

Hydraulic hammers shall have a power plant with sufficient capacity to maintain at the hammer, under working conditions, the volume and pressure specified by the manufacturer. The power plant and equipment shall be equipped with accurate pressure gauges which are easily accessible to the Engineer.

Commentary: *Pile inspectors frequently do not possess adequate knowledge or technical information concerning even the most basic details of the Contractor's hammer. Chapters 21 and 23 provide information on driving equipment and inspection. Highway agencies should also provide pile inspectors with basic manuals such as FHWA/RD-86/160 "The Performance of Pile Driving Systems: "Inspections Manual" or "Inspectors Manual for Pile Foundations" and "A Pile Inspectors Guide to Hammers, Second Edition" available from the Deep Foundation Institute, 120 Charlotte Place, Englewood Cliffs, NJ 07632.*

On large projects or on projects using high capacity piles, specifications should consider requiring kinetic energy readout devices for hammers as described in Section 21.16 of Chapter 21. Several manufacturers can

equip their hammers with these devices when requested. Any existing hammer can also be retrofitted with a kinetic energy readout device. These devices allow improved quality control and can detect changes in hammer performance over time that may necessitate adjustment to the pile installation criterion.

Non-impact hammers, such as vibratory hammers, or driving aids such as jets, followers and prebored holes shall not be used unless either specifically permitted in writing by the Engineer or stated in the contract documents. When permitted, such equipment shall be used for installing production piles only after the pile toe elevation for the ultimate pile capacity is established by load testing and/or test piles driven with an impact hammer. The Contractor shall perform, at his cost, such load tests and/or extra work required to drive test piles as determined by the Engineer as a condition of approval of the non-impact hammers or driving aids. Installation of production piles with vibratory hammers shall be controlled according to power consumption, rate of penetration, specified toe elevation, or other means acceptable to the Engineer which assure the ultimate pile capacity equals or exceeds the ultimate capacity of the test pile. In addition, one of every ten piles driven with a vibratory hammer shall be restruck with an impact hammer of suitable energy to verify the ultimate pile capacity as in XXX.04(D).

Commentary: *At present no formula exists to reliably predict the capacity of piles driven with vibratory hammers. Until reliable procedures are developed for vibratory installation, special precautions must be taken to insure foundation piles installed with vibratory hammers have both adequate capacity and structural integrity. On critical projects, highway agencies should consider the use of dynamic testing during restrike to substantiate pile capacity and integrity.*

- B. Approval of Pile Driving Equipment. All pile driving equipment furnished by the Contractor shall be subject to the approval of the Engineer. It is the intent of this specification that all pile driving equipment be sized such that the project piles can be driven with reasonable effort to the ordered lengths without damage. Approval of pile driving equipment by the Engineer will be based on wave equation analysis and/or other judgments. In no case shall the driving equipment be transported to the project site until approval of the Engineer is received in writing. Prerequisite to such approval, the Contractor shall submit to the Engineer the necessary pile driving

equipment information at least 30 days prior to driving piles. The form which the Contractor shall complete with the above information is shown in Figure 11.1a (SI unit version) and Figure 11.1b (US unit version). If a follower is to be used, detailed drawings of the follower shall be included as part of this submittal.

Commentary: *Use of wave equation analysis for approval of driving equipment can substantially reduce pile driving costs and pile driving claims by checking that the equipment mobilized to the job can drive the pile to the required penetration depth without damage. Public agencies should encourage Contractors to use wave equation analysis to select the optimum hammer for each project. In cases where disputes arise over rejection of pile driving equipment, the Engineer should request the Contractor to submit proof of the adequacy of the pile driving equipment. Such proof should consist of, but not be limited to, a wave equation analysis of the proposed driving equipment performed by a registered professional engineer. All costs of such submissions, if required, shall be the responsibility of the Contractor.*

The pile and driving equipment data form should be submitted for approval even if wave equation analysis will not be used for hammer approval. The approved form should be used by the pile inspector to check the proposed hammer and drive system components are as furnished and are maintained during the driving operation. Few agencies currently supply the pile inspector with any such information on which rational inspection can be based.

| | |
|--|--|
| Contract No.: _____ Project: _____ County: _____ | Structure Name and/or No.: _____ Pile Driving Contractor or Subcontractor: _____ <div style="text-align: right;">(Piles driven by)</div> |
|--|--|

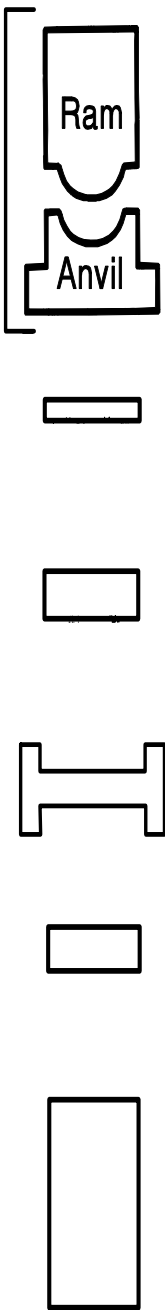
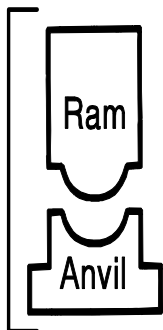
| | | | |
|---|--|---|--|
| <div style="writing-mode: vertical-rl; transform: rotate(180deg); font-weight: bold;">Hammer Components</div> |  | <p>Hammer</p> <p>Striker Plate</p> <p>Hammer Cushion</p> <p>Helmet (Drive Head)</p> <p>Pile Cushion</p> <p>Pile</p> | <p> Manufacturer: _____ Model No.: _____ Hammer Type: _____ Serial No.: _____ Manufacturers Maximum Rated Energy: _____ (Joules) Stroke at Maximum Rated Energy: _____ (meters) Range in Operating Energy: _____ to _____ (Joules) Range in Operating Stroke: _____ to _____ (meters) Ram Weight: _____ (kg) Modifications: _____ _____ _____ </p> <p> Weight: _____ (N) Diameter: _____ (mm) Thickness: _____ (mm) </p> <p> Material #1 _____ Material #2 _____ (for Composite Cushion) Name: _____ Name: _____ Area: _____ (cm²) Area: _____ (cm²) Thickness/Plate: _____ (mm) Thickness/Plate: _____ (mm) No. of Plates: _____ No. of Plates: _____ Total Thickness of Hammer Cushion: _____ </p> <p> Weight: _____ including inserts (kN) </p> <p> Material: _____ Area: _____ (cm²) Thickness/Sheet: _____ (mm) No. of Sheets: _____ Total Thickness of Pile Cushion: _____ (mm) </p> <p> Pile Type: _____ Wall Thickness: _____ (mm) Taper: _____ Cross Sectional Area: _____ (cm²) Weight/Meter: _____ </p> <p> Ordered Length: _____ (m) Design Load: _____ (kN) Ultimate Pile Capacity: _____ (kN) </p> <p> Description of Splice: _____ _____ Driving Shoe/Closure Plate Description: _____ _____ </p> <p> Submitted By: _____ Date: _____ Telephone No.: _____ Fax No.: _____ </p> |
|---|--|---|--|

Figure 11.1a Pile and Driving Equipment Data Form – SI Version

Contract No.: _____ Structure Name and/or No.: _____
 Project: _____
 County: _____ Pile Driving Contractor or Subcontractor: _____
 (Piles driven by)

Hammer Components



Hammer

Manufacturer: _____ Model No.: _____
 Hammer Type: _____ Serial No.: _____
 Manufacturers Maximum Rated Energy: _____ (ft-lbs)
 Stroke at Maximum Rated Energy: _____ (ft)
 Range in Operating Energy: _____ to _____ (ft-lbs)
 Range in Operating Stroke: _____ to _____ (ft)
 Ram Weight: _____ (kips)
 Modifications: _____

**Striker
Plate**



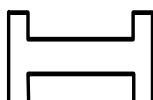
Weight: _____ (kips) Diameter: _____ (in)
 Thickness: _____ (in)

**Hammer
Cushion**



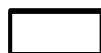
Material #1 Material #2
 (for Composite Cushion)
 Name: _____ Name: _____
 Area: _____ (in²) Area: _____ (in²)
 Thickness/Plate: _____ (in) Thickness/Plate: _____ (in)
 No. of Plates: _____ No. of Plates: _____
 Total Thickness of Hammer Cushion: _____

**Helmet
(Drive Head)**



Weight: _____ including inserts (kips)

**Pile
Cushion**



Material: _____
 Area: _____ (in²) Thickness/Sheet: _____ (in)
 No. of Sheets: _____
 Total Thickness of Pile Cushion: _____ (in)

Pile



Pile Type: _____
 Wall Thickness: _____ (in) Taper: _____
 Cross Sectional Area: _____ (in²) Weight/Ft: _____
 Ordered Length: _____ (ft)
 Design Load: _____ (kips)
 Ultimate Pile Capacity: _____ (kips)

Description of Splice: _____

 Driving Shoe/Closure Plate Description: _____

Submitted By: _____ Date: _____
 Telephone No.: _____ Fax No.: _____

Figure 11.1b Pile and Driving Equipment Data Form – US Version

The criteria, which the Engineer will use to evaluate the driving equipment from the wave equation results, consists of both the required number of hammer blows per 0.25 meter of penetration as well as the pile stresses at the required ultimate pile capacity. The required number of hammer blows indicated by the wave equation at the ultimate pile capacity shall be between 25 and 98 blows per 0.25 meter (30 and 120 blows per foot) for the driving equipment to be acceptable.

In addition, for the driving equipment to be acceptable the pile stresses which are indicated by the wave equation to be generated by the driving equipment shall not exceed allowable values. For steel piles, maximum compressive driving stresses shall not exceed 90% of the minimum yield strength of the pile material. For prestressed concrete piles in normal environments, tensile stresses shall not exceed 0.25 multiplied by the square root of the concrete compressive strength, f'_c plus the effective prestress value, f_{pe} , *i.e.* $(0.25 \sqrt{f'_c} + f_{pe})$. Both f'_c and f_{pe} in this equation must be in MPa. (In US units, tensile stresses shall not exceed 3 multiplied by the square root of the concrete compressive strength, f'_c plus the effective prestress value, f_{pe} , with both f'_c and f_{pe} in psi.) For prestressed concrete piles in severe corrosive environments, tensile stresses shall not exceed f_{pe} . Compressive stresses for prestressed concrete piles shall not exceed 85% of the compressive strength minus the effective prestress value, *i.e.* $(0.85 f'_c - f_{pe})$. For timber piles, the compressive driving stress shall not exceed three times the allowable static design strength listed on the plans. These criteria will be used in evaluating wave equation results to determine acceptability of the Contractor's proposed driving system.

The Contractor will be notified of the acceptance or rejection of the driving system within 14 calendar days of the Engineer's receipt of the Pile and Driving Equipment Data Form. If the wave equation analyses show that either pile damage or inability to drive the pile with a reasonable driving resistance to the desired ultimate capacity will result from the Contractor's proposed equipment or methods, the Contractor shall modify or replace the proposed methods or equipment at his expense until subsequent wave equation analyses indicate the piles can be reasonably driven to the desired ultimate capacity, without damage. The Engineer will notify the Contractor of the acceptance or rejection of the revised driving system within 7 calendar days of receipt of a revised Pile and Driving Equipment Data Form.

During pile driving operations, the Contractor shall use the approved system. No variations in the driving system will be permitted without the Engineer's written approval. Any change in the driving system will only be considered after the Contractor has submitted the necessary information for a revised wave equation analysis. The Contractor will be notified of the acceptance or rejection of the driving system changes within 7 calendar days of the Engineer's receipt of the requested change. The time required for submission, review, and approval of a revised driving system shall not constitute the basis for a contract time extension to the Contractor.

Commentary: *The ultimate pile capacity during driving is the soil resistance which must be overcome (including resistance from unsuitable layers and scour zone soils) to reach the pile penetration depth where the design load can be obtained with an acceptable safety factor. The safety factor selected will depend on design factors, such as quantity of subsurface information and geotechnical analysis, as well as construction factors such as the use of load tests, wave equation or dynamic formula to determine pile capacity. When proper foundation exploration procedures and static analyses such as those described in this manual are employed, the following safety factors on design load may be used, based on the pile construction control procedures specified:*

| <u>Construction Control Method</u> | <u>Factor of Safety</u> |
|---|-------------------------|
| Static load test (ASTM D-1143) with wave equation analysis | 2.00 |
| Dynamic testing (ASTM D-4945) with signal matching and wave equation analysis | 2.25 |
| Indicator piles with wave equation analysis | 2.50 |
| Wave equation analysis | 2.75 |
| Modified Gates dynamic formula | 3.50 |

The factor of safety for other test methods should be determined by the individual designer.

The ultimate pile capacity during driving is affected by:

- 1. The resistance in unsuitable soil layers overlying suitable support layers,*

2. *Temporary loss or increase in soil strength due to driving operations.*
3. *Pile installation methods which alter the in place soil resistance such as jetting, preboring, etc.*

The designer must estimate the ultimate pile capacity to be encountered during driving if pile driving resistance is to be used to determine pile capacity. Only on the most routine pile projects will the ultimate pile capacity be equal to the pile design load multiplied by the design safety factor. More typically, piles are used to penetrate upper soil layers which are unsuitable for load support due to either poor soil characteristics, or future loss of load support by scour or erosion. In such cases the resistance in unsuitable layers is not considered in determining the pile penetration necessary to support the design load at the appropriate safety factor. However, the estimated ultimate pile capacity to be encountered during driving must include the resistance to be encountered in penetrating those unsuitable layers, in addition to the design load multiplied by the safety factor. This ultimate pile capacity must be shown on the contract documents to permit the Contractor to properly size the driving equipment and the Engineer to judge the acceptability of the Contractor's driving equipment. Optimum pile installation generally occurs when the ultimate pile capacity is obtained with a driving effort below the point of maximum curvature (usually 60-100 blows per 0.25 meter or 75-120 blows per foot) of the wave equation bearing graph. Larger driving resistances result in negligible pile penetration per blow and generally inefficient driving conditions. Excessive driving resistances can also result in damage to the pile or the driving system.

1. **Alternate Approval Method:** An alternate method of driving equipment approval will be used when either the contract documents contain a provision that wave equation analysis will not be used for approval of driving equipment. The alternate approval method requires that the energy of the driving equipment submitted for approval on the Pile and Driving Equipment Data form, be rated by the manufacturer at or above the appropriate minimum energy level in Table 11-1 corresponding to the ultimate pile capacity shown on the plans.

| TABLE 11-1 ALTERNATE APPROVAL METHOD Minimum Pile Hammer Requirements | |
|--|--|
| Ultimate Pile Capacity (kN) | Minimum Manufacturers Rated Hammer Energy (Joules)* |
| 800 and under (180 kips) | ----- |
| 800 to 1350 (180 to 300 kips) | ----- |
| 1351 to 1850 (300 to 420 kips) | ----- |
| 1851 to 2400 (420 to 540 kips) | ----- |
| 2401 to 2650 (540 to 600 kips) | ----- |
| 2650 and over (600 kips) | ----- |

* Previously published tables which include specific values were based on assumptions which might not be appropriate for local conditions and were subject to misinterpretation.

Commentary: *A table of the minimum rated hammer energy vs. ultimate pile capacity should be developed using wave equation analyses of commonly available driving systems for the pile types, pile lengths, and pile loads routinely used by the specific agency. These analyses should model the typical soil and pile installation conditions. The wave equation results should be evaluated for driving stress levels and driving resistances to determine which hammer energies are too large (driving stress problems or driving resistances at ultimate capacity less than 25 blows per 0.25 meter (30 blows/ft.)) and which energies are too small (driving resistances at ultimate capacity greater than 98 blows per 0.25 meter (120 blows /ft.)).*

Once the specific table of energy values has been developed, it should only be considered for routine projects in uniform soil conditions or when the agency is in the process of phasing the wave equation analysis into standard use. Projects involving long piles or large ultimate pile capacities relative to the design load (such as scour piles or piles to be driven through embankments) should use job specific wave equation analysis to establish minimum driving equipment requirements. Piles to rock should also be evaluated by wave equation analysis to reduce the risk of pile damage from too large a hammer.

During pile driving operations, the Contractor shall use the approved system. If the Engineer determines the Contractor's hammer is unable to transfer sufficient energy to the pile, the hammer shall be removed from service until repaired to the satisfaction of the Engineer. No variations in the driving system will be permitted without the Engineer's written approval. Any changes in the driving system will be considered only after the Contractor has submitted a new Pile and Driving Equipment Data form. The Contractor will be notified of the acceptance or rejection of the proposed change in driving equipment within 7 calendar days of the Engineer's receipt of the form.

C. Drive System Components and Accessories

1. **Hammer Cushion:** Impact pile driving equipment designed to be used with a hammer cushion shall be equipped with a suitable thickness of hammer cushion material to prevent damage to the hammer or pile and to insure uniform driving behavior. Hammer cushions shall be made of durable manufactured materials, provided in accordance with the hammer manufacturer's guidelines. Wood, wire rope, and asbestos hammer cushions are specifically disallowed and shall not be used. A striker plate as recommended by the hammer manufacturer shall be placed on the hammer cushion to insure uniform compression of the cushion material. The hammer cushion shall be removed from the helmet and inspected in the presence of the Engineer when beginning pile driving at each structure or after each 100 hours of pile driving, whichever is less. Any reduction of hammer cushion thickness exceeding 25% of the original thickness shall be replaced by the Contractor before driving is permitted to continue.

Commentary: *For hammers requiring cushion material, mandatory use of a durable hammer cushion material which will retain uniform properties during driving is necessary to accurately relate driving resistance to pile capacity. Non-durable materials which deteriorate during driving cause erratic estimates of pile capacity and, if allowed to dissolve, result in damage to the pile or driving system.*

2. **Helmet:** Piles driven with impact hammers require an adequate helmet or drive head to distribute the hammer blow to the pile head. The helmet shall be axially aligned with the hammer and the pile. The helmet shall be guided by the leads and not be free-swinging. The helmet shall fit around the pile head in such a manner as to prevent transfer of torsional forces during driving, while maintaining

proper alignment of hammer and pile. An insert may be used with a helmet to adapt the helmet to different types or sizes of piles.

For steel and timber piling, the pile heads shall be cut squarely and a helmet, as recommended by the hammer manufacturer, shall be provided to hold the axis of the pile in line with the axis of the hammer.

For precast concrete and prestressed concrete piles, the pile head shall be plane and perpendicular to the longitudinal axis of the pile to prevent eccentric impacts from the helmet.

For special types of piles, appropriate helmets, mandrels or other devices shall be provided in accordance with the manufacturer's recommendations so that the piles may be driven without damage.

3. **Pile Cushion:** The heads of concrete piles shall each be protected by a pile cushion having the same cross sectional area as the pile top. Pile cushions shall be made of plywood, hardwood, or composite plywood and hardwood materials. The minimum pile cushion thickness placed on the pile head prior to driving shall not be less than 100 mm (4 inches).

A new pile cushion shall be provided for each pile. In addition the pile cushion shall be replaced if, during the driving of any pile, the cushion is compressed more than one-half the original thickness or it begins to burn. Pile cushions shall be protected from the weather, and kept dry prior to use. Pile cushion shall not be soaked in any liquid unless approved by the Engineer. The use of manufactured pile cushion materials in lieu of a wood pile cushion shall be evaluated on a case by case basis.

A used pile cushion in good condition shall be used for restrrike tests. The used cushion shall be the same pile cushion from the end of initial driving unless that cushion condition has deteriorated. If the original cushion has deteriorated, a used cushion of similar thickness as the end of drive pile cushion shall be used.

Commentary: *A pile cushion is only needed for the protection of concrete piles. If the wave equation analysis of the Contractor's hammer indicates tension stresses exceed specification limits, the pile cushion may need to be substantially thicker than 100 mm (4 inches). Pile cushion thicknesses up*

to 460 mm (18 inches) have been used to mitigate tension stresses. Compressive stresses at the pile head can be controlled with a relatively thin pile cushion. However, wood pile cushions may become overly compressed and hard after about 1000 hammer blows. The physical characteristics of manufactured pile cushion materials should be determined by standard test procedures such as the Deep Foundations Institute standard "Testing of Pile Driving Cushion Material".

4. **Leads:** Piles shall be supported in line and position with leads while being driven. Pile driver leads shall be constructed in a manner that affords freedom of movement of the hammer while maintaining alignment of the hammer and the pile to insure concentric impact for each blow. Leads may be either fixed or swinging type. Swinging leads, when used, shall be fitted with a pile gate at the bottom of the leads and, in the case of batter piles, a horizontal brace may be required between the crane and the leads. The pile section being driven shall not extend above the leads. The leads shall be adequately embedded in the ground or the pile constrained in a structural frame such as a template to maintain alignment. The leads shall be of sufficient length to make the use of a follower unnecessary, and shall be so designed as to permit proper alignment of batter piles.
5. **Followers:** Followers shall only be used when approved in writing by the Engineer, or when specifically stated in the contract documents. In cases where a follower is permitted, the first pile in each bent and every tenth pile driven thereafter shall be driven full length without a follower, to determine that adequate pile penetration is being attained to develop the ultimate pile capacity.

The follower and pile shall be held and maintained in equal and proper alignment during driving. The follower shall be of such material and dimensions to permit the piles to be driven to the penetration depth determined necessary from the driving of the full length piles. When driving concrete piles, the cross sectional area of the steel follower shall be at least 20% of the cross sectional area of the concrete pile. When driving steel piles, the cross sectional area of the steel follower shall be greater than or equal to the cross section area of the steel pile. The lower end of the follower shall be equipped with a helmet or follower-pile connection suitable for the pile type being driven.

The final position and alignment of the first two piles installed with followers in each substructure unit shall be verified to be in accordance with the location tolerances in Section XXX.04(E) before additional piles are installed.

Commentary: *The use of a follower often causes substantial and erratic reductions in the hammer energy transmitted to the pile due to the follower flexibility, poor connection to the pile head, frequent misalignment, etc. Reliable correlations of driving resistance with ultimate pile capacity are very difficult when followers are used. Severe problems with pile alignment and location frequently occur when driving batter piles with a follower in a cofferdam unless a multi-tier template is used.*

6. **Jets:** Jetting shall only be permitted if approved in writing by the Engineer or when specifically stated in the contract documents. When jetting is not required in the contract documents, but approved after the Contractor's request, the Contractor shall determine the number of jets and the volume and pressure of water at the jet nozzles necessary to freely erode the material adjacent to the pile without affecting the lateral stability of the final in place pile. The Contractor shall be responsible for all damage to the site caused by unapproved or improper jetting operations. When jetting is specifically required in the contract documents, the jetting plant shall have sufficient capacity to deliver at all times a pressure equivalent to at least 700 kPa (100 psi) at two 19 mm (0.75 inch) jet nozzles. In either case, unless otherwise indicated by the Engineer, jet pipes shall be removed when the pile toe is a minimum of 1.5 m (5 ft) above prescribed toe elevation and the pile shall be driven to the required ultimate pile capacity with an impact hammer. Also, the Contractor shall control, treat if necessary, and dispose of all jet water in a manner satisfactory to the Engineer.

When jetting is used, the Contractor shall submit details of the proposed jetting and pile driving plan. Where practical, all piles in a pile group shall be jetted to the required penetration depth before beginning pile driving. When large pile groups or pile spacing and batter make this impractical, restrike tests on a select number of previously driven piles shall be performed to check pile capacity after jetting operations are completed.

7. **Preboring:** When stated in the contract documents, the Contractor shall prebore holes at pile locations to the depths shown on the plans. Prebored holes shall be of a size smaller than the diameter or diagonal of the pile cross section that is

sufficient to allow penetration of the pile to the specified depth. If subsurface obstructions, such as boulders or rock layers, are encountered, the hole diameter may be increased to the least dimension which is adequate for pile installation. Any void space remaining around the pile after completion of driving shall be filled with sand or other approved material. The use of spuds, a short strong driven member which is removed to make a hole for inserting a pile, shall not be permitted in lieu of preboring.

SECTION XXX.04 CONSTRUCTION METHODS

A. Driven Pile Capacity

1. **Wave Equation:** The ultimate pile capacity shall be determined by the Engineer, based on a wave equation analysis. Piles shall be driven with the approved driving equipment to the ordered length or other lengths necessary to obtain the required ultimate pile capacity. Jetting or other methods to facilitate pile penetration shall not be used unless specifically permitted either in the contract documents or approved by the Engineer after a revised driving resistance is established from the wave equation analysis. Adequate pile penetration shall be considered to be obtained when the specified wave equation resistance criteria is achieved within 1.5 m (5 ft) of the pile toe elevation, based on ordered length. Piles not achieving the specified resistance within these limits shall be driven to penetrations established by the Engineer.
2. **Dynamic Formula:** The ultimate pile capacity will only be determined by dynamic formula if either the contract documents contain a provision that dynamic formula shall be used or the Engineer approves dynamic formula use. In such cases, piles shall be driven to a penetration depth necessary to obtain the ultimate pile capacity according to the following formula:

Modified Gates Formula In SI Units

$$R_u = [6.7\sqrt{E_r} \log(10N_b)] - 445$$

Where: R_u = the ultimate pile capacity (kN).

E_r = the manufacturer's rated hammer energy (Joules) at the **field**

observed ram stroke.

$\log(10N_b)$ = logarithm to the base 10 of the quantity 10 multiplied by N_b , the number of hammer blows per 25 mm at final penetration.

The number of hammer blows per 0.25 meter of pile penetration required to obtain the ultimate pile capacity shall be calculated as follows:

$$N_{qm} = 10 (10^x)$$

Where: $x = [(R_u + 445) / (6.7\sqrt{E_r})] - 1$

Modified Gates Formula In US Units

$$R_u = [1.75\sqrt{E_r} \log(10N_b)] - 100$$

Where: R_u = the ultimate pile capacity (kips).

E_r = the manufacturer's rated hammer energy (ft-lbs) at the **field observed ram stroke**.

$\log(10N_b)$ = logarithm to the base 10 of the quantity 10 multiplied by N_b , the number of hammer blows per 1 inch at final penetration

The number of hammer blows per foot of pile penetration required to obtain the ultimate pile capacity shall be calculated as follows:

$$N_{ft} = 12 (10^x)$$

Where: $x = [(R_u + 100) / 1.75\sqrt{E_r} \log] - 1$

Commentary: *Driven pile capacity should be monitored in terms of ultimate pile capacity; not design load. The driving resistance at any penetration depth reflects the total capacity mobilized by the pile. This total capacity may include capacity mobilized temporarily in soil deposits unsuited for bearing, as well as suitable bearing layers. Therefore, the driving resistance should be*

established for the ultimate pile capacity that must be overcome in order to reach anticipated pile penetration depth. These ultimate capacities are determined by static analysis procedures. In the case of piles to be driven to a specified minimum pile toe elevation, the ultimate pile capacity must be computed by static analysis to include the capacity of all soil layers penetrated by the pile above the minimum pile toe elevation as well as the end bearing resistance at that depth. Also, the ultimate pile capacity is directly related to the maximum pile driving stress during installation. This stress is more critical than the stress caused after installation by the design load.

Good piling practices dictate use of the wave equation in place of dynamic formulas to monitor driven pile capacity for all projects. The driving resistance and maximum pile stresses should be determined for the ultimate pile capacity. Use of the wave equation will permit the use of lower safety factors on the design load and the minimum permissible pile section to resist the driving force. This will result in significant cost reductions due to savings in pile lengths and use of smaller pile sections. FHWA recommends that all agencies phase in wave equation analysis with an ultimate goal of eliminating use of dynamic formulas on all pile projects. Wave equation analysis is discussed in greater detail in Chapter 16 of this manual.

The Engineering News formula is recognized to be the least accurate and least consistent of all dynamic formula, yet the vast majority of all States continue to use this formula. The Washington State DOT study WA-RD-163.1 "Comparison of Methods for Estimating Pile Capacity" (1988) found that the Hiley, Gates, Janbu, and Pacific Coast Uniform Building code formulas all provide relatively more dependable results than the Engineering News formula. The dynamic formula contained in this specification is the modified Gates formula and it already includes the 80% efficiency factor on the rated energy, E , recommended by Gates.

The Gates formula was also studied by Olson and Flaate (1967) and found to be the most consistent of the dynamic formulas studied. However, all dynamic formulas are not suited for soft cohesive soils. Engineers planning to use dynamic formula should carefully read these

references to comprehend the limitations involved with their use. A design safety factor of 3.5 is recommended when using the modified Gates formula to determine the safe design load, i.e., if a design load of 1000 kN (225 kips) is required in the bearing layer, then an ultimate pile capacity of 3500 kN (788 kips) should be used in the modified Gates formula to determine the necessary driving resistance. The formula was selected for its relative accuracy, consistency and simplicity of use. However, the top priority for highway agencies should be to change from dynamic formulas to wave equation analysis.

B. Compression Load Tests*

*** Commentary:** *Compression tests with the Osterberg Cell (Chapter 19) and Statnamic (Chapter 20) are not covered by this generic specification. The individual design should prepare the project specification for either of these test methods.*

- 1. Static Load Tests:** Compression load tests shall be performed by procedures set forth in ASTM D-1143 using the quick load test method, except that the test shall be taken to plunging failure or the capacity of the loading system. Testing equipment and measuring systems shall conform to ASTM D-1143, except that the loading system shall be capable of applying 150% of the ultimate pile capacity or 9000 kN (2000 kips), whichever is less, and that a load cell and spherical bearing plate shall be used.

The Contractor shall submit to the Engineer for approval detailed plans prepared by a licensed professional engineer of the proposed loading apparatus. The submittal shall include calibrations for the hydraulic jack, load cell, and pressure gage conducted within 30 days of the load test. If requested by the Engineer, the jack, load cell, and pressure gage shall be recalibrated after the load test

The loading apparatus shall be constructed to allow the various increments of the load to be placed gradually, without causing vibration to the test pile. When the approved method requires the use of tension (reaction) piles, the tension piles, when feasible, shall be of the same type and diameter as the production piles, and shall be driven in the location of permanent piles. Timber or tapered piles installed in permanent locations shall not be used as tension piles.

While performing the load test, the contractor shall provide safety equipment and

employ adequate safety procedures. Adequate support for the load test plates, jack, and ancillary devices shall be provided to prevent them from falling in the event of a release of load due to hydraulic failure, test pile failure, or other cause.

The design load shall be defined as 50% of the failure load. The failure load for the pile shall be defined as follows: for piles 610 mm (24 inches) or less in diameter or width, the failure load of a pile tested under axial compressive load is that load which produces a settlement at failure of the pile head equal to:

$$\text{In SI units} \quad s_f = \Delta + (4.0 + 0.008b)$$

$$\text{In US Units} \quad s_f = \Delta + (0.15 + 0.008b)$$

Where: s_f = Settlement at failure in mm (inches).

b = Pile diameter or width in mm (inches).

Δ = Elastic deformation of total pile length in mm (inches).

For piles greater than 610 mm (24 inches) in diameter or width, the failure load can be defined as a pile head settlement equal to:

$$s_f = \Delta + (b / 30)$$

The top elevation of the test pile shall be determined immediately after driving and again just before load testing to check for heave. Any pile which heaves more than 6 mm (0.25 inches) shall be redriven or jacked to the original elevation prior to testing. Unless otherwise specified in the contract, a minimum 3-day waiting period shall be observed between the driving of any anchor piles or the load test pile and the commencement of the load test.

Commentary: *The pile capacity may increase (soil setup) or decrease (relaxation) after the end of driving. Therefore, it is essential that static load testing be performed after equilibrium conditions in the soil have re-established. Static load tests performed before equilibrium conditions have re-established will underestimate the long term pile capacity in soil setup*

conditions and overestimate the long term capacity in relaxation cases. For piles in clays, specifications should require at least 2 weeks or longer to elapse between driving and load testing. In sandy silts and sands, 5 days to a week is usually sufficient. Load testing of piles driven into shales should also be delayed for at least 2 weeks after driving. Additional discussion on time dependent changes in pile capacity may be found in Section 9.10.1.

Each static load test pile should be determining the load transferred to the pile toe. Instrumentation commonly consists of strain gages and/or telltale rods mounted at varying depths from the pile toe. Also, a load cell and spherical bearing plate should be mounted between the load frame and the pile head to verify the readings from the hydraulic jack pressure gauge. Due to jack ram friction, loads indicated by a jack pressure gauge are commonly 10% to 20% higher than the actual load imposed on the pile. Last, after completion of a load test on a non production pile, the static test pile should be pulled and checked for damage. The examination of the extracted pile will determine driving damage and its effect on capacity.

When static load tests are used to control production pile driving, the time required to analyze the load test results and establish driving criteria should be specified so that the delay time to the contractor is clearly identified. Static load testing is discussed in greater detail in Chapter 18 of this manual. A more detailed specification for static load testing may be found in FHWA-SA-91-042, Static Testing of Deep Foundations.

- 2. Dynamic Load Tests:** Dynamic measurements following procedures set forth in ASTM D-4945 will be taken by the Engineer during the driving of piles designated as dynamic load test piles.

Commentary: *When static load tests are specified, dynamic load tests are recommended to be performed on at least half the reaction piles prior to driving the static load test pile. The dynamic test results are used both to verify that the desired ultimate pile capacity can be attained at the proposed estimated static load test pile penetration depth and to fine tune the dynamic test equipment for site soil conditions. Dynamic monitoring of the load test pile during both initial driving and during restriking after completion of the static load test are also recommended. This allows correlation of static test*

results with dynamic test results. Signal matching techniques using the dynamic test data can further quantify dynamic soil parameters such as soil quake and damping for the site. When dynamic tests are specified on production piles, the first pile driven in each substructure foundation is recommended to be tested. Where uniform soil conditions exist across a site, the number of dynamic tests may be reduced based on recommendations from the geotechnical engineer.

*This section of the specifications applies to the Contractor's activities as they relate to the dynamic testing of piles. **If the dynamic tests are to be performed by an independent firm retained by the Contractor and not transportation department personnel, an additional specification section detailing the dynamic test analysis and reporting requirements must be added. In addition, testing personnel should have attained an appropriate level of expertise on the Foundation QA Examination for providers of dynamic testing services.** Dynamic tests and the Foundation QA Examination are discussed in greater detail in Chapter 17 of this manual.*

Prior to placement in the leads, the Contractor shall make each designated concrete and/or timber pile available for taking of wave speed measurements and for predrilling the required instrument attachment holes. Predriving wave speed measurements will not be required for steel piles. When wave speed measurements are made, the piling shall be in a horizontal position and not in contact with other piling. The Engineer will furnish the equipment, materials, and labor necessary for drilling holes in the piles for mounting the instruments. The instruments will be attached near the head of the pile with bolts placed in masonry anchors for the concrete piles, or through drilled holes on the steel piles, or with wood screws for timber piles.

The Contractor shall provide the Engineer reasonable means of access to the pile for attaching instruments after the pile is placed in the leads. A platform with minimum size of 1.2 x 1.2 m (4 x 4 ft) designed to be raised to the top of the pile while the pile is located in the leads shall be provided by the Contractor. Alternatively, Contractor's personnel following the Engineer's instructions can attach the instruments to the pile after it is placed in the leads. It is estimated that approximately 1 hour per pile will be needed for instrument attachment and removal.

The Contractor shall furnish electric power for the dynamic test equipment. The power supply at the outlet shall be 10 amp, 115 volt, 55-60 cycle, A.C. only. Field generators used as the power source shall be equipped with functioning meters for monitoring voltage and frequency levels.

The Contractor shall furnish a shelter to protect the dynamic test equipment from the elements. The shelter shall have a minimum floor size of 2.5 x 2.5 m (8 x 8 ft) and minimum roof height of 2 m (6.5 ft). The inside temperature of the shelter shall be maintained above 45 degrees. The shelter shall be located within 15 m (50 ft) of the test location.

With the dynamic testing equipment attached, the Contractor shall drive the pile to the design penetration depth or to a depth determined by the Engineer. The Engineer will use the ultimate pile capacity estimates at the time of driving and/or restriking from dynamic test methods to determine the required pile penetration depth for the ultimate pile capacity. The stresses in the piles will be monitored during driving with the dynamic test equipment to ensure that the values determined do not exceed the values in Section XXX.03(B). If necessary, the Contractor shall reduce the driving energy transmitted to the pile by using additional cushions or reducing the energy output of the hammer in order to maintain stresses below the values in Section XXX.03(B). If non-axial driving is indicated by dynamic test equipment measurements, the Contractor shall immediately realign the driving system.

The Contractor shall wait up to 24 hours (or a longer duration specified in the contract documents) and restrike the dynamic load test pile with the dynamic testing instruments attached. It is estimated that the Engineer will require approximately 30 minutes to reattach the instruments. A cold hammer shall not be used for the restrike. The hammer shall be warmed up before restrike begins by applying at least 20 blows to another pile or to timber mats placed on the ground. The maximum amount of penetration required during restrike shall be 150 mm (6 inches), or the maximum total number of hammer blows required will be 50, whichever occurs first. After restriking, the Engineer will either provide the cutoff elevation or specify additional pile penetration and testing.

Commentary: *For purposes of measurement and payment one dynamic test includes all data collected on one pile during both the initial pile driving and a restrike done up to 24 hours after the initial driving. Additional long term restrikes*

should be paid for as separate tests unless the restrrike schedule is specifically stated in the dynamic test specification.

The restrrike time and frequency should be clearly stated in the specifications and should be based on the time dependent strength change characteristics of the soil. The following restrrike durations are often used:

| <u>Soil Type</u> | <u>Time Delay Until Restrike</u> |
|---------------------|----------------------------------|
| <i>Cleans Sands</i> | <i>1 Day</i> |
| <i>Silty Sands</i> | <i>2 Days</i> |
| <i>Sandy Silts</i> | <i>3-5 Days</i> |
| <i>Silty Clays</i> | <i>7-14 Days*</i> |
| <i>Shales</i> | <i>10-14 Days*</i> |

** - Longer times sometimes required.*

The restrrike time interval is particularly important when dynamic testing is used for construction control. Specifying too short of a restrrike time for friction piles in fine grained deposits may result in pile length overruns. However, it is sometimes difficult for long term restrikes to be accommodated in the construction schedule. In these cases, multiple restrikes are sometimes specified on selected piles with shorter term restrikes at other locations.

The time necessary to analyze the dynamic test results and provide driving criteria to the contractor once restrikes are completed should also be stated in the specifications. *This is important when the testing is done by agency personnel or their consultants as well as when the testing firm is retained by the contractor. In cases where the testing is retained by the contractor, the time required for the agency to review the test results and provide driving criteria should be specified relative to the agency's receiving the test results.*

3. **General:** On completion of the load testing, any test or anchor piling not a part of the finished structure shall be removed or cut off at least 300 mm (1 ft) below either the bottom of footing or the finished ground elevation, if not located within the footing area.
- C. Test Piles (Indicator Piles). Test piles shall be driven when shown on the plans at the locations and to the penetration depths specified by the Engineer. All test piles shall be driven with impact hammers unless specifically stated otherwise in the plans. In general, the specified length of test piles will be greater than the estimated length of production piles in order to provide for variation in soil conditions. The driving equipment used for driving test piles shall be identical to that which the Contractor proposes to use on the production piling. Approval of driving equipment shall conform with the requirements of these Specifications. The Contractor shall excavate the ground at each test pile to the elevation of the bottom of the footing before the pile is driven.

Test piles shall be driven to a driving resistance established by the Engineer at the estimated pile toe elevation. Test piles which do not attain the driving resistance specified above at a depth of 0.25 meter (1 ft) above the estimated pile toe elevation shown on the plans shall be allowed to "set up" for 12 to 24 hours, or as directed by the Engineer, before being redriven. A cold hammer shall not be used for redrive. The hammer shall be warmed up before driving begins by applying at least 20 blows to another pile. If the specified driving resistance is not attained on redriving, the Engineer may direct the Contractor to drive a portion or all of the remaining test pile length and repeat the "set up" redrive procedure. Test piles driven to plan grade and not having the driving resistance required, shall be spliced and driven until the required capacity is obtained.

A record of driving of the test pile will be prepared by the Engineer, including the number of hammer blows per 0.25 meter (1 ft) for the entire driven length, the as-driven length of the test pile, cutoff elevation, penetration in ground, and any other pertinent information. The Contractor shall provide the information listed in Figure 11.1 of Section XXX.03(B) to the Engineer for inclusion in the record. If a redrive is necessary, the Engineer will record the number of hammer blows per 25 mm (1 inch) of pile movement for the first 0.25 meter (1 ft) of redrive. The Contractor shall not order piling to be used in the permanent structure until test pile data has been reviewed and pile order lengths are authorized by the Engineer. The Engineer will provide the pile order list within 7 calendar days after completion of all test pile driving specified in the contract documents.

Commentary: *Test piles are recommended on projects where: 1) large quantities or long length of friction piling are estimated, even if load tests are to be used at adjacent footings; 2) large ultimate soil resistance is expected in relation to the design load and, 3) where concrete piles are used.*

- D. Ultimate Pile Capacity. Piles shall be driven by the Contractor to the penetration depth shown on the plans or to a greater depth if necessary to obtain the ultimate pile capacity. The ultimate pile capacity shall be determined by the Engineer based on one of the methods listed in Section XXX.04(A).

Jetting or other methods shall not be used to facilitate pile penetration unless specifically permitted in the contract plans or in writing by the Engineer. The ultimate pile capacity of jetted piles shall be based on driving resistances recorded during impact driving after the jet pipes have been removed. Jetted piles not attaining the ultimate pile capacity at the ordered length shall be spliced, as required, at the Contractor's cost, and driven with an impact hammer until the ultimate pile capacity is achieved, as indicated by the appropriate criteria in Section XXX.04(A).

The ultimate pile capacity of piles driven with followers shall only be considered acceptable when the follower driven piles attain the same pile toe elevation as the full length piles driven without followers, installed per Section XXX.03(C), which attained the required ultimate pile capacity.

The ultimate pile capacity of piles driven with vibratory hammers shall be based on the driving resistance recorded during impact driving after the vibratory equipment has been removed from the first pile in each group of 10 piles. Vibrated piles not attaining the ultimate pile capacity at the ordered length shall be spliced, as required, at the Contractor's cost, and driven with an impact hammer until the ultimate pile capacity is achieved, as indicated by the appropriate criteria in Section XXX.04(A). When the ultimate pile capacity is attained, the remaining 9 piles shall be installed to similar depths with similar vibratory hammer power consumption and rate of penetration as the first pile.

E. Preparation and Driving

1. **General:** The heads of all piles shall be plane and perpendicular to the longitudinal axis of the pile before the helmet is attached. The heads of all concrete piles shall be protected with a pile cushion as described in Section XXX.03(C).

During pile driving, the pile cushion shall be changed as described in Section XXX.03(C) before excessive compression or damage takes place. Approval of a pile hammer relative to driving stress damage shall not relieve the Contractor of responsibility for piles damaged because of misalignment of the leads, failure of cushion materials, failure of splices, malfunctioning of the pile hammer, or other improper construction methods. Piles damaged for such reasons shall be rejected and replaced at the Contractor's expense when the Engineer determines that the damage impairs the strength of the pile.

2. **Preboring:** Augering, wet-rotary drilling, or other methods of preboring shall be used only when approved by the Engineer or in the same manner as used for any indicator piles or load test piles. When permitted, such procedures shall be carried out in a manner which will not impair the capacity of the piles already in place or the safety of existing adjacent structures.

Except for end bearing piles, preboring shall be stopped at least 1.5 m (5 ft) above the pile toe elevation, determined from the ordered length and the pile shall be driven with an impact hammer to a driving resistance specified by the Engineer. Where piles are to be end-bearing on rock or hardpan, preboring may be carried to the surface of the rock or hardpan, and the piles shall be restruck with an impact hammer to insure proper seating.

If the Engineer determines that preboring has disturbed the capacities of previously installed piles, those piles that have been disturbed shall be restored to conditions meeting the requirements of this specification by re-driving or by other methods acceptable to the Engineer. Redriving or other remedial measures shall be instituted after the preboring operations in the area have been completed. The Contractor shall be responsible for the costs of any necessary remedial measures, unless the preboring method was specifically included in the contract documents and properly executed by the Contractor.

3. **Location and Alignment Tolerance:** The pile head at cutoff elevation shall be within 50 mm (2 inches) of plan locations for bent caps supported by piles, and shall be within 150 mm (6 inches) of plan locations for all piles capped below final grade. The as-driven centroid of load of any pile group at cutoff elevation shall be within 5% of the plan location of the designed centroid of load. No pile shall be nearer than 100 mm (4 inches) from any edge of the cap. Any increase in size of cap to meet this edge distance requirement shall be at the Contractor's expense.

Piles shall be installed so that the axial alignment of the top 3 m (10 ft) of the pile is within 2% of the specified alignment. For piles that cannot be inspected internally after installation, an alignment check shall be made before installing the last 1.5 m (5 ft) of pile, or after installation is completed provided the exposed portion of the pile is not less than 1.5 m (5 ft) in length. The Engineer may require that driving be stopped in order to check the pile alignment. Pulling laterally on piles to correct misalignment, or splicing a properly aligned section on a misaligned section shall not be permitted.

If the location and/or alignment tolerances specified in the preceding paragraphs are exceeded, the extent of overloading shall be evaluated by the Engineer. If in the judgment of the Engineer, corrective measures are necessary, suitable measures shall be designed and constructed by the Contractor. The Contractor shall bear all costs, including delays, associated with the corrective action.

Commentary: *Conditions exist, such as soft overburden soils directly overlying a sloping bedrock, where final pile location and/or alignment may be beyond the contractor's control. These cases should be identified during the design stage with specifications tailored to meet the site and project requirements.*

4. **Heaved Piles:** Level readings to measure pile heave after driving shall be made by the Engineer at the start of pile driving operations and shall continue until the Engineer determines that such checking is no longer required. Level readings shall be taken immediately after the pile has been driven and again after piles within a radius of 5 m (16 ft) have been driven. If pile heave is observed, accurate level readings referenced to a fixed datum shall be taken by the Engineer on all piles immediately after installation and periodically thereafter as adjacent piles are driven to determine the pile heave range. All piles that have been heaved more than 6 mm (0.25 in) shall be redriven to the required resistance or penetration.

Concrete shall not be placed in pile casings until pile driving has progressed beyond a radius of 5 m (16 ft) from the pile to be concreted. If pile heave is detected for pipe or shell piles which have been filled with concrete, the piles shall be redriven to original position after the concrete has obtained sufficient strength and a proper hammer-pile cushion system, satisfactory to the Engineer, is used. All work performed in conjunction with redriving piles due to pile heave shall be paid for by the Department provided the initial driving was done in accordance with the specified installation sequence.

5. **Obstructions:** If piles encounter unforeseeable, isolated obstructions, the Department shall pay for the cost of obstruction removal and for all remedial design or construction measures caused by the obstruction.
6. **Installation Sequence:** The order of placing individual piles in pile groups shall be either starting from the center of the group and proceeding outwards in both directions or starting at the outside row and proceeding progressively across the group.
7. **Practical and Absolute Refusal:** Practical refusal is defined as 20 blows per 25 mm of penetration (20 blows per inch) with the hammer operated at its maximum fuel or energy setting, or at a reduced fuel or energy setting recommended by the Engineer based on pile installation stress control. In no case should driving continue for more than 75 mm (3 inches) at practical refusal driving conditions.

Absolute refusal is defined as a penetration resistance 50% greater than that of practical refusal, i.e. 30 blows per 25 mm (30 blows per inch). Driving should be terminated immediately once absolute refusal driving conditions are encountered.

- F. Unsatisfactory Piles. The method used in driving piles shall not subject the piles to excessive or undue abuse producing crushing and spalling of concrete, injurious splitting, splintering, and brooming of the wood, or deformation of the steel. Misaligned piles shall not be forced into proper position. Any pile damaged during driving by reason of internal defects, or by improper driving, or driven out of its proper location, or driven below the designated cutoff elevation, shall be corrected by the Contractor, without added compensation, by a method approved by the Engineer.

Commentary: *The following procedures may be used to correct unsatisfactory pile conditions:*

- 1. The pile may be withdrawn and replaced by a new and, when necessary, longer pile. In removing piles, jets may be used in conjunction with jacks or other devices for pulling in an effort to remove the whole pile.*
- 2. A second pile may be driven adjacent to the defective pile.*
- 3. The pile may be spliced or built up as otherwise provided herein, or a sufficient portion of the footing extended to properly embed the pile.*
- 4. All piles pushed up by the driving of adjacent piles, or by any other cause, shall be redriven.*

Piles which have been bent during installation shall be considered unsatisfactory unless the ultimate capacity is proven by load tests performed at the Contractor's expense. If such tests indicate inadequate capacity, corrective measures as determined by the Engineer shall be taken, such as use of bent piles at reduced capacity, installation of additional piles, strengthening of bent piles, or replacement of bent piles.

A concrete pile will be considered defective if a visible crack, or cracks, appears around the entire periphery of the pile, or if any defect is observed which, as determined by the Engineer, affects the strength or life of the pile.

G. Splices. Full length piles shall always be used where practical. In no case shall timber piles be spliced. Where splices are unavoidable for steel or concrete piles, their number, locations and details shall be subject to approval of the Engineer. Splices in steel piles and steel pile casings shall be welded in conformance with Section XXX. Splices for cast in place piles shall be watertight. Splices for concrete piles shall be made by the cement dowel method as detailed on the plans unless the Engineer approves alternate splices. Mechanical splices for concrete or steel piles may be approved by the Engineer if the splice can transfer the full pile strength in compression, tension and bending. Shop drawings of any proposed mechanical splice shall be submitted to the Engineer for approval.

H. Pile Shoes. Pile shoes of the type and dimensions specified shall be provided and installed when shown on the contract plans. Shoes for timber piles shall be metal and shall be fastened securely to the pile. Timber pile toes shall be carefully shaped to secure an even uniform bearing on the pile shoe. Steel pile shoes shall be fabricated from cast steel conforming to ASTM A 27.

Commentary: *H-pile shoes composed of steel plates welded to the flanges and webs are not recommended because this reinforcement provides neither protection nor increased strength at the critical area of the flange to web connection. Only prefabricated pile shoes made of ASTM A 27 cast steel have been proven reliable. The designer should select and detail on the plans the proper pile shoe to suit the application. Additional information on pile shoes is presented in Chapter 22 of this manual.*

I. Cutoff Lengths. The pile head of all permanent piles and pile casings shall be cutoff at the elevation shown on the plans or as ordered by the Engineer. All cutoff lengths shall become the property of the Contractor, and shall be removed by the Contractor from the site of the work.

Commentary: *Additional structural details for timber, steel, concrete and cast in place piles should be included by each agency in this driven pile specification, either directly or by reference to appropriate sections of the individual agency's standard specification. Typical items include: timber pile butt treatment and preservative treatment; precast concrete pile reinforcement, forming, casting, curing, and handling; steel pile field painting; cast in place pile details for shell, interior reinforcement and concrete.*

SECTION XXX.05. METHOD OF MEASUREMENT

A. Timber, Steel, and Precast Concrete Piles

1. **Piles Furnished:** The unit of measurement for payment for furnishing timber, steel, and precast concrete piles shall be the linear meter. The quantity to be paid for will be the sum of the lengths in meters of the piles, of the types and lengths ordered in writing by the Engineer, furnished in compliance with the material requirements of these specifications, stockpiled in good condition at the site of the work by the Contractor, and accepted by the Engineer. No allowance will be made

for that length of piles, including test piles, furnished by the Contractor to replace piles which were previously accepted by the Engineer, but are subsequently damaged prior to completion of the contract.

When extensions of piles are necessary, the extension length ordered in writing by the Engineer will be included in the linear meters of piling furnished.

2. **Piles Driven:** The units of measurement for driving timber, steel, and precast concrete piles shall be per linear meter (linear ft) of piling in place measured below the cutoff elevation. The measured length will be rounded to the nearest meter. Preboring, jetting or other methods used for facilitating pile driving procedures will not be measured and payment shall be considered included in the unit price bid for the Piles Driven pay item.

- B. Cast in Place Pipe or Shell Concrete Piles. The quantity of cast in place pipe or shell concrete piles to be paid for will be the actual number of linear meters (linear ft) of steel pipe or shell piles driven, cast, and left in place in the completed and accepted work. Measurements will be made from the toe of the steel pipe or shell pile to the bottom of the cap or bottom of the footing, as the case may be.

No separate measurement will be made for reinforcing steel, excavation, drilling, cleaning of drilled holes, drilling fluids, sealing materials, concrete, casing, and or any other items required to complete the work. Preboring, jetting or other methods used for facilitating pile driving procedures will not be measured and payment shall be considered included in the unit price bid for the driven and cast in place pay item.

- C. Pile Shoes. The number of pile shoes measured for payment shall be those shoes actually installed on piles and accepted for payment by the Engineer.

- D. Load Tests. The quantity of load tests to be paid for will be the number of load tests completed and accepted, except that load tests made at the option of the Contractor will not be included in the quantity measured for payment.

Reaction and test piling which are not a part of the permanent structure will be included in the unit price bid for each load test. Reaction and test piling, which are a part of the permanent structure, will be paid for under the appropriate pay item.

- E. Splices. The number of splices measured for payment shall be only those splices actually made as required to drive the piles in excess of the ordered length furnished by the Engineer.
- F. Furnishing Equipment for Driving Piles. Payment will be made at the lump sum price bid for this item as follows: Seventy-five percent (75%) of the amount bid will be paid when the equipment for driving piles is furnished and driving of satisfactory piles has commenced. The remaining 25% will be paid when the work of driving piles is completed. The lump sum price bid shall include the cost of furnishing all labor, materials and equipment necessary for transporting, erecting, maintaining, replacing any ordered equipment, dismantling and removing of the entire pile driving equipment. The cost of all labor, including the manipulation of the pile driving equipment and materials in connection with driving piles, shall be included in the unit price bid per linear meter for the piles to be driven. The furnishing of equipment for driving sheet piling is not included in this work. Payment for furnishing and using a follower, augers or jetting will be considered as included in the unit price bid for piles.

SECTION XXX.06 BASIS OF PAYMENT

The accepted quantities, determined as provided above, will be paid for at the contract price per unit of measurement, respectively, for each of the particular pay items listed below that is shown in the bid schedule, which prices and payment will be full compensation for the work prescribed in this section. Payment will be made under:

| Pay Item | Pay Unit |
|---|----------------------------|
| XXX(1) ____ piles, furnished | Linear meter (linear foot) |
| XXX(2) ____ piles, driven | Linear meter (linear foot) |
| XXX(3) ____ piles, driven & cast in place | Linear meter (linear foot) |
| XXX(4) ____ test piles, furnished | Linear meter (linear foot) |
| XXX(5) ____ test piles, driven | Linear meter (linear foot) |
| XXX(6) ____ test piles, driven & cast in place | Linear meter (linear foot) |
| XXX(7) Pile load test (static) | Each |
| XXX(8) Pile load test (rapid) | Each |
| XXX(9) Pile load test (dynamic) | Each |
| XXX(10) Splices | Each |

| | | |
|---------|---------------------------------------|------|
| XXX(11) | Pile Shoes | Each |
| XXX(12) | Furnishing Equipment for Pile Driving | Each |

Commentary: *The above pile payment items have been chosen to separate the major fixed costs from the variable costs. Many highway agencies oversimplify pile payment by including all costs associated with the driving operation in the price per meter of pile installed. Contractors bidding such "simple" items need to break down the total cost of the mobilization, splices, shoes, etc., to a price per linear meter (linear ft) based on the total estimated quantity. If that quantity underruns, the contractor does not recover the full cost of mobilization, splices, shoes, etc. If that quantity overruns, the highway agency pays an unfair price for the overrun quantity. The use of separate items for operations of major fixed cost such as mobilization can substantially mitigate the inequitable impact of length variations. Similarly, the ordered pile length is the highway agency's responsibility. Separate payment for furnishing piles and driving piles compensates the contractor for actual materials used and installation costs, even when overruns or underruns occur.*

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Chapter 12

PILE FOUNDATION DESIGN SUMMARY

12.1 INTRODUCTION

In this chapter, the total design process will be reviewed. However, this time the design process will be illustrated through a proposed bridge construction project. A condensed version of the Foundation Design Process flow chart presented in Figure 2.1 is repeated for convenience here as Figure 12.1. The proposed project is a bridge that will carry the imaginary Peach Freeway over Dismal Creek. This is a new freeway that is to be built in a city in the southeastern part of the United States. The alignment of the roadway has been defined and the foundation design now comes into consideration. The design process will be followed using Figure 12.1.

12.2 BLOCK 1 - ESTABLISH GLOBAL PROJECT PERFORMANCE

The general structure requirements will now be reviewed following the list from Chapter 2, Section 2.4.

1. The project is a new bridge.
2. The structure will be constructed at one time by a single contract.
3. The structure layout has not been finalized at the time that the foundation engineer first becomes involved. The alignment is quite well defined but the grades have not been established.
4. The foundation engineer has briefly visited the proposed site. Dismal Creek is a flat, shallow stream that, at low water, is more than 30 meters (98 ft) wide in the vicinity of the proposed bridge. At the north end of the structure there is a bank about eight meters high while on the south end the bank slopes up quite slowly. The new bridge will probably be about 80-100 meters (262-328 ft) long with an approach embankment required for the south approach. Bridge piers will probably be located in Dismal Creek.

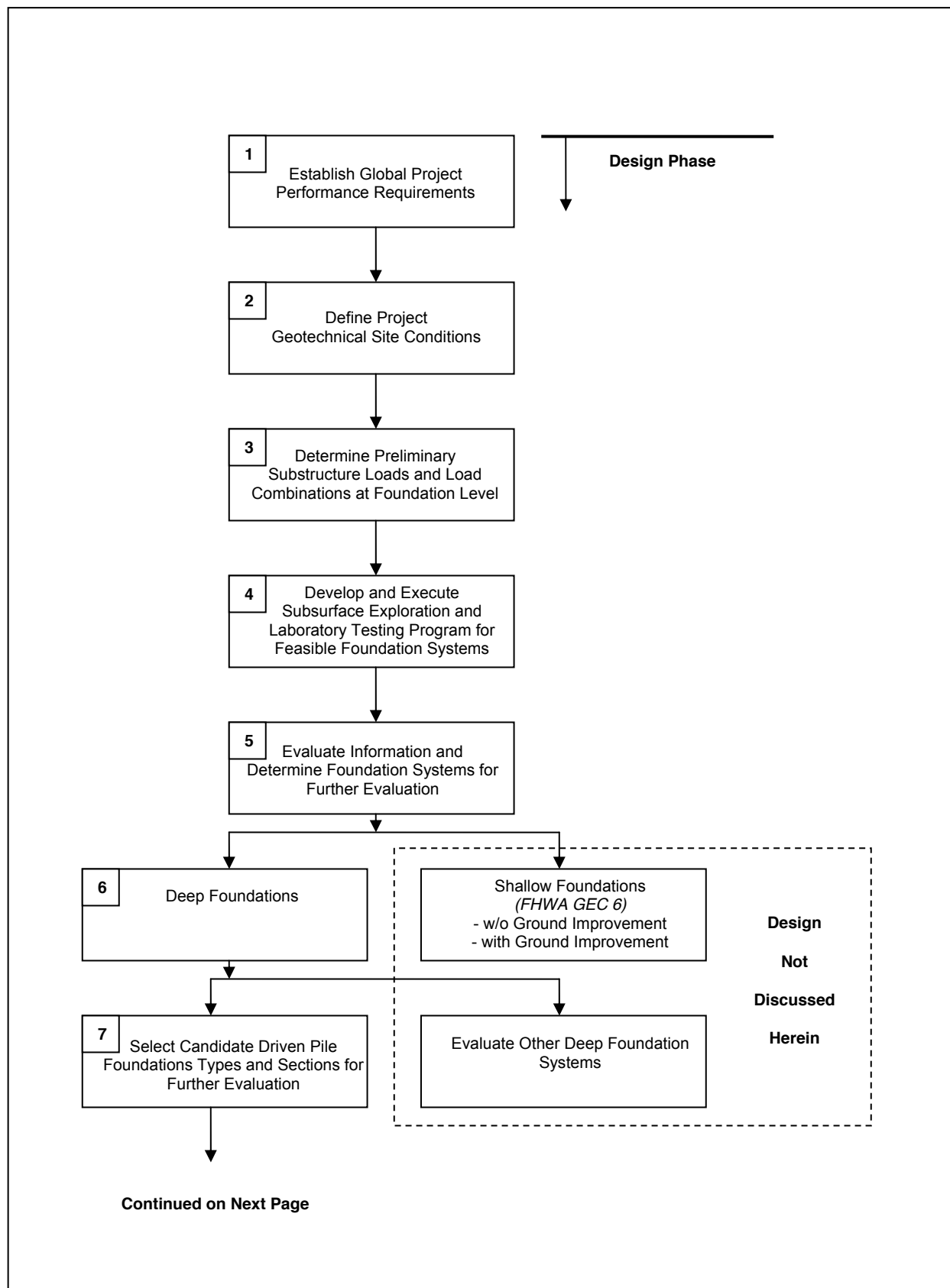


Figure 12.1 Driven Pile Design and Construction Process

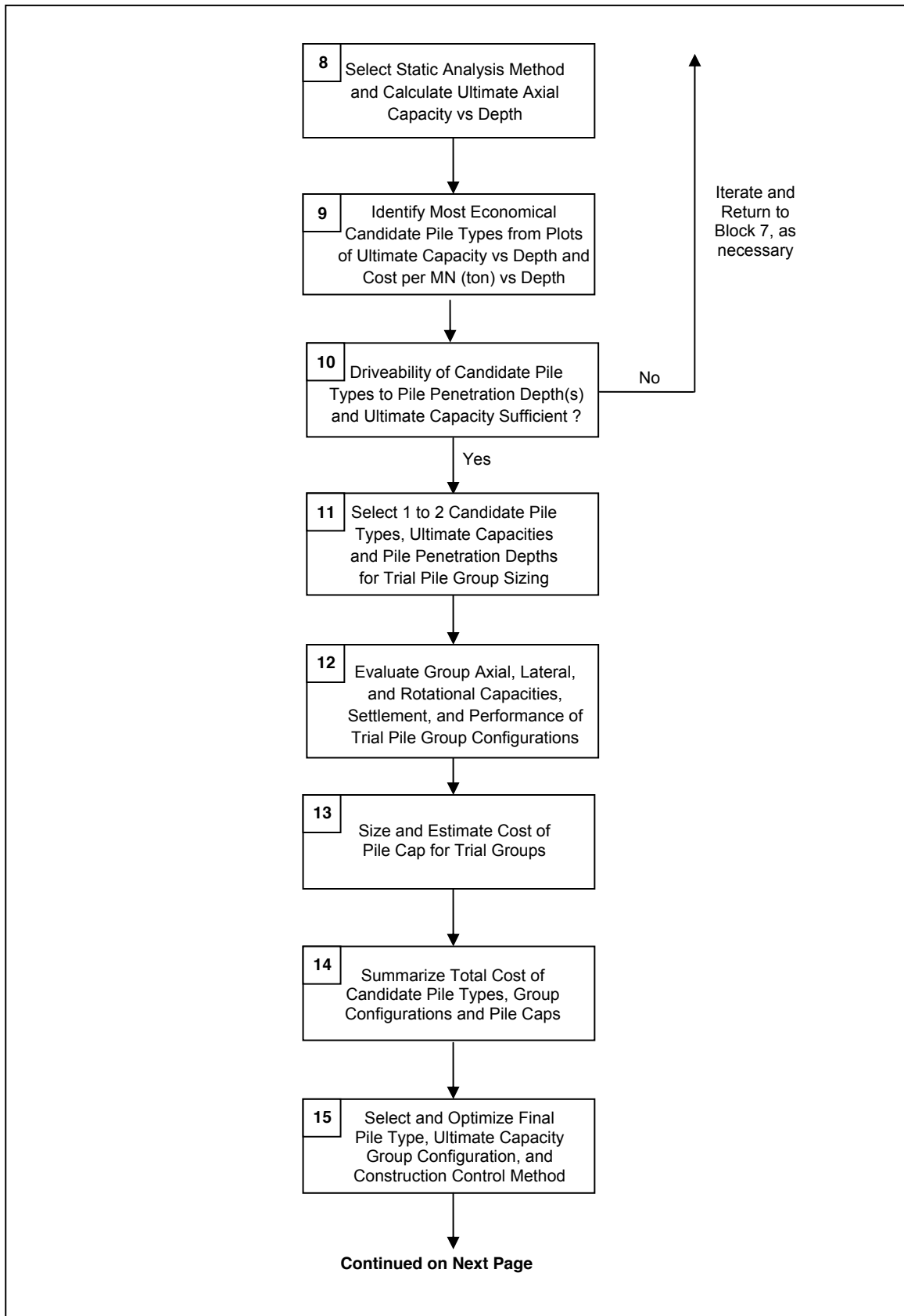


Figure 12.1 Driven Pile Design and Construction Process (continued)

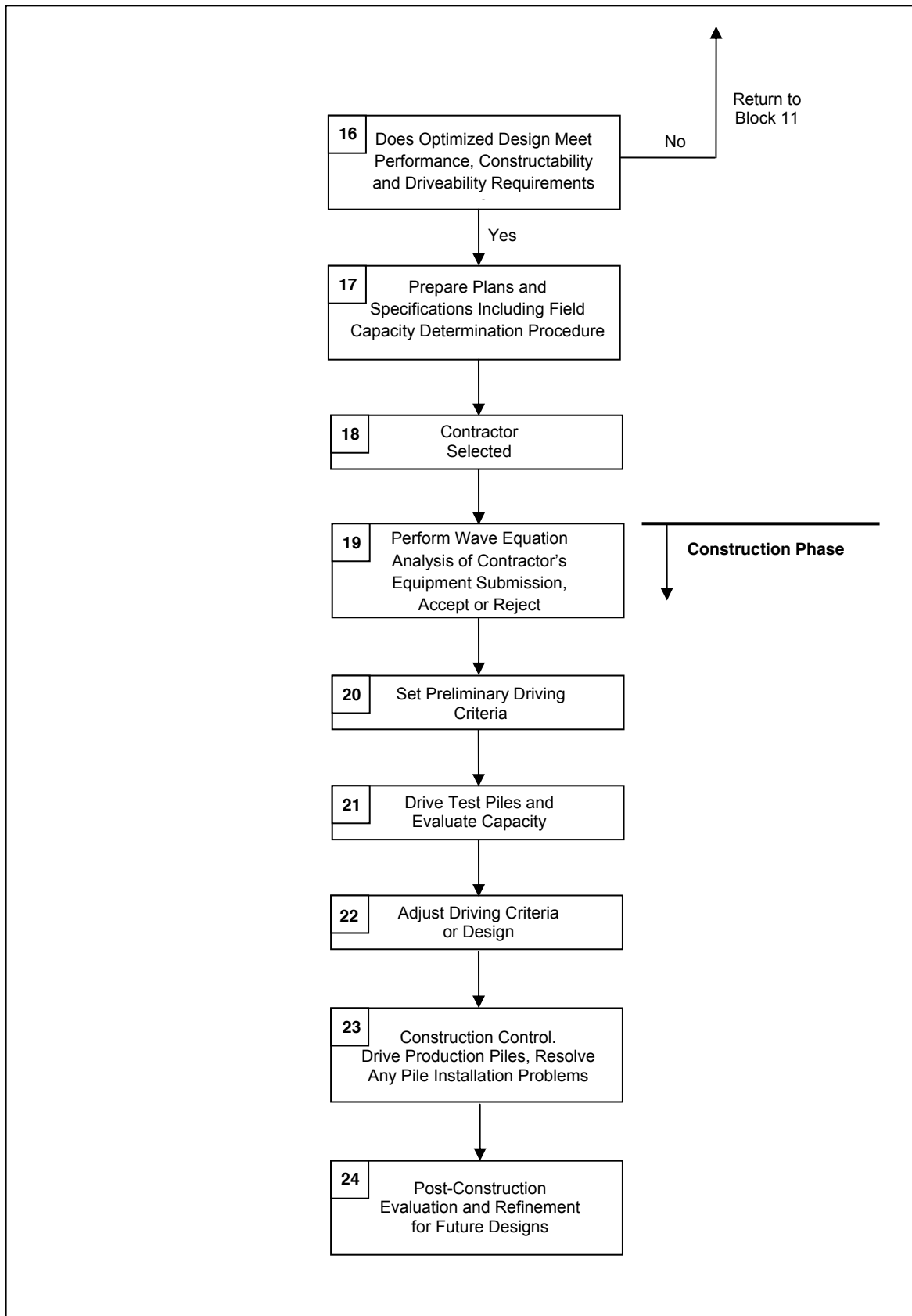


Figure 12.1 Driven Pile Design and Construction Process (continued)

5. Seismic and vessel impact loads are not a design consideration. However, scour and debris loading must be considered for the bridge piers.
6. As yet the structure is not sufficiently defined to consider modifications in the structure due to site considerations.
7. Foundation loads cannot be estimated very accurately at this time. A meeting with the bridge engineer indicates that, based on his experience, compression loads on the order of 10,000 to 15,000 kN (2248 to 3372 kips) per substructure location are likely. Typical deflection and deformation requirements are anticipated.
8. There are no special environmental conditions that must be considered in the design.

12.3 BLOCK 2 – DEFINE PROJECT GEOTECHNICAL SITE CONDITIONS

Published data from the sources listed in Table 4-2 has been reviewed in the office planning stage. Geologists have also been contacted to provide information regarding the site geology. At first glance, an extensive subsurface exploration would probably not be required for this modest sized structure. However, a field reconnaissance survey of the area has been made by the foundation engineer and the project bridge engineer. Field observations of the eroded stream banks indicated that the surficial soils on the north side of Dismal Creek consist of silty sands while silty clays were noted in the south stream bank. The granular upland soils on the north approach and the cohesive lowland soils on the south approach further suggest that the subsurface conditions may be quite complex. Therefore, it would be desirable that fairly extensive subsurface exploration be made. The foundation engineer expected the site to be underlain by limestone bedrock at a depth of 30 to 50 meters (98 to 164 ft), based on previous experience.

Agency files have been reviewed to determine if there are any existing soil borings in the area of the proposed bridge site. However, no previous subsurface information has been located. There are also no existing bridges in the vicinity of the planned structure to provide details on subsurface conditions or previous construction information and/or problems.

12.4 BLOCK 3 – DETERMINE PRELIMINARY FOUNDATION LOADS AT THE SUBSTRUCTURE LEVEL

Preliminary substructure loads and reasonable vertical and lateral deformation requirements are now available. Accurate load information and performance criteria are essential to the development and implementation of an adequate subsurface exploration program for the structure. The total axial compression loads have been established at 12,600 kN (2,830 kips) per substructure location. Other load conditions that include several combinations of axial and transverse loads result in axial compression, uplift, lateral, and moment loads at each substructure unit. These load combinations are too extensive to be repeated here. However, the lateral loads will range from 600 kN (135 kips) at the interior piers to 900 kN (202 kips) at the abutments. Maximum uplift loads on a pile group will be less than 1800 kN (405 kips).

The foundation performance requirements have also been established. Maximum pile group settlements less than 25 mm (1 inch) are required under the compression loads with maximum differential settlements between substructure units of 15 mm (0.60 inch). Maximum horizontal deflections of up to 10 mm (0.40 inch) are permissible under lateral loading.

12.5 BLOCK 4 - DEVELOP AND EXECUTE SUBSURFACE EXPLORATION PROGRAM FOR FEASIBLE FOUNDATION SYSTEMS

Based on the information generated in Blocks 1 to 3, a subsurface exploration program was planned. The foundation engineer requested that the bridge engineer provide additional information on the planned structural configuration. Since some time had elapsed since the initial discussions regarding the proposed structural configuration, it was possible to better define the structure geometry. The proposed bridge will be supported at two abutments and two interior piers. Due to the possibly complex subsurface conditions, both a soil boring and an in-situ cone penetration test will be performed at each substructure location.

The subsurface program was performed and results of the exploration are included in Appendix E. This data was evaluated and a subsurface profile was prepared and is given in Figure 12.2.

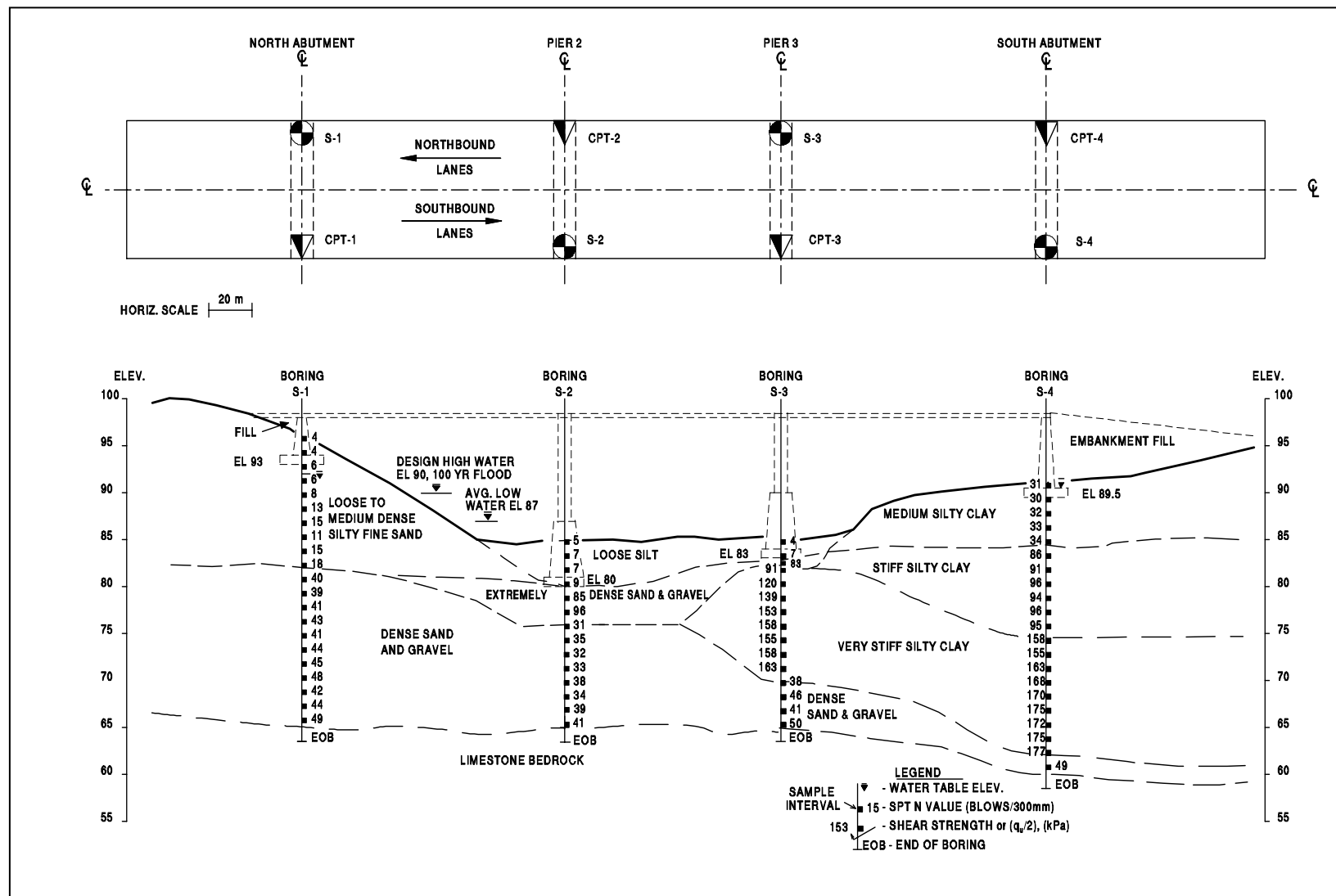


Figure 12.2 Peach Freeway Subsurface Profile.

12.6 BLOCK 5 - EVALUATE INFORMATION AND SELECT CANDIDATE FOUNDATION SYSTEMS FOR FURTHER EVALUATION

A decision must now be made regarding candidate foundation systems that will be evaluated. First, the foundation engineer met again with the bridge engineer to verify the final design loads and foundation locations. It was determined that the foundations will be located as anticipated at the last meeting. The Peach Freeway Bridge over Dismal Creek will be a three span structure supported at North and South Abutments and interior piers, Pier 2 and Pier 3. At the proposed bridge location, the only extreme event that must be considered is scour. The bridge is not in a region where seismic loads will influence the design and vessel impact is not a design consideration. Lateral loads will be induced by stream debris.

A hydraulics division study indicates that a shallow foundation should not be used under the two piers due to scour. In addition, settlement of a shallow foundation at Pier 3 is expected to be excessive. Therefore, the use of a shallow foundation was ruled out and a deep foundation will be required.

12.7 BLOCK 6 - DEEP FOUNDATION TYPE

A decision must now be made between the use of driven piles, drilled shafts, micropiles, or auger cast piles. Both driven piles and drilled shafts are commonly used in the region. A cost evaluation indicates that a driven pile option will be the most economical deep foundation type because of the complex subsurface conditions. Therefore, a driven pile foundation system is selected.

12.8 BLOCK 7 - SELECT CANDIDATE DRIVEN PILE TYPES AND SECTIONS FOR FURTHER STUDY

Five candidate pile types suitable for the subsurface conditions and loads are now chosen for further evaluation. The candidate pile types selected are 356 mm (14 inch) and 457 mm (18 inch) precast, prestressed concrete piles, 406 mm (16 inch) and 457 mm (18 inch) O.D. closed-end steel pipe piles, and a HP 360 x 152 (HP 14x102) H-pile.

12.9 BLOCK 8 - SELECT STATIC ANALYSIS METHOD AND CALCULATE ULTIMATE CAPACITY VERSUS DEPTH

Static pile capacity calculations have been performed for each candidate pile section to determine the ultimate capacity versus pile penetration depth at each substructure unit (*i.e.*, North Abutment, Pier 2, Pier 3, and South Abutment). The static analyses were performed using applicable static analysis methods for the candidate pile types and the subsurface conditions at each substructure location. Static analysis procedures are presented in Chapter 9.

12.10 BLOCK 9 – IDENTIFY MOST ECONOMICAL CANDIDATE PILE TYPES AND/OR SECTIONS

Pile support cost versus depth plots are now developed for each candidate pile type. The pile support cost in dollars per kN (ton) supported versus pile penetration depth plots are obtained by dividing the ultimate pile capacity at a given depth by the pile cost to reach that depth. Details of this process are presented in Chapter 3. Based on the pile support cost evaluations, 356 mm (14 inch) concrete piles appear the most cost effective pile type and section.

12.11 BLOCK 10 - CALCULATE DRIVEABILITY OF CANDIDATE PILE TYPES

The driveability of each candidate pile type, section(s) and lengths for the required ultimate pile capacity must now be evaluated using a wave equation program analysis. The soil resistance versus depth has been calculated for each substructure location using the DRIVEN program and then input into a wave equation program. Details on the DRIVEN program are given in Chapter 9 and the wave equation is presented in Chapter 16 of Volume II.

At this stage, driveability analysis results indicate that the proposed 356 mm (14 inch) concrete piles would work well at the abutments. Sample input and output screens for the North and South Abutments are shown in Appendices F.9.1 and F.9.4. Wave equation driveability studies in the North Abutment show penetration resistance with an assumed air hammer reach 111 blows per 0.25 m at the final penetration of 14.5 m below the surface.

Compression stresses reach 13.7 MPa and tension stresses reach 3 MPa. These stresses and the predicted penetration resistance are with FHWA recommended limits.

At the South Abutment, the predicted penetration resistance is predicted to reach 23 blows per 0.25 m at the end of driving if the hammer is run at full stroke. This value is lower than the FHWA required 25 blows per 0.25 m. If the hammer is equipped with and operated at a short stroke setting, the pile penetration resistance will be higher and acceptable. Stresses in compression and tension when driving at full stroke reach 13.4 and 5.7 MPa, both within recommended limits.

At the interior piers, however, the driveability of the concrete displacement piles through the extremely dense sand and gravel layer may be quite difficult. The driveability results at Pier 2 are presented and discussed in greater detail in Section 16.5.5. More complete input and output results of the driveability studies of Pier 2 and Pier 3 are included in Appendices F.9.2 and F.9.3, respectively. These results indicate concrete displacement piles would like encounter refusal driving conditions when penetrating the extremely dense sand and gravel layer. The driveability of the candidate pipe pile sections is worse since these piles have similar soil resistances to overcome but have a reduced pile impedance compared to the 356mm (14 inch) concrete pile. Therefore, the low displacement H-pile, may be necessary at the interior piers to meet pile penetration requirements dictated by scour. The HP 360 x 152 (14 x 102) H-pile section has a predicted penetration resistance of 31 blows/0.25 m at end of drive in Pier 2 and 21 blows/0.25 m in Pier 3. If the air hammer is equipped with and operated at a short stroke setting, the FHWA minimum pile penetration resistance requirements will be met in Pier 3. Compressive stresses in Piers 2 and 3 will reach 149 and 163 MPa, respectively.

Based on the driveability analysis results and earlier cost evaluations, both pipe pile sections and the 457 mm (18 inch) precast, prestressed concrete pile have been dropped from further evaluation.

12.12 BLOCK 11 – SELECT 1 TO 2 FINAL CANDIDATE PILE TYPES FOR TRIAL GROUP SIZING

The most viable candidate pile types and/or sections from the cost and driveability evaluations in Blocks 9 and 10 are now evaluated for trial group sizing using the final loads and performance requirements. The remaining candidate pile types are the 356 mm (14

inch) precast, prestressed concrete pile and the HP 360 x 152 (HP 14x102) H-pile. Multiple pile penetration depths and the resulting ultimate capacity at those depths are used to establish multiple trial pile group configurations for each the two remaining candidate pile types. Trial pile group sizing and configurations are discussed in Chapter 10. The trial group configurations are carried forward to Block 13.

12.13 BLOCK 12 - EVALUATE CAPACITY, SETTLEMENT, AND PERFORMANCE OF TRIAL PILE GROUPS

Trial group configurations for the two remaining candidate pile type are now evaluated for axial group capacity, group uplift, group lateral load performance, and settlement. These computations and analysis procedures are described in Chapter 9. Block 15 discusses these computations for the final pile type.

12.14 BLOCK 13 - SIZE AND ESTIMATE PILE CAP COST FOR TRIAL PILE GROUPS

The size and thickness of the pile cap for each trial group is now evaluated and the cost of the resulting pile cap is estimated. It is not necessary to design the cap reinforcement at this time only to determine cap size. Pile cap cost is a key component in selecting the most cost effective pile type and must not be overlooked. A procedure for preliminary sizing of pile caps is provided in Chapter 10.

12.15 BLOCK 14 - SUMMARIZE TOTAL COST OF FINAL CANDIDATE PILES

The total cost of the two remaining candidate pile types should now be determined. A given pile type may have several total cost options depending upon the pile penetration depths, ultimate capacities, group configurations, and pile cap sizes carried through the design process. The cost of any special construction considerations and environmental restrictions should also be included in the total cost for each final candidate pile type. An example of the cost optimization process for a single pile section is presented in Chapter 3. Based on the cost optimization process, the 356 mm (14 inch) precast, prestressed concrete piles are selected for final design.

12.16 BLOCK 15 – SELECT AND OPTIMIZE FINAL PILE TYPE, CAPACITY AND GROUP CONFIGURATION

Based on all of the available information, it is now time to select the final pile type as well as optimize the number of piles and pile group configuration. The selected pile type and section is the 356 mm (14 inch) precast, prestressed, concrete pile. The optimized pile group design consists of 24 piles arranged in three rows of eight piles each at each substructure location. The maximum compressive design load is 890 kN, the design uplift load is 100 kN, and the maximum lateral load is 40 kN per pile. A complete evaluation of the group lateral and rotational resistance should also be performed at this time. This final design should be optimized for final structure loads, performance requirements, and construction efficiency.

12.16.1 Single Pile Capacity

Construction control procedures have been selected that will make a factor of safety of 2.0 appropriate. Therefore, an ultimate axial capacity of 1780 kN (400 kips) is required. At Piers 2 and 3, the effect of scour on the static axial capacity should also be calculated. Static capacity calculation details are given in Appendix F (including the scour calculation at Pier 2) and summaries of the calculations are provided in Tables 12-1 to 12-4.

The capacity calculation summaries indicate different static analysis methods will yield different results. Therefore, designers should use a method they fully understand, including the method limitations. Based upon the analyses performed, pile penetration lengths of 11.5 m (38 ft) are selected for the North Abutment, 14 m (46 ft) for Pier 2 (after scour), 13 m (43 ft) for Pier 3 (total stress α -method so scour effect limited) and 21 m (69 ft) for the South Abutment (17.5 m (58 ft) if drag load not considered).

12.16.2 Pile Group Capacity

The North Abutment piles will be driven into a dense cohesionless soil at center to center pile spacings greater than 4 diameters. Therefore, the ultimate pile group capacity for the North Abutment may be taken as the sum of the ultimate capacities of the individual piles in the group as discussed in Section 9.8.1.1. Similarly, the Pier 2 piles will be driven into a dense cohesionless soil at center to center pile spacings greater than 4 diameters. Therefore, the ultimate pile group capacity at Pier 2 may also be taken as the sum of the ultimate capacities of the individual piles in the group.

At Pier 3, the piles will be driven through cohesive soils and into a dense cohesionless layer at center to center pile spacings of 4 diameters. Since the piles will be founded in a dense cohesionless layer, the pile group capacity should be equal to the sum of the ultimate capacities of the individual piles in the group. However, the possibility of block failure should be checked in accordance with the procedures detailed in Section 9.8.1.3 particularly if the dense layer is underlain by a weaker deposit.

| TABLE 12-1(a) NORTH ABUTMENT PILE CAPACITY SUMMARY FOR 11.5 m PILE EMBEDMENT | | | |
|--|---------------------------------------|-------------------------------------|--|
| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
| Meyerhof Method - SPT Data | 418 | 854 | 1,272 |
| Nordlund Method - SPT Data | 898 | 940 | 1,838 |
| Effective Stress Method - SPT Data | 537 | 1,294 | 1,831 |
| Driven Program – SPT Data | 920 | 920 | 1,840 |
| LPC CPT Program - CPT Data | 780 | 511 | 1,291 |
| Schmertmann Method - CPT Data | 604 | 1,111 | 1,715 |

1 kip = 4.448 kN

| TABLE 12-1(b) NORTH ABUTMENT PILE LENGTH SUMMARY FOR A 1,780 kN ULTIMATE PILE CAPACITY | |
|--|--|
| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
| Meyerhof Method - SPT Data | 13.0 meters for 1,840 kN |
| Nordlund Method - SPT Data | 11.5 meters for 1,838 kN |
| Effective Stress Method | 11.5 meters for 1,831 kN |
| Driven Program - SPT Data | 11.5 meters for 2,145 kN |
| LPC CPT Program - CPT Data | 13.5 meters for 1,815 kN |
| Schmertmann Method - CPT Data | 11.7 meters for 1,939 kN |

1 ft = 0.305 m, 1 kip = 4.448 kN

| TABLE 12-2(a) PIER 2 PILE CAPACITY SUMMARY FOR 10.0 m PILE EMBEDMENT | | | |
|--|--|--|---|
| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
| Meyerhof Method - SPT Data | 1,134 | 1,676 | 2,810 |
| Nordlund Method - SPT Data | 984 | 854 | 1,838 |
| Effective Stress Method | 451 | 1,155 | 1,606 |
| Driven Program - SPT Data | 994 | 878 | 1,873 |

1 kip = 4.448 kN

| TABLE 12-2(b) PIER 2 PILE LENGTH SUMMARY FOR A 1,780 kN ULTIMATE PILE | |
|---|---|
| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
| Meyerhof Method - SPT Data | 1.0 meters for 2,136 kN |
| Nordlund Method - SPT Data | 10.0 meters for 1,838 kN |
| Effective Stress Method | 12.5 meters for 1,847 kN |
| Driven Program - SPT Data | 10.0 meters for 1,873 kN |

1 ft = 0.305 m, 1 kip = 4.448 kN

| TABLE 12-2(c) PIER 2 PILE CAPACITY SUMMARY BEFORE AND AFTER CHANNEL DEGRADATION SCOUR BASED ON NORDLUND METHOD | | |
|--|------------------------|-------------|
| Pile Embedment | Ultimate Pile Capacity | |
| | Before Scour | After Scour |
| 10 meters | 1,838 kN | 1,347 kN |
| 14 meters | 2,331 kN | 1,887 kN |

1 ft = 0.305 m, 1 kip = 4.448 kN

| TABLE 12-3(a) PIER 3 PILE CAPACITY SUMMARY FOR 13.0 m PILE EMBEDMENT | | | |
|--|--|--|---|
| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
| Nordlund and α Method - SPT Data | 1,171 | 635 | 1,806 |
| Effective Stress Method | 525 | 1,059 | 1,584 |
| Driven Program - SPT Data | 1,345 | 920 | 2,265 |
| LPC CPT Program - CPT Data | 1,189 | 841 | 2,030 |
| Schmertmann Method - CPT Data | 1,727 | 1,231 | 2,958 |

1 ft = 0.305 m, 1 kip = 4.448 kN

| TABLE 12-3(b) PIER 3 PILE LENGTH SUMMARY FOR A 1,780 kN ULTIMATE PILE CAPACITY | |
|---|---|
| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
| Nordlund and α Method - SPT Data | 13.0 meters for 1,806 kN |
| Effective Stress Method | 14.0 meters for 1,980 kN |
| Driven Program - SPT Data | 13.0 meters for 2,265 kN |
| LPC CPT Program - CPT Data | 12.5 meters for 1,826 kN |
| Schmertmann Method - CPT Data | 10.2 meters for 1,808 kN |

1 ft = 0.305 m, 1 kip = 4.448 kN

Note: Strata transitions from very stiff clay to dense sand and gravel at an embedded pile length of 13 m (43 ft).

| TABLE 12-4(a) SOUTH ABUTMENT PILE CAPACITY SUMMARY FOR 17.5 m PILE EMBEDMENT | | | |
|--|---------------------------------------|-------------------------------------|--|
| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
| α Method | 1,648 | 182 | 1,830 |
| Effective Stress Method | 898 | 715 | 1,613 |
| Driven Program | 1,644 | 190 | 1,834 |
| LPC CPT Program - CPT Data | 1,361 | 328 | 1,689 |
| Schmertmann Method - CPT Data | 1,717 | 353 | 2,070 |

1 kip = 4.448 kN

| TABLE 12-4(b) SOUTH ABUTMENT PILE LENGTH SUMMARY FOR A 1,780 kN ULTIMATE PILE CAPACITY | |
|--|--|
| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
| α Method | 17.5 meters for 1,830 kN |
| Effective Stress Method | 18.7 meters for 1,800 kN |
| Driven Program | 17.5 meters for 1,834 kN |
| LPC CPT Program - CPT Data | 19.5 meters for 1,807 kN |
| Schmertmann Method - CPT Data | 15.2 meters for 1,828 kN |

1 ft = 0.305 m, 1 kip = 4.448 kN

Note: These analyses do not consider the influence of downdrag loads on pile capacity which is discussed in Section 12.16.6.

At the South Abutment, the ultimate pile group capacity against block failure has been calculated and compared with the ultimate pile group capacity from the sum of the ultimate capacities of the individual piles times the group efficiency. Based on the design recommendations outlined in Section 9.8.1.2, a group efficiency of 1.0 was used. This calculation, included in Section F.2.4.1 of Appendix F, indicates that ultimate capacity

against block failure is greater than the ultimate capacity of the group. Therefore, block failure is not a design issue.

At all four substructure locations, the group capacity meets the design requirements.

12.16.3 Group Settlement Calculations

The optimized foundation layout resulted in a pile group having 3 rows of piles with 8 piles in each row. The piles are arranged at 1.5 m (5 ft) center to center spacing with a total pile group area of 3.36 m by 10.86 m (11.0 x 35.6 ft). Piles in a group are combined with a pile cap having a dimension of 4.5 m by 12 m (14.8 x 39.4 ft). The maximum pile group settlement should be less than 25 mm (1 inch) under the compression loads with maximum differential settlements of 15 mm (0.6 inch) between substructure units.

At the North Abutment, group settlement has been calculated using the Meyerhof Method detailed in Section 9.8.2.2. Results of this calculation are given in Appendix F.3.1 and indicate that the total pile group settlement is 12.2 mm (0.48 inch) due to soil compression and elastic pile compression. This is less than the maximum allowable settlement of 25 mm (1 inch).

At Pier 2, group settlement has also been calculated using the Meyerhof Method detailed in Section 9.8.2.2. Results of this calculation are given in Appendix F.3.2 and indicate that the total pile group settlement is 13.2 mm (0.52 inch) due to soil compression and elastic pile compression. This is less than the maximum allowable of 25 mm (1 inch).

At Pier 3, group settlement has been calculated using the equivalent footing method for layered soils described in Section 9.8.2.4 and the Meyerhof Method detailed in Section 9.8.2.2. Results of these calculations are given in Appendix F.3.3. The calculated settlement using the equivalent footing method is 16.1 mm (0.63 inch) including soil settlement and elastic pile compression. Most of this calculated settlement (12 mm or 0.47 inch) is in the clay layer. Since the piles are supported in an underlying dense sand and gravel layer where settlements are calculated to be 3.0 mm (0.12 inch), it is unlikely that the calculated settlement in the clay layer could develop due to the lack of strain compatibility between layers. The Meyerhof Method calculation indicates a group settlement of 9.0 mm (0.35 inch) including soil settlement and pile compression. In this soil profile, the Meyerhof Method calculation is considered a better indicator of probable foundation performance under load. Therefore the calculated settlement at Pier 3 of 9.0 mm (0.35 inch) is less than the maximum allowable of 25 mm (1 inch).

At the South Abutment, group settlement has been calculated using the equivalent footing method described in Section 9.8.2.3. Results of this calculation are provided in Appendix F.3.4 and indicate that the group settlement at the South Abutment is 28 mm (1.10 inch) including soil and pile compression. This is larger than the maximum allowable pile group settlement of 25 mm (1 inch). The group settlement will even be larger after the placement of the approach embankment fill materials behind the abutment wall. The settlement from embankment construction alone is calculated to be 500 mm (19.7 inches). Therefore, preloading of the South Abutment should be performed prior to pile installation.

With preloading of the South Abutment, group settlements could be kept within the foundation performance criteria. Differential settlements between substructure units have been calculated to be within the 15 mm (0.60 inch) criterion for differential settlement provided preloading at the South Abutment is performed.

12.16.4 Lateral Pile Capacity Analysis

The bridge division has determined that the group lateral loads range from 600 kN (135 kips) at the interior pile groups to 900 kN (202 kips) at the abutment pile groups. The maximum lateral load per pile is limited to 40 kN (9 kips). A horizontal deflection of up to 10 mm (0.40 inch) is permissible under lateral loading.

A simple Broms' Method lateral pile capacity analysis has been performed for the North Abutment piles. This calculation, included in Appendix F.4.1, indicates that the maximum lateral load per pile is 25 kN (6 kips) in order to meet the 10 mm (0.40 inch) deflection requirement. This lateral load is less than desired. Therefore, the group capacity of 600 kN (135 kips) based on 24 piles at 25 kN/pile (6 kips) is less than the 900 kN (202 kips) required, and more piles would be needed.

A more rigorous LPILE analysis was also performed to evaluate the lateral load capacity of the 356 mm (14 inch) square prestressed concrete piles at the North Abutment. This analysis is included in Appendix F.4.2 and indicates that the pile deflection under the 40 kN (9 kips) design load will be 3.2 mm (0.12 inch). The corresponding maximum moment and shear stress are -54.2 kN-m (40 kip-ft) and 14,500 kN/m² (304 kips/ft²). The deflection, moment and shear stress under the design load are acceptable. Hence, the LPILE analysis indicates a 40 kN (9 kips) design lateral load could be used whereas the Broms' Method indicated only a 25 kN (6 kips) design load.

An LPILE analysis was also performed to evaluate the lateral load capacity of the 356 mm (14 inch) square prestressed concrete pile at the South Abutment. This analysis is included in Appendix F.4.5 and indicates that the pile deflection under the 40 kN (9 kips) design load will be 1.9 mm (0.07 inch). The corresponding maximum moment and shear stress are - 44.4 kN-m (32.7 kip-ft) and 13,100 kN/m² (275.1 kips/ft²). The deflection, moment and shear stress under the design load are acceptable.

Additional LPILE analyses should be performed to evaluate the 356 mm (14 inch) concrete piles in Piers 2 and 3. These analyses are not included here.

12.16.5 Uplift Capacity Calculations

The maximum uplift load on a pile group is estimated to be 1,800 kN (405 kips) with a maximum uplift load per pile of 100 kN (23 kips). A calculation of the uplift capacity of the North Abutment pile group has been performed following AASHTO Code (2002) for service load design as outlined in Section 9.8.3.1. Following this procedure, the uplift capacity of the North Abutment pile group is 2,475 kN (556 kips), which is greater than the maximum uplift load of 1,800 kN (405 kips). Uplift calculation results are included in Appendix F.5.1.

A calculation of the uplift capacity of the Pier 2 pile group has also been performed in Appendix F.5.2. Following this procedure, the uplift capacity of the Pier 2 pile group is 2,616 kN (588 kips), which is greater than the maximum uplift load of 1,800 kN (405 kips).

At Pier 3, an uplift capacity calculation in accordance with AASHTO code yielded an uplift capacity of 3,354 kN (754 kips), which is greater than the maximum uplift load of 1,800 kN (405 kips). Uplift calculation results for Pier 3 are included in Appendix F.5.3.

A calculation of the uplift capacity of the South Abutment pile group has also been performed. The uplift capacity of the South Abutment pile group is 4,275 kN (961 kips), which is greater than the maximum uplift load of 1,800 kN (405 kips). Uplift calculation results for the South Abutment are included in Appendix F.5.4.

12.16.6 Negative Shaft Resistance

Piles at the South Abutment will be subjected to negative shaft resistance or downdrag loading due to soil settlement following the placement of 10 m (33 ft) of approach embankment material behind the abutment after pile installation. This settlement needs to

be estimated prior to determining the location of the negative and positive shaft resistances along the pile. The α -method is now used to estimate both the positive and negative shaft resistance components. The step by step procedure for the calculation of downdrag loading is presented in Section 9.9.1.1a.

Following this procedure, a drag load of 259 kN (58 kips) has been calculated. The net ultimate pile capacity for a 17.5 m (58 ft) embedded length available to resist imposed loads is then only 1,312 kN (295 kips) which is smaller than the required ultimate pile capacity. Therefore, alternatives such as preloading to reduce settlement and thereby the drag load, use of bitumen coatings to reduce pile-soil adhesion and thereby the drag load, or use of longer length piles to carry the drag load should be evaluated.

Calculations indicate use of bitumen coating to a depth of 5.5 m (18 ft) would reduce the negative shaft resistance to 78 kN (18 kips). However, the net ultimate pile capacity available to resist imposed loads on a 17.5 m (58 ft) embedded length pile is still only 1,493 kN (336 kips) which is less than the required ultimate pile capacity of 1780 kN (400 kips).

Calculations indicate the use of a 21 m (69 ft) long pile with a bitumen coating to a depth of 5.5 m (18 ft) would increase the ultimate pile capacity to 1,908 kN (429 kips). With these 21 m (69 ft) long piles, the net ultimate pile capacity available to resist imposed loads is 1,830 kN (411 kips). Hence, this alternate provides the required ultimate capacity. However, cost analyses of preloading, bitumen coatings, and longer piles in conjunction with meeting performance criteria requirements should be performed before making the final selection. The negative shaft resistance calculations are given in Appendix F.6.1.

A stub abutment instead of a full height abutment may also be a solution at the South Abutment. The stub abutment could be supported on a spread footing with specified embankment material and density control in the foundation area. A stub abutment with pile foundation is another alternative available for consideration.

This design problem illustrates the difficulties encountered in designing pile foundations in clay where substantial settlements occur and large drag loads are encountered by piles.

12.16.7 Lateral Squeeze Evaluation

The South Abutment should be evaluated for the potential for lateral squeeze following the guidelines presented in Section 9.9.3 of Chapter 9. Following these procedures, calculations presented in Appendix F.7.1 indicate that abutment tilting can occur. If piles are placed before any soil compression occurs, calculations indicate horizontal movement of 124 mm (4.9 inches), which is not tolerable. If piles are driven after 90% of vertical settlement has occurred, calculations indicate horizontal movements of 12.4 mm (0.49 inches). This is greater than the performance criteria but could be tolerated if provisions were made in the bridge shoe and expansion joint design.

12.16.8 Group Lateral Response Evaluation

The pile group response should be evaluated at all substructure units using the p-multiplier approach described in Section 9.8.4 or using software routines such as GROUP or FBPIER.

A series of LPILE analyses was performed to check the group deflection, moments and stresses imposed on the 356 mm (14 inch) square concrete piles in each row in the North Abutment. The lateral load on the group was assumed to act along the three pile axis and perpendicular to the eight pile axis. At the maximum lateral load on a single pile of 40 kN (9 kips), the calculations from Appendix F.8.1 show an estimated group deflection of 5.4 mm (0.21 inches), which corresponds to total stresses of 19,000; 16,000 and 14,500 kPa (2.75, 2.32, and 2.10 ksi) in the Front Row, Second Row and Third Row, respectively.

The deflection and total stresses are acceptable, but an analysis of the interaction between the substructure and superstructure should be performed. Analyses of lateral loading parallel to the eight pile axis, on the Piers and on the South Abutment should also be performed, but are not included here.

12.17 BLOCK 16 – DOES OPTIMIZED DESIGN MEET ALL REQUIREMENTS?

The selected pile lengths have now been checked for compression, lateral, and uplift loading as well as settlements. With preloading at the South Abutment group capacities and settlements are satisfactory. At this point the design has been found acceptable from a geotechnical perspective to meet the performance requirements. Pile lengths, loads and pile group configurations have been optimized.

A final pile driveability review of the design indicates the 356 mm (14 inch) concrete piles may be too difficult to install to the required penetration depths at the interior piers. Therefore, the interior pier foundations are re-designed and optimized using the second most cost effective option, the HP 360 x 152 (HP 14x102) H-piles. LPILE analyses for the H-piles at Piers 2 and 3 are performed and are presented in Appendix F.4.3. and F.4.4, respectively. To satisfy capacity requirements in the event of scour, the H-piles would need to be driven to within 1.5 meters of bedrock. Driveability results for the H-pile solution at Pier 2, are presented in Section 16.5.5 and Appendix F.9.2.3. These results indicate H-piles could be driven to bedrock. Therefore, the final design of the interior pier foundations was optimized using fewer higher capacity piles. This optimized H-pile design at the interior piers was found to meet all the design requirements including driveability. Therefore, all of the design requirements are now satisfied and the design is finalized.

12.18 BLOCK 17 - PREPARE PLANS AND SPECIFICATIONS, SET FIELD CAPACITY DETERMINATION PROCEDURE

The foundation design report should now be prepared. This report should summarize the results of the subsurface exploration program, laboratory test data, static analyses, an specific design and construction recommendations. The report should also highlight any special notes which should be incorporated into the plans or specifications which are also prepared at this time. For example, the preloading requirement at the South Abutment to reduce foundation settlements and drag loads should be clearly stated in the project plans and specifications.

Because of the variability of the subsurface site conditions, the foundation report recommended construction control using a static load test. Wave equation analysis is also required for driving system approval. In addition, dynamic testing has been specified during initial driving and restriking of two test piles per each substructure location. These test piles are to be driven in advance of production pile driving. The required ultimate pile capacity, driving stress limits, and testing methods are then incorporated into the plans and specifications.

12.19 BLOCK 18 - CONTRACTOR SELECTION

At this time the bidding process is completed, a successful contractor is selected.

12.20 BLOCK 19 - PERFORM WAVE EQUATION ANALYSIS OF CONTRACTOR'S EQUIPMENT SUBMISSION

The engineering effort now shifts to the field. The contractor has submitted the Pile Driving and Equipment Data form shown in Figure 11.1 for the engineer's evaluation of the proposed driving system. The design stage driveability studies were saved and can now be reanalyzed using the proposed driving system as part of the hammer approval process. Additional wave equation analyses are now performed to determine the driving resistance that must be achieved in the field to meet the required capacity and pile penetration depth. Driving stresses are also determined and checked against specification requirements. All conditions are satisfactory, and the equipment is approved for pile driving.

12.21 BLOCK 20 - SET PRELIMINARY DRIVING CRITERIA

Based on the results of the wave equation analysis of Block 19 along with minimum pile penetration requirements for scour, the preliminary driving criteria is set.

12.22 BLOCK 21 - DRIVE TEST PILE AND EVALUATE CAPACITY

Test piles are now driven using the preliminary driving criteria at each substructure location. Dynamic testing is performed on the test piles during initial driving and during restrike. The ultimate pile capacity is confirmed at each substructure unit by the dynamic test results and the correlating static load test.

12.23 BLOCK 22 - ADJUST DRIVING CRITERIA OR DESIGN

At this stage the final conditions can be set. If test results from Block 21 had indicated the capacity was inadequate, the driving criteria may have to be changed. In a few cases, it may be necessary to make changes in the design as far back as Block 7. If major changes are required, it will be necessary to repeat Blocks 19, 20, and 21.

12.24 BLOCK 23 - CONSTRUCTION CONTROL

After the driving criteria is set, the production pile driving proceeds following established quality control procedures.

12.25 BLOCK 24 – POST CONSTRUCTION EVALUATION AND REVIEW

After completion of the foundation construction, the design is reviewed and evaluated for its ability to satisfy the design requirements and its cost effectiveness.

Chapter 13

FOUNDATION DESIGN REPORT PREPARATION

A foundation design report should be prepared to present the results of the subsurface explorations, laboratory test data, analysis, and specific design and construction recommendations for the foundation system of a structure. The foundation report is referred to frequently during the design and construction period as well as in resolving post construction issues such as claims. It is therefore important that the foundation report be clear, concise and accurate. The foundation report is a very important document and should be prepared and reviewed accordingly.

As described in Chapter 12, the foundation design evolves as information is gathered and analyzed. Preliminary design recommendations based on, and/or transmitted with initial subsurface data does not constitute a foundation design report. A foundation design report should be developed with the full knowledge of loads, special design events, performance criteria and any site restrictions. Only with this full knowledge can a foundation design report be prepared with appropriate content and quality. The parts of a foundation design report are described in greater detail in Section 13.2.

The foundation report should be widely distributed to design, construction and maintenance engineers involved in the project. The foundation report should also furnish information regarding anticipated construction problems and solutions. This will provide a basis for the contractor's cost estimates.

The foundation design report should be completed and available to the designer prior to final design. The foundation drawings, special provisions, and foundation design report should all be cross-checked for compliance upon completion of final design documents. Conflicts between any of these documents greatly increases the potential for construction problems.

13.1 GUIDELINES FOR FOUNDATION DESIGN REPORT PREPARATION

1. The geotechnical engineer responsible for the report preparation should have a broad enough background in geotechnical and highway engineering to have knowledge of the foundation requirements and limitations for various types of structures. This includes knowledge in specifications, construction procedures, construction methods, quality control and assurance, and structural components.

2. The geotechnical engineer must have a clear and complete understanding of the compression, uplift and lateral load demands, performance criteria regarding deformations and constraints or restrictions.
3. The report should contain an interpretation and analysis of subsurface and site data. This includes a description of analysis and results in a summarized form.
4. The report should contain specific engineering recommendations for design.
5. Recommendations should be brief, concise, and definitive.
6. Reasons for recommendations and their supporting data should always be included.
7. Extraneous data of little use to the designer or Project Engineer should be omitted.
8. Discussion of soil materials and subsurface conditions which may be encountered during construction should be included.
9. Possible design and/or construction problems should be anticipated and recommendations for their solution should be included in the report.
10. The report should highlight any special notes which need to be placed on the plans or in the specifications.

13.2 PARTS OF A FOUNDATION DESIGN REPORT

A standard format provides uniformity of report writing as well as a checklist, so that major foundation design and construction considerations are not overlooked. The Soil and Foundations Workshop Manual FHWA HI-00-045 by Cheney and Chassie (2000) contains a foundation report outline that has been modified to include information from the AASHTO manual on Subsurface Investigations (1988). This modified outline is presented below and is recommended as a report preparation guide.

I. Table of Contents

II. Introduction

1. Summary of proposed construction, including foundation loading conditions (vertical and horizontal, static and dynamic, various combinations).

2. Summary of special design events: scour, seismic, vessel impact.
3. Foundation performance criteria (total and differential settlements, lateral deformation, vibration limits).

III. Scope of Explorations

1. Field explorations (summary of dates and methods, appended results).
2. Laboratory Testing (summary of types of tests, appended results).

IV. Interpretation of Subsurface Conditions

1. Description of formations.
2. Soil types.
3. Dip and strike of rock.
 - a. Regional.
 - b. Local.
4. Water table data.
 - a. Perched.
 - b. Regional.
 - c. Artesian.

V. Design Soil Parameters

1. Narrative to describe procedure for evaluating all factual data to establish design values.
 - a. Shear strength.
 - b. Compressibility.

VI. Design Analysis

1. Description of design procedures.
2. Summary of results.

3. Explanation of interpretation.

VII. Geotechnical Conclusions and Recommendations

1. Approach embankment considerations (primarily for fills over soft, weak subsoils).

a. Stability.

1. Excavation and replacement of unsuitable materials.
2. Counter berm.
3. Stage construction, time delay.
4. Other treatment methods: change alignment, lower grade, lightweight fill, *etc.*
5. Estimated factors of safety with and without treatment: estimated costs for treatment alternates, recommended treatment.

b. Settlement of subsoils.

1. Estimated settlement amount.
2. Estimated settlement time.
3. Surcharge height.
4. Special foundation treatment: vertical drains, soil densification, soil removal and replacement, *etc.*
5. Waiting periods.
6. Downdrag loads on deep foundations.
7. Lateral squeeze of soft subsoils.

c. Construction considerations.

1. Select fill material: gradation and compaction requirements.
2. Construction monitoring (instrumentation).

d. Special notes.

2. Spread footing support.

a. Elevation of bottom of footing: based on frost depth, scour depth, or depth to competent bearing material.

b. Allowable bearing pressure: based on settlement or bearing capacity, considering soil or rock type, adjacent foundations, water table, *etc.*

- c. Footing size used in computations.
- d. Estimated settlement of soil supported footings.
- e. Resistance to sliding of soil supported footings.
- f. Excavation, structural fill, and dewatering requirements.
- g. Special notes.

3. Pile foundation support.

- a. Method of pile support: shaft resistance, toe resistance, or both. Delineation of unsuitable support layers due to compressibility, scour, or liquefaction.
- b. Suitable pile types: reasons for choice and/or exclusion of types and optimization of the recommended section.
- c. Pile toe elevations.
 - 1. Estimated toe elevation, (average estimated values from static analyses with probable variation potential).
 - 2. Specified toe elevation, (toe elevation required due to underlying soft layers, negative shaft resistance, scour, lateral or uplift loads, piles uneconomically long, *etc.*).
- d. Estimated pile lengths.
- e. Allowable pile design loads for compression, uplift, and lateral loading.
- f. Estimated pile group settlement; very important for pile groups in cohesive soils and large groups in a cohesionless soil deposit underlain by compressible soils.
- g. Test piles to establish order lengths; specify test locations for maximum utility.
- h. Static pile load tests; specify test locations for maximum utility.
 - 1. Axial compression.

2. Axial tension.

3. Lateral.

- i. O-cell or Statnamic load tests; specify test locations.
- j. Dynamic pile load tests; specify test locations and retap frequency.
- k. Driving criteria; specify use of wave equation analysis or dynamic formula.
- l. Estimated soil resistance to overcome in order to reach estimated pile length.
- m. Preboring, pile toe reinforcement, or other requirements to reach pile penetration requirements or handle potential obstructions.
- n. Pile driving requirements: hammer size, tolerances, *etc.*
- o. Cofferdams and seals; seal design should consider potential conflicts between batter piles driven at alignment tolerance limits and depth of sheeting. Group densification inside sheeting for displacement piles in sands, or heave for displacement piles in clays should be considered.
- p. Corrosion effects or chemical attack; particular concern in marine environments, old dumps, areas with soil or groundwater contaminants.
- q. Effects of pile driving on adjacent construction; settlements from vibrations and development of excess pore water pressures in soil.
- r. Special notes.

4. Drilled shaft support.

- a. Method of drilled shaft support: shaft resistance, toe resistance, or both. Delineation of unsuitable support layers.
- b. Shaft diameter and configuration: straight shafts, belled, rock sockets.
- c. Anticipated support elevation and resulting shaft length.
- d. Specified or likely construction method: dry, casing, slurry.

- e. Allowable shaft load for compression, uplift, and lateral loading with consideration of construction method.
 - f. Estimated settlement.
 - g. Load tests; specify test locations for maximum utility.
 - 1. Axial compression (specify static, O-cell, Statnamic, or dynamic)
 - 2. Axial tension.
 - 3. Lateral.
 - h. Integrity tests; specify type, frequency, and access tube material and placement, (if required).
 - 1. Low strain pulse echo tests.
 - 2. Cross hole - sonic logging.
 - 3. Down hole - parallel seismic.
 - 4. High strain dynamic tests.
 - i. Anticipated construction difficulties due to boulders, obstructions, groundwater, artesian conditions, unstable ground, *etc.*
 - j. Special notes.
5. Special design considerations.
- a. Seismic design; design earthquake ground acceleration, liquefaction potential (loose saturated sands and silts).
 - b. Lateral earth pressures against retaining walls and high bridge abutments.

VIII. Construction Considerations

- 1. Water table: fluctuations, control in excavation, pumping, tremie seals, *etc.*
- 2. Excavations: safe slopes for open excavations, need for sheeting shoring, *etc.*
- 3. Adjacent structures: protection against damage from excavation, pile driving vibrations, drilled shaft ground loss, drainage, *etc.*
- 4. Special notes.

VIV. Appendix: Graphic Presentations

1. Map showing project location.
2. Detailed plan of the site showing proposed structure(s) borehole locations and existing structures.
3. Laboratory test data.
4. Finished boring logs and interpreted soil profile.

X. Report Distribution

Copies of the completed Foundation Report should be transmitted to:

1. Bridge design section.
2. Roadway design section.
3. Construction section.
4. Project engineer.
5. Residency or maintenance group.
6. Others, as required by agency policy.

13.3 GEOTECHNICAL REPORT REVIEWS

The FHWA developed a checklist to aid highway engineers in the review of geotechnical reports, plans, and special provisions. This document, FHWA ED-88-053 was originally produced in 1988 and revised in 2003. A copy of the document can be downloaded from: www.fhwa.dot.gov/bridge/checklist.htm

The review checklist and guidelines were developed to assist highway engineers in:

- Review of geotechnical reports and plan, specification, and estimate (PS&E) packages;

- Recognize potential cost saving opportunities;
- Identify potential claim problems and deficiencies in the geotechnical report, analysis, or design;
- Recognize when a geotechnical specialist should be consulted for additional technical guidance.

13.4 INFORMATION MADE AVAILABLE TO BIDDERS

The information developed during the foundation design is of value to contractors bidding on the project. Disagreement exists among owners, engineers and lawyers as to what information should be made available to the bidders. It is generally in the interest of the highway agency to release all pertinent information prior to the bid.

The finished boring logs and/or generalized soil profile should be included in the contract plans. Other subsurface information, such as soil and rock samples, results of field and laboratory testing and the foundation design report, should be made available for inspection by bidders.

Disclaimers should be used very carefully. "General" disclaimer clauses should be avoided. "Specific" disclaimer clauses are given more weight by the courts in settling contract disputes. A good example of a "specific" disclaimer is provided in the paragraph below. Refer to Cheney and Chassie (2000) for additional information.

"The observed water levels and/or conditions indicated on the subsurface profiles are as recorded at the time of exploration. These water levels and/or conditions may vary considerably, with time, according to the prevailing climate, rainfall or other factors and are otherwise dependent on the duration of and methods used in the explorations program."

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- Cheney, R.S. and Chassie, R.G. (2000). Soils and Foundations Workshop Reference Manual. Publication No. FHWA HI-00-045, U.S. Department of Transportation, National Highway Institute, Federal Highway Administration, Washington, D.C., 358.

APPENDIX A

List of FHWA Pile Foundation Design and Construction References

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- Wang, S-T, and Reese, L.C. (1993). COM624P - Laterally Loaded Pile Analysis Program for the Microcomputer, Version 2.0. Report No. FHWA-SA-91-048, U.S. Department of Transportation, Federal Highway Administration, Office of Technology Applications, Washington, D.C., 504.

APPENDIX B

List of ASTM Pile Design and Testing Specifications

DESIGN

Standard Specification for Welded and Seamless Steel Pipe Piles.
ASTM Designation: A 252

Standard Specification for Round Timber Piles.
ASTM Designation: D 25

Standard Method for Establishing Design Stresses for Round Timber Piles.
ASTM Designation: D 2899

Standard Methods for Establishing Clear Wood Strength Values.
ASTM Designation: D 2555

TESTING

Standard Method for Testing Piles under Axial Compressive Load.
ASTM Designation: D 1143

Standard Method for Testing Individual Piles under Static Axial Tensile Load.
ASTM Designation: D 3689

Standard Method for Testing Piles under Lateral Load.
ASTM Designation: D 3966

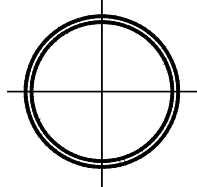
Standard Test Method for High Strain Dynamic Testing of Piles.
ASTM Designation: D 4945

Standard Test Method for Low Strain Dynamic Testing of Piles.
ASTM Designation: D 5882

APPENDIX C-1

Information and Data on Various Pile Types, Metric Units

| | Page |
|---|-------------|
| Dimensions and Properties of Pipe Piles | C1-3 |
| Data for Steel Monotube Piles..... | C1-17 |
| Typical Prestressed Concrete Pile Sections..... | C1-18 |
| Dimensions and Properties of H-Piles..... | C1-21 |



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|-------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| PP203 | 3.58 | 2,245 | 173 | 11.197 | 110.12 | 70.61 | 0.64 | 30,193 | 0.0301 | 266 |
| | 4.17 | 2,607 | 200 | 12.903 | 127.00 | 70.36 | 0.64 | 29,806 | 0.0298 | 422 |
| | 4.37 | 2,729 | 210 | 13.486 | 132.74 | 70.36 | 0.64 | 29,677 | 0.0296 | 487 |
| | 4.55 | 2,839 | 218 | 13.985 | 137.82 | 70.36 | 0.64 | 29,613 | 0.0296 | 548 |
| | 4.78 | 2,974 | 229 | 14.651 | 144.21 | 70.10 | 0.64 | 29,484 | 0.0293 | 621 |
| | 5.56 | 3,452 | 266 | 16.857 | 165.51 | 69.85 | 0.64 | 28,968 | 0.0291 | 874 |
| PP219 | 2.77 | 1,884 | 145 | 10.989 | 100.45 | 76.45 | 0.69 | 35,806 | 0.0359 | 97 |
| | 3.18 | 2,155 | 166 | 12.570 | 114.55 | 76.45 | 0.69 | 35,548 | 0.0356 | 147 |
| | 3.58 | 2,426 | 187 | 14.069 | 128.47 | 76.20 | 0.69 | 35,290 | 0.0354 | 212 |
| | 3.96 | 2,678 | 206 | 15.484 | 141.42 | 75.95 | 0.69 | 35,032 | 0.0351 | 288 |
| | 4.17 | 2,813 | 216 | 16.233 | 148.30 | 75.95 | 0.69 | 34,903 | 0.0349 | 335 |
| | 4.37 | 2,949 | 227 | 16.982 | 155.02 | 75.95 | 0.69 | 34,774 | 0.0349 | 388 |
| | 4.55 | 3,065 | 236 | 17.648 | 160.92 | 75.95 | 0.69 | 34,645 | 0.0346 | 438 |
| | 4.78 | 3,213 | 247 | 18.481 | 168.79 | 75.69 | 0.69 | 34,452 | 0.0344 | 508 |
| | 5.16 | 3,465 | 266 | 19.813 | 180.26 | 75.69 | 0.69 | 34,258 | 0.0341 | 623 |
| | 5.56 | 3,729 | 287 | 21.269 | 195.01 | 75.44 | 0.69 | 33,935 | 0.0339 | 744 |
| | 6.35 | 4,245 | 326 | 24.017 | 219.59 | 75.18 | 0.69 | 33,419 | 0.0334 | 979 |
| | 7.04 | 4,684 | 360 | 26.389 | 240.89 | 74.93 | 0.69 | 33,032 | 0.0331 | 1,180 |
| | 7.92 | 5,258 | 404 | 29.344 | 267.11 | 74.68 | 0.69 | 32,452 | 0.0324 | 1,500 |
| | 8.18 | 5,420 | 417 | 30.177 | 275.30 | 74.68 | 0.69 | 32,258 | 0.0324 | 1,600 |
| | 8.74 | 5,775 | 444 | 31.967 | 291.69 | 74.42 | 0.69 | 31,935 | 0.0319 | 1,820 |
| | 9.53 | 6,271 | 482 | 34.506 | 314.63 | 74.17 | 0.69 | 31,419 | 0.0314 | 2,120 |
| | 10.31 | 6,775 | 520 | 36.920 | 337.57 | 73.91 | 0.69 | 30,903 | 0.0309 | 2,420 |
| | 11.13 | 7,291 | 559 | 39.417 | 358.88 | 73.66 | 0.69 | 30,452 | 0.0304 | 2,740 |
| | 12.70 | 8,259 | 633 | 44.121 | 401.48 | 73.15 | 0.69 | 29,484 | 0.0293 | 3,340 |
| PP254 | 2.77 | 2,187 | 168 | 17.232 | 135.68 | 88.90 | 0.80 | 48,516 | 0.0484 | 62 |
| | 3.05 | 2,400 | 185 | 18.939 | 148.96 | 88.65 | 0.80 | 48,258 | 0.0482 | 83 |
| | 3.40 | 2,678 | 206 | 21.020 | 165.51 | 88.65 | 0.80 | 48,000 | 0.0479 | 116 |

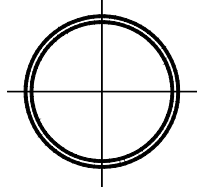
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|-------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 3.58 | 2,820 | 217 | 22.102 | 173.70 | 88.65 | 0.80 | 47,871 | 0.0479 | 135 |
| | 3.81 | 2,994 | 230 | 23.434 | 185.17 | 88.39 | 0.80 | 47,677 | 0.0477 | 163 |
| | 4.17 | 3,271 | 251 | 25.515 | 201.56 | 88.39 | 0.80 | 47,419 | 0.0474 | 214 |
| | 4.37 | 3,426 | 263 | 26.680 | 209.75 | 88.39 | 0.80 | 47,226 | 0.0472 | 247 |
| | 4.55 | 3,562 | 274 | 27.721 | 217.95 | 88.14 | 0.80 | 47,097 | 0.0472 | 279 |
| | 4.78 | 3,742 | 287 | 29.053 | 229.42 | 88.14 | 0.80 | 46,903 | 0.0469 | 324 |
| | 5.16 | 4,033 | 310 | 31.217 | 245.81 | 87.88 | 0.80 | 46,645 | 0.0467 | 409 |
| | 5.56 | 4,342 | 334 | 33.507 | 263.83 | 87.88 | 0.80 | 46,322 | 0.0464 | 515 |
| | 5.84 | 4,555 | 350 | 35.088 | 276.94 | 87.88 | 0.80 | 46,129 | 0.0462 | 588 |
| | 6.35 | 4,942 | 380 | 37.919 | 298.24 | 87.63 | 0.80 | 45,742 | 0.0457 | 719 |
| PP273 | 2.77 | 2,349 | 181 | 21.478 | 157.32 | 95.50 | 0.86 | 56,193 | 0.0562 | 50 |
| | 3.05 | 2,587 | 199 | 23.559 | 172.06 | 95.50 | 0.86 | 56,000 | 0.0559 | 67 |
| | 3.18 | 2,690 | 207 | 24.516 | 180.26 | 95.50 | 0.86 | 55,871 | 0.0559 | 76 |
| | 3.40 | 2,884 | 222 | 26.223 | 191.73 | 95.25 | 0.86 | 55,677 | 0.0557 | 93 |
| | 3.58 | 3,032 | 233 | 27.513 | 201.56 | 95.25 | 0.86 | 55,548 | 0.0554 | 109 |
| | 3.81 | 3,226 | 248 | 29.219 | 214.67 | 95.25 | 0.86 | 55,355 | 0.0554 | 131 |
| | 3.96 | 3,349 | 258 | 30.343 | 222.86 | 95.25 | 0.86 | 55,226 | 0.0552 | 148 |
| | 4.17 | 3,516 | 271 | 31.800 | 232.70 | 95.00 | 0.86 | 55,032 | 0.0549 | 172 |
| | 4.37 | 3,691 | 284 | 33.299 | 244.17 | 95.00 | 0.86 | 54,839 | 0.0549 | 199 |
| | 4.55 | 3,832 | 295 | 34.589 | 254.00 | 95.00 | 0.86 | 54,710 | 0.0547 | 224 |
| | 4.78 | 4,026 | 310 | 36.212 | 265.47 | 94.74 | 0.86 | 54,516 | 0.0544 | 260 |
| | 5.16 | 4,342 | 334 | 38.959 | 285.13 | 94.74 | 0.86 | 54,193 | 0.0542 | 328 |
| | 5.56 | 4,679 | 359 | 41.623 | 306.44 | 94.49 | 0.86 | 53,871 | 0.0539 | 414 |
| | 5.84 | 4,904 | 377 | 43.704 | 321.19 | 94.49 | 0.86 | 53,677 | 0.0537 | 480 |
| | 6.35 | 5,323 | 409 | 47.450 | 347.41 | 94.23 | 0.86 | 53,226 | 0.0532 | 605 |
| | 7.09 | 5,923 | 455 | 52.445 | 383.46 | 93.98 | 0.86 | 52,645 | 0.0527 | 781 |
| | 7.80 | 6,517 | 500 | 57.024 | 419.51 | 93.73 | 0.86 | 52,064 | 0.0522 | 951 |
| | 8.74 | 7,226 | 558 | 63.267 | 465.39 | 93.47 | 0.86 | 51,290 | 0.0514 | 1,180 |

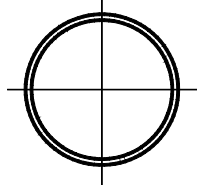
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 9.27 | 7,678 | 591 | 67.013 | 489.97 | 93.22 | 0.86 | 50,903 | 0.0509 | 1,320 |
| | 11.13 | 9,162 | 704 | 78.668 | 576.82 | 92.71 | 0.86 | 49,419 | 0.0494 | 1,890 |
| | 12.70 | 10,389 | 799 | 88.241 | 645.65 | 92.20 | 0.86 | 48,193 | 0.0482 | 2,380 |
| PP305 | 3.40 | 3,226 | 248 | 36.587 | 240.89 | 106.68 | 0.96 | 69,677 | 0.0697 | 67 |
| | 3.58 | 3,387 | 261 | 38.460 | 252.36 | 106.43 | 0.96 | 69,677 | 0.0695 | 78 |
| | 3.81 | 3,600 | 277 | 40.791 | 267.11 | 106.43 | 0.96 | 69,677 | 0.0695 | 94 |
| | 4.17 | 3,936 | 303 | 44.537 | 291.69 | 106.43 | 0.96 | 69,032 | 0.0690 | 123 |
| | 4.37 | 4,123 | 317 | 46.618 | 304.80 | 106.17 | 0.96 | 69,032 | 0.0687 | 142 |
| | 4.55 | 4,291 | 330 | 48.283 | 317.91 | 106.17 | 0.96 | 68,387 | 0.0687 | 161 |
| | 4.78 | 4,503 | 346 | 50.780 | 332.66 | 106.17 | 0.96 | 68,387 | 0.0685 | 186 |
| | 5.16 | 4,852 | 373 | 54.526 | 357.24 | 105.92 | 0.96 | 68,387 | 0.0682 | 235 |
| | 5.56 | 5,233 | 402 | 58.689 | 383.46 | 105.92 | 0.96 | 67,742 | 0.0677 | 296 |
| | 5.84 | 5,484 | 422 | 61.186 | 403.12 | 105.66 | 0.96 | 67,742 | 0.0675 | 344 |
| | 6.35 | 5,955 | 458 | 66.181 | 435.90 | 105.66 | 0.96 | 67,097 | 0.0670 | 443 |
| | 7.14 | 6,646 | 513 | 74.089 | 485.06 | 105.16 | 0.96 | 66,451 | 0.0662 | 616 |
| | 7.92 | 7,420 | 568 | 81.581 | 534.22 | 104.90 | 0.96 | 65,806 | 0.0655 | 784 |
| PP324 | 2.77 | 2,794 | 215 | 36.004 | 222.86 | 113.54 | 1.02 | 79,355 | 0.0795 | 30 |
| | 3.18 | 3,200 | 246 | 41.124 | 254.00 | 113.28 | 1.02 | 79,355 | 0.0793 | 45 |
| | 3.40 | 3,426 | 264 | 44.121 | 272.03 | 113.28 | 1.02 | 78,710 | 0.0790 | 56 |
| | 3.58 | 3,607 | 277 | 46.202 | 285.13 | 113.28 | 1.02 | 78,710 | 0.0788 | 65 |
| | 3.81 | 3,832 | 295 | 49.115 | 303.16 | 113.29 | 1.02 | 78,710 | 0.0785 | 78 |
| | 3.96 | 3,981 | 306 | 50.780 | 314.63 | 113.03 | 1.02 | 78,710 | 0.0785 | 88 |
| | 4.17 | 4,181 | 322 | 53.278 | 329.38 | 113.03 | 1.02 | 78,064 | 0.0783 | 103 |
| | 4.37 | 4,387 | 337 | 55.775 | 345.77 | 113.03 | 1.02 | 78,064 | 0.0780 | 118 |
| | 4.55 | 4,562 | 351 | 58.272 | 358.88 | 113.03 | 1.02 | 78,064 | 0.0778 | 134 |
| | 4.78 | 4,787 | 368 | 60.770 | 376.90 | 112.78 | 1.02 | 77,419 | 0.0775 | 155 |
| | 5.16 | 5,162 | 397 | 65.765 | 404.76 | 112.78 | 1.02 | 77,419 | 0.0773 | 196 |
| | 5.56 | 5,562 | 428 | 70.343 | 435.90 | 112.52 | 1.02 | 76,774 | 0.0768 | 246 |

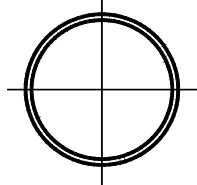
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 5.84 | 5,839 | 449 | 73.673 | 455.56 | 112.52 | 1.02 | 76,774 | 0.0765 | 286 |
| | 6.35 | 6,336 | 487 | 79.916 | 493.25 | 112.27 | 1.02 | 76,129 | 0.0760 | 368 |
| | 7.14 | 7,097 | 546 | 89.074 | 550.61 | 112.01 | 1.02 | 75,484 | 0.0753 | 526 |
| | 7.92 | 7,871 | 605 | 98.231 | 606.32 | 111.76 | 1.02 | 74,193 | 0.0745 | 684 |
| | 8.38 | 8,323 | 639 | 103.225 | 639.10 | 111.51 | 1.02 | 74,193 | 0.0740 | 776 |
| | 8.74 | 8,646 | 665 | 107.388 | 663.68 | 111.51 | 1.02 | 73,548 | 0.0737 | 848 |
| | 9.53 | 9,420 | 723 | 116.129 | 717.75 | 111.25 | 1.02 | 72,903 | 0.0730 | 1,010 |
| | 10.31 | 10,131 | 781 | 124.869 | 771.83 | 111.00 | 1.02 | 72,258 | 0.0722 | 1,170 |
| | 11.13 | 10,905 | 840 | 133.610 | 825.91 | 110.74 | 1.02 | 71,613 | 0.0715 | 1,350 |
| | 12.70 | 12,389 | 955 | 150.676 | 929.15 | 109.98 | 1.02 | 69,677 | 0.0700 | 1,760 |
| PP356 | 3.40 | 3,768 | 290 | 58.272 | 327.74 | 124.47 | 1.12 | 95,484 | 0.0956 | 42 |
| | 3.58 | 3,962 | 305 | 61.186 | 345.77 | 124.47 | 1.12 | 95,484 | 0.0953 | 49 |
| | 3.81 | 4,213 | 324 | 65.348 | 367.07 | 124.46 | 1.12 | 94,839 | 0.0951 | 59 |
| | 3.96 | 4,374 | 337 | 67.846 | 380.18 | 124.21 | 1.12 | 94,839 | 0.0948 | 66 |
| | 4.17 | 4,600 | 354 | 71.176 | 399.84 | 124.21 | 1.12 | 94,839 | 0.0948 | 77 |
| | 4.37 | 4,820 | 371 | 74.505 | 417.87 | 124.21 | 1.12 | 94,193 | 0.0946 | 89 |
| | 4.55 | 5,013 | 386 | 77.419 | 434.26 | 124.21 | 1.12 | 94,193 | 0.0943 | 101 |
| | 4.78 | 5,265 | 405 | 81.165 | 455.56 | 123.95 | 1.12 | 94,193 | 0.0941 | 117 |
| | 5.16 | 5,678 | 436 | 86.992 | 489.97 | 123.95 | 1.12 | 93,548 | 0.0936 | 147 |
| | 5.33 | 5,871 | 451 | 89.906 | 506.36 | 123.95 | 1.12 | 93,548 | 0.0936 | 163 |
| | 5.56 | 6,116 | 470 | 93.652 | 527.66 | 123.70 | 1.12 | 92,903 | 0.0933 | 815 |
| | 5.84 | 6,420 | 494 | 98.231 | 552.24 | 123.70 | 1.12 | 92,903 | 0.0928 | 215 |
| | 6.35 | 6,968 | 536 | 106.139 | 598.13 | 123.44 | 1.12 | 92,258 | 0.0923 | 277 |
| | 7.14 | 7,807 | 601 | 118.626 | 666.95 | 123.19 | 1.12 | 91,613 | 0.0916 | 395 |
| | 7.92 | 8,646 | 666 | 130.697 | 735.78 | 122.94 | 1.12 | 90,968 | 0.0906 | 542 |
| | 8.74 | 9,549 | 732 | 143.184 | 806.24 | 122.68 | 1.12 | 89,677 | 0.0898 | 691 |
| | 9.53 | 10,389 | 796 | 155.254 | 873.43 | 122.43 | 1.12 | 89,032 | 0.0890 | 835 |
| | 11.13 | 12,065 | 926 | 178.563 | 1,006.17 | 121.92 | 1.12 | 87,097 | 0.0873 | 1,130 |

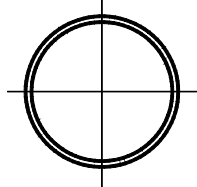
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Example of suggested method of designation: PP219 x 2.77

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PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| PP406 | 11.91 | 12,839 | 989 | 190.218 | 1,070.08 | 121.67 | 1.12 | 86,451 | 0.0865 | 1,280 |
| | 12.70 | 13,678 | 1,052 | 201.456 | 1,132.35 | 121.41 | 1.12 | 85,806 | 0.0855 | 1,460 |
| | 3.40 | 4,310 | 331 | 87.409 | 430.98 | 142.49 | 1.28 | 125,161 | 1.2542 | 28 |
| | 3.58 | 4,529 | 348 | 91.987 | 452.28 | 142.49 | 1.28 | 125,161 | 0.1252 | 33 |
| | 3.81 | 4,820 | 371 | 97.814 | 480.14 | 142.24 | 1.28 | 125,161 | 0.1249 | 39 |
| | 3.96 | 5,007 | 385 | 101.560 | 499.81 | 142.24 | 1.28 | 124,516 | 0.1247 | 44 |
| | 4.17 | 5,265 | 405 | 106.555 | 524.39 | 142.24 | 1.28 | 124,516 | 0.1244 | 52 |
| | 4.37 | 5,516 | 424 | 111.550 | 548.97 | 142.24 | 1.28 | 124,516 | 0.1242 | 60 |
| | 4.55 | 5,742 | 441 | 115.712 | 570.27 | 141.99 | 1.28 | 123,871 | 0.1239 | 67 |
| | 4.78 | 6,026 | 463 | 121.540 | 598.13 | 141.99 | 1.28 | 123,871 | 0.1237 | 78 |
| | 5.16 | 6,517 | 500 | 130.697 | 644.01 | 141.99 | 1.28 | 123,226 | 0.1232 | 98 |
| | 5.56 | 7,033 | 539 | 140.686 | 693.17 | 141.73 | 1.28 | 122,580 | 0.1227 | 124 |
| | 5.84 | 7,355 | 565 | 147.346 | 725.95 | 141.73 | 1.28 | 122,580 | 0.1224 | 144 |
| | 6.35 | 8,000 | 614 | 159.833 | 786.58 | 141.48 | 1.28 | 121,935 | 0.1217 | 185 |
| | 7.14 | 8,968 | 688 | 178.563 | 878.35 | 141.22 | 1.28 | 120,645 | 0.1207 | 264 |
| | 7.92 | 9,936 | 763 | 196.877 | 970.11 | 140.97 | 1.28 | 120,000 | 0.1199 | 362 |
| | 8.74 | 10,905 | 839 | 216.024 | 1,061.88 | 140.72 | 1.28 | 118,709 | 0.1189 | 487 |
| | 9.53 | 11,873 | 913 | 233.922 | 1,152.01 | 140.46 | 1.28 | 118,064 | 0.1179 | 617 |
| | 11.13 | 13,807 | 1,062 | 270.134 | 1,328.99 | 139.70 | 1.28 | 116,129 | 0.1159 | 874 |
| | 11.91 | 14,775 | 1,135 | 287.616 | 1,414.20 | 139.45 | 1.28 | 114,838 | 0.1149 | 1,000 |
| | 12.70 | 15,679 | 1,208 | 304.681 | 1,499.42 | 139.19 | 1.28 | 114,193 | 0.1141 | 1,130 |
| PP457 | 3.58 | 5,104 | 392 | 131.113 | 573.55 | 160.27 | 1.44 | 159,355 | 0.1590 | 23 |
| | 4.37 | 6,213 | 478 | 159.417 | 696.45 | 160.02 | 1.44 | 158,064 | 0.1580 | 42 |
| | 4.78 | 6,775 | 522 | 173.569 | 760.36 | 160.02 | 1.44 | 157,419 | 0.1573 | 55 |
| | 5.16 | 7,291 | 563 | 186.888 | 817.71 | 159.77 | 1.44 | 156,774 | 0.1568 | 69 |
| | 5.56 | 7,871 | 607 | 201.456 | 879.99 | 159.77 | 1.44 | 156,129 | 0.1563 | 87 |
| | 5.84 | 8,259 | 637 | 211.029 | 922.59 | 159.51 | 1.44 | 156,129 | 0.1558 | 101 |
| | 6.35 | 8,968 | 692 | 228.511 | 999.61 | 159.51 | 1.44 | 155,484 | 0.1553 | 129 |

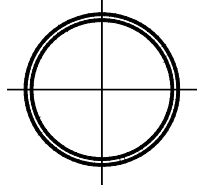
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PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 7.14 | 10,065 | 776 | 255.566 | 1,117.60 | 159.26 | 1.44 | 154,193 | 0.1540 | 184 |
| | 7.92 | 11,163 | 860 | 282.205 | 1,235.58 | 158.75 | 1.44 | 152,903 | 0.1530 | 253 |
| | 8.74 | 12,323 | 947 | 309.676 | 1,353.57 | 158.50 | 1.44 | 151,613 | 0.1518 | 341 |
| | 9.53 | 13,420 | 1,030 | 335.899 | 1,468.28 | 158.24 | 1.44 | 150,967 | 0.1508 | 443 |
| | 10.31 | 14,452 | 1,113 | 361.705 | 1,581.35 | 157.99 | 1.44 | 149,677 | 0.1498 | 559 |
| | 11.13 | 15,615 | 1,199 | 387.928 | 1,704.25 | 157.73 | 1.44 | 148,387 | 0.1485 | 675 |
| | 11.91 | 16,646 | 1,281 | 413.318 | 1,802.58 | 157.48 | 1.44 | 147,742 | 0.1475 | 788 |
| | 12.70 | 17,743 | 1,364 | 437.043 | 1,917.29 | 157.23 | 1.44 | 146,451 | 0.1465 | 900 |
| PP508 | 3.58 | 5,678 | 436 | 180.644 | 711.20 | 178.31 | 1.60 | 196,774 | 0.1969 | 17 |
| | 4.37 | 6,904 | 531 | 219.354 | 863.60 | 178.05 | 1.60 | 195,483 | 0.1957 | 30 |
| | 4.78 | 7,549 | 581 | 238.917 | 940.62 | 177.80 | 1.60 | 194,838 | 0.1952 | 40 |
| | 5.16 | 8,130 | 626 | 257.647 | 1,014.36 | 177.80 | 1.60 | 194,838 | 0.1947 | 50 |
| | 5.56 | 8,775 | 675 | 277.210 | 1,091.38 | 177.55 | 1.60 | 194,193 | 0.1939 | 63 |
| | 6.35 | 10,002 | 769 | 314.671 | 1,238.86 | 177.29 | 1.60 | 192,903 | 0.1926 | 94 |
| | 7.14 | 11,226 | 864 | 352.132 | 1,386.35 | 177.04 | 1.60 | 191,613 | 0.1914 | 134 |
| | 7.92 | 12,452 | 957 | 389.176 | 1,532.19 | 176.78 | 1.60 | 190,322 | 0.1901 | 184 |
| | 8.74 | 13,678 | 1,054 | 428.718 | 1,687.87 | 176.53 | 1.60 | 189,032 | 0.1889 | 247 |
| | 9.53 | 14,904 | 1,147 | 462.017 | 1,818.96 | 176.28 | 1.60 | 187,742 | 0.1879 | 321 |
| | 10.31 | 16,130 | 1,240 | 499.478 | 1,966.45 | 176.02 | 1.60 | 186,451 | 0.1866 | 409 |
| | 11.13 | 17,357 | 1,335 | 536.939 | 2,113.93 | 175.77 | 1.60 | 185,161 | 0.1854 | 515 |
| | 11.91 | 18,583 | 1,428 | 570.237 | 2,245.03 | 175.51 | 1.60 | 183,871 | 0.1841 | 618 |
| | 12.70 | 19,743 | 1,520 | 607.698 | 2,392.51 | 175.26 | 1.60 | 183,225 | 0.1829 | 719 |
| PP559 | 4.37 | 7,613 | 585 | 292.611 | 1,047.13 | 196.09 | 1.76 | 237,419 | 0.2375 | 23 |
| | 4.78 | 8,323 | 639 | 318.833 | 1,142.18 | 195.83 | 1.76 | 236,774 | 0.2370 | 30 |
| | 5.56 | 9,678 | 743 | 370.030 | 1,324.07 | 195.58 | 1.76 | 235,483 | 0.2355 | 47 |
| | 6.35 | 11,034 | 847 | 420.394 | 1,504.33 | 195.33 | 1.76 | 234,193 | 0.2343 | 70 |
| | 7.14 | 12,389 | 951 | 470.342 | 1,687.87 | 195.07 | 1.76 | 232,903 | 0.2328 | 100 |
| | 7.92 | 13,744 | 1,055 | 520.289 | 1,868.13 | 194.82 | 1.76 | 231,612 | 0.2315 | 138 |

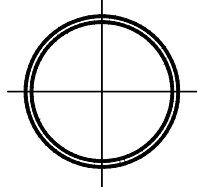
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 8.74 | 15,099 | 1,161 | 570.237 | 2,048.38 | 194.56 | 1.76 | 230,322 | 0.2303 | 185 |
| | 9.53 | 16,454 | 1,264 | 620.185 | 2,212.25 | 194.31 | 1.76 | 229,032 | 0.2288 | 241 |
| | 10.31 | 17,743 | 1,366 | 670.133 | 2,392.51 | 194.06 | 1.76 | 227,741 | 0.2275 | 306 |
| | 11.13 | 19,162 | 1,472 | 715.918 | 2,572.77 | 193.55 | 1.76 | 225,806 | 0.2260 | 386 |
| | 11.91 | 20,454 | 1,574 | 765.866 | 2,736.64 | 193.29 | 1.76 | 224,516 | 0.2248 | 475 |
| | 12.70 | 21,809 | 1,675 | 811.651 | 2,900.51 | 193.04 | 1.76 | 223,225 | 0.2235 | 571 |
| PP610 | 4.37 | 8,323 | 639 | 380.436 | 1,248.69 | 213.87 | 1.91 | 283,870 | 0.2834 | 18 |
| | 4.78 | 9,097 | 698 | 414.983 | 1,361.77 | 213.87 | 1.91 | 282,580 | 0.2834 | 23 |
| | 5.56 | 10,582 | 812 | 482.828 | 1,579.71 | 213.61 | 1.91 | 281,290 | 0.2809 | 36 |
| | 6.35 | 12,065 | 925 | 549.425 | 1,802.58 | 213.36 | 1.91 | 279,999 | 0.2809 | 54 |
| | 7.14 | 13,486 | 1,039 | 611.860 | 2,015.61 | 213.11 | 1.91 | 278,064 | 0.2784 | 77 |
| | 7.92 | 14,970 | 1,152 | 678.457 | 2,228.64 | 212.85 | 1.91 | 276,774 | 0.2759 | 106 |
| | 8.74 | 16,517 | 1,268 | 745.054 | 2,441.67 | 212.34 | 1.91 | 275,483 | 0.2759 | 142 |
| | 9.53 | 17,937 | 1,381 | 807.489 | 2,654.70 | 212.09 | 1.91 | 274,193 | 0.2734 | 185 |
| | 10.31 | 19,421 | 1,493 | 869.924 | 2,867.74 | 211.84 | 1.91 | 272,258 | 0.2734 | 235 |
| | 11.13 | 20,904 | 1,608 | 936.521 | 3,080.77 | 211.58 | 1.91 | 270,967 | 0.2709 | 296 |
| | 11.91 | 22,388 | 1,720 | 998.955 | 3,277.41 | 211.33 | 1.91 | 269,677 | 0.2684 | 364 |
| | 12.70 | 23,809 | 1,831 | 1,061.390 | 3,474.06 | 211.07 | 1.91 | 267,741 | 0.2684 | 443 |
| PP660 | 6.35 | 13,033 | 1,003 | 699.269 | 2,113.93 | 231.14 | 2.08 | 329,677 | 0.3286 | 43 |
| | 7.14 | 14,646 | 1,126 | 782.515 | 2,359.74 | 230.89 | 2.08 | 327,741 | 0.3286 | 61 |
| | 7.92 | 16,259 | 1,249 | 865.761 | 2,621.93 | 230.63 | 2.08 | 326,451 | 0.3261 | 83 |
| | 8.74 | 17,872 | 1,376 | 949.008 | 2,884.12 | 230.38 | 2.08 | 324,515 | 0.3236 | 112 |
| | 9.53 | 19,485 | 1,498 | 1,032.254 | 3,129.93 | 230.12 | 2.08 | 323,225 | 0.3236 | 145 |
| | 10.31 | 21,034 | 1,620 | 1,111.338 | 3,375.74 | 229.87 | 2.08 | 321,290 | 0.3211 | 184 |
| | 11.13 | 22,711 | 1,745 | 1,194.584 | 3,621.54 | 229.62 | 2.08 | 319,999 | 0.3211 | 232 |
| | 11.91 | 24,260 | 1,866 | 1,277.830 | 3,867.35 | 229.36 | 2.08 | 318,064 | 0.3186 | 286 |
| | 12.70 | 25,873 | 1,987 | 1,356.914 | 4,113.15 | 229.11 | 2.08 | 316,774 | 0.3161 | 347 |
| | 14.27 | 28,969 | 2,228 | 1,510.920 | 4,588.38 | 228.60 | 2.08 | 313,548 | 0.3135 | 495 |

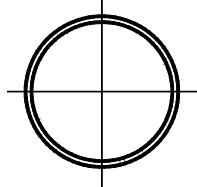
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| PP711 | 15.88 | 32,132 | 2,472 | 1,669.088 | 5,063.60 | 227.84 | 2.08 | 310,322 | 0.3110 | 656 |
| | 17.48 | 35,292 | 2,714 | 1,823.094 | 5,522.44 | 227.33 | 2.08 | 307,096 | 0.3060 | 814 |
| | 19.05 | 38,389 | 2,951 | 1,977.099 | 5,981.28 | 226.82 | 2.08 | 303,870 | 0.3035 | 970 |
| | 6.35 | 14,065 | 1,081 | 874.086 | 2,458.06 | 249.17 | 2.23 | 383,225 | 0.3838 | 34 |
| | 7.14 | 15,807 | 1,214 | 978.144 | 2,753.03 | 248.92 | 2.23 | 381,290 | 0.3813 | 48 |
| | 7.92 | 17,486 | 1,346 | 1,082.202 | 3,047.99 | 248.67 | 2.23 | 379,999 | 0.3788 | 66 |
| | 8.74 | 19,291 | 1,483 | 1,190.422 | 3,342.96 | 248.41 | 2.23 | 378,064 | 0.3788 | 89 |
| | 9.53 | 20,969 | 1,615 | 1,294.480 | 3,637.93 | 248.16 | 2.23 | 376,128 | 0.3763 | 116 |
| | 10.31 | 22,711 | 1,746 | 1,394.375 | 3,916.51 | 247.90 | 2.23 | 374,838 | 0.3737 | 147 |
| | 11.13 | 24,453 | 1,881 | 1,498.433 | 4,211.48 | 247.65 | 2.23 | 372,902 | 0.3737 | 185 |
| | 11.91 | 26,195 | 2,012 | 1,598.329 | 4,506.44 | 247.40 | 2.23 | 370,967 | 0.3712 | 228 |
| | 12.70 | 27,874 | 2,143 | 1,698.224 | 4,785.02 | 246.89 | 2.23 | 369,677 | 0.3687 | 277 |
| | 14.27 | 31,229 | 2,403 | 1,898.015 | 5,342.18 | 246.38 | 2.23 | 365,806 | 0.3587 | 395 |
| | 15.88 | 34,713 | 2,667 | 2,097.806 | 5,899.34 | 245.87 | 2.23 | 362,580 | 0.3612 | 544 |
| | 17.48 | 38,068 | 2,929 | 2,293.435 | 6,440.12 | 245.36 | 2.23 | 359,354 | 0.3587 | 691 |
| | 19.05 | 41,423 | 3,185 | 2,480.739 | 6,980.89 | 244.86 | 2.23 | 356,128 | 0.3562 | 835 |
| PP762 | 6.35 | 15,099 | 1,159 | 1,078.039 | 2,818.58 | 266.70 | 2.39 | 440,644 | 0.4415 | 28 |
| | 7.14 | 16,904 | 1,302 | 1,207.071 | 3,162.70 | 266.70 | 2.39 | 439,354 | 0.4390 | 39 |
| | 7.92 | 18,775 | 1,444 | 1,336.103 | 3,506.83 | 266.70 | 2.39 | 437,418 | 0.4365 | 54 |
| | 8.74 | 20,646 | 1,590 | 1,465.135 | 3,850.96 | 266.70 | 2.39 | 435,483 | 0.4365 | 72 |
| | 9.53 | 22,517 | 1,731 | 1,594.166 | 4,178.70 | 266.70 | 2.39 | 433,548 | 0.4340 | 94 |
| | 10.31 | 24,324 | 1,873 | 1,719.036 | 4,522.83 | 266.70 | 2.39 | 431,612 | 0.4314 | 120 |
| | 11.13 | 26,261 | 2,018 | 1,848.068 | 4,850.57 | 266.70 | 2.39 | 429,677 | 0.4289 | 150 |
| | 11.91 | 28,066 | 2,159 | 1,972.937 | 5,178.31 | 264.16 | 2.39 | 427,741 | 0.4289 | 185 |
| | 12.70 | 29,874 | 2,299 | 2,097.806 | 5,506.05 | 264.16 | 2.39 | 426,451 | 0.4264 | 225 |
| | 14.27 | 33,550 | 2,578 | 2,343.383 | 6,145.15 | 264.16 | 2.39 | 422,580 | 0.4214 | 321 |
| | 15.88 | 37,228 | 2,861 | 2,588.959 | 6,800.63 | 264.16 | 2.39 | 418,709 | 0.4189 | 443 |
| | 17.48 | 40,907 | 3,143 | 2,834.536 | 7,439.73 | 264.16 | 2.39 | 415,483 | 0.4164 | 584 |

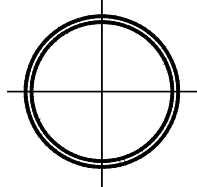
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|---------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| PP813 | 19.05 | 44,454 | 3,419 | 3,071.788 | 8,062.44 | 261.62 | 2.39 | 411,612 | 0.4114 | 719 |
| | 6.35 | 16,065 | 1,237 | 1,306.967 | 3,211.86 | 284.48 | 2.55 | 502,580 | 0.5017 | 23 |
| | 7.14 | 18,067 | 1,389 | 1,465.135 | 3,605.15 | 284.488 | 2.55 | 500,644 | 0.5017 | 32 |
| | 7.92 | 20,067 | 1,541 | 1,623.303 | 3,998.44 | 284.48 | 2.55 | 498,709 | 0.4992 | 44 |
| | 8.74 | 22,067 | 1,697 | 1,785.633 | 4,391.73 | 284.48 | 2.55 | 496,773 | 0.4967 | 60 |
| | 9.53 | 24,067 | 1,848 | 1,939.638 | 4,768.64 | 284.48 | 2.55 | 494,838 | 0.4942 | 77 |
| | 10.31 | 26,002 | 1,999 | 2,093.644 | 5,145.54 | 284.48 | 2.55 | 492,902 | 0.4916 | 98 |
| | 11.13 | 28,003 | 2,155 | 2,251.812 | 5,538.83 | 284.48 | 2.55 | 490,967 | 0.4916 | 124 |
| | 11.91 | 30,003 | 2,305 | 2,401.655 | 5,915.73 | 281.94 | 2.55 | 489,031 | 0.4891 | 152 |
| | 12.70 | 31,937 | 2,455 | 2,555.661 | 6,292.63 | 281.94 | 2.55 | 487,096 | 0.4866 | 185 |
| | 14.27 | 35,810 | 2,754 | 2,855.348 | 7,030.05 | 281.94 | 2.55 | 483,225 | 0.4841 | 264 |
| | 15.88 | 39,744 | 3,056 | 3,155.034 | 7,767.47 | 281.94 | 2.55 | 479,354 | 0.4791 | 364 |
| | 17.48 | 43,680 | 3,358 | 3,454.721 | 8,504.89 | 281.94 | 2.55 | 475,483 | 0.4741 | 487 |
| | 19.05 | 47,488 | 3,653 | 3,741.921 | 9,209.53 | 281.94 | 2.55 | 471,612 | 0.4716 | 617 |
| PP864 | 6.35 | 17,099 | 1,315 | 1,569.192 | 3,637.93 | 302.26 | 2.71 | 568,386 | 0.5694 | 19 |
| | 7.14 | 19,228 | 1,477 | 1,760.659 | 4,080.38 | 302.26 | 2.71 | 566,450 | 0.5669 | 27 |
| | 7.92 | 21,293 | 1,638 | 1,947.963 | 4,522.83 | 302.26 | 2.71 | 564,515 | 0.5644 | 37 |
| | 8.74 | 23,485 | 1,804 | 2,143.592 | 4,965.28 | 302.26 | 2.71 | 562,580 | 0.5619 | 50 |
| | 9.53 | 25,551 | 1,965 | 2,330.896 | 5,391.34 | 302.26 | 2.71 | 559,999 | 0.5594 | 64 |
| | 10.31 | 27,615 | 2,126 | 2,518.200 | 5,833.79 | 302.26 | 2.71 | 558,063 | 0.5569 | 82 |
| | 11.13 | 29,808 | 2,291 | 2,705.504 | 6,276.25 | 302.26 | 2.71 | 556,128 | 0.5569 | 103 |
| | 11.91 | 31,873 | 2,451 | 2,888.646 | 6,702.31 | 302.26 | 2.71 | 554,192 | 0.5544 | 127 |
| | 12.70 | 33,938 | 2,611 | 3,071.788 | 7,111.99 | 299.72 | 2.71 | 551,612 | 0.5518 | 154 |
| | 14.27 | 38,068 | 2,929 | 3,433.909 | 7,964.11 | 299.72 | 2.71 | 547,741 | 0.5468 | 219 |
| | 15.88 | 42,262 | 3,251 | 3,800.193 | 8,799.85 | 299.72 | 2.71 | 543,225 | 0.5443 | 303 |
| | 17.48 | 46,454 | 3,572 | 4,158.152 | 9,635.59 | 299.72 | 2.71 | 539,354 | 0.5393 | 405 |
| | 19.05 | 50,519 | 3,887 | 4,495.299 | 10,438.56 | 299.72 | 2.71 | 535,483 | 0.5343 | 527 |
| | 22.23 | 58,779 | 4,517 | 5,202.893 | 12,044.49 | 297.18 | 2.71 | 527,096 | 0.5268 | 767 |

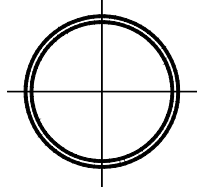
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| PP914 | 25.40 | 67,102 | 5,143 | 5,868.863 | 13,617.65 | 297.18 | 2.71 | 518,709 | 0.5192 | 1,010 |
| | 6.35 | 18,130 | 1,393 | 1,868.879 | 4,080.38 | 320.04 | 2.87 | 638,708 | 0.6396 | 16 |
| | 7.14 | 20,325 | 1,564 | 2,093.644 | 4,571.99 | 320.04 | 2.87 | 636,128 | 0.6371 | 23 |
| | 7.92 | 22,582 | 1,735 | 2,318.409 | 5,063.60 | 320.04 | 2.87 | 634,192 | 0.6346 | 31 |
| | 8.74 | 24,840 | 1,912 | 2,547.336 | 5,571.60 | 320.04 | 2.87 | 631,612 | 0.6321 | 42 |
| | 9.53 | 27,098 | 2,082 | 2,772.101 | 6,063.21 | 320.04 | 2.87 | 629,676 | 0.6296 | 54 |
| | 10.31 | 29,292 | 2,252 | 2,992.704 | 6,538.44 | 320.04 | 2.87 | 627,096 | 0.6271 | 69 |
| | 11.13 | 31,550 | 2,428 | 3,221.631 | 7,046.44 | 320.04 | 2.87 | 625,160 | 0.6246 | 87 |
| | 11.91 | 33,808 | 2,597 | 3,438.072 | 7,521.66 | 320.04 | 2.87 | 623,225 | 0.6221 | 107 |
| | 12.70 | 36,002 | 2,766 | 3,658.674 | 7,996.89 | 320.04 | 2.87 | 620,644 | 0.6221 | 129 |
| | 14.27 | 40,390 | 3,104 | 4,087.393 | 8,947.34 | 317.50 | 2.87 | 616,128 | 0.6171 | 184 |
| | 15.88 | 44,841 | 3,446 | 4,536.923 | 9,897.79 | 317.50 | 2.87 | 611,612 | 0.6120 | 254 |
| | 17.48 | 49,230 | 3,786 | 4,953.154 | 10,831.85 | 317.50 | 2.87 | 607,741 | 0.6070 | 341 |
| | 19.05 | 53,616 | 4,120 | 5,369.385 | 11,749.52 | 317.50 | 2.87 | 603,225 | 0.6020 | 443 |
| | 22.23 | 62,326 | 4,790 | 6,201.848 | 13,568.49 | 314.96 | 2.87 | 594,192 | 0.5945 | 674 |
| | 25.40 | 70,972 | 5,455 | 7,034.311 | 15,338.29 | 314.96 | 2.87 | 585,805 | 0.5870 | 900 |
| | 31.75 | 87,747 | 6,770 | 8,574.367 | 18,845.12 | 312.42 | 2.87 | 568,386 | 0.5694 | 1,380 |
| PP965 | 6.35 | 19,099 | 1,471 | 2,197.702 | 4,555.60 | 337.82 | 3.03 | 709,676 | 0.7124 | 14 |
| | 7.14 | 21,485 | 1,652 | 2,464.090 | 5,112.76 | 337.82 | 3.03 | 709,676 | 0.7099 | 19 |
| | 7.92 | 23,809 | 1,833 | 2,730.478 | 5,653.54 | 337.82 | 3.03 | 709,676 | 0.7074 | 26 |
| | 8.74 | 26,261 | 2,019 | 3,001.029 | 6,227.08 | 337.82 | 3.03 | 703,224 | 0.7049 | 35 |
| | 9.53 | 28,582 | 2,199 | 3,263.254 | 6,767.86 | 337.82 | 3.03 | 703,224 | 0.7023 | 46 |
| | 10.31 | 30,971 | 2,379 | 3,525.480 | 7,308.63 | 337.82 | 3.03 | 703,224 | 0.6998 | 59 |
| | 11.13 | 33,358 | 2,564 | 3,796.031 | 7,865.79 | 337.82 | 3.03 | 696,773 | 0.6973 | 74 |
| | 11.91 | 35,680 | 2,743 | 4,054.094 | 8,406.56 | 337.82 | 3.03 | 696,773 | 0.6973 | 90 |
| | 12.70 | 38,002 | 2,922 | 4,328.807 | 8,930.95 | 337.82 | 3.03 | 696,773 | 0.6923 | 110 |
| | 14.27 | 42,649 | 3,279 | 4,828.285 | 9,996.11 | 335.28 | 3.03 | 690,321 | 0.6898 | 156 |
| | 15.88 | 47,359 | 3,641 | 5,327.762 | 11,061.27 | 335.28 | 3.03 | 683,870 | 0.6848 | 216 |

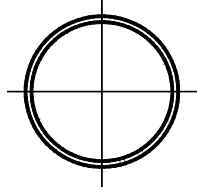
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Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

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PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 17.48 | 52,003 | 4,001 | 5,827.240 | 12,110.04 | 335.28 | 3.03 | 677,418 | 0.6798 | 289 |
| | 19.05 | 56,649 | 4,354 | 6,326.718 | 13,142.43 | 335.28 | 3.03 | 677,418 | 0.6748 | 376 |
| | 22.23 | 65,810 | 5,063 | 7,325.673 | 15,174.42 | 332.74 | 3.03 | 664,515 | 0.6647 | 590 |
| | 25.40 | 74,843 | 5,767 | 8,283.005 | 17,206.42 | 332.74 | 3.03 | 658,063 | 0.6572 | 805 |
| | 31.75 | 92,909 | 7,160 | 10,156.047 | 20,975.44 | 330.20 | 3.03 | 638,708 | 0.6396 | 1,230 |
| | 38.10 | 110,974 | 8,533 | 11,945.842 | 24,744.47 | 327.66 | 3.03 | 620,644 | 0.6221 | 1,780 |
| PP1016 | 7.92 | 25,098 | 1,930 | 3,188.333 | 6,276.25 | 355.60 | 3.20 | 787,095 | 0.7851 | 23 |
| | 8.74 | 27,679 | 2,126 | 3,508.831 | 6,898.95 | 355.60 | 3.20 | 780,644 | 0.7826 | 30 |
| | 9.53 | 30,131 | 2,316 | 3,812.680 | 7,505.28 | 355.60 | 3.20 | 780,644 | 0.7801 | 39 |
| | 10.31 | 32,583 | 2,505 | 4,120.691 | 8,111.60 | 355.60 | 3.20 | 780,644 | 0.7776 | 50 |
| | 11.13 | 35,099 | 2,701 | 4,453.676 | 8,734.31 | 355.60 | 3.20 | 774,192 | 0.7751 | 63 |
| | 11.91 | 37,551 | 2,890 | 4,745.038 | 9,324.24 | 355.60 | 3.20 | 774,192 | 0.7726 | 77 |
| | 12.70 | 40,002 | 3,078 | 5,036.400 | 9,914.17 | 355.60 | 3.20 | 767,740 | 0.7701 | 94 |
| | 14.27 | 44,906 | 3,454 | 5,619.124 | 11,094.04 | 353.06 | 3.20 | 767,740 | 0.7651 | 134 |
| | 15.88 | 49,874 | 3,836 | 6,243.471 | 12,273.91 | 353.06 | 3.20 | 761,289 | 0.7600 | 185 |
| | 17.48 | 54,842 | 4,215 | 6,826.195 | 13,453.78 | 353.06 | 3.20 | 754,837 | 0.7550 | 247 |
| | 19.05 | 59,681 | 4,588 | 7,408.919 | 14,600.87 | 353.06 | 3.20 | 748,386 | 0.7500 | 321 |
| | 22.23 | 69,682 | 5,336 | 8,574.367 | 16,878.68 | 350.52 | 3.20 | 741,934 | 0.7425 | 514 |
| | 25.40 | 79,360 | 6,078 | 9,698.192 | 19,172.86 | 350.52 | 3.20 | 729,031 | 0.7324 | 719 |
| | 31.75 | 98,070 | 7,549 | 11,904.219 | 23,433.50 | 347.98 | 3.20 | 709,676 | 0.7124 | 1,130 |
| | 38.10 | 116,781 | 9,001 | 14,026.999 | 27,530.27 | 345.44 | 3.20 | 696,773 | 0.6923 | 1,620 |
| | 44.45 | 135,492 | 10,433 | 16,024.910 | 31,627.03 | 342.90 | 3.20 | 677,418 | 0.6748 | 2,140 |
| PP1067 | 7.92 | 26,389 | 2,027 | 3,696.135 | 6,931.73 | 373.38 | 3.35 | 864,514 | 0.8679 | 20 |
| | 8.74 | 29,034 | 2,233 | 4,066.581 | 7,619.98 | 373.38 | 3.35 | 864,514 | 0.8654 | 26 |
| | 9.53 | 31,615 | 2,433 | 4,412.053 | 8,291.85 | 373.38 | 3.35 | 864,514 | 0.8629 | 34 |
| | 10.31 | 34,260 | 2,632 | 4,786.661 | 8,947.34 | 373.38 | 3.35 | 864,514 | 0.8604 | 43 |
| | 11.13 | 36,905 | 2,837 | 5,161.270 | 9,635.59 | 373.38 | 3.35 | 858,063 | 0.8579 | 54 |
| | 11.91 | 39,486 | 3,036 | 5,494.255 | 10,291.08 | 373.38 | 3.35 | 851,611 | 0.8554 | 67 |

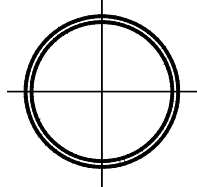
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|------------------|-----------------------------------|-----------------------------------|--------|--------------------------|-----------------------------|-------------------|-------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 12.70 | 42,067 | 3,234 | 5,827.240 | 10,946.56 | 373.38 | 3.35 | 851,611 | 0.8528 | 81 |
| | 14.27 | 47,229 | 3,630 | 6,534.833 | 12,257.52 | 373.38 | 3.35 | 845,160 | 0.8478 | 116 |
| | 15.88 | 52,390 | 4,030 | 7,242.427 | 13,568.49 | 370.84 | 3.35 | 838,708 | 0.8403 | 159 |
| | 17.48 | 57,616 | 4,430 | 7,950.020 | 14,863.07 | 370.84 | 3.35 | 838,708 | 0.8353 | 213 |
| | 19.05 | 62,713 | 4,822 | 8,615.991 | 16,141.26 | 370.84 | 3.35 | 832,256 | 0.8303 | 277 |
| | 22.23 | 72,908 | 5,608 | 9,947.931 | 18,681.25 | 368.30 | 3.35 | 819,353 | 0.8202 | 443 |
| | 25.40 | 83,231 | 6,390 | 11,279.872 | 21,139.31 | 368.30 | 3.35 | 812,902 | 0.8102 | 641 |
| | 31.75 | 103,232 | 7,939 | 13,818.883 | 25,891.56 | 365.76 | 3.35 | 793,547 | 0.7901 | 1,030 |
| | 38.10 | 123,233 | 9,468 | 16,316.272 | 30,643.81 | 363.22 | 3.35 | 767,740 | 0.7701 | 1,460 |
| | 44.45 | 142,589 | 10,978 | 18,688.791 | 35,068.32 | 360.68 | 3.35 | 748,386 | 0.7500 | 1,970 |
| | 50.80 | 161,945 | 12,468 | 20,978.064 | 39,328.95 | 360.68 | 3.35 | 729,031 | 0.7324 | 2,470 |
| PP1118 | 8.74 | 30,453 | 2,341 | 4,661.792 | 8,373.79 | 391.16 | 3.51 | 948,385 | 0.9507 | 23 |
| | 9.53 | 33,163 | 2,550 | 5,078.023 | 9,111.21 | 391.16 | 3.51 | 948,385 | 0.9482 | 30 |
| | 10.31 | 35,873 | 2,759 | 5,494.255 | 9,832.24 | 391.16 | 3.51 | 941,934 | 0.9457 | 38 |
| | 11.13 | 38,647 | 2,974 | 5,910.486 | 10,586.04 | 391.16 | 3.51 | 941,934 | 0.9432 | 47 |
| | 11.91 | 41,357 | 3,182 | 6,326.718 | 11,323.46 | 391.16 | 3.51 | 941,934 | 0.9406 | 58 |
| | 12.70 | 44,067 | 3,390 | 6,742.949 | 12,044.49 | 391.16 | 3.51 | 935,482 | 0.9381 | 70 |
| | 15.88 | 54,971 | 4,225 | 8,324.629 | 14,928.62 | 388.62 | 3.51 | 929,030 | 0.9256 | 138 |
| | 19.05 | 65,810 | 5,056 | 9,906.308 | 17,698.03 | 388.62 | 3.51 | 916,127 | 0.9156 | 241 |
| | 22.23 | 76,779 | 5,881 | 11,487.987 | 20,483.83 | 388.62 | 3.51 | 903,224 | 0.9055 | 384 |
| | 25.40 | 87,102 | 6,702 | 12,986.420 | 23,269.63 | 386.08 | 3.51 | 896,772 | 0.8930 | 571 |
| | 31.75 | 108,394 | 8,328 | 15,983.287 | 28,513.49 | 383.54 | 3.51 | 870,966 | 0.8729 | 941 |
| | 38.10 | 129,040 | 9,936 | 18,855.284 | 33,757.35 | 381.00 | 3.51 | 851,611 | 0.8528 | 1,300 |
| | 44.45 | 149,686 | 11,524 | 21,602.411 | 38,673.47 | 381.00 | 3.51 | 832,256 | 0.8303 | 1,810 |
| | 50.80 | 170,333 | 13,092 | 24,266.292 | 43,425.72 | 378.46 | 3.51 | 812,902 | 0.8102 | 2,290 |
| | 57.15 | 190,334 | 14,641 | 26,846.927 | 48,014.10 | 375.92 | 3.51 | 793,547 | 0.7901 | 2,770 |
| PP1219 | 8.74 | 33,228 | 2,555 | 6,076.979 | 9,979.72 | 426.72 | 3.84 | 1,135,482 | 1.1338 | 18 |
| | 9.53 | 36,196 | 2,784 | 6,618.080 | 10,864.62 | 426.72 | 3.84 | 1,129,030 | 1.1313 | 23 |

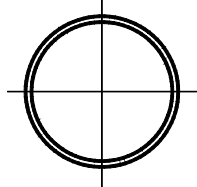
Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|---|-------------------|-----------------|------------------------|-----------------------------------|-----------------------------------|--------|--------------------------------|--------------------------------------|-------------------|-------------------------------|
| | | | | I | S | r | | | | |
| mm | mm | mm ² | N | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | m ² /m | mm ² | m ³ /m | * |
| | 10.31 | 39,164 | 3,012 | 7,159.181 | 11,733.14 | 426.72 | 3.84 | 1,129,030 | 1.1288 | 29 |
| | 11.13 | 42,196 | 3,247 | 7,700.281 | 12,634.43 | 426.72 | 3.84 | 1,122,578 | 1.1263 | 36 |
| | 11.91 | 45,164 | 3,474 | 8,241.382 | 13,502.94 | 426.72 | 3.84 | 1,122,578 | 1.1212 | 45 |
| | 12.70 | 48,132 | 3,702 | 8,740.860 | 14,371.46 | 426.72 | 3.84 | 1,116,127 | 1.1187 | 54 |
| | 15.88 | 60,004 | 4,615 | 10,863.640 | 17,861.90 | 426.72 | 3.84 | 1,109,675 | 1.1087 | 106 |
| | 19.05 | 71,617 | 5,523 | 12,944.797 | 21,139.31 | 424.18 | 3.84 | 1,096,772 | 1.0962 | 185 |
| | 22.23 | 83,876 | 6,427 | 14,984.331 | 24,580.60 | 424.18 | 3.84 | 1,083,869 | 1.0836 | 295 |
| | 25.40 | 95,490 | 7,325 | 16,982.242 | 27,858.01 | 421.64 | 3.84 | 1,070,966 | 1.0711 | 443 |
| | 31.75 | 118,717 | 9,108 | 20,894.818 | 34,248.96 | 419.10 | 3.84 | 1,051,611 | 1.0485 | 787 |
| | 38.10 | 141,299 | 10,871 | 24,682.524 | 40,476.05 | 416.56 | 3.84 | 1,025,804 | 1.0259 | 1,130 |
| | 44.45 | 163,881 | 12,614 | 28,345.360 | 46,539.26 | 416.56 | 3.84 | 1,006,450 | 1.0034 | 1,530 |
| | 50.80 | 186,463 | 14,339 | 31,883.327 | 52,274.73 | 414.02 | 3.84 | 980,643 | 0.9808 | 1,970 |
| | 57.15 | 208,400 | 16,043 | 35,296.425 | 57,846.34 | 411.48 | 3.84 | 961,288 | 0.9582 | 2,410 |
| | 63.50 | 230,336 | 17,729 | 38,626.276 | 63,254.07 | 408.94 | 3.84 | 935,482 | 0.9381 | 2,850 |

Pile design data converted to SI units from US units published in 1985 version of this manual.

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP219 x 2.77

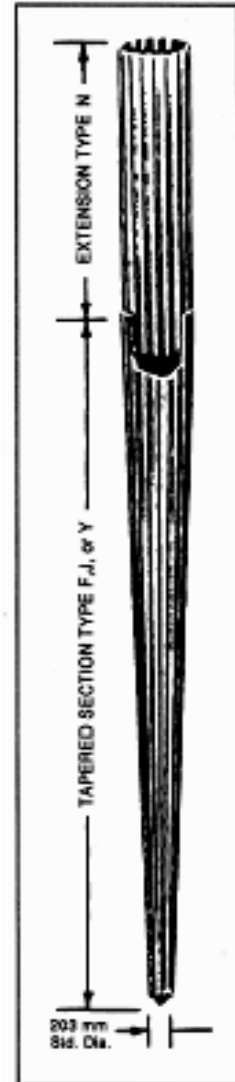
* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

MONOTUBE PILES **Standard Monotube Weights and Volumes**

| TYPE | SIZE POINT DIAMETER x BUTT DIAMETER x LENGTH | Weight (N) per m | | | | EST. CONC. VOL. m ³ |
|------------------------------------|--|------------------|-------|-------|-------|---|
| | | 9 GA. | 7 GA. | 5 GA. | 3 GA. | |
| F Taper 3.6 mm per Meter | 216 mm x 305 mm x 7.62 m | 248 | 292 | 350 | 409 | 0.329 |
| | 203 mm x 305 mm x 9.14 m | 233 | 292 | 336 | 394 | 0.420 |
| | 216 mm x 356 mm x 12.19 m | 277 | 321 | 379 | 452 | 0.726 |
| | 203 mm x 406 mm x 18.29 m | 292 | 350 | 409 | 482 | 1.284 |
| | 203 mm x 457 mm x 22.86 m | - | 379 | 452 | 511 | 1.979 |
| J Taper 6.4 mm per Meter | 203 mm x 305 mm x 5.18 m | 248 | 292 | 336 | 394 | 0.244 |
| | 203 mm x 356 mm x 7.62 m | 263 | 321 | 379 | 438 | 0.443 |
| | 203 mm x 406 mm x 10.06 m | 292 | 350 | 409 | 467 | 0.726 |
| | 203 mm x 457 mm x 12.19 m | - | 379 | 438 | 511 | 1.047 |
| Y Taper 10.2 mm per Meter | 203 mm x 305 mm x 3.05 m | 248 | 292 | 350 | 409 | 0.138 |
| | 203 mm x 356 mm x 4.57 m | 277 | 321 | 379 | 438 | 0.260 |
| | 203 mm x 406 mm x 6.10 m | 292 | 350 | 409 | 482 | 0.428 |
| | 203 mm x 457 mm x 7.62 m | - | 379 | 452 | 511 | 0.657 |

Extensions (Overall Length 0.305 m Greater than indicated)

| TYPE | DIAMETER + LENGTH | 9 GA. | 7 GA. | 5 GA. | 3 GA. | m ³ /m |
|------|------------------------------------|-------|-------|-------|-------|-------------------|
| N 12 | 305 mm x 305 mm x 6.10 / 12.19 m | 292 | 350 | 409 | 482 | 0.065 |
| N 14 | 356 mm x 356 mm x 6.10 m / 12.19 m | 350 | 423 | 496 | 598 | 0.088 |
| N 16 | 406 mm x 406 mm x 6.10 m / 12.19 m | 409 | 482 | 569 | 671 | 0.113 |
| N 18 | 457 mm x 457 mm x 6.10 m / 12.19 m | - | 555 | 642 | 759 | 0.145 |



Note: Designer must confirm section properties of selected pile section.

Pile design data converted to SI units from US units published in Monotube Pile Corporation Catalog 592.

MONOTUBE PILES

Physical Properties

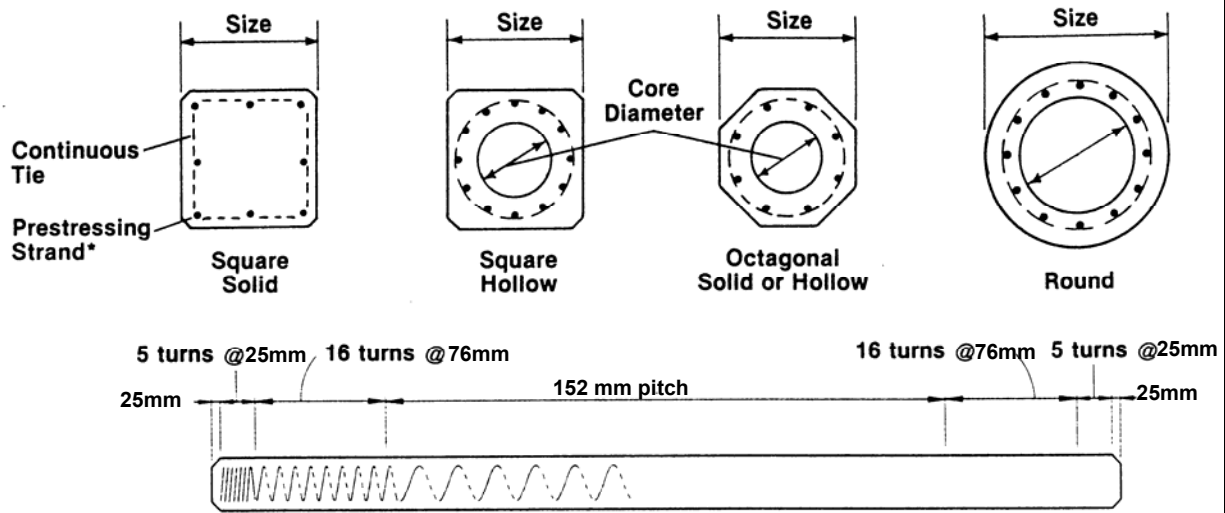
| STEEL THICKNESS | POINTS | | BUTTS OF PILE SECTIONS | | | | | | | |
|----------------------------------|-------------------|-------------------|------------------------|-------------------------------------|-------------------------------------|------|-------------------|-------------------------------------|-------------------------------------|------|
| | 203 mm | 216 mm | 305 mm | | | | 356 mm | | | |
| | A mm ² | A mm ² | A mm ² | I mm ⁴ x 10 ⁶ | S mm ³ x 10 ³ | r mm | A mm ² | I mm ⁴ x 10 ⁶ | S mm ³ x 10 ³ | r mm |
| 9 GAUGE 3.797 mm | 2,342 | 2,535 | 3,748 | 42.456 | 267.109 | 106 | 4,355 | 66.181 | 360.515 | 123 |
| 7 GAUGE 4.554 mm | 2,839 | 3,077 | 4,497 | 50.780 | 319.548 | 106 | 5,252 | 80.749 | 437.535 | 124 |
| 5 GAUGE 5.314 mm | 3,348 | 3,619 | 5,277 | 60.354 | 376.902 | 107 | 6,129 | 94.485 | 507.999 | 124 |
| 3 GAUGE 6.073 mm | 3,787 | 4,245 | 5,781 | 61.602 | 396.567 | 103 | 6,839 | 99.479 | 550.605 | 121 |
| CONCRETE AREA mm ² | 27,290 | 30,518 | 65,161 | | | | 87,742 | | | |

| STEEL THICKNESS | POINTS | | BUTTS OF PILE SECTIONS | | | | | | | |
|----------------------------------|-------------------|-------------------|------------------------|-------------------------------------|-------------------------------------|------|-------------------|-------------------------------------|-------------------------------------|------|
| | 203 mm | 216 mm | 406 mm | | | | 457 mm | | | |
| | A mm ² | A mm ² | A mm ² | I mm ⁴ x 10 ⁶ | S mm ³ x 10 ³ | r mm | A mm ² | I mm ⁴ x 10 ⁶ | S mm ³ x 10 ³ | r mm |
| 9 GAUGE 3.797 mm | 2,342 | 2,535 | 4,929 | 96.566 | 463.754 | 140 | - | - | - | - |
| 7 GAUGE 4.554 mm | 2,839 | 3,077 | 5,923 | 115.712 | 555.521 | 140 | 6,710 | 168.157 | 712.837 | 158 |
| 5 GAUGE 5.314 mm | 3,348 | 3,619 | 6,968 | 136.940 | 555.521 | 140 | 7,871 | 198.959 | 839.018 | 159 |
| 3 GAUGE 6.073 mm | 3,787 | 4,245 | 7,742 | 144.849 | 706.282 | 137 | 8,774 | 209.781 | 907.843 | 155 |
| CONCRETE AREA mm ² | 27,290 | 30,518 | 113,548 | | | | 144,516 | | | |

Note: Designer must confirm section properties of selected pile section.

Pile design data converted to SI units from US units published in Monotube Pile Corporation Catalog 592.

PRECAST/PRESTRESSED CONCRETE PILES



* Strand pattern may be circular or square.

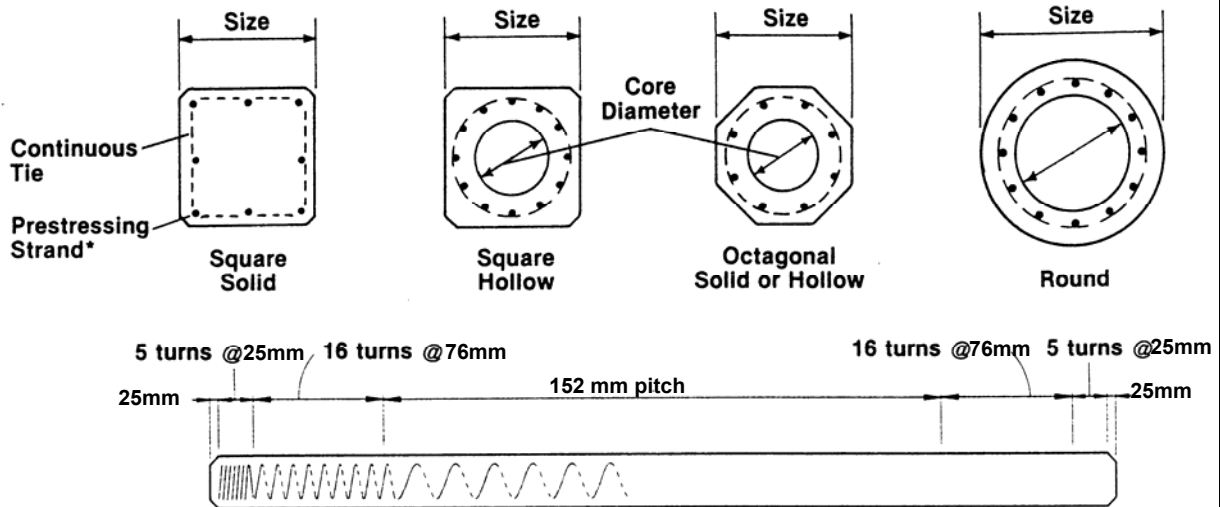
Typical Elevation

| | | Section Properties | | | | | |
|--------------|------------------------|-------------------------|---------------|---|---|-----------------------------|----------------|
| Size mm | Core Diameter mm | Area mm ² | Weight N/m | Moment of Inertia mm ⁴ x 10 ⁶ | Section Modulus mm ³ x 10 ³ | Radius of Gyration mm | Perimeter m |
| Square Piles | | | | | | | |
| 254 | Solid | 64,516 | 1,518 | 346.721 | 2,736.640 | 73.4 | 1.015 |
| 305 | Solid | 92,903 | 2,189 | 719.248 | 4,719.474 | 87.9 | 1.219 |
| 356 | Solid | 126,451 | 2,977 | 1,332.357 | 7,488.888 | 102.6 | 1.423 |
| 406 | Solid | 165,161 | 3,896 | 2,273.040 | 11,192.365 | 117.3 | 1.625 |
| 457 | Solid | 209,032 | 4,932 | 3,641.193 | 15,928.226 | 132.1 | 1.829 |
| 508 | Solid | 258,064 | 6,085 | 5,549.614 | 21,843.956 | 146.6 | 2.033 |
| 508 | 279 mm | 196,774 | 4,641 | 5,250.759 | 20,680.475 | 163.3 | 2.033 |
| 610 | Solid | 371,612 | 8,756 | 11,507.966 | 37,755.795 | 176.0 | 2.438 |
| 610 | 305 mm | 298,709 | 7,034 | 11,084.243 | 36,362.895 | 192.5 | 2.438 |
| 610 | 356 mm | 272,258 | 6,406 | 10,722.954 | 35,183.026 | 198.4 | 2.438 |
| 610 | 381 mm | 257,419 | 6,056 | 10,473.631 | 34,363.673 | 201.7 | 2.438 |
| 762 | 457 mm | 416,773 | 9,807 | 25,950.781 | 68,121.025 | 249.4 | 3.048 |
| 914 | 457 mm | 672,257 | 15,834 | 56,114.240 | 122,739.109 | 289.1 | 3.658 |

Note: Designer must confirm section properties for a selected pile. Form dimensions may vary with producers, with corresponding variations in section properties.

Data converted to SI units from US unit properties in PCI (1993), Precast/Prestressed Concrete Institute Journal, Volume 38, No. 2, March-April, 1993.

PRECAST/PRESTRESSED CONCRETE PILES



* Strand pattern may be circular or square.

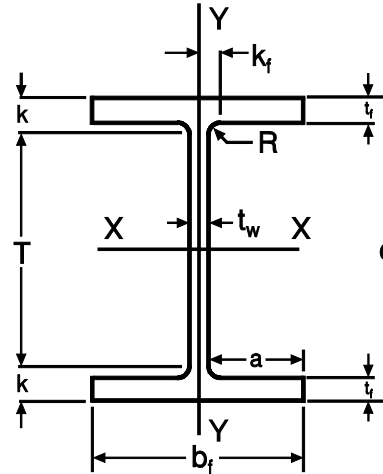
Typical Elevation

| | | Section Properties | | | | | |
|-----------------|------------------------|-------------------------|---------------|---|---|-----------------------------|----------------|
| Size mm | Core Diameter mm | Area mm ² | Weight N/m | Moment of Inertia mm ⁴ x 10 ⁶ | Section Modulus mm ³ x 10 ³ | Radius of Gyration mm | Perimeter m |
| Octagonal Piles | | | | | | | |
| 254 | Solid | 53,548 | 1,240 | 231.008 | 1,818.964 | 65.8 | 0.841 |
| 305 | Solid | 76,774 | 1,824 | 472.006 | 3,097.155 | 78.5 | 1.009 |
| 356 | Solid | 104,516 | 2,466 | 876.167 | 4,932.506 | 91.4 | 1.180 |
| 406 | Solid | 136,774 | 3,210 | 1,495.103 | 7,357.792 | 104.6 | 1.347 |
| 457 | Solid | 172,903 | 4,086 | 2,374.600 | 10,471.334 | 117.1 | 1.515 |
| 508 | Solid | 213,548 | 5,035 | 3,650.350 | 14,371.455 | 130.8 | 1.682 |
| 508 | 279 mm | 152,258 | 3,575 | 3,350.663 | 13,191.587 | 148.3 | 1.682 |
| 559 | Solid | 258,709 | 6,129 | 5,343.163 | 19,123.704 | 143.8 | 1.853 |
| 559 | 330 mm | 172,903 | 4,086 | 4,761.688 | 17,042.547 | 165.9 | 1.853 |
| 610 | Solid | 307,741 | 7,224 | 7,567.087 | 24,826.402 | 156.7 | 2.021 |
| 610 | 381 mm | 193,548 | 4,597 | 6,533.168 | 21,434.280 | 183.6 | 2.021 |
| Round Piles | | | | | | | |
| 914 | 660 mm | 314,193 | 7,399 | 24,976.799 | 54,634.471 | 281.9 | 2.874 |
| 1,067 | 813 mm | 374,838 | 8,829 | 42,153.005 | 79,034.810 | 335.3 | 3.353 |
| 1,219 | 965 mm | 435,483 | 10,259 | 65,856.969 | 108,023.526 | 388.9 | 3.831 |
| 1,372 | 1118 mm | 496,773 | 11,704 | 97,137.176 | 141,633.394 | 442.2 | 4.310 |
| 1,676 | 1372 mm | 729,676 | 17,191 | 213,954.191 | 255,261.296 | 541.5 | 5.267 |

Note: Designer must confirm section properties for a selected pile. Form dimensions may vary with producers, with corresponding variations in section properties.

Data converted to SI units from US unit properties in PCI (1993), Precast/Prestressed Concrete Institute Journal, Volume 38, No. 2, March-April, 1993.

H-PILES



| Section Designation | Area A | Depth d | Web Thickness t _w | Flange | | Distance | | | | Fillet Radius R | Elastic Properties | | | | | |
|------------------------|-----------------|------------|------------------------------------|-------------------------|-----------------------------|----------|----|----------------|-----|-----------------------|-----------------------------------|-----------------------------------|-----|-----------------------------------|-----------------------------------|----|
| | | | | Width b _f | Thickness t _f | T | k | k _f | a | | X-X | | | Y-Y | | |
| | | | | | | | | | | | I | S | r | I | S | r |
| mm x kg/m | mm ² | mm | mm | mm | mm | mm | mm | mm | mm | mm | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm | mm ⁴ x 10 ⁶ | mm ³ x 10 ³ | mm |
| HP360 x 174 | 22,200 | 361 | 20.4 | 378 | 20 | 277 | 42 | 30.2 | 179 | 20 | 511 | 2,830 | 152 | 183 | 968 | 91 |
| HP360 x 152 | 19,400 | 356 | 17.9 | 376 | 18 | 277 | 40 | 29.0 | 179 | 20 | 442 | 2,480 | 151 | 158 | 840 | 90 |
| HP360 x 132 | 16,900 | 351 | 15.6 | 373 | 16 | 277 | 37 | 27.8 | 179 | 20 | 378 | 2,150 | 150 | 135 | 724 | 89 |
| HP360 x 108 | 13,800 | 346 | 12.8 | 370 | 13 | 277 | 34 | 26.4 | 179 | 20 | 306 | 1,770 | 148 | 108 | 584 | 88 |
| HP310 x 125 | 15,800 | 312 | 17.4 | 312 | 17 | 244 | 34 | 23.7 | 147 | 15 | 270 | 1,730 | 131 | 88 | 565 | 75 |
| HP310 x 110 | 14,000 | 308 | 15.4 | 310 | 15 | 244 | 32 | 22.7 | 147 | 15 | 236 | 1,530 | 130 | 77 | 497 | 74 |
| HP310 x 93 | 11,800 | 303 | 13.1 | 308 | 13 | 244 | 30 | 21.6 | 148 | 15 | 196 | 1,290 | 129 | 64 | 414 | 74 |
| HP310 x 79 | 9,970 | 299 | 11.0 | 306 | 11 | 244 | 28 | 20.5 | 148 | 15 | 162 | 1,080 | 127 | 53 | 343 | 73 |
| HP250 x 85 | 10,800 | 254 | 14.4 | 260 | 14 | 196 | 29 | 20.2 | 123 | 13 | 123 | 969 | 107 | 42 | 325 | 63 |
| HP250 x 62 | 7,980 | 246 | 10.5 | 256 | 11 | 96 | 25 | 18.3 | 123 | 13 | 88 | 711 | 105 | 30 | 234 | 61 |
| HP200 x 53 | 6,810 | 204 | 11.3 | 207 | 11 | 158 | 23 | 15.7 | 98 | 10 | 50 | 487 | 86 | 17 | 161 | 50 |

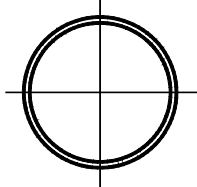
Note: Designer must confirm section properties for a selected pile.

Data obtained from FHWA Geotechnical Metrication Guidelines (1995) FHWA-SA-95-035.

APPENDIX C-2

Information and Data on Various Pile Types, US Units

| | Page |
|---|-------------|
| Dimensions and Properties of Pipe Piles | C2-3 |
| Data for Steel Monotube Piles..... | C2-17 |
| Typical Prestressed Concrete Pile Sections..... | C2-19 |
| Dimensions and Properties of H-Piles..... | C2-21 |



PIPE PILES

Approximate Pile Dimensions and Design Properties

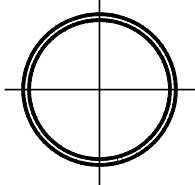
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|---|-------------------|-----------------|-----------------------|--------------------|-----------------|------|--------------------------------|--------------------------------------|---------------------|-------------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP8 | 0.141 | 3.48 | 11.83 | 26.9 | 6.72 | 2.78 | 2.09 | 46.8 | 0.0120 | 266 |
| | 0.164 | 4.04 | 13.72 | 31.0 | 7.75 | 2.77 | 2.09 | 46.2 | 0.0119 | 422 |
| | 0.172 | 4.23 | 14.38 | 32.4 | 8.10 | 2.77 | 2.09 | 46.0 | 0.0118 | 487 |
| | 0.179 | 4.40 | 14.95 | 33.6 | 8.41 | 2.77 | 2.09 | 45.9 | 0.0118 | 548 |
| | 0.188 | 4.61 | 15.69 | 35.2 | 8.80 | 2.76 | 2.09 | 45.7 | 0.0117 | 621 |
| | 0.219 | 5.35 | 18.20 | 40.5 | 10.1 | 2.75 | 2.09 | 44.9 | 0.0116 | 874 |
| PP8-5/8 | 0.109 | 2.92 | 9.91 | 26.4 | 6.13 | 3.01 | 2.26 | 55.5 | 0.0143 | 97 |
| | 0.125 | 3.34 | 11.35 | 30.2 | 6.99 | 3.01 | 2.26 | 55.1 | 0.0142 | 147 |
| | 0.141 | 3.76 | 12.78 | 33.8 | 7.84 | 3.00 | 2.26 | 54.7 | 0.0141 | 212 |
| | 0.156 | 4.15 | 14.11 | 37.2 | 8.63 | 2.99 | 2.26 | 54.3 | 0.0140 | 288 |
| | 0.164 | 4.36 | 14.82 | 39.0 | 9.05 | 2.99 | 2.26 | 54.1 | 0.0139 | 335 |
| | 0.172 | 4.57 | 15.53 | 40.8 | 9.46 | 2.99 | 2.26 | 53.9 | 0.0139 | 388 |
| | 0.179 | 4.75 | 16.15 | 42.4 | 9.82 | 2.99 | 2.26 | 53.7 | 0.0138 | 438 |
| | 0.188 | 4.98 | 16.94 | 44.4 | 10.3 | 2.98 | 2.26 | 53.4 | 0.0137 | 508 |
| | 0.203 | 5.37 | 18.26 | 47.6 | 11.0 | 2.98 | 2.26 | 53.1 | 0.0136 | 623 |
| | 0.219 | 5.78 | 19.66 | 51.1 | 11.9 | 2.97 | 2.26 | 52.6 | 0.0135 | 744 |
| | 0.250 | 6.58 | 22.36 | 57.7 | 13.4 | 2.96 | 2.26 | 51.8 | 0.0133 | 979 |
| | 0.277 | 7.26 | 24.70 | 63.4 | 14.7 | 2.95 | 2.26 | 51.2 | 0.0132 | 1180 |
| | 0.312 | 8.15 | 27.70 | 70.5 | 16.3 | 2.94 | 2.26 | 50.3 | 0.0129 | 1500 |
| | 0.322 | 8.40 | 28.55 | 72.5 | 16.8 | 2.94 | 2.26 | 50.0 | 0.0129 | 1600 |
| | 0.344 | 8.95 | 30.42 | 76.8 | 17.8 | 2.93 | 2.26 | 49.5 | 0.0127 | 1820 |
| | 0.375 | 9.72 | 33.04 | 82.9 | 19.2 | 2.92 | 2.26 | 48.7 | 0.0125 | 2120 |
| | 0.406 | 10.50 | 35.64 | 88.7 | 20.6 | 2.91 | 2.26 | 47.9 | 0.0123 | 2420 |
| | 0.438 | 11.3 | 38.30 | 94.7 | 21.9 | 2.90 | 2.26 | 47.2 | 0.0121 | 2740 |
| | 0.500 | 12.8 | 43.39 | 106.0 | 24.5 | 2.88 | 2.26 | 45.7 | 0.0117 | 3340 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

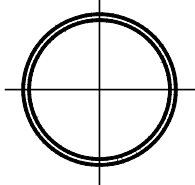
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP10 | 0.109 | 3.39 | 11.51 | 41.4 | 8.28 | 3.50 | 2.62 | 75.2 | 0.0193 | 62 |
| | 0.120 | 3.72 | 12.66 | 45.5 | 9.09 | 3.49 | 2.62 | 74.8 | 0.0192 | 83 |
| | 0.134 | 4.15 | 14.12 | 50.5 | 10.10 | 3.49 | 2.62 | 74.4 | 0.0191 | 116 |
| | 0.141 | 4.37 | 14.85 | 53.1 | 10.60 | 3.49 | 2.62 | 74.2 | 0.0191 | 135 |
| | 0.150 | 4.64 | 15.78 | 56.3 | 11.30 | 3.48 | 2.62 | 73.9 | 0.0190 | 163 |
| | 0.164 | 5.07 | 17.23 | 61.3 | 12.30 | 3.48 | 2.62 | 73.5 | 0.0189 | 214 |
| | 0.172 | 5.31 | 18.05 | 64.1 | 12.80 | 3.48 | 2.62 | 73.2 | 0.0188 | 247 |
| | 0.179 | 5.52 | 18.78 | 66.6 | 13.30 | 3.47 | 2.62 | 73.0 | 0.0188 | 279 |
| | 0.188 | 5.80 | 19.70 | 69.8 | 14.00 | 3.47 | 2.62 | 72.7 | 0.0187 | 324 |
| | 0.203 | 6.25 | 21.24 | 75.0 | 15.00 | 3.46 | 2.62 | 72.3 | 0.0186 | 409 |
| | 0.219 | 6.73 | 22.88 | 80.5 | 16.10 | 3.46 | 2.62 | 71.8 | 0.0185 | 515 |
| | 0.230 | 7.06 | 24.00 | 84.3 | 16.90 | 3.46 | 2.62 | 71.5 | 0.0184 | 588 |
| | 0.250 | 7.66 | 26.03 | 91.1 | 18.20 | 3.45 | 2.62 | 70.9 | 0.0182 | 719 |
| PP10-3/4 | 0.109 | 3.64 | 12.39 | 51.6 | 9.60 | 3.76 | 2.81 | 87.1 | 0.0224 | 50 |
| | 0.120 | 4.01 | 13.62 | 56.6 | 10.50 | 3.76 | 2.81 | 86.8 | 0.0223 | 67 |
| | 0.125 | 4.17 | 14.18 | 58.9 | 11.00 | 3.76 | 2.81 | 86.6 | 0.0223 | 76 |
| | 0.134 | 4.47 | 15.19 | 63.0 | 11.70 | 3.75 | 2.81 | 86.3 | 0.0222 | 93 |
| | 0.141 | 4.70 | 15.98 | 66.1 | 12.30 | 3.75 | 2.81 | 86.1 | 0.0221 | 109 |
| | 0.150 | 5.00 | 16.98 | 70.2 | 13.10 | 3.75 | 2.81 | 85.8 | 0.0221 | 131 |
| | 0.156 | 5.19 | 17.65 | 72.9 | 13.60 | 3.75 | 2.81 | 85.6 | 0.0220 | 148 |
| | 0.164 | 5.45 | 18.54 | 76.4 | 14.20 | 3.74 | 2.81 | 85.3 | 0.0219 | 172 |
| | 0.172 | 5.72 | 19.43 | 80.0 | 14.90 | 3.74 | 2.81 | 85.0 | 0.0219 | 199 |
| | 0.179 | 5.94 | 20.21 | 83.1 | 15.50 | 3.74 | 2.81 | 84.8 | 0.0218 | 224 |
| | 0.188 | 6.24 | 21.21 | 87.0 | 16.20 | 3.73 | 2.81 | 84.5 | 0.0217 | 260 |
| | 0.203 | 6.73 | 22.87 | 93.6 | 17.40 | 3.73 | 2.81 | 84.0 | 0.0216 | 328 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

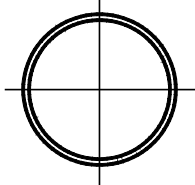
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| In | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP10-3/4 (cont'd) | 0.219 | 7.25 | 24.63 | 100.0 | 18.7 | 3.72 | 2.81 | 83.5 | 0.0215 | 414 |
| | 0.230 | 7.60 | 25.84 | 105.0 | 19.6 | 3.72 | 2.81 | 83.2 | 0.0214 | 480 |
| | 0.250 | 8.25 | 28.04 | 114.0 | 21.2 | 3.71 | 2.81 | 82.5 | 0.0212 | 605 |
| | 0.279 | 9.18 | 31.20 | 126.0 | 23.4 | 3.70 | 2.81 | 81.6 | 0.0210 | 781 |
| | 0.307 | 10.10 | 34.24 | 137.0 | 25.6 | 3.69 | 2.81 | 80.7 | 0.0208 | 951 |
| | 0.344 | 11.20 | 38.23 | 152.0 | 28.4 | 3.68 | 2.81 | 79.5 | 0.0205 | 1180 |
| | 0.365 | 11.90 | 40.48 | 161.0 | 29.9 | 3.67 | 2.81 | 78.9 | 0.0230 | 1320 |
| | 0.438 | 14.20 | 48.24 | 189.0 | 35.2 | 3.65 | 2.81 | 76.6 | 0.0197 | 1890 |
| | 0.500 | 16.10 | 54.74 | 212.0 | 39.4 | 3.63 | 2.81 | 74.7 | 0.0192 | 2380 |
| PP12 | 0.134 | 5.00 | 16.98 | 87.9 | 14.7 | 4.20 | 3.14 | 108.0 | 0.0278 | 67 |
| | 0.141 | 5.25 | 17.86 | 92.4 | 15.4 | 4.19 | 3.14 | 108.0 | 0.0277 | 78 |
| | 0.150 | 5.58 | 18.98 | 98.0 | 16.3 | 4.19 | 3.14 | 108.0 | 0.0277 | 94 |
| | 0.164 | 6.10 | 20.73 | 107.0 | 17.8 | 4.19 | 3.14 | 107.0 | 0.0275 | 123 |
| | 0.172 | 6.39 | 21.73 | 112.0 | 18.6 | 4.18 | 3.14 | 107.0 | 0.0274 | 142 |
| | 0.179 | 6.65 | 22.60 | 116.0 | 19.4 | 4.18 | 3.14 | 106.0 | 0.0274 | 161 |
| | 0.188 | 6.98 | 23.72 | 122.0 | 20.3 | 4.18 | 3.14 | 106.0 | 0.0273 | 186 |
| | 0.203 | 7.52 | 25.58 | 131.0 | 21.8 | 4.17 | 3.14 | 106.0 | 0.0272 | 235 |
| | 0.219 | 8.11 | 27.55 | 141.0 | 23.4 | 4.17 | 3.14 | 105.0 | 0.0270 | 296 |
| | 0.230 | 8.50 | 28.91 | 147.0 | 24.6 | 4.16 | 3.14 | 105.0 | 0.0269 | 344 |
| | 0.250 | 9.23 | 31.37 | 159.0 | 26.6 | 4.16 | 3.14 | 104.0 | 0.0267 | 443 |
| | 0.281 | 10.30 | 35.17 | 178.0 | 29.6 | 4.14 | 3.14 | 103.0 | 0.0264 | 616 |
| | 0.312 | 11.50 | 38.95 | 196.0 | 32.6 | 4.13 | 3.14 | 102.0 | 0.0261 | 784 |
| PP12-3/4 | 0.109 | 4.33 | 14.72 | 86.5 | 13.6 | 4.47 | 3.34 | 123.0 | 0.0317 | 30 |
| | 0.125 | 4.96 | 16.85 | 98.8 | 15.5 | 4.46 | 3.34 | 123.0 | 0.0316 | 45 |
| | 0.134 | 5.31 | 18.06 | 106.0 | 16.6 | 4.46 | 3.34 | 122.0 | 0.0315 | 56 |
| | 0.141 | 5.59 | 18.99 | 111.0 | 17.4 | 4.46 | 3.34 | 122.0 | 0.0314 | 65 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

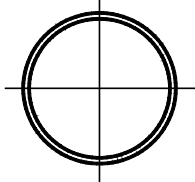
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP12-3/4 (cont'd) | 0.150 | 5.94 | 20.19 | 118 | 18.5 | 4.46 | 3.34 | 122 | 0.0313 | 78 |
| | 0.156 | 6.17 | 20.98 | 122 | 19.2 | 4.45 | 3.34 | 122 | 0.0313 | 88 |
| | 0.164 | 6.48 | 22.04 | 128 | 20.1 | 4.45 | 3.34 | 121 | 0.0312 | 103 |
| | 0.172 | 0.68 | 23.11 | 134 | 21.1 | 4.45 | 3.34 | 121 | 0.0311 | 118 |
| | 0.179 | 7.07 | 24.03 | 140 | 21.9 | 4.45 | 3.34 | 121 | 0.0310 | 134 |
| | 0.188 | 7.42 | 25.22 | 146 | 23.0 | 4.44 | 3.34 | 120 | 0.0309 | 155 |
| | 0.203 | 8.00 | 27.20 | 158 | 24.7 | 4.44 | 3.34 | 120 | 0.0308 | 196 |
| | 0.219 | 8.62 | 29.31 | 169 | 26.6 | 4.43 | 3.34 | 119 | 0.0306 | 246 |
| | 0.230 | 9.05 | 30.75 | 177 | 27.8 | 4.43 | 3.34 | 119 | 0.0305 | 286 |
| | 0.250 | 9.82 | 33.38 | 192 | 30.1 | 4.42 | 3.34 | 118 | 0.0303 | 368 |
| | 0.281 | 11.00 | 37.42 | 214 | 33.6 | 4.41 | 3.34 | 117 | 0.0300 | 526 |
| | 0.312 | 12.20 | 41.45 | 236 | 37.0 | 4.40 | 3.34 | 115 | 0.0297 | 684 |
| | 0.330 | 12.90 | 43.77 | 248 | 39.0 | 4.39 | 3.34 | 115 | 0.0295 | 776 |
| | 0.344 | 13.40 | 45.58 | 258 | 40.5 | 4.39 | 3.34 | 114 | 0.0294 | 848 |
| | 0.375 | 14.60 | 49.56 | 279 | 43.8 | 4.38 | 3.34 | 113 | 0.0291 | 1010 |
| | 0.406 | 15.70 | 53.52 | 300 | 47.1 | 4.37 | 3.34 | 112 | 0.0288 | 1170 |
| | 0.438 | 16.90 | 57.59 | 321 | 50.4 | 4.36 | 3.34 | 111 | 0.0285 | 1350 |
| | 0.500 | 19.20 | 65.42 | 362 | 56.7 | 4.33 | 3.34 | 108 | 0.0279 | 1760 |
| PP14 | 0.134 | 5.84 | 19.84 | 140 | 20.0 | 4.90 | 3.67 | 148 | 0.0381 | 42 |
| | 0.141 | 6.14 | 20.87 | 147 | 21.1 | 4.90 | 3.67 | 148 | 0.0380 | 49 |
| | 0.150 | 6.53 | 22.19 | 157 | 22.4 | 4.90 | 3.67 | 147 | 0.0379 | 59 |
| | 0.156 | 6.78 | 23.07 | 163 | 23.2 | 4.89 | 3.67 | 147 | 0.0378 | 66 |
| | 0.164 | 7.13 | 24.23 | 171 | 24.4 | 4.89 | 3.67 | 147 | 0.0378 | 77 |
| | 0.172 | 7.47 | 25.40 | 179 | 25.5 | 4.89 | 3.67 | 146 | 0.0377 | 89 |
| | 0.179 | 7.77 | 26.42 | 186 | 26.5 | 4.89 | 3.67 | 146 | 0.0376 | 101 |
| | 0.188 | 8.16 | 27.73 | 195 | 27.8 | 4.88 | 3.67 | 146 | 0.0375 | 117 |
| | 0.203 | 8.80 | 29.91 | 209 | 29.9 | 4.88 | 3.67 | 145 | 0.0373 | 147 |
| | 0.210 | 9.10 | 30.93 | 216 | 30.9 | 4.88 | 3.67 | 145 | 0.0373 | 163 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

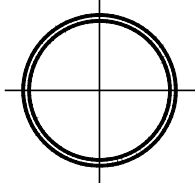
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP14 (cont'd) | 0.219 | 9.48 | 32.23 | 225 | 32.2 | 4.87 | 3.67 | 144 | 0.0372 | 815 |
| | 0.230 | 9.95 | 33.82 | 236 | 33.7 | 4.87 | 3.67 | 144 | 0.0370 | 215 |
| | 0.250 | 10.80 | 36.71 | 255 | 36.5 | 4.86 | 3.67 | 143 | 0.0368 | 277 |
| | 0.281 | 12.10 | 41.17 | 285 | 40.7 | 4.85 | 3.67 | 142 | 0.0365 | 395 |
| | 0.312 | 13.40 | 45.61 | 314 | 44.9 | 4.84 | 3.67 | 141 | 0.0361 | 542 |
| | 0.344 | 14.80 | 50.17 | 344 | 49.2 | 4.83 | 3.67 | 139 | 0.0358 | 691 |
| | 0.375 | 16.10 | 54.57 | 373 | 53.3 | 4.82 | 3.67 | 138 | 0.0355 | 835 |
| | 0.438 | 18.70 | 63.44 | 429 | 61.4 | 4.80 | 3.67 | 135 | 0.0348 | 1130 |
| | 0.469 | 19.90 | 67.78 | 457 | 65.3 | 4.79 | 3.67 | 134 | 0.0345 | 1280 |
| | 0.500 | 21.20 | 72.09 | 484 | 69.1 | 4.78 | 3.67 | 133 | 0.0341 | 1460 |
| PP16 | 0.134 | 6.68 | 22.71 | 210 | 26.3 | 5.61 | 4.19 | 194 | 0.5000 | 28 |
| | 0.141 | 7.02 | 23.88 | 221 | 27.6 | 5.61 | 4.19 | 194 | 0.0499 | 33 |
| | 0.150 | 7.47 | 25.39 | 235 | 29.3 | 5.60 | 4.19 | 194 | 0.0498 | 39 |
| | 0.156 | 7.76 | 26.40 | 244 | 30.5 | 5.60 | 4.19 | 193 | 0.0497 | 44 |
| | 0.164 | 8.16 | 27.74 | 256 | 32.0 | 5.60 | 4.19 | 193 | 0.0496 | 52 |
| | 0.172 | 8.55 | 29.08 | 268 | 33.5 | 5.60 | 4.19 | 193 | 0.0495 | 60 |
| | 0.179 | 8.90 | 30.25 | 278 | 34.8 | 5.59 | 4.19 | 192 | 0.0494 | 67 |
| | 0.188 | 9.34 | 31.75 | 292 | 36.5 | 5.59 | 4.19 | 192 | 0.0493 | 78 |
| | 0.203 | 10.10 | 34.25 | 314 | 39.3 | 5.59 | 4.19 | 191 | 0.0491 | 98 |
| | 0.219 | 10.90 | 36.91 | 338 | 42.3 | 5.58 | 4.19 | 190 | 0.0489 | 124 |
| | 0.230 | 11.40 | 38.74 | 354 | 44.3 | 5.58 | 4.19 | 190 | 0.0488 | 144 |
| | 0.250 | 12.40 | 42.05 | 384 | 48.0 | 5.57 | 4.19 | 189 | 0.0485 | 185 |
| | 0.281 | 13.90 | 47.17 | 429 | 53.6 | 5.56 | 4.19 | 187 | 0.0481 | 264 |
| | 0.312 | 15.40 | 52.27 | 473 | 59.2 | 5.55 | 4.19 | 186 | 0.0478 | 362 |
| | 0.344 | 16.90 | 57.52 | 519 | 64.8 | 5.54 | 4.19 | 184 | 0.0474 | 487 |
| | 0.375 | 18.40 | 62.58 | 562 | 70.3 | 5.53 | 4.19 | 183 | 0.0470 | 617 |
| | 0.438 | 21.40 | 72.80 | 649 | 81.1 | 5.50 | 4.19 | 180 | 0.0462 | 874 |
| | 0.469 | 22.90 | 77.79 | 691 | 86.3 | 5.49 | 4.19 | 178 | 0.0458 | 1000 |
| | 0.500 | 24.30 | 82.77 | 732 | 91.5 | 5.48 | 4.19 | 177 | 0.0455 | 1130 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

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PIPE PILES

Approximate Pile Dimensions and Design Properties

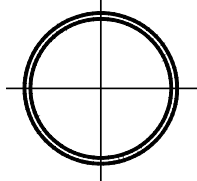
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP18 | 0.141 | 7.91 | 26.89 | 315 | 35.0 | 6.31 | 4.71 | 247 | 0.0634 | 23 |
| | 0.172 | 9.63 | 32.75 | 383 | 42.5 | 6.30 | 4.71 | 245 | 0.0630 | 42 |
| | 0.188 | 10.50 | 35.76 | 417 | 46.4 | 6.30 | 4.71 | 244 | 0.0627 | 55 |
| | 0.203 | 11.30 | 38.58 | 449 | 49.9 | 6.29 | 4.71 | 243 | 0.0625 | 69 |
| | 0.219 | 12.20 | 41.59 | 484 | 53.7 | 6.29 | 4.71 | 242 | 0.0623 | 87 |
| | 0.230 | 12.80 | 43.65 | 507 | 56.3 | 6.28 | 4.71 | 242 | 0.0621 | 101 |
| | 0.250 | 13.90 | 47.39 | 549 | 61.0 | 6.28 | 4.71 | 241 | 0.0619 | 129 |
| | 0.281 | 15.60 | 53.18 | 614 | 68.2 | 6.27 | 4.71 | 239 | 0.0614 | 184 |
| | 0.312 | 17.30 | 58.94 | 678 | 75.4 | 6.25 | 4.71 | 237 | 0.0610 | 253 |
| | 0.344 | 19.10 | 64.87 | 744 | 82.6 | 6.24 | 4.71 | 235 | 0.0605 | 341 |
| | 0.375 | 20.80 | 70.59 | 807 | 89.6 | 6.23 | 4.71 | 234 | 0.0601 | 443 |
| | 0.406 | 22.40 | 76.29 | 869 | 96.5 | 6.22 | 4.71 | 232 | 0.0597 | 559 |
| | 0.438 | 24.20 | 82.15 | 932 | 104.0 | 6.21 | 4.71 | 230 | 0.0592 | 675 |
| | 0.469 | 25.80 | 87.81 | 993 | 110.0 | 6.20 | 4.71 | 229 | 0.0588 | 788 |
| | 0.500 | 27.50 | 93.45 | 1050 | 117.0 | 6.19 | 4.71 | 227 | 0.0584 | 900 |
| PP20 | 0.141 | 8.80 | 29.91 | 434 | 43.4 | 7.02 | 5.24 | 305 | 0.0785 | 17 |
| | 0.172 | 10.70 | 36.42 | 527 | 52.7 | 7.01 | 5.24 | 303 | 0.0780 | 30 |
| | 0.188 | 11.70 | 39.78 | 574 | 57.4 | 7.00 | 5.24 | 302 | 0.0778 | 40 |
| | 0.203 | 12.60 | 42.92 | 619 | 61.9 | 7.00 | 5.24 | 302 | 0.0776 | 50 |
| | 0.219 | 13.60 | 46.27 | 666 | 66.6 | 6.99 | 5.24 | 301 | 0.0773 | 63 |
| | 0.250 | 15.50 | 52.73 | 756 | 75.6 | 6.98 | 5.24 | 299 | 0.0768 | 94 |
| | 0.281 | 17.40 | 59.18 | 846 | 84.6 | 6.97 | 5.24 | 297 | 0.0763 | 134 |
| | 0.312 | 19.30 | 65.60 | 935 | 93.5 | 6.96 | 5.24 | 295 | 0.0758 | 184 |
| | 0.344 | 21.20 | 72.21 | 1030 | 103.0 | 6.95 | 5.24 | 293 | 0.0753 | 247 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

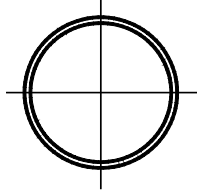
| <div>  <div> PIPE PILES Approximate Pile Dimensions and Design Properties </div> </div> | | | | | | | | | | |
|--|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP20 (cont'd) | 0.375 | 23.10 | 78.60 | 1110 | 111.0 | 6.94 | 5.24 | 291 | 0.0749 | 321 |
| | 0.406 | 25.00 | 84.96 | 1200 | 120.0 | 6.93 | 5.24 | 289 | 0.0744 | 409 |
| | 0.438 | 26.90 | 91.51 | 1290 | 129.0 | 6.92 | 5.24 | 287 | 0.0739 | 515 |
| | 0.469 | 28.80 | 97.83 | 1370 | 137.0 | 6.91 | 5.24 | 285 | 0.0734 | 618 |
| | 0.500 | 30.60 | 104.13 | 1460 | 146.0 | 6.90 | 5.24 | 284 | 0.0729 | 719 |
| PP22 | 0.172 | 11.80 | 40.10 | 703 | 63.9 | 7.72 | 5.76 | 368 | 0.0947 | 23 |
| | 0.188 | 12.90 | 43.80 | 766 | 69.7 | 7.71 | 5.76 | 367 | 0.0945 | 30 |
| | 0.219 | 15.00 | 50.94 | 889 | 80.8 | 7.70 | 5.76 | 365 | 0.0939 | 47 |
| | 0.250 | 17.10 | 58.07 | 1010 | 91.8 | 7.69 | 5.76 | 363 | 0.0934 | 70 |
| | 0.281 | 19.20 | 65.18 | 1130 | 103.0 | 7.68 | 5.76 | 361 | 0.0928 | 100 |
| | 0.312 | 21.30 | 72.27 | 1250 | 114.0 | 7.67 | 5.76 | 359 | 0.0923 | 138 |
| | 0.344 | 23.40 | 79.56 | 1370 | 125.0 | 7.66 | 5.76 | 357 | 0.0918 | 185 |
| | 0.375 | 25.50 | 86.61 | 1490 | 135.0 | 7.65 | 5.76 | 355 | 0.0912 | 241 |
| | 0.406 | 27.50 | 93.63 | 1610 | 146.0 | 7.64 | 5.76 | 353 | 0.0907 | 306 |
| | 0.438 | 29.70 | 100.86 | 1720 | 157.0 | 7.62 | 5.76 | 350 | 0.0901 | 386 |
| | 0.469 | 31.70 | 107.85 | 1840 | 167.0 | 7.61 | 5.76 | 348 | 0.0896 | 475 |
| | 0.500 | 33.80 | 114.81 | 1950 | 177.0 | 7.60 | 5.76 | 346 | 0.0891 | 571 |
| PP24 | 0.172 | 12.90 | 43.77 | 914 | 76.2 | 8.42 | 6.28 | 440 | 0.1130 | 18 |
| | 0.188 | 14.10 | 47.81 | 997 | 83.1 | 8.42 | 6.28 | 438 | 0.1130 | 23 |
| | 0.219 | 16.40 | 55.62 | 1160 | 96.4 | 8.41 | 6.28 | 436 | 0.1120 | 36 |
| | 0.250 | 18.70 | 63.41 | 1320 | 110.0 | 8.40 | 6.28 | 434 | 0.1120 | 54 |
| | 0.281 | 20.90 | 71.18 | 1470 | 123.0 | 8.39 | 6.28 | 431 | 0.1110 | 77 |
| | 0.312 | 23.20 | 78.93 | 1630 | 136.0 | 8.38 | 6.28 | 429 | 0.1100 | 106 |
| | 0.344 | 25.60 | 86.91 | 1790 | 149.0 | 8.36 | 6.28 | 427 | 0.1100 | 142 |
| | 0.375 | 27.80 | 94.62 | 1940 | 162.0 | 8.35 | 6.28 | 425 | 0.1090 | 185 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

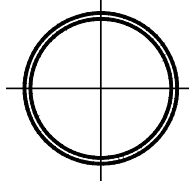
| <div>  <h2>PIPE PILES</h2> <p>Approximate Pile Dimensions and Design Properties</p> </div> | | | | | | | | | | |
|---|----------------|-----------------|-----------------|--------------------|-----------------|------|--------------------------|-----------------------------|---------------------|-------------------------|
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
| | | | | I | S | r | | | | |
| In | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP24 (cont'd) | 0.406 | 30.10 | 102.31 | 2090 | 175 | 8.34 | 6.28 | 422 | 0.109 | 235 |
| | 0.438 | 32.40 | 110.22 | 2250 | 188 | 8.33 | 6.28 | 420 | 0.108 | 296 |
| | 0.469 | 34.70 | 117.86 | 2400 | 200 | 8.32 | 6.28 | 418 | 0.107 | 364 |
| | 0.500 | 36.90 | 125.49 | 2550 | 212 | 8.31 | 6.28 | 415 | 0.107 | 443 |
| PP26 | 0.250 | 20.20 | 68.75 | 1680 | 129 | 9.10 | 6.81 | 511 | 0.131 | 43 |
| | 0.281 | 22.70 | 77.18 | 1880 | 144 | 9.09 | 6.81 | 508 | 0.131 | 61 |
| | 0.312 | 25.20 | 85.60 | 2080 | 160 | 9.08 | 6.81 | 506 | 0.130 | 83 |
| | 0.344 | 27.70 | 94.26 | 2280 | 176 | 9.07 | 6.81 | 503 | 0.129 | 112 |
| | 0.375 | 30.20 | 102.63 | 2480 | 191 | 9.06 | 6.81 | 501 | 0.129 | 145 |
| | 0.406 | 32.60 | 110.98 | 2670 | 206 | 9.05 | 6.81 | 498 | 0.128 | 184 |
| | 0.438 | 35.20 | 119.57 | 2870 | 221 | 9.04 | 6.81 | 496 | 0.128 | 232 |
| | 0.469 | 37.60 | 127.88 | 3070 | 236 | 9.03 | 6.81 | 493 | 0.127 | 286 |
| | 0.500 | 40.10 | 136.17 | 3260 | 251 | 9.02 | 6.81 | 491 | 0.126 | 347 |
| | 0.562 | 44.90 | 152.68 | 3630 | 280 | 9.00 | 6.81 | 486 | 0.125 | 495 |
| | 0.625 | 49.80 | 169.38 | 4010 | 309 | 8.97 | 6.81 | 481 | 0.124 | 656 |
| | 0.688 | 54.70 | 185.99 | 4380 | 337 | 8.95 | 6.81 | 476 | 0.122 | 814 |
| | 0.750 | 59.50 | 202.25 | 4750 | 365 | 8.93 | 6.81 | 471 | 0.121 | 970 |
| PP28 | 0.250 | 21.80 | 74.09 | 2100 | 150 | 9.81 | 7.33 | 594 | 0.153 | 34 |
| | 0.281 | 24.50 | 83.19 | 2350 | 168 | 9.80 | 7.33 | 591 | 0.152 | 48 |
| | 0.312 | 27.10 | 92.26 | 2600 | 186 | 9.79 | 7.33 | 589 | 0.151 | 66 |
| | 0.344 | 29.90 | 101.61 | 2860 | 204 | 9.78 | 7.33 | 586 | 0.151 | 89 |
| | 0.375 | 32.50 | 110.64 | 3110 | 222 | 9.77 | 7.33 | 583 | 0.150 | 116 |
| | 0.406 | 35.20 | 119.65 | 3350 | 239 | 9.76 | 7.33 | 581 | 0.149 | 147 |
| | 0.438 | 37.90 | 128.93 | 3600 | 257 | 9.75 | 7.33 | 578 | 0.149 | 185 |
| | 0.469 | 40.60 | 137.90 | 3840 | 275 | 9.74 | 7.33 | 575 | 0.148 | 228 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

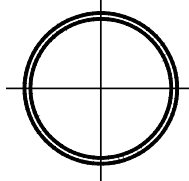
| <div>  <h2>PIPE PILES</h2> <p>Approximate Pile Dimensions and Design Properties</p> </div> | | | | | | | | | | |
|---|----------------|-----------------|------------------|--------------------|-----------------|-------|--------------------------|-----------------------------|---------------------|-------------------------|
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Meter | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
| | | | | I | S | r | | | | |
| In | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP28 (cont'd) | 0.500 | 43.20 | 146.85 | 4080 | 292 | 9.72 | 7.33 | 573 | 0.147 | 277 |
| | 0.562 | 48.40 | 164.69 | 4560 | 326 | 9.70 | 7.33 | 567 | 0.143 | 395 |
| | 0.625 | 53.80 | 182.73 | 5040 | 360 | 9.68 | 7.33 | 562 | 0.144 | 544 |
| | 0.688 | 59.00 | 200.68 | 5510 | 393 | 9.66 | 7.33 | 557 | 0.143 | 691 |
| | 0.750 | 64.20 | 218.27 | 5960 | 426 | 9.64 | 7.33 | 552 | 0.142 | 835 |
| PP30 | 0.250 | 23.40 | 79.43 | 2590 | 172 | 10.50 | 7.85 | 683 | 0.176 | 28 |
| | 0.281 | 26.20 | 89.19 | 2900 | 193 | 10.50 | 7.85 | 681 | 0.175 | 39 |
| | 0.312 | 29.10 | 98.93 | 3210 | 214 | 10.50 | 7.85 | 678 | 0.174 | 54 |
| | 0.344 | 32.00 | 108.95 | 3520 | 235 | 10.50 | 7.85 | 675 | 0.174 | 72 |
| | 0.375 | 34.90 | 118.65 | 3830 | 255 | 10.50 | 7.85 | 672 | 0.173 | 94 |
| | 0.406 | 37.70 | 128.32 | 4130 | 276 | 10.50 | 7.85 | 669 | 0.172 | 120 |
| | 0.438 | 40.70 | 138.29 | 4440 | 296 | 10.50 | 7.85 | 666 | 0.171 | 150 |
| | 0.469 | 43.50 | 147.92 | 4740 | 316 | 10.40 | 7.85 | 663 | 0.171 | 185 |
| | 0.500 | 46.30 | 157.53 | 5040 | 336 | 10.40 | 7.85 | 661 | 0.170 | 225 |
| | 0.562 | 52.00 | 176.69 | 5630 | 375 | 10.40 | 7.85 | 655 | 0.168 | 321 |
| | 0.625 | 57.70 | 196.08 | 6220 | 415 | 10.40 | 7.85 | 649 | 0.167 | 443 |
| | 0.688 | 63.40 | 215.38 | 6810 | 454 | 10.40 | 7.85 | 644 | 0.166 | 584 |
| | 0.750 | 68.90 | 234.29 | 7380 | 492 | 10.30 | 7.85 | 638 | 0.164 | 719 |
| PP32 | 0.250 | 24.90 | 84.77 | 3140 | 196 | 11.20 | 8.38 | 779 | 0.200 | 23 |
| | 0.281 | 28.00 | 95.19 | 3520 | 220 | 11.20 | 8.38 | 776 | 0.200 | 32 |
| | 0.312 | 31.10 | 105.59 | 3900 | 244 | 11.20 | 8.38 | 773 | 0.199 | 44 |
| | 0.344 | 34.20 | 116.30 | 4290 | 268 | 11.20 | 8.38 | 770 | 0.198 | 60 |
| | 0.375 | 37.30 | 126.66 | 4660 | 291 | 11.20 | 8.38 | 767 | 0.197 | 77 |
| | 0.406 | 40.30 | 136.99 | 5030 | 314 | 11.20 | 8.38 | 764 | 0.196 | 98 |
| | 0.438 | 43.40 | 147.64 | 5410 | 338 | 11.20 | 8.38 | 761 | 0.196 | 124 |
| | 0.469 | 46.50 | 157.94 | 5770 | 361 | 11.10 | 8.38 | 758 | 0.195 | 152 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

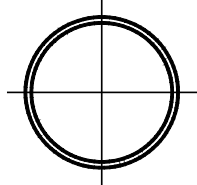
| <div>  <h2>PIPE PILES</h2> <p>Approximate Pile Dimensions and Design Properties</p> </div> | | | | | | | | | | |
|---|----------------|-----------------|-----------------|--------------------|-----------------|-------|--------------------------|-----------------------------|---------------------|-------------------------|
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP32 (cont'd) | 0.500 | 49.50 | 168.21 | 6140 | 384 | 11.10 | 8.38 | 755 | 0.194 | 185 |
| | 0.562 | 55.50 | 188.70 | 6860 | 429 | 11.10 | 8.38 | 749 | 0.193 | 264 |
| | 0.625 | 61.60 | 209.43 | 7580 | 474 | 11.10 | 8.38 | 743 | 0.191 | 364 |
| | 0.688 | 67.70 | 230.08 | 8300 | 519 | 11.10 | 8.38 | 737 | 0.189 | 487 |
| | 0.750 | 73.60 | 250.31 | 8990 | 562 | 11.10 | 8.38 | 731 | 0.188 | 617 |
| PP34 | 0.250 | 26.50 | 90.11 | 3770 | 222 | 11.90 | 8.90 | 881 | 0.227 | 19 |
| | 0.281 | 29.80 | 101.19 | 4230 | 249 | 11.90 | 8.90 | 878 | 0.226 | 27 |
| | 0.312 | 33.00 | 112.25 | 4680 | 276 | 11.90 | 8.90 | 875 | 0.225 | 37 |
| | 0.344 | 36.40 | 123.65 | 5150 | 303 | 11.90 | 8.90 | 872 | 0.224 | 50 |
| | 0.375 | 39.60 | 134.67 | 5600 | 329 | 11.90 | 8.90 | 868 | 0.223 | 64 |
| | 0.406 | 42.80 | 145.67 | 6050 | 356 | 11.90 | 8.90 | 865 | 0.222 | 82 |
| | 0.438 | 46.20 | 157.00 | 6500 | 383 | 11.90 | 8.90 | 862 | 0.222 | 103 |
| | 0.469 | 49.40 | 167.95 | 6940 | 409 | 11.90 | 8.90 | 859 | 0.221 | 127 |
| | 0.500 | 52.60 | 178.89 | 7380 | 434 | 11.80 | 8.90 | 855 | 0.220 | 154 |
| | 0.562 | 59.00 | 200.70 | 8250 | 486 | 11.80 | 8.90 | 849 | 0.218 | 219 |
| | 0.625 | 65.50 | 222.78 | 9130 | 537 | 11.80 | 8.90 | 842 | 0.217 | 303 |
| | 0.688 | 72.00 | 244.77 | 9990 | 588 | 11.80 | 8.90 | 836 | 0.215 | 405 |
| | 0.750 | 78.30 | 266.33 | 10800 | 637 | 11.80 | 8.90 | 830 | 0.213 | 527 |
| | 0.875 | 91.10 | 309.55 | 12500 | 735 | 11.70 | 8.90 | 817 | 0.210 | 767 |
| | 1.000 | 104.00 | 352.44 | 14100 | 831 | 11.70 | 8.90 | 804 | 0.207 | 1010 |
| PP36 | 0.250 | 28.10 | 95.45 | 4490 | 249 | 12.60 | 9.42 | 990 | 0.255 | 16 |
| | 0.281 | 31.50 | 107.20 | 5030 | 279 | 12.60 | 9.42 | 986 | 0.254 | 23 |
| | 0.312 | 35.00 | 118.92 | 5570 | 309 | 12.60 | 9.42 | 983 | 0.253 | 31 |
| | 0.344 | 38.50 | 131.00 | 6120 | 340 | 12.60 | 9.42 | 979 | 0.252 | 42 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

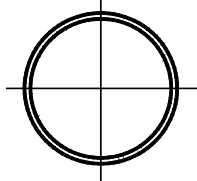
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|-------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | ft ² /ft | in ² | ft ³ /ft | * |
| PP36 (cont'd) | 0.375 | 42.00 | 142.68 | 6660 | 370 | 12.60 | 9.42 | 976 | 0.2510 | 54 |
| | 0.406 | 45.40 | 154.34 | 7190 | 399 | 12.60 | 9.42 | 972 | 0.2500 | 69 |
| | 0.438 | 48.90 | 166.35 | 7740 | 430 | 12.60 | 9.42 | 969 | 0.2490 | 87 |
| | 0.469 | 52.40 | 177.97 | 8260 | 459 | 12.60 | 9.42 | 966 | 0.2480 | 107 |
| | 0.500 | 55.80 | 189.57 | 8790 | 488 | 12.60 | 9.42 | 962 | 0.2480 | 129 |
| | 0.562 | 62.60 | 212.70 | 9820 | 546 | 12.50 | 9.42 | 955 | 0.2460 | 184 |
| | 0.625 | 69.50 | 236.13 | 10900 | 604 | 12.50 | 9.42 | 948 | 0.2440 | 254 |
| | 0.688 | 76.30 | 259.47 | 11900 | 661 | 12.50 | 9.42 | 942 | 0.2420 | 341 |
| | 0.750 | 83.10 | 282.35 | 12900 | 717 | 12.50 | 9.42 | 935 | 0.2400 | 443 |
| | 0.875 | 96.60 | 328.24 | 14900 | 828 | 12.40 | 9.42 | 921 | 0.2370 | 674 |
| | 1.000 | 110.00 | 373.80 | 16900 | 936 | 12.40 | 9.42 | 908 | 0.2340 | 900 |
| | 1.250 | 136.00 | 463.91 | 20600 | 1150 | 12.30 | 9.42 | 881 | 0.2270 | 1380 |
| PP38 | 0.250 | 29.60 | 100.79 | 5280 | 278 | 13.30 | 9.95 | 1100 | 0.2840 | 14 |
| | 0.281 | 33.30 | 113.20 | 5920 | 312 | 13.30 | 9.95 | 1100 | 0.2830 | 19 |
| | 0.312 | 36.90 | 125.58 | 6560 | 345 | 13.30 | 9.95 | 1100 | 0.2820 | 26 |
| | 0.344 | 40.70 | 138.35 | 7210 | 380 | 13.30 | 9.95 | 1090 | 0.2810 | 35 |
| | 0.375 | 44.30 | 150.69 | 7840 | 413 | 13.30 | 9.95 | 1090 | 0.2800 | 46 |
| | 0.406 | 48.00 | 163.01 | 8470 | 446 | 13.30 | 9.95 | 1090 | 0.2790 | 59 |
| | 0.438 | 51.70 | 175.71 | 9120 | 480 | 13.30 | 9.95 | 1080 | 0.2780 | 74 |
| | 0.469 | 55.30 | 187.99 | 9740 | 513 | 13.30 | 9.95 | 1080 | 0.2780 | 90 |
| | 0.500 | 58.90 | 200.25 | 10400 | 545 | 13.30 | 9.95 | 1080 | 0.2760 | 110 |
| | 0.562 | 66.10 | 224.71 | 11600 | 610 | 13.20 | 9.95 | 1070 | 0.2750 | 156 |
| | 0.625 | 73.40 | 249.48 | 12800 | 675 | 13.20 | 9.95 | 1060 | 0.2730 | 216 |
| | 0.688 | 80.60 | 274.16 | 14000 | 739 | 13.20 | 9.95 | 1050 | 0.2710 | 289 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

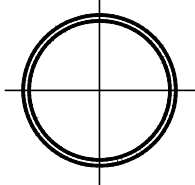
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|---|----------------|-----------------|-----------------|--------------------|-----------------|-------|--------------------------|-----------------------------|---------------------|-------------------------|
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | Ft ² /ft | in ² | ft ³ /ft | * |
| PP38 (cont'd) | 0.750 | 87.8 | 298.37 | 15200 | 802 | 13.20 | 9.95 | 1050 | 0.269 | 376 |
| | 0.875 | 102.0 | 346.93 | 17600 | 926 | 13.10 | 9.95 | 1030 | 0.265 | 590 |
| | 1.000 | 116.0 | 395.16 | 19900 | 1050 | 13.10 | 9.95 | 1020 | 0.262 | 805 |
| | 1.250 | 144.0 | 490.61 | 24400 | 1280 | 13.00 | 9.95 | 990 | 0.255 | 1230 |
| | 1.500 | 172.0 | 584.73 | 28700 | 1510 | 12.90 | 9.95 | 962 | 0.248 | 1780 |
| PP40 | 0.312 | 38.9 | 132.25 | 7660 | 383 | 14.00 | 10.50 | 1220 | 0.313 | 23 |
| | 0.344 | 42.9 | 145.69 | 8430 | 421 | 14.00 | 10.50 | 1210 | 0.312 | 30 |
| | 0.375 | 46.7 | 158.70 | 9160 | 458 | 14.00 | 10.50 | 1210 | 0.311 | 39 |
| | 0.406 | 50.5 | 171.68 | 9900 | 495 | 14.00 | 10.50 | 1210 | 0.310 | 50 |
| | 0.438 | 54.4 | 185.06 | 10700 | 533 | 14.00 | 10.50 | 1200 | 0.309 | 63 |
| | 0.469 | 58.2 | 198.01 | 11400 | 569 | 14.00 | 10.50 | 1200 | 0.308 | 77 |
| | 0.500 | 62.0 | 210.93 | 12100 | 605 | 14.00 | 10.50 | 1190 | 0.307 | 94 |
| | 0.562 | 69.6 | 236.71 | 13500 | 677 | 13.90 | 10.50 | 1190 | 0.305 | 134 |
| | 0.625 | 77.3 | 262.83 | 15000 | 749 | 13.90 | 10.50 | 1180 | 0.303 | 185 |
| | 0.688 | 85.0 | 288.86 | 16400 | 821 | 13.90 | 10.50 | 1170 | 0.301 | 247 |
| | 0.750 | 92.5 | 314.39 | 17800 | 891 | 13.90 | 10.50 | 1160 | 0.299 | 321 |
| | 0.875 | 108.0 | 365.62 | 20600 | 1030 | 13.80 | 10.50 | 1150 | 0.296 | 514 |
| | 1.000 | 123.0 | 416.52 | 23300 | 1170 | 13.80 | 10.50 | 1130 | 0.292 | 719 |
| | 1.250 | 152.0 | 517.31 | 28600 | 1430 | 13.70 | 10.50 | 1100 | 0.284 | 1130 |
| | 1.500 | 181.0 | 616.77 | 33700 | 1680 | 13.60 | 10.50 | 1080 | 0.276 | 1620 |
| | 1.750 | 210.0 | 714.89 | 38500 | 1930 | 13.50 | 10.50 | 1050 | 0.269 | 2140 |
| PP42 | 0.312 | 40.9 | 138.91 | 8880 | 423 | 14.70 | 11.00 | 1340 | 0.346 | 20 |
| | 0.344 | 45.0 | 153.04 | 9770 | 465 | 14.70 | 11.00 | 1340 | 0.345 | 26 |
| | 0.375 | 49.0 | 166.71 | 10600 | 506 | 14.70 | 11.00 | 1340 | 0.344 | 34 |
| | 0.406 | 53.1 | 180.35 | 11500 | 546 | 14.70 | 11.00 | 1340 | 0.343 | 43 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.



PIPE PILES

Approximate Pile Dimensions and Design Properties

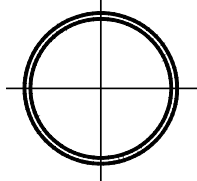
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
|----------------------------------|----------------|-----------------|-----------------|--------------------|-----------------|-------|--------------------------|-----------------------------|---------------------|-------------------------|
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | Ft ² /ft | in ² | ft ³ /ft | * |
| PP42 (cont'd) | 0.438 | 57.2 | 194.42 | 12400 | 588 | 14.70 | 11.00 | 1330 | 0.342 | 54 |
| | 0.469 | 61.2 | 208.03 | 13200 | 628 | 14.70 | 11.00 | 1320 | 0.341 | 67 |
| | 0.500 | 65.2 | 221.61 | 14000 | 668 | 14.70 | 11.00 | 1320 | 0.340 | 81 |
| | 0.562 | 73.2 | 248.72 | 15700 | 748 | 14.70 | 11.00 | 1310 | 0.338 | 116 |
| | 0.625 | 81.2 | 276.18 | 17400 | 828 | 14.60 | 11.00 | 1300 | 0.335 | 159 |
| | 0.688 | 89.3 | 303.55 | 19100 | 907 | 14.60 | 11.00 | 1300 | 0.333 | 213 |
| | 0.750 | 97.2 | 330.41 | 20700 | 985 | 14.60 | 11.00 | 1290 | 0.331 | 277 |
| | 0.875 | 113.0 | 384.31 | 23900 | 1140 | 14.50 | 11.00 | 1270 | 0.327 | 443 |
| | 1.000 | 129.0 | 437.88 | 27100 | 1290 | 14.50 | 11.00 | 1260 | 0.323 | 641 |
| | 1.250 | 160.0 | 544.01 | 33200 | 1580 | 14.40 | 11.00 | 1230 | 0.315 | 1030 |
| | 1.500 | 191.0 | 648.81 | 39200 | 1870 | 14.30 | 11.00 | 1190 | 0.307 | 1460 |
| | 1.750 | 221.0 | 752.27 | 44900 | 2140 | 14.20 | 11.00 | 1160 | 0.299 | 1970 |
| | 2.000 | 251.0 | 854.40 | 50400 | 2400 | 14.20 | 11.00 | 1130 | 0.292 | 2470 |
| PP44 | 0.344 | 47.2 | 160.39 | 11200 | 511 | 15.40 | 11.50 | 1470 | 0.379 | 23 |
| | 0.375 | 51.4 | 174.72 | 12200 | 556 | 15.40 | 11.50 | 1470 | 0.378 | 30 |
| | 0.406 | 55.6 | 189.03 | 13200 | 600 | 15.40 | 11.50 | 1460 | 0.377 | 38 |
| | 0.438 | 59.9 | 203.78 | 14200 | 646 | 15.40 | 11.50 | 1460 | 0.376 | 47 |
| | 0.469 | 64.1 | 218.04 | 15200 | 691 | 15.40 | 11.50 | 1460 | 0.375 | 58 |
| | 0.500 | 68.3 | 232.29 | 16200 | 735 | 15.40 | 11.50 | 1450 | 0.374 | 70 |
| | 0.625 | 85.2 | 289.53 | 20000 | 911 | 15.30 | 11.50 | 1440 | 0.369 | 138 |
| | 0.750 | 102.0 | 346.43 | 23800 | 1080 | 15.30 | 11.50 | 1420 | 0.365 | 241 |
| | 0.875 | 119.0 | 403.00 | 27600 | 1250 | 15.30 | 11.50 | 1400 | 0.361 | 384 |
| | 1.000 | 135.0 | 459.24 | 31200 | 1420 | 15.20 | 11.50 | 1390 | 0.356 | 571 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

| <div>  <div> PIPE PILES Approximate Pile Dimensions and Design Properties </div> </div> | | | | | | | | | | |
|--|----------------|-----------------|-----------------|--------------------|-----------------|-------|--------------------------|-----------------------------|---------------------|-------------------------|
| Designation and Outside Diameter | Wall Thickness | Area A | Weight per Foot | Section Properties | | | Area of Exterior Surface | Inside Cross Sectional Area | Inside Volume | External Collapse Index |
| | | | | I | S | r | | | | |
| in | in | in ² | lb | in ⁴ | in ³ | in | Ft ² /ft | in ² | ft ³ /ft | * |
| PP44 (cont'd) | 1.250 | 168.0 | 570.71 | 38400 | 1740 | 15.10 | 11.50 | 1350 | 0.348 | 941 |
| | 1.500 | 200.0 | 680.85 | 45300 | 2060 | 15.00 | 11.50 | 1320 | 0.340 | 1300 |
| | 1.750 | 232.0 | 789.65 | 51900 | 2360 | 15.00 | 11.50 | 1290 | 0.331 | 1810 |
| | 2.000 | 264.0 | 897.12 | 58300 | 2650 | 14.90 | 11.50 | 1260 | 0.323 | 2290 |
| | 2.250 | 295.0 | 1003.25 | 64500 | 2930 | 14.80 | 11.50 | 1230 | 0.315 | 2770 |
| PP48 | 0.344 | 51.5 | 175.08 | 14600 | 609 | 16.80 | 12.60 | 1760 | 0.452 | 18 |
| | 0.375 | 56.1 | 190.74 | 15900 | 663 | 16.80 | 12.60 | 1750 | 0.451 | 23 |
| | 0.406 | 60.7 | 206.37 | 17200 | 716 | 16.80 | 12.60 | 1750 | 0.450 | 29 |
| | 0.438 | 65.4 | 222.49 | 18500 | 771 | 16.80 | 12.60 | 1740 | 0.449 | 36 |
| | 0.469 | 70.0 | 238.08 | 19800 | 824 | 16.80 | 12.60 | 1740 | 0.447 | 45 |
| | 0.500 | 74.6 | 253.65 | 21000 | 877 | 16.80 | 12.60 | 1730 | 0.446 | 54 |
| | 0.625 | 93.0 | 316.23 | 26100 | 1090 | 16.80 | 12.60 | 1720 | 0.442 | 106 |
| | 0.750 | 111.0 | 378.47 | 31100 | 1290 | 16.70 | 12.60 | 1700 | 0.437 | 185 |
| | 0.875 | 130.0 | 440.38 | 36000 | 1500 | 16.70 | 12.60 | 1680 | 0.432 | 295 |
| | 1.000 | 148.0 | 501.96 | 40800 | 1700 | 16.60 | 12.60 | 1660 | 0.427 | 443 |
| | 1.250 | 184.0 | 624.11 | 50200 | 2090 | 16.50 | 12.60 | 1630 | 0.418 | 787 |
| | 1.500 | 219.0 | 744.93 | 59300 | 2470 | 16.40 | 12.60 | 1590 | 0.409 | 1130 |
| | 1.750 | 254.0 | 864.41 | 68100 | 2840 | 16.40 | 12.60 | 1560 | 0.400 | 1530 |
| | 2.000 | 289.0 | 982.56 | 76600 | 3190 | 16.30 | 12.60 | 1520 | 0.391 | 1970 |
| | 2.250 | 323.0 | 1099.37 | 84800 | 3530 | 16.20 | 12.60 | 1490 | 0.382 | 2410 |
| | 2.500 | 357.0 | 1214.85 | 92800 | 3860 | 16.10 | 12.60 | 1450 | 0.374 | 2850 |

Note: Designer must confirm section properties and local availability of selected pile section.

Material Specifications - ASTM A252

Example of suggested method of designation: PP8 x 0.141

* The External Collapse Index is a non-dimensional function of the diameter to wall thickness ratio and is for general guidance only. The higher the number, the greater is the resistance to collapse.

Monotube Piles

Standard Monotube Weights and Volumes

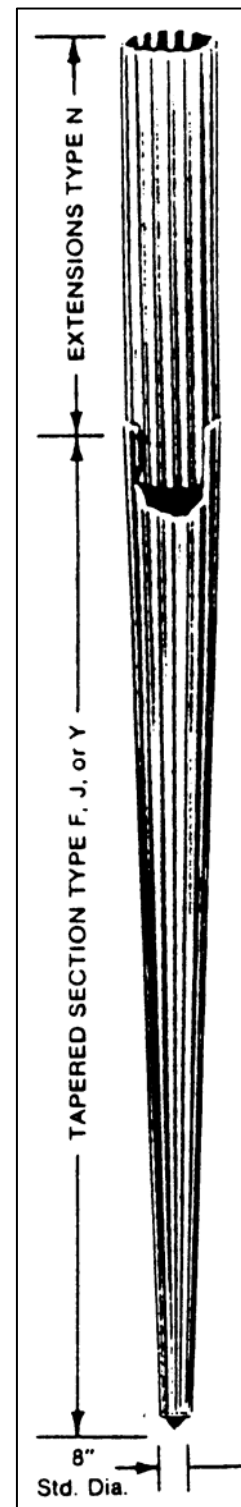
| TYPE | SIZE POINT DIAMETER x BUTT DIAMETER x LENGTH | Weight (N) per m | | | | EST. CONC. VOL. yd ³ |
|-------------------------------------|--|------------------|-------|-------|-------|--|
| | | 9 GA. | 7 GA. | 5 GA. | 3 GA. | |
| F Taper 0.14 inch per foot | 8½" x 12" x 25' | 17 | 20 | 24 | 28 | 0.43 |
| | 8" x 12" x 30' | 16 | 20 | 23 | 27 | 0.55 |
| | 8½" x 14" x 40' | 19 | 22 | 26 | 31 | 0.95 |
| | 8" x 16" x 60' | 20 | 24 | 28 | 33 | 1.68 |
| | 8" x 18" x 75' | -- | 26 | 31 | 35 | 2.59 |
| J Taper 0.25 inch per foot | 8" x 12" x 17' | 17 | 20 | 23 | 27 | 0.32 |
| | 8" x 14" x 25' | 18 | 22 | 26 | 30 | 0.58 |
| | 8" x 16" x 33' | 20 | 24 | 28 | 32 | 0.95 |
| | 8" x 18" x 40' | -- | 26 | 30 | 35 | 1.37 |
| Y Taper 0.40 inch per foot | 8" x 12" x 10' | 17 | 20 | 24 | 28 | 0.18 |
| | 8" x 14" x 15' | 19 | 22 | 26 | 30 | 0.34 |
| | 8" x 16" x 20' | 20 | 24 | 28 | 33 | 0.56 |
| | 8" x 18" x 25' | -- | 26 | 31 | 35 | 0.86 |

Extensions (Overall Length 1 Foot than indicated)

| TYPE | DIAMETER x LENGTH | 9 GA. | 7 GA. | 5 GA. | 3 GA. | yd ³ /ft |
|------|-----------------------|-------|-------|-------|-------|---------------------|
| N 12 | 12" x 12" x 20' / 40' | 20 | 24 | 28 | 33 | 0.026 |
| N 14 | 14" x 14" x 20' / 40' | 24 | 29 | 34 | 41 | 0.035 |
| N 16 | 16" x 16" x 20' / 40' | 28 | 33 | 39 | 46 | 0.045 |
| N 18 | 18" x 18" x 20' / 40' | -- | 38 | 44 | 52 | 0.058 |

Note: Designer must confirm section properties of selected pile section.

Pile design data converted to SI units from US units published in Monotube Pile Corporation Catalog 592.



MONOTUBE PILES

Physical Properties

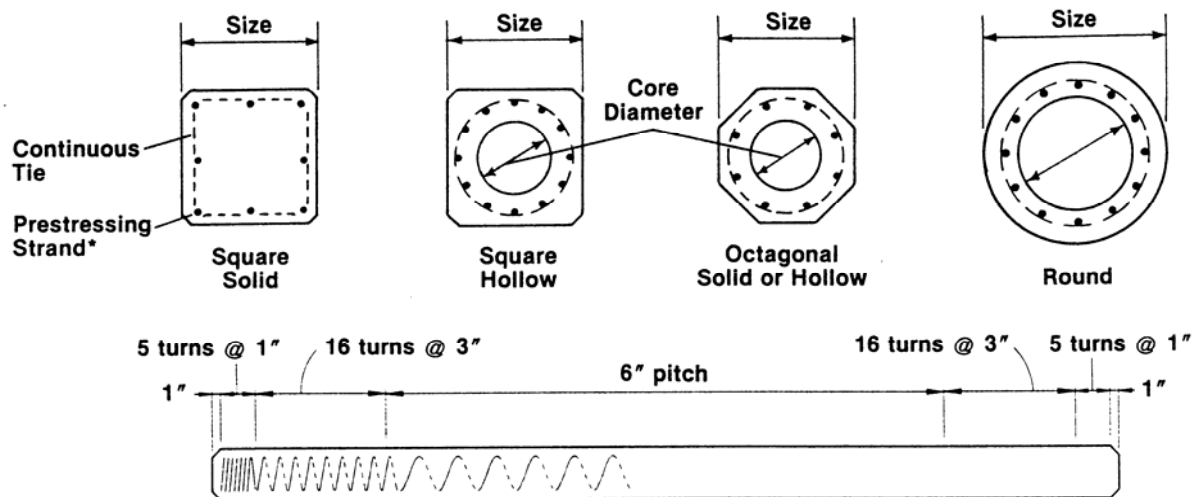
| STEEL THICKNESS | POINTS | | BUTTS OF PILE SECTIONS | | | | | | | |
|-------------------------------|-------------------|-------------------|------------------------|-------------------|-------------------|------|-------------------|-------------------|-------------------|------|
| | 8 in | 8 ½ in | 12 in | | | | 14 in | | | |
| | A in ² | A in ² | A in ² | I in ⁴ | S in ³ | r in | A in ² | I in ⁴ | S in ³ | r in |
| 9 GAUGE (0.1495") | 3.63 | 3.93 | 5.81 | 102 | 16.3 | 4.18 | 6.75 | 159 | 22.0 | 4.86 |
| 7 GAUGE (0.1793") | 4.40 | 4.77 | 6.97 | 122 | 19.5 | 4.18 | 8.14 | 194 | 26.7 | 4.89 |
| 5 GAUGE (0.2391") | 5.19 | 5.61 | 8.18 | 145 | 23.0 | 4.21 | 9.50 | 227 | 31.0 | 4.88 |
| 3 GAUGE (0.2391") | 5.87 | 6.58 | 8.96 | 148 | 24.2 | 4.07 | 10.60 | 239 | 33.6 | 4.77 |
| CONCRETE AREA in ² | 42.3 | 47.3 | 101 | | | | 136 | | | |

| STEEL THICKNESS | POINTS | | BUTTS OF PILE SECTIONS | | | | | | | |
|-------------------------------|-------------------|-------------------|------------------------|-------------------|-------------------|------|-------------------|-------------------|-------------------|------|
| | 8 in | 8 ½ in | 16 in | | | | 18 in | | | |
| | A in ² | A in ² | A in ² | I in ⁴ | S in ³ | r in | A in ² | I in ⁴ | S in ³ | r in |
| 9 GAUGE (0.1495") | 3.63 | 3.93 | 7.64 | 232 | 28.3 | 5.50 | -- | -- | -- | -- |
| 7 GAUGE (0.1793") | 4.40 | 4.77 | 9.18 | 278 | 33.9 | 5.51 | 10.4 | 404 | 43.5 | 6.23 |
| 5 GAUGE (0.2391") | 5.19 | 5.61 | 10.8 | 329 | 33.9 | 5.53 | 12.2 | 478 | 51.2 | 6.26 |
| 3 GAUGE (0.2391") | 5.87 | 6.58 | 12.0 | 348 | 43.1 | 5.40 | 13.6 | 504 | 55.4 | 6.10 |
| CONCRETE AREA in ² | 42.3 | 47.3 | 176 | | | | 224 | | | |

Note: Designer must confirm section properties of selected pile section.

Pile design data converted to SI units from US units published in Monotube Pile Corporation Catalog 592.

PRECAST/PRESTRESSED CONCRETE PILES



* Strand pattern may be circular or square.

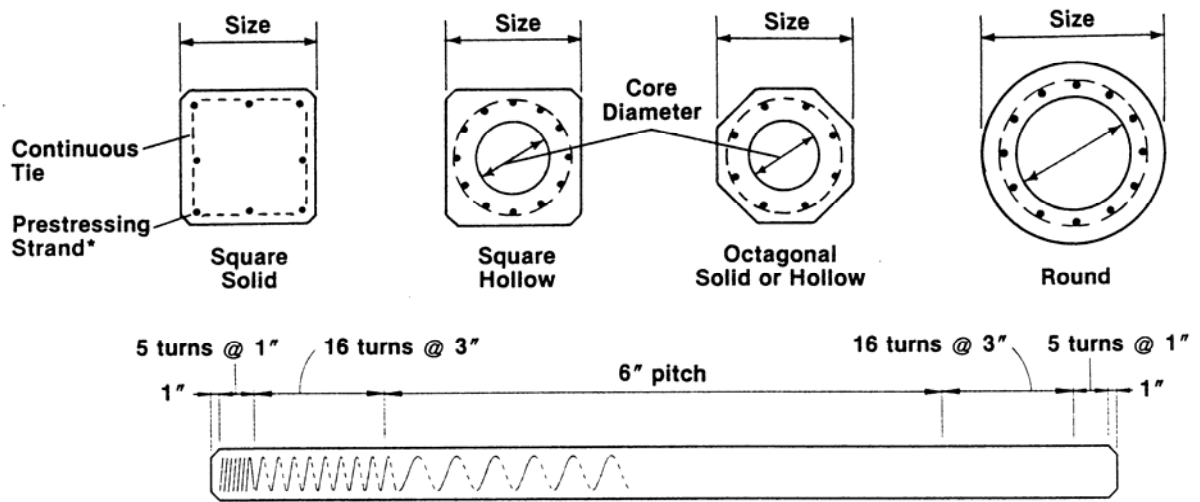
Typical Elevation

| Size in | Section Properties | | | | | | |
|--------------|------------------------|-------------------------|-----------------|---|---------------------------------------|-----------------------------|-----------------|
| | Core Diameter in | Area in ² | Weight lb/ft | Moment of Inertia in ⁴ | Section Modulus in ³ | Radius of Gyration in | Perimeter ft |
| Square Piles | | | | | | | |
| 10 | Solid | 100 | 104 | 833 | 167 | 2.89 | 3.33 |
| 12 | Solid | 144 | 150 | 1,728 | 288 | 3.46 | 4.00 |
| 14 | Solid | 196 | 204 | 3,201 | 457 | 4.04 | 4.67 |
| 16 | Solid | 256 | 267 | 5,461 | 683 | 4.62 | 5.33 |
| 18 | Solid | 324 | 338 | 8,748 | 972 | 5.20 | 6.00 |
| 20 | Solid | 400 | 417 | 13,333 | 1,333 | 5.77 | 6.67 |
| 20 | 11 | 305 | 318 | 12,615 | 1,262 | 6.43 | 6.67 |
| 24 | Solid | 576 | 600 | 27,648 | 2,304 | 6.93 | 8.00 |
| 24 | 12 | 463 | 482 | 26,630 | 2,219 | 7.58 | 8.00 |
| 24 | 14 | 422 | 439 | 25,762 | 2,147 | 7.81 | 8.00 |
| 24 | 16 | 399 | 415 | 25,163 | 2,097 | 7.94 | 8.00 |
| 30 | 18 | 646 | 672 | 62,347 | 4,157 | 9.82 | 10.00 |
| 36 | 18 | 1,042 | 1085 | 134,815 | 7,490 | 11.38 | 12.00 |

Note: Designer must confirm section properties for a selected pile. Form dimensions may vary with producers, with corresponding variations in section properties.

PCI (1993), Precast/Prestressed Concrete Institute Journal, Volume 38, No. 2, March-April, 1993.

PRECAST/PRESTRESSED CONCRETE PILES



* Strand pattern may be circular or square.

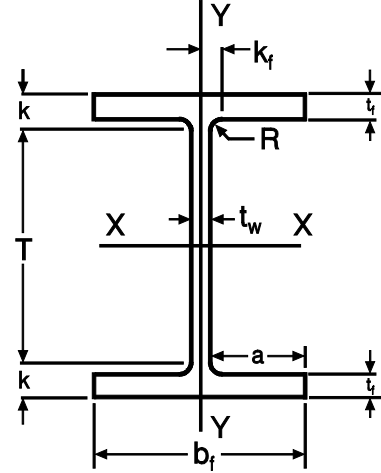
Typical Elevation

| Size in | Section Properties | | | | | | |
|-----------------|------------------------|-------------------------|-----------------|---|---------------------------------------|------------------------------|-----------------|
| | Core Diameter in | Area in ² | Weight lb/ft | Moment of Inertia in ⁴ | Section Modulus in ³ | Radius of Gyrations in | Perimeter ft |
| Octagonal Piles | | | | | | | |
| 10 | Solid | 83 | 85 | 555 | 111 | 2.59 | 2.76 |
| 12 | Solid | 119 | 125 | 1,134 | 189 | 3.09 | 3.31 |
| 14 | Solid | 162 | 169 | 2,105 | 301 | 3.60 | 3.87 |
| 16 | Solid | 212 | 220 | 3,592 | 449 | 4.12 | 4.42 |
| 18 | Solid | 268 | 280 | 5,705 | 639 | 4.61 | 4.97 |
| 20 | Solid | 331 | 345 | 8,770 | 877 | 5.15 | 5.52 |
| 20 | 11 | 236 | 245 | 8,050 | 805 | 5.84 | 5.52 |
| 22 | Solid | 401 | 420 | 12,837 | 1167 | 5.66 | 6.08 |
| 22 | 13 | 268 | 280 | 11,440 | 1040 | 6.53 | 6.08 |
| 24 | Solid | 477 | 495 | 18,180 | 1515 | 6.17 | 6.63 |
| 24 | 15 | 300 | 315 | 15,696 | 1308 | 7.23 | 6.63 |
| Round Piles | | | | | | | |
| 36 | 26 | 487 | 507 | 60,007 | 3,334 | 11.10 | 9.43 |
| 42 | 32 | 581 | 605 | 101,273 | 4,823 | 13.20 | 11.00 |
| 48 | 38 | 675 | 703 | 158,222 | 6,592 | 15.31 | 12.57 |
| 54 | 44 | 770 | 802 | 233,373 | 8,643 | 17.41 | 14.14 |
| 66 | 54 | 1,131 | 1,178 | 514,027 | 15,577 | 21.32 | 17.28 |

Note: Designer must confirm section properties for a selected pile. Form dimensions may vary with producers, with corresponding variations in section properties.

PCI (1993), Precast/Prestressed Concrete Institute Journal, Volume 38, No. 2, March-April, 1993.

H-PILES



| Section Designation | Area A | Depth d | Web Thickness t_w | Flange | | Distance | | | | Fillet Radius R | Elastic Properties | | | | | |
|---------------------|-----------------|---------|---------------------|-------------|-----------------|----------|------|-------|------|-----------------|--------------------|-----------------|------|-----------------|-----------------|------|
| | | | | Width b_f | Thickness t_f | T | k | k_f | a | | X-X | | | Y-Y | | |
| | | | | | | | | | | | I | S | r | I | S | r |
| in x lb/ft | in ² | in | in | in | in | in | in | in | in | in | in ⁴ | in ³ | in | in ⁴ | in ³ | in |
| HP14 x 117 | 34.4 | 14.21 | 0.805 | 14.885 | 0.805 | 10.91 | 1.65 | 1.19 | 7.05 | 0.79 | 1220 | 172 | 5.96 | 443 | 59.5 | 3.59 |
| HP14 x 102 | 30.0 | 14.01 | 0.705 | 14.785 | 0.705 | 10.91 | 1.57 | 1.14 | 7.05 | 0.79 | 1050 | 150 | 5.92 | 380 | 51.4 | 3.56 |
| HP14 x 89 | 26.1 | 13.83 | 0.615 | 14.695 | 0.615 | 10.91 | 1.46 | 1.09 | 7.05 | 0.79 | 904 | 131 | 5.88 | 326 | 44.3 | 3.53 |
| HP14 x 73 | 21.4 | 13.61 | 0.505 | 14.585 | 0.505 | 10.91 | 1.34 | 1.04 | 7.05 | 0.79 | 729 | 107 | 5.84 | 261 | 35.8 | 3.49 |
| HP12 x 84 | 24.6 | 12.28 | 0.685 | 12.295 | 0.685 | 9.61 | 1.34 | 0.93 | 5.79 | 0.59 | 650 | 106 | 5.14 | 213 | 34.6 | 2.94 |
| HP12 x 73 | 21.8 | 12.13 | 0.605 | 12.215 | 0.610 | 9.61 | 1.26 | 0.89 | 5.79 | 0.59 | 569 | 93 | 5.11 | 186 | 30.4 | 2.92 |
| HP12 x 63 | 18.4 | 11.94 | 0.515 | 12.125 | 0.515 | 9.61 | 1.18 | 0.85 | 5.83 | 0.59 | 472 | 79 | 5.06 | 153 | 25.3 | 2.88 |
| HP12 x 53 | 15.5 | 11.78 | 0.435 | 12.045 | 0.435 | 9.61 | 1.10 | 0.81 | 5.83 | 0.59 | 393 | 66 | 5.03 | 127 | 21.1 | 2.86 |
| HP10 x 57 | 16.8 | 9.99 | 0.565 | 10.225 | 0.565 | 7.72 | 1.14 | 0.80 | 4.84 | 0.51 | 294 | 59 | 4.18 | 101 | 19.7 | 2.45 |
| HP10 x 42 | 12.4 | 9.70 | 0.415 | 10.075 | 0.420 | 3.78 | 0.98 | 0.72 | 4.84 | 0.51 | 210 | 43 | 4.13 | 72 | 14.2 | 2.41 |
| HP8 x 36 | 10.6 | 8.02 | 0.445 | 8.155 | 0.445 | 6.22 | 0.91 | 0.62 | 3.86 | 0.39 | 119 | 30 | 3.36 | 41 | 9.88 | 1.95 |

Note: Designer must confirm section properties for a selected pile.

AISC (1989), Manual of Steel Construction, Allowable Stress Design. Ninth Edition, American Institute of Steel Construction, Inc. 1989.

APPENDIX D

Pile Hammer Information

| | |
|--|------|
| Table D-1 DIESEL HAMMER LISTING (sorted by Rated Energy) | D-3 |
| Table D-2 EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | D-11 |
| Table D-3 VIBRATORY HAMMER LISTING (sorted by Power) | D-25 |
| Table D-4 COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | D-29 |

Note: GRLWEAP hammer ID numbers correspond to those contained in Version 2003-1 of the GRLWEAP program.

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 81 | LINKBELT | LB 180 | CED | 10.98 | 7.70 | 1.43 | 8.10 | 1.73 | 4.68 |
| 120 | ICE | 180 | CED | 11.03 | 7.70 | 1.43 | 8.13 | 1.73 | 4.70 |
| 146 | MKT | DE 10 | OED | 11.93 | 4.90 | 3.35 | 8.80 | 1.10 | 11.00 |
| 1 | DELMAG | D 5 | OED | 14.24 | 4.90 | 2.93 | 10.51 | 1.10 | 9.62 |
| 36 | DELMAG | D 6-32 | OED | 18.31 | 5.87 | 3.12 | 13.50 | 1.32 | 10.23 |
| 82 | LINKBELT | LB 312 | CED | 20.36 | 17.18 | 1.19 | 15.02 | 3.86 | 3.89 |
| 147 | MKT | DE 20 | OED | 21.70 | 8.90 | 2.74 | 16.00 | 2.00 | 9.00 |
| 402 | BERMINGH | B200 | OED | 24.41 | 8.90 | 2.74 | 18.00 | 2.00 | 9.00 |
| 578 | APE | D 8-32 | OED | 24.41 | 7.83 | 3.12 | 18.00 | 1.76 | 10.25 |
| 83 | LINKBELT | LB 440 | CED | 24.68 | 17.80 | 1.39 | 18.20 | 4.00 | 4.55 |
| 122 | ICE | 440 | CED | 25.17 | 17.80 | 1.41 | 18.56 | 4.00 | 4.64 |
| 142 | MKT 20 | DE333020 | OED | 27.12 | 8.90 | 3.51 | 20.00 | 2.00 | 11.50 |
| 2 | DELMAG | D 8-22 | OED | 27.25 | 7.83 | 3.67 | 20.10 | 1.76 | 12.05 |
| 151 | MKT | DA 35B | CED | 28.48 | 12.46 | 2.29 | 21.00 | 2.80 | 7.50 |
| 167 | MKT | DA 35C | CED | 28.48 | 12.46 | 2.29 | 21.00 | 2.80 | 7.50 |
| 422 | BERMINGH | B2005 | OED | 28.48 | 8.90 | 3.20 | 21.00 | 2.00 | 10.50 |
| 148 | MKT | DE 30 | OED | 30.37 | 12.46 | 3.05 | 22.40 | 2.80 | 10.00 |
| 50 | FEC | FEC 1200 | OED | 30.50 | 12.24 | 2.49 | 22.50 | 2.75 | 8.18 |
| 127 | ICE | 30-S | OED | 30.51 | 13.35 | 2.34 | 22.50 | 3.00 | 7.67 |
| 3 | DELMAG | D 12 | OED | 30.65 | 12.24 | 3.29 | 22.61 | 2.75 | 10.80 |
| 401 | BERMINGH | B23 | CED | 31.17 | 12.46 | 2.50 | 22.99 | 2.80 | 8.21 |
| 414 | BERMINGH | B23 5 | CED | 31.17 | 12.46 | 2.50 | 22.99 | 2.80 | 8.21 |
| 121 | ICE | 422 | CED | 31.35 | 17.80 | 1.76 | 23.12 | 4.00 | 5.78 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 149 | MKT | DA35B SA | OED | 32.27 | 12.46 | 3.96 | 23.80 | 2.80 | 13.00 |
| 150 | MKT | DE 30B | OED | 32.27 | 12.46 | 3.05 | 23.80 | 2.80 | 10.00 |
| 61 | MITSUBIS | M 14 | OED | 34.23 | 13.22 | 2.59 | 25.25 | 2.97 | 8.50 |
| 350 | HERA | 1250 | OED | 34.37 | 12.50 | 2.75 | 25.35 | 2.81 | 9.02 |
| 101 | KOBE | K 13 | OED | 34.48 | 12.77 | 2.70 | 25.43 | 2.87 | 8.86 |
| 139 | ICE | 32-S | OED | 35.27 | 13.35 | 3.25 | 26.01 | 3.00 | 10.67 |
| 415 | BERMINGH | B250 5 | OED | 35.60 | 11.13 | 3.20 | 26.25 | 2.50 | 10.50 |
| 84 | LINKBELT | LB 520 | CED | 35.68 | 22.56 | 1.58 | 26.31 | 5.07 | 5.19 |
| 4 | DELMAG | D 15 | OED | 36.74 | 14.69 | 3.29 | 27.09 | 3.30 | 10.80 |
| 51 | FEC | FEC 1500 | OED | 36.74 | 14.69 | 2.50 | 27.09 | 3.30 | 8.21 |
| 143 | MKT 30 | DE333020 | OED | 37.97 | 12.46 | 3.51 | 28.00 | 2.80 | 11.50 |
| 62 | MITSUBIS | MH 15 | OED | 38.15 | 14.73 | 2.59 | 28.14 | 3.31 | 8.50 |
| 403 | BERMINGH | B225 | OED | 39.66 | 13.35 | 2.97 | 29.25 | 3.00 | 9.75 |
| 360 | ICE | I-12 | OED | 40.95 | 12.55 | 3.51 | 30.20 | 2.82 | 11.50 |
| 123 | ICE | 520 | CED | 41.18 | 22.56 | 1.83 | 30.37 | 5.07 | 5.99 |
| 351 | HERA | 1500 | OED | 41.22 | 15.00 | 2.75 | 30.40 | 3.37 | 9.02 |
| 152 | MKT | DA 45 | CED | 41.66 | 17.80 | 2.34 | 30.72 | 4.00 | 7.68 |
| 37 | DELMAG | D 12-32 | OED | 42.48 | 12.55 | 3.60 | 31.33 | 2.82 | 11.81 |
| 153 | MKT | DE 40 | OED | 43.39 | 17.80 | 3.05 | 32.00 | 4.00 | 10.00 |
| 144 | MKT 33 | DE333020 | OED | 44.75 | 14.69 | 3.51 | 33.00 | 3.30 | 11.50 |
| 38 | DELMAG | D 12-42 | OED | 45.16 | 12.55 | 3.60 | 33.30 | 2.82 | 11.81 |
| 39 | DELMAG | D 14-42 | OED | 46.84 | 13.75 | 3.60 | 34.55 | 3.09 | 11.81 |
| 154 | MKT | DE 42/35 | OED | 47.46 | 15.58 | 4.11 | 35.00 | 3.50 | 13.50 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 423 | BERMINGH | B2505 | OED | 48.00 | 13.35 | 3.60 | 35.40 | 3.00 | 11.80 |
| 161 | MKT | DA 55B | CED | 51.80 | 22.25 | 2.33 | 38.20 | 5.00 | 7.64 |
| 168 | MKT | DA 55C | CED | 51.80 | 22.25 | 2.33 | 38.20 | 5.00 | 7.64 |
| 579 | APE | D 16-32 | OED | 53.37 | 15.71 | 3.43 | 39.36 | 3.53 | 11.25 |
| 128 | ICE | 40-S | OED | 54.24 | 17.80 | 3.10 | 40.00 | 4.00 | 10.17 |
| 145 | MKT 40 | DE333020 | OED | 54.24 | 17.80 | 3.51 | 40.00 | 4.00 | 11.50 |
| 160 | MKT | DA55B SA | OED | 54.24 | 22.25 | 3.66 | 40.00 | 5.00 | 12.00 |
| 5 | DELMAG | D 16-32 | OED | 54.51 | 15.66 | 3.58 | 40.20 | 3.52 | 11.76 |
| 404 | BERMINGH | B300 | OED | 54.66 | 16.69 | 3.28 | 40.31 | 3.75 | 10.75 |
| 410 | BERMINGH | B300 M | OED | 54.66 | 16.69 | 3.28 | 40.31 | 3.75 | 10.75 |
| 6 | DELMAG | D 22 | OED | 55.06 | 21.85 | 2.90 | 40.61 | 4.91 | 9.50 |
| 124 | ICE | 640 | CED | 55.08 | 26.70 | 2.06 | 40.62 | 6.00 | 6.77 |
| 155 | MKT | DE 42/35 | OED | 56.95 | 18.69 | 4.11 | 42.00 | 4.20 | 13.50 |
| 129 | ICE | 42-S | OED | 56.96 | 18.20 | 3.18 | 42.00 | 4.09 | 10.42 |
| 40 | DELMAG | D 19-32 | OED | 57.55 | 17.80 | 3.58 | 42.44 | 4.00 | 11.76 |
| 159 | MKT | DE 50B | OED | 57.63 | 22.25 | 3.35 | 42.50 | 5.00 | 11.00 |
| 571 | APE | D 19-32 | OED | 58.07 | 18.65 | 3.12 | 42.82 | 4.19 | 10.25 |
| 580 | APE | D 19-42 | OED | 58.07 | 18.65 | 3.23 | 42.82 | 4.19 | 10.60 |
| 63 | MITSUBIS | M 23 | OED | 58.32 | 22.52 | 2.59 | 43.01 | 5.06 | 8.50 |
| 361 | ICE | I-19 | OED | 58.56 | 17.84 | 3.75 | 43.19 | 4.01 | 12.30 |
| 412 | BERMINGH | B400 4.8 | OED | 58.58 | 21.36 | 2.74 | 43.20 | 4.80 | 9.00 |
| 35 | DELMAG | D 19-52 | OED | 58.63 | 17.80 | 3.61 | 43.24 | 4.00 | 11.86 |
| 41 | DELMAG | D 19-42 | OED | 58.63 | 17.80 | 3.61 | 43.24 | 4.00 | 11.86 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|--------------------|------------------|-----------------------|-------------------------|--------------------|------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 349 | HERA | 1900 | OED | 60.23 | 18.65 | 3.23 | 44.41 | 4.19 | 10.60 |
| 413 | BERMINGH | B400 5.0 | OED | 61.02 | 22.25 | 2.74 | 45.00 | 5.00 | 9.00 |
| 103 | KOBE | K22-Est | OED | 61.49 | 21.58 | 2.85 | 45.35 | 4.85 | 9.35 |
| 64 | MITSUBIS | MH 25 | OED | 63.51 | 24.52 | 2.59 | 46.84 | 5.51 | 8.50 |
| 416 | BERMINGH | B350 5 | OED | 64.00 | 17.80 | 3.60 | 47.20 | 4.00 | 11.80 |
| 7 | DELMAG | D 22-02 | OED | 65.77 | 21.58 | 4.10 | 48.50 | 4.85 | 13.44 |
| 8 | DELMAG | D 22-13 | OED | 65.77 | 21.58 | 4.10 | 48.50 | 4.85 | 13.44 |
| 52 | FEC | FEC 2500 | OED | 67.79 | 24.48 | 2.77 | 50.00 | 5.50 | 9.09 |
| 157 | MKT | DE 50C | OED | 67.80 | 22.25 | 3.96 | 50.00 | 5.00 | 13.00 |
| 163 | MKT 50 | DE70/50B | OED | 67.80 | 22.25 | 3.66 | 50.00 | 5.00 | 12.00 |
| 352 | HERA | 2500 | OED | 68.74 | 25.01 | 2.75 | 50.69 | 5.62 | 9.02 |
| 9 | DELMAG | D 22-23 | OED | 69.45 | 21.58 | 4.10 | 51.22 | 4.85 | 13.44 |
| 104 | KOBE | K 25 | OED | 69.86 | 24.52 | 2.85 | 51.52 | 5.51 | 9.35 |
| 85 | LINKBELT | LB 660 | CED | 70.01 | 33.69 | 2.08 | 51.63 | 7.57 | 6.82 |
| 125 | ICE | 660 | CED | 70.01 | 33.69 | 2.08 | 51.63 | 7.57 | 6.82 |
| 405 | BERMINGH | B400 | OED | 72.89 | 22.25 | 3.28 | 53.75 | 5.00 | 10.75 |
| 411 | BERMINGH | B400 M | OED | 72.89 | 22.25 | 3.28 | 53.75 | 5.00 | 10.75 |
| 46 | DELMAG | D 21-42 | OED | 75.59 | 20.60 | 4.27 | 55.75 | 4.63 | 14.00 |
| 53 | FEC | FEC 2800 | OED | 75.93 | 27.41 | 2.77 | 55.99 | 6.16 | 9.09 |
| 353 | HERA | 2800 | OED | 76.93 | 27.99 | 2.75 | 56.74 | 6.29 | 9.02 |
| 581 | APE | D 25-32 | OED | 78.45 | 24.52 | 3.20 | 57.86 | 5.51 | 10.50 |
| 417 | BERMINGH | B400 5 | OED | 80.00 | 22.25 | 3.60 | 59.00 | 5.00 | 11.80 |
| 162 | MKT | DE 70B | OED | 80.68 | 31.15 | 3.66 | 59.50 | 7.00 | 12.00 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 11 | DELMAG | D 30 | OED | 80.99 | 29.37 | 2.90 | 59.73 | 6.60 | 9.50 |
| 130 | ICE | 60-S | OED | 81.35 | 31.15 | 3.18 | 59.99 | 7.00 | 10.42 |
| 65 | MITSUBIS | M 33 | OED | 83.68 | 32.31 | 2.59 | 61.71 | 7.26 | 8.50 |
| 54 | FEC | FEC 3000 | OED | 85.47 | 29.37 | 2.91 | 63.03 | 6.60 | 9.55 |
| 66 | MITSUBIS | MH 35 | OED | 88.98 | 34.35 | 2.59 | 65.62 | 7.72 | 8.50 |
| 12 | DELMAG | D 30-02 | OED | 89.76 | 29.37 | 4.10 | 66.20 | 6.60 | 13.44 |
| 13 | DELMAG | D 30-13 | OED | 89.76 | 29.37 | 4.10 | 66.20 | 6.60 | 13.44 |
| 10 | DELMAG | D 25-32 | OED | 89.96 | 24.52 | 4.19 | 66.34 | 5.51 | 13.76 |
| 131 | ICE | 70-S | OED | 94.92 | 31.15 | 3.10 | 70.00 | 7.00 | 10.17 |
| 158 | MKT | DE 70C | OED | 94.92 | 31.15 | 3.96 | 70.00 | 7.00 | 13.00 |
| 164 | MKT 70 | DE70/50B | OED | 94.92 | 31.15 | 3.66 | 70.00 | 7.00 | 12.00 |
| 572 | APE | D 30-32 | OED | 95.01 | 29.41 | 3.23 | 70.07 | 6.61 | 10.60 |
| 354 | HERA | 3500 | OED | 96.26 | 35.02 | 2.75 | 70.99 | 7.87 | 9.02 |
| 107 | KOBE | K 35 | OED | 97.88 | 34.35 | 2.85 | 72.18 | 7.72 | 9.35 |
| 126 | ICE | 1070 | CED | 98.45 | 44.50 | 2.21 | 72.60 | 10.00 | 7.26 |
| 55 | FEC | FEC 3400 | OED | 98.99 | 33.29 | 2.97 | 73.00 | 7.48 | 9.76 |
| 14 | DELMAG | D 30-23 | OED | 100.06 | 29.37 | 4.10 | 73.79 | 6.60 | 13.44 |
| 362 | ICE | I-30 | OED | 102.27 | 29.41 | 3.84 | 75.42 | 6.61 | 12.60 |
| 15 | DELMAG | D 30-32 | OED | 102.29 | 29.37 | 4.18 | 75.44 | 6.60 | 13.73 |
| 418 | BERMINGH | B450 5 | OED | 105.61 | 29.37 | 3.60 | 77.88 | 6.60 | 11.80 |
| 132 | ICE | 80-S | OED | 108.48 | 35.60 | 3.79 | 80.00 | 8.00 | 12.42 |
| 67 | MITSUBIS | M 43 | OED | 109.04 | 42.10 | 2.59 | 80.41 | 9.46 | 8.50 |
| 16 | DELMAG | D 36 | OED | 113.66 | 35.29 | 3.22 | 83.82 | 7.93 | 10.57 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|--------------------|------------------|-----------------------|-------------------------|--------------------|------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 17 | DELMAG | D 36-02 | OED | 113.66 | 35.29 | 3.96 | 83.82 | 7.93 | 12.98 |
| 18 | DELMAG | D 36-13 | OED | 113.66 | 35.29 | 6.09 | 83.82 | 7.93 | 19.98 |
| 573 | APE | D 36-32 | OED | 113.98 | 35.29 | 3.23 | 84.06 | 7.93 | 10.60 |
| 68 | MITSUBIS | MH 45 | OED | 115.84 | 44.72 | 2.59 | 85.43 | 10.05 | 8.50 |
| 421 | BERMINGH | B550 C | OED | 119.33 | 48.95 | 2.44 | 88.00 | 11.00 | 8.00 |
| 19 | DELMAG | D 36-23 | OED | 120.00 | 35.29 | 3.96 | 88.50 | 7.93 | 12.98 |
| 133 | ICE | 90-S | OED | 122.04 | 40.05 | 3.10 | 90.00 | 9.00 | 10.17 |
| 21 | DELMAG | D 44 | OED | 122.25 | 42.28 | 2.90 | 90.16 | 9.50 | 9.52 |
| 20 | DELMAG | D 36-32 | OED | 122.80 | 35.29 | 4.01 | 90.56 | 7.93 | 13.14 |
| 363 | ICE | I-36 | OED | 122.96 | 35.33 | 3.69 | 90.67 | 7.94 | 12.10 |
| 419 | BERMINGH | B500 5 | OED | 124.81 | 34.71 | 3.60 | 92.04 | 7.80 | 11.80 |
| 110 | KOBE | K 45 | OED | 125.77 | 44.14 | 2.85 | 92.75 | 9.92 | 9.35 |
| 24 | DELMAG | D 46-13 | OED | 130.90 | 45.12 | 3.94 | 96.53 | 10.14 | 12.94 |
| 134 | ICE | 100-S | OED | 135.60 | 44.50 | 3.66 | 100.00 | 10.00 | 12.00 |
| 136 | ICE | 200-S | OED | 135.60 | 89.00 | 1.83 | 100.00 | 20.00 | 6.00 |
| 355 | HERA | 5000 | OED | 137.48 | 50.02 | 2.75 | 101.38 | 11.24 | 9.02 |
| 420 | BERMINGH | B550 5 | OED | 144.01 | 40.05 | 3.60 | 106.20 | 9.00 | 11.80 |
| 22 | DELMAG | D 46 | OED | 145.20 | 45.12 | 3.22 | 107.08 | 10.14 | 10.57 |
| 23 | DELMAG | D 46-02 | OED | 145.20 | 45.12 | 3.94 | 107.08 | 10.14 | 12.94 |
| 25 | DELMAG | D 46-23 | OED | 145.20 | 45.12 | 3.94 | 107.08 | 10.14 | 12.94 |
| 574 | APE | D 46-32 | OED | 145.75 | 45.12 | 3.23 | 107.48 | 10.14 | 10.60 |
| 364 | ICE | I-46 | OED | 146.17 | 45.17 | 3.69 | 107.79 | 10.15 | 12.12 |
| 165 | MKT 110 | DE110150 | OED | 149.16 | 48.95 | 4.11 | 110.00 | 11.00 | 13.50 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 356 | HERA | 5700 | OED | 156.68 | 57.00 | 2.75 | 115.55 | 12.81 | 9.02 |
| 135 | ICE | 120-S | OED | 162.72 | 53.40 | 3.79 | 120.00 | 12.00 | 12.42 |
| 26 | DELMAG | D 46-32 | OED | 165.69 | 45.12 | 3.99 | 122.19 | 10.14 | 13.10 |
| 27 | DELMAG | D 55 | OED | 169.51 | 52.78 | 3.40 | 125.00 | 11.86 | 11.15 |
| 357 | HERA | 6200 | OED | 170.38 | 61.99 | 2.75 | 125.65 | 13.93 | 9.02 |
| 112 | KOBE | KB 60 | OED | 176.53 | 58.87 | 3.00 | 130.18 | 13.23 | 9.84 |
| 140 | ICE | 120S-15 | OED | 179.60 | 66.75 | 3.73 | 132.45 | 15.00 | 12.25 |
| 70 | MITSUBIS | MH 72B | OED | 183.26 | 70.76 | 2.59 | 135.15 | 15.90 | 8.50 |
| 71 | MITSUBIS | MH 80B | OED | 202.86 | 78.32 | 2.59 | 149.60 | 17.60 | 8.50 |
| 166 | MKT 150 | DE110150 | OED | 203.40 | 66.75 | 4.11 | 150.00 | 15.00 | 13.50 |
| 358 | HERA | 7500 | OED | 206.09 | 74.98 | 2.75 | 151.99 | 16.85 | 9.02 |
| 28 | DELMAG | D 62-02 | OED | 206.72 | 60.79 | 3.87 | 152.45 | 13.66 | 12.71 |
| 29 | DELMAG | D 62-12 | OED | 206.72 | 60.79 | 3.87 | 152.45 | 13.66 | 12.71 |
| 575 | APE | D 62-22 | OED | 218.94 | 60.79 | 3.60 | 161.46 | 13.66 | 11.82 |
| 30 | DELMAG | D 62-22 | OED | 223.20 | 60.79 | 4.04 | 164.60 | 13.66 | 13.26 |
| 365 | ICE | I-62 | OED | 223.71 | 64.97 | 4.34 | 164.98 | 14.60 | 14.25 |
| 137 | ICE | 205-S | OED | 230.52 | 89.00 | 3.20 | 170.00 | 20.00 | 10.50 |
| 113 | KOBE | KB 80 | OED | 235.37 | 78.50 | 3.00 | 173.58 | 17.64 | 9.84 |
| 359 | HERA | 8800 | OED | 241.93 | 88.02 | 2.75 | 178.42 | 19.78 | 9.02 |
| 31 | DELMAG | D 80-12 | OED | 252.55 | 78.41 | 3.92 | 186.24 | 17.62 | 12.87 |
| 576 | APE | D 80-23 | OED | 267.12 | 78.41 | 3.41 | 196.99 | 17.62 | 11.18 |
| 366 | ICE | I-80 | OED | 288.01 | 78.77 | 4.11 | 212.40 | 17.70 | 13.50 |
| 32 | DELMAG | D 80-23 | OED | 288.15 | 78.41 | 3.98 | 212.50 | 17.62 | 13.05 |

| TABLE D-1: DIESEL HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 577 | APE | D 100-13 | OED | 333.98 | 98.03 | 3.41 | 246.30 | 22.03 | 11.18 |
| 33 | DELMAG | D100-13 | OED | 360.32 | 98.21 | 4.11 | 265.72 | 22.07 | 13.50 |
| 43 | DELMAG | D120-42 | OED | 409.23 | 117.70 | 3.60 | 301.79 | 26.45 | 11.81 |
| 582 | APE | D 125-32 | OED | 416.69 | 122.64 | 3.40 | 307.29 | 27.56 | 11.15 |
| 45 | DELMAG | D125-42 | OED | 425.29 | 122.64 | 4.15 | 313.63 | 27.56 | 13.60 |
| 44 | DELMAG | D150-42 | OED | 511.66 | 147.16 | 3.60 | 377.33 | 33.07 | 11.81 |
| 42 | DELMAG | D200-42 | OED | 667.21 | 196.20 | 5.13 | 492.04 | 44.09 | 16.83 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 301 | MKT | No. 5 | ECH | 1.36 | 0.89 | 1.52 | 1.00 | 0.20 | 5.00 |
| 302 | MKT | No. 6 | ECH | 3.39 | 1.78 | 1.91 | 2.50 | 0.40 | 6.25 |
| 303 | MKT | No. 7 | ECH | 5.63 | 3.56 | 1.58 | 4.15 | 0.80 | 5.19 |
| 205 | VULCAN | VUL 02 | ECH | 9.84 | 13.35 | 0.74 | 7.26 | 3.00 | 2.42 |
| 220 | VULCAN | VUL 30C | ECH | 9.84 | 13.35 | 0.74 | 7.26 | 3.00 | 2.42 |
| 521 | DAWSON | HPH1200 | ECH | 11.82 | 10.24 | 1.16 | 8.72 | 2.30 | 3.79 |
| 304 | MKT | 9B3 | ECH | 11.87 | 7.12 | 1.67 | 8.75 | 1.60 | 5.47 |
| 305 | MKT | 10B3 | ECH | 17.78 | 13.35 | 1.33 | 13.11 | 3.00 | 4.37 |
| 522 | DAWSON | HPH1800 | ECH | 18.62 | 14.69 | 1.27 | 13.73 | 3.30 | 4.16 |
| 567 | HMC | 19D | ECH | 18.98 | 15.58 | 1.22 | 14.00 | 3.50 | 4.00 |
| 306 | MKT | C5-Air | ECH | 19.26 | 22.25 | 0.87 | 14.20 | 5.00 | 2.84 |
| 171 | CONMACO | C 50 | ECH | 20.34 | 22.25 | 0.91 | 15.00 | 5.00 | 3.00 |
| 204 | VULCAN | VUL 01 | ECH | 20.34 | 22.25 | 0.91 | 15.00 | 5.00 | 3.00 |
| 251 | RAYMOND | R 1 | ECH | 20.34 | 22.25 | 0.91 | 15.00 | 5.00 | 3.00 |
| 221 | VULCAN | VUL 50C | ECH | 20.48 | 22.25 | 0.92 | 15.10 | 5.00 | 3.02 |
| 307 | MKT | C5-Steam | ECH | 21.97 | 22.25 | 0.99 | 16.20 | 5.00 | 3.24 |
| 380 | BSP | HH 1.5 | ECH | 22.02 | 14.69 | 1.50 | 16.24 | 3.30 | 4.92 |
| 308 | MKT | S-5 | ECH | 22.04 | 22.25 | 0.99 | 16.25 | 5.00 | 3.25 |
| 514 | UDDCOMB | H2H | ECH | 22.49 | 19.58 | 1.15 | 16.59 | 4.40 | 3.77 |
| 523 | DAWSON | HPH2400 | ECH | 23.47 | 18.65 | 1.26 | 17.30 | 4.19 | 4.13 |
| 541 | BANUT | 3 Tonnes | ECH | 23.48 | 29.41 | 0.80 | 17.32 | 6.61 | 2.62 |
| 309 | MKT | 11B3 | ECH | 25.97 | 22.25 | 1.17 | 19.15 | 5.00 | 3.83 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 222 | VULCAN | VUL 65C | ECH | 26.00 | 28.93 | 0.90 | 19.18 | 6.50 | 2.95 |
| 172 | CONMACO | C 65 | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 206 | VULCAN | VUL 06 | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 252 | RAYMOND | R 1S | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 253 | RAYMOND | R 65C | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 254 | RAYMOND | R 65CH | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 223 | VULCAN | VUL 65CA | ECH | 26.53 | 28.93 | 0.92 | 19.57 | 6.50 | 3.01 |
| 550 | ICE | 70 | ECH | 28.48 | 31.15 | 0.91 | 21.00 | 7.00 | 3.00 |
| 561 | HMC | 28B | ECH | 28.48 | 31.15 | 0.91 | 21.00 | 7.00 | 3.00 |
| 311 | MKT | C826 Air | ECH | 28.75 | 35.60 | 0.81 | 21.20 | 8.00 | 2.65 |
| 335 | IHC | SC-30 | ECH | 29.57 | 16.73 | 1.77 | 21.81 | 3.76 | 5.80 |
| 542 | BANUT | 4 Tonnes | ECH | 31.33 | 39.25 | 0.80 | 23.11 | 8.82 | 2.62 |
| 255 | RAYMOND | R 0 | ECH | 33.05 | 33.38 | 0.99 | 24.38 | 7.50 | 3.25 |
| 310 | MKT | C826 Stm | ECH | 33.09 | 35.60 | 0.93 | 24.40 | 8.00 | 3.05 |
| 224 | VULCAN | VUL 80C | ECH | 33.19 | 35.60 | 0.93 | 24.48 | 8.00 | 3.06 |
| 256 | RAYMOND | R 80C | ECH | 33.19 | 35.60 | 0.93 | 24.48 | 8.00 | 3.06 |
| 257 | RAYMOND | R 80CH | ECH | 33.19 | 35.60 | 0.93 | 24.48 | 8.00 | 3.06 |
| 449 | MENCK | MHF3-3 | ECH | 33.55 | 31.37 | 1.07 | 24.75 | 7.05 | 3.51 |
| 515 | UDDCOMB | H3H | ECH | 33.74 | 29.37 | 1.15 | 24.88 | 6.60 | 3.77 |
| 173 | CONMACO | C 550 | ECH | 33.90 | 22.25 | 1.52 | 25.00 | 5.00 | 5.00 |
| 192 | CONMACO | C 50E5 | ECH | 33.90 | 22.25 | 1.52 | 25.00 | 5.00 | 5.00 |
| 235 | VULCAN | VUL 505 | ECH | 33.90 | 22.25 | 1.52 | 25.00 | 5.00 | 5.00 |
| 320 | IHC | S-35 | ECH | 34.61 | 29.50 | 1.17 | 25.53 | 6.63 | 3.85 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 225 | VULCAN | VUL 85C | ECH | 35.24 | 37.91 | 0.93 | 25.99 | 8.52 | 3.05 |
| 175 | CONMACO | C 80 | ECH | 35.26 | 35.60 | 0.99 | 26.00 | 8.00 | 3.25 |
| 207 | VULCAN | VUL 08 | ECH | 35.26 | 35.60 | 0.99 | 26.00 | 8.00 | 3.25 |
| 312 | MKT | S-8 | ECH | 35.26 | 35.60 | 0.99 | 26.00 | 8.00 | 3.25 |
| 591 | APE | 5.4mT | ECH | 35.31 | 53.40 | 0.66 | 26.04 | 12.00 | 2.17 |
| 381 | BSP | HH 3 | ECH | 35.31 | 29.41 | 1.20 | 26.04 | 6.61 | 3.94 |
| 530 | Bruce | SGH-0312 | ECH | 35.31 | 29.41 | 1.20 | 26.04 | 6.61 | 3.94 |
| 535 | BANUT | 3000 | ECH | 35.31 | 29.41 | 1.20 | 26.04 | 6.61 | 3.94 |
| 481 | JUNTTAN | HHK 3 | ECH | 36.00 | 29.46 | 1.22 | 26.55 | 6.62 | 4.01 |
| 560 | HMC | 28A | ECH | 37.97 | 31.15 | 1.22 | 28.00 | 7.00 | 4.00 |
| 568 | HMC | 38D | ECH | 37.97 | 31.15 | 1.22 | 28.00 | 7.00 | 4.00 |
| 543 | BANUT | 5 Tonnes | ECH | 39.15 | 49.04 | 0.80 | 28.87 | 11.02 | 2.62 |
| 336 | IHC | SC-40 | ECH | 40.50 | 24.52 | 1.65 | 29.86 | 5.51 | 5.42 |
| 551 | ICE | 75 | ECH | 40.68 | 33.38 | 1.22 | 30.00 | 7.50 | 4.00 |
| 313 | MKT | MS-350 | ECH | 41.77 | 34.35 | 1.22 | 30.80 | 7.72 | 3.99 |
| 450 | MENCK | MHF3-4 | ECH | 41.98 | 39.25 | 1.07 | 30.96 | 8.82 | 3.51 |
| 174 | CONMACO | C 565 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 176 | CONMACO | C 100 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 193 | CONMACO | C 65E5 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 208 | VULCAN | VUL 010 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 236 | VULCAN | VUL 506 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 258 | RAYMOND | R 2/0 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 314 | MKT | S 10 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 506 | HPSI | 650 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 372 | FAIRCHLD | F-32 | ECH | 44.14 | 48.28 | 0.91 | 32.55 | 10.85 | 3.00 |
| 226 | VULCAN | VUL 100C | ECH | 44.61 | 44.50 | 1.00 | 32.90 | 10.00 | 3.29 |
| 516 | UDDCOMB | H4H | ECH | 44.99 | 39.16 | 1.15 | 33.18 | 8.80 | 3.77 |
| 544 | BANUT | 6 Tonnes | ECH | 47.00 | 58.87 | 0.80 | 34.66 | 13.23 | 2.62 |
| 536 | BANUT | 4000 | ECH | 47.12 | 39.25 | 1.20 | 34.75 | 8.82 | 3.94 |
| 482 | JUNTTAN | HHK 4 | ECH | 47.96 | 39.25 | 1.22 | 35.37 | 8.82 | 4.01 |
| 227 | VULCAN | VUL 140C | ECH | 48.79 | 62.30 | 0.78 | 35.98 | 14.00 | 2.57 |
| 337 | IHC | SC-50 | ECH | 49.92 | 32.44 | 1.54 | 36.81 | 7.29 | 5.05 |
| 177 | CONMACO | C 115 | ECH | 50.68 | 51.18 | 0.99 | 37.38 | 11.50 | 3.25 |
| 315 | MKT | S 14 | ECH | 50.88 | 62.30 | 0.82 | 37.52 | 14.00 | 2.68 |
| 552 | ICE | 110-SH | ECH | 51.15 | 51.18 | 1.00 | 37.72 | 11.50 | 3.28 |
| 553 | ICE | 115-SH | ECH | 51.46 | 51.18 | 1.01 | 37.95 | 11.50 | 3.30 |
| 441 | MENCK | MHF5-5 | ECH | 52.45 | 49.04 | 1.07 | 38.68 | 11.02 | 3.51 |
| 451 | MENCK | MHF3-5 | ECH | 52.45 | 49.04 | 1.07 | 38.68 | 11.02 | 3.51 |
| 209 | VULCAN | VUL 012 | ECH | 52.88 | 53.40 | 0.99 | 39.00 | 12.00 | 3.25 |
| 178 | CONMACO | C 80E5 | ECH | 54.24 | 35.60 | 1.52 | 40.00 | 8.00 | 5.00 |
| 237 | VULCAN | VUL 508 | ECH | 54.24 | 35.60 | 1.52 | 40.00 | 8.00 | 5.00 |
| 545 | BANUT | 7 Tonnes | ECH | 54.82 | 68.66 | 0.80 | 40.43 | 15.43 | 2.62 |
| 259 | RAYMOND | R 3/0 | ECH | 55.09 | 55.63 | 0.99 | 40.63 | 12.50 | 3.25 |
| 517 | UDDCOMB | H5H | ECH | 56.23 | 48.95 | 1.15 | 41.47 | 11.00 | 3.77 |
| 182 | CONMACO | C 140 | ECH | 56.95 | 62.30 | 0.91 | 42.00 | 14.00 | 3.00 |
| 210 | VULCAN | VUL 014 | ECH | 56.95 | 62.30 | 0.91 | 42.00 | 14.00 | 3.00 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 382 | BSP | HH 5 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 531 | Bruce | SGH-0512 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 537 | BANUT | 5000 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 801 | DKH | PH-5 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 316 | MKT | MS 500 | ECH | 59.66 | 48.95 | 1.22 | 44.00 | 11.00 | 4.00 |
| 501 | HPSI | 110 | ECH | 59.66 | 48.95 | 1.22 | 44.00 | 11.00 | 4.00 |
| 489 | JUNTTAN | HHK 5A | ECH | 59.77 | 49.04 | 1.22 | 44.08 | 11.02 | 4.00 |
| 483 | JUNTTAN | HHK 5 | ECH | 59.98 | 49.08 | 1.22 | 44.23 | 11.03 | 4.01 |
| 338 | IHC | SC-60 | ECH | 60.96 | 59.19 | 1.03 | 44.95 | 13.30 | 3.38 |
| 371 | FAIRCHLD | F-45 | ECH | 61.02 | 66.75 | 0.91 | 45.00 | 15.00 | 3.00 |
| 282 | MENCK | MRBS 500 | ECH | 61.12 | 49.04 | 1.25 | 45.07 | 11.02 | 4.09 |
| 554 | ICE | 115 | ECH | 62.38 | 51.18 | 1.22 | 46.00 | 11.50 | 4.00 |
| 562 | HMC | 62 | ECH | 62.38 | 51.18 | 1.22 | 46.00 | 11.50 | 4.00 |
| 442 | MENCK | MHF5-6 | ECH | 62.97 | 58.87 | 1.07 | 46.44 | 13.23 | 3.51 |
| 452 | MENCK | MHF3-6 | ECH | 62.97 | 58.87 | 1.07 | 46.44 | 13.23 | 3.51 |
| 524 | DAWSON | HPH6500 | ECH | 63.66 | 45.61 | 1.40 | 46.95 | 10.25 | 4.58 |
| 183 | CONMACO | C 160 | ECH | 66.11 | 72.31 | 0.91 | 48.75 | 16.25 | 3.00 |
| 211 | VULCAN | VUL 016 | ECH | 66.11 | 72.31 | 0.91 | 48.75 | 16.25 | 3.00 |
| 260 | RAYMOND | R 150C | ECH | 66.11 | 66.75 | 0.99 | 48.75 | 15.00 | 3.25 |
| 261 | RAYMOND | R 4/0 | ECH | 66.11 | 66.75 | 0.99 | 48.75 | 15.00 | 3.25 |
| 271 | MENCK | MH 68 | ECH | 66.68 | 34.35 | 1.94 | 49.18 | 7.72 | 6.37 |
| 518 | UDDCOMB | H6H | ECH | 67.48 | 58.74 | 1.15 | 49.76 | 13.20 | 3.77 |
| 179 | CONMACO | C 100E5 | ECH | 67.80 | 44.50 | 1.52 | 50.00 | 10.00 | 5.00 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 238 | VULCAN | VUL 510 | ECH | 67.80 | 44.50 | 1.52 | 50.00 | 10.00 | 5.00 |
| 507 | HPSI | 1000 | ECH | 67.80 | 44.50 | 1.52 | 50.00 | 10.00 | 5.00 |
| 228 | VULCAN | VUL 200C | ECH | 68.07 | 89.00 | 0.77 | 50.20 | 20.00 | 2.51 |
| 321 | IHC | S-70 | ECH | 69.49 | 34.40 | 2.02 | 51.25 | 7.73 | 6.63 |
| 592 | APE | 7.2mT | ECH | 69.64 | 72.09 | 0.97 | 51.35 | 16.20 | 3.17 |
| 191 | CONMACO | C 160 ** | ECH | 70.21 | 76.81 | 0.91 | 51.78 | 17.26 | 3.00 |
| 538 | BANUT | 6000 | ECH | 70.68 | 58.87 | 1.20 | 52.13 | 13.23 | 3.94 |
| 484 | JUNTTAN | HHK 6 | ECH | 71.94 | 58.87 | 1.22 | 53.05 | 13.23 | 4.01 |
| 443 | MENCK | MHF5-7 | ECH | 73.44 | 68.66 | 1.07 | 54.16 | 15.43 | 3.51 |
| 453 | MENCK | MHF3-7 | ECH | 73.44 | 68.66 | 1.07 | 54.16 | 15.43 | 3.51 |
| 339 | IHC | SC-75 | ECH | 74.30 | 54.07 | 1.37 | 54.80 | 12.15 | 4.51 |
| 262 | RAYMOND | R 5/0 | ECH | 77.12 | 77.88 | 0.99 | 56.88 | 17.50 | 3.25 |
| 180 | CONMACO | C 115E5 | ECH | 77.97 | 51.18 | 1.52 | 57.50 | 11.50 | 5.00 |
| 184 | CONMACO | C 200 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 212 | VULCAN | VUL 020 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 231 | VULCAN | VUL 320 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 239 | VULCAN | VUL 512 | ECH | 81.36 | 53.40 | 1.52 | 60.00 | 12.00 | 5.00 |
| 317 | MKT | S 20 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 502 | HPSI | 150 | ECH | 81.36 | 66.75 | 1.22 | 60.00 | 15.00 | 4.00 |
| 383 | BSP | HH 7 | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |
| 532 | Bruce | SGH-0712 | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |
| 802 | DKH | PH-7 | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |
| 803 | DKH | PH-7S | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 503 | HPSI | 154 | ECH | 83.53 | 68.53 | 1.22 | 61.60 | 15.40 | 4.00 |
| 490 | JUNTTAN | HHK 7A | ECH | 83.69 | 68.66 | 1.22 | 61.72 | 15.43 | 4.00 |
| 485 | JUNTTAN | HHK 7 | ECH | 83.96 | 68.71 | 1.22 | 61.91 | 15.44 | 4.01 |
| 444 | MENCK | MHF5-8 | ECH | 83.96 | 78.50 | 1.07 | 61.92 | 17.64 | 3.51 |
| 181 | CONMACO | C 125E5 | ECH | 84.75 | 55.63 | 1.52 | 62.50 | 12.50 | 5.00 |
| 555 | ICE | 160-SH | ECH | 86.78 | 71.20 | 1.22 | 64.00 | 16.00 | 4.00 |
| 556 | ICE | 160 | ECH | 86.78 | 71.20 | 1.22 | 64.00 | 16.00 | 4.00 |
| 563 | HMC | 86 | ECH | 86.78 | 71.20 | 1.22 | 64.00 | 16.00 | 4.00 |
| 322 | IHC | S-90 | ECH | 89.36 | 44.23 | 2.02 | 65.90 | 9.94 | 6.63 |
| 283 | MENCK | MRBS 750 | ECH | 91.90 | 73.56 | 1.25 | 67.77 | 16.53 | 4.10 |
| 272 | MENCK | MH 96 | ECH | 94.14 | 49.04 | 1.92 | 69.43 | 11.02 | 6.30 |
| 384 | BSP | HH 8 | ECH | 94.24 | 78.50 | 1.20 | 69.50 | 17.64 | 3.94 |
| 539 | BANUT | 8000 | ECH | 94.24 | 78.50 | 1.20 | 69.50 | 17.64 | 3.94 |
| 445 | MENCK | MHF5-9 | ECH | 94.43 | 88.29 | 1.07 | 69.64 | 19.84 | 3.51 |
| 263 | RAYMOND | R 30X | ECH | 101.70 | 133.50 | 0.76 | 75.00 | 30.00 | 2.50 |
| 446 | MENCK | MHF5-10 | ECH | 104.90 | 98.08 | 1.07 | 77.36 | 22.04 | 3.51 |
| 385 | BSP | HH 9 | ECH | 106.00 | 88.29 | 1.20 | 78.17 | 19.84 | 3.94 |
| 491 | JUNTTAN | HHK 9A | ECH | 107.61 | 88.29 | 1.22 | 79.36 | 19.84 | 4.00 |
| 504 | HPSI | 200 | ECH | 108.48 | 89.00 | 1.22 | 80.00 | 20.00 | 4.00 |
| 512 | HPSI | 2000 | ECH | 108.48 | 89.00 | 1.22 | 80.00 | 20.00 | 4.00 |
| 595 | APE | 10-60 | ECH | 108.48 | 89.00 | 1.22 | 80.00 | 20.00 | 4.00 |
| 264 | RAYMOND | R 8/0 | ECH | 110.18 | 111.25 | 0.99 | 81.25 | 25.00 | 3.25 |
| 340 | IHC | SC-110 | ECH | 111.04 | 77.70 | 1.43 | 81.89 | 17.46 | 4.69 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 519 | UDDCOMB | H8H | ECH | 111.45 | 78.32 | 1.42 | 82.19 | 17.60 | 4.67 |
| 508 | HPSI | 1605 | ECH | 112.55 | 73.87 | 1.52 | 83.00 | 16.60 | 5.00 |
| 447 | MENCK | MHF5-11 | ECH | 115.42 | 107.91 | 1.07 | 85.12 | 24.25 | 3.51 |
| 804 | DKH | PH-10 | ECH | 117.75 | 98.08 | 1.20 | 86.84 | 22.04 | 3.94 |
| 520 | UDDCOMB | H10H | ECH | 117.81 | 98.12 | 1.20 | 86.88 | 22.05 | 3.94 |
| 533 | Bruce | SGH-1012 | ECH | 117.81 | 98.12 | 1.20 | 86.88 | 22.05 | 3.94 |
| 540 | BANUT | 10000 | ECH | 117.81 | 98.12 | 1.20 | 86.88 | 22.05 | 3.94 |
| 557 | ICE | 220 | ECH | 119.33 | 97.90 | 1.22 | 88.00 | 22.00 | 4.00 |
| 564 | HMC | 119 | ECH | 119.33 | 97.90 | 1.22 | 88.00 | 22.00 | 4.00 |
| 486 | JUNTTAN | HHK 10 | ECH | 119.90 | 98.12 | 1.22 | 88.42 | 22.05 | 4.01 |
| 323 | IHC | S-120 | ECH | 121.19 | 59.99 | 2.02 | 89.37 | 13.48 | 6.63 |
| 185 | CONMACO | C 300 | ECH | 122.04 | 133.50 | 0.91 | 90.00 | 30.00 | 3.00 |
| 213 | VULCAN | VUL 030 | ECH | 122.04 | 133.50 | 0.91 | 90.00 | 30.00 | 3.00 |
| 232 | VULCAN | VUL 330 | ECH | 122.04 | 133.50 | 0.91 | 90.00 | 30.00 | 3.00 |
| 505 | HPSI | 225 | ECH | 122.04 | 100.13 | 1.22 | 90.00 | 22.50 | 4.00 |
| 448 | MENCK | MHF5-12 | ECH | 125.89 | 117.70 | 1.07 | 92.84 | 26.45 | 3.51 |
| 285 | MENCK | MRBS 850 | ECH | 126.49 | 84.37 | 1.50 | 93.28 | 18.96 | 4.92 |
| 509 | HPSI | 2005 | ECH | 128.96 | 84.64 | 1.52 | 95.10 | 19.02 | 5.00 |
| 386 | BSP | HH11-1.2 | ECH | 129.56 | 107.91 | 1.20 | 95.55 | 24.25 | 3.94 |
| 186 | CONMACO | C 5200 | ECH | 135.60 | 89.00 | 1.52 | 100.00 | 20.00 | 5.00 |
| 194 | CONMACO | C 200E5 | ECH | 135.60 | 89.00 | 1.52 | 100.00 | 20.00 | 5.00 |
| 240 | VULCAN | VUL 520 | ECH | 135.60 | 89.00 | 1.52 | 100.00 | 20.00 | 5.00 |
| 265 | RAYMOND | R 40X | ECH | 135.60 | 178.00 | 0.76 | 100.00 | 40.00 | 2.50 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 492 | JUNTTAN | HHK 12A | ECH | 141.31 | 117.70 | 1.20 | 104.21 | 26.45 | 3.94 |
| 273 | MENCK | MH 145 | ECH | 142.11 | 73.56 | 1.93 | 104.80 | 16.53 | 6.34 |
| 487 | JUNTTAN | HHK 12 | ECH | 143.88 | 117.75 | 1.22 | 106.10 | 26.46 | 4.01 |
| 341 | IHC | SC-150 | ECH | 148.28 | 108.14 | 1.37 | 109.35 | 24.30 | 4.50 |
| 558 | ICE | 275 | ECH | 149.16 | 122.38 | 1.22 | 110.00 | 27.50 | 4.00 |
| 565 | HMC | 149 | ECH | 149.16 | 122.38 | 1.22 | 110.00 | 27.50 | 4.00 |
| 324 | IHC | S-150 | ECH | 149.24 | 73.87 | 2.02 | 110.06 | 16.60 | 6.63 |
| 805 | DKH | PH-13 | ECH | 153.12 | 127.54 | 1.20 | 112.92 | 28.66 | 3.94 |
| 229 | VULCAN | VUL 400C | ECH | 154.04 | 178.00 | 0.87 | 113.60 | 40.00 | 2.84 |
| 393 | BSP | HH11-1.5 | ECH | 161.78 | 107.91 | 1.50 | 119.31 | 24.25 | 4.92 |
| 214 | VULCAN | VUL 040 | ECH | 162.72 | 178.00 | 0.91 | 120.00 | 40.00 | 3.00 |
| 233 | VULCAN | VUL 340 | ECH | 162.72 | 178.00 | 0.91 | 120.00 | 40.00 | 3.00 |
| 387 | BSP | HH14-1.2 | ECH | 164.87 | 137.33 | 1.20 | 121.59 | 30.86 | 3.94 |
| 493 | JUNTTAN | HHK 14A | ECH | 164.87 | 137.33 | 1.20 | 121.59 | 30.86 | 3.94 |
| 286 | MENCK | MRBS1100 | ECH | 167.37 | 107.91 | 1.55 | 123.43 | 24.25 | 5.09 |
| 488 | JUNTTAN | HHK 14 | ECH | 167.86 | 137.37 | 1.22 | 123.79 | 30.87 | 4.01 |
| 454 | MENCK | MHF10-15 | ECH | 169.01 | 147.12 | 1.15 | 124.64 | 33.06 | 3.77 |
| 287 | MENCK | MRBS1502 | ECH | 183.86 | 147.16 | 1.25 | 135.59 | 33.07 | 4.10 |
| 566 | HMC | 187 | ECH | 187.13 | 153.53 | 1.22 | 138.00 | 34.50 | 4.00 |
| 388 | BSP | HH16-1.2 | ECH | 188.43 | 156.95 | 1.20 | 138.96 | 35.27 | 3.94 |
| 494 | JUNTTAN | HHK 16A | ECH | 188.43 | 156.95 | 1.20 | 138.96 | 35.27 | 3.94 |
| 274 | MENCK | MH 195 | ECH | 191.36 | 98.12 | 1.95 | 141.12 | 22.05 | 6.40 |
| 325 | IHC | S-200 | ECH | 197.49 | 97.90 | 2.02 | 145.64 | 22.00 | 6.62 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 461 | MENCK | MHUT 200 | ECH | 199.85 | 117.75 | 1.70 | 147.38 | 26.46 | 5.57 |
| 187 | CONMACO | C 5300 | ECH | 203.40 | 133.50 | 1.52 | 150.00 | 30.00 | 5.00 |
| 195 | CONMACO | C 300E5 | ECH | 203.40 | 133.50 | 1.52 | 150.00 | 30.00 | 5.00 |
| 241 | VULCAN | VUL 530 | ECH | 203.40 | 133.50 | 1.52 | 150.00 | 30.00 | 5.00 |
| 266 | RAYMOND | R 60X | ECH | 203.40 | 267.00 | 0.76 | 150.00 | 60.00 | 2.50 |
| 394 | BSP | HH14-1.5 | ECH | 205.88 | 137.33 | 1.50 | 151.83 | 30.86 | 4.92 |
| 342 | IHC | SC-200 | ECH | 206.80 | 134.39 | 1.54 | 152.51 | 30.20 | 5.05 |
| 510 | HPSI | 3005 | ECH | 209.23 | 137.33 | 1.52 | 154.30 | 30.86 | 5.00 |
| 495 | JUNTTAN | HHK 18A | ECH | 212.00 | 176.58 | 1.20 | 156.34 | 39.68 | 3.94 |
| 275 | MENCK | MHU 220 | ECH | 215.70 | 111.83 | 1.93 | 159.07 | 25.13 | 6.33 |
| 455 | MENCK | MHF10-20 | ECH | 225.29 | 196.11 | 1.15 | 166.14 | 44.07 | 3.77 |
| 395 | BSP | HH16-1.5 | ECH | 235.30 | 156.95 | 1.50 | 173.53 | 35.27 | 4.92 |
| 389 | BSP | HH 20 | ECH | 235.56 | 196.20 | 1.20 | 173.71 | 44.09 | 3.94 |
| 390 | BSP | HH 20S | ECH | 235.56 | 196.20 | 1.20 | 173.71 | 44.09 | 3.94 |
| 511 | HPSI | 3505 | ECH | 239.06 | 156.91 | 1.52 | 176.30 | 35.26 | 5.00 |
| 230 | VULCAN | VUL 600C | ECH | 243.27 | 267.00 | 0.91 | 179.40 | 60.00 | 2.99 |
| 215 | VULCAN | VUL 060 | ECH | 244.08 | 267.00 | 0.91 | 180.00 | 60.00 | 3.00 |
| 234 | VULCAN | VUL 360 | ECH | 244.08 | 267.00 | 0.91 | 180.00 | 60.00 | 3.00 |
| 288 | MENCK | MRBS1800 | ECH | 257.39 | 171.68 | 1.50 | 189.81 | 38.58 | 4.92 |
| 242 | VULCAN | VUL 540 | ECH | 271.20 | 182.01 | 1.49 | 200.00 | 40.90 | 4.89 |
| 326 | IHC | S-280 | ECH | 278.40 | 133.77 | 2.08 | 205.31 | 30.06 | 6.83 |
| 806 | DKH | PH-20 | ECH | 294.15 | 196.20 | 1.50 | 216.92 | 44.09 | 4.92 |
| 188 | CONMACO | C 5450 | ECH | 305.10 | 200.25 | 1.52 | 225.00 | 45.00 | 5.00 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 290 | MENCK | MRBS2502 | ECH | 306.39 | 245.24 | 1.25 | 225.95 | 55.11 | 4.10 |
| 291 | MENCK | MRBS2504 | ECH | 306.39 | 245.24 | 1.25 | 225.95 | 55.11 | 4.10 |
| 391 | BSP | HA 30 | ECH | 353.31 | 294.28 | 1.20 | 260.55 | 66.13 | 3.94 |
| 289 | MENCK | MRBS2500 | ECH | 355.43 | 284.49 | 1.25 | 262.11 | 63.93 | 4.10 |
| 276 | MENCK | MHU 400 | ECH | 392.64 | 225.66 | 1.74 | 289.55 | 50.71 | 5.71 |
| 327 | IHC | S-400 | ECH | 396.77 | 196.69 | 2.02 | 292.60 | 44.20 | 6.62 |
| 462 | MENCK | MHUT 400 | ECH | 400.18 | 234.52 | 1.71 | 295.12 | 52.70 | 5.60 |
| 243 | VULCAN | VUL 560 | ECH | 406.80 | 278.13 | 1.46 | 300.00 | 62.50 | 4.80 |
| 245 | VULCAN | VUL 3100 | ECH | 406.80 | 445.00 | 0.91 | 300.00 | 100.00 | 3.00 |
| 292 | MENCK | MRBS3000 | ECH | 441.19 | 294.28 | 1.50 | 325.36 | 66.13 | 4.92 |
| 807 | DKH | PH-30 | ECH | 441.19 | 294.28 | 1.50 | 325.36 | 66.13 | 4.92 |
| 392 | BSP | HA 40 | ECH | 471.11 | 392.40 | 1.20 | 347.43 | 88.18 | 3.94 |
| 189 | CONMACO | C 5700 | ECH | 474.60 | 311.50 | 1.52 | 350.00 | 70.00 | 5.00 |
| 328 | IHC | S-500 | ECH | 496.41 | 246.09 | 2.02 | 366.09 | 55.30 | 6.62 |
| 596 | APE | HI 400U | ECH | 542.40 | 356.00 | 1.52 | 400.00 | 80.00 | 5.00 |
| 463 | MENCK | MHUT 500 | ECH | 550.59 | 294.28 | 1.87 | 406.04 | 66.13 | 6.14 |
| 277 | MENCK | MHU 600 | ECH | 588.01 | 343.36 | 1.71 | 433.64 | 77.16 | 5.62 |
| 808 | DKH | PH-40 | ECH | 588.29 | 392.40 | 1.50 | 433.85 | 88.18 | 4.92 |
| 329 | IHC | S-600 | ECH | 601.44 | 298.15 | 2.02 | 443.54 | 67.00 | 6.62 |
| 294 | MENCK | MRBS4600 | ECH | 676.56 | 451.27 | 1.50 | 498.94 | 101.41 | 4.92 |
| 246 | VULCAN | VUL 5100 | ECH | 678.00 | 445.00 | 1.52 | 500.00 | 100.00 | 5.00 |
| 190 | CONMACO | C 6850 | ECH | 691.56 | 378.25 | 1.83 | 510.00 | 85.00 | 6.00 |
| 293 | MENCK | MRBS3900 | ECH | 696.09 | 386.53 | 1.80 | 513.34 | 86.86 | 5.91 |

| TABLE D-2: EXTERNAL COMBUSTION HAMMER LISTING (sorted by Rated Energy) | | | | | | | | | |
|---|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 464 | MENCK | MHUT700U | ECH | 699.88 | 413.09 | 1.69 | 516.13 | 92.83 | 5.56 |
| 295 | MENCK | MRBS5000 | ECH | 735.40 | 490.52 | 1.50 | 542.33 | 110.23 | 4.92 |
| 468 | MENCK | MHU 800S | ECH | 799.02 | 441.44 | 1.81 | 589.25 | 99.20 | 5.94 |
| 465 | MENCK | MHUT700A | ECH | 839.60 | 413.09 | 2.03 | 619.18 | 92.83 | 6.67 |
| 297 | MENCK | MRBS7000 | ECH | 856.18 | 685.30 | 1.25 | 631.40 | 154.00 | 4.10 |
| 330 | IHC | S-900 | ECH | 892.73 | 442.55 | 2.02 | 658.36 | 99.45 | 6.62 |
| 466 | MENCK | MHUT1000 | ECH | 999.25 | 588.74 | 1.70 | 736.91 | 132.30 | 5.57 |
| 278 | MENCK | MHU 1000 | ECH | 1000.32 | 565.02 | 1.77 | 737.70 | 126.97 | 5.81 |
| 247 | VULCAN | VUL 5150 | ECH | 1017.00 | 667.50 | 1.52 | 750.00 | 150.00 | 5.00 |
| 296 | MENCK | MRBS6000 | ECH | 1029.52 | 588.60 | 1.75 | 759.23 | 132.27 | 5.74 |
| 298 | MENCK | MRBS8000 | ECH | 1176.66 | 784.85 | 1.50 | 867.74 | 176.37 | 4.92 |
| 469 | MENCK | MHU 1200 | ECH | 1202.34 | 657.62 | 1.83 | 886.68 | 147.78 | 6.00 |
| 331 | IHC | S-1200 | ECH | 1208.27 | 598.97 | 2.02 | 891.05 | 134.60 | 6.62 |
| 299 | MENCK | MRBS8800 | ECH | 1294.34 | 863.34 | 1.50 | 954.53 | 194.01 | 4.92 |
| 332 | IHC | S-1800 | ECH | 1586.93 | 738.70 | 2.15 | 1170.30 | 166.00 | 7.05 |
| 279 | MENCK | MHU 1700 | ECH | 1666.35 | 922.17 | 1.81 | 1228.87 | 207.23 | 5.93 |
| 280 | MENCK | MHU 2100 | ECH | 2098.53 | 1138.31 | 1.84 | 1547.59 | 255.80 | 6.05 |
| 467 | MENCK | MHU2100S | ECH | 2100.02 | 1010.51 | 2.08 | 1548.69 | 227.08 | 6.82 |
| 300 | MENCK | MBS12500 | ECH | 2144.96 | 1226.33 | 1.75 | 1581.83 | 275.58 | 5.74 |
| 333 | IHC | S-2300 | ECH | 2280.09 | 1130.30 | 2.02 | 1681.48 | 254.00 | 6.62 |
| 248 | VULCAN | VUL 6300 | ECH | 2440.80 | 1335.00 | 1.83 | 1800.00 | 300.00 | 6.00 |
| 281 | MENCK | MHU 3000 | ECH | 2944.75 | 1618.73 | 1.82 | 2171.65 | 363.76 | 5.97 |

| TABLE D-3: VIBRATORY HAMMER LISTING (sorted by Power) | | | | | | | | | |
|--|------------------------|----------------|----------------|-------------|---------------------|-----------------|-------------|-----------------------|-----------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Power kW | Ram Weight kN | Frequency Hz | Power kW | Ram Weight kips | Frequency Hz |
| 770 | APE | 3 | VIB | 10.58 | 0.00 | 38.30 | 10.58 | 0.00 | 38.30 |
| 771 | APE | 6 | VIB | 10.58 | 0.04 | 38.30 | 10.58 | 0.01 | 38.30 |
| 700 | ICE | 23-28 | VIB | 21.00 | 0.45 | 26.70 | 21.00 | 0.10 | 26.70 |
| 720 | HMC | 3+28 | VIB | 21.00 | 0.49 | 26.80 | 21.00 | 0.11 | 26.80 |
| 750 | MKT | V-2B | VIB | 52.00 | 0.67 | 30.00 | 52.00 | 0.15 | 30.00 |
| 721 | HMC | 3+75 | VIB | 56.00 | 0.49 | 36.10 | 56.00 | 0.11 | 36.10 |
| 772 | APE | 15 | VIB | 59.67 | 0.49 | 30.00 | 59.67 | 0.11 | 30.00 |
| 773 | APE | 20 | VIB | 59.67 | 0.67 | 38.30 | 59.67 | 0.15 | 38.30 |
| 774 | APE | 20E | VIB | 59.67 | 0.67 | 38.30 | 59.67 | 0.15 | 38.30 |
| 701 | ICE | 216 | VIB | 130.00 | 2.05 | 26.70 | 130.00 | 0.46 | 26.70 |
| 702 | ICE | 216E | VIB | 130.00 | 2.05 | 26.70 | 130.00 | 0.46 | 26.70 |
| 751 | MKT | V-5C | VIB | 138.00 | 1.91 | 28.33 | 138.00 | 0.43 | 28.33 |
| 722 | HMC | 13+200 | VIB | 149.00 | 1.56 | 26.70 | 149.00 | 0.35 | 26.70 |
| 723 | HMC | 13S+200 | VIB | 149.00 | 1.56 | 26.70 | 149.00 | 0.35 | 26.70 |
| 703 | ICE | 11-23 | VIB | 164.00 | 2.05 | 31.70 | 164.00 | 0.46 | 31.70 |
| 724 | HMC | 13H+200 | VIB | 164.00 | 1.56 | 29.80 | 164.00 | 0.35 | 29.80 |
| 725 | HMC | 25+220 | VIB | 164.00 | 2.71 | 20.90 | 164.00 | 0.61 | 20.90 |
| 775 | APE | 50 | VIB | 194.00 | 1.02 | 30.00 | 194.00 | 0.23 | 30.00 |
| 776 | APE | 50E | VIB | 194.00 | 1.02 | 30.00 | 194.00 | 0.23 | 30.00 |

| TABLE D-3: VIBRATORY HAMMER LISTING (sorted by Power) | | | | | | | | | |
|--|------------------------|----------------|----------------|-------------|---------------------|-----------------|-------------|-----------------------|-----------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Power kW | Ram Weight kN | Frequency Hz | Power kW | Ram Weight kips | Frequency Hz |
| 777 | APE | 100 | VIB | 194.00 | 1.42 | 30.00 | 194.00 | 0.32 | 30.00 |
| 778 | APE | 100E | VIB | 194.00 | 0.62 | 30.00 | 194.00 | 0.14 | 30.00 |
| 704 | ICE | 223 | VIB | 242.00 | 2.05 | 38.30 | 242.00 | 0.46 | 38.30 |
| 705 | ICE | 416L | VIB | 242.00 | 4.09 | 26.70 | 242.00 | 0.92 | 26.70 |
| 708 | ICE | 44-30 | VIB | 242.00 | 5.79 | 20.00 | 242.00 | 1.30 | 20.00 |
| 726 | HMC | 26+335 | VIB | 242.00 | 3.16 | 25.60 | 242.00 | 0.71 | 25.60 |
| 727 | HMC | 26S+335 | VIB | 242.00 | 3.16 | 25.60 | 242.00 | 0.71 | 25.60 |
| 728 | HMC | 51+335 | VIB | 242.00 | 5.38 | 19.50 | 242.00 | 1.21 | 19.50 |
| 752 | MKT | V-20B | VIB | 242.00 | 35.60 | 28.33 | 242.00 | 8.00 | 28.33 |
| 779 | APE | 100HF | VIB | 260.00 | 0.62 | 43.00 | 260.00 | 0.14 | 43.00 |
| 780 | APE | 150 | VIB | 260.00 | 0.62 | 30.00 | 260.00 | 0.14 | 30.00 |
| 781 | APE | 150T | VIB | 260.00 | 0.76 | 30.00 | 260.00 | 0.17 | 30.00 |
| 706 | ICE | 812 | VIB | 375.00 | 8.10 | 26.70 | 375.00 | 1.82 | 26.70 |
| 707 | ICE | 815 | VIB | 375.00 | 8.19 | 26.70 | 375.00 | 1.84 | 26.70 |
| 709 | ICE | 44-50 | VIB | 377.00 | 5.79 | 26.70 | 377.00 | 1.30 | 26.70 |
| 729 | HMC | 51+535 | VIB | 377.00 | 5.38 | 26.40 | 377.00 | 1.21 | 26.40 |
| 730 | HMC | 51S+535 | VIB | 377.00 | 5.38 | 26.40 | 377.00 | 1.21 | 26.40 |
| 753 | MKT | V-30 | VIB | 448.00 | 6.54 | 28.33 | 448.00 | 1.47 | 28.33 |
| 782 | APE | 150HF | VIB | 466.00 | 1.42 | 43.00 | 466.00 | 0.32 | 43.00 |
| 783 | APE | 200 | VIB | 466.00 | 1.29 | 30.00 | 466.00 | 0.29 | 30.00 |

| TABLE D-3: VIBRATORY HAMMER LISTING (sorted by Power) | | | | | | | | | |
|--|------------------------|----------------|----------------|-------------|---------------------|-----------------|-------------|-----------------------|-----------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Power kW | Ram Weight kN | Frequency Hz | Power kW | Ram Weight kips | Frequency Hz |
| 784 | APE | 200T | VIB | 466.00 | 1.51 | 30.83 | 466.00 | 0.34 | 30.83 |
| 714 | ICE | 1412C | VIB | 470.00 | 8.99 | 23.00 | 470.00 | 2.02 | 23.00 |
| 710 | ICE | 44-65 | VIB | 485.00 | 5.79 | 27.50 | 485.00 | 1.30 | 27.50 |
| 711 | ICE | 66-65 | VIB | 485.00 | 8.68 | 21.70 | 485.00 | 1.95 | 21.70 |
| 731 | HMC | 51+740 | VIB | 485.00 | 5.38 | 27.50 | 485.00 | 1.21 | 27.50 |
| 732 | HMC | 76+740 | VIB | 485.00 | 8.10 | 21.70 | 485.00 | 1.82 | 21.70 |
| 754 | MKT | V-35 | VIB | 485.00 | 7.12 | 28.33 | 485.00 | 1.60 | 28.33 |
| 712 | ICE | 66-80 | VIB | 597.00 | 8.68 | 26.70 | 597.00 | 1.95 | 26.70 |
| 713 | ICE | 1412B | VIB | 597.00 | 9.08 | 21.00 | 597.00 | 2.04 | 21.00 |
| 733 | HMC | 76+800 | VIB | 597.00 | 8.10 | 26.10 | 597.00 | 1.82 | 26.10 |
| 734 | HMC | 115+800 | VIB | 597.00 | 6.01 | 20.40 | 597.00 | 1.35 | 20.40 |
| 785 | APE | 200T HF | VIB | 738.00 | 1.51 | 43.00 | 738.00 | 0.34 | 43.00 |
| 786 | APE | 300 | VIB | 738.00 | 1.51 | 25.00 | 738.00 | 0.34 | 25.00 |
| 787 | APE | 400B | VIB | 738.00 | 3.47 | 23.33 | 738.00 | 0.78 | 23.33 |
| 788 | APE | 600 | VIB | 800.00 | 4.67 | 23.30 | 800.00 | 1.05 | 23.30 |
| 810 | MGF | RBH 2400 | VIB | 975.00 | 23.99 | 23.50 | 975.00 | 5.39 | 23.50 |
| 735 | HMC | 230+1600 | VIB | 1193.00 | 11.97 | 20.40 | 1193.00 | 2.69 | 20.40 |
| 755 | MKT | V-140 | VIB | 1341.00 | 20.78 | 23.33 | 1341.00 | 4.67 | 23.33 |
| 789 | APE | Tan 400 | VIB | 1476.00 | 6.10 | 23.33 | 1476.00 | 1.37 | 23.33 |
| 790 | APE | Tan 600 | VIB | 1800.00 | 9.39 | 23.30 | 1800.00 | 2.11 | 23.30 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|------------------------|----------------|----------------|-----------------------|---------------------|--------------------------|----------------------------|-----------------------|---------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 1 | DELMAG | D 5 | OED | 14.24 | 4.90 | 2.93 | 10.51 | 1.10 | 9.62 |
| 2 | DELMAG | D 8-22 | OED | 27.25 | 7.83 | 3.67 | 20.10 | 1.76 | 12.05 |
| 3 | DELMAG | D 12 | OED | 30.65 | 12.24 | 3.29 | 22.61 | 2.75 | 10.80 |
| 4 | DELMAG | D 15 | OED | 36.74 | 14.69 | 3.29 | 27.09 | 3.30 | 10.80 |
| 5 | DELMAG | D 16-32 | OED | 54.51 | 15.66 | 3.58 | 40.20 | 3.52 | 11.76 |
| 6 | DELMAG | D 22 | OED | 55.06 | 21.85 | 2.90 | 40.61 | 4.91 | 9.50 |
| 7 | DELMAG | D 22-02 | OED | 65.77 | 21.58 | 4.10 | 48.50 | 4.85 | 13.44 |
| 8 | DELMAG | D 22-13 | OED | 65.77 | 21.58 | 4.10 | 48.50 | 4.85 | 13.44 |
| 9 | DELMAG | D 22-23 | OED | 69.45 | 21.58 | 4.10 | 51.22 | 4.85 | 13.44 |
| 10 | DELMAG | D 25-32 | OED | 89.96 | 24.52 | 4.19 | 66.34 | 5.51 | 13.76 |
| 11 | DELMAG | D 30 | OED | 80.99 | 29.37 | 2.90 | 59.73 | 6.60 | 9.50 |
| 12 | DELMAG | D 30-02 | OED | 89.76 | 29.37 | 4.10 | 66.20 | 6.60 | 13.44 |
| 13 | DELMAG | D 30-13 | OED | 89.76 | 29.37 | 4.10 | 66.20 | 6.60 | 13.44 |
| 14 | DELMAG | D 30-23 | OED | 100.06 | 29.37 | 4.10 | 73.79 | 6.60 | 13.44 |
| 15 | DELMAG | D 30-32 | OED | 102.29 | 29.37 | 4.18 | 75.44 | 6.60 | 13.73 |
| 16 | DELMAG | D 36 | OED | 113.66 | 35.29 | 3.22 | 83.82 | 7.93 | 10.57 |
| 17 | DELMAG | D 36-02 | OED | 113.66 | 35.29 | 3.96 | 83.82 | 7.93 | 12.98 |
| 18 | DELMAG | D 36-13 | OED | 113.66 | 35.29 | 6.09 | 83.82 | 7.93 | 19.98 |
| 19 | DELMAG | D 36-23 | OED | 120.00 | 35.29 | 3.96 | 88.50 | 7.93 | 12.98 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 20 | DELMAG | D 36-32 | OED | 122.80 | 35.29 | 4.01 | 90.56 | 7.93 | 13.14 |
| 21 | DELMAG | D 44 | OED | 122.25 | 42.28 | 2.90 | 90.16 | 9.50 | 9.52 |
| 22 | DELMAG | D 46 | OED | 145.20 | 45.12 | 3.22 | 107.08 | 10.14 | 10.57 |
| 23 | DELMAG | D 46-02 | OED | 145.20 | 45.12 | 3.94 | 107.08 | 10.14 | 12.94 |
| 24 | DELMAG | D 46-13 | OED | 130.90 | 45.12 | 3.94 | 96.53 | 10.14 | 12.94 |
| 25 | DELMAG | D 46-23 | OED | 145.20 | 45.12 | 3.94 | 107.08 | 10.14 | 12.94 |
| 26 | DELMAG | D 46-32 | OED | 165.69 | 45.12 | 3.99 | 122.19 | 10.14 | 13.10 |
| 27 | DELMAG | D 55 | OED | 169.51 | 52.78 | 3.40 | 125.00 | 11.86 | 11.15 |
| 28 | DELMAG | D 62-02 | OED | 206.72 | 60.79 | 3.87 | 152.45 | 13.66 | 12.71 |
| 29 | DELMAG | D 62-12 | OED | 206.72 | 60.79 | 3.87 | 152.45 | 13.66 | 12.71 |
| 30 | DELMAG | D 62-22 | OED | 223.20 | 60.79 | 4.04 | 164.60 | 13.66 | 13.26 |
| 31 | DELMAG | D 80-12 | OED | 252.55 | 78.41 | 3.92 | 186.24 | 17.62 | 12.87 |
| 32 | DELMAG | D 80-23 | OED | 288.15 | 78.41 | 3.98 | 212.50 | 17.62 | 13.05 |
| 33 | DELMAG | D100-13 | OED | 360.32 | 98.21 | 4.11 | 265.72 | 22.07 | 13.50 |
| 35 | DELMAG | D 19-52 | OED | 58.63 | 17.80 | 3.61 | 43.24 | 4.00 | 11.86 |
| 36 | DELMAG | D 6-32 | OED | 18.31 | 5.87 | 3.12 | 13.50 | 1.32 | 10.23 |
| 37 | DELMAG | D 12-32 | OED | 42.48 | 12.55 | 3.60 | 31.33 | 2.82 | 11.81 |
| 38 | DELMAG | D 12-42 | OED | 45.16 | 12.55 | 3.60 | 33.30 | 2.82 | 11.81 |
| 39 | DELMAG | D 14-42 | OED | 46.84 | 13.75 | 3.60 | 34.55 | 3.09 | 11.81 |
| 40 | DELMAG | D 19-32 | OED | 57.55 | 17.80 | 3.58 | 42.44 | 4.00 | 11.76 |
| 41 | DELMAG | D 19-42 | OED | 58.63 | 17.80 | 3.61 | 43.24 | 4.00 | 11.86 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 42 | DELMAG | D200-42 | OED | 667.21 | 196.20 | 5.13 | 492.04 | 44.09 | 16.83 |
| 43 | DELMAG | D120-42 | OED | 409.23 | 117.70 | 3.60 | 301.79 | 26.45 | 11.81 |
| 44 | DELMAG | D150-42 | OED | 511.66 | 147.16 | 3.60 | 377.33 | 33.07 | 11.81 |
| 45 | DELMAG | D125-42 | OED | 425.29 | 122.64 | 4.15 | 313.63 | 27.56 | 13.60 |
| 46 | DELMAG | D 21-42 | OED | 75.59 | 20.60 | 4.27 | 55.75 | 4.63 | 14.00 |
| 50 | FEC | FEC 1200 | OED | 30.50 | 12.24 | 2.49 | 22.50 | 2.75 | 8.18 |
| 51 | FEC | FEC 1500 | OED | 36.74 | 14.69 | 2.50 | 27.09 | 3.30 | 8.21 |
| 52 | FEC | FEC 2500 | OED | 67.79 | 24.48 | 2.77 | 50.00 | 5.50 | 9.09 |
| 53 | FEC | FEC 2800 | OED | 75.93 | 27.41 | 2.77 | 55.99 | 6.16 | 9.09 |
| 54 | FEC | FEC 3000 | OED | 85.47 | 29.37 | 2.91 | 63.03 | 6.60 | 9.55 |
| 55 | FEC | FEC 3400 | OED | 98.99 | 33.29 | 2.97 | 73.00 | 7.48 | 9.76 |
| 61 | MITSUBIS | M 14 | OED | 34.23 | 13.22 | 2.59 | 25.25 | 2.97 | 8.50 |
| 62 | MITSUBIS | MH 15 | OED | 38.15 | 14.73 | 2.59 | 28.14 | 3.31 | 8.50 |
| 63 | MITSUBIS | M 23 | OED | 58.32 | 22.52 | 2.59 | 43.01 | 5.06 | 8.50 |
| 64 | MITSUBIS | MH 25 | OED | 63.51 | 24.52 | 2.59 | 46.84 | 5.51 | 8.50 |
| 65 | MITSUBIS | M 33 | OED | 83.68 | 32.31 | 2.59 | 61.71 | 7.26 | 8.50 |
| 66 | MITSUBIS | MH 35 | OED | 88.98 | 34.35 | 2.59 | 65.62 | 7.72 | 8.50 |
| 67 | MITSUBIS | M 43 | OED | 109.04 | 42.10 | 2.59 | 80.41 | 9.46 | 8.50 |
| 68 | MITSUBIS | MH 45 | OED | 115.84 | 44.72 | 2.59 | 85.43 | 10.05 | 8.50 |
| 70 | MITSUBIS | MH 72B | OED | 183.26 | 70.76 | 2.59 | 135.15 | 15.90 | 8.50 |
| 71 | MITSUBIS | MH 80B | OED | 202.86 | 78.32 | 2.59 | 149.60 | 17.60 | 8.50 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 81 | LINKBELT | LB 180 | CED | 10.98 | 7.70 | 1.43 | 8.10 | 1.73 | 4.68 |
| 82 | LINKBELT | LB 312 | CED | 20.36 | 17.18 | 1.19 | 15.02 | 3.86 | 3.89 |
| 83 | LINKBELT | LB 440 | CED | 24.68 | 17.80 | 1.39 | 18.20 | 4.00 | 4.55 |
| 84 | LINKBELT | LB 520 | CED | 35.68 | 22.56 | 1.58 | 26.31 | 5.07 | 5.19 |
| 85 | LINKBELT | LB 660 | CED | 70.01 | 33.69 | 2.08 | 51.63 | 7.57 | 6.82 |
| 101 | KOBE | K 13 | OED | 34.48 | 12.77 | 2.70 | 25.43 | 2.87 | 8.86 |
| 103 | KOBE | K22-Est | OED | 61.49 | 21.58 | 2.85 | 45.35 | 4.85 | 9.35 |
| 104 | KOBE | K 25 | OED | 69.86 | 24.52 | 2.85 | 51.52 | 5.51 | 9.35 |
| 107 | KOBE | K 35 | OED | 97.88 | 34.35 | 2.85 | 72.18 | 7.72 | 9.35 |
| 110 | KOBE | K 45 | OED | 125.77 | 44.14 | 2.85 | 92.75 | 9.92 | 9.35 |
| 112 | KOBE | KB 60 | OED | 176.53 | 58.87 | 3.00 | 130.18 | 13.23 | 9.84 |
| 113 | KOBE | KB 80 | OED | 235.37 | 78.50 | 3.00 | 173.58 | 17.64 | 9.84 |
| 120 | ICE | 180 | CED | 11.03 | 7.70 | 1.43 | 8.13 | 1.73 | 4.70 |
| 121 | ICE | 422 | CED | 31.35 | 17.80 | 1.76 | 23.12 | 4.00 | 5.78 |
| 122 | ICE | 440 | CED | 25.17 | 17.80 | 1.41 | 18.56 | 4.00 | 4.64 |
| 123 | ICE | 520 | CED | 41.18 | 22.56 | 1.83 | 30.37 | 5.07 | 5.99 |
| 124 | ICE | 640 | CED | 55.08 | 26.70 | 2.06 | 40.62 | 6.00 | 6.77 |
| 125 | ICE | 660 | CED | 70.01 | 33.69 | 2.08 | 51.63 | 7.57 | 6.82 |
| 126 | ICE | 1070 | CED | 98.45 | 44.50 | 2.21 | 72.60 | 10.00 | 7.26 |
| 127 | ICE | 30-S | OED | 30.51 | 13.35 | 2.34 | 22.50 | 3.00 | 7.67 |
| 128 | ICE | 40-S | OED | 54.24 | 17.80 | 3.10 | 40.00 | 4.00 | 10.17 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 129 | ICE | 42-S | OED | 56.96 | 18.20 | 3.18 | 42.00 | 4.09 | 10.42 |
| 130 | ICE | 60-S | OED | 81.35 | 31.15 | 3.18 | 59.99 | 7.00 | 10.42 |
| 131 | ICE | 70-S | OED | 94.92 | 31.15 | 3.10 | 70.00 | 7.00 | 10.17 |
| 132 | ICE | 80-S | OED | 108.48 | 35.60 | 3.79 | 80.00 | 8.00 | 12.42 |
| 133 | ICE | 90-S | OED | 122.04 | 40.05 | 3.10 | 90.00 | 9.00 | 10.17 |
| 134 | ICE | 100-S | OED | 135.60 | 44.50 | 3.66 | 100.00 | 10.00 | 12.00 |
| 135 | ICE | 120-S | OED | 162.72 | 53.40 | 3.79 | 120.00 | 12.00 | 12.42 |
| 136 | ICE | 200-S | OED | 135.60 | 89.00 | 1.83 | 100.00 | 20.00 | 6.00 |
| 137 | ICE | 205-S | OED | 230.52 | 89.00 | 3.20 | 170.00 | 20.00 | 10.50 |
| 139 | ICE | 32-S | OED | 35.27 | 13.35 | 3.25 | 26.01 | 3.00 | 10.67 |
| 140 | ICE | 120S-15 | OED | 179.60 | 66.75 | 3.73 | 132.45 | 15.00 | 12.25 |
| 142 | MKT 20 | DE333020 | OED | 27.12 | 8.90 | 3.51 | 20.00 | 2.00 | 11.50 |
| 143 | MKT 30 | DE333020 | OED | 37.97 | 12.46 | 3.51 | 28.00 | 2.80 | 11.50 |
| 144 | MKT 33 | DE333020 | OED | 44.75 | 14.69 | 3.51 | 33.00 | 3.30 | 11.50 |
| 145 | MKT 40 | DE333020 | OED | 54.24 | 17.80 | 3.51 | 40.00 | 4.00 | 11.50 |
| 146 | MKT | DE 10 | OED | 11.93 | 4.90 | 3.35 | 8.80 | 1.10 | 11.00 |
| 147 | MKT | DE 20 | OED | 21.70 | 8.90 | 2.74 | 16.00 | 2.00 | 9.00 |
| 148 | MKT | DE 30 | OED | 30.37 | 12.46 | 3.05 | 22.40 | 2.80 | 10.00 |
| 149 | MKT | DA35B SA | OED | 32.27 | 12.46 | 3.96 | 23.80 | 2.80 | 13.00 |
| 150 | MKT | DE 30B | OED | 32.27 | 12.46 | 3.05 | 23.80 | 2.80 | 10.00 |
| 151 | MKT | DA 35B | CED | 28.48 | 12.46 | 2.29 | 21.00 | 2.80 | 7.50 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 152 | MKT | DA 45 | CED | 41.66 | 17.80 | 2.34 | 30.72 | 4.00 | 7.68 |
| 153 | MKT | DE 40 | OED | 43.39 | 17.80 | 3.05 | 32.00 | 4.00 | 10.00 |
| 154 | MKT | DE 42/35 | OED | 47.46 | 15.58 | 4.11 | 35.00 | 3.50 | 13.50 |
| 155 | MKT | DE 42/35 | OED | 56.95 | 18.69 | 4.11 | 42.00 | 4.20 | 13.50 |
| 157 | MKT | DE 50C | OED | 67.80 | 22.25 | 3.96 | 50.00 | 5.00 | 13.00 |
| 158 | MKT | DE 70C | OED | 94.92 | 31.15 | 3.96 | 70.00 | 7.00 | 13.00 |
| 159 | MKT | DE 50B | OED | 57.63 | 22.25 | 3.35 | 42.50 | 5.00 | 11.00 |
| 160 | MKT | DA55B SA | OED | 54.24 | 22.25 | 3.66 | 40.00 | 5.00 | 12.00 |
| 161 | MKT | DA 55B | CED | 51.80 | 22.25 | 2.33 | 38.20 | 5.00 | 7.64 |
| 162 | MKT | DE 70B | OED | 80.68 | 31.15 | 3.66 | 59.50 | 7.00 | 12.00 |
| 163 | MKT 50 | DE70/50B | OED | 67.80 | 22.25 | 3.66 | 50.00 | 5.00 | 12.00 |
| 164 | MKT 70 | DE70/50B | OED | 94.92 | 31.15 | 3.66 | 70.00 | 7.00 | 12.00 |
| 165 | MKT 110 | DE110150 | OED | 149.16 | 48.95 | 4.11 | 110.00 | 11.00 | 13.50 |
| 166 | MKT 150 | DE110150 | OED | 203.40 | 66.75 | 4.11 | 150.00 | 15.00 | 13.50 |
| 167 | MKT | DA 35C | CED | 28.48 | 12.46 | 2.29 | 21.00 | 2.80 | 7.50 |
| 168 | MKT | DA 55C | CED | 51.80 | 22.25 | 2.33 | 38.20 | 5.00 | 7.64 |
| 171 | CONMACO | C 50 | ECH | 20.34 | 22.25 | 0.91 | 15.00 | 5.00 | 3.00 |
| 172 | CONMACO | C 65 | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 173 | CONMACO | C 550 | ECH | 33.90 | 22.25 | 1.52 | 25.00 | 5.00 | 5.00 |
| 174 | CONMACO | C 565 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 175 | CONMACO | C 80 | ECH | 35.26 | 35.60 | 0.99 | 26.00 | 8.00 | 3.25 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 176 | CONMACO | C 100 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 177 | CONMACO | C 115 | ECH | 50.68 | 51.18 | 0.99 | 37.38 | 11.50 | 3.25 |
| 178 | CONMACO | C 80E5 | ECH | 54.24 | 35.60 | 1.52 | 40.00 | 8.00 | 5.00 |
| 179 | CONMACO | C 100E5 | ECH | 67.80 | 44.50 | 1.52 | 50.00 | 10.00 | 5.00 |
| 180 | CONMACO | C 115E5 | ECH | 77.97 | 51.18 | 1.52 | 57.50 | 11.50 | 5.00 |
| 181 | CONMACO | C 125E5 | ECH | 84.75 | 55.63 | 1.52 | 62.50 | 12.50 | 5.00 |
| 182 | CONMACO | C 140 | ECH | 56.95 | 62.30 | 0.91 | 42.00 | 14.00 | 3.00 |
| 183 | CONMACO | C 160 | ECH | 66.11 | 72.31 | 0.91 | 48.75 | 16.25 | 3.00 |
| 184 | CONMACO | C 200 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 185 | CONMACO | C 300 | ECH | 122.04 | 133.50 | 0.91 | 90.00 | 30.00 | 3.00 |
| 186 | CONMACO | C 5200 | ECH | 135.60 | 89.00 | 1.52 | 100.00 | 20.00 | 5.00 |
| 187 | CONMACO | C 5300 | ECH | 203.40 | 133.50 | 1.52 | 150.00 | 30.00 | 5.00 |
| 188 | CONMACO | C 5450 | ECH | 305.10 | 200.25 | 1.52 | 225.00 | 45.00 | 5.00 |
| 189 | CONMACO | C 5700 | ECH | 474.60 | 311.50 | 1.52 | 350.00 | 70.00 | 5.00 |
| 190 | CONMACO | C 6850 | ECH | 691.56 | 378.25 | 1.83 | 510.00 | 85.00 | 6.00 |
| 191 | CONMACO | C 160 ** | ECH | 70.21 | 76.81 | 0.91 | 51.78 | 17.26 | 3.00 |
| 192 | CONMACO | C 50E5 | ECH | 33.90 | 22.25 | 1.52 | 25.00 | 5.00 | 5.00 |
| 193 | CONMACO | C 65E5 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 194 | CONMACO | C 200E5 | ECH | 135.60 | 89.00 | 1.52 | 100.00 | 20.00 | 5.00 |
| 195 | CONMACO | C 300E5 | ECH | 203.40 | 133.50 | 1.52 | 150.00 | 30.00 | 5.00 |
| 204 | VULCAN | VUL 01 | ECH | 20.34 | 22.25 | 0.91 | 15.00 | 5.00 | 3.00 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 205 | VULCAN | VUL 02 | ECH | 9.84 | 13.35 | 0.74 | 7.26 | 3.00 | 2.42 |
| 206 | VULCAN | VUL 06 | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 207 | VULCAN | VUL 08 | ECH | 35.26 | 35.60 | 0.99 | 26.00 | 8.00 | 3.25 |
| 208 | VULCAN | VUL 010 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 209 | VULCAN | VUL 012 | ECH | 52.88 | 53.40 | 0.99 | 39.00 | 12.00 | 3.25 |
| 210 | VULCAN | VUL 014 | ECH | 56.95 | 62.30 | 0.91 | 42.00 | 14.00 | 3.00 |
| 211 | VULCAN | VUL 016 | ECH | 66.11 | 72.31 | 0.91 | 48.75 | 16.25 | 3.00 |
| 212 | VULCAN | VUL 020 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 213 | VULCAN | VUL 030 | ECH | 122.04 | 133.50 | 0.91 | 90.00 | 30.00 | 3.00 |
| 214 | VULCAN | VUL 040 | ECH | 162.72 | 178.00 | 0.91 | 120.00 | 40.00 | 3.00 |
| 215 | VULCAN | VUL 060 | ECH | 244.08 | 267.00 | 0.91 | 180.00 | 60.00 | 3.00 |
| 220 | VULCAN | VUL 30C | ECH | 9.84 | 13.35 | 0.74 | 7.26 | 3.00 | 2.42 |
| 221 | VULCAN | VUL 50C | ECH | 20.48 | 22.25 | 0.92 | 15.10 | 5.00 | 3.02 |
| 222 | VULCAN | VUL 65C | ECH | 26.00 | 28.93 | 0.90 | 19.18 | 6.50 | 2.95 |
| 223 | VULCAN | VUL 65CA | ECH | 26.53 | 28.93 | 0.92 | 19.57 | 6.50 | 3.01 |
| 224 | VULCAN | VUL 80C | ECH | 33.19 | 35.60 | 0.93 | 24.48 | 8.00 | 3.06 |
| 225 | VULCAN | VUL 85C | ECH | 35.24 | 37.91 | 0.93 | 25.99 | 8.52 | 3.05 |
| 226 | VULCAN | VUL 100C | ECH | 44.61 | 44.50 | 1.00 | 32.90 | 10.00 | 3.29 |
| 227 | VULCAN | VUL 140C | ECH | 48.79 | 62.30 | 0.78 | 35.98 | 14.00 | 2.57 |
| 228 | VULCAN | VUL 200C | ECH | 68.07 | 89.00 | 0.77 | 50.20 | 20.00 | 2.51 |
| 229 | VULCAN | VUL 400C | ECH | 154.04 | 178.00 | 0.87 | 113.60 | 40.00 | 2.84 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 230 | VULCAN | VUL 600C | ECH | 243.27 | 267.00 | 0.91 | 179.40 | 60.00 | 2.99 |
| 231 | VULCAN | VUL 320 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 232 | VULCAN | VUL 330 | ECH | 122.04 | 133.50 | 0.91 | 90.00 | 30.00 | 3.00 |
| 233 | VULCAN | VUL 340 | ECH | 162.72 | 178.00 | 0.91 | 120.00 | 40.00 | 3.00 |
| 234 | VULCAN | VUL 360 | ECH | 244.08 | 267.00 | 0.91 | 180.00 | 60.00 | 3.00 |
| 235 | VULCAN | VUL 505 | ECH | 33.90 | 22.25 | 1.52 | 25.00 | 5.00 | 5.00 |
| 236 | VULCAN | VUL 506 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 237 | VULCAN | VUL 508 | ECH | 54.24 | 35.60 | 1.52 | 40.00 | 8.00 | 5.00 |
| 238 | VULCAN | VUL 510 | ECH | 67.80 | 44.50 | 1.52 | 50.00 | 10.00 | 5.00 |
| 239 | VULCAN | VUL 512 | ECH | 81.36 | 53.40 | 1.52 | 60.00 | 12.00 | 5.00 |
| 240 | VULCAN | VUL 520 | ECH | 135.60 | 89.00 | 1.52 | 100.00 | 20.00 | 5.00 |
| 241 | VULCAN | VUL 530 | ECH | 203.40 | 133.50 | 1.52 | 150.00 | 30.00 | 5.00 |
| 242 | VULCAN | VUL 540 | ECH | 271.20 | 182.01 | 1.49 | 200.00 | 40.90 | 4.89 |
| 243 | VULCAN | VUL 560 | ECH | 406.80 | 278.13 | 1.46 | 300.00 | 62.50 | 4.80 |
| 245 | VULCAN | VUL 3100 | ECH | 406.80 | 445.00 | 0.91 | 300.00 | 100.00 | 3.00 |
| 246 | VULCAN | VUL 5100 | ECH | 678.00 | 445.00 | 1.52 | 500.00 | 100.00 | 5.00 |
| 247 | VULCAN | VUL 5150 | ECH | 1017.00 | 667.50 | 1.52 | 750.00 | 150.00 | 5.00 |
| 248 | VULCAN | VUL 6300 | ECH | 2440.80 | 1335.00 | 1.83 | 1800.00 | 300.00 | 6.00 |
| 251 | RAYMOND | R 1 | ECH | 20.34 | 22.25 | 0.91 | 15.00 | 5.00 | 3.00 |
| 252 | RAYMOND | R 1S | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 253 | RAYMOND | R 65C | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 254 | RAYMOND | R 65CH | ECH | 26.44 | 28.93 | 0.91 | 19.50 | 6.50 | 3.00 |
| 255 | RAYMOND | R 0 | ECH | 33.05 | 33.38 | 0.99 | 24.38 | 7.50 | 3.25 |
| 256 | RAYMOND | R 80C | ECH | 33.19 | 35.60 | 0.93 | 24.48 | 8.00 | 3.06 |
| 257 | RAYMOND | R 80CH | ECH | 33.19 | 35.60 | 0.93 | 24.48 | 8.00 | 3.06 |
| 258 | RAYMOND | R 2/0 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 259 | RAYMOND | R 3/0 | ECH | 55.09 | 55.63 | 0.99 | 40.63 | 12.50 | 3.25 |
| 260 | RAYMOND | R 150C | ECH | 66.11 | 66.75 | 0.99 | 48.75 | 15.00 | 3.25 |
| 261 | RAYMOND | R 4/0 | ECH | 66.11 | 66.75 | 0.99 | 48.75 | 15.00 | 3.25 |
| 262 | RAYMOND | R 5/0 | ECH | 77.12 | 77.88 | 0.99 | 56.88 | 17.50 | 3.25 |
| 263 | RAYMOND | R 30X | ECH | 101.70 | 133.50 | 0.76 | 75.00 | 30.00 | 2.50 |
| 264 | RAYMOND | R 8/0 | ECH | 110.18 | 111.25 | 0.99 | 81.25 | 25.00 | 3.25 |
| 265 | RAYMOND | R 40X | ECH | 135.60 | 178.00 | 0.76 | 100.00 | 40.00 | 2.50 |
| 266 | RAYMOND | R 60X | ECH | 203.40 | 267.00 | 0.76 | 150.00 | 60.00 | 2.50 |
| 271 | MENCK | MH 68 | ECH | 66.68 | 34.35 | 1.94 | 49.18 | 7.72 | 6.37 |
| 272 | MENCK | MH 96 | ECH | 94.14 | 49.04 | 1.92 | 69.43 | 11.02 | 6.30 |
| 273 | MENCK | MH 145 | ECH | 142.11 | 73.56 | 1.93 | 104.80 | 16.53 | 6.34 |
| 274 | MENCK | MH 195 | ECH | 191.36 | 98.12 | 1.95 | 141.12 | 22.05 | 6.40 |
| 275 | MENCK | MHU 220 | ECH | 215.70 | 111.83 | 1.93 | 159.07 | 25.13 | 6.33 |
| 276 | MENCK | MHU 400 | ECH | 392.64 | 225.66 | 1.74 | 289.55 | 50.71 | 5.71 |
| 277 | MENCK | MHU 600 | ECH | 588.01 | 343.36 | 1.71 | 433.64 | 77.16 | 5.62 |
| 278 | MENCK | MHU 1000 | ECH | 1000.32 | 565.02 | 1.77 | 737.70 | 126.97 | 5.81 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 279 | MENCK | MHU 1700 | ECH | 1666.35 | 922.17 | 1.81 | 1228.87 | 207.23 | 5.93 |
| 280 | MENCK | MHU 2100 | ECH | 2098.53 | 1138.31 | 1.84 | 1547.59 | 255.80 | 6.05 |
| 281 | MENCK | MHU 3000 | ECH | 2944.75 | 1618.73 | 1.82 | 2171.65 | 363.76 | 5.97 |
| 282 | MENCK | MRBS 500 | ECH | 61.12 | 49.04 | 1.25 | 45.07 | 11.02 | 4.09 |
| 283 | MENCK | MRBS 750 | ECH | 91.90 | 73.56 | 1.25 | 67.77 | 16.53 | 4.10 |
| 285 | MENCK | MRBS 850 | ECH | 126.49 | 84.37 | 1.50 | 93.28 | 18.96 | 4.92 |
| 286 | MENCK | MRBS1100 | ECH | 167.37 | 107.91 | 1.55 | 123.43 | 24.25 | 5.09 |
| 287 | MENCK | MRBS1502 | ECH | 183.86 | 147.16 | 1.25 | 135.59 | 33.07 | 4.10 |
| 288 | MENCK | MRBS1800 | ECH | 257.39 | 171.68 | 1.50 | 189.81 | 38.58 | 4.92 |
| 289 | MENCK | MRBS2500 | ECH | 355.43 | 284.49 | 1.25 | 262.11 | 63.93 | 4.10 |
| 290 | MENCK | MRBS2502 | ECH | 306.39 | 245.24 | 1.25 | 225.95 | 55.11 | 4.10 |
| 291 | MENCK | MRBS2504 | ECH | 306.39 | 245.24 | 1.25 | 225.95 | 55.11 | 4.10 |
| 292 | MENCK | MRBS3000 | ECH | 441.19 | 294.28 | 1.50 | 325.36 | 66.13 | 4.92 |
| 293 | MENCK | MRBS3900 | ECH | 696.09 | 386.53 | 1.80 | 513.34 | 86.86 | 5.91 |
| 294 | MENCK | MRBS4600 | ECH | 676.56 | 451.27 | 1.50 | 498.94 | 101.41 | 4.92 |
| 295 | MENCK | MRBS5000 | ECH | 735.40 | 490.52 | 1.50 | 542.33 | 110.23 | 4.92 |
| 296 | MENCK | MRBS6000 | ECH | 1029.52 | 588.60 | 1.75 | 759.23 | 132.27 | 5.74 |
| 297 | MENCK | MRBS7000 | ECH | 856.18 | 685.30 | 1.25 | 631.40 | 154.00 | 4.10 |
| 298 | MENCK | MRBS8000 | ECH | 1176.66 | 784.85 | 1.50 | 867.74 | 176.37 | 4.92 |
| 299 | MENCK | MRBS8800 | ECH | 1294.34 | 863.34 | 1.50 | 954.53 | 194.01 | 4.92 |
| 300 | MENCK | MBS12500 | ECH | 2144.96 | 1226.33 | 1.75 | 1581.83 | 275.58 | 5.74 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|--------------------|------------------|-----------------------|-------------------------|--------------------|------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 301 | MKT | No. 5 | ECH | 1.36 | 0.89 | 1.52 | 1.00 | 0.20 | 5.00 |
| 302 | MKT | No. 6 | ECH | 3.39 | 1.78 | 1.91 | 2.50 | 0.40 | 6.25 |
| 303 | MKT | No. 7 | ECH | 5.63 | 3.56 | 1.58 | 4.15 | 0.80 | 5.19 |
| 304 | MKT | 9B3 | ECH | 11.87 | 7.12 | 1.67 | 8.75 | 1.60 | 5.47 |
| 305 | MKT | 10B3 | ECH | 17.78 | 13.35 | 1.33 | 13.11 | 3.00 | 4.37 |
| 306 | MKT | C5-Air | ECH | 19.26 | 22.25 | 0.87 | 14.20 | 5.00 | 2.84 |
| 307 | MKT | C5-Steam | ECH | 21.97 | 22.25 | 0.99 | 16.20 | 5.00 | 3.24 |
| 308 | MKT | S-5 | ECH | 22.04 | 22.25 | 0.99 | 16.25 | 5.00 | 3.25 |
| 309 | MKT | 11B3 | ECH | 25.97 | 22.25 | 1.17 | 19.15 | 5.00 | 3.83 |
| 310 | MKT | C826 Stm | ECH | 33.09 | 35.60 | 0.93 | 24.40 | 8.00 | 3.05 |
| 311 | MKT | C826 Air | ECH | 28.75 | 35.60 | 0.81 | 21.20 | 8.00 | 2.65 |
| 312 | MKT | S-8 | ECH | 35.26 | 35.60 | 0.99 | 26.00 | 8.00 | 3.25 |
| 313 | MKT | MS-350 | ECH | 41.77 | 34.35 | 1.22 | 30.80 | 7.72 | 3.99 |
| 314 | MKT | S 10 | ECH | 44.07 | 44.50 | 0.99 | 32.50 | 10.00 | 3.25 |
| 315 | MKT | S 14 | ECH | 50.88 | 62.30 | 0.82 | 37.52 | 14.00 | 2.68 |
| 316 | MKT | MS 500 | ECH | 59.66 | 48.95 | 1.22 | 44.00 | 11.00 | 4.00 |
| 317 | MKT | S 20 | ECH | 81.36 | 89.00 | 0.91 | 60.00 | 20.00 | 3.00 |
| 320 | IHC | S-35 | ECH | 34.61 | 29.50 | 1.17 | 25.53 | 6.63 | 3.85 |
| 321 | IHC | S-70 | ECH | 69.49 | 34.40 | 2.02 | 51.25 | 7.73 | 6.63 |
| 322 | IHC | S-90 | ECH | 89.36 | 44.23 | 2.02 | 65.90 | 9.94 | 6.63 |
| 323 | IHC | S-120 | ECH | 121.19 | 59.99 | 2.02 | 89.37 | 13.48 | 6.63 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 324 | IHC | S-150 | ECH | 149.24 | 73.87 | 2.02 | 110.06 | 16.60 | 6.63 |
| 325 | IHC | S-200 | ECH | 197.49 | 97.90 | 2.02 | 145.64 | 22.00 | 6.62 |
| 326 | IHC | S-280 | ECH | 278.40 | 133.77 | 2.08 | 205.31 | 30.06 | 6.83 |
| 327 | IHC | S-400 | ECH | 396.77 | 196.69 | 2.02 | 292.60 | 44.20 | 6.62 |
| 328 | IHC | S-500 | ECH | 496.41 | 246.09 | 2.02 | 366.09 | 55.30 | 6.62 |
| 329 | IHC | S-600 | ECH | 601.44 | 298.15 | 2.02 | 443.54 | 67.00 | 6.62 |
| 330 | IHC | S-900 | ECH | 892.73 | 442.55 | 2.02 | 658.36 | 99.45 | 6.62 |
| 331 | IHC | S-1200 | ECH | 1208.27 | 598.97 | 2.02 | 891.05 | 134.60 | 6.62 |
| 332 | IHC | S-1800 | ECH | 1586.93 | 738.70 | 2.15 | 1170.30 | 166.00 | 7.05 |
| 333 | IHC | S-2300 | ECH | 2280.09 | 1130.30 | 2.02 | 1681.48 | 254.00 | 6.62 |
| 335 | IHC | SC-30 | ECH | 29.57 | 16.73 | 1.77 | 21.81 | 3.76 | 5.80 |
| 336 | IHC | SC-40 | ECH | 40.50 | 24.52 | 1.65 | 29.86 | 5.51 | 5.42 |
| 337 | IHC | SC-50 | ECH | 49.92 | 32.44 | 1.54 | 36.81 | 7.29 | 5.05 |
| 338 | IHC | SC-60 | ECH | 60.96 | 59.19 | 1.03 | 44.95 | 13.30 | 3.38 |
| 339 | IHC | SC-75 | ECH | 74.30 | 54.07 | 1.37 | 54.80 | 12.15 | 4.51 |
| 340 | IHC | SC-110 | ECH | 111.04 | 77.70 | 1.43 | 81.89 | 17.46 | 4.69 |
| 341 | IHC | SC-150 | ECH | 148.28 | 108.14 | 1.37 | 109.35 | 24.30 | 4.50 |
| 342 | IHC | SC-200 | ECH | 206.80 | 134.39 | 1.54 | 152.51 | 30.20 | 5.05 |
| 349 | HERA | 1900 | OED | 60.23 | 18.65 | 3.23 | 44.41 | 4.19 | 10.60 |
| 350 | HERA | 1250 | OED | 34.37 | 12.50 | 2.75 | 25.35 | 2.81 | 9.02 |
| 351 | HERA | 1500 | OED | 41.22 | 15.00 | 2.75 | 30.40 | 3.37 | 9.02 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 352 | HERA | 2500 | OED | 68.74 | 25.01 | 2.75 | 50.69 | 5.62 | 9.02 |
| 353 | HERA | 2800 | OED | 76.93 | 27.99 | 2.75 | 56.74 | 6.29 | 9.02 |
| 354 | HERA | 3500 | OED | 96.26 | 35.02 | 2.75 | 70.99 | 7.87 | 9.02 |
| 355 | HERA | 5000 | OED | 137.48 | 50.02 | 2.75 | 101.38 | 11.24 | 9.02 |
| 356 | HERA | 5700 | OED | 156.68 | 57.00 | 2.75 | 115.55 | 12.81 | 9.02 |
| 357 | HERA | 6200 | OED | 170.38 | 61.99 | 2.75 | 125.65 | 13.93 | 9.02 |
| 358 | HERA | 7500 | OED | 206.09 | 74.98 | 2.75 | 151.99 | 16.85 | 9.02 |
| 359 | HERA | 8800 | OED | 241.93 | 88.02 | 2.75 | 178.42 | 19.78 | 9.02 |
| 360 | ICE | I-12 | OED | 40.95 | 12.55 | 3.51 | 30.20 | 2.82 | 11.50 |
| 361 | ICE | I-19 | OED | 58.56 | 17.84 | 3.75 | 43.19 | 4.01 | 12.30 |
| 362 | ICE | I-30 | OED | 102.27 | 29.41 | 3.84 | 75.42 | 6.61 | 12.60 |
| 363 | ICE | I-36 | OED | 122.96 | 35.33 | 3.69 | 90.67 | 7.94 | 12.10 |
| 364 | ICE | I-46 | OED | 146.17 | 45.17 | 3.69 | 107.79 | 10.15 | 12.12 |
| 365 | ICE | I-62 | OED | 223.71 | 64.97 | 4.34 | 164.98 | 14.60 | 14.25 |
| 366 | ICE | I-80 | OED | 288.01 | 78.77 | 4.11 | 212.40 | 17.70 | 13.50 |
| 371 | FAIRCHLD | F-45 | ECH | 61.02 | 66.75 | 0.91 | 45.00 | 15.00 | 3.00 |
| 372 | FAIRCHLD | F-32 | ECH | 44.14 | 48.28 | 0.91 | 32.55 | 10.85 | 3.00 |
| 380 | BSP | HH 1.5 | ECH | 22.02 | 14.69 | 1.50 | 16.24 | 3.30 | 4.92 |
| 381 | BSP | HH 3 | ECH | 35.31 | 29.41 | 1.20 | 26.04 | 6.61 | 3.94 |
| 382 | BSP | HH 5 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 383 | BSP | HH 7 | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 384 | BSP | HH 8 | ECH | 94.24 | 78.50 | 1.20 | 69.50 | 17.64 | 3.94 |
| 385 | BSP | HH 9 | ECH | 106.00 | 88.29 | 1.20 | 78.17 | 19.84 | 3.94 |
| 386 | BSP | HH11-1.2 | ECH | 129.56 | 107.91 | 1.20 | 95.55 | 24.25 | 3.94 |
| 387 | BSP | HH14-1.2 | ECH | 164.87 | 137.33 | 1.20 | 121.59 | 30.86 | 3.94 |
| 388 | BSP | HH16-1.2 | ECH | 188.43 | 156.95 | 1.20 | 138.96 | 35.27 | 3.94 |
| 389 | BSP | HH 20 | ECH | 235.56 | 196.20 | 1.20 | 173.71 | 44.09 | 3.94 |
| 390 | BSP | HH 20S | ECH | 235.56 | 196.20 | 1.20 | 173.71 | 44.09 | 3.94 |
| 391 | BSP | HA 30 | ECH | 353.31 | 294.28 | 1.20 | 260.55 | 66.13 | 3.94 |
| 392 | BSP | HA 40 | ECH | 471.11 | 392.40 | 1.20 | 347.43 | 88.18 | 3.94 |
| 393 | BSP | HH11-1.5 | ECH | 161.78 | 107.91 | 1.50 | 119.31 | 24.25 | 4.92 |
| 394 | BSP | HH14-1.5 | ECH | 205.88 | 137.33 | 1.50 | 151.83 | 30.86 | 4.92 |
| 395 | BSP | HH16-1.5 | ECH | 235.30 | 156.95 | 1.50 | 173.53 | 35.27 | 4.92 |
| 401 | BERMINGH | B23 | CED | 31.17 | 12.46 | 2.50 | 22.99 | 2.80 | 8.21 |
| 402 | BERMINGH | B200 | OED | 24.41 | 8.90 | 2.74 | 18.00 | 2.00 | 9.00 |
| 403 | BERMINGH | B225 | OED | 39.66 | 13.35 | 2.97 | 29.25 | 3.00 | 9.75 |
| 404 | BERMINGH | B300 | OED | 54.66 | 16.69 | 3.28 | 40.31 | 3.75 | 10.75 |
| 405 | BERMINGH | B400 | OED | 72.89 | 22.25 | 3.28 | 53.75 | 5.00 | 10.75 |
| 410 | BERMINGH | B300 M | OED | 54.66 | 16.69 | 3.28 | 40.31 | 3.75 | 10.75 |
| 411 | BERMINGH | B400 M | OED | 72.89 | 22.25 | 3.28 | 53.75 | 5.00 | 10.75 |
| 412 | BERMINGH | B400 4.8 | OED | 58.58 | 21.36 | 2.74 | 43.20 | 4.80 | 9.00 |
| 413 | BERMINGH | B400 5.0 | OED | 61.02 | 22.25 | 2.74 | 45.00 | 5.00 | 9.00 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 414 | BERMINGH | B23 5 | CED | 31.17 | 12.46 | 2.50 | 22.99 | 2.80 | 8.21 |
| 415 | BERMINGH | B250 5 | OED | 35.60 | 11.13 | 3.20 | 26.25 | 2.50 | 10.50 |
| 416 | BERMINGH | B350 5 | OED | 64.00 | 17.80 | 3.60 | 47.20 | 4.00 | 11.80 |
| 417 | BERMINGH | B400 5 | OED | 80.00 | 22.25 | 3.60 | 59.00 | 5.00 | 11.80 |
| 418 | BERMINGH | B450 5 | OED | 105.61 | 29.37 | 3.60 | 77.88 | 6.60 | 11.80 |
| 419 | BERMINGH | B500 5 | OED | 124.81 | 34.71 | 3.60 | 92.04 | 7.80 | 11.80 |
| 420 | BERMINGH | B550 5 | OED | 144.01 | 40.05 | 3.60 | 106.20 | 9.00 | 11.80 |
| 421 | BERMINGH | B550 C | OED | 119.33 | 48.95 | 2.44 | 88.00 | 11.00 | 8.00 |
| 422 | BERMINGH | B2005 | OED | 28.48 | 8.90 | 3.20 | 21.00 | 2.00 | 10.50 |
| 423 | BERMINGH | B2505 | OED | 48.00 | 13.35 | 3.60 | 35.40 | 3.00 | 11.80 |
| 441 | MENCK | MHF5-5 | ECH | 52.45 | 49.04 | 1.07 | 38.68 | 11.02 | 3.51 |
| 442 | MENCK | MHF5-6 | ECH | 62.97 | 58.87 | 1.07 | 46.44 | 13.23 | 3.51 |
| 443 | MENCK | MHF5-7 | ECH | 73.44 | 68.66 | 1.07 | 54.16 | 15.43 | 3.51 |
| 444 | MENCK | MHF5-8 | ECH | 83.96 | 78.50 | 1.07 | 61.92 | 17.64 | 3.51 |
| 445 | MENCK | MHF5-9 | ECH | 94.43 | 88.29 | 1.07 | 69.64 | 19.84 | 3.51 |
| 446 | MENCK | MHF5-10 | ECH | 104.90 | 98.08 | 1.07 | 77.36 | 22.04 | 3.51 |
| 447 | MENCK | MHF5-11 | ECH | 115.42 | 107.91 | 1.07 | 85.12 | 24.25 | 3.51 |
| 448 | MENCK | MHF5-12 | ECH | 125.89 | 117.70 | 1.07 | 92.84 | 26.45 | 3.51 |
| 449 | MENCK | MHF3-3 | ECH | 33.55 | 31.37 | 1.07 | 24.75 | 7.05 | 3.51 |
| 450 | MENCK | MHF3-4 | ECH | 41.98 | 39.25 | 1.07 | 30.96 | 8.82 | 3.51 |
| 451 | MENCK | MHF3-5 | ECH | 52.45 | 49.04 | 1.07 | 38.68 | 11.02 | 3.51 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 452 | MENCK | MHF3-6 | ECH | 62.97 | 58.87 | 1.07 | 46.44 | 13.23 | 3.51 |
| 453 | MENCK | MHF3-7 | ECH | 73.44 | 68.66 | 1.07 | 54.16 | 15.43 | 3.51 |
| 454 | MENCK | MHF10-15 | ECH | 169.01 | 147.12 | 1.15 | 124.64 | 33.06 | 3.77 |
| 455 | MENCK | MHF10-20 | ECH | 225.29 | 196.11 | 1.15 | 166.14 | 44.07 | 3.77 |
| 461 | MENCK | MHUT 200 | ECH | 199.85 | 117.75 | 1.70 | 147.38 | 26.46 | 5.57 |
| 462 | MENCK | MHUT 400 | ECH | 400.18 | 234.52 | 1.71 | 295.12 | 52.70 | 5.60 |
| 463 | MENCK | MHUT 500 | ECH | 550.59 | 294.28 | 1.87 | 406.04 | 66.13 | 6.14 |
| 464 | MENCK | MHUT700U | ECH | 699.88 | 413.09 | 1.69 | 516.13 | 92.83 | 5.56 |
| 465 | MENCK | MHUT700A | ECH | 839.60 | 413.09 | 2.03 | 619.18 | 92.83 | 6.67 |
| 466 | MENCK | MHUT1000 | ECH | 999.25 | 588.74 | 1.70 | 736.91 | 132.30 | 5.57 |
| 467 | MENCK | MHU2100S | ECH | 2100.02 | 1010.51 | 2.08 | 1548.69 | 227.08 | 6.82 |
| 468 | MENCK | MHU 800S | ECH | 799.02 | 441.44 | 1.81 | 589.25 | 99.20 | 5.94 |
| 469 | MENCK | MHU 1200 | ECH | 1202.34 | 657.62 | 1.83 | 886.68 | 147.78 | 6.00 |
| 481 | JUNTTAN | HHK 3 | ECH | 36.00 | 29.46 | 1.22 | 26.55 | 6.62 | 4.01 |
| 482 | JUNTTAN | HHK 4 | ECH | 47.96 | 39.25 | 1.22 | 35.37 | 8.82 | 4.01 |
| 483 | JUNTTAN | HHK 5 | ECH | 59.98 | 49.08 | 1.22 | 44.23 | 11.03 | 4.01 |
| 484 | JUNTTAN | HHK 6 | ECH | 71.94 | 58.87 | 1.22 | 53.05 | 13.23 | 4.01 |
| 485 | JUNTTAN | HHK 7 | ECH | 83.96 | 68.71 | 1.22 | 61.91 | 15.44 | 4.01 |
| 486 | JUNTTAN | HHK 10 | ECH | 119.90 | 98.12 | 1.22 | 88.42 | 22.05 | 4.01 |
| 487 | JUNTTAN | HHK 12 | ECH | 143.88 | 117.75 | 1.22 | 106.10 | 26.46 | 4.01 |
| 488 | JUNTTAN | HHK 14 | ECH | 167.86 | 137.37 | 1.22 | 123.79 | 30.87 | 4.01 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 489 | JUNTTAN | HHK 5A | ECH | 59.77 | 49.04 | 1.22 | 44.08 | 11.02 | 4.00 |
| 490 | JUNTTAN | HHK 7A | ECH | 83.69 | 68.66 | 1.22 | 61.72 | 15.43 | 4.00 |
| 491 | JUNTTAN | HHK 9A | ECH | 107.61 | 88.29 | 1.22 | 79.36 | 19.84 | 4.00 |
| 492 | JUNTTAN | HHK 12A | ECH | 141.31 | 117.70 | 1.20 | 104.21 | 26.45 | 3.94 |
| 493 | JUNTTAN | HHK 14A | ECH | 164.87 | 137.33 | 1.20 | 121.59 | 30.86 | 3.94 |
| 494 | JUNTTAN | HHK 16A | ECH | 188.43 | 156.95 | 1.20 | 138.96 | 35.27 | 3.94 |
| 495 | JUNTTAN | HHK 18A | ECH | 212.00 | 176.58 | 1.20 | 156.34 | 39.68 | 3.94 |
| 501 | HPSI | 110 | ECH | 59.66 | 48.95 | 1.22 | 44.00 | 11.00 | 4.00 |
| 502 | HPSI | 150 | ECH | 81.36 | 66.75 | 1.22 | 60.00 | 15.00 | 4.00 |
| 503 | HPSI | 154 | ECH | 83.53 | 68.53 | 1.22 | 61.60 | 15.40 | 4.00 |
| 504 | HPSI | 200 | ECH | 108.48 | 89.00 | 1.22 | 80.00 | 20.00 | 4.00 |
| 505 | HPSI | 225 | ECH | 122.04 | 100.13 | 1.22 | 90.00 | 22.50 | 4.00 |
| 506 | HPSI | 650 | ECH | 44.07 | 28.93 | 1.52 | 32.50 | 6.50 | 5.00 |
| 507 | HPSI | 1000 | ECH | 67.80 | 44.50 | 1.52 | 50.00 | 10.00 | 5.00 |
| 508 | HPSI | 1605 | ECH | 112.55 | 73.87 | 1.52 | 83.00 | 16.60 | 5.00 |
| 509 | HPSI | 2005 | ECH | 128.96 | 84.64 | 1.52 | 95.10 | 19.02 | 5.00 |
| 510 | HPSI | 3005 | ECH | 209.23 | 137.33 | 1.52 | 154.30 | 30.86 | 5.00 |
| 511 | HPSI | 3505 | ECH | 239.06 | 156.91 | 1.52 | 176.30 | 35.26 | 5.00 |
| 512 | HPSI | 2000 | ECH | 108.48 | 89.00 | 1.22 | 80.00 | 20.00 | 4.00 |
| 514 | UDDCOMB | H2H | ECH | 22.49 | 19.58 | 1.15 | 16.59 | 4.40 | 3.77 |
| 515 | UDDCOMB | H3H | ECH | 33.74 | 29.37 | 1.15 | 24.88 | 6.60 | 3.77 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 516 | UDDCOMB | H4H | ECH | 44.99 | 39.16 | 1.15 | 33.18 | 8.80 | 3.77 |
| 517 | UDDCOMB | H5H | ECH | 56.23 | 48.95 | 1.15 | 41.47 | 11.00 | 3.77 |
| 518 | UDDCOMB | H6H | ECH | 67.48 | 58.74 | 1.15 | 49.76 | 13.20 | 3.77 |
| 519 | UDDCOMB | H8H | ECH | 111.45 | 78.32 | 1.42 | 82.19 | 17.60 | 4.67 |
| 520 | UDDCOMB | H10H | ECH | 117.81 | 98.12 | 1.20 | 86.88 | 22.05 | 3.94 |
| 521 | DAWSON | HPH1200 | ECH | 11.82 | 10.24 | 1.16 | 8.72 | 2.30 | 3.79 |
| 522 | DAWSON | HPH1800 | ECH | 18.62 | 14.69 | 1.27 | 13.73 | 3.30 | 4.16 |
| 523 | DAWSON | HPH2400 | ECH | 23.47 | 18.65 | 1.26 | 17.30 | 4.19 | 4.13 |
| 524 | DAWSON | HPH6500 | ECH | 63.66 | 45.61 | 1.40 | 46.95 | 10.25 | 4.58 |
| 530 | Bruce | SGH-0312 | ECH | 35.31 | 29.41 | 1.20 | 26.04 | 6.61 | 3.94 |
| 531 | Bruce | SGH-0512 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 532 | Bruce | SGH-0712 | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |
| 533 | Bruce | SGH-1012 | ECH | 117.81 | 98.12 | 1.20 | 86.88 | 22.05 | 3.94 |
| 535 | BANUT | 3000 | ECH | 35.31 | 29.41 | 1.20 | 26.04 | 6.61 | 3.94 |
| 536 | BANUT | 4000 | ECH | 47.12 | 39.25 | 1.20 | 34.75 | 8.82 | 3.94 |
| 537 | BANUT | 5000 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 538 | BANUT | 6000 | ECH | 70.68 | 58.87 | 1.20 | 52.13 | 13.23 | 3.94 |
| 539 | BANUT | 8000 | ECH | 94.24 | 78.50 | 1.20 | 69.50 | 17.64 | 3.94 |
| 540 | BANUT | 10000 | ECH | 117.81 | 98.12 | 1.20 | 86.88 | 22.05 | 3.94 |
| 541 | BANUT | 3 Tonnes | ECH | 23.48 | 29.41 | 0.80 | 17.32 | 6.61 | 2.62 |
| 542 | BANUT | 4 Tonnes | ECH | 31.33 | 39.25 | 0.80 | 23.11 | 8.82 | 2.62 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 543 | BANUT | 5 Tonnes | ECH | 39.15 | 49.04 | 0.80 | 28.87 | 11.02 | 2.62 |
| 544 | BANUT | 6 Tonnes | ECH | 47.00 | 58.87 | 0.80 | 34.66 | 13.23 | 2.62 |
| 545 | BANUT | 7 Tonnes | ECH | 54.82 | 68.66 | 0.80 | 40.43 | 15.43 | 2.62 |
| 550 | ICE | 70 | ECH | 28.48 | 31.15 | 0.91 | 21.00 | 7.00 | 3.00 |
| 551 | ICE | 75 | ECH | 40.68 | 33.38 | 1.22 | 30.00 | 7.50 | 4.00 |
| 552 | ICE | 110-SH | ECH | 51.15 | 51.18 | 1.00 | 37.72 | 11.50 | 3.28 |
| 553 | ICE | 115-SH | ECH | 51.46 | 51.18 | 1.01 | 37.95 | 11.50 | 3.30 |
| 554 | ICE | 115 | ECH | 62.38 | 51.18 | 1.22 | 46.00 | 11.50 | 4.00 |
| 555 | ICE | 160-SH | ECH | 86.78 | 71.20 | 1.22 | 64.00 | 16.00 | 4.00 |
| 556 | ICE | 160 | ECH | 86.78 | 71.20 | 1.22 | 64.00 | 16.00 | 4.00 |
| 557 | ICE | 220 | ECH | 119.33 | 97.90 | 1.22 | 88.00 | 22.00 | 4.00 |
| 558 | ICE | 275 | ECH | 149.16 | 122.38 | 1.22 | 110.00 | 27.50 | 4.00 |
| 560 | HMC | 28A | ECH | 37.97 | 31.15 | 1.22 | 28.00 | 7.00 | 4.00 |
| 561 | HMC | 28B | ECH | 28.48 | 31.15 | 0.91 | 21.00 | 7.00 | 3.00 |
| 562 | HMC | 62 | ECH | 62.38 | 51.18 | 1.22 | 46.00 | 11.50 | 4.00 |
| 563 | HMC | 86 | ECH | 86.78 | 71.20 | 1.22 | 64.00 | 16.00 | 4.00 |
| 564 | HMC | 119 | ECH | 119.33 | 97.90 | 1.22 | 88.00 | 22.00 | 4.00 |
| 565 | HMC | 149 | ECH | 149.16 | 122.38 | 1.22 | 110.00 | 27.50 | 4.00 |
| 566 | HMC | 187 | ECH | 187.13 | 153.53 | 1.22 | 138.00 | 34.50 | 4.00 |
| 567 | HMC | 19D | ECH | 18.98 | 15.58 | 1.22 | 14.00 | 3.50 | 4.00 |
| 568 | HMC | 38D | ECH | 37.97 | 31.15 | 1.22 | 28.00 | 7.00 | 4.00 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 571 | APE | D 19-32 | OED | 58.07 | 18.65 | 3.12 | 42.82 | 4.19 | 10.25 |
| 572 | APE | D 30-32 | OED | 95.01 | 29.41 | 3.23 | 70.07 | 6.61 | 10.60 |
| 573 | APE | D 36-32 | OED | 113.98 | 35.29 | 3.23 | 84.06 | 7.93 | 10.60 |
| 574 | APE | D 46-32 | OED | 145.75 | 45.12 | 3.23 | 107.48 | 10.14 | 10.60 |
| 575 | APE | D 62-22 | OED | 218.94 | 60.79 | 3.60 | 161.46 | 13.66 | 11.82 |
| 576 | APE | D 80-23 | OED | 267.12 | 78.41 | 3.41 | 196.99 | 17.62 | 11.18 |
| 577 | APE | D 100-13 | OED | 333.98 | 98.03 | 3.41 | 246.30 | 22.03 | 11.18 |
| 578 | APE | D 8-32 | OED | 24.41 | 7.83 | 3.12 | 18.00 | 1.76 | 10.25 |
| 579 | APE | D 16-32 | OED | 53.37 | 15.71 | 3.43 | 39.36 | 3.53 | 11.25 |
| 580 | APE | D 19-42 | OED | 58.07 | 18.65 | 3.23 | 42.82 | 4.19 | 10.60 |
| 581 | APE | D 25-32 | OED | 78.45 | 24.52 | 3.20 | 57.86 | 5.51 | 10.50 |
| 582 | APE | D 125-32 | OED | 416.69 | 122.64 | 3.40 | 307.29 | 27.56 | 11.15 |
| 591 | APE | 5.4mT | ECH | 35.31 | 53.40 | 0.66 | 26.04 | 12.00 | 2.17 |
| 592 | APE | 7.2mT | ECH | 69.64 | 72.09 | 0.97 | 51.35 | 16.20 | 3.17 |
| 595 | APE | 10-60 | ECH | 108.48 | 89.00 | 1.22 | 80.00 | 20.00 | 4.00 |
| 596 | APE | HI 400U | ECH | 542.40 | 356.00 | 1.52 | 400.00 | 80.00 | 5.00 |
| 700 | ICE | 23-28 | VIB | 21.00 | 0.45 | 8.14 | 21.00 | 0.10 | 26.70 |
| 701 | ICE | 216 | VIB | 130.00 | 2.05 | 8.14 | 130.00 | 0.46 | 26.70 |
| 702 | ICE | 216E | VIB | 130.00 | 2.05 | 8.14 | 130.00 | 0.46 | 26.70 |
| 703 | ICE | 11-23 | VIB | 164.00 | 2.05 | 9.66 | 164.00 | 0.46 | 31.70 |
| 704 | ICE | 223 | VIB | 242.00 | 2.05 | 11.67 | 242.00 | 0.46 | 38.30 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 705 | ICE | 416L | VIB | 242.00 | 4.09 | 8.14 | 242.00 | 0.92 | 26.70 |
| 706 | ICE | 812 | VIB | 375.00 | 8.10 | 8.14 | 375.00 | 1.82 | 26.70 |
| 707 | ICE | 815 | VIB | 375.00 | 8.19 | 8.14 | 375.00 | 1.84 | 26.70 |
| 708 | ICE | 44-30 | VIB | 242.00 | 5.79 | 6.10 | 242.00 | 1.30 | 20.00 |
| 709 | ICE | 44-50 | VIB | 377.00 | 5.79 | 8.14 | 377.00 | 1.30 | 26.70 |
| 710 | ICE | 44-65 | VIB | 485.00 | 5.79 | 8.38 | 485.00 | 1.30 | 27.50 |
| 711 | ICE | 66-65 | VIB | 485.00 | 8.68 | 6.61 | 485.00 | 1.95 | 21.70 |
| 712 | ICE | 66-80 | VIB | 597.00 | 8.68 | 8.14 | 597.00 | 1.95 | 26.70 |
| 713 | ICE | 1412B | VIB | 597.00 | 9.08 | 6.40 | 597.00 | 2.04 | 21.00 |
| 714 | ICE | 1412C | VIB | 470.00 | 8.99 | 7.01 | 470.00 | 2.02 | 23.00 |
| 720 | HMC | 3+28 | VIB | 21.00 | 0.49 | 8.17 | 21.00 | 0.11 | 26.80 |
| 721 | HMC | 3+75 | VIB | 56.00 | 0.49 | 11.00 | 56.00 | 0.11 | 36.10 |
| 722 | HMC | 13+200 | VIB | 149.00 | 1.56 | 8.14 | 149.00 | 0.35 | 26.70 |
| 723 | HMC | 13S+200 | VIB | 149.00 | 1.56 | 8.14 | 149.00 | 0.35 | 26.70 |
| 724 | HMC | 13H+200 | VIB | 164.00 | 1.56 | 9.08 | 164.00 | 0.35 | 29.80 |
| 725 | HMC | 25+220 | VIB | 164.00 | 2.71 | 6.37 | 164.00 | 0.61 | 20.90 |
| 726 | HMC | 26+335 | VIB | 242.00 | 3.16 | 7.80 | 242.00 | 0.71 | 25.60 |
| 727 | HMC | 26S+335 | VIB | 242.00 | 3.16 | 7.80 | 242.00 | 0.71 | 25.60 |
| 728 | HMC | 51+335 | VIB | 242.00 | 5.38 | 5.94 | 242.00 | 1.21 | 19.50 |
| 729 | HMC | 51+535 | VIB | 377.00 | 5.38 | 8.05 | 377.00 | 1.21 | 26.40 |
| 730 | HMC | 51S+535 | VIB | 377.00 | 5.38 | 8.05 | 377.00 | 1.21 | 26.40 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|--------------------|------------------|-----------------------|-------------------------|--------------------|------------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 731 | HMC | 51+740 | VIB | 485.00 | 5.38 | 8.38 | 485.00 | 1.21 | 27.50 |
| 732 | HMC | 76+740 | VIB | 485.00 | 8.10 | 6.61 | 485.00 | 1.82 | 21.70 |
| 733 | HMC | 76+800 | VIB | 597.00 | 8.10 | 7.96 | 597.00 | 1.82 | 26.10 |
| 734 | HMC | 115+800 | VIB | 597.00 | 6.01 | 6.22 | 597.00 | 1.35 | 20.40 |
| 735 | HMC | 230+1600 | VIB | 0.00 | 11.97 | 6.22 | 0.00 | 2.69 | 20.40 |
| 750 | MKT | V-2B | VIB | 52.00 | 0.67 | 9.14 | 52.00 | 0.15 | 30.00 |
| 751 | MKT | V-5C | VIB | 138.00 | 1.91 | 8.63 | 138.00 | 0.43 | 28.33 |
| 752 | MKT | V-20B | VIB | 242.00 | 35.60 | 8.63 | 242.00 | 8.00 | 28.33 |
| 753 | MKT | V-30 | VIB | 448.00 | 6.54 | 8.63 | 448.00 | 1.47 | 28.33 |
| 754 | MKT | V-35 | VIB | 485.00 | 7.12 | 8.63 | 485.00 | 1.60 | 28.33 |
| 755 | MKT | V-140 | VIB | 0.00 | 20.78 | 7.11 | 0.00 | 4.67 | 23.33 |
| 770 | APE | 3 | VIB | 10.58 | 0.00 | 11.67 | 10.58 | 0.00 | 38.30 |
| 771 | APE | 6 | VIB | 10.58 | 0.04 | 11.67 | 10.58 | 0.01 | 38.30 |
| 772 | APE | 15 | VIB | 59.67 | 0.49 | 9.14 | 59.67 | 0.11 | 30.00 |
| 773 | APE | 20 | VIB | 59.67 | 0.67 | 11.67 | 59.67 | 0.15 | 38.30 |
| 774 | APE | 20E | VIB | 59.67 | 0.67 | 11.67 | 59.67 | 0.15 | 38.30 |
| 775 | APE | 50 | VIB | 194.00 | 1.02 | 9.14 | 194.00 | 0.23 | 30.00 |
| 776 | APE | 50E | VIB | 194.00 | 1.02 | 9.14 | 194.00 | 0.23 | 30.00 |
| 777 | APE | 100 | VIB | 194.00 | 1.42 | 9.14 | 194.00 | 0.32 | 30.00 |
| 778 | APE | 100E | VIB | 194.00 | 0.62 | 9.14 | 194.00 | 0.14 | 30.00 |
| 779 | APE | 100HF | VIB | 260.00 | 0.62 | 13.11 | 260.00 | 0.14 | 43.00 |

| TABLE D-4: COMPLETE HAMMER LISTING (sorted by GRLWEAP ID Numbers) | | | | | | | | | |
|--|---------------------|-------------|-------------|-----------------|---------------|--------------------|----------------------|-----------------|---------------------|
| Hammer Description | | | | SI Units | | | US Units | | |
| GRLWEAP ID | Hammer Manufacturer | Hammer Name | Hammer Type | Rated Energy kJ | Ram Weight kN | Eq. Rated Stroke m | Rated Energy ft-kips | Ram Weight kips | Eq. Rated Stroke ft |
| 780 | APE | 150 | VIB | 260.00 | 0.62 | 9.14 | 260.00 | 0.14 | 30.00 |
| 781 | APE | 150T | VIB | 260.00 | 0.76 | 9.14 | 260.00 | 0.17 | 30.00 |
| 782 | APE | 150HF | VIB | 466.00 | 1.42 | 13.11 | 466.00 | 0.32 | 43.00 |
| 783 | APE | 200 | VIB | 466.00 | 1.29 | 9.14 | 466.00 | 0.29 | 30.00 |
| 784 | APE | 200T | VIB | 466.00 | 1.51 | 9.40 | 466.00 | 0.34 | 30.83 |
| 785 | APE | 200T HF | VIB | 738.00 | 1.51 | 13.11 | 738.00 | 0.34 | 43.00 |
| 786 | APE | 300 | VIB | 738.00 | 1.51 | 7.62 | 738.00 | 0.34 | 25.00 |
| 787 | APE | 400B | VIB | 738.00 | 3.47 | 7.11 | 738.00 | 0.78 | 23.33 |
| 788 | APE | 600 | VIB | 800.00 | 4.67 | 7.10 | 800.00 | 1.05 | 23.30 |
| 789 | APE | Tan 400 | VIB | 1476.00 | 6.10 | 7.11 | 1476.00 | 1.37 | 23.33 |
| 790 | APE | Tan 600 | VIB | 1800.00 | 9.39 | 7.10 | 1800.00 | 2.11 | 23.30 |
| 801 | DKH | PH-5 | ECH | 58.88 | 49.04 | 1.20 | 43.42 | 11.02 | 3.94 |
| 802 | DKH | PH-7 | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |
| 803 | DKH | PH-7S | ECH | 82.44 | 68.66 | 1.20 | 60.79 | 15.43 | 3.94 |
| 804 | DKH | PH-10 | ECH | 117.75 | 98.08 | 1.20 | 86.84 | 22.04 | 3.94 |
| 805 | DKH | PH-13 | ECH | 153.12 | 127.54 | 1.20 | 112.92 | 28.66 | 3.94 |
| 806 | DKH | PH-20 | ECH | 294.15 | 196.20 | 1.50 | 216.92 | 44.09 | 4.92 |
| 807 | DKH | PH-30 | ECH | 441.19 | 294.28 | 1.50 | 325.36 | 66.13 | 4.92 |
| 808 | DKH | PH-40 | ECH | 588.29 | 392.40 | 1.50 | 433.85 | 88.18 | 4.92 |
| 810 | MGF | RBH 2400 | VIB | 975.00 | 23.99 | 7.16 | 975.00 | 5.39 | 23.50 |

APPENDIX E

Subsurface Exploration Results for Peach Freeway Design Problem

| | Page |
|-------------------------------------|-------------|
| SOIL BORING LOGS | E-3 |
| CONE PENETRATION TEST RESULTS | E-11 |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. <u>S - 1</u> | SHEET NO. <u>1</u> OF <u>2</u> |
|----------------------------------|--------------------------------------|--|--------------------------------|-------------------------|--------------------------------|
| Region <u>6</u> | Hammer Fall-Casing <u>--</u> | | Line <u>Baseline</u> | | |
| County <u>James</u> | Hammer Fall-Sampler <u>--</u> | | Station <u>1223 + 88</u> | | |
| Project <u>Peach Freeway</u> | Wt. of Hammer-Casing <u>--</u> | | Offset <u>20 m Rt</u> | | |
| Structure <u>Dismal River</u> | Wt. of Hammer-Sampler <u>64 kg</u> | | Surface Elev. <u>96.0 m</u> | | |
| Date Start <u>10-1-1995</u> | SPT Hammer Type <u>Safety Hammer</u> | | Water Tbl. Elev. <u>92.0 m</u> | | |
| Date Finish <u>10-2-1995</u> | Core Barrel Type <u>Double Tube</u> | | Date <u>10-3-1995</u> | | |
| Backfill/Sealed <u>10-3-1995</u> | Drill Rig Type <u>Rotary</u> | | Time <u>5:00 p.m.</u> | | |
| | | | Depth <u>4.0 m</u> | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | | | | N | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | q _u kPa (tsf) | γ _D kN/m ³ (pcf) | w _c % |
|-------|-----------------------------|---------|---------|---------|---|-------------------|---|--------------------------------|--|---------------------|
| | 0-150 | 150-300 | 300-450 | 450-600 | | | | | | |
| SS-1 | 1 | 1 | 3 | 4 | | 0 - 0 | LOOSE TO MEDIUM DENSE, SILTY FINE SAND | | | |
| | | | | | | 1 - 5 | | | | |
| SS-2 | 1 | 2 | 2 | 4 | | 2 - 5 | | | | |
| | | | | | | 3 - 10 | | | | |
| SS-3 | 2 | 2 | 4 | 6 | | 4 - 10 | | | | |
| | | | | | | 5 - 15 | | | | |
| SS-4 | 2 | 3 | 3 | 6 | | 6 - 20 | | | | |
| | | | | | | 7 - 25 | | | | |
| SS-5 | 2 | 3 | 5 | 8 | | 8 - 30 | | | | |
| | | | | | | 9 - 35 | | | | |
| SS-6 | 3 | 6 | 7 | 13 | | 10 - 40 | | | | |
| | | | | | | 11 - 45 | | | | |
| SS-7 | 4 | 7 | 8 | 15 | | 12 - 50 | | | | |
| | | | | | | 13 - 55 | | | | |
| SS-8 | 3 | 5 | 6 | 11 | | 14 - 60 | | | | |
| | | | | | | 15 - 65 | | | | |
| SS-9 | 6 | 7 | 8 | 15 | | | DENSE SAND AND GRAVEL | | | |
| | | | | | | | | | | |
| SS-10 | 7 | 9 | 9 | 18 | | | | | | |
| | | | | | | | | | | |
| SS-11 | 10 | 19 | 21 | 40 | | | | | | |
| | | | | | | | | | | |
| SS-12 | 15 | 19 | 20 | 39 | | | | | | |
| | | | | | | | | | | |
| SS-13 | 15 | 20 | 21 | 41 | | | | | | |
| | | | | | | | | | | |
| SS-14 | 16 | 21 | 22 | 43 | | | | | | |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. <u>S - 1</u> | SHEET NO. <u>2</u> OF <u>2</u> |
|----------------------------------|--------------------------------------|--|--------------------------------|-------------------------|--------------------------------|
| Region <u>6</u> | Hammer Fall-Casing <u>--</u> | | Line <u>Baseline</u> | | |
| County <u>James</u> | Hammer Fall-Sampler <u>--</u> | | Station <u>1223 + 88</u> | | |
| Project <u>Peach Freeway</u> | Wt. of Hammer-Casing <u>--</u> | | Offset <u>20 m Rt</u> | | |
| Structure <u>Dismal River</u> | Wt. of Hammer-Sampler <u>64 kg</u> | | Surface Elev. <u>96.0 m</u> | | |
| Date Start <u>10-1-1995</u> | SPT Hammer Type <u>Safety Hammer</u> | | Water Tbl. Elev. <u>92.0 m</u> | | |
| Date Finish <u>10-3-1995</u> | Core Barrel Type <u>Double Tube</u> | | Date <u>10-3-1995</u> | | |
| Backfill/Sealed <u>10-3-1995</u> | Drill Rig Type <u>Rotary</u> | | Time <u>5:00 p.m.</u> | | |
| | | | Depth <u>4.0 m</u> | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | | | | | N | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | Q _u kPa (tsf) | γ _D kN/m ³ (pcf) | w _c % |
|-------|-----------------------------|-----|-----|-----|--|----|-------------------|------------------------------|--------------------------------|--|---------------------|
| | 0 | 150 | 300 | 450 | | | | | | | |
| | | | | | | | 20 | DENSE SAND AND GRAVEL | | | |
| SS-15 | 15 | 19 | 22 | 41 | | 21 | | | | | |
| | | | | | | 22 | | | | | |
| SS-16 | 17 | 21 | 23 | 44 | | 23 | | | | | |
| | | | | | | 24 | | | | | |
| SS-17 | 18 | 20 | 25 | 45 | | 25 | | | | | |
| | | | | | | 26 | | | | | |
| SS-18 | 19 | 23 | 25 | 48 | | 27 | | | | | |
| | | | | | | 28 | | | | | |
| SS-19 | 15 | 21 | 21 | 42 | | 29 | | | | | |
| | | | | | | 30 | | | | | |
| SS-20 | 17 | 21 | 23 | 44 | | 31 | | | | | |
| | | | | | | 32 | | | | | |
| SS-21 | 20 | 23 | 26 | 49 | | 33 | | | | | |
| | | | | | | 34 | | | | | |
| RUN 1 | | | | | | 35 | | | | | |
| | | | | | | 36 | | | | | |
| | | | | | | 37 | | | | | |
| | | | | | | 38 | | | | | |
| | | | | | | 39 | | | | | |
| | | | | | | 40 | | | | | |

| | | |
|--|---|--|
| | LIMESTONE BEDROCK RUN 1 31.0-32.5m REC=83% RQD=81% | |
| | END OF BORING @32.5m | |
| | NOTES: SPT N VALUES FROM SAFETY HAMMER. | |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. <u>S - 2</u> | | SHEET NO. <u>1</u> OF <u>2</u> | |
|----------------------------------|--|--------------------------------------|--|--------------------------------|--|--------------------------------|--|
| Region <u>6</u> | | Hammer Fall-Casing <u>--</u> | | Line <u>Baseline</u> | | | |
| County <u>James</u> | | Hammer Fall-Sampler <u>--</u> | | Station <u>1225 + 13</u> | | | |
| Project <u>Peach Freeway</u> | | Wt. of Hammer-Casing <u>--</u> | | Offset <u>20 m Lt</u> | | | |
| Structure <u>Dismal River</u> | | Wt. of Hammer-Sampler <u>64 kg</u> | | Surface Elev. <u>85.0 m</u> | | | |
| Date Start <u>10-3-1995</u> | | SPT Hammer Type <u>Safety Hammer</u> | | Water Tbl. Elev. <u>87.0 m</u> | | | |
| Date Finish <u>10-3-1995</u> | | Core Barrel Type <u>Double Tube</u> | | Date <u>10-3-1995</u> | | | |
| Backfill/Sealed <u>10-3-1995</u> | | Drill Rig Type <u>Rotary</u> | | Time <u>5:00 p.m.</u> | | | |
| | | | | Depth <u>Surface</u> | | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | | | | N | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | q _u kPa (tsf) | γ _D kN/m ³ (pcf) | w _c % |
|-------|-----------------------------|-----|-----|-----|---|-------------------|---------------------------------------|--------------------------------|--|---------------------|
| | 0 | 150 | 300 | 450 | | | | | | |
| SS-1 | 2 | 2 | 3 | 5 | | 0 - 0 | LOOSE SILT | | | |
| | | | | | | 1 - 5 | | | | |
| SS-2 | 2 | 3 | 4 | 7 | | 2 - 5 | | | | |
| | | | | | | 3 - 10 | | | | |
| SS-3 | 3 | 3 | 4 | 7 | | 4 - 10 | | | | |
| | | | | | | 5 - 15 | | | | |
| SS-4 | 3 | 4 | 5 | 9 | | 6 - 20 | EXTREMELY DENSE SAND AND GRAVEL | | | |
| | | | | | | 7 - 25 | | | | |
| SS-5 | 25 | 39 | 46 | 85 | | 8 - 25 | | | | |
| | | | | | | 9 - 30 | DENSE SAND AND GRAVEL | | | |
| SS-6 | 33 | 41 | 55 | 96 | | 10 - 35 | | | | |
| | | | | | | 11 - 40 | | | | |
| SS-7 | 12 | 13 | 18 | 31 | | 12 - 45 | NOTE: OCCASIONAL COBBLES 15-15.5m. | | | |
| | | | | | | 13 - 50 | | | | |
| SS-8 | 15 | 16 | 19 | 35 | | 14 - 55 | | | | |
| | | | | | | 15 - 60 | | | | |
| SS-9 | 11 | 16 | 16 | 32 | | 16 - 65 | | | | |
| | | | | | | | | | | |
| SS-10 | 12 | 15 | 18 | 33 | | | | | | |
| | | | | | | | | | | |
| SS-11 | 15 | 17 | 21 | 38 | | | | | | |
| | | | | | | | | | | |
| SS-12 | 13 | 16 | 18 | 34 | | | | | | |
| | | | | | | | | | | |
| SS-13 | 17 | 19 | 20 | 39 | | | | | | |
| | | | | | | | | | | |
| SS-14 | 16 | 19 | 22 | 41 | | | | | | |
| | | | | | | | | | | |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. <u>S - 2</u> | SHEET NO. <u>2</u> OF <u>2</u> |
|----------------------------------|--------------------------------------|--------------------------------|--|-------------------------|--------------------------------|
| Region <u>6</u> | Hammer Fall-Casing <u>--</u> | Line <u>Baseline</u> | | | |
| County <u>James</u> | Hammer Fall-Sampler <u>--</u> | Station <u>1225 + 13</u> | | | |
| Project <u>Peach Freeway</u> | Wt. of Hammer-Casing <u>--</u> | Offset <u>20 m Lt</u> | | | |
| Structure <u>Dismal River</u> | Wt. of Hammer-Sampler <u>64 kg</u> | Surface Elev. <u>85.0 m</u> | | | |
| Date Start <u>10-3-1995</u> | SPT Hammer Type <u>Safety Hammer</u> | Water Tbl. Elev. <u>87.0 m</u> | | | |
| Date Finish <u>10-3-1995</u> | Core Barrel Type <u>Double Tube</u> | Date <u>10-3-1995</u> | | | |
| Backfill/Sealed <u>10-3-1995</u> | Drill Rig Type <u>Rotary</u> | Time <u>5:00 p.m.</u> | | | |
| | | Depth <u>Surface</u> | | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | N | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | q _u | γ _D | w _c |
|-------|-----------------------------|---|-------------------|--|----------------|----------------------------|----------------|
| | | | | | kPa (tsf) | kN/m ³ (pcf) | % |
| | 0 150 300 | | 20 — 65 | | | | |
| | 150 300 450 | | 21 — 70 | | | | |
| RUN 1 | | | 22 — 75 | LIMESTONE BEDROCK RUN 1 20.5-22.0m REC.=98%, RQD=67% RUN 2 22.0-23.5m REC.=100%, RQD=85% | | | |
| RUN 2 | | | 23 — 80 | END OF BORING @20.0m | | | |
| | | | 24 — 85 | NOTES: SPT N VALUES FROM SAFETY HAMMER. | | | |
| | | | 25 — 90 | | | | |
| | | | 26 — 95 | | | | |
| | | | 27 — 100 | | | | |
| | | | 28 — 105 | | | | |
| | | | 29 — 110 | | | | |
| | | | 30 — 115 | | | | |
| | | | 31 — 120 | | | | |
| | | | 32 — 125 | | | | |
| | | | 33 — 130 | | | | |
| | | | 34 — 135 | | | | |
| | | | 35 — 140 | | | | |
| | | | 36 — 145 | | | | |
| | | | 37 — 150 | | | | |
| | | | 38 — 155 | | | | |
| | | | 39 — 160 | | | | |
| | | | 40 — 165 | | | | |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. <u>S - 3</u> | | SHEET NO. <u>1</u> OF <u>2</u> | |
|----------------------------------|--|--------------------------------------|--|--------------------------------|--|--------------------------------|--|
| Region <u>6</u> | | Hammer Fall-Casing <u>--</u> | | Line <u>Baseline</u> | | | |
| County <u>James</u> | | Hammer Fall-Sampler <u>--</u> | | Station <u>1226 + 13</u> | | | |
| Project <u>Peach Freeway</u> | | Wt. of Hammer-Casing <u>--</u> | | Offset <u>20 m Rt</u> | | | |
| Structure <u>Dismal River</u> | | Wt. of Hammer-Sampler <u>64 kg</u> | | Surface Elev. <u>85.0 m</u> | | | |
| Date Start <u>10-4-1995</u> | | SPT Hammer Type <u>Safety Hammer</u> | | Water Tbl. Elev. <u>87.0 m</u> | | | |
| Date Finish <u>10-4-1995</u> | | Core Barrel Type <u>Double Tube</u> | | Date <u>10-4-1995</u> | | | |
| Backfill/Sealed <u>10-4-1995</u> | | Drill Rig Type <u>Rotary</u> | | Time <u>5:00 p.m.</u> | | | |
| Depth <u>Surface</u> | | | | | | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | | | | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | Q _u kPa (tsf) | γ _D kN/m ³ (pcf) | W _c % | |
|------|-----------------------------|-----|-----|-----|-------------------|---------------------------------|--------------------------------|--|---------------------|--|
| | 0 | 150 | 300 | 450 | | | | | | |
| SS-1 | 1 | 2 | 2 | 4 | 0 | LOOSE SILT | | | | |
| | | | | | 1 | | | | | |
| SS-2 | 2 | 3 | 4 | 7 | 2 | EXTREMELY DENSE SAND AND GRAVEL | | | | |
| SS-3 | 38 | 41 | 42 | 83 | 3 | | | | | |
| UD-1 | | | | | 4 | STIFF TO VERY STIFF SILTY CLAY | 182 (1.90) | 14.6 (93) | 33 | |
| UD-2 | | | | | 5 | | 240 (2.51) | 15.1 (96) | 31 | |
| UD-3 | | | | | 6 | | 278 (2.90) | 15.7 (100) | 27 | |
| UD-4 | | | | | 7 | | 307 (3.21) | 16.2 (103) | 24 | |
| UD-5 | | | | | 8 | | 316 (3.30) | 16.7 (106) | 22 | |
| UD-6 | | | | | 9 | | 311 (3.25) | 16.3 (104) | 23 | |
| UD-7 | | | | | 10 | | 316 (3.30) | 16.7 (106) | 22 | |
| UD-8 | | | | | 11 | | 326 (3.40) | 17.0 (108) | 21 | |
| SS-4 | 18 | 19 | 19 | 38 | 12 | | DENSE SAND AND GRAVEL | | | |
| | | | | | 13 | | | | | |
| SS-5 | 21 | 22 | 24 | 46 | 14 | | | | | |
| | | | | | 15 | | | | | |
| SS-6 | 19 | 19 | 22 | 41 | 16 | | | | | |
| | | | | | 17 | | | | | |
| SS-7 | 21 | 24 | 26 | 50 | 18 | | | | | |
| | | | | | 19 | | | | | |
| | | | | | 20 | | | | | |

| SUBSURFACE EXPLORATION LOG | | | BORING NO. <u>S - 3</u> | SHEET NO. <u>2</u> OF <u>2</u> |
|----------------------------------|--------------------------------------|--------------------------------|-------------------------|--------------------------------|
| Region <u>6</u> | Hammer Fall-Casing <u>--</u> | Line <u>Baseline</u> | | |
| County <u>James</u> | Hammer Fall-Sampler <u>--</u> | Station <u>1226 + 13</u> | | |
| Project <u>Peach Freeway</u> | Wt. of Hammer-Casing <u>--</u> | Offset <u>20 m Rt</u> | | |
| Structure <u>Dismal River</u> | Wt. of Hammer-Sampler <u>64 kg</u> | Surface Elev. <u>85.0 m</u> | | |
| Date Start <u>10-4-1995</u> | SPT Hammer Type <u>Safety Hammer</u> | Water Tbl. Elev. <u>87.0 m</u> | | |
| Date Finish <u>10-4-1995</u> | Core Barrel Type <u>Double Tube</u> | Date <u>10-4-1995</u> | | |
| Backfill/Sealed <u>10-4-1995</u> | Drill Rig Type <u>Rotary</u> | Time <u>5:00 p.m.</u> | | |
| | | Depth <u>Surface</u> | | |

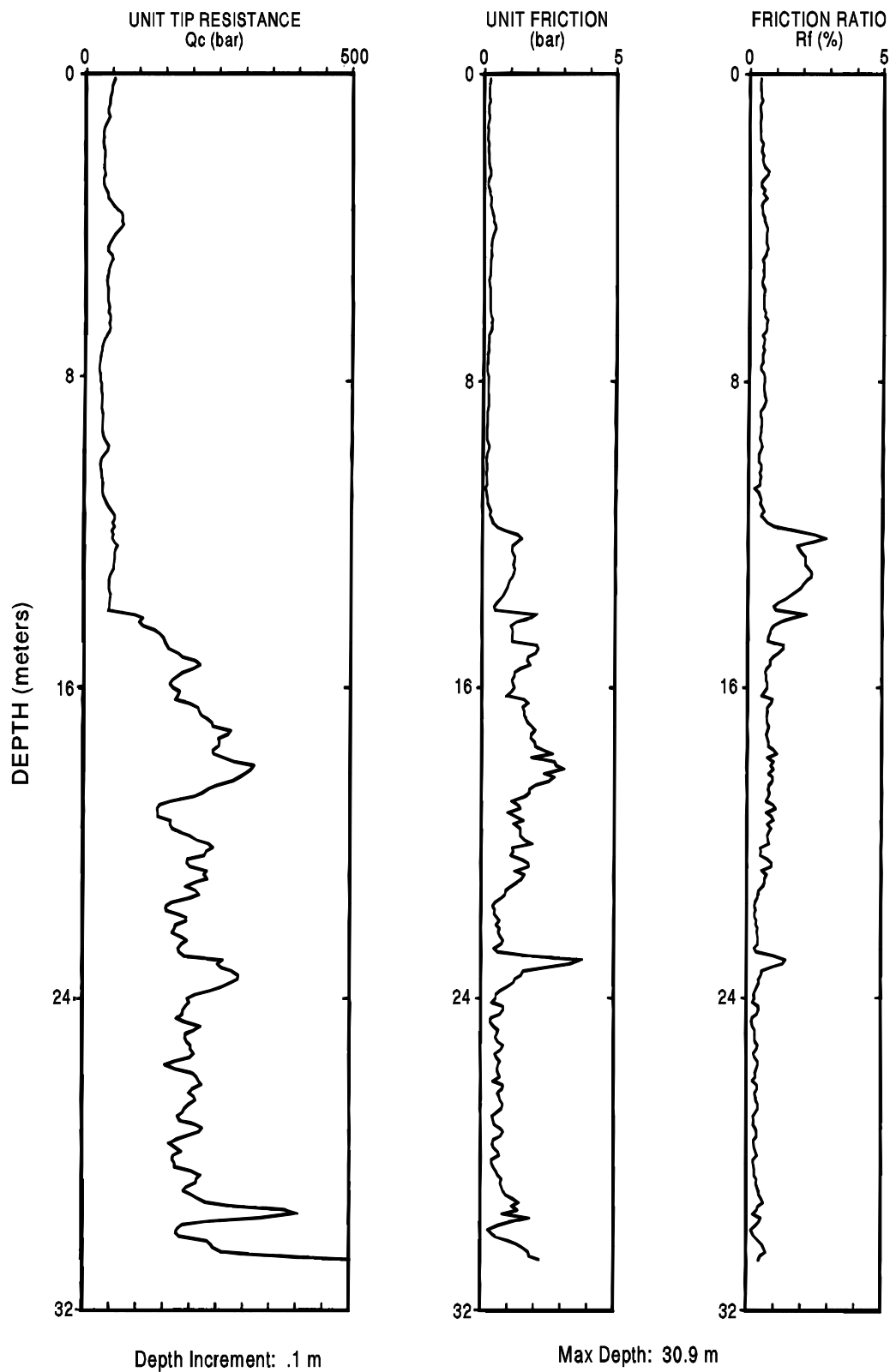
| NO. | BLOWS ON SAMPLER PER 150 mm | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | q _u | γ _D | w _c | | | | | | | | |
|-------|--|-------------------|------------------------------|----------------|----------------------------|----------------|--|--|--|---------|--|--|--|--|
| | | | | kPa (tsf) | kN/m ³ (pcf) | % | | | | | | | | |
| | <table border="1" style="display: inline-table; border-collapse: collapse;"> <tr> <td style="width: 25%;">0</td> <td style="width: 25%;">150</td> <td style="width: 25%;">300</td> <td style="width: 25%;">450</td> </tr> <tr> <td style="text-align: center;">N</td> <td></td> <td></td> <td></td> </tr> </table> | 0 | 150 | 300 | 450 | N | | | | 20 — 65 | <p style="text-align: center;">LIMESTONE BEDROCK</p> <p>RUN 1 20-21.5m REC.=90%, RQD=79%</p> <p style="text-align: center;">END OF BORING @21.5m</p> <p>NOTES:</p> <p>SPT N VALUES FROM SAFETY HAMMER.</p> | | | |
| 0 | 150 | 300 | 450 | | | | | | | | | | | |
| N | | | | | | | | | | | | | | |
| RUN 1 | | 21 — 70 | | | | | | | | | | | | |
| | | 22 — 75 | | | | | | | | | | | | |
| | | 23 — 80 | | | | | | | | | | | | |
| | | 24 — 85 | | | | | | | | | | | | |
| | | 25 — 90 | | | | | | | | | | | | |
| | | 26 — 95 | | | | | | | | | | | | |
| | | 27 — 100 | | | | | | | | | | | | |
| | | 28 — 105 | | | | | | | | | | | | |
| | | 29 — 110 | | | | | | | | | | | | |
| | | 30 — 115 | | | | | | | | | | | | |
| | | 31 — 120 | | | | | | | | | | | | |
| | | 32 — 125 | | | | | | | | | | | | |
| | | 33 — 130 | | | | | | | | | | | | |
| | | 34 — 135 | | | | | | | | | | | | |
| | | 35 — 140 | | | | | | | | | | | | |
| | | 36 — 145 | | | | | | | | | | | | |
| | | 37 — 150 | | | | | | | | | | | | |
| | | 38 — 155 | | | | | | | | | | | | |
| | | 39 — 160 | | | | | | | | | | | | |
| | | 40 — 165 | | | | | | | | | | | | |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. S - 4 | | SHEET NO. 1 OF 2 | |
|----------------------------|--|-------------------------------|--|-------------------------|--|------------------|--|
| Region 6 | | Hammer Fall-Casing -- | | Line Baseline | | | |
| County James | | Hammer Fall-Sampler -- | | Station 1227 + 38 | | | |
| Project Peach Freeway | | Wt. of Hammer-Casing -- | | Offset 20 m Lt | | | |
| Structure Dismal River | | Wt. of Hammer-Sampler 64 kg | | Surface Elev. 91.0 m | | | |
| Date Start 10-5-1995 | | SPT Hammer Type Safety Hammer | | Water Tbl. Elev. 90.5 m | | | |
| Date Finish 10-5-1995 | | Core Barrel Type Double Tube | | Date 10-6-1995 | | | |
| Backfill/Sealed 10-5-1995 | | Drill Rig Type Rotary | | Time 5:00 p.m. | | | |
| | | | | Depth 0.5 m | | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | | | | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | q _u kPa (tsf) | γ _D kN/m ³ (pcf) | w _c % |
|-------|-----------------------------|-----|-----|-----|-------------------|------------------------------|--------------------------------|--|---------------------|
| | 0 | 150 | 300 | 450 | | | | | |
| UD-1 | | | | | 0 | MEDIUM SILTY CLAY | 62 | 13.9 | 35 |
| | | | | | 1 | | (0.65) | (89) | |
| UD-2 | | | | | 2 | | 60 | 13.6 | 38 |
| | | | | | 3 | | (0.63) | (87) | |
| UD-3 | | | | | 4 | | 65 | 14.1 | 34 |
| | | | | | 5 | (0.68) | (90) | | |
| UD-4 | | | | | 6 | STIFF SILTY CLAY | 67 | 14.4 | 32 |
| | | | | | 7 | | (0.70) | (92) | |
| UD-5 | | | | | 8 | | 69 | 14.6 | 31 |
| | | | | | 9 | | (0.72) | (93) | |
| UD-6 | | | | | 10 | | 172 | 14.9 | 30 |
| | | | | | 11 | (1.79) | (95) | | |
| UD-7 | | | | | 12 | VERY STIFF SILTY CLAY | 182 | 15.7 | 27 |
| | | | | | 13 | | (1.89) | (100) | |
| UD-8 | | | | | 14 | | 192 | 16.3 | 24 |
| | | | | | 15 | | (2.00) | (104) | |
| UD-9 | | | | | 16 | | 188 | 16.0 | 26 |
| | | | | | 17 | (1.96) | (102) | | |
| UD-10 | | | | | 18 | | 192 | 16.3 | 24 |
| | | | | | 19 | | (2.00) | (104) | |
| UD-11 | | | | | 20 | | 190 | 16.2 | 25 |
| | | | | | 21 | | (1.98) | (103) | |
| UD-12 | | | | | 22 | | 316 | 16.7 | 22 |
| | | | | | 23 | (3.30) | (106) | | |
| UD-13 | | | | | 24 | | 310 | 16.5 | 23 |
| | | | | | 25 | | (3.24) | (105) | |
| UD-14 | | | | | 26 | | 326 | 17.0 | 21 |
| | | | | | 27 | | (3.40) | (108) | |

| SUBSURFACE EXPLORATION LOG | | | | BORING NO. S - 4 | | SHEET NO. 2 OF 2 | |
|----------------------------|--|-------------------------------|--|-----------------------|--|------------------|--|
| Region 6 | | Hammer Fall-Casing -- | | Line Baseline | | | |
| County James | | Hammer Fall-Sampler -- | | Station 1227 + 38 | | | |
| Project Peach Freeway | | Wt. of Hammer-Casing -- | | Offset 20 m Lt | | | |
| Structure Dismal River | | Wt. of Hammer-Sampler 64 kg | | Surface Elev. 91.0 m | | | |
| Date Start 10-5-1995 | | SPT Hammer Type Safety Hammer | | Water Tbl. Elev. 90.5 | | | |
| Date Finish 10-5-1995 | | Core Barrel Type Double Tube | | Date 10-6-1995 | | | |
| Backfill/Sealed 10-6-1995 | | Drill Rig Type Rotary | | Time 5:00 p.m. | | | |
| | | | | Depth 0.5 m | | | |

| NO. | BLOWS ON SAMPLER PER 150 mm | | | | DEPTH (m) (ft) | SOIL DESCRIPTION AND REMARKS | q _u kPa (tsf) | γ _D kN/m ³ (pcf) | w _c % |
|-------|-----------------------------|-----|-----|-----|-------------------|------------------------------|--------------------------------|--|---------------------|
| | 0 | 150 | 300 | 450 | | | | | |
| | | | | | 20 | 65 | | | |
| UD-15 | | | | | 21 | 70 | 335 (3.50) | 16.8 (107) | 21 |
| UD-16 | | | | | 22 | 75 | 340 (3.55) | 17.0 (108) | 20 |
| UD-17 | | | | | 23 | 80 | 350 (3.65) | 17.1 (109) | 19 |
| UD-18 | | | | | 24 | 85 | 345 (3.60) | 17.0 (108) | 20 |
| UD-19 | | | | | 25 | 90 | 350 (3.65) | 17.2 (110) | 19 |
| UD-20 | | | | | 26 | 95 | 354 (3.70) | 17.3 (110) | 18 |
| SS-1 | 20 | 22 | 27 | 49 | 27 | 100 | | | |
| RUN 1 | | | | | 28 | 105 | | | |
| | | | | | 29 | 110 | | | |
| | | | | | 30 | 115 | | | |
| | | | | | 31 | 120 | | | |
| | | | | | 32 | 125 | | | |
| | | | | | 33 | 130 | | | |



Licensed to: InSituTech Ltd.
Address: 5 del Valle
City: Orinda, CA 94563, U.S.A.

Interpreter Name: Mike Holloway

File Number: 202
Operator: DM HOLLOWAY
Cone Type: 186

Date: 8/21/89
On Site Location: Peach Freeway CPT-1
Comment: 93/2/1001

SUMMARY SHEET

'a' for calculating Q_t : 0.800
Value for Water Table (in m): 4.000
Valid Zone Classification based on: R_f
Missing unit weight to start depth: 15.720
Method for calculating s_u : N_k
Value of the constant N_k : 15.000
Define Zone 6 for Sand Parameters? Yes
Sand Compressibility for calc D_r : All sands

Soil Behavior Type Zone Numbers for R_f Zone and B_q Zone Classification

| | |
|----------------------------------|--------------------------------------|
| Zone #1 = Sensitive fine grained | Zone #7 = Sand with some silt |
| Zone #2 = Organic material | Zone #8 = Fine sand |
| Zone #3 = Clay | Zone #9 = Sand |
| Zone #4 = Silty clay | Zone #10 = Gravelly sand |
| Zone #5 = Clayey silt | Zone #11 = Very stiff fine grained * |
| Zone #6 = Silty sand | Zone #12 = Sand to clayey sand * |

* Overconsolidated and/or cemented

NOTE: For 8011 classification, R_f values > are assumed to be 8.

NOTE: Since U_2 (pore pressure) has not been defined, Q_t cannot be calculated, therefore, the value of Q_t has been made equal to q_c .

NOTE: ---- means out of range.

| PEACH FREEWAY CPT-1 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 0.25 | 49.900 | 0.195 | 0.391 | 0.054 | 0.054 | 8 | 12 | 18 | 89 | ---- | ---- |
| 0.50 | 46.867 | 0.190 | 0.405 | 0.103 | 0.103 | 8 | 12 | 18 | 78 | ---- | ---- |
| 0.75 | 43.900 | 0.180 | 0.410 | 0.152 | 0.152 | 8 | 11 | 17 | 71 | ---- | ---- |
| 1.00 | 42.633 | 0.167 | 0.391 | 0.201 | 0.201 | 8 | 11 | 17 | 66 | ---- | ---- |
| 1.25 | 38.650 | 0.150 | 0.388 | 0.251 | 0.251 | 8 | 10 | 15 | 60 | ---- | ---- |
| 1.50 | 33.600 | 0.130 | 0.387 | 0.299 | 0.299 | 7 | 11 | 17 | 54 | ---- | ---- |
| 1.75 | 32.450 | 0.145 | 0.447 | 0.346 | 0.346 | 7 | 11 | 17 | 51 | ---- | ---- |
| 2.00 | 34.700 | 0.157 | 0.451 | 0.393 | 0.393 | 7 | 12 | 18 | 51 | ---- | ---- |
| 2.25 | 34.250 | 0.165 | 0.482 | 0.440 | 0.440 | 7 | 11 | 17 | 49 | ---- | ---- |
| 2.50 | 34.400 | 0.220 | 0.640 | 0.487 | 0.487 | 7 | 11 | 17 | 47 | ---- | ---- |
| 2.75 | 32.150 | 0.150 | 0.467 | 0.534 | 0.534 | 7 | 11 | 17 | 44 | ---- | ---- |
| 3.00 | 36.633 | 0.180 | 0.491 | 0.582 | 0.582 | 7 | 12 | 18 | 47 | ---- | ---- |
| 3.25 | 44.200 | 0.245 | 0.554 | 0.630 | 0.630 | 8 | 11 | 15 | 51 | ---- | ---- |
| 3.50 | 58.667 | 0.267 | 0.455 | 0.679 | 0.679 | 8 | 15 | 20 | 58 | ---- | ---- |
| 3.75 | 67.250 | 0.360 | 0.535 | 0.728 | 0.728 | 8 | 17 | 21 | 61 | ---- | ---- |
| 4.00 | 63.733 | 0.393 | 0.617 | 0.777 | 0.777 | 8 | 16 | 19 | 58 | ---- | ---- |
| 4.25 | 49.750 | 0.305 | 0.613 | 0.826 | 0.802 | 8 | 12 | 14 | 51 | ---- | ---- |
| 4.50 | 41.733 | 0.263 | 0.631 | 0.874 | 0.825 | 7 | 14 | 16 | 45 | ---- | ---- |
| 4.75 | 48.500 | 0.250 | 0.515 | 0.922 | 0.849 | 8 | 12 | 13 | 49 | ---- | ---- |
| 5.00 | 43.733 | 0.223 | 0.511 | 0.972 | 0.874 | 8 | 11 | 12 | 46 | ---- | ---- |
| 5.25 | 40.200 | 0.200 | 0.498 | 1.020 | 0.897 | 7 | 13 | 14 | 43 | ---- | ---- |
| 5.50 | 39.667 | 0.193 | 0.487 | 1.067 | 0.920 | 7 | 13 | 13 | 42 | ---- | ---- |
| 5.75 | 41.350 | 0.215 | 0.520 | 1.115 | 0.943 | 8 | 10 | 10 | 43 | ---- | ---- |
| 6.00 | 42.400 | 0.217 | 0.511 | 1.164 | 0.968 | 8 | 11 | 11 | 43 | ---- | ---- |
| 6.25 | 43.950 | 0.250 | 0.569 | 1.213 | 0.993 | 8 | 11 | 11 | 44 | ---- | ---- |
| 6.50 | 44.600 | 0.283 | 0.635 | 1.261 | 1.016 | 7 | 15 | 14 | 44 | ---- | ---- |
| 6.75 | 41.550 | 0.225 | 0.542 | 1.309 | 1.039 | 7 | 14 | 13 | 42 | ---- | ---- |
| 7.00 | 32.767 | 0.170 | 0.519 | 1.356 | 1.061 | 7 | 11 | 10 | 35 | ---- | ---- |
| 7.25 | 29.100 | 0.150 | 0.515 | 1.403 | 1.084 | 7 | 10 | 9 | 31 | ---- | ---- |
| 7.50 | 26.567 | 0.123 | 0.464 | 1.450 | 1.107 | 7 | 9 | 8 | 28 | ---- | ---- |
| 7.75 | 26.350 | 0.125 | 0.474 | 1.497 | 1.129 | 7 | 9 | 8 | 28 | ---- | ---- |
| 8.00 | 28.900 | 0.160 | 0.554 | 1.544 | 1.152 | 7 | 10 | 9 | 30 | ---- | ---- |
| 8.25 | 29.950 | 0.160 | 0.551 | 1.591 | 1.175 | 7 | 10 | 9 | 31 | ---- | ---- |
| 8.50 | 31.033 | 0.183 | 0.591 | 1.639 | 1.197 | 7 | 10 | 8 | 31 | ---- | ---- |
| 8.75 | 31.400 | 0.145 | 0.462 | 1.686 | 1.220 | 7 | 10 | 8 | 31 | ---- | ---- |

| PEACH FREEWAY cpt-1 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 9.00 | 32.833 | 0.147 | 0.447 | 1.733 | 1.242 | 7 | 11 | 9 | 33 | ---- | ---- |
| 9.25 | 32.100 | 0.140 | 0.436 | 1.780 | 1.265 | 7 | 11 | 9 | 32 | ---- | ---- |
| 9.50 | 36.133 | 0.150 | 0.415 | 1.827 | 1.288 | 7 | 12 | 10 | 35 | ---- | ---- |
| 9.75 | 42.700 | 0.195 | 0.457 | 1.875 | 1.311 | 8 | 11 | 9 | 39 | ---- | ---- |
| 10.00 | 32.867 | 0.123 | 0.375 | 1.923 | 1.335 | 7 | 11 | 9 | 32 | ---- | ---- |
| 10.25 | 29.150 | 0.130 | 0.446 | 1.971 | 1.358 | 7 | 10 | 8 | 28 | ---- | ---- |
| 10.50 | 31.500 | 0.133 | 0.423 | 2.018 | 1.380 | 7 | 11 | 8 | 30 | ---- | ---- |
| 10.75 | 33.350 | 0.105 | 0.315 | 2.065 | 1.403 | 7 | 11 | 8 | 31 | ---- | ---- |
| 11.00 | 35.100 | 0.143 | 0.408 | 2.112 | 1.425 | 7 | 12 | 9 | 32 | ---- | ---- |
| 11.25 | 42.650 | 0.195 | 0.457 | 2.160 | 1.449 | 8 | 11 | 8 | 38 | ---- | ---- |
| 11.50 | 54.300 | 0.290 | 0.534 | 2.209 | 1.474 | 8 | 14 | 10 | 44 | ---- | ---- |
| 11.75 | 53.500 | 0.445 | 0.832 | 2.258 | 1.498 | 8 | 13 | 9 | 44 | ---- | ---- |
| 12.00 | 51.333 | 1.207 | 2.351 | 2.308 | 1.523 | 6 | 21 | 15 | 42 | ---- | ---- |
| 12.25 | 58.350 | 1.215 | 2.082 | 2.356 | 1.546 | 7 | 19 | 13 | 46 | ---- | ---- |
| 12.50 | 56.700 | 1.140 | 2.011 | 2.403 | 1.569 | 7 | 19 | 13 | 45 | ---- | ---- |
| 12.75 | 55.000 | 1.165 | 2.118 | 2.451 | 1.593 | 6 | 22 | 15 | 44 | ---- | ---- |
| 13.00 | 50.200 | 1.163 | 2.317 | 2.500 | 1.617 | 6 | 20 | 13 | 41 | ---- | ---- |
| 13.25 | 46.500 | 0.990 | 2.129 | 2.549 | 1.642 | 6 | 19 | 13 | 38 | ---- | ---- |
| 13.50 | 47.267 | 0.843 | 1.784 | 2.597 | 1.665 | 7 | 16 | 10 | 39 | ---- | ---- |
| 13.75 | 47.300 | 0.590 | 1.247 | 2.645 | 1.688 | 7 | 16 | 10 | 39 | ---- | ---- |
| 14.00 | 62.467 | 0.973 | 1.558 | 2.692 | 1.711 | 7 | 21 | 13 | 46 | ---- | ---- |
| 14.25 | 106.350 | 1.525 | 1.434 | 2.740 | 1.734 | 8 | 27 | 17 | 61 | ---- | ---- |
| 14.50 | 127.733 | 1.110 | 0.869 | 2.789 | 1.759 | 9 | 26 | 16 | 66 | ---- | ---- |
| 14.75 | 149.800 | 1.110 | 0.741 | 2.838 | 1.784 | 9 | 30 | 19 | 71 | ---- | ---- |
| 15.00 | 162.900 | 2.047 | 1.256 | 2.887 | 1.808 | 8 | 41 | 25 | 73 | ---- | ---- |
| 15.25 | 196.200 | 1.715 | 0.874 | 2.936 | 1.833 | 9 | 39 | 24 | 78 | ---- | ---- |
| 15.50 | 203.300 | 1.477 | 0.726 | 2.985 | 1.857 | 9 | 41 | 25 | 79 | ---- | ---- |
| 15.75 | 170.900 | 1.155 | 0.676 | 3.035 | 1.882 | 9 | 34 | 20 | 74 | ---- | ---- |
| 16.00 | 168.633 | 1.153 | 0.684 | 3.084 | 1.907 | 9 | 34 | 20 | 73 | ---- | ---- |
| 16.25 | 173.950 | 1.240 | 0.713 | 3.133 | 1.931 | 9 | 35 | 20 | 74 | ---- | ---- |
| 16.50 | 208.867 | 1.610 | 0.771 | 3.182 | 1.956 | 9 | 42 | 24 | 79 | ---- | ---- |
| 16.75 | 224.800 | 1.605 | 0.714 | 3.231 | 1.980 | 9 | 45 | 26 | 81 | ---- | ---- |
| 17.00 | 252.367 | 1.877 | 0.744 | 3.280 | 2.005 | 9 | 50 | 28 | 84 | ---- | ---- |
| 17.25 | 260.650 | 1.840 | 0.706 | 3.329 | 2.030 | 9 | 52 | 29 | 85 | ---- | ---- |
| 17.50 | 249.233 | 2.083 | 0.836 | 3.378 | 2.054 | 9 | 50 | 28 | 83 | ---- | ---- |

| PEACH FREEWAY CPT-1 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 17.75 | 252.400 | 2.275 | 0.901 | 3.428 | 2.079 | 9 | 50 | 28 | 84 | ---- | ---- |
| 18.00 | 305.000 | 2.860 | 0.938 | 3.477 | 2.103 | 9 | 61 | 33 | 89 | ---- | ---- |
| 18.25 | 297.400 | 2.555 | 0.859 | 3.526 | 2.128 | 9 | 59 | 32 | 88 | ---- | ---- |
| 18.50 | 254.833 | 2.123 | 0.833 | 3.575 | 2.153 | 9 | 51 | 27 | 83 | ---- | ---- |
| 18.75 | 214.850 | 1.705 | 0.794 | 3.624 | 2.177 | 9 | 43 | 23 | 78 | ---- | ---- |
| 19.00 | 148.067 | 1.310 | 0.885 | 3.673 | 2.202 | 9 | 30 | 16 | 67 | ---- | ---- |
| 19.25 | 139.100 | 1.125 | 0.809 | 3.722 | 2.226 | 9 | 28 | 15 | 66 | ---- | ---- |
| 19.50 | 162.450 | 1.390 | 0.856 | 3.771 | 2.251 | 9 | 32 | 17 | 70 | ---- | ---- |
| 19.75 | 173.100 | 1.450 | 0.838 | 3.821 | 2.276 | 9 | 35 | 18 | 71 | ---- | ---- |
| 20.00 | 214.933 | 1.657 | 0.771 | 3.870 | 2.300 | 9 | 43 | 22 | 78 | ---- | ---- |
| 20.25 | 236.350 | 1.165 | 0.493 | 3.919 | 2.325 | 9 | 47 | 24 | 80 | ---- | ---- |
| 20.50 | 204.867 | 1.427 | 0.696 | 3.968 | 2.349 | 9 | 41 | 21 | 76 | ---- | ---- |
| 20.75 | 214.700 | 1.515 | 0.706 | 4.017 | 2.374 | 9 | 43 | 22 | 77 | ---- | ---- |
| 21.00 | 221.533 | 1.477 | 0.667 | 4.066 | 2.399 | 9 | 44 | 22 | 78 | ---- | ---- |
| 21.25 | 201.300 | 1.015 | 0.504 | 4.115 | 2.423 | 9 | 40 | 20 | 75 | ---- | ---- |
| 21.50 | 192.700 | 0.710 | 0.368 | 4.164 | 2.448 | 9 | 39 | 20 | 74 | ---- | ---- |
| 21.75 | 154.550 | 0.465 | 0.301 | 4.214 | 2.472 | 9 | 31 | 16 | 67 | ---- | ---- |
| 22.00 | 186.733 | 0.577 | 0.309 | 4.263 | 2.497 | 9 | 37 | 19 | 72 | ---- | ---- |
| 22.25 | 172.050 | 0.615 | 0.357 | 4.312 | 2.522 | 9 | 34 | 17 | 70 | ---- | ---- |
| 22.50 | 180.900 | 0.713 | 0.394 | 4.361 | 2.546 | 9 | 36 | 18 | 71 | ---- | ---- |
| 22.75 | 180.450 | 0.615 | 0.341 | 4.410 | 2.571 | 9 | 36 | 18 | 71 | ---- | ---- |
| 23.00 | 209.567 | 2.040 | 0.973 | 4.459 | 2.595 | 9 | 42 | 21 | 75 | ---- | ---- |
| 23.25 | 255.250 | 2.870 | 1.124 | 4.508 | 2.620 | 9 | 51 | 26 | 81 | ---- | ---- |
| 23.50 | 286.267 | 1.450 | 0.507 | 4.558 | 2.646 | 10 | 48 | 24 | 84 | ---- | ---- |
| 23.75 | 267.100 | 1.085 | 0.406 | 4.610 | 2.672 | 10 | 45 | 23 | 82 | ---- | ---- |
| 24.00 | 213.833 | 0.607 | 0.284 | 4.661 | 2.699 | 10 | 36 | 18 | 75 | ---- | ---- |
| 24.25 | 195.400 | 0.615 | 0.315 | 4.711 | 2.724 | 9 | 39 | 20 | 72 | ---- | ---- |
| 24.50 | 183.033 | 0.630 | 0.344 | 4.760 | 2.749 | 9 | 37 | 19 | 70 | ---- | ---- |
| 24.75 | 205.600 | 0.395 | 0.192 | 4.810 | 2.774 | 10 | 34 | 17 | 74 | ---- | ---- |
| 25.00 | 197.667 | 0.590 | 0.298 | 4.860 | 2.800 | 9 | 40 | 20 | 72 | ---- | ---- |
| 25.25 | 198.400 | 0.730 | 0.368 | 4.909 | 2.825 | 9 | 40 | 20 | 72 | ---- | ---- |
| 25.50 | 203.167 | 0.617 | 0.304 | 4.958 | 2.849 | 9 | 41 | 21 | 73 | ---- | ---- |
| 25.75 | 164.050 | 0.675 | 0.411 | 5.008 | 2.874 | 9 | 33 | 17 | 67 | ---- | ---- |
| 26.00 | 197.300 | 0.653 | 0.331 | 5.057 | 2.898 | 9 | 39 | 20 | 72 | ---- | ---- |
| 26.25 | 219.850 | 0.645 | 0.293 | 5.107 | 2.924 | 10 | 37 | 19 | 75 | ---- | ---- |

| PEACH FREEWAY CPT-1 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 26.50 | 204.100 | 0.700 | 0.343 | 5.157 | 2.950 | 9 | 41 | 21 | 72 | ---- | ---- |
| 26.75 | 205.200 | 0.770 | 0.375 | 5.206 | 2.974 | 9 | 41 | 21 | 73 | ---- | ---- |
| 27.00 | 185.200 | 0.600 | 0.324 | 5.255 | 2.999 | 9 | 37 | 19 | 69 | ---- | ---- |
| 27.25 | 196.050 | 0.480 | 0.245 | 5.304 | 3.023 | 9 | 39 | 20 | 71 | ---- | ---- |
| 27.50 | 211.900 | 0.753 | 0.356 | 5.353 | 3.048 | 9 | 42 | 21 | 73 | ---- | ---- |
| 27.75 | 167.800 | 0.440 | 0.262 | 5.402 | 3.073 | 9 | 34 | 17 | 66 | ---- | ---- |
| 28.00 | 175.400 | 0.593 | 0.338 | 5.452 | 3.097 | 9 | 35 | 18 | 67 | ---- | ---- |
| 28.25 | 169.000 | 0.400 | 0.237 | 5.501 | 3.122 | 9 | 34 | 17 | 66 | ---- | ---- |
| 28.50 | 198.167 | 0.560 | 0.283 | 5.550 | 3.146 | 9 | 40 | 20 | 71 | ---- | ---- |
| 28.75 | 213.100 | 0.755 | 0.354 | 5.599 | 3.171 | 9 | 43 | 22 | 73 | ---- | ---- |
| 29.00 | 194.933 | 0.837 | 0.429 | 5.648 | 3.196 | 9 | 39 | 20 | 70 | ---- | ---- |
| 29.25 | 222.300 | 1.285 | 0.578 | 5.697 | 3.220 | 9 | 44 | 22 | 74 | ---- | ---- |
| 29.50 | 351.033 | 1.137 | 0.324 | 5.747 | 3.246 | 10 | 59 | 30 | 87 | ---- | ---- |
| 29.75 | 282.400 | 1.410 | 0.499 | 5.798 | 3.272 | 10 | 47 | 24 | 80 | ---- | ---- |
| 30.00 | 179.367 | 0.430 | 0.240 | 5.849 | 3.298 | 9 | 36 | 18 | 67 | ---- | ---- |
| 30.25 | 207.250 | 0.805 | 0.388 | 5.898 | 3.323 | 9 | 41 | 21 | 71 | ---- | ---- |
| 30.50 | 248.033 | 1.580 | 0.637 | 5.947 | 3.347 | 9 | 50 | 25 | 76 | ---- | ---- |
| 30.75 | 425.400 | 2.005 | 0.471 | 5.997 | 3.373 | 10 | 71 | 36 | 92 | ---- | ---- |

InSituTech

Engineer: DM HOLLOWAY

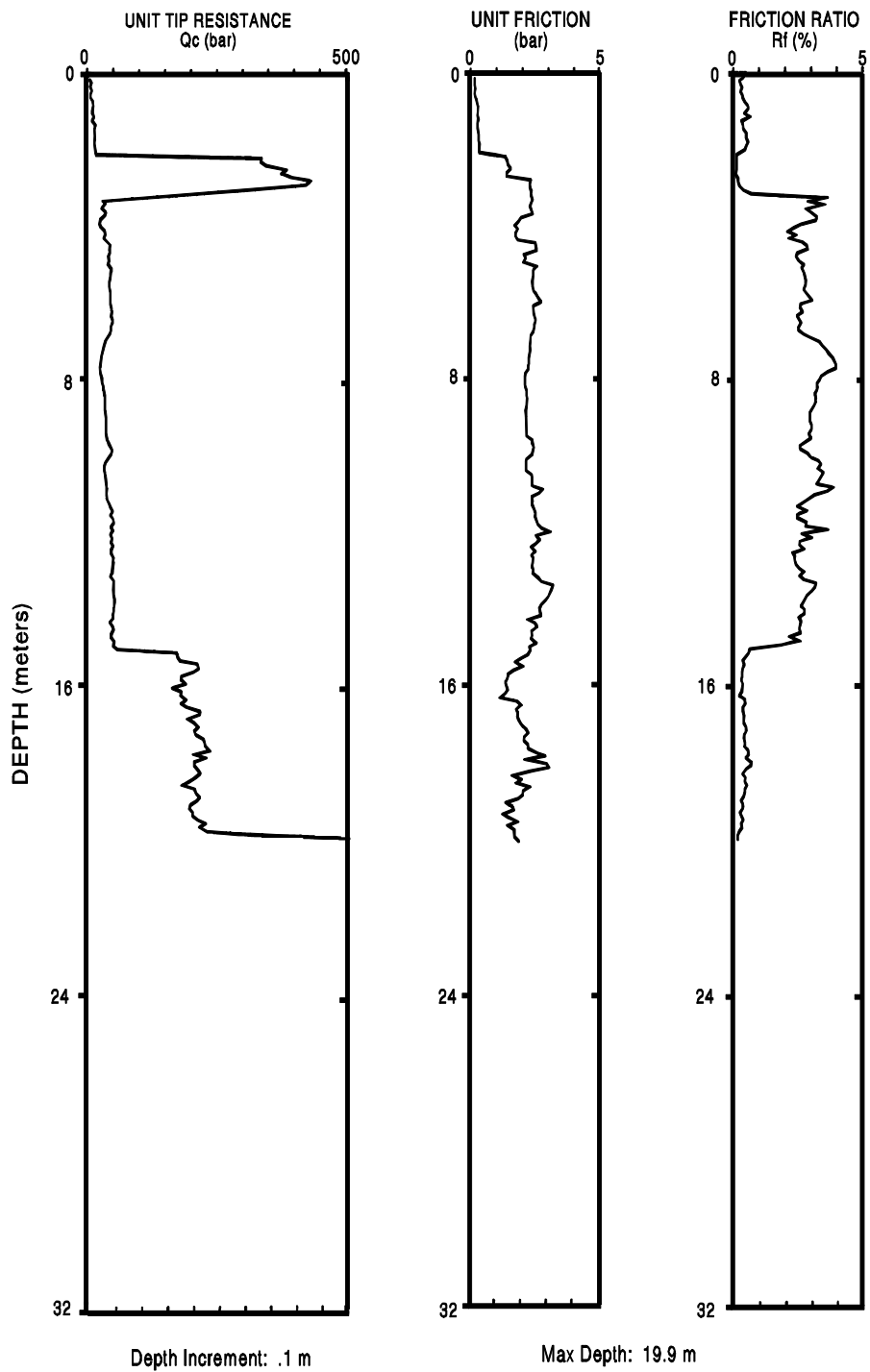
CPT Date: 8/22/89

Page No.: 1 / 1

Location: PEACH FREEWAY, CPT3

Cone Used: 186

Job No.: 93/2/1001



Licensed to: InSituTech Ltd.
Address: 5 del Valle
City: Orinda, CA 94563, U.S.A.

Interpreter Name: Mike Holloway

| | |
|-----------------------|---------------------------------------|
| File Number: 203 | Date: 8/22/89 |
| Operator: DM HOLLOWAY | On Site Location: Peach Freeway CPT-3 |
| Cone Type: 186 | Comment: 93/2/1001 |

SUMMARY SHEET

| | |
|---------------------------------------|-----------|
| 'a' for calculating Q_t : | 0.800 |
| Value for Water Table (in m): | 0.000 |
| Valid Zone Classification based on: | R_f |
| Missing unit weight to start depth: | 15.720 |
| Method for calculating s_u : | N_k |
| Value of the constant N_k : | 15.000 |
| Define Zone 6 for Sand Parameters? | Yes |
| Sand Compressibility for calc D_r : | All sands |

Soil Behavior Type Zone Numbers for R_f Zone and B_q Zone Classification

| | |
|----------------------------------|--------------------------------------|
| Zone #1 = Sensitive fine grained | Zone #7 = Sand with some silt |
| Zone #2 = Organic material | Zone #8 = Fine sand |
| Zone #3 = Clay | Zone #9 = Sand |
| Zone #4 = Silty clay | Zone #10 = Gravelly sand |
| Zone #5 = Clayey silt | Zone #11 = Very stiff fine grained * |
| Zone #6 = Silty sand | Zone #12 = Sand to clayey sand * |

* Overconsolidated and/or cemented

NOTE: For 8011 classification, R_f values > are assumed to be 8.

NOTE: Since U_2 (pore pressure) has not been defined, Q_t cannot be calculated, therefore, the value of Q_t has been made equal to Q_c .

NOTE: ---- means out of range.

| PEACH FREEWAY CPT-3 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------------------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | D _r (%) | s _u (bars) | s _u /EOS (ratio) |
| 0.25 | 12.400 | 0.110 | 0.887 | 0.051 | 0.027 | 6 | 5 | 8 | 60 | ---- | ---- |
| 0.50 | 11.867 | 0.117 | 0.983 | 0.098 | 0.049 | 6 | 5 | 8 | 50 | ---- | ---- |
| 0.75 | 13.900 | 0.155 | 1.115 | 0.145 | 0.072 | 6 | 6 | 9 | 49 | ---- | ---- |
| 1.00 | 12.633 | 0.157 | 1.240 | 0.193 | 0.094 | 6 | 5 | 8 | 42 | ---- | ---- |
| 1.25 | 13.650 | 0.150 | 1.099 | 0.240 | 0.117 | 6 | 5 | 8 | 41 | ---- | ---- |
| 1.50 | 13.600 | 0.137 | 1.005 | 0.287 | 0.140 | 6 | 5 | 8 | 39 | ---- | ---- |
| 1.75 | 12.450 | 0.145 | 1.165 | 0.334 | 0.162 | 6 | 5 | 8 | 34 | ---- | ---- |
| 2.00 | 121.367 | 0.490 | 0.404 | 0.382 | 0.186 | 9 | 24 | 36 | 97 | ---- | ---- |
| 2.25 | 339.750 | 1.265 | 0.372 | 0.432 | 0.211 | 10 | 57 | 86 | 125 | ---- | ---- |
| 2.50 | 384.400 | 1.287 | 0.335 | 0.483 | 0.238 | 10 | 64 | 96 | 127 | ---- | ---- |
| 2.75 | 427.650 | 2.150 | 0.503 | 0.534 | 0.265 | 10 | 71 | 107 | 128 | ---- | ---- |
| 3.00 | 236.633 | 2.180 | 0.921 | 0.585 | 0.290 | 9 | 47 | 71 | 110 | ---- | ---- |
| 3.25 | 34.200 | 2.245 | 6.564 | 0.634 | 0.315 | 3 | 34 | 51 | ---- | 2.238 | 7.108 |
| 3.50 | 35.333 | 2.267 | 6.415 | 0.683 | 0.339 | 3 | 35 | 53 | ---- | 2.311 | 6.805 |
| 3.75 | 27.250 | 1.810 | 6.642 | 0.732 | 0.364 | 3 | 27 | 41 | ---- | 1.768 | 4.856 |
| 4.00 | 33.733 | 1.660 | 4.921 | 0.781 | 0.389 | 3 | 34 | 51 | ---- | 2.198 | 5.653 |
| 4.25 | 34.750 | 1.655 | 4.763 | 0.830 | 0.413 | 4 | 23 | 35 | ---- | 2.262 | 5.472 |
| 4.50 | 41.733 | 2.363 | 5.663 | 0.879 | 0.438 | 3 | 42 | 63 | ---- | 2.725 | 6.221 |
| 4.75 | 38.500 | 1.900 | 4.935 | 0.928 | 0.462 | 3 | 39 | 59 | ---- | 2.506 | 5.416 |
| 5.00 | 40.400 | 2.133 | 5.281 | 0.978 | 0.487 | 3 | 40 | 60 | ---- | 2.629 | 5.396 |
| 5.25 | 40.200 | 2.200 | 5.473 | 1.027 | 0.512 | 3 | 40 | 60 | ---- | 2.613 | 5.104 |
| 5.50 | 39.667 | 2.193 | 5.529 | 1.076 | 0.536 | 3 | 40 | 60 | ---- | 2.573 | 4.798 |
| 5.75 | 41.350 | 2.365 | 5.719 | 1.125 | 0.561 | 3 | 41 | 62 | ---- | 2.682 | 4.782 |
| 6.00 | 42.400 | 2.317 | 5.464 | 1.174 | 0.585 | 3 | 42 | 61 | ---- | 2.748 | 4.695 |
| 6.25 | 43.950 | 2.250 | 5.119 | 1.223 | 0.610 | 3 | 44 | 62 | ---- | 2.848 | 4.669 |
| 6.50 | 44.600 | 2.283 | 5.120 | 1.272 | 0.635 | 3 | 45 | 62 | ---- | 2.889 | 4.551 |
| 6.75 | 41.550 | 2.225 | 5.355 | 1.321 | 0.659 | 3 | 42 | 56 | ---- | 2.682 | 4.068 |
| 7.00 | 32.767 | 2.170 | 6.623 | 1.371 | 0.684 | 3 | 33 | 43 | ---- | 2.093 | 3.061 |
| 7.25 | 29.100 | 2.150 | 7.388 | 1.420 | 0.708 | 3 | 29 | 37 | ---- | 1.845 | 2.605 |
| 7.50 | 26.567 | 2.123 | 7.992 | 1.469 | 0.733 | 3 | 27 | 33 | ---- | 1.673 | 2.283 |

| PEACH FREEWAY CPT-3 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 7.75 | 26.350 | 2.055 | 7.799 | 1.518 | 0.758 | 3 | 26 | 31 | ---- | 1.655 | 2.185 |
| 8.00 | 28.900 | 1.960 | 6.782 | 1.567 | 0.782 | 3 | 29 | 34 | ---- | 1.822 | 2.329 |
| 8.25 | 29.950 | 1.965 | 6.561 | 1.616 | 0.807 | 3 | 30 | 34 | ---- | 1.889 | 2.341 |
| 8.50 | 31.033 | 1.983 | 6.391 | 1.665 | 0.831 | 3 | 31 | 35 | ---- | 1.958 | 2.355 |
| 8.75 | 31.400 | 1.945 | 6.194 | 1.714 | 0.856 | 3 | 31 | 34 | ---- | 1.979 | 2.312 |
| 9.00 | 32.833 | 1.947 | 5.929 | 1.764 | 0.881 | 3 | 33 | 35 | ---- | 2.071 | 2.352 |
| 9.25 | 32.100 | 1.940 | 6.044 | 1.813 | 0.905 | 3 | 32 | 33 | ---- | 2.019 | 2.231 |
| 9.50 | 36.133 | 2.083 | 5.766 | 1.862 | 0.930 | 3 | 36 | 37 | ---- | 2.285 | 2.457 |
| 9.75 | 42.700 | 2.195 | 5.141 | 1.911 | 0.954 | 3 | 43 | 43 | ---- | 2.719 | 2.849 |
| 10.00 | 32.867 | 1.990 | 6.055 | 1.960 | 0.979 | 3 | 33 | 32 | ---- | 2.060 | 2.105 |
| 10.25 | 29.150 | 1.930 | 6.621 | 2.009 | 1.004 | 3 | 29 | 28 | ---- | 1.809 | 1.803 |
| 10.50 | 31.500 | 2.133 | 6.772 | 2.058 | 1.028 | 3 | 32 | 30 | ---- | 1.963 | 1.909 |
| 10.75 | 33.350 | 2.355 | 7.061 | 2.107 | 1.053 | 3 | 33 | 31 | ---- | 2.083 | 1.978 |
| 11.00 | 35.100 | 2.243 | 6.391 | 2.157 | 1.077 | 3 | 35 | 32 | ---- | 2.196 | 2.038 |
| 11.25 | 42.650 | 2.195 | 5.147 | 2.206 | 1.102 | 3 | 43 | 39 | ---- | 2.696 | 2.447 |
| 11.50 | 44.300 | 2.290 | 5.169 | 2.255 | 1.127 | 3 | 44 | 39 | ---- | 2.803 | 2.488 |
| 11.75 | 43.500 | 2.445 | 5.621 | 2.304 | 1.151 | 3 | 44 | 38 | ---- | 2.746 | 2.386 |
| 12.00 | 41.333 | 2.540 | 6.145 | 2.353 | 1.176 | 3 | 41 | 35 | ---- | 2.599 | 2.210 |
| 12.25 | 43.350 | 2.215 | 5.110 | 2.402 | 1.200 | 3 | 43 | 36 | ---- | 2.730 | 2.274 |
| 12.50 | 45.033 | 2.207 | 4.900 | 2.451 | 1.225 | 4 | 30 | 25 | ---- | 2.839 | 2.317 |
| 12.75 | 45.000 | 2.165 | 4.811 | 2.500 | 1.250 | 4 | 30 | 24 | ---- | 2.833 | 2.267 |
| 13.00 | 43.533 | 2.263 | 5.199 | 2.550 | 1.274 | 3 | 44 | 35 | ---- | 2.732 | 2.144 |
| 13.25 | 46.500 | 2.740 | 5.892 | 2.599 | 1.299 | 3 | 47 | 37 | ---- | 2.927 | 2.253 |
| 13.50 | 47.267 | 2.843 | 6.016 | 2.648 | 1.323 | 3 | 47 | 37 | ---- | 2.975 | 2.248 |
| 13.75 | 47.300 | 2.590 | 5.476 | 2.697 | 1.348 | 3 | 47 | 36 | ---- | 2.974 | 2.206 |
| 14.00 | 45.800 | 2.473 | 5.400 | 2.746 | 1.373 | 3 | 46 | 35 | ---- | 2.870 | 2.091 |
| 14.25 | 41.350 | 2.125 | 5.139 | 2.795 | 1.397 | 3 | 41 | 31 | ---- | 2.570 | 1.840 |
| 14.50 | 43.067 | 2.210 | 5.132 | 2.844 | 1.422 | 3 | 43 | 32 | ---- | 2.681 | 1.886 |
| 14.75 | 46.800 | 2.210 | 4.722 | 2.893 | 1.446 | 4 | 31 | 23 | ---- | 2.927 | 2.024 |
| 15.00 | 130.900 | 2.047 | 1.564 | 2.943 | 1.471 | 8 | 33 | 24 | 70 | ---- | ---- |
| 15.25 | 191.200 | 1.615 | 0.845 | 2.992 | 1.496 | 9 | 38 | 27 | 80 | ---- | ---- |

| PEACH FREEWAY CPT-3 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 15.50 | 195.967 | 1.477 | 0.754 | 3.041 | 1.520 | 9 | 39 | 27 | 81 | ---- | ---- |
| 15.75 | 180.900 | 1.155 | 0.638 | 3.090 | 1.545 | 9 | 36 | 25 | 78 | ---- | ---- |
| 16.00 | 170.967 | 1.153 | 0.675 | 3.139 | 1.569 | 9 | 34 | 23 | 76 | ---- | ---- |
| 16.25 | 181.450 | 1.240 | 0.683 | 3.188 | 1.594 | 9 | 36 | 24 | 78 | ---- | ---- |
| 16.50 | 203.867 | 1.610 | 0.790 | 3.237 | 1.619 | 9 | 41 | 27 | 81 | ---- | ---- |
| 16.75 | 194.800 | 1.605 | 0.824 | 3.286 | 1.643 | 9 | 39 | 26 | 80 | ---- | ---- |
| 17.00 | 205.700 | 1.877 | 0.912 | 3.336 | 1.668 | 9 | 41 | 27 | 81 | ---- | ---- |
| 17.25 | 220.650 | 1.840 | 0.834 | 3.385 | 1.692 | 9 | 44 | 28 | 83 | ---- | ---- |
| 17.50 | 219.233 | 2.083 | 0.950 | 3.434 | 1.717 | 9 | 44 | 28 | 82 | ---- | ---- |
| 17.75 | 212.400 | 2.275 | 1.071 | 3.483 | 1.742 | 9 | 42 | 27 | 81 | ---- | ---- |
| 18.00 | 208.333 | 2.527 | 1.213 | 3.532 | 1.766 | 9 | 42 | 26 | 80 | ---- | ---- |
| 18.25 | 197.400 | 1.555 | 0.788 | 3.581 | 1.791 | 9 | 39 | 24 | 79 | ---- | ---- |
| 18.50 | 194.833 | 1.790 | 0.919 | 3.630 | 1.815 | 9 | 39 | 24 | 78 | ---- | ---- |
| 18.75 | 209.850 | 1.705 | 0.812 | 3.679 | 1.840 | 9 | 42 | 25 | 80 | ---- | ---- |
| 19.00 | 194.733 | 1.310 | 0.673 | 3.729 | 1.865 | 9 | 39 | 23 | 78 | ---- | ---- |
| 19.25 | 204.100 | 1.125 | 0.551 | 3.778 | 1.889 | 9 | 41 | 24 | 79 | ---- | ---- |
| 19.50 | 217.450 | 1.390 | 0.639 | 3.827 | 1.914 | 9 | 43 | 25 | 81 | ---- | ---- |
| 19.75 | 273.100 | 1.450 | 0.531 | 3.877 | 1.939 | 10 | 46 | 27 | 87 | ---- | ---- |
| 20.00 | 505.050 | 1.545 | 0.306 | 3.928 | 1.966 | 10 | 84 | 48 | ---- | ---- | ---- |

InSituTech

Engineer: DM HOLLOWAY

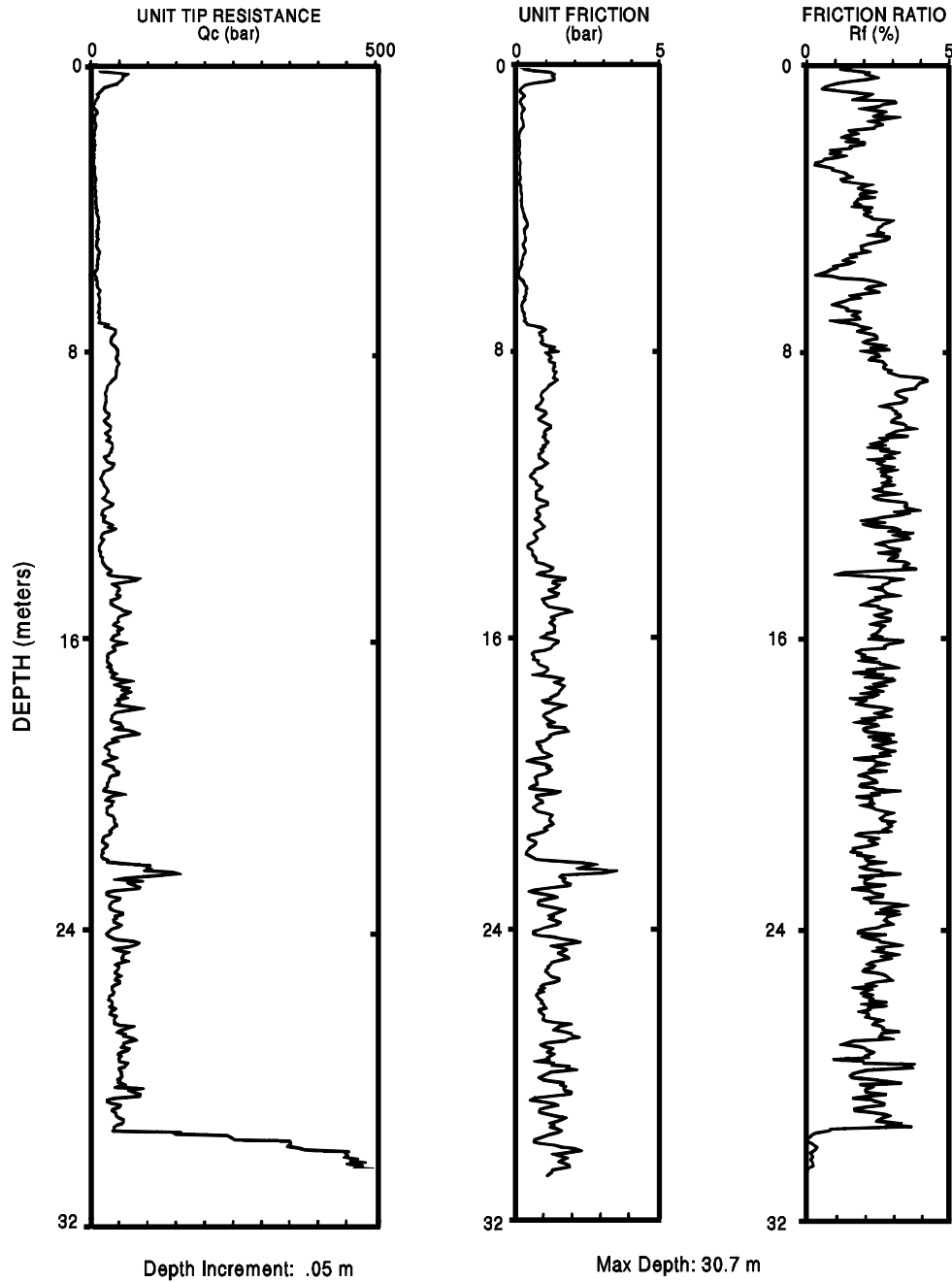
CPT Date: 8/19/89

Page No.: 1 / 1

Location: PEACH FREEWAY, CPT4

Cone Used: 186

Job No.: 93/2/1001



Licensed to: InSituTech Ltd.
Address: 5 del Valle
City: Orinda, CA 94563, U.S.A.

Interpreter Name: Mike Holloway

| | |
|-----------------------|---------------------------------------|
| File Number: 8 0 | Date: 8/19/89 |
| Operator: DM HOLLOWAY | On Site Location: Peach Freeway CPT-4 |
| Cone Type: 186 | Comment: 93/2/1001 |

SUMMARY SHEET

| | |
|---------------------------------------|-----------|
| 'a' for calculating Q_t : | 0.800 |
| Value for Water Table (in m): | 1.000 |
| Valid Zone Classification based on: | R_f |
| Missing unit weight to start depth: | 15.720 |
| Method for calculating s_u : | N_k |
| Value of the constant N_k : | 15.000 |
| Define Zone 6 for Sand Parameters? | Yes |
| Sand Compressibility for calc D_r : | All sands |

Soil Behavior Type Zone Numbers for R_f Zone and B_q Zone Classification

| | |
|----------------------------------|--------------------------------------|
| Zone #1 = Sensitive fine grained | Zone #7 = Sand with some silt |
| Zone #2 = Organic material | Zone #8 = Fine sand |
| Zone #3 = Clay | Zone #9 = Sand |
| Zone #4 = Silty clay | Zone #10 = Gravelly sand |
| Zone #5 = Clayey silt | Zone #11 = Very stiff fine grained * |
| Zone #6 = Silty sand | Zone #12 = Sand to clayey sand * |

* Overconsolidated and/or cemented

NOTE: For soil classification, R_f values > 8 are assumed to be 8.

NOTE: Since U_2 (pore pressure) has not been defined, Q_t cannot be calculated, therefore, the value of Q_t has been made equal to Q_c .

NOTE: ---- means out of range.

| PEACH FREEWAY CPT-4 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------------------|--------------------------|--------------------------------|
| Depth (Meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | D _r (%) | s _u (bars) | s _u /EOS (ratio) |
| 0.25 | 56.040 | 2.612 | 4.661 | 0.054 | 0.054 | 4 | 37 | 56 | ---- | 3.732 | 69.071 |
| 0.50 | 29.040 | 0.964 | 3.320 | 0.103 | 0.103 | 5 | 15 | 23 | ---- | 1.929 | 18.700 |
| 0.75 | 12.560 | 0.417 | 3.320 | 0.151 | 0.151 | 4 | 8 | 12 | ---- | 0.827 | 5.468 |
| 1.00 | 6.480 | 0.345 | 5.327 | 0.198 | 0.198 | 3 | 6 | 9 | ---- | 0.419 | 2.110 |
| 1.25 | 8.820 | 0.463 | 5.252 | 0.246 | 0.221 | 3 | 9 | 14 | ---- | 0.572 | 2.586 |
| 1.50 | 8.240 | 0.457 | 5.544 | 0.293 | 0.244 | 3 | 8 | 12 | ---- | 0.530 | 1.174 |
| 1.75 | 6.900 | 0.325 | 4.713 | 0.340 | 0.266 | 3 | 7 | 11 | ---- | 0.437 | 1.642 |
| 2.00 | 5.960 | 0.208 | 3.487 | 0.387 | 0.289 | 3 | 6 | 9 | ---- | 0.372 | 1.286 |
| 2.25 | 5.160 | 0.189 | 3.663 | 0.434 | 0.312 | 3 | 5 | 8 | ---- | 0.315 | 1.011 |
| 2.50 | 4.520 | 0.110 | 2.442 | 0.481 | 0.334 | 3 | 5 | 8 | ---- | 0.269 | 0.806 |
| 2.75 | 5.560 | 0.085 | 1.536 | 0.527 | 0.355 | 1 | 3 | 5 | ---- | 0.336 | 0.946 |
| 3.00 | 6.720 | 0.208 | 3.098 | 0.572 | 0.376 | 3 | 7 | 11 | ---- | 0.410 | 1.091 |
| 3.25 | 6.780 | 0.258 | 3.808 | 0.619 | 0.398 | 3 | 7 | 11 | ---- | 0.411 | 1.032 |
| 3.50 | 7.680 | 0.336 | 4.370 | 0.666 | 0.421 | 3 | 8 | 12 | ---- | 0.468 | 1.111 |
| 3.75 | 7.900 | 0.329 | 4.162 | 0.713 | 0.443 | 3 | 8 | 12 | ---- | 0.479 | 1.080 |
| 4.00 | 10.220 | 0.459 | 4.495 | 0.761 | 0.467 | 3 | 10 | 15 | ---- | 0.631 | 1.350 |
| 4.25 | 12.000 | 0.648 | 5.397 | 0.810 | 0.492 | 3 | 12 | 18 | ---- | 0.746 | 1.517 |
| 4.50 | 10.800 | 0.599 | 5.544 | 0.860 | 0.516 | 3 | 11 | 17 | ---- | 0.663 | 1.284 |
| 4.75 | 10.040 | 0.577 | 5.745 | 0.909 | 0.541 | 3 | 10 | 15 | ---- | 0.609 | 1.126 |
| 5.00 | 11.100 | 0.495 | 4.456 | 0.958 | 0.565 | 3 | 11 | 17 | ---- | 0.676 | 1.196 |
| 5.25 | 10.840 | 0.421 | 3.880 | 1.007 | 0.590 | 3 | 11 | 16 | ---- | 0.656 | 1.111 |
| 5.50 | 9.040 | 0.268 | 2.962 | 1.055 | 0.614 | 4 | 6 | 8 | ---- | 0.532 | 0.867 |
| 5.75 | 6.360 | 0.108 | 1.701 | 1.102 | 0.636 | 4 | 4 | 5 | ---- | 0.351 | 0.551 |
| 6.00 | 9.740 | 0.469 | 4.811 | 1.149 | 0.659 | 3 | 10 | 13 | ---- | 0.573 | 0.869 |
| 6.25 | 13.120 | 0.637 | 4.852 | 1.198 | 0.683 | 3 | 13 | 17 | ---- | 0.795 | 1.165 |
| 6.50 | 13.420 | 0.448 | 3.337 | 1.246 | 0.706 | 4 | 9 | 11 | ---- | 0.812 | 1.149 |
| 6.75 | 13.160 | 0.411 | 3.125 | 1.293 | 0.729 | 4 | 9 | 11 | ---- | 0.791 | 1.086 |
| 7.00 | 16.120 | 0.537 | 3.330 | 1.340 | 0.751 | 4 | 11 | 13 | ---- | 0.985 | 1.311 |
| 7.25 | 35.860 | 1.482 | 4.133 | 1.388 | 0.775 | 4 | 24 | 28 | ---- | 2.298 | 2.965 |
| 7.50 | 34.820 | 1.692 | 4.859 | 1.437 | 0.800 | 3 | 35 | 40 | ---- | 2.226 | 2.783 |

| PEACH FREEWAY CPT-4 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 7.75 | 41.900 | 2.076 | 4.955 | 1.486 | 0.824 | 3 | 42 | 47 | ---- | 2.694 | 3.269 |
| 8.00 | 44.460 | 2.370 | 5.331 | 1.535 | 0.849 | 3 | 44 | 48 | ---- | 2.862 | 3.371 |
| 8.25 | 45.780 | 2.494 | 5.448 | 1.585 | 0.873 | 3 | 46 | 49 | ---- | 2.946 | 3.373 |
| 8.50 | 42.960 | 2.622 | 6.103 | 1.634 | 0.898 | 3 | 43 | 45 | ---- | 2.755 | 3.068 |
| 8.75 | 31.400 | 2.582 | 8.223 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 9.00 | 25.280 | 1.944 | 7.690 | 1.683 | 0.898 | 3 | 25 | 26 | ---- | 1.573 | 1.752 |
| 9.25 | 24.700 | 1.738 | 7.036 | 1.732 | 0.923 | 3 | 25 | 26 | ---- | 1.531 | 1.660 |
| 9.50 | 24.920 | 1.578 | 6.332 | 1.781 | 0.947 | 3 | 25 | 25 | ---- | 1.543 | 1.628 |
| 9.75 | 25.980 | 1.758 | 6.767 | 1.830 | 0.972 | 3 | 26 | 26 | ---- | 1.610 | 1.657 |
| 10.00 | 31.420 | 2.184 | 6.951 | 1.879 | 0.996 | 3 | 31 | 30 | ---- | 1.969 | 1.976 |
| 10.25 | 28.120 | 1.938 | 6.892 | 1.928 | 0.021 | 3 | 28 | 27 | ---- | 1.746 | 1.710 |
| 10.50 | 35.760 | 2.010 | 5.621 | 1.978 | 0.046 | 3 | 36 | 34 | ---- | 2.252 | 2.154 |
| 10.75 | 28.640 | 1.676 | 5.852 | 2.027 | 0.070 | 3 | 29 | 27 | ---- | 1.774 | 1.658 |
| 11.00 | 33.540 | 1.884 | 5.617 | 2.076 | 0.095 | 3 | 34 | 31 | ---- | 2.098 | 1.916 |
| 11.25 | 22.160 | 1.320 | 5.957 | 2.125 | 0.119 | 3 | 22 | 20 | ---- | 1.336 | 1.193 |
| 11.50 | 19.440 | 1.182 | 6.080 | 2.174 | 0.144 | 3 | 19 | 17 | ---- | 1.151 | 1.006 |
| 11.75 | 27.160 | 1.564 | 5.758 | 2.223 | 0.169 | 3 | 27 | 23 | ---- | 1.662 | 1.423 |
| 12.00 | 27.240 | 1.530 | 5.617 | 2.272 | 0.193 | 3 | 27 | 23 | ---- | 1.665 | 1.395 |
| 12.25 | 25.480 | 1.788 | 7.017 | 2.321 | 0.218 | 3 | 25 | 21 | ---- | 1.544 | 1.268 |
| 12.50 | 21.400 | 1.464 | 6.841 | 2.371 | 0.242 | 3 | 21 | 17 | ---- | 1.269 | 1.021 |
| 12.75 | 34.800 | 1.734 | 4.983 | 2.420 | 0.267 | 3 | 35 | 28 | ---- | 2.159 | 1.704 |
| 13.00 | 19.540 | 1.338 | 6.847 | 2.469 | 0.292 | 3 | 20 | 16 | ---- | 1.138 | 0.881 |
| 13.25 | 16.000 | 1.062 | 6.638 | 2.518 | 0.316 | 3 | 16 | 13 | ---- | 0.899 | 0.683 |
| 13.50 | 16.300 | 1.030 | 6.319 | 2.567 | 1.341 | 3 | 16 | 12 | ---- | 0.916 | 0.683 |
| 13.75 | 21.620 | 1.442 | 6.670 | 2.616 | 1.365 | 3 | 22 | 17 | ---- | 1.267 | 0.928 |
| 14.00 | 31.480 | 2.244 | 7.128 | 2.665 | 1.390 | 3 | 31 | 23 | ---- | 1.921 | 1.382 |
| 14.25 | 61.400 | 2.602 | 4.238 | 2.714 | 1.415 | 5 | 31 | 23 | ---- | 3.912 | 2.766 |
| 14.50 | 45.740 | 2.640 | 5.772 | 2.764 | 1.439 | 3 | 46 | 34 | ---- | 2.865 | 1.991 |
| 14.75 | 41.460 | 2.466 | 5.948 | 2.813 | 1.464 | 3 | 41 | 30 | ---- | 2.576 | 1.760 |
| 15.00 | 45.200 | 2.240 | 4.956 | 2.862 | 1.488 | 4 | 30 | 21 | ---- | 2.823 | 1.896 |
| 15.25 | 54.840 | 3.188 | 5.813 | 2.911 | 1.513 | 3 | 55 | 39 | ---- | 3.462 | 2.288 |

| PEACH FREEWAY CPT-4 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 15.50 | 44.960 | 2.530 | 5.627 | 2.960 | 1.538 | 3 | 45 | 31 | ---- | 2.800 | 1.821 |
| 15.75 | 43.120 | 2.408 | 5.584 | 3.009 | 1.562 | 3 | 43 | 30 | ---- | 2.674 | 1.712 |
| 16.00 | 42.380 | 2.494 | 5.885 | 3.058 | 1.587 | 3 | 42 | 28 | ---- | 2.621 | 1.652 |
| 16.25 | 33.980 | 1.820 | 5.356 | 3.107 | 1.611 | 3 | 34 | 23 | ---- | 2.058 | 1.277 |
| 16.50 | 29.100 | 1.292 | 4.440 | 3.157 | 1.636 | 4 | 19 | 13 | ---- | 1.730 | 1.057 |
| 16.75 | 34.500 | 1.968 | 5.704 | 3.206 | 1.661 | 3 | 35 | 23 | ---- | 2.086 | 1.256 |
| 17.00 | 45.820 | 2.352 | 5.133 | 3.255 | 1.685 | 3 | 46 | 30 | ---- | 2.838 | 1.684 |
| 17.25 | 55.860 | 3.070 | 5.496 | 3.304 | 1.710 | 3 | 56 | 36 | ---- | 3.504 | 2.049 |
| 17.50 | 53.160 | 2.690 | 5.060 | 3.353 | 1.734 | 4 | 35 | 22 | ---- | 3.320 | 1.914 |
| 17.75 | 62.300 | 2.602 | 4.177 | 3.402 | 1.759 | 5 | 31 | 19 | ---- | 3.927 | 2.232 |
| 18.00 | 37.040 | 2.150 | 5.805 | 3.451 | 1.784 | 3 | 37 | 23 | ---- | 2.239 | 1.255 |
| 18.25 | 46.560 | 2.264 | 4.863 | 3.500 | 1.808 | 4 | 31 | 19 | ---- | 2.871 | 1.588 |
| 18.50 | 64.020 | 3.082 | 4.814 | 3.550 | 1.833 | 4 | 43 | 26 | ---- | 4.031 | 2.199 |
| 18.75 | 32.000 | 1.844 | 5.763 | 3.599 | 1.857 | 3 | 32 | 19 | ---- | 1.893 | 1.019 |
| 19.00 | 30.440 | 1.768 | 5.808 | 3.648 | 1.882 | 3 | 30 | 18 | ---- | 1.786 | 0.949 |
| 19.25 | 28.940 | 1.534 | 5.301 | 3.697 | 1.907 | 3 | 29 | 17 | ---- | 1.683 | 0.883 |
| 19.50 | 42.220 | 2.222 | 5.263 | 3.746 | 1.931 | 3 | 42 | 24 | ---- | 2.565 | 1.328 |
| 19.75 | 30.340 | 1.482 | 4.885 | 3.795 | 1.956 | 3 | 30 | 17 | ---- | 1.770 | 0.905 |
| 20.00 | 27.260 | 1.326 | 4.864 | 3.844 | 1.980 | 3 | 27 | 15 | ---- | 1.561 | 0.788 |
| 20.25 | 36.500 | 1.944 | 5.326 | 3.893 | 2.005 | 3 | 37 | 21 | ---- | 2.174 | 1.084 |
| 20.50 | 30.500 | 1.482 | 4.859 | 3.943 | 2.030 | 3 | 31 | 17 | ---- | 1.770 | 0.872 |
| 20.75 | 33.600 | 1.936 | 5.762 | 3.992 | 2.054 | 3 | 34 | 19 | ---- | 1.974 | 0.961 |
| 21.00 | 39.780 | 2.348 | 5.902 | 4.041 | 2.079 | 3 | 40 | 22 | ---- | 2.383 | 1.146 |
| 21.25 | 27.360 | 1.592 | 5.819 | 4.090 | 2.103 | 3 | 27 | 15 | ---- | 1.551 | 0.738 |
| 21.50 | 22.380 | 1.064 | 4.754 | 4.139 | 2.128 | 3 | 22 | 12 | ---- | 1.216 | 0.571 |
| 21.75 | 18.540 | 0.782 | 4.218 | 4.188 | 2.153 | 3 | 19 | 10 | ---- | 0.957 | 0.444 |
| 22.00 | 46.920 | 2.124 | 4.527 | 4.237 | 2.177 | 4 | 31 | 16 | ---- | 2.846 | 1.307 |
| 22.25 | 116.780 | 5.476 | 4.689 | 4.288 | 2.204 | 11 | 117 | 62 | ---- | ---- | ---- |
| 22.50 | 71.180 | 3.778 | 5.308 | 4.341 | 2.232 | 11 | 71 | 37 | ---- | ---- | ---- |
| 22.75 | 61.100 | 2.856 | 4.674 | 4.393 | 2.259 | 4 | 41 | 21 | ---- | 3.780 | 1.674 |
| 23.00 | 38.180 | 1.962 | 5.139 | 4.442 | 2.284 | 3 | 38 | 19 | ---- | 2.249 | 0.985 |

| PEACH FREEWAY CPT-4 | | | | | | | | | | | |
|---------------------|-------------------------------------|-------------------------------------|-----------------------|-------------------------|--------------------------|---------------------------------|----------------------|-----------------------|-----------|--------------------------|--------------------------------|
| Depth (meter) | q _c Average (bars) | f _s Average (bars) | R _f (%) | OS Average (bars) | EOS Average (bars) | R _f Zone (zone #) | SPT N (blow/.3 m) | SPT N1 (blow/.3 m) | Dr (%) | s _u (bars) | s _u /EOS (ratio) |
| 23.25 | 33.420 | 1.898 | 5.679 | 4.491 | 2.308 | 3 | 33 | 17 | ---- | 1.929 | 0.836 |
| 23.50 | 46.080 | 2.788 | 6.050 | 4.540 | 2.333 | 3 | 46 | 23 | ---- | 2.769 | 1.187 |
| 23.75 | 43.620 | 2.644 | 6.061 | 4.589 | 2.357 | 3 | 44 | 22 | ---- | 2.602 | 1.104 |
| 24.00 | 46.060 | 1.416 | 4.711 | 4.638 | 2.382 | 3 | 30 | 15 | ---- | 1.695 | 0.712 |
| 24.25 | 68.280 | 3.522 | 5.158 | 4.689 | 2.408 | 11 | 68 | 34 | ---- | ---- | ---- |
| 24.50 | 51.380 | 3.012 | 5.862 | 4.740 | 2.435 | 3 | 51 | 26 | ---- | 3.109 | 1.277 |
| 24.75 | 51.620 | 3.144 | 6.091 | 4.790 | 2.460 | 3 | 52 | 26 | ---- | 3.122 | 1.269 |
| 25.00 | 39.188 | 1.978 | 5.046 | 4.839 | 2.484 | 3 | 39 | 20 | ---- | 2.290 | 0.922 |
| 25.25 | 36.660 | 1.674 | 4.566 | 4.888 | 2.509 | 4 | 24 | 12 | ---- | 2.118 | 0.844 |
| 25.50 | 51.300 | 2.602 | 5.072 | 4.937 | 2.533 | 4 | 34 | 17 | ---- | 3.091 | 1.220 |
| 25.75 | 54.840 | 3.222 | 5.875 | 4.986 | 2.558 | 3 | 55 | 28 | ---- | 3.324 | 1.299 |
| 26.00 | 60.740 | 2.974 | 4.896 | 5.035 | 2.583 | 4 | 40 | 20 | ---- | 3.714 | 1.438 |
| 26.25 | 54.660 | 2.224 | 4.069 | 5.084 | 2.607 | 5 | 27 | 14 | ---- | 3.305 | 1.268 |
| 26.50 | 52.220 | 2.088 | 3.998 | 5.133 | 2.632 | 5 | 26 | 13 | ---- | 3.139 | 1.193 |
| 26.75 | 50.380 | 3.148 | 6.249 | 5.183 | 2.656 | 3 | 50 | 25 | ---- | 3.013 | 1.134 |
| 27.00 | 48.320 | 1.854 | 3.837 | 5.232 | 2.681 | 5 | 24 | 12 | ---- | 2.873 | 1.071 |
| 27.25 | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ---- |
| 27.50 | 61.950 | 3.197 | 5.161 | 5.283 | 2.683 | 11 | 62 | 31 | ---- | ---- | ---- |
| 27.75 | 61.100 | 2.856 | 4.674 | 5.334 | 2.710 | 4 | 41 | 21 | ---- | 3.718 | 1.372 |
| 28.00 | 0.180 | 1.962 | 5.139 | 5.383 | 2.734 | 3 | 38 | 19 | ---- | 2.186 | 0.800 |
| 28.25 | 38.420 | 1.898 | 4.582 | 5.432 | 2.759 | 4 | 28 | 14 | ---- | 2.399 | 0.870 |
| 28.50 | 41.080 | 2.788 | 5.799 | 5.481 | 2.783 | 3 | 48 | 24 | ---- | 2.840 | 1.020 |
| 28.75 | 121.620 | 2.644 | 2.174 | 5.529 | 2.807 | 7 | 41 | 21 | 58 | ---- | ---- |
| 29.00 | 306.060 | 1.416 | 0.463 | 5.578 | 2.832 | 10 | 51 | 26 | 85 | ---- | ---- |
| 29.25 | 394.280 | 3.522 | 0.893 | 5.629 | 2.857 | 9 | 79 | 40 | 92 | ---- | ---- |
| 29.50 | 457.380 | 3.012 | 0.659 | 5.679 | 2.883 | 10 | 76 | 38 | 96 | ---- | ---- |
| 29.75 | 495.620 | 3.144 | 0.634 | 5.730 | 2.909 | 10 | 83 | 42 | 98 | ---- | ---- |
| 30.00 | 699.567 | 2.203 | 0.315 | 5.781 | 2.936 | 10 | 117 | 59 | ---- | ---- | ---- |

APPENDIX F

Peach Freeway Example Problem Calculations

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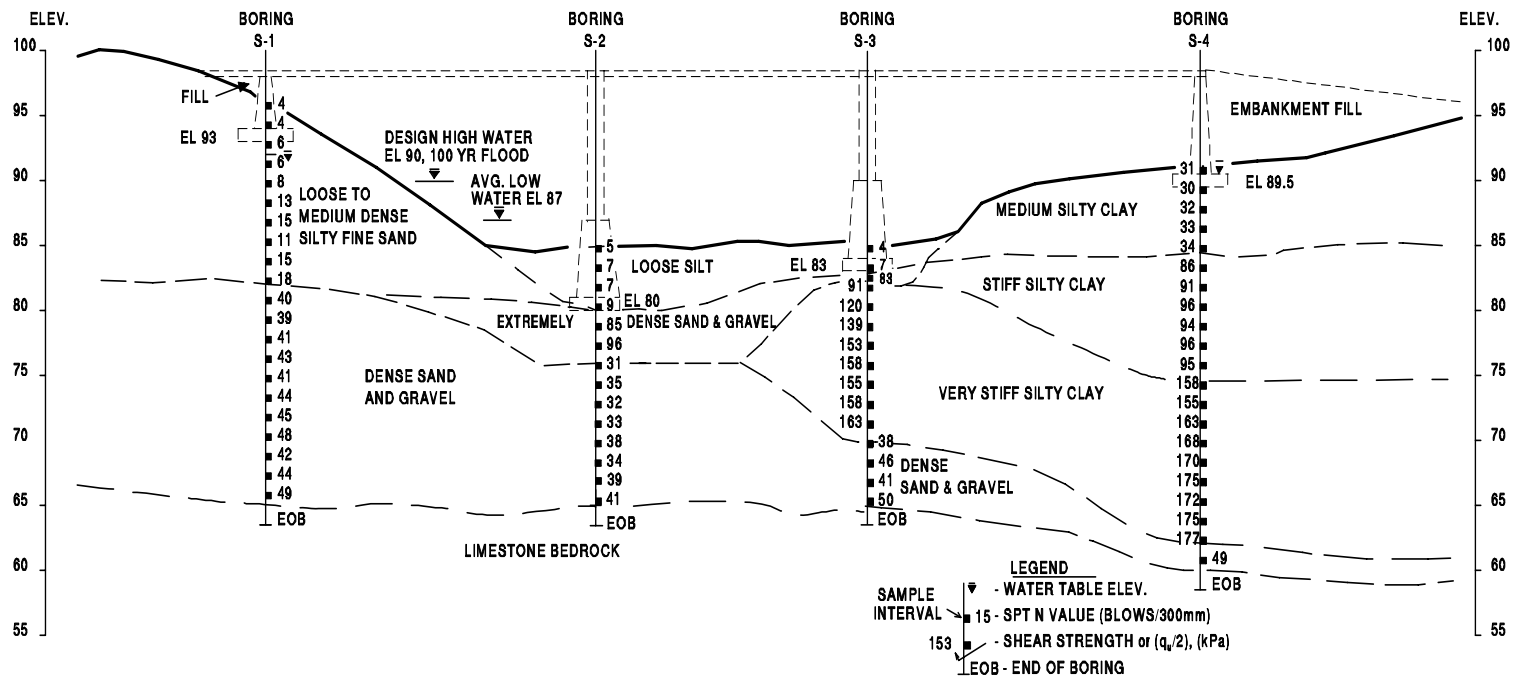
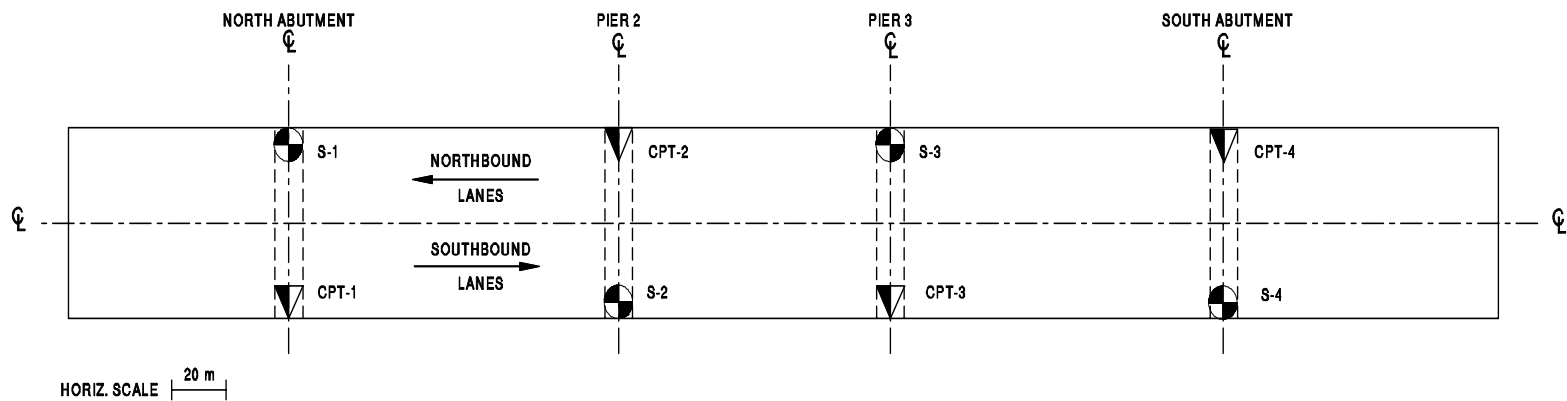
F.1 INTRODUCTION

The various design methods presented in Chapter 9 of the manual will be illustrated by applying these methods to foundation design problems for the Peach Freeway Bridge over Dismal Creek. In many real design problems, additional analyses beyond those presented in these example problems would be used to complete the actual foundation design. For example, group lateral load capacity evaluations are not completed at each substructure location in these example problems.

The Peach Freeway Bridge over Dismal Creek will be a three span structure supported at North and South Abutments and interior piers, Pier 2 and Pier 3. One soil boring and one cone penetration test were performed for each substructure location. The subsurface exploration results were included in Appendix E of this manual. The cone penetration test at Pier 2, CPT-2, encountered shallow refusal and therefore, a log of CPT-2 is not included in Appendix E. The subsurface profile developed from the subsurface exploration and laboratory testing program results is presented in Figure F.1.

The "bridge division" has estimated that the maximum compression loads per substructure unit will be 12,600 kN. Each substructure location will be supported on a pile group having three rows of eight piles per row. For abutment pile groups, fewer piles are often required in the middle and rear rows as compared to the front row. The maximum design compression load on any pile will be 890 kN. Lateral loads will range from 600 kN at the interior piers to 900 kN at the abutments with a maximum lateral load per pile of 40 kN. The maximum uplift load on a pile group will be 1,800 kN with a maximum uplift load per pile of 100 kN. Maximum pile group settlements less than 25 mm are required under the compression loads and horizontal deflections of up to 10 mm are permissible under lateral loading. The pile location plan for each substructure location is presented in Figure F.2.

Initial design estimates and local availability of materials indicate square, precast, prestressed concrete piles will probably be the most cost effective foundation type. This pile type should work well at the abutments because they will develop significant load support through both shaft and toe resistance. However, at the interior piers, the driveability of these displacement piles through the extremely dense sand and gravel layer will need to be carefully evaluated. A low displacement pile may be necessary at the interior piers to meet pile penetration requirements.



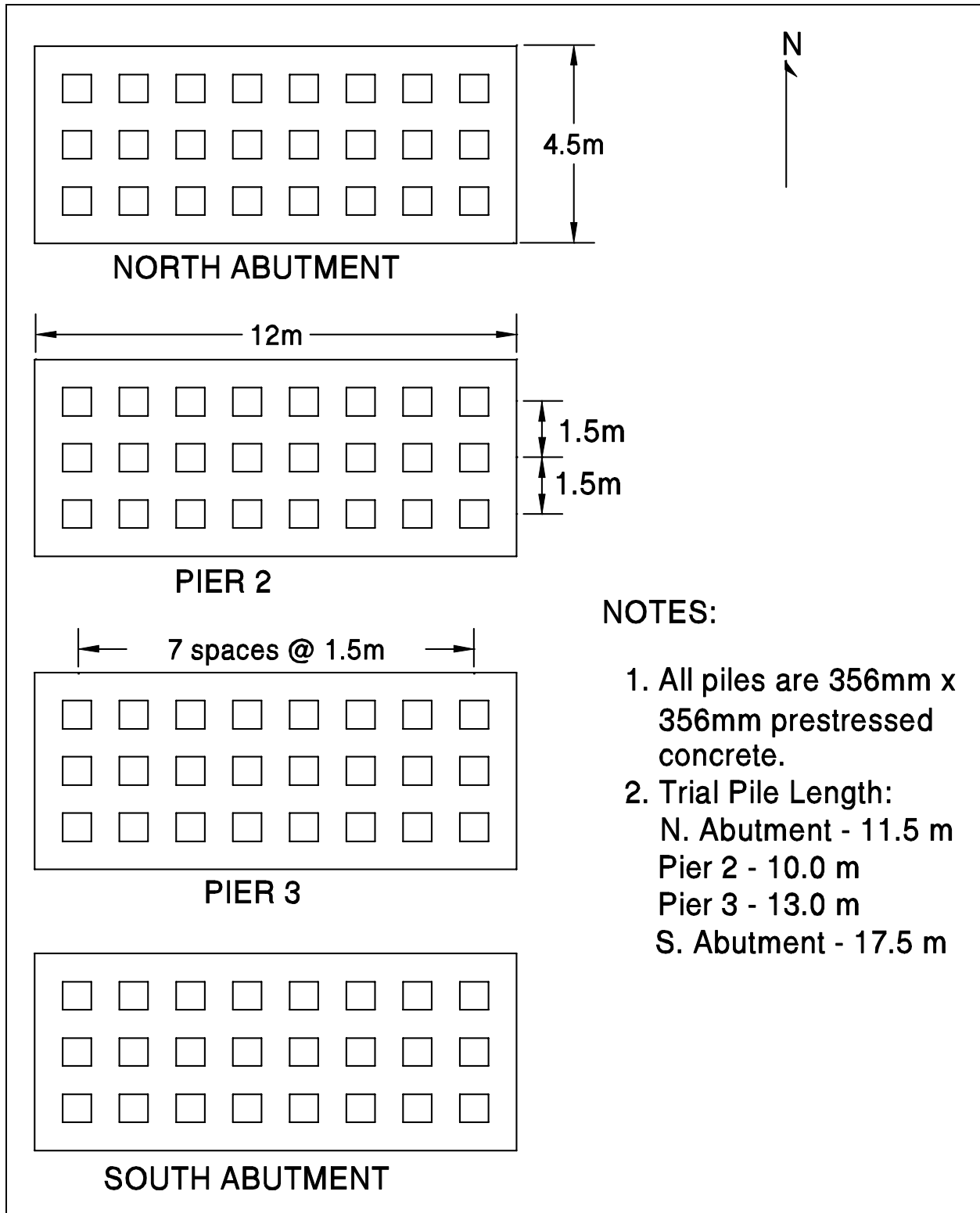


Figure F.2 Pile Foundation Plan

Section F.2 of this Appendix presents static capacity calculations using the applicable methods at each substructure location. Pile group settlement computations for each substructure location are provided in Section F.3. Section F.4 presents lateral pile capacity analyses performed for the North Abutment using both the Brom's Method and the LPILE program. Lateral capacity analysis for Pier 2, Pier 3 and the South Abutment using the LPILE program are also presented. Group uplift computation at each substructure location following AASHTO code are presented in Section F.5. Last, special design considerations of negative shaft resistance and lateral squeeze are presented for the South Abutment in Sections F.6 and F.7, respectively.

F.2 STATIC AXIAL PILE CAPACITY CALCULATIONS

The design load per pile group will be 12,600 kN. The bridge office has determined that the maximum axial design load to be imposed on a single pile will be 890 kN. (At the abutments, the design load on piles in the front row will be 890 kN, whereas the middle and rear rows of piles will have smaller design loads). Construction control will be based on static load test results and a factor of safety of 2.0 will be used on the design load. Therefore, static capacity calculations will be used to evaluate the required pile lengths for a 1780 kN ultimate pile capacity at each substructure location.

Several static axial capacity calculations and computer solutions will be used to determine the required pile length at each substructure unit (*i.e.*, North Abutment, Pier 2, Pier 3, and South Abutment). At Pier 2 location, the effect of scour on the static axial capacity will also be calculated. At all substructure location, pile group capacity will be evaluated. At the South Abutment location, the ultimate pile group capacity against block failure will be calculated and compared with the ultimate pile group capacity from the sum of the ultimate capacities of the individual piles.

The static capacity calculations for each substructure location are presented in the following sections.

F.2.1 North Abutment - Soil Boring S-1 (Cohesionless Soil)

F.2.1.1 Static Axial Pile Capacity Calculations by Meyerhof SPT Method

For the soil profile interpreted from Soil Boring S-1 shown in Figure F.3, perform a Meyerhof method pile capacity calculation for an embedded length of 11.5 meters. The pile top is 3 meters below the existing ground surface. The step-by-step method outlined in Section 9.7.1.1a should be followed.

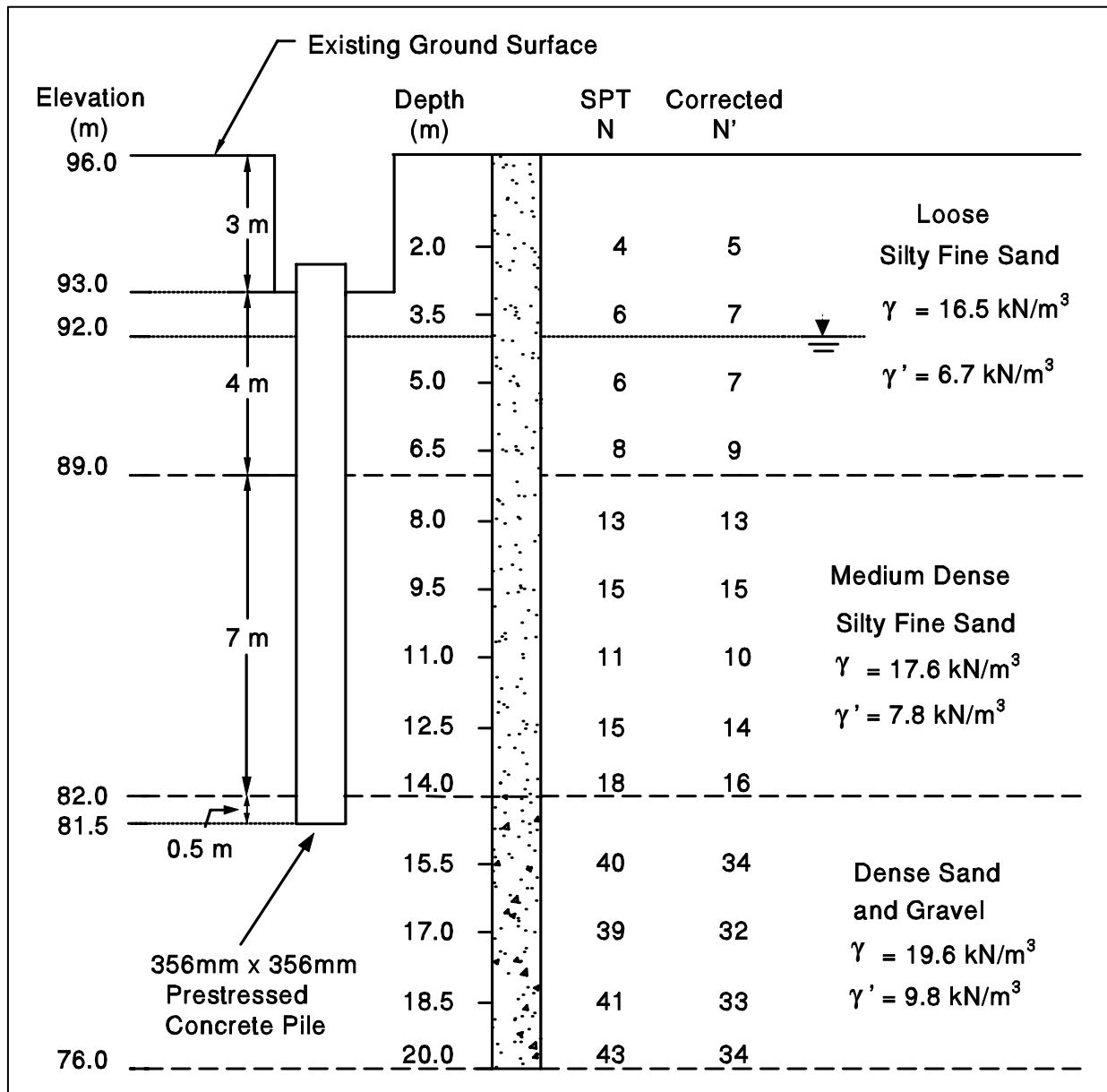


Figure F.3 Interpreted Soil Profile from Soil Boring S-1 at the North Abutment

STEP 1 Correct SPT field N values for overburden pressure.

Effective overburden pressures, p_o , are needed to correct SPT field N values. The method for calculating the effective overburden pressure is explained in Section 9.4. First, the soil profile should be delineated into layers based on soil type and density indicated by the corrected SPT N' value. However, since the corrected SPT N' value has yet to be calculated, the SPT field N' value should be used to estimate soil unit weights. Re-adjust the soil unit weight (if necessary) after the corrected SPT N' value has been obtained. The empirical correlation between soil unit weight and corrected SPT N' value is presented in Table 4-6. The effective overburden pressure diagram is presented below in Figure F.4.

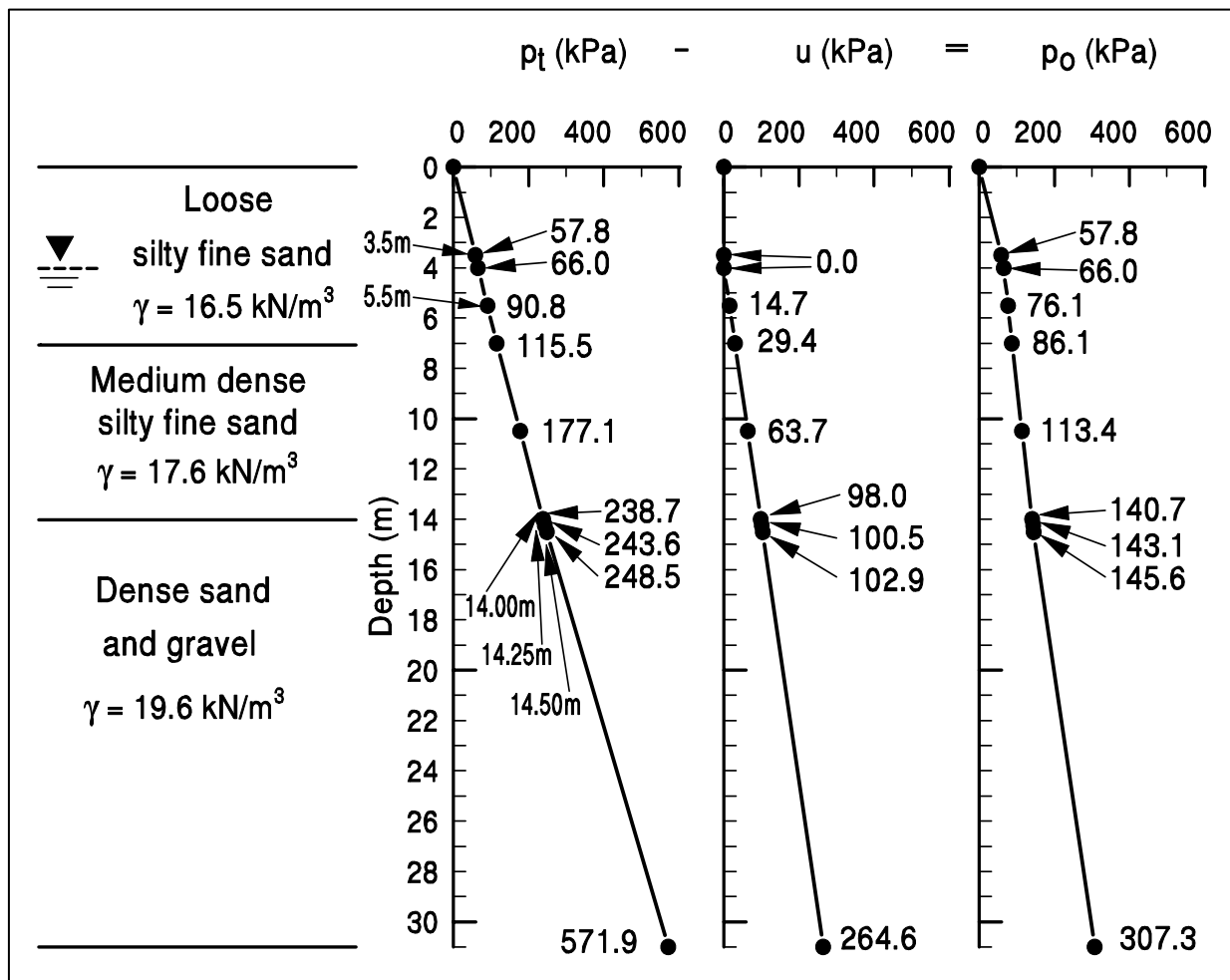


Figure F.4 Effective Overburden Pressure Diagram – North Abutment

STEP 1 (continued)

Use correction factors from Figure 4.6 (Chapter 4) to obtain corrected SPT N' values.

| Depth (m) | p _o (kPa) | Field SPT N value | Correction Factor | Corrected SPT N' (Field SPT N x Correction Factor) |
|--------------|-------------------------|----------------------|----------------------|--|
| 0.8 | 13.2 | 4 | 1.65 | 7 |
| 2.0 | 33.0 | 4 | 1.35 | 5 |
| 3.5 | 57.8 | 6 | 1.17 | 7 |
| 5.0 | 72.7 | 6 | 1.12 | 7 |
| 6.5 | 82.8 | 8 | 1.08 | 9 |
| 8.0 | 93.9 | 13 | 1.02 | 13 |
| 9.5 | 105.6 | 15 | 0.98 | 15 |
| 11.0 | 117.3 | 11 | 0.95 | 10 |
| 12.5 | 129.0 | 15 | 0.91 | 14 |
| 14.0 | 140.7 | 18 | 0.87 | 16 |
| 15.5 | 155.4 | 40 | 0.85 | 34 |
| 17.0 | 170.1 | 39 | 0.82 | 32 |
| 18.5 | 184.8 | 41 | 0.80 | 33 |
| 20.0 | 199.5 | 43 | 0.78 | 34 |
| 21.5 | 214.2 | 41 | 0.74 | 30 |
| 23.0 | 228.9 | 44 | 0.72 | 32 |
| 24.5 | 243.6 | 45 | 0.70 | 32 |
| 26.0 | 258.3 | 48 | 0.68 | 33 |
| 27.5 | 273.0 | 42 | 0.67 | 28 |
| 29.0 | 287.7 | 44 | 0.64 | 28 |
| 30.5 | 302.4 | 49 | 0.63 | 31 |

STEP 2 Compute the average corrected SPT N' value, \bar{N}' , for each soil layer.

Along the pile embedded length, the soil profile is delineated into three layers. Layer 1 is loose silty fine sand that is 4 meters thick, layer 2 is medium dense silty fine sand that is 7 meters thick, and layer 3 is dense sand and gravel that is 0.5 meter thick.

$$\bar{N}_1' = \frac{7 + 7 + 9}{3} = 8$$

(Layer 1 - depth 3 to 7 m;
Loose silty fine sand)

$$\bar{N}_2' = \frac{13 + 15 + 10 + 14 + 16}{5} = 14$$

(Layer 2 - depth 7 to 14 m;
Medium dense silty fine sand)

$$\bar{N}_3' = 34$$

(Layer 3 - depth 14 to 14.5 m;
Dense sand and gravel)

STEP 3 Compute the unit shaft resistance, f_s (kPa), for each layer using the equation for driven displacement piles:

$$f_s = 2\bar{N}' \leq 100 \text{ kPa}$$

$$\text{Layer 1: } f_{s-1} = 2 (8) = 16 \text{ kPa}$$

$$\text{Layer 2: } f_{s-2} = 2 (14) = 28 \text{ kPa}$$

$$\text{Layer 3: } f_{s-3} = 2 (34) = 68 \text{ kPa}$$

STEP 4 Compute the ultimate shaft resistance, R_s (kN).

$$R_s = f_s A_s$$

$$\text{Layer 1: } R_{s1} = 16 \text{ kPa } (4)(0.356 \text{ m})(4 \text{ m}) = 91 \text{ kN}$$

$$\text{Layer 2: } R_{s2} = 28 \text{ kPa } (4)(0.356 \text{ m})(7 \text{ m}) = 279 \text{ kN}$$

$$\text{Layer 3: } R_{s3} = 68 \text{ kPa } (4)(0.356 \text{ m})(0.5 \text{ m}) = 48 \text{ kN}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} + R_{s3} = 91 \text{ kN} + 279 \text{ kN} + 48 \text{ kN} \\ &= 418 \text{ kN} \end{aligned}$$

STEP 5 Compute the average corrected SPT N' values, \bar{N}'_O and \bar{N}'_B , near pile toe.

The soil near the pile toe is a dense sand and gravel. Since the pile toe is situated near the interface of a weaker stratum overlying the bearing stratum, the average corrected SPT N' value for both the bearing stratum, \bar{N}'_B , and the overlying stratum, \bar{N}'_O , need to be calculated.

Average corrected SPT N' value for the overlying stratum:

$$\bar{N}'_O = \frac{13 + 15 + 10 + 14 + 16}{5} = 14$$

Average corrected SPT N' value for the bearing stratum:

$$\bar{N}'_B = 34$$

STEP 6 Compute the unit toe resistance, q_t (kPa).

Since a weaker stratum overlies the bearing stratum:

$$q_t = 400 \bar{N}'_O + \frac{(40 \bar{N}'_B - 40 \bar{N}'_O) D_B}{b} \leq 400 \bar{N}'_B$$

STEP 6 (continued)

$$= 400 (14) + \frac{ \{ 40 (34) - 40 (14) \} (0.5) }{ 0.356 } \leq 400 (34)$$

$$= 6,724 \leq 13,600 \rightarrow \text{so } q_t = 6,724 \text{ kPa}$$

STEP 7 Compute the ultimate toe resistance, R_t (kN).

$$R_t = q_t A_t = 6,724 \text{ kPa } (0.356 \text{ m }) (0.356 \text{ m })$$

$$= 854 \text{ kN}$$

STEP 8 Compute the ultimate pile capacity, Q_u (kN).

$$Q_u = R_s + R_t$$

$$= 418 \text{ kN } + 854 \text{ kN}$$

$$= 1,272 \text{ kN}$$

Note: The ultimate capacity according to the Meyerhof method is less than the required 1780 kN ultimate capacity. The Meyerhof method would require a pile penetration depth of 13 meters for a 1,780 kN capacity.

STEP 9 Compute allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,272 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.1.2 Static Axial Pile Capacity Calculations by Nordlund Method

For the soil profile interpreted from Soil Boring S-1 as shown in Figure F.3. Perform a Nordlund method pile capacity calculation for an embedded length of 11.5 meters. Use the step-by-step method outlined in Section 9.7.1.1c.

STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer.

- a. Construct p_o diagram using procedure described in Section 9.4. This is completed in Figure F.4.
- b. Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values. For Soil Boring S-1, this has been done in the previous example (see Section F.2.1.1, Step 1).
- c. Determine the ϕ angle for each layer from laboratory tests or in-situ data.

Since the ϕ angle is not provided by either laboratory or in-situ data, it should be determined using the average corrected SPT N' value, \bar{N}' , as calculated below.

- d. In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, \bar{N}' , for each soil layer and estimate ϕ angle from Table 4-6 in Chapter 4.

As the example in Section F.2.1.1, the soil profile along the pile embedded length is delineated into three layers of 4.0, 7.0, and 0.5 meters thick. The average corrected SPT N' value for each soil layer is as follow.

| | | |
|----------|-------------------|--|
| Layer 1: | $\bar{N}'_1 = 8$ | (Layer 1 - depth 3 to 7 m; Loose silty fine sand) |
| Layer 2: | $\bar{N}'_2 = 14$ | (Layer 2 - depth 7 to 14 m; Medium dense silty fine sand) |
| Layer 3: | $\bar{N}'_3 = 34$ | (Layer 3 - depth 14 to 14.5 m; Dense sand and gravel) |

STEP 1 (continued)

Use the average corrected SPT N' value for each soil layer to estimate ϕ angle from Table 4-6 in Chapter 4.

$$\text{Layer 1: } \phi_1 = 29^\circ \quad \text{for } \bar{N}_1' = 8$$

$$\text{Layer 2: } \phi_2 = 31^\circ \quad \text{for } \bar{N}_2' = 14$$

$$\text{Layer 3: } \phi_3 = 36^\circ \quad \text{for } \bar{N}_3' = 34$$

STEP 2 Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .

- a. Compute the volume of soil displaced per unit length of pile, V .
Since this is a uniform cross section ($\omega = 0^\circ$) pile,

$$V = (0.356 \text{ m}) (0.356 \text{ m}) (1.0 \text{ m/m}) = 0.127 \text{ m}^3/\text{m}$$

For a non-uniform pile cross section ($\omega \neq 0^\circ$), the pile should be divided into sections and the volume for each section should be calculated.

- b. Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.

For a precast, prestressed concrete pile with $V = 0.127 \text{ m}^3/\text{m}$,

$$\delta/\phi = 0.84$$

- c. Calculate δ from δ/ϕ ratio.

$$\text{Layer 1: } \delta_1 = 0.84 (29^\circ) = 24.4^\circ$$

$$\text{Layer 2: } \delta_2 = 0.84 (31^\circ) = 26.0^\circ$$

$$\text{Layer 3: } \delta_3 = 0.84 (36^\circ) = 30.2^\circ$$

STEP 3 Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.

- a. Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.

The pile taper angle, ω , = 0° .

For Layer 1:

$\phi_1 = 29^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

First, use linear interpolation to determine K_δ for the required ϕ angle of 29° at the given displaced volume curves of 0.093 and $0.93 \text{ m}^3/\text{m}$.

For $V = 0.093 \text{ m}^3/\text{m}$:

$\phi = 25^\circ$ $K_\delta = 0.85$ (from Figure 9.11)

$\phi = 29^\circ$ $K_\delta =$ (using linear interpolation)

$\phi = 30^\circ$ $K_\delta = 1.15$ (from Figure 9.12)

Using linear interpolation to determine K_δ for $\phi = 29^\circ$:

$$\begin{aligned} K_\delta &= 0.85 + \frac{(29 - 25)}{(30 - 25)} (1.15 - 0.85) \\ &= 1.09 \end{aligned}$$

For $V = 0.93 \text{ m}^3/\text{m}$:

$\phi = 25^\circ$ $K_\delta = 1.00$ (from Figure 9.11)

$\phi = 29^\circ$ $K_\delta =$ (using linear interpolation)

$\phi = 30^\circ$ $K_\delta = 1.45$ (from Figure 9.12)

STEP 3 (continued)

Using linear interpolation to determine K_δ for $\phi = 29^\circ$:

$$\begin{aligned} K_\delta &= 1.0 + \frac{(29 - 25)}{(30 - 25)} (1.45 - 1.0) \\ &= 1.36 \end{aligned}$$

Then use log linear interpolation to determine K_δ for $\phi = 29^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$.

$$V = 0.093 \text{ m}^3/\text{m} \quad K_\delta = 1.09$$

$$V = 0.127 \text{ m}^3/\text{m} \quad K_\delta = \quad (\text{using log linear interpolation})$$

$$V = 0.186 \text{ m}^3/\text{m} \quad K_\delta = 1.36$$

Log linear interpolation for $V = 0.127 \text{ m}^3/\text{m}$:

$$\begin{aligned} K_{\delta 1} &= 1.09 + \frac{\log(0.127) - \log(0.093)}{\log(0.186) - \log(0.093)} (1.36 - 1.09) \\ &= 1.13 \end{aligned}$$

Table 9-4b can be used to check the above calculations. From Table 9-4b, for $\phi = 29^\circ$:

$$V = 0.093 \text{ m}^3/\text{m} \quad K_\delta = 1.09 \text{ (from Table 9-4b)}$$

$$V = 0.127 \text{ m}^3/\text{m} \quad K_\delta = 1.13 \text{ (from log linear interpolation)}$$

$$V = 0.186 \text{ m}^3/\text{m} \quad K_\delta = 1.17 \text{ (from Table 9-4b)}$$

STEP 3 (continued)

For Layer 2:

$\phi_2 = 31^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

First, use linear interpolation to determine K_δ for the required ϕ angle of 31° at the given displaced volume curves of 0.093 and $0.93 \text{ m}^3/\text{m}$.

For $V = 0.093 \text{ m}^3/\text{m}$:

$$\phi = 30^\circ \quad K_\delta = 1.15 \quad (\text{from Figure 9.12})$$

$$\phi = 31^\circ \quad K_\delta = \quad (\text{using linear interpolation})$$

$$\phi = 35^\circ \quad K_\delta = 1.75 \quad (\text{from Figure 9.13})$$

Using linear interpolation to determine K_δ for $\phi = 31^\circ$:

$$\begin{aligned} K_\delta &= 1.15 + \frac{(31 - 30)}{(35 - 30)} (1.75 - 1.15) \\ &= 1.27 \end{aligned}$$

For $V = 0.93 \text{ m}^3/\text{m}$:

$$\phi = 30^\circ \quad K_\delta = 1.45 \quad (\text{from Figure 9.12})$$

$$\phi = 31^\circ \quad K_\delta = \quad (\text{using linear interpolation})$$

$$\phi = 35^\circ \quad K_\delta = 2.35 \quad (\text{from Figure 9.13})$$

Using linear interpolation to determine K_δ for $\phi = 31^\circ$:

$$K_\delta = 1.45 + \frac{(31 - 30)}{(35 - 30)} (2.35 - 1.45) = 1.63$$

STEP 3 (continued)

Then use log linear interpolation to determine K_δ for $\phi = 31^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$.

$$V = 0.093 \text{ m}^3/\text{m} \quad K_\delta = 1.27$$

$$V = 0.127 \text{ m}^3/\text{m} \quad K_\delta = \quad (\text{using log linear interpolation})$$

$$V = 0.186 \text{ m}^3/\text{m} \quad K_\delta = 1.63$$

Log linear interpolation for $V = 0.127 \text{ m}^3/\text{m}$:

$$\begin{aligned} K_{\delta 2} &= 1.27 + \frac{\log(0.127) - \log(0.093)}{\log(0.186) - \log(0.093)} (1.63 - 1.27) \\ &= 1.32 \end{aligned}$$

Table 9-4b can be used to check the above calculations. From Table 9-4b, for $\phi = 31^\circ$:

$$V = 0.093 \text{ m}^3/\text{m} \quad K_\delta = 1.27 \text{ (from Table 9-4b)}$$

$$V = 0.127 \text{ m}^3/\text{m} \quad K_\delta = 1.32 \text{ (from log linear interpolation)}$$

$$V = 0.186 \text{ m}^3/\text{m} \quad K_\delta = 1.38 \text{ (from Table 9-4b)}$$

STEP 3 (continued)

For Layer 3:

$\phi_3 = 36^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

First, use linear interpolation to determine K_δ for the required ϕ angle of 36° at the given displaced volume curves of 0.093 and $0.93 \text{ m}^3/\text{m}$.

For $V = 0.093 \text{ m}^3/\text{m}$:

$$\phi = 35^\circ \quad K_\delta = 1.75 \quad (\text{from Figure 9.13})$$

$$\phi = 36^\circ \quad K_\delta = \quad (\text{using linear interpolation})$$

$$\phi = 40^\circ \quad K_\delta = 3.00 \quad (\text{from Figure 9.14})$$

Using linear interpolation to determine K_δ for $\phi = 36^\circ$:

$$\begin{aligned} K_\delta &= 1.75 + \frac{(36 - 35)}{(40 - 35)} (3.00 - 1.75) \\ &= 2.00 \end{aligned}$$

For $V = 0.93 \text{ m}^3/\text{m}$:

$$\phi = 35^\circ \quad K_\delta = 2.35 \quad (\text{from Figure 9.13})$$

$$\phi = 36^\circ \quad K_\delta = \quad (\text{using linear interpolation})$$

$$\phi = 40^\circ \quad K_\delta = 4.30 \quad (\text{from Figure 9.14})$$

Using linear interpolation to determine K_δ for $\phi = 36^\circ$:

$$K_\delta = 2.35 + \frac{(36 - 35)}{(40 - 35)} (4.30 - 2.35) = 2.74$$

STEP 3 (continued)

Then use log linear interpolation to determine K_δ for $\phi = 36^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$.

$$V = 0.093 \text{ m}^3/\text{m} \quad K_\delta = 2.00$$

$$V = 0.127 \text{ m}^3/\text{m} \quad K_\delta = \quad \text{(using log linear interpolation)}$$

$$V = 0.93 \text{ m}^3/\text{m} \quad K_\delta = 2.74$$

Log linear interpolation for $V = 0.127 \text{ m}^3/\text{m}$:

$$\begin{aligned} K_{\delta 3} &= 2.00 + \frac{\log(0.127) - \log(0.093)}{\log(0.93) - \log(0.093)} (2.74 - 2.00) \\ &= 2.10 \end{aligned}$$

Table 9-4b can be used to check the above calculations. From Table 9-4b, for $\phi = 36^\circ$:

$$V = 0.093 \text{ m}^3/\text{m} \quad K_\delta = 2.00 \text{ (from Table 9-4b)}$$

$$V = 0.127 \text{ m}^3/\text{m} \quad K_\delta = 2.10 \text{ (from log linear interpolation)}$$

$$V = 0.186 \text{ m}^3/\text{m} \quad K_\delta = 2.22 \text{ (from Table 9-4b)}$$

STEP 4 Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and $\delta/\phi=0.84$ to determine C_F .

Layer 1: For $\phi_1 = 29^\circ \rightarrow C_{F1} = 0.96$

Layer 2: For $\phi_2 = 31^\circ \rightarrow C_{F2} = 0.94$

Layer 3: For $\phi_3 = 36^\circ \rightarrow C_{F3} = 0.93$

STEP 5 Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa). (Note: a limiting value is not applied to p_d).

The effective overburden pressure at the midpoint of each soil layer is equal to the average effective overburden pressure of that layer. The effective overburden pressure versus depth for the North Abutment has been computed and tabulated in the previous example (see Section F.2.1.1, Step 1). The effective overburden pressure diagram for the North Abutment is presented in Figure F.4. Since the effective overburden pressure is non linear in layer 1, this layer should be split at the water table location into layer 1a and layer 1b. The effective overburden pressure is then calculated at the midpoint of each of these layers.

Layer 1a: $p_{d1a} = 57.8 \text{ kPa}$ (midpoint of layer 1a - at depth of 3.5 m)

Layer 1b: $p_{d1b} = 76.1 \text{ kPa}$ (midpoint of layer 1b - at depth of 5.5 m)

Layer 2: $p_{d2} = 113.4 \text{ kPa}$ (midpoint of layer 2 - at depth of 10.5 m)

Layer 3: $p_{d3} = 143.1 \text{ kPa}$ (midpoint of layer 3 - at depth of 14.25 m)

STEP 6 Compute the shaft resistance in each soil layer. Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$R_s = K_\delta C_F p_d \sin \delta C_d D \quad (\text{for uniform pile cross section})$$

$$\text{where : } C_d = (4)(0.356 \text{ m}) = 1.424 \text{ m}$$

$$\begin{aligned} \text{Layer 1a: } R_{s1a} &= 1.13 (0.96) (57.8 \text{ kPa}) (\sin 24.4^\circ) (1.424 \text{ m}) (1 \text{ m}) \\ &= 37 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 1b: } R_{s1b} &= 1.13 (0.96) (76.1 \text{ kPa}) (\sin 24.4^\circ) (1.424 \text{ m}) (3 \text{ m}) \\ &= 146 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 1.32 (0.94) (113.4 \text{ kPa}) (\sin 26.0^\circ) (1.424 \text{ m}) (7 \text{ m}) \\ &= 615 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 3: } R_{s3} &= 2.10 (0.93) (143.2 \text{ kPa}) (\sin 30.2^\circ) (1.424 \text{ m}) (0.5 \text{ m}) \\ &= 100 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1a} + R_{s1b} + R_{s2} + R_{s3} \\ &= 37 \text{ kN} + 146 \text{ kN} + 615 \text{ kN} + 100 \text{ kN} \\ &= 898 \text{ kN} \end{aligned}$$

STEP 7 Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

Since the ϕ angle is not provided by either laboratory tests or in-situ data, the ϕ angle can be estimated from Table 4-6 using the average corrected SPT N' value over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{toe} = 34 \rightarrow \phi_{toe} = 36^\circ$$

- a. Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.

$$(D/b) = (11.5 \text{ m}) / (0.356 \text{ m}) = 32.3$$

$$\text{For } \phi_{toe} = 36^\circ \text{ and } (D/b) = 32.3 \rightarrow \alpha_t = 0.68$$

- b. Enter Figure 9.16(b) with ϕ angle near pile toe to determine N'_q .

$$\text{For } \phi_{toe} = 36^\circ \rightarrow N'_q = 75$$

STEP 8 Compute the effective overburden pressure at the pile toe, p_t (kPa).

The effective overburden pressure at the pile toe should be limited to a maximum of 150 kPa.

The effective overburden pressure at the pile toe, p_t , has been computed in the previous example (Section F.2.1.1, Step 1):

$$p_t = 145.6 \text{ kPa} < 150 \text{ kPa} \rightarrow \text{OK}$$

STEP 9 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} \text{a. } R_t &= \alpha_t N'_q A_t p_t \\ &= 0.68 (75) (0.356 \text{ m})(0.356 \text{ m}) (145.6 \text{ kPa}) \\ &= 943 \text{ kN} \end{aligned}$$

$$\text{b. limiting } R_t = q_L A_t$$

Using the estimated $\phi=36^\circ$ and Figure 9.17, the limiting unit toe resistance is:

$$q_L = 7,400 \text{ kPa}$$

Therefore,

$$R_t = 7,400 \text{ kPa} (0.356 \text{ m})(0.356 \text{ m}) = 940 \text{ kN}$$

c. Use lesser of the two R_t values obtained in steps a and b which is:

$$R_t = 940 \text{ kN}$$

STEP 10 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 898 \text{ kN} + 940 \text{ kN} = 1,838 \text{ kN} \end{aligned}$$

STEP 11 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,838 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.1.3 Static Axial Pile Capacity Calculations by Effective Stress Method

For the soil profile interpreted from Soil Boring S-1 as shown in Figure F.3. Perform an Effective Stress method pile capacity calculation for an embedded length of 11.5 meters. Use the step-by-step method outlined in Section 9.7.1.3.

STEP 1 Delineate the soil profile into layers and determine ϕ' angle for each layer.

- a. Use the procedure described in Section 9.4 to construct a p_o diagram.

For Soil Boring S-1, the p_o diagram has been constructed in Section F.2.1.1 - Step 1 and also presented in Figure F.4.

- b. Divide the soil profile throughout the pile penetration depth into layers and determine the effective overburden pressure, p_o , at the midpoint of each layer.

As the example in Section F.2.1.1, the soil profile along the pile embedded length is delineated into three layers of 4.0, 7.0, and 0.5 meter thick. Since the effective overburden pressure is non linear in layer 1, this layer should be split at the water table location into layer 1a and 1b. The average effective overburden pressure of each layer is equal to the effective overburden pressure at the midpoint of that layer, as follows.

Layer 1a: $p_{o1a} = 57.8 \text{ kPa}$ (midpoint of layer 1a - at depth of 3.5 m)

Layer 1b: $p_{o1b} = 76.1 \text{ kPa}$ (midpoint of layer 1b - at depth of 5.5 m)

Layer 2: $p_{o2} = 113.4 \text{ kPa}$ (midpoint of layer 2 - at depth of 10.5 m)

Layer 3: $p_{o3} = 143.1 \text{ kPa}$ (midpoint of layer 3 - at depth of 14.25 m)

- c. Determine the ϕ' angle for each soil layer from laboratory or in-situ test data.

Since the ϕ' angle is not provided by either laboratory or in-situ test data, the average corrected SPT N' value will be used to estimate the ϕ' angle.

STEP 1 (continued)

- d. In the absence of laboratory or in-situ test data for cohesionless soil layers, determine the average corrected SPT N' value for each soil layer and estimate the ϕ' angle from Table 4-6 in Chapter 4.

As in the previous example (Section F.2.1.1), the average corrected SPT N' value and the soil type for each soil layer is as follows.

| | | |
|----------|-------------------|--|
| Layer 1: | $\bar{N}_1' = 8$ | (Layer 1 - depth 3 to 7 m; Loose silty fine sand) |
| Layer 2: | $\bar{N}_2' = 14$ | (Layer 2 - depth 7 to 14 m; Medium dense silty fine sand) |
| Layer 3: | $\bar{N}_3' = 34$ | (Layer 3 - depth 14 to 14.5 m; Dense sand and gravel) |

Use the average corrected SPT N' value for each soil layer to estimate ϕ' angle from Table 4-6 in Chapter 4.

| | | |
|----------|----------------------|-----------------------|
| Layer 1: | $\phi_1' = 29^\circ$ | for $\bar{N}_1' = 8$ |
| Layer 2: | $\phi_2' = 31^\circ$ | for $\bar{N}_2' = 14$ |
| Layer 3: | $\phi_3' = 36^\circ$ | for $\bar{N}_3' = 34$ |

STEP 2 Select the β coefficient for each soil layer.

- a. Use local experience to select β coefficient for each layer.

Assume no local experience.

STEP 2 (continued)

- b. In the absence of local experience, use Table 9-6 or Figure 9.20 to estimate β coefficient from ϕ' angle for each layer.

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.20 to estimate the β coefficient for each layer.

$$\text{Layer 1: } \beta_1 = 0.30 \quad (\text{For loose silty fine sand with } \phi'_1 = 29^\circ)$$

$$\text{Layer 2: } \beta_2 = 0.33 \quad (\text{For medium dense silty fine sand with } \phi'_2 = 31^\circ)$$

$$\text{Layer 3: } \beta_3 = 0.40 \quad (\text{For dense sand and gravel with } \phi'_3 = 36^\circ)$$

STEP 3 For each soil layer compute the unit shaft resistance, f_s (kPa).

$$f_s = \beta p_o$$

$$\text{Layer 1a: } f_{s1a} = 0.30 (57.8 \text{ kPa}) = 17.34 \text{ kPa}$$

$$\text{Layer 1b: } f_{s1b} = 0.30 (76.1 \text{ kPa}) = 22.83 \text{ kPa}$$

$$\text{Layer 2: } f_{s2} = 0.33 (113.4 \text{ kPa}) = 37.42 \text{ kPa}$$

$$\text{Layer 3: } f_{s3} = 0.40 (143.1 \text{ kPa}) = 57.24 \text{ kPa}$$

STEP 4 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s (kN), from the sum of the shaft resistance from each soil layer.

$$R_s = f_s A_s$$

where A_s = Pile-soil surface area from pile perimeter and length

$$\text{Layer 1a: } R_{s1a} = 17.34 (4) (0.356 \text{ m}) (1 \text{ m}) = 25 \text{ kN}$$

$$\text{Layer 1b: } R_{s1b} = 22.83 (4) (0.356 \text{ m}) (3 \text{ m}) = 98 \text{ kN}$$

STEP 4 (continued)

$$\text{Layer 2: } R_{s2} = 37.42 (4) (0.356 \text{ m}) (7 \text{ m}) = 373 \text{ kN}$$

$$\text{Layer 3: } R_{s3} = 57.24 (4) (0.356 \text{ m}) (0.5 \text{ m}) = 41 \text{ kN}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1a} + R_{s1b} + R_{s2} + R_{s3} \\ &= 25 \text{ kN} + 98 \text{ kN} + 373 \text{ kN} + 41 \text{ kN} \\ &= 537 \text{ kN} \end{aligned}$$

STEP 5 Compute the unit toe resistance, q_t (kPa).

$$q_t = N_t p_t$$

- a. Use local experience to select N_t coefficient.

Assume no local experience.

- b. In the absence of local experience, estimate N_t coefficient from Table 9-6 or Figure 9.21 based on ϕ' angle.

Table 9-6 or Figure 9.21 are a function of soil type and the ϕ' angle. The soil type for each layer can be obtained from the soil boring. The ϕ' angle for each layer can be obtained from laboratory tests or in-situ data. In the absence of either laboratory or in-situ test data, the ϕ' angle should be estimated from Table 4-6 in Chapter 4 using the average corrected SPT N' value, \bar{N}' , over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{\text{toe}} = 34 \rightarrow \phi'_{\text{toe}} = 36^\circ$$

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.21 to estimate the N_t coefficient.

$$N_t = 70 \quad (\text{For dense sand and gravel with } \phi'_{\text{toe}} = 36^\circ)$$

- c. Calculate the effective overburden pressure at the pile toe, p_t .

The effective overburden pressure at the pile toe, p_t , has been computed in the previous example (Section F.2.1.1, Step 1):

$$p_t = 145.6 \text{ kPa}$$

The unit toe resistance, q_t is:

$$\begin{aligned} q_t &= N_t p_t \\ &= 70 (145.6 \text{ kPa}) = 10,192 \text{ kPa} \end{aligned}$$

STEP 6 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} R_t &= q_t A_t \\ &= 10,192 (0.356 \text{ m}) (0.356 \text{ m}) \\ &= 1,294 \text{ kN} \end{aligned}$$

STEP 7 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 537 \text{ kN} + 1,294 \text{ kN} \\ &= 1,831 \text{ kN} \end{aligned}$$

STEP 8 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,831 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.1.4 Static Axial Pile Capacity Calculations by Driven Computer Program

Note: In the following tables, the depth corresponding to the pile tip is 14.5 m. The “driving strength loss (%)” factor used in Driven for Boring S-2 was selected based on Table 9-20. Because these soils are cohesionless sands and gravels, the soil set-up factor selected was 1.0. For this problem, the driving strength loss is therefore 0%. In the Driven results, the “Ultimate,” “Restrike” and “Driving” tables are the same because no strength was lost during driving to be regained when the restrike is performed and no effective stress losses due to scour are present.

DRIVEN 1.2 **GENERAL PROJECT INFORMATION**

Filename: C:\DRIVEN\S1.DVN
Project Name: Boring S-1 Project Date: 09/11/2003
Project Client: FHWA Manual
Computed By: BRR
Project Manager:

PILE INFORMATION

Pile Type: Concrete Pile
Top of Pile: 2.50 m
Length of Square Side: 356.00 mm

ULTIMATE CONSIDERATIONS

Water Table Depth At Time Of: - Drilling: 4.00 m
 - Driving/Restrike 4.00 m
 - Ultimate: 4.00 m
Ultimate Considerations: - Local Scour: 0.00 m
 - Long Term Scour: 0.00 m
 - Soft Soil: 0.00 m

ULTIMATE PROFILE

| Layer | Type | Thickness | Driving Loss | Unit Weight | Strength | Ultimate Curve |
|-------|--------------|-----------|--------------|-------------------------|-----------|----------------|
| 1 | Cohesionless | 7.00 m | 0.00% | 16.50 kN/m ³ | 29.0/29.0 | Nordlund |
| 2 | Cohesionless | 7.00 m | 0.00% | 17.60 kN/m ³ | 31.0/31.0 | Nordlund |
| 3 | Cohesionless | 0.50 m | 0.00% | 19.60 kN/m ³ | 36.0/36.0 | Nordlund |
| 4 | Cohesionless | 5.50 m | 0.00% | 19.60 kN/m ³ | 36.0/36.0 | Nordlund |

RESTRIKE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|----------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.49 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.50 m | Cohesionless | 41.25 kPa | 24.43 | N/A | 0.00 kN |
| 3.01 m | Cohesionless | 45.46 kPa | 24.43 | N/A | 14.68 kN |
| 3.99 m | Cohesionless | 53.54 kPa | 24.43 | N/A | 50.52 kN |
| 4.01 m | Cohesionless | 66.04 kPa | 24.43 | N/A | 51.35 kN |
| 6.99 m | Cohesionless | 76.02 kPa | 24.43 | N/A | 194.85 kN |
| 7.01 m | Cohesionless | 86.14 kPa | 26.11 | N/A | 196.07 kN |
| 10.01 m | Cohesionless | 97.84 kPa | 26.11 | N/A | 426.25 kN |
| 13.01 m | Cohesionless | 109.53 kPa | 26.11 | N/A | 711.46 kN |
| 13.99 m | Cohesionless | 113.35 kPa | 26.11 | N/A | 816.55 kN |
| 14.01 m | Cohesionless | 140.74 kPa | 30.32 | N/A | 819.63 kN |
| 14.49 m | Cohesionless | 143.09 kPa | 30.32 | N/A | 915.98 kN |
| 14.51 m | Cohesionless | 145.64 kPa | 30.32 | N/A | 920.06 kN |
| 17.51 m | Cohesionless | 160.33 kPa | 30.32 | N/A | 1594.81 kN |
| 19.99 m | Cohesionless | 172.48 kPa | 30.32 | N/A | 2245.97 kN |

RESTRIKE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 26.40 | 80.82 kN | 0.00 kN |
| 2.49 m | Cohesionless | 0.00 kPa | 26.40 | 80.82 kN | 0.00 kN |
| 2.50 m | Cohesionless | 41.25 kPa | 26.40 | 80.82 kN | 77.01 kN |
| 3.01 m | Cohesionless | 49.67 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 3.99 m | Cohesionless | 65.84 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 4.01 m | Cohesionless | 66.07 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 6.99 m | Cohesionless | 86.03 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 7.01 m | Cohesionless | 86.18 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 10.01 m | Cohesionless | 109.57 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 13.01 m | Cohesionless | 132.97 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 13.99 m | Cohesionless | 140.61 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 14.01 m | Cohesionless | 140.79 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 14.49 m | Cohesionless | 145.49 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 14.51 m | Cohesionless | 145.69 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 17.51 m | Cohesionless | 175.08 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 19.99 m | Cohesionless | 199.38 kPa | 77.60 | 919.89 kN | 919.89 kN |

RESTRIKE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.49 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.50 m | 0.00 kN | 77.01 kN | 77.01 kN |
| 3.01 m | 14.68 kN | 80.82 kN | 95.50 kN |
| 3.99 m | 50.52 kN | 80.82 kN | 131.34 kN |
| 4.01 m | 51.35 kN | 80.82 kN | 132.18 kN |
| 6.99 m | 194.85 kN | 80.82 kN | 275.67 kN |
| 7.01 m | 196.07 kN | 125.39 kN | 321.45 kN |
| 10.01 m | 426.25 kN | 125.39 kN | 551.64 kN |
| 13.01 m | 711.46 kN | 125.39 kN | 836.84 kN |
| 13.99 m | 816.55 kN | 125.39 kN | 941.94 kN |
| 14.01 m | 819.63 kN | 919.89 kN | 1739.51 kN |
| 14.49 m | 915.98 kN | 919.89 kN | 1835.86 kN |
| 14.51 m | 920.06 kN | 919.89 kN | 1839.95 kN |
| 17.51 m | 1594.81 kN | 919.89 kN | 2514.69 kN |
| 19.99 m | 2245.97 kN | 919.89 kN | 3165.86 kN |

DRIVING - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|----------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.49 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.50 m | Cohesionless | 41.25 kPa | 24.43 | N/A | 0.00 kN |
| 3.01 m | Cohesionless | 45.46 kPa | 24.43 | N/A | 14.68 kN |
| 3.99 m | Cohesionless | 53.54 kPa | 24.43 | N/A | 50.52 kN |
| 4.01 m | Cohesionless | 66.04 kPa | 24.43 | N/A | 51.35 kN |
| 6.99 m | Cohesionless | 76.02 kPa | 24.43 | N/A | 194.85 kN |
| 7.01 m | Cohesionless | 86.14 kPa | 26.11 | N/A | 196.07 kN |
| 10.01 m | Cohesionless | 97.84 kPa | 26.11 | N/A | 426.25 kN |
| 13.01 m | Cohesionless | 109.53 kPa | 26.11 | N/A | 711.46 kN |
| 13.99 m | Cohesionless | 113.35 kPa | 26.11 | N/A | 816.55 kN |
| 14.01 m | Cohesionless | 140.74 kPa | 30.32 | N/A | 819.63 kN |
| 14.49 m | Cohesionless | 143.09 kPa | 30.32 | N/A | 915.98 kN |
| 14.51 m | Cohesionless | 145.64 kPa | 30.32 | N/A | 920.06 kN |
| 17.51 m | Cohesionless | 160.33 kPa | 30.32 | N/A | 1594.81 kN |
| 19.99 m | Cohesionless | 172.48 kPa | 30.32 | N/A | 2245.97 kN |

DRIVING - END BEARING

| Depth | Soil Type | Effective Stress At Tip Factor | Bearing Cap. | Limiting End Bearing | End Bearing |
|---------|--------------|-----------------------------------|--------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 26.40 | 80.82 kN | 0.00 kN |
| 2.49 m | Cohesionless | 0.00 kPa | 26.40 | 80.82 kN | 0.00 kN |
| 2.50 m | Cohesionless | 41.25 kPa | 26.40 | 80.82 kN | 77.01 kN |
| 3.01 m | Cohesionless | 49.67 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 3.99 m | Cohesionless | 65.84 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 4.01 m | Cohesionless | 66.07 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 6.99 m | Cohesionless | 86.03 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 7.01 m | Cohesionless | 86.18 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 10.01 m | Cohesionless | 109.57 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 13.01 m | Cohesionless | 132.97 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 13.99 m | Cohesionless | 140.61 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 14.01 m | Cohesionless | 140.79 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 14.49 m | Cohesionless | 145.49 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 14.51 m | Cohesionless | 145.69 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 17.51 m | Cohesionless | 175.08 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 19.99 m | Cohesionless | 199.38 kPa | 77.60 | 919.89 kN | 919.89 kN |

DRIVING - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.49 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.50 m | 0.00 kN | 77.01 kN | 77.01 kN |
| 3.01 m | 14.68 kN | 80.82 kN | 95.50 kN |
| 3.99 m | 50.52 kN | 80.82 kN | 131.34 kN |
| 4.01 m | 51.35 kN | 80.82 kN | 132.18 kN |
| 6.99 m | 194.85 kN | 80.82 kN | 275.67 kN |
| 7.01 m | 196.07 kN | 125.39 kN | 321.45 kN |
| 10.01 m | 426.25 kN | 125.39 kN | 551.64 kN |
| 13.01 m | 711.46 kN | 125.39 kN | 836.84 kN |
| 13.99 m | 816.55 kN | 125.39 kN | 941.94 kN |
| 14.01 m | 819.63 kN | 919.89 kN | 1739.51 kN |
| 14.49 m | 915.98 kN | 919.89 kN | 1835.86 kN |
| 14.51 m | 920.06 kN | 919.89 kN | 1839.95 kN |
| 17.51 m | 1594.81 kN | 919.89 kN | 2514.69 kN |
| 19.99 m | 2245.97 kN | 919.89 kN | 3165.86 kN |

ULTIMATE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|----------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.49 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.50 m | Cohesionless | 41.25 kPa | 24.43 | N/A | 0.00 kN |
| 3.01 m | Cohesionless | 45.46 kPa | 24.43 | N/A | 14.68 kN |
| 3.99 m | Cohesionless | 53.54 kPa | 24.43 | N/A | 50.52 kN |
| 4.01 m | Cohesionless | 66.04 kPa | 24.43 | N/A | 51.35 kN |
| 6.99 m | Cohesionless | 76.02 kPa | 24.43 | N/A | 194.85 kN |
| 7.01 m | Cohesionless | 86.14 kPa | 26.11 | N/A | 196.07 kN |
| 10.01 m | Cohesionless | 97.84 kPa | 26.11 | N/A | 426.25 kN |
| 13.01 m | Cohesionless | 109.53 kPa | 26.11 | N/A | 711.46 kN |
| 13.99 m | Cohesionless | 113.35 kPa | 26.11 | N/A | 816.55 kN |
| 14.01 m | Cohesionless | 140.74 kPa | 30.32 | N/A | 819.63 kN |
| 14.49 m | Cohesionless | 143.09 kPa | 30.32 | N/A | 915.98 kN |
| 14.51 m | Cohesionless | 145.64 kPa | 30.32 | N/A | 920.06 kN |
| 17.51 m | Cohesionless | 160.33 kPa | 30.32 | N/A | 1594.81 kN |
| 19.99 m | Cohesionless | 172.48 kPa | 30.32 | N/A | 2245.97 kN |

ULTIMATE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 26.40 | 80.82 kN | 0.00 kN |
| 2.49 m | Cohesionless | 0.00 kPa | 26.40 | 80.82 kN | 0.00 kN |
| 2.50 m | Cohesionless | 41.25 kPa | 26.40 | 80.82 kN | 77.01 kN |
| 3.01 m | Cohesionless | 49.67 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 3.99 m | Cohesionless | 65.84 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 4.01 m | Cohesionless | 66.07 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 6.99 m | Cohesionless | 86.03 kPa | 26.40 | 80.82 kN | 80.82 kN |
| 7.01 m | Cohesionless | 86.18 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 10.01 m | Cohesionless | 109.57 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 13.01 m | Cohesionless | 132.97 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 13.99 m | Cohesionless | 140.61 kPa | 35.20 | 125.39 kN | 125.39 kN |
| 14.01 m | Cohesionless | 140.79 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 14.49 m | Cohesionless | 145.49 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 14.51 m | Cohesionless | 145.69 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 17.51 m | Cohesionless | 175.08 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 19.99 m | Cohesionless | 199.38 kPa | 77.60 | 919.89 kN | 919.89 kN |

ULTIMATE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.49 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.50 m | 0.00 kN | 77.01 kN | 77.01 kN |
| 3.01 m | 14.68 kN | 80.82 kN | 95.50 kN |
| 3.99 m | 50.52 kN | 80.82 kN | 131.34 kN |
| 4.01 m | 51.35 kN | 80.82 kN | 132.18 kN |
| 6.99 m | 194.85 kN | 80.82 kN | 275.67 kN |
| 7.01 m | 196.07 kN | 125.39 kN | 321.45 kN |
| 10.01 m | 426.25 kN | 125.39 kN | 551.64 kN |
| 13.01 m | 711.46 kN | 125.39 kN | 836.84 kN |
| 13.99 m | 816.55 kN | 125.39 kN | 941.94 kN |
| 14.01 m | 819.63 kN | 919.89 kN | 1739.51 kN |
| 14.49 m | 915.98 kN | 919.89 kN | 1835.86 kN |
| 14.51 m | 920.06 kN | 919.89 kN | 1839.95 kN |
| 17.51 m | 1594.81 kN | 919.89 kN | 2514.69 kN |
| 19.99 m | 2245.97 kN | 919.89 kN | 3165.86 kN |

F.2.1.5 Static Axial Pile Capacity Calculations by LPC CPT Method - Computer Program

L.P.C. CPT Method

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Peach Freeway CPT-1 at North Abutment -- 356 mm-square PCPS

Concrete Pile

Installation Method: 9 - Driven Prefabricated Piles (Concrete)

Depth to Water Table: 4.0 meter

| Pile No. | Toe Area (m ²) | Perimeter (m) |
|----------|-------------------------------|------------------|
| 1 | 0.127 | 1.424 |

| Depth to Bottom of Layer (m) | Soil Type |
|------------------------------------|-----------|
| 14.021 | 5 |
| 30.785 | 7 |

| Depth (m) | Cone Tip Resistance (kPa) |
|--------------|---------------------------------|
| .0 | 3,926.20 |
| 5.0 | 3,926.20 |
| 10.0 | 3,399.48 |
| 11.5 | 3,591.00 |
| 13.0 | 5,171.04 |
| 14.0 | 5,075.28 |
| 15.0 | 13,071.24 |
| 16.0 | 15,369.48 |
| 17.0 | 20,588.40 |
| 18.0 | 23,078.16 |
| 20.0 | 19,199.88 |
| 23.0 | 17,188.92 |
| 24.0 | 24,466.68 |
| 27.0 | 18,050.80 |

Peach Freeway CPT-1 at North Abutment -- 356 mm-square PCPS

Concrete Pile

| Depth (m) | Unit Friction (kPa) | Toe Bearing (kPa) | Shaft Resistance (kN) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|------------------------|----------------------|-----------------------------|---------------------------|------------------------------|
| 0.00 | 60.66 | 2,355.70 | 0.0 | 298.0 | 298.0 |
| 5.00 | 36.96 | 1,474.70 | 347.4 | 186.4 | 533.8 |
| 10.00 | 17.05 | 1,292.76 | 539.5 | 163.7 | 703.2 |
| 11.50 | 35.96 | 1,484.28 | 596.0 | 187.7 | 783.7 |
| 13.00 | 40.75 | 2,312.60 | 678.3 | 292.2 | 970.6 |
| 14.00 | 40.46 | 3,413.84 | 735.7 | 431.5 | 1,167.2 |
| 15.00 | 62.72 | 4,677.88 | 824.7 | 591.1 | 1,415.8 |
| 16.00 | 63.58 | 6,171.73 | 914.5 | 780.6 | 1,695.1 |
| 17.00 | 65.60 | 7,340.00 | 1,006.1 | 928.3 | 1,934.4 |
| 18.00 | 66.55 | 7,986.38 | 1,099.1 | 1,010.1 | 2,109.2 |
| 20.00 | 65.07 | 7,445.34 | 1,287.7 | 941.6 | 2,229.3 |
| 23.00 | 64.30 | 7,411.82 | 1,563.5 | 936.7 | 2,500.2 |
| 24.00 | 67.08 | 8,158.75 | 1,657.3 | 1,031.5 | 2,688.8 |
| 27.00 | 64.64 | 6,846.84 | 1,938.0 | 866.0 | 2,804.0 |

Note: Depth is referenced from the original ground surface.

F.2.1.6 Static Axial Pile Capacity Calculations by Schmertmann Method

Location: Peach Freeway CPT-1 at North Abutment.

| Depth (m) | fs (avg) (bars) | Unit Friction (bars) | Increment Friction (kN) | Shaft Resist. (kN) | qc (avg) (bars) | qc1 (min) (bars) | qc2 (bars) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|-----------------------|----------------------------|-------------------------------|--------------------------|-----------------------|------------------------|---------------|---------------------------|------------------------------|
| 12.00 | 1.21 | 1.03 | 35.86 | 286 | 51.33 | | | | |
| 12.25 | 1.22 | 1.03 | 36.00 | 322 | 58.35 | | | | |
| 12.50 | 1.14 | 0.97 | 33.78 | 356 | 56.70 | | | | |
| 12.75 | 1.17 | 0.99 | 34.52 | 390 | 55.00 | | | | |
| 13.00 | 1.16 | 0.99 | 34.46 | 425 | 50.20 | 47.37 | 23.63 | 430 | 855 |
| 13.25 | 0.99 | 0.84 | 29.34 | 454 | 46.50 | | | | |
| 13.50 | 0.84 | 0.72 | 24.98 | 479 | 47.27 | | | | |
| 13.75 | 0.59 | 0.50 | 17.48 | 497 | 47.30 | | | | |
| 14.00 | 0.97 | 0.83 | 28.83 | 526 | 62.47 | | | | |
| 14.25 | 1.53 | 1.30 | 45.19 | 571 | 106.35 | | | | |
| 14.50 | 1.11 | 0.94 | 32.89 | 604 | 127.73 | | | | |
| 14.75 | 1.11 | 0.94 | 32.89 | 637 | 149.80 | | | | |
| 15.00 | 2.05 | 1.74 | 60.66 | 697 | 162.90 | 173.94 | 68.33 | 1,467 | 2,164 |
| 15.25 | 1.72 | 1.46 | 50.82 | 748 | 196.20 | | | | |
| 15.50 | 1.48 | 1.26 | 43.77 | 792 | 203.30 | | | | |
| 15.75 | 1.16 | 0.98 | 34.23 | 826 | 170.90 | 169.20 | 98.38 | 1,620 | 2,446 |
| 16.00 | 1.15 | 0.98 | 34.17 | 860 | 168.63 | | | | |
| 16.25 | 1.24 | 1.05 | 36.75 | 897 | 173.95 | | | | |
| 16.50 | 1.61 | 1.37 | 47.71 | 945 | 208.87 | 216.83 | 129.36 | 2,096 | 3,041 |
| 16.75 | 1.61 | 1.36 | 47.56 | 992 | 224.80 | | | | |
| 17.00 | 1.88 | 1.60 | 55.62 | 1,048 | 252.37 | | | | |
| 17.25 | 1.84 | 1.56 | 54.53 | 1,102 | 260.65 | 252.40 | 173.18 | 2,577 | 3,679 |
| 17.50 | 2.08 | 1.77 | 61.73 | 1,164 | 249.23 | | | | |
| 17.75 | 2.28 | 1.93 | 67.42 | 1,231 | 252.40 | | | | |
| 18.00 | 2.86 | 2.43 | 84.75 | 1,316 | 305.00 | | | | |
| 18.25 | 2.56 | 2.17 | 75.71 | 1,392 | 297.40 | | | | |
| 18.50 | 2.12 | 1.80 | 62.91 | 1,455 | 254.83 | | | | |
| 18.75 | 1.71 | 1.45 | 50.52 | 1,505 | 214.85 | | | | |
| 19.00 | 1.31 | 1.11 | 38.82 | 1,544 | 148.70 | | | | |

Note: Depth is referenced from the original ground surface.

F.2.1.7 Summary of North Abutment Capacity Calculation Results

Summary of Pile Capacity Estimates with an Embedded Pile Length of 11.5 meters

| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
|--|--|--|---|
| Meyerhof Method - SPT Data | 418 | 854 | 1,272 |
| Nordlund Method - SPT Data | 898 | 940 | 1,838 |
| Effective Stress Method - SPT Data | 537 | 1,294 | 1,831 |
| Driven Program - SPT Data | 920 | 920 | 1,840 |
| LPC CPT Program - CPT Data | 780 | 511 | 1,291 |
| Schmertmann Method - CPT Data | 604 | 1,111 | 1,715 |

Summary of Pile Length Estimates for the 1,780 kN Ultimate Pile Capacity

| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
|--|---|
| Meyerhof Method - SPT Data | 13.0 meters for 1,840 kN |
| Nordlund Method - SPT Data | 11.5 meters for 1,838 kN |
| Effective Stress Method | 14.5 meters for 1,840 kN |
| Driven Program - SPT Data | 11.5 meters for 1,840 kN |
| LPC CPT Program - CPT Data | 13.5 meters for 1,815 kN |
| Schmertmann Method - CPT Data | 11.7 meters for 1,939 kN |

The ultimate pile group capacity at the North Abutment may be taken as the sum of the ultimate capacities of the individual piles in the group as discussed by the design recommendation for estimating group capacity in cohesionless soil presented in Section 9.8.1.1.

F.2.2 Pier 2 - Soil Boring S-2 (Cohesionless Soil)

F.2.2.1 Static Axial Pile Capacity Calculations by Meyerhof SPT Method (before scour)

For the soil profile interpreted from Soil Boring S-2 as shown in Figure F.5. Perform a Meyerhof method pile capacity calculation for an embedded length of 10 meters. Assume that scour has not occurred. Use the step-by-step method outlined in Section 9.7.1.1a.

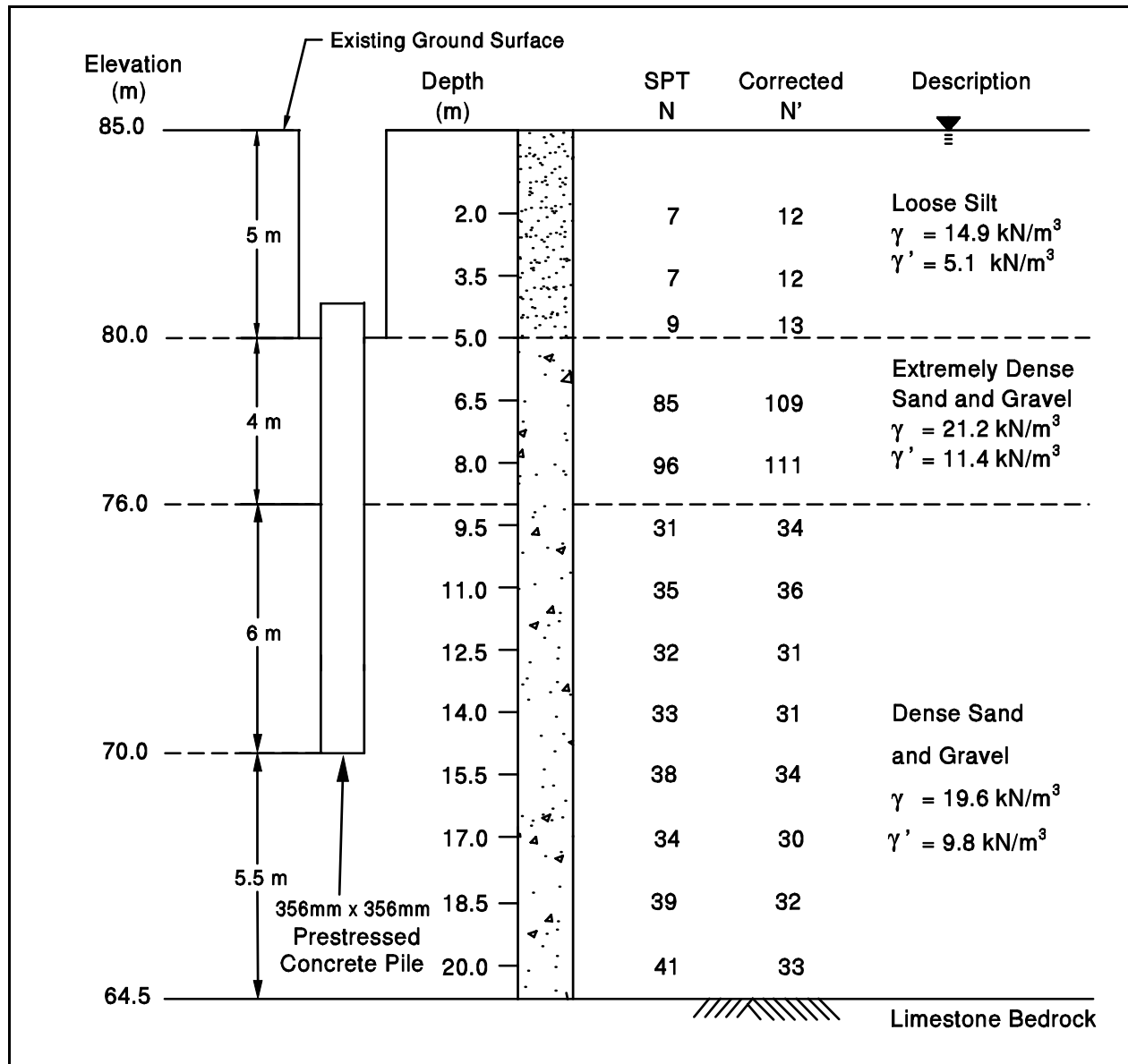


Figure F.5 Interpreted Soil Profile from Soil Boring S-2 at Pier 2

STEP 1 Correct SPT field N values for overburden pressure.

Effective overburden pressures, p_o , are needed to correct SPT field N values. The method for calculating the effective overburden pressure is explained in Section 9.4 and an example was presented earlier in Section F.2.1.1. The effective overburden pressure diagram and the soil layers are presented in Figure F.6 below.

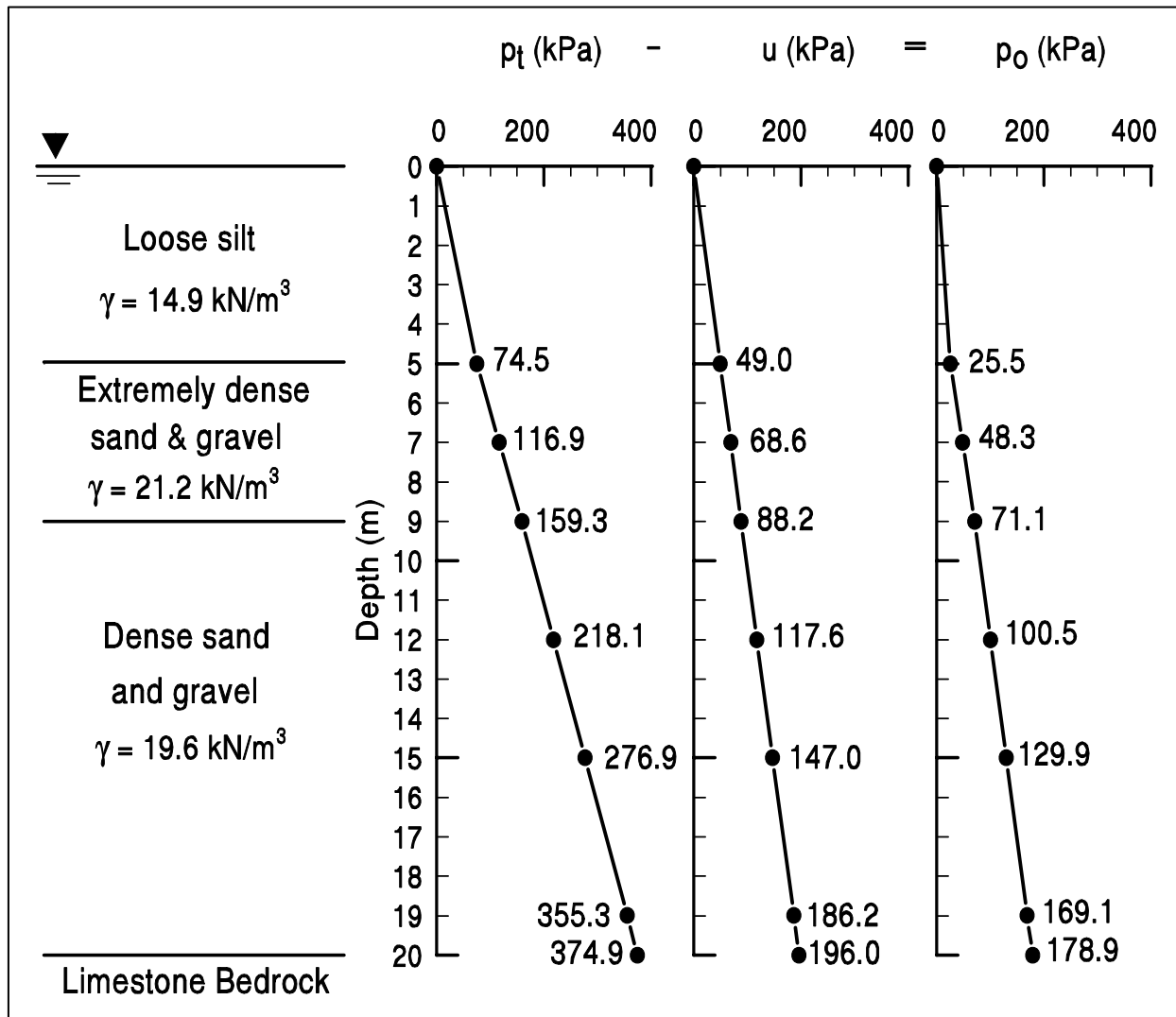


Figure F.6 Effective Overburden Pressure Diagram – Pier 2

STEP 1 (continued)

Use correction factors from Figure 4.6 (Chapter 4) to obtain corrected SPT N' values.

| Depth (m) | p_o (kPa) | Field SPT N value | Correction Factor | Corrected SPT N' (Field SPT N x Correction Factor) |
|--------------|----------------|----------------------|----------------------|--|
| 2.0 | 10.2 | 7 | 1.75 | 12 |
| 3.5 | 17.9 | 7 | 1.65 | 12 |
| 5.0 | 25.5 | 9 | 1.43 | 13 |
| 6.5 | 42.6 | 85 | 1.28 | 109 |
| 8.0 | 59.7 | 96 | 1.16 | 111 |
| 9.5 | 76.0 | 31 | 1.09 | 34 |
| 11.0 | 90.7 | 35 | 1.04 | 36 |
| 12.5 | 105.4 | 32 | 0.98 | 31 |
| 14.0 | 120.1 | 33 | 0.95 | 31 |
| 15.5 | 134.8 | 38 | 0.90 | 34 |
| 17.0 | 149.5 | 34 | 0.87 | 30 |
| 18.5 | 164.2 | 39 | 0.83 | 32 |
| 20.0 | 178.9 | 41 | 0.81 | 33 |

STEP 2 Compute the average corrected SPT N' value, \bar{N}' , for each soil layer.

Along the pile embedded length, the soil profile is delineated into two layers. Layer 1 is extremely dense sand and gravel that is 4 meters thick, and layer 2 is dense sand and gravel that is 6 meters thick.

$$\bar{N}_1' = \frac{109 + 111}{2} = 110 \quad \begin{array}{l} \text{(Layer 1 - depth 5 to 9 m;} \\ \text{Extremely dense sand and gravel)} \end{array}$$

$$\bar{N}_2' = \frac{34 + 36 + 31 + 31}{4} = 33 \quad \begin{array}{l} \text{(Layer 2 - depth 9 to 15 m;} \\ \text{Dense sand and gravel)} \end{array}$$

STEP 3 Compute unit shaft resistance, f_s (kPa), using the equation for driven displacement piles:

$$f_s = 2\bar{N}' \leq 100 \text{ kPa}$$

$$\text{Layer 1: } f_{s1} = 2 (110) = 220 \text{ kPa, so use } f_{s1} = 100 \text{ kPa}$$

$$\text{Layer 2: } f_{s2} = 2 (33) = 66 \text{ kPa}$$

STEP 4 Compute ultimate shaft resistance, R_s (kN).

$$R_s = f_s A_s$$

$$\text{Layer 1: } R_{s1} = 100 \text{ kPa } (4) (0.356 \text{ m }) (4 \text{ m }) = 570 \text{ kN}$$

$$\text{Layer 2: } R_{s2} = 66 \text{ kPa } (4) (0.356 \text{ m }) (6 \text{ m }) = 564 \text{ kN}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} = 570 \text{ kN} + 564 \text{ kN} \\ &= 1,134 \text{ kN} \end{aligned}$$

STEP 5 Compute average corrected SPT N' value, \bar{N}'_O and \bar{N}'_B near pile toe.

When the pile is embedded to more than 10 pile diameters into the bearing stratum, the effect of overlying stratum becomes irrelevant. The unit toe resistance is governed by the limiting unit toe resistance of the bearing stratum that is $400\bar{N}'_B$.

The average corrected SPT N' value for the bearing stratum should be calculated from the average N' value within the zone extending 3 pile diameters below the pile toe or in this case 1.065 meter. The average corrected SPT N' value for the bearing stratum which consists of dense sand and gravel is:

$$\bar{N}'_B = \frac{34 + 36 + 31 + 31 + 34}{5} = 33$$

STEP 6 Compute unit toe resistance, q_t (kPa).

$$q_t = \frac{40\bar{N}'_B D_B}{b} \leq 400\bar{N}'_B$$
$$= \frac{40\bar{N}'_B (6 \text{ m})}{0.356 \text{ m}} = 674\bar{N}'_B, \text{ so use } q_t = 400\bar{N}'_B$$

$$q_t = 400 (33) = 13,200 \text{ kPa}$$

STEP 7 Compute ultimate toe resistance, R_t (kN).

$$R_t = q_t A_t = 13,200 \text{ kPa} (0.356 \text{ m}) (0.356 \text{ m})$$
$$= 1,676 \text{ kN}$$

STEP 8 Compute ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 1,134 \text{ kN} + 1,676 \text{ kN} \\ &= 2,810 \text{ kN} \end{aligned}$$

STEP 9 Compute allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{2,810 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.2.2 Static Axial Pile Capacity Calculations by Nordlund Method (before scour at 10 m)

For the soil profile interpreted from Soil Boring S-2 as shown in Figure F.5. Perform a Nordlund method pile capacity calculation for an embedded length of 10 meters. Assume that scour has not occurred. Use the step-by-step method outlined in Section 9.7.1.1b.

STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer.

- a. Construct p_o diagram using the procedure described in Section 9.4. This is completed in Figure F.6.
- b. Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values. For Soil Boring S-2, this has been done in the previous example (see Section F.2.2.1, Step 1).
- c. Determine ϕ angle for each layer from laboratory tests or in-situ data.

Since the ϕ angle is not provided by either laboratory or in-situ data, it should be determined using the average corrected SPT N' value, \bar{N}' , as calculated below.

- d. In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, \bar{N}' , for each soil layer and estimate ϕ angle from Table 4-6 in Chapter 4.

As the example in Section F.2.2.1, the soil profile along the pile embedded length is delineated into two layers of 4, and 6 meters thick. The average corrected SPT N' value for each soil layer is as follows:

| | | |
|----------|--------------------|--|
| Layer 1: | $\bar{N}_1' = 110$ | (Layer 1 - depth 5 to 9 m; Extremely dense sand and gravel) |
| Layer 2: | $\bar{N}_2' = 33$ | (Layer 2 - depth 9 to 15 m; Dense sand and gravel) |

Use the average corrected SPT N' value for each soil layer to estimate ϕ angle from Table 4-6 in Chapter 4.

STEP 1 (continued)

Based on Table 4-6, the ϕ angle is indicated to be as high as 43° when N' is greater than 50. However, as discussed in Section 9.5, in soil layers with greater than 50% gravel the ϕ angle for shaft resistance calculations should be limited to:

36° for hard angular gravel, and
32° for soft rounded gravel.

A limiting friction angle should be used for layer 1.

Layer 1: $\phi_1 = 36^\circ$ limiting friction angle for hard angular gravel

For layer 2, the friction angle is computed from Table 4-6:

Layer 2: $\phi_2 = 35^\circ$ for $\bar{N}_2' = 33$

STEP 2 Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .

- a. Compute volume of soil displaced per unit length of pile, V .

Since this is a uniform cross section ($\omega = 0^\circ$) pile,

$$V = (0.356 \text{ m})(0.356 \text{ m})(1.0 \text{ m/m}) = 0.127 \text{ m}^3/\text{m}$$

For a non-uniform pile cross section ($\omega \neq 0^\circ$), the pile should be divided into sections and the volume for each section should be calculated.

- b. Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.

For a precast, prestressed concrete pile with $V = 0.127 \text{ m}^3/\text{m}$

$$\delta/\phi = 0.84$$

STEP 2 (continued)

- c. Calculate δ from δ/ϕ ratio.

$$\text{Layer 1: } \delta_1 = 0.84 (36^\circ) = 30.2^\circ$$

$$\text{Layer 2: } \delta_2 = 0.84 (35^\circ) = 29.4^\circ$$

STEP 3 Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.

- a. Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.

The pile taper angle, ω , = 0° .

For Layer 1:

$$\phi_1 = 36^\circ \quad \text{and} \quad V = 0.127 \text{ m}^3/\text{m}, \text{ therefore use Step 3e.}$$

A step by step procedure for determining K_δ using the linear interpolation and the log linear interpolation is presented in Section F.2.1.2 - Step 3.

$$\text{For } \phi_1 = 36^\circ, \omega = 0^\circ, \text{ and } V = 0.127 \text{ m}^3/\text{m}:$$

$$K_{\delta 1} = 2.10$$

For Layer 2:

$$\phi_2 = 35^\circ \quad \text{and} \quad V = 0.127 \text{ m}^3/\text{m}, \text{ therefore use Step 3d.}$$

A step by step procedure for determining K_δ using the log linear interpolation is presented in Section F.2.1.2 - Step 3.

$$\text{For } \phi_2 = 35^\circ, \omega = 0^\circ, \text{ and } V = 0.127 \text{ m}^3/\text{m}:$$

$$K_{\delta 2} = 1.83$$

STEP 4 Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and $\delta/\phi=0.84$ to determine C_F .

Layer 1: For $\phi_1 = 36^\circ \rightarrow C_{F1} = 0.92$

Layer 2: For $\phi_2 = 35^\circ \rightarrow C_{F2} = 0.93$

STEP 5 Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa). (Note: a limiting value is not applied to p_d).

The effective overburden pressure at the midpoint of each soil layer is equal to the average effective overburden pressure of that layer. The effective overburden pressure versus depth for Pier 2 has been computed and tabulated in the previous example (see Section F.2.2.1 - Step 1). The effective overburden pressure diagram for Pier 2 is presented in Figure F.6.

Layer 1: $p_{d1} = 48.3 \text{ kPa}$ (midpoint of layer 1 - at depth of 7.0 m)

Layer 2: $p_{d2} = 100.5 \text{ kPa}$ (midpoint of layer 2 - at depth of 12.0 m)

STEP 6 Compute the shaft resistance in each soil layer. Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$R_s = K_\delta C_F p_d \sin \delta C_d D \quad (\text{for uniform pile cross section})$$

$$\text{where : } C_d = (4) (0.356 \text{ m}) = 1.424 \text{ m}$$

$$\text{Layer 1: } R_{s1} = 2.10 (0.92) (48.3 \text{ kPa}) (\sin 30.2^\circ) (1.424 \text{ m}) (4 \text{ m})$$

$$= 267 \text{ kN}$$

$$\text{Layer 2: } R_{s2} = 1.83 (0.93) (100.5 \text{ kPa}) (\sin 29.4^\circ) (1.424 \text{ m}) (6 \text{ m})$$

$$= 717 \text{ kN}$$

STEP 6 (continued)

$$\begin{aligned}\text{Total: } R_s &= R_{s1} + R_{s2} \\ &= 267 \text{ kN} + 717 \text{ kN} = 984 \text{ kN}\end{aligned}$$

STEP 7 Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

Since the ϕ angle is not provided by either laboratory tests or in-situ data, the ϕ angle can be estimated from Table 4-6 using the average corrected SPT N' value over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{\text{toe}} = 34 \rightarrow \phi_{\text{toe}} = 36^\circ$$

- a. Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.

$$(D/b) = (10.0 \text{ m}) / (0.356 \text{ m}) = 28.1$$

$$\text{For } \phi_{\text{toe}} = 36^\circ \text{ and } (D/b) = 28.1 \rightarrow \alpha_t = 0.69$$

- b. Enter Figure 9.16(b) with ϕ angle near pile toe to determine N'_q .

$$\text{For } \phi_{\text{toe}} = 36^\circ \rightarrow N'_q = 75$$

STEP 8 Compute the effective overburden pressure at the pile toe, p_t (kPa).

The effective overburden pressure at the pile toe should be limited to a maximum of 150 kPa.

The effective overburden pressure at the pile toe, p_t , has been computed in the previous example (Section F.2.2.1, Step 1):

$$p_t = 129.9 \text{ kPa} < 150 \text{ kPa} \rightarrow \text{OK}$$

STEP 9 Compute ultimate toe resistance, R_t (kN).

$$\begin{aligned} \text{a. } R_t &= \alpha_t N'_q A_t p_t \\ &= 0.69 (75) (0.356 \text{ m})(0.356 \text{ m})(129.9 \text{ kPa}) \\ &= 854 \text{ kN} \end{aligned}$$

$$\text{b. limiting } R_t = q_L A_t$$

Using the estimated $\phi=36^\circ$ and Figure 9.17, the limiting unit toe resistance is:

$$q_L = 7,400 \text{ kPa}$$

Therefore,

$$R_t = 7,400 \text{ kPa} (0.356 \text{ m})(0.356 \text{ m}) = 940 \text{ kN}$$

c. Use lesser of the two R_t values obtained in steps a and b which is:

$$R_t = 854 \text{ kN}$$

STEP 10 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 984 \text{ kN} + 854 \text{ kN} = 1,838 \text{ kN} \end{aligned}$$

STEP 11 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,838 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.2.3 Static Axial Pile Capacity Calculations by Nordlund Method (after scour at 10 m)

For the soil profile interpreted from Soil Boring S-2 after scour as shown in Figure F.7. Perform a Nordlund method pile capacity calculation for an embedded length of 10 meters. Assume that channel degradation scour has removed the 5 meter thick loose silt layer. Use the step-by-step method outlined in Section 9.7.1.1b.

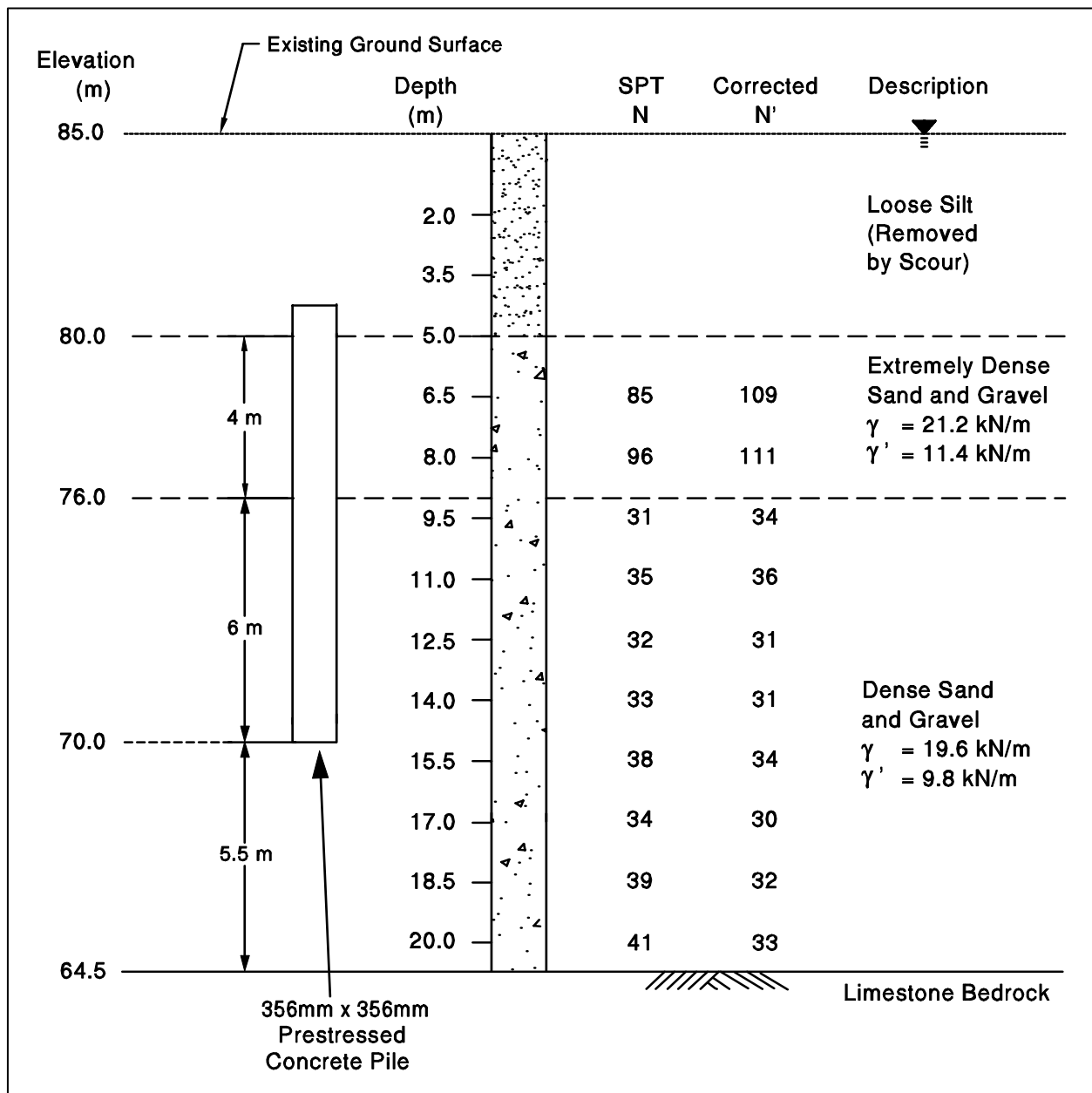


Figure F.7 Interpreted Soil Profile at Pier 2 after Scour

STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer.

- a. Construct p_o diagram using procedure described in Section 9.4. This is completed in Figure F.6.
- b. Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values. For Soil Boring S-2, this was done in the previous example (see Section F.2.2.1, Step 1).

Note: Although scour has eroded the 5 meter thick loose silt layer, the original overburden pressure (with the loose silt layer still in place) should be used when correcting the SPT field N values.

- c. Determine ϕ angle for each layer from laboratory tests or in-situ data.

Since the ϕ angle is not provided by either laboratory or in-situ data, it should be determined using the average corrected SPT N' value, \bar{N}' , as calculated below.

- d. In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, \bar{N}' , for each soil layer and estimate ϕ angle from Table 4-6 in Chapter 4.

As the example in Section F.2.2.2, the soil profile along the pile embedded length is delineated into two layers of 4, and 6 meters thick. The average corrected SPT N' value for each soil layer is as follow.

Layer 1: $\bar{N}'_1 = 110$ (Layer 1 - depth 5 to 9 m below existing ground surface; Extremely dense sand and gravel)

Layer 2: $\bar{N}'_2 = 33$ (Layer 2 - depth 9 to 15 m below existing ground surface; Dense sand and gravel)

Use the average corrected SPT N' value for each soil layer to estimate ϕ angle from Table 4-6 in Chapter 4.

STEP 1 (continued)

As discussed in Section F.2.2.2 - Step 1, a limiting friction angle should be used for the hard angular gravel of layer 1.

Layer 1: $\phi_1 = 36^\circ$ from limiting friction angle

For layer 2, the friction angle is computed from Table 4-6:

Layer 2: $\phi_2 = 35^\circ$ for $\bar{N}_2' = 33$

STEP 2 Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .

- a. Compute volume of soil displaced per unit length of pile, V .
Since this is a uniform cross section ($\omega = 0^\circ$) pile,

$$V = (0.356 \text{ m})(0.356 \text{ m})(1.0 \text{ m/m}) = 0.127 \text{ m}^3/\text{m}$$

For a non-uniform pile cross section ($\omega \neq 0^\circ$), the pile should be divided into sections and the volume for each section should be calculated.

- b. Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.

For a precast, prestressed concrete pile with $V = 0.127 \text{ m}^3/\text{m}$

$$\delta/\phi = 0.84$$

- c. Calculate δ from δ/ϕ ratio.

$$\text{Layer 1: } \delta_1 = 0.84 (36^\circ) = 30.2^\circ$$

$$\text{Layer 2: } \delta_2 = 0.84 (35^\circ) = 29.4^\circ$$

STEP 3 Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.

- a. Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.

The pile taper angle, ω , = 0° .

For Layer 1:

$\phi_1 = 36^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

A step by step procedure for determining K_δ using the linear interpolation and the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_1 = 36^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 1} = 2.10$$

For Layer 2:

$\phi_2 = 35^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3d.

A step by step procedure for determining K_δ using the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_2 = 35^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 2} = 1.83$$

STEP 4 Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and $\delta/\phi=0.84$ to determine C_F .

Layer 1: For $\phi_1 = 36^\circ \rightarrow C_{F1} = 0.92$

Layer 2: For $\phi_2 = 35^\circ \rightarrow C_{F2} = 0.93$

STEP 5 Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa). (Note: a limiting value is not applied to p_d)

The effective overburden pressure at the midpoint of each layer is equal to the average effective overburden pressure of that layer. The effective overburden pressure diagram for Pier 2 after scour is presented in Figure F.8. The purpose of this example is to illustrate how scour reduces the average effective overburden pressures, and hence the pile shaft and toe resistance.

Layer 1: $p_{d1} = 22.8$ kPa (midpoint of layer 1 - at depth of 7.0 m below existing ground surface)

Layer 2: $p_{d2} = 75.0$ kPa (midpoint of layer 2 - at depth of 12.0 m below existing ground surface)

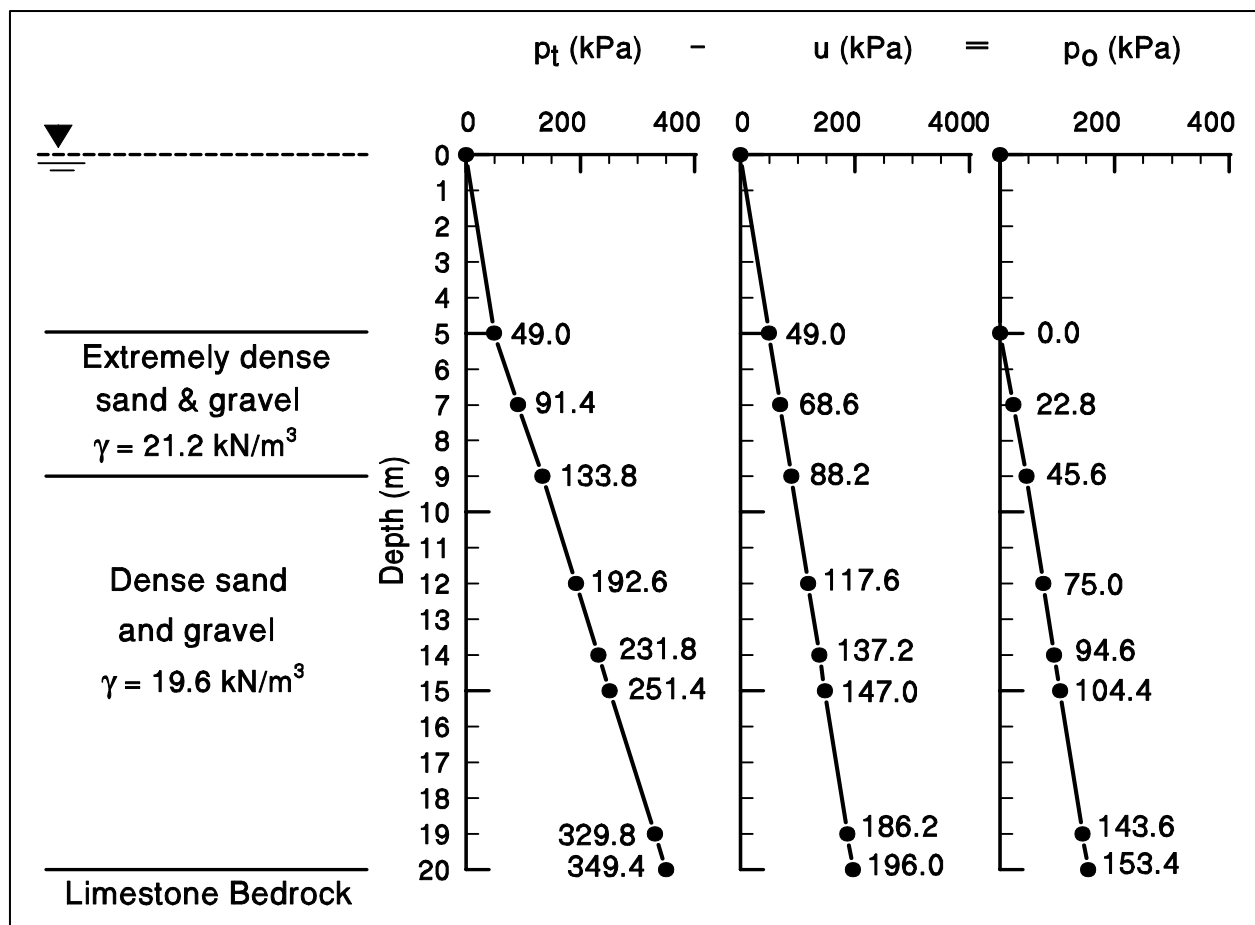


Figure F.8 Effective Overburden Pressure Design – Pier 2 after Scour

STEP 6 Compute the shaft resistance in each soil layer. Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$R_s = K_\delta C_F p_d \sin \delta C_d D \quad (\text{for uniform pile cross section})$$

$$\text{where : } C_d = (4) (0.356 \text{ m}) = 1.424 \text{ m}$$

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 2.10 (0.92) (22.8 \text{ kPa}) (\sin 30.2^\circ) (1.424 \text{ m}) (4 \text{ m}) \\ &= 126 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 1.83 (0.93) (75.0 \text{ kPa}) (\sin 29.4^\circ) (1.424 \text{ m}) (6 \text{ m}) \\ &= 535 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} = 126 \text{ kN} + 535 \text{ kN} \\ &= 661 \text{ kN} \rightarrow \text{as compared to 984 kN before scour.} \end{aligned}$$

STEP 7 Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

As in Section F.2.2.2,

$$\bar{N}'_{toe} = 34 \rightarrow \phi_{toe} = 36^\circ$$

a. Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.

$$(D/b) = (10.0 \text{ m}) / (0.356 \text{ m}) = 28.1$$

$$\text{For } \phi_{toe} = 36^\circ \text{ and } (D/b) = 28.1 \rightarrow \alpha_t = 0.69$$

b. Enter Figure 9.16(b) with ϕ angle near pile toe to determine N'_q .

$$\text{For } \phi_{toe} = 36^\circ \rightarrow N'_q = 75$$

STEP 8 Compute the effective overburden pressure at the pile toe, p_t (kPa).

The effective overburden pressure at the pile toe should be limited to a maximum of 150 kPa.

The effective overburden pressure at the pile toe, p_t , after scour has been computed and shown in Figure F.8:

$$p_t = 104.4 \text{ kPa} < 150 \text{ kPa} \rightarrow \text{OK}$$

STEP 9 Compute the ultimate toe resistance, R_t (kN).

a. $R_t = \alpha_t N'_q A_t p_t$

$$= 0.69 (75) (0.356 \text{ m}) (0.356 \text{ m}) (104.4 \text{ kPa})$$

$$= 686 \text{ kN}$$

b. limiting $R_t = q_L A_t$

Using the estimated $\phi=36^\circ$ and Figure 9.17, the limiting unit toe resistance is:

$$q_L = 7,400 \text{ kPa}$$

Therefore,

$$R_t = 7,400 \text{ kPa} (0.356 \text{ m}) (0.356 \text{ m})$$

$$= 940 \text{ kN}$$

c. Use lesser of the two R_t values obtained in steps a and b which is:

$$R_t = 686 \text{ kN} \rightarrow \text{as compared to 854 kN before scour.}$$

STEP 10 Compute the ultimate pile capacity, Q_u (kN).

$$Q_u = R_s + R_t$$

$$= 661 \text{ kN} + 686 \text{ kN}$$

$$= 1,347 \text{ kN} \rightarrow \text{as compared to } 1,838 \text{ kN before scour.}$$

Note: After scour has occurred, the factor of safety is only:

$$\text{Factor of Safety} = \frac{Q_u}{\text{Design Load}} = \frac{1,347 \text{ kN}}{890 \text{ kN}} = 1.51$$

F.2.2.4 Static Axial Pile Capacity Calculations by Nordlund Method (before scour at 14 m)

For the soil profile interpreted from Soil Boring S-2 as shown in Figure F.5. Perform a Nordlund method pile capacity calculation for an embedded length of 14 meters. Assume that scour has not occurred. Use the step-by-step method outlined in Section 9.7.1.1b.

STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer.

- a. Construct p_o diagram using procedure described in Section 9.4. This is completed in Figure F.6.
- b. Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values. For Soil Boring S-2, this has been done in a previous example (see Section F.2.2.1, Step 1).
- c. Determine ϕ angle for each layer from laboratory tests or in-situ data.

Since the ϕ angle is not provided by either laboratory or in-situ data, it should be determined using the average corrected SPT N' value, \bar{N}' , as calculated below.

- d. In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, \bar{N}' , for each soil layer and estimate ϕ angle from Table 4-6 in Chapter 4.

The soil profile along the pile embedded length is delineated into two layers of 4, and 10 meters thick. The average corrected SPT N' value for each soil layer is as follow.

$$\bar{N}_1' = 110 \quad \begin{array}{l} \text{(Layer 1 - depth 5 to 9 m;} \\ \text{Extremely dense sand and gravel)} \end{array}$$

$$\bar{N}_2' = \frac{34 + 36 + 31 + 31 + 34 + 30 + 32}{7} = 33$$

(Layer 2 - depth 9 to 19 m;
Dense sand and gravel)

STEP 1 (continued)

Use the average corrected SPT N' value for each soil layer to estimate ϕ angle from Table 4-6 in Chapter 4.

As discussed in Section F.2.2.2 - Step 1, a limiting friction angle should be used for the hard angular gravel of layer 1.

Layer 1: $\phi_1 = 36^\circ$ from limiting friction angle

For layer 2, the friction angle is computed from Table 4-6:

Layer 2: $\phi_2 = 35^\circ$ for $\bar{N}_2' = 33$

STEP 2 Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .

- a. Compute volume of soil displaced per unit length of pile, V .
Since this is a uniform cross section ($\omega = 0^\circ$) pile,

$$V = (0.356 \text{ m})(0.356 \text{ m})(1.0 \text{ m/m}) = 0.127 \text{ m}^3/\text{m}$$

- b. Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.

For a precast, prestressed concrete pile with $V = 0.127 \text{ m}^3/\text{m}$

$$\delta/\phi = 0.84$$

- c. Calculate δ from δ/ϕ ratio.

Layer 1: $\delta_1 = 0.84 (36^\circ) = 30.2^\circ$

Layer 2: $\delta_2 = 0.84 (35^\circ) = 29.4^\circ$

STEP 3 Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.

- a. Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.

The pile taper angle, ω , = 0° .

For Layer 1:

$\phi_1 = 36^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

A step by step procedure for determining K_δ using the linear interpolation and the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_1 = 36^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 1} = 2.10$$

For Layer 2:

$\phi_2 = 35^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3d.

A step by step procedure for determining K_δ using the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_2 = 35^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 2} = 1.83$$

STEP 4 Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and $\delta/\phi=0.84$ to determine C_F .

Layer 1: For $\phi_1 = 36^\circ \rightarrow C_{F1} = 0.92$

Layer 2: For $\phi_2 = 35^\circ \rightarrow C_{F2} = 0.93$

STEP 5 Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa). (Note: a limiting value is not applied to p_d).

The effective overburden pressure at the midpoint of each soil layer is equal to the average effective overburden pressure of that layer. The effective overburden pressure versus depth for the Pier 2 has been computed and tabulated in a previous example (see Section F.2.2.1 - Step 1). The effective overburden pressure diagram for Pier 2 is presented in Figure F.6.

Layer 1: $p_{d1} = 48.3 \text{ kPa}$ (midpoint of layer 1 - at depth of 7.0 m)

Layer 2: $p_{d2} = 120.1 \text{ kPa}$ (midpoint of layer 2 - at depth of 14.0 m)

STEP 6 Compute the shaft resistance in each soil layer. Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$R_s = K_\delta C_F p_d \sin \delta C_d D \quad (\text{for uniform pile cross section})$$

$$\text{where: } C_d = (4)(0.355 \text{ m}) = 1.424 \text{ m}$$

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 2.10 (0.92) (48.3 \text{ kPa}) (\sin 30.2^\circ) (1.424 \text{ m}) (4 \text{ m}) \\ &= 267 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 1.83 (0.93) (120.1 \text{ kPa}) (\sin 29.4^\circ) (1.424 \text{ m}) (10 \text{ m}) \\ &= 1,429 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= 267 \text{ kN} + 1,429 \text{ kN} \\ &= 1,696 \text{ kN} \end{aligned}$$

STEP 7 Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

Since the ϕ angle is not provided by either laboratory tests or in-situ data, the ϕ angle can be estimated from Table 4-6 using the average corrected SPT N' value over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{toe} = 33 \rightarrow \phi_{toe} = 35^\circ$$

- a. Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.

$$(D/b) = (14.0 \text{ m}) / (0.356 \text{ m}) = 39.3$$

$$\text{For } \phi_{toe} = 35^\circ \text{ and } (D/b) = 39.3 \rightarrow \alpha_t = 0.66$$

- b. Enter Figure 9.16(b) with ϕ angle near pile toe to determine N'_q .

$$\text{For } \phi_{toe} = 35^\circ \rightarrow N'_q = 65$$

STEP 8 Compute the effective overburden pressure at the pile toe, p_t (kPa).

The effective overburden pressure at the pile toe should be limited to a maximum of 150 kPa.

The effective overburden pressure at the pile toe, p_t , has been computed in the previous example (Section F.2.2.1, Step 1):

$$p_t = 169.1 \text{ kPa} > 150 \text{ kPa} \rightarrow \text{so use } p_t = 150 \text{ kPa}$$

STEP 9 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} \text{a. } R_t &= \alpha_t N'_q A_t p_t \\ &= 0.66 (65) (0.356 \text{ m}) (0.356 \text{ m}) (150.0 \text{ kPa}) \\ &= 817 \text{ kN} \end{aligned}$$

$$\text{b. limiting } R_t = q_L A_t$$

Using the estimated $\phi=35^\circ$ and Figure 9.17, the limiting unit toe resistance is:

$$q_L = 5,000 \text{ kPa}$$

Therefore,

$$R_t = 5,000 \text{ kPa} (0.356 \text{ m}) (0.356 \text{ m}) = 635 \text{ kN}$$

c. Use lesser of the two R_t values obtained in steps a and b which is:

$$R_t = 635 \text{ kN}$$

STEP 10 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 1,696 \text{ kN} + 635 \text{ kN} = 2,331 \text{ kN} \end{aligned}$$

STEP 11 Compute allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{2,331 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.2.5 Static Axial Pile Capacity Calculations by Nordlund Method (after scour at 14 m)

For the soil profile interpreted from Soil Boring S-2 after scour as shown in Figure F.7. Perform a Nordlund method pile capacity calculation for an embedded length of 14 meters. Assume that scour has removed the 5 meter thick loose silt layer. Use the step-by-step method outlined in Section 9.7.1.1b.

STEP 1 Delineate the soil profile into layers and determine the ϕ angle for each layer.

- a. Construct p_o diagram using procedure described in Section 9.4. This is completed in Figure F.6.
- b. Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values. For Soil Boring S-2, this has been done in the previous example (see Chapter F.2.2.1 - Step 1).

Note: Although scour has eroded the 5 meter thick loose silt layer, the original overburden pressure (with the loose silt layer still in place) should be used when correcting the SPT field N values.

- c. Determine ϕ angle for each layer from laboratory tests or in-situ data.

Since the ϕ angle is not provided by either laboratory or in-situ data, it should be determined using the average corrected SPT N' value, \bar{N}' , as calculated below.

- d. In the absence of laboratory or in-situ test data, determine the average corrected SPT N' value, \bar{N}' , for each soil layer and estimate ϕ angle from Table 4-6 in Chapter 4.

The soil profile along the pile embedded length is delineated into two layers of 4, and 10 meters thick. The average corrected SPT N' value for each soil layer is as follow.

$$\bar{N}_1' = 110$$

(Layer 1 - depth 5 to 9 m;
Extremely dense sand and gravel)

STEP 1 (continued)

$$\bar{N}_2' = \frac{34 + 36 + 31 + 31 + 34 + 30 + 32}{7} = 33$$

(Layer 2 - depth 9 to 19 m;
Dense sand and gravel)

Use the average corrected SPT N' value for each soil layer to estimate ϕ angle from Table 4-6 in Chapter 4.

As discussed in Section F.2.2.2 - Step 1, a limiting friction angle should be used for the hard angular gravel of layer 1.

Layer 1: $\phi_1 = 36^\circ$ from limiting friction angle

For layer 2, the friction angle is computed from Table 4-6:

Layer 2: $\phi_2 = 35^\circ$ for $\bar{N}_2' = 33$

STEP 2 Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .

- a. Compute volume of soil displaced per unit length of pile, V .
Since this is a uniform cross section ($\omega = 0^\circ$) pile,

$$V = (0.356 \text{ m})(0.356 \text{ m})(1.0 \text{ m/m}) = 0.127 \text{ m}^3/\text{m}$$

- b. Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.

For a precast, prestressed concrete pile with $V = 0.127 \text{ m}^3/\text{m}$

$$\delta/\phi = 0.84$$

- c. Calculate δ from δ/ϕ ratio.

$$\text{Layer 1: } \delta_1 = 0.84 (36^\circ) = 30.2^\circ$$

$$\text{Layer 2: } \delta_2 = 0.84 (35^\circ) = 29.4^\circ$$

STEP 3 Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.

- a. Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.

The pile taper angle, ω , = 0° .

For Layer 1:

$\phi_1 = 36^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

A step by step procedure for determining K_δ using the linear interpolation and the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_1 = 36^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 1} = 2.10$$

For Layer 2:

$\phi_2 = 35^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3d.

A step by step procedure for determining K_δ using the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_2 = 35^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 2} = 1.83$$

STEP 4 Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and $\delta/\phi=0.84$ to determine C_F .

Layer 1: For $\phi_1 = 36^\circ \rightarrow C_{F1} = 0.92$

Layer 2: For $\phi_2 = 35^\circ \rightarrow C_{F2} = 0.93$

STEP 5 Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa). (Note: a limiting value is not applied to p_d).

The effective overburden pressure at the midpoint of each soil layer is equal to the average effective overburden pressure of that layer. The effective overburden pressure diagram for Pier 2 after scour is presented in Figure F.8.

Layer 1: $p_{d1} = 22.8 \text{ kPa}$ (midpoint of layer 1 - at depth of 7.0 m)

Layer 2: $p_{d2} = 94.6 \text{ kPa}$ (midpoint of layer 2 - at depth of 14.0 m)

STEP 6 Compute the shaft resistance in each soil layer. Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$R_s = K_\delta C_F p_d \sin \delta C_d D \quad (\text{for uniform pile cross section})$$

$$\text{where : } C_d = (4) (0.356 \text{ m}) = 1.424 \text{ m}$$

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 2.10 (0.92) (22.8 \text{ kPa}) (\sin 30.2^\circ) (1.424 \text{ m}) (4 \text{ m}) \\ &= 126 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 1.83 (0.93) (94.6 \text{ kPa}) (\sin 29.4^\circ) (1.424 \text{ m}) (10 \text{ m}) \\ &= 1,126 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} \\ &= 126 \text{ kN} + 1,126 \text{ kN} \\ &= 1,252 \text{ kN} \end{aligned}$$

STEP 7 Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

Since the ϕ angle is not provided by either laboratory tests or in-situ data, the ϕ angle can be estimated from Table 4-6 using the average corrected SPT N' value over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{toe} = 33 \rightarrow \phi_{toe} = 35^\circ$$

a. Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.

$$\begin{aligned}(D/b) &= (14.0 \text{ m}) / (0.356 \text{ m}) \\ &= 39.3\end{aligned}$$

$$\text{For } \phi_{toe} = 35^\circ \text{ and } (D/b) = 39.3 \rightarrow \alpha_t = 0.66$$

b. Enter Figure 9.16(b) with ϕ angle near pile toe to determine N'_q .

$$\text{For } \phi_{toe} = 35^\circ \rightarrow N'_q = 65$$

STEP 8 Compute the effective overburden pressure at the pile toe, p_t (kPa).

The effective overburden pressure at the pile toe should be limited to a maximum of 150 kPa.

The effective overburden pressure at the pile toe, p_t , after scour has been computed and shown in Figure F.8:

$$p_t = 143.6 \text{ kPa} < 150 \text{ kPa} \rightarrow \text{OK}$$

STEP 9 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} \text{a. } R_t &= \alpha_t N'_q A_t p_t \\ &= 0.66 (65) (0.356 \text{ m}) (0.356 \text{ m}) (143.6 \text{ kPa}) \\ &= 782 \text{ kN} \end{aligned}$$

$$\text{b. limiting } R_t = q_L A_t$$

Use the estimated $\phi=35^\circ$ and Figure 9.17, the limiting unit toe resistance is:

$$\begin{aligned} q_L &= 5,000 \text{ kPa} \\ R_t &= 5,000 \text{ kPa} (0.356 \text{ m}) (0.356 \text{ m}) \\ &= 635 \text{ kN} \end{aligned}$$

c. Use lesser of the two R_t values obtained in steps a and b which is:

$$R_t = 635 \text{ kN}$$

STEP 10 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 1,252 \text{ kN} + 635 \text{ kN} = 1,887 \text{ kN} \end{aligned}$$

STEP 11 Compute allowable design load, Q_a .

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,887 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.2.6 Static Axial Pile Capacity Calculations by Effective Stress Method (before scour)

For the soil profile interpreted from Soil Boring S-2 as shown in Figure F.5. Perform an Effective Stress method pile capacity calculation for an embedded length of 10 meters. Assuming that scour has not occurred. Use the step-by-step method outlined in Section 9.7.1.3.

STEP 1 Delineate the soil profile into layers and determine ϕ' angle for each layer.

- a. Use the procedure described in Section 9.4 to construct a p_o diagram.

For Soil Boring S-2, the p_o diagram has been constructed in Section F.2.2.1 - Step 1 and also presented in Figure F.6.

- b. Divide the soil profile throughout the pile penetration depth into layers and determine the effective overburden pressure, p_o , at the midpoint of each layer.

As for the example in Section F.2.2.1, the soil profile along the pile embedded length is delineated into two layers of 4 and 6 meters thick. The average effective overburden pressure of each layer is equal to the effective overburden pressure at the midpoint of that layer as follows.

Layer 1: $p_{o1} = 48.3 \text{ kPa}$ (midpoint of layer 1 - at depth of 7.0 m)

Layer 2: $p_{o2} = 100.5 \text{ kPa}$ (midpoint of layer 2 - at depth of 12.0 m)

- c. Determine the ϕ' angle for each soil layer from laboratory or in-situ test data.

Since the ϕ' angle is not provided by either laboratory or in-situ test data, the average corrected SPT N' value will be used to estimate the ϕ' angle.

- d. In the absence of laboratory or in-situ test data for cohesionless soil layers, determine the average corrected SPT N' value for each soil layer and estimate the ϕ' angle from Table 4-6 in Chapter 4.

STEP 1 (continued)

As in the previous example (Section F.2.2.1), the average corrected SPT N' value and the soil type for each soil layer are as follows.

Layer 1: $\bar{N}_1' = 110$ (Layer 1 - depth 5 to 9 m;
Extremely dense sand and gravel)

Layer 2: $\bar{N}_2' = 33$ (Layer 2 - depth 9 to 15 m;
Dense sand and gravel)

Use the average corrected SPT N' value for each soil layer to estimate ϕ' angle from Table 4-6 in Chapter 4.

Layer 1: $\phi_1' = 36^\circ$ (From limiting friction angle; see discussion in
Section F.2.2.2 - Step 1)

Layer 2: $\phi_2' = 35^\circ$ for $\bar{N}_2' = 33$

STEP 2 Select the β coefficient for each soil layer.

- a. Use local experience to select β coefficient for each layer.

Assume no local experience.

- b. In the absence of local experience, use Table 9-6 or Figure 9.20 to estimate β coefficient from ϕ' angle for each layer.

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.20 to estimate the β coefficient for each layer.

Layer 1: $\beta_1 = 0.42$ (For extremely dense sand and gravel
with $\phi_1' = 36^\circ$)

Layer 2: $\beta_2 = 0.39$ (For dense sand and gravel with $\phi_2' = 35^\circ$)

STEP 3 For each soil layer compute the unit shaft resistance, f_s (kPa).

$$f_s = \beta p_o$$

$$\text{Layer 1: } f_{s1} = 0.42 (48.3 \text{ kPa}) = 20.29 \text{ kPa}$$

$$\text{Layer 2: } f_{s2} = 0.39 (100.5 \text{ kPa}) = 39.20 \text{ kPa}$$

STEP 4 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s (kN) from the sum of the shaft resistance from each soil layer.

$$R_s = f_s A_s$$

where A_s = Pile-soil surface area from pile perimeter and length

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 20.29 (4) (0.356 \text{ m}) (4 \text{ m}) \\ &= 116 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 39.20 (4) (0.356 \text{ m}) (6 \text{ m}) \\ &= 335 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} \\ &= 116 \text{ kN} + 335 \text{ kN} \\ &= 451 \text{ kN} \end{aligned}$$

STEP 5 Compute the unit toe resistance, q_t (kPa).

$$q_t = N_t p_t$$

a. Use local experience to select N_t coefficient.

Assume no local experience.

STEP 5 (continued)

- b. In the absence of local experience, estimate N_t coefficient from Table 9-6 or Figure 9.21 based on ϕ' angle.

Table 9-6 or Figure 9.21 are a function of soil type and the ϕ' angle. The soil type for each layer can be obtained from the soil boring. The ϕ' angle for each layer can be obtained from laboratory tests or in-situ data. In the absence of either laboratory or in-situ test data, the ϕ' angle should be estimated from Table 4-6 in Chapter 4 using the average corrected SPT N' value, \bar{N}' , over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{\text{toe}} = 34 \quad \rightarrow \quad \phi'_{\text{toe}} = 36^\circ$$

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.21 to estimate the N_t coefficient.

$$N_t = 70 \quad (\text{For dense sand and gravel with } \phi'_{\text{toe}} = 36^\circ)$$

- c. Calculate the effective overburden pressure at the pile toe, p_t .

The effective overburden pressure at the pile toe, p_t , has been computed in the previous example (Section F.2.2.1, Step 1):

$$p_t = 129.9 \text{ kPa}$$

The unit toe resistance, q_t is:

$$\begin{aligned} q_t &= N_t p_t \\ &= 70 (129.9 \text{ kPa}) \\ &= 9,093 \text{ kPa} \end{aligned}$$

STEP 6 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} R_t &= q_t A_t \\ &= 9,093 (0.356 \text{ m}) (0.356 \text{ m}) \\ &= 1,155 \text{ kN} \end{aligned}$$

STEP 7 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 451 \text{ kN} + 1,155 \text{ kN} \\ &= 1,606 \text{ kN} \end{aligned}$$

Note: The ultimate capacity according to the Effective Stress method is less than the required 1780 kN ultimate capacity. The Effective Stress method would require a pile penetration depth of 12.5 meters for a 1780 kN capacity.

STEP 8 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,606 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.2.7 Static Axial Pile Capacity Calculations by Driven Computer Program (considering Scour)

Note: In the following tables, the depth corresponding to the pile tip is 15 m. The “driving strength loss (%)” factor used in Driven for Boring S-2 was selected based on Table 9-20. Because these soils are cohesionless sands and gravels, the soil set-up factor selected was 1.0. For this problem, the driving strength loss is therefore 0%. In the Driven results, the “Restrike” and “Driving” tables are the same because no strength was lost during driving to be regained when the restrike is performed. The “Ultimate” tables consider the removal of the silty upper 5 m of the soil profile due to scour.

DRIVEN 1.2 **GENERAL PROJECT INFORMATION**

Filename: C:\DRIVEN\S2.DVN
Project Name: Boring S-2 Project Date: 09/11/2003
Project Client: FHWA Manual
Computed By: BRR
Project Manager:

PILE INFORMATION

Pile Type: Concrete Pile
Top of Pile: 4.99 m
Length of Square Side: 356.00 mm

ULTIMATE CONSIDERATIONS

| | | |
|-------------------------------|--------------------|--------|
| Water Table Depth At Time Of: | - Drilling: | 0.00 m |
| | - Driving/Restrike | 0.00 m |
| | - Ultimate: | 0.00 m |
| Ultimate Considerations: | - Local Scour: | 0.00 m |
| | - Long Term Scour: | 5.00 m |
| | - Soft Soil: | 0.00 m |

ULTIMATE PROFILE

| Layer | Type | Thickness | Driving Loss | Unit Weight | Strength | Ultimate Curve |
|-------|--------------|-----------|--------------|-------------------------|-----------|----------------|
| 1 | Cohesionless | 5.00 m | 0.00% | 14.90 kN/m ³ | 30.7/30.7 | Nordlund |
| 2 | Cohesionless | 4.00 m | 0.00% | 21.20 kN/m ³ | 36.0/36.0 | Nordlund |
| 3 | Cohesionless | 6.00 m | 0.00% | 19.60 kN/m ³ | 35.0/36.0 | Nordlund |
| 4 | Cohesionless | 5.50 m | 0.00% | 19.60 kN/m ³ | 35.0/36.0 | Nordlund |

RESTRIKE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|----------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 3.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 4.99 m | Cohesionless | 25.47 kPa | 25.83 | N/A | 0.00 kN |
| 5.01 m | Cohesionless | 25.55 kPa | 30.32 | N/A | 0.45 kN |
| 8.01 m | Cohesionless | 42.65 kPa | 30.32 | N/A | 180.11 kN |
| 8.99 m | Cohesionless | 48.23 kPa | 30.32 | N/A | 269.98 kN |
| 9.01 m | Cohesionless | 71.14 kPa | 29.48 | N/A | 271.82 kN |
| 12.01 m | Cohesionless | 85.83 kPa | 29.48 | N/A | 580.23 kN |
| 14.99 m | Cohesionless | 100.43 kPa | 29.48 | N/A | 991.08 kN |
| 15.01 m | Cohesionless | 129.93 kPa | 29.48 | N/A | 994.18 kN |
| 18.01 m | Cohesionless | 144.63 kPa | 29.48 | N/A | 1513.70 kN |
| 20.49 m | Cohesionless | 156.78 kPa | 29.48 | N/A | 2022.87 kN |

RESTRIKE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 33.50 | 110.80 kN | 0.00 kN |
| 3.01 m | Cohesionless | 0.00 kPa | 33.50 | 110.80 kN | 0.00 kN |
| 4.99 m | Cohesionless | 0.00 kPa | 33.50 | 110.80 kN | 0.00 kN |
| 4.98 m | Cohesionless | 0.00 kPa | 33.50 | 110.80 kN | 0.00 kN |
| 4.99 m | Cohesionless | 25.47 kPa | 33.50 | 110.80 kN | 64.36 kN |
| 5.01 m | Cohesionless | 25.61 kPa | 77.60 | 919.89 kN | 174.59 kN |
| 8.01 m | Cohesionless | 59.80 kPa | 77.60 | 919.89 kN | 407.27 kN |
| 8.99 m | Cohesionless | 70.97 kPa | 77.60 | 919.89 kN | 482.70 kN |
| 9.01 m | Cohesionless | 71.18 kPa | 77.60 | 919.89 kN | 484.13 kN |
| 12.01 m | Cohesionless | 100.58 kPa | 77.60 | 919.89 kN | 681.68 kN |
| 14.99 m | Cohesionless | 129.78 kPa | 77.60 | 919.89 kN | 877.21 kN |
| 15.01 m | Cohesionless | 129.98 kPa | 77.60 | 919.89 kN | 878.52 kN |
| 18.01 m | Cohesionless | 159.37 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 20.49 m | Cohesionless | 183.67 kPa | 77.60 | 919.89 kN | 919.89 kN |

RESTRIKE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 3.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 4.99 m | 0.00 kN | 64.36 kN | 64.36 kN |
| 5.01 m | 0.45 kN | 174.59 kN | 175.05 kN |
| 8.01 m | 180.11 kN | 407.27 kN | 587.38 kN |
| 8.99 m | 269.98 kN | 482.70 kN | 752.68 kN |
| 9.01 m | 271.82 kN | 484.13 kN | 755.95 kN |
| 12.01 m | 580.23 kN | 681.68 kN | 1261.91 kN |
| 14.99 m | 991.08 kN | 877.21 kN | 1868.29 kN |
| 15.01 m | 994.18 kN | 878.52 kN | 1872.71 kN |
| 18.01 m | 1513.70 kN | 919.89 kN | 2433.59 kN |
| 20.49 m | 2022.87 kN | 919.89 kN | 2942.76 kN |

DRIVING - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|----------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 3.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 4.99 m | Cohesionless | 25.47 kPa | 25.83 | N/A | 0.00 kN |
| 5.01 m | Cohesionless | 25.55 kPa | 30.32 | N/A | 0.45 kN |
| 8.01 m | Cohesionless | 42.65 kPa | 30.32 | N/A | 180.11 kN |
| 8.99 m | Cohesionless | 48.23 kPa | 30.32 | N/A | 269.98 kN |
| 9.01 m | Cohesionless | 71.14 kPa | 29.48 | N/A | 271.82 kN |
| 12.01 m | Cohesionless | 85.83 kPa | 29.48 | N/A | 580.23 kN |
| 14.99 m | Cohesionless | 100.43 kPa | 29.48 | N/A | 991.08 kN |
| 15.01 m | Cohesionless | 129.93 kPa | 29.48 | N/A | 994.18 kN |
| 18.01 m | Cohesionless | 144.63 kPa | 29.48 | N/A | 1513.70 kN |
| 20.49 m | Cohesionless | 156.78 kPa | 29.48 | N/A | 2022.87 kN |

DRIVING - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 33.50 | 110.80 kN | 0.00 kN |
| 3.01 m | Cohesionless | 0.00 kPa | 33.50 | 110.80 kN | 0.00 kN |
| 4.99 m | Cohesionless | 25.47 kPa | 33.50 | 110.80 kN | 64.36 kN |
| 5.01 m | Cohesionless | 25.61 kPa | 77.60 | 919.89 kN | 174.59 kN |
| 8.01 m | Cohesionless | 59.80 kPa | 77.60 | 919.89 kN | 407.27 kN |
| 8.99 m | Cohesionless | 70.97 kPa | 77.60 | 919.89 kN | 482.70 kN |
| 9.01 m | Cohesionless | 71.18 kPa | 77.60 | 919.89 kN | 484.13 kN |
| 12.01 m | Cohesionless | 100.58 kPa | 77.60 | 919.89 kN | 681.68 kN |
| 14.99 m | Cohesionless | 129.78 kPa | 77.60 | 919.89 kN | 877.21 kN |
| 15.01 m | Cohesionless | 129.98 kPa | 77.60 | 919.89 kN | 878.52 kN |
| 18.01 m | Cohesionless | 159.37 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 20.49 m | Cohesionless | 183.67 kPa | 77.60 | 919.89 kN | 919.89 kN |

DRIVING - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 3.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 4.99 m | 0.00 kN | 64.36 kN | 64.36 kN |
| 5.01 m | 0.45 kN | 174.59 kN | 175.05 kN |
| 8.01 m | 180.11 kN | 407.27 kN | 587.38 kN |
| 8.99 m | 269.98 kN | 482.70 kN | 752.68 kN |
| 9.01 m | 271.82 kN | 484.13 kN | 755.95 kN |
| 12.01 m | 580.23 kN | 681.68 kN | 1261.91 kN |
| 14.99 m | 991.08 kN | 877.21 kN | 1868.29 kN |
| 15.01 m | 994.18 kN | 878.52 kN | 1872.71 kN |
| 18.01 m | 1513.70 kN | 919.89 kN | 2433.59 kN |
| 20.49 m | 2022.87 kN | 919.89 kN | 2942.76 kN |

ULTIMATE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|----------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 3.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 4.99 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 5.01 m | Cohesionless | 0.06 kPa | 30.32 | N/A | 0.00 kN |
| 8.01 m | Cohesionless | 17.16 kPa | 30.32 | N/A | 72.41 kN |
| 8.99 m | Cohesionless | 22.74 kPa | 30.32 | N/A | 127.24 kN |
| 9.01 m | Cohesionless | 45.64 kPa | 29.48 | N/A | 128.43 kN |
| 12.01 m | Cohesionless | 60.34 kPa | 29.48 | N/A | 345.29 kN |
| 14.99 m | Cohesionless | 74.94 kPa | 29.48 | N/A | 665.21 kN |
| 15.01 m | Cohesionless | 104.44 kPa | 29.48 | N/A | 667.71 kN |
| 18.01 m | Cohesionless | 119.13 kPa | 29.48 | N/A | 1095.68 kN |
| 20.49 m | Cohesionless | 131.28 kPa | 29.48 | N/A | 1529.18 kN |

ULTIMATE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | 0.00 kN | 0.00 kN |
| 3.01 m | Cohesionless | 0.00 kPa | 0.00 | 0.00 kN | 0.00 kN |
| 4.99 m | Cohesionless | 0.00 kPa | 0.00 | 0.00 kN | 0.00 kN |
| 5.01 m | Cohesionless | 0.11 kPa | 77.60 | 919.89 kN | 0.78 kN |
| 8.01 m | Cohesionless | 34.31 kPa | 77.60 | 919.89 kN | 233.94 kN |
| 8.99 m | Cohesionless | 45.48 kPa | 77.60 | 919.89 kN | 310.11 kN |
| 9.01 m | Cohesionless | 45.69 kPa | 77.60 | 919.89 kN | 311.55 kN |
| 12.01 m | Cohesionless | 75.09 kPa | 77.60 | 919.89 kN | 511.99 kN |
| 14.99 m | Cohesionless | 104.29 kPa | 77.60 | 919.89 kN | 708.33 kN |
| 15.01 m | Cohesionless | 104.48 kPa | 77.60 | 919.89 kN | 709.64 kN |
| 18.01 m | Cohesionless | 133.88 kPa | 77.60 | 919.89 kN | 906.55 kN |
| 20.49 m | Cohesionless | 158.18 kPa | 77.60 | 919.89 kN | 919.89 kN |

ULTIMATE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 3.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 4.99 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 5.01 m | 0.00 kN | 0.78 kN | 0.78 kN |
| 8.01 m | 72.41 kN | 233.94 kN | 306.35 kN |
| 8.99 m | 127.24 kN | 310.11 kN | 437.35 kN |
| 9.01 m | 128.43 kN | 311.55 kN | 439.98 kN |
| 12.01 m | 345.29 kN | 511.99 kN | 857.27 kN |
| 14.99 m | 665.21 kN | 708.33 kN | 1373.53 kN |
| 15.01 m | 667.71 kN | 709.64 kN | 1377.35 kN |
| 18.01 m | 1095.68 kN | 906.55 kN | 2002.23 kN |
| 20.49 m | 1529.18 kN | 919.89 kN | 2449.06 kN |

F.2.2.8 Summary of Pier 2 Capacity Calculation Results

Summary of Pile Capacity Estimates with an Embedded Pile Length of 10.0 meters

| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
|--|--|--|---|
| Meyerhof Method - SPT Data | 1,134 | 1,676 | 2,810 |
| Nordlund Method - SPT Data | 984 | 854 | 1,838 |
| Effective Stress Method | 451 | 1,155 | 1,606 |
| Driven Program - SPT Data | 994 | 878 | 1,873 |

Summary of Pile Length Estimates for the 1,780 kN Ultimate Pile Capacity

| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
|--|---|
| Meyerhof Method - SPT Data | 1.0 meters for 2,136 kN |
| Nordlund Method - SPT Data | 10.0 meters for 1,838 kN |
| Effective Stress Method | 12.5 meters for 1,847 kN |
| Driven Program - SPT Data | 10.0 meters for 1,873 kN |

Note: All analyses do not consider scour effects on ultimate capacity.

Summary of Pile Capacity Estimates Before and After Channel Degradation Scour
Based on Nordlund Method

| Pile Embedment | Ultimate Pile Capacity | |
|----------------|------------------------|-------------|
| | Before Scour | After Scour |
| 10 meters | 1,838 kN | 1,347 kN |
| 14 meters | 2,331 kN | 1,887 kN |

Summary of Pile Capacity Estimates Before and After Channel Degradation Scour
Based on Driven Program

| Pile Embedment | Ultimate Pile Capacity | |
|----------------|------------------------|-------------|
| | Before Scour | After Scour |
| 10 meters | 1873 kN | 1377 kN |
| 13 meters | 2433 kN | 2002 kN |

Similar to the North Abutment, the ultimate pile group capacity at Pier 2, may also be taken as the sum of the ultimate capacities of the individual piles in the group. The design recommendation for estimating group capacity in cohesionless soil, presented in Section 9.8.1.1, should be referred to for detail considerations.

F.2.3 Pier 3 - Soil Boring S-3 (Cohesive and Cohesionless Soil)

F.2.3.1 Static Axial Pile Capacity Calculations by Nordlund and α -Method

For the soil profile interpreted from Soil Boring S-3 as shown in Figure F.9. Perform a static pile capacity calculation using the Nordlund and α methods for an embedded length of 13 meters. Use the Nordlund method for the cohesionless soil layer and α -Method for the cohesive soil layer. Use the appropriate portions of the step-by-step methods outlined in Section 9.7.1.1b and 9.7.1.2a.

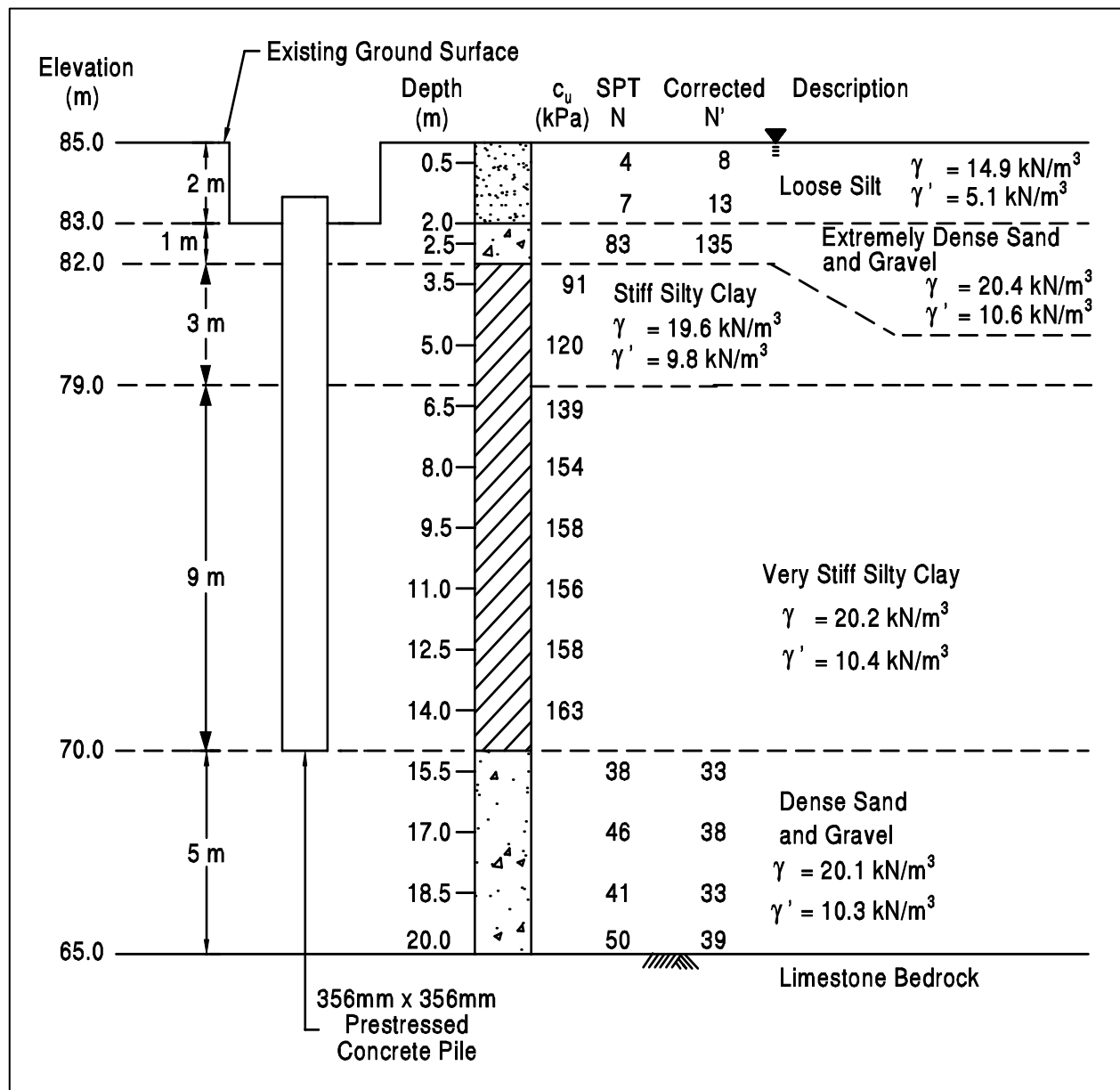


Figure F.9 Interpreted Soil Profile from Soil Boring S-3 at Pier 3

STEP 1 Delineate the soil profile into layers. Determine the ϕ angle for the cohesionless layer, and the undrained shear strength, c_u , for the cohesive layer.

a. Construct p_o diagram using procedure described in Section 9.4.

Effective overburden pressures, p_o , are needed to correct SPT field N values. The method for calculating the effective overburden pressure is explained in Section 9.4. A working example is presented in Section F.2.1.1. The effective overburden pressure diagram and soil layers are presented in Figure F.10.

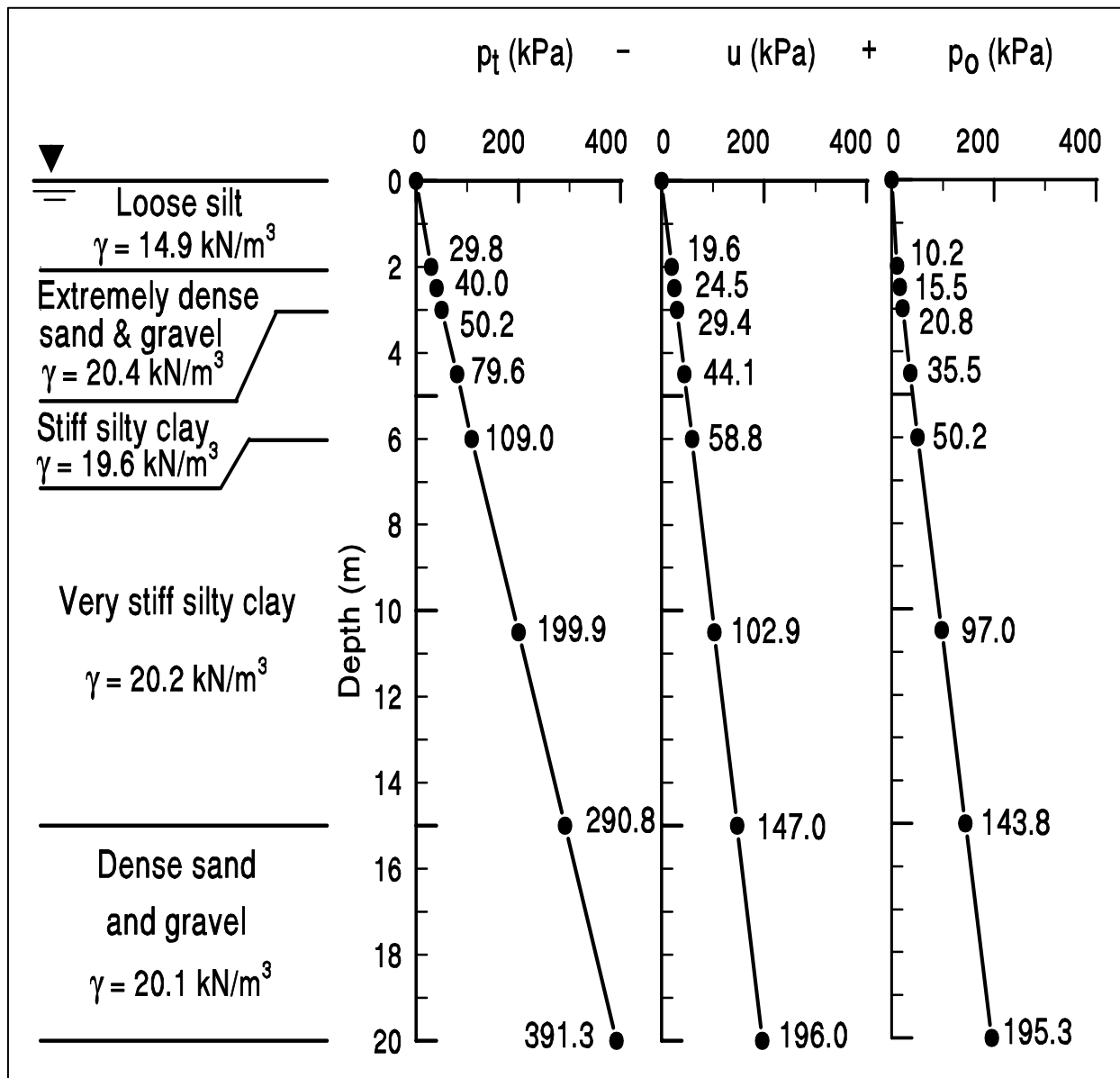


Figure F.10 Effective Overburden Pressure Diagram – Pier 3

STEP 1 (continued)

- b. Correct SPT field N values for overburden pressure using Figure 4.6 from Chapter 4 and obtain corrected SPT N' values.

| Depth (m) | p_o (kPa) | Field SPT N value | Correction Factor | Corrected SPT N' (Field SPT N x Correction Factor) |
|--------------|----------------|----------------------|----------------------|--|
| 2.0 | 10.2 | 7 | 1.80 | 13 |
| 2.5 | 15.5 | 83 | 1.63 | 135 |
| 15.5 | 149.0 | 38 | 0.87 | 33 |
| 17.0 | 164.6 | 46 | 0.83 | 38 |
| 18.5 | 180.2 | 41 | 0.80 | 33 |
| 20.0 | 195.3 | 50 | 0.77 | 39 |

Along the pile embedded length, the soil profile is delineated into three layers. Layer 1 is extremely dense sand and gravel that is 1.0 meter thick (cohesionless), layer 2 is stiff silty clay that is 3.0 meters thick (cohesive), and layer 3 is very stiff silty clay that is 9.0 meters thick (cohesive).

For the cohesionless soil layer, determine the average corrected SPT N' value, \bar{N}' , for the layer and estimate the ϕ angle from Table 4-6 in Chapter 4.

Layer 1: $\bar{N}'_1 = 135$ (Layer 1 - depth 2 to 3 m;
Extremely dense sand and Gravel)

For $N' > 50$, the ϕ angle computed by Table 4-6 can be as high as 43° . However, a limiting friction angle (as discussed in Section F.2.2.2 - Step 1) will govern for soil layer 1 since this layer contains hard angular gravel.

Layer 1: $\phi_1 = 36^\circ$ from limiting friction angle

STEP 1 (continued)

For the cohesive soil layer, determine the average undrained shear strength, c_u for each soil layer.

$$\text{Layer 2: } c_{u2} = \frac{91 + 120}{2} = 106 \text{ kPa} \quad (\text{Layer 2 - depth 3 to 6 m;} \\ \text{Stiff silty clay})$$

$$\text{Layer 3: } c_{u3} = \frac{139 + 154 + 158 + 156 + 158 + 163}{6} = 155 \text{ kPa} \\ (\text{Layer 3 - depth 6 to 15 m;} \\ \text{Very stiff silty clay})$$

STEP 2 Compute the shaft resistance at soil layer 1 (cohesionless) using Nordlund method.

a. (Nordlund - Step 2): Determine δ , the friction angle between pile and soil based on displaced soil volume, V , and the soil friction angle, ϕ .

(i) Compute volume of soil displaced per unit length of pile, V .

Since this is a uniform cross section ($\omega = 0^\circ$) pile,

$$V = (0.356 \text{ m})(0.356 \text{ m})(1.0 \text{ m/m}) = 0.127 \text{ m}^3/\text{m}$$

(ii) Enter Figure 9.10 with V and determine δ/ϕ ratio for pile type.

For a precast, prestressed concrete pile with $V = 0.127 \text{ m}^3/\text{m}$,

$$\delta/\phi = 0.84$$

(iii) Calculate δ from δ/ϕ ratio.

$$\text{Layer 1: } \delta_1 = 0.84 (36^\circ) = 30.2^\circ$$

STEP 2 (continued)

- b. (Nordlund - Step 3): Determine the coefficient of lateral earth pressure, K_δ , for each ϕ angle.

- (i) Determine K_δ for ϕ angle based on displaced volume, V , and pile taper angle, ω , using either Figure 9.11, 9.12, 9.13, or 9.14 and the appropriate procedure described in Step 3b, 3c, 3d, or 3e.

For $\phi_1 = 36^\circ$ and $V = 0.127 \text{ m}^3/\text{m}$, therefore use Step 3e.

A step by step procedure for determining K_δ using the linear interpolation and the log linear interpolation is presented in Section F.2.1.2 - Step 3.

For $\phi_1 = 36^\circ$, $\omega = 0^\circ$, and $V = 0.127 \text{ m}^3/\text{m}$:

$$K_{\delta 1} = 2.10$$

- c. (Nordlund - Step 4): Determine the correction factor, C_F , to be applied to K_δ if $\delta \neq \phi$.

Use Figure 9.15 to determine the correction factor for each K_δ . Enter figure with ϕ angle and $\delta/\phi=0.84$ to determine C_F .

Layer 1: For $\phi_1 = 36^\circ \rightarrow C_{F1} = 0.92$

- d. (Nordlund - Step 5): Compute the average effective overburden pressure at the midpoint of each soil layer, p_d (kPa). (Note: a limiting value is not applied to p_d).

The effective overburden pressure at the midpoint of the soil layer is equal to the average effective overburden pressure of that layer. The effective overburden pressure diagram for Pier 3 is presented in Figure F.10.

Layer 1: $p_{d1} = 15.5 \text{ kPa}$ (midpoint of layer 1 - at depth of 2.5 m)

STEP 2 (continued)

- e. (Nordlund - Step 6): Compute the shaft resistance in soil layer 1.

$$R_s = K_\delta C_F p_d \sin \delta C_d D \quad (\text{for uniform pile cross section})$$

$$\text{where : } C_d = (4) (0.356 \text{ m}) = 1.424 \text{ m}$$

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 2.10 (0.92) (15.5 \text{ kPa}) (\sin 30.2^\circ) (1.424 \text{ m}) (1 \text{ m}) \\ &= 22 \text{ kN} \end{aligned}$$

STEP 3 Compute the shaft resistance at soil layers 2 and 3 (cohesive) using α -method.

- a. (α -Method - Steps 1 and 2): Determine the adhesion, c_a , from Figure 9.18 or adhesion factor, α , from Figure 9.19 for the cohesive soil layer.

An extremely dense sand and gravel overlying stiff silty clay of soil layer 2 agrees with the soil stratigraphy shown in Figure 9.19a. The depth to pile diameter ratio is:

$$(D/b) = (3.0 \text{ m}) / (0.356 \text{ m}) = 8.43$$

For $c_{u2} = 106 \text{ kPa}$ and $(D/b) = 8.43$, the adhesion factor interpolated from Figure 9.19a is:

$$\alpha = 1.0$$

The adhesion is:

$$\begin{aligned} c_{a2} &= \alpha c_{u2} \\ &= 1.0 (106 \text{ kPa}) = 106 \text{ kPa} \end{aligned}$$

Therefore, the unit shaft resistance of soil layer 2 is :

$$\text{Layer 2: } f_{s2} = c_{a2} = 106 \text{ kPa}$$

STEP 3 (continued)

For soil layer 3, Figure 9.19 and 9.18 should be used to compute the adhesion of the very stiff silty clay. Depending on the thickness of the extremely dense sand and gravel of soil layer 1 and the thickness of the stiff silty clay of soil layer 2, the soil stratigraphy for soil layer 3 may also agree with that of Figure 9.19a. However, it is reasonable to assume here that the pile would not be able to drag the sand and gravel far enough from soil layer 1 through the stiff silty clay of soil layer 2 to reach soil layer 3. Therefore, soil layer 3 should not be affected by the sand and gravel from soil layer 1 and hence, the adhesion should be determined from Figure 9.19c or 9.18. The depth, D , to pile diameter, b , ratio is:

$$(D/b) = (9.0 \text{ m}) / (0.356 \text{ m}) = 25.28$$

Interpolating the adhesion factor from Figure 9.19c, for $c_{u3} = 155 \text{ kPa}$ and $(D/b) = 25.28$:

$$\alpha = 0.35$$

The adhesion is therefore:

$$\begin{aligned} c_{a3} &= \alpha c_{u3} \\ &= 0.35 (155 \text{ kPa}) \\ &= 54.3 \text{ kPa} \end{aligned}$$

For comparison, using Figure 9.18 for concrete pile with $(D/b) = 25.35$ and $c_{u3} = 155 \text{ kPa}$, the adhesion obtained from the interpolation between curves is:

$$c_{a3} = 54.7 \text{ kPa} \rightarrow \text{similar to Figure 9.19c.}$$

Therefore,

$$\text{Layer 3: } f_{s3} = c_{a3} = 54.3 \text{ kPa}$$

STEP 3 (continued)

- b. (α -Method - Step 3): Compute the ultimate shaft resistance in soil layer 2 and soil layer 3.

$$\begin{aligned}\text{Layer 2: } R_{s2} &= f_{s2} A_s \\ &= 106.0 \text{ kPa } (4)(0.356 \text{ m})(3 \text{ m}) = 453 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Layer 3: } R_{s3} &= f_{s3} A_s \\ &= 54.3 \text{ kPa } (4)(0.356 \text{ m})(9 \text{ m}) = 696 \text{ kN}\end{aligned}$$

- STEP 4 Sum the shaft resistance from each soil layer to obtain the ultimate shaft resistance, R_s (kN).

$$\begin{aligned}\text{Total: } R_s &= R_{s1} + R_{s2} + R_{s3} \\ &= 22 \text{ kN} + 453 \text{ kN} + 696 \text{ kN} = 1,171 \text{ kN}\end{aligned}$$

- STEP 5 Compute the ultimate toe resistance using Nordlund method.

Use Nordlund method, since the soil at pile toe is dense sand and gravel (cohesionless).

- (i) (Nordlund - Step 7): Determine the α_t coefficient and the bearing capacity factor, N'_q , from the ϕ angle near the pile toe.

Since the ϕ angle is not provided by either laboratory tests or in-situ data, it can be estimated from Table 4-6 using the average corrected SPT N' value over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters).

$$\bar{N}'_{\text{toe}} = 33 \rightarrow \phi_{\text{toe}} = 35^\circ$$

STEP 5 (continued)

- a. Enter Figure 9.16(a) with ϕ angle near pile toe to determine α_t coefficient based on pile length to diameter ratio.

$$(D/b) = (13.0 \text{ m}) / (0.356 \text{ m}) = 36.52$$

$$\text{For } \phi_{\text{toe}} = 35^\circ \text{ and } (D/b) = 36.52 \rightarrow \alpha_t = 0.67$$

- b. Enter Figure 9.16(b) with ϕ angle near pile toe to determine N'_q .

$$\text{For } \phi_{\text{toe}} = 35^\circ \rightarrow N'_q = 65$$

- (ii) (Nordlund - Step 8): Compute the effective overburden pressure at the pile toe, p_t (kPa).

The effective overburden pressure at the pile toe should be limited to a maximum of 150 kPa.

The effective overburden pressure at the pile toe, p_t , has been computed in Figure F.10:

$$p_t = 143.8 \text{ kPa} < 150 \text{ kPa} \rightarrow \text{OK}$$

- (iii) (Nordlund - Step 9): Compute the ultimate toe resistance, R_t (kN).

$$\text{a. } R_t = \alpha_t N'_q A_t p_t$$

$$= 0.67 (65) (0.356 \text{ m})(0.356 \text{ m})(143.8 \text{ kPa}) = 795 \text{ kN}$$

$$\text{b. limiting } R_t = q_L A_t$$

Using the estimated $\phi=35^\circ$ and Figure 9.17, the limiting unit toe resistance is:

$$q_L = 5,000 \text{ kPa}$$

STEP 5 (continued)

Therefore,

$$\begin{aligned} R_t &= 5,000 \text{ kPa } (0.356 \text{ m})(0.356 \text{ m}) \\ &= 635 \text{ kN} \end{aligned}$$

c. Use lesser of the two R_t values obtained in steps a and b which is:

$$R_t = 635 \text{ kN}$$

STEP 6 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 1,171 \text{ kN} + 635 \text{ kN} \\ &= 1,806 \text{ kN} \end{aligned}$$

Note: In reality, the pile toe will not stop at the top of the bearing stratum. The pile toe will be driven further into the dense sand and gravel bearing stratum and therefore the ultimate toe resistance of the pile is expected to be higher than 635 kN.

STEP 7 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,806 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.3.2 Static Axial Pile Capacity Calculations by Effective Stress Method

For the soil profile interpreted from Soil Boring S-3 as shown in Figure F.9. Perform an Effective Stress method pile capacity calculation for an embedded length of 13 meters. Use the step-by-step method outlined in Section 9.7.1.3.

STEP 1 Delineate the soil profile into layers and determine ϕ' angle for each layer.

- a. Use the procedure described in Section 9.4 to construct a p_o diagram.

For Soil Boring S-3, the p_o diagram has been constructed in Section F.2.3.1 - Step 1 and also presented in Figure F.10.

- b. Divide the soil profile throughout the pile penetration depth into layers and determine the effective overburden pressure, p_o , at the midpoint of each layer.

As the example in Section F.2.3.1, the soil profile along the pile embedded length is delineated into three layers of 1, 3, and 9 meters thick. The average effective overburden pressure of each layer is equal to the effective overburden pressure at the midpoint of that layer as follows.

Layer 1: $p_{o1} = 15.5 \text{ kPa}$ (midpoint of layer 1 - at depth of 2.5 m)

Layer 2: $p_{o2} = 35.5 \text{ kPa}$ (midpoint of layer 2 - at depth of 4.5 m)

Layer 3: $p_{o3} = 97.0 \text{ kPa}$ (midpoint of layer 3 - at depth of 10.5 m)

- c. Determine the ϕ' angle for each soil layer from laboratory or in-situ test data.

Since the ϕ' angle is not provided by either laboratory or in-situ test data, the average corrected SPT N' value will be used to estimate the ϕ' angle.

- d. In the absence of laboratory or in-situ test data for cohesionless soil layers, determine the average corrected SPT N' value for each soil layer and estimate the ϕ' angle from Table 4-6 in Chapter 4.

STEP 1 (continued)

For cohesionless soil layer 1, the average corrected SPT N' value and the soil type for each soil layer is as follows.

Layer 1: $\bar{N}_1' = 135$ (Layer 1 - depth 2 to 3 m;
Extremely dense sand and gravel)

Use the average corrected SPT N' value for soil layer 1 to estimate the ϕ' angle from Table 4-6 in Chapter 4.

Layer 1: $\phi_1' = 36^\circ$ (Limiting friction angle is used; See discussion in
Section F.2.2.2 - Step 1)

For the cohesive soil layers 2 and 3, the effective friction angle is obtained from from the laboratory triaxial test.

Layer 2: $\phi_2' = 27^\circ$

Layer 3: $\phi_3' = 29^\circ$

STEP 2 Select the β coefficient for each soil layer.

- a. Use local experience to select β coefficient for each layer.

Assume no local experience.

- b. In the absence of local experience, use Table 9-6 or Figure 9.20 to estimate β coefficient from ϕ' angle for each layer.

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.20 to estimate the β coefficient for each soil layer.

Layer 1: $\beta_1 = 0.40$ (For extremely dense sand and gravel
with $\phi_1' = 36^\circ$)

Layer 2: $\beta_2 = 0.29$ (For stiff silty clay with $\phi_2' = 27^\circ$)

STEP 2 (continued)

$$\text{Layer 3: } \beta_3 = 0.38 \quad (\text{For stiff silty clay with } \phi_3' = 29^\circ)$$

STEP 3 For each soil layer compute the unit shaft resistance, f_s (kPa).

$$f_s = \beta p_o$$

$$\text{Layer 1: } f_{s1} = 0.40 (15.5 \text{ kPa}) = 6.20 \text{ kPa}$$

$$\text{Layer 2: } f_{s2} = 0.29 (35.5 \text{ kPa}) = 10.30 \text{ kPa}$$

$$\text{Layer 3: } f_{s3} = 0.38 (97.0 \text{ kPa}) = 36.86 \text{ kPa}$$

STEP 4 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s (kN), from the sum of the shaft resistance from each soil layer.

$$R_s = f_s A_s$$

where A_s = Pile-soil surface area from pile perimeter and length

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 6.20 (4) (0.356 \text{ m}) (1 \text{ m}) \\ &= 9 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 10.30 (4) (0.356 \text{ m}) (3 \text{ m}) \\ &= 44 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 3: } R_{s3} &= 36.86 (4) (0.356 \text{ m}) (9 \text{ m}) \\ &= 472 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} + R_{s3} \\ &= 9 \text{ kN} + 44 \text{ kN} + 472 \text{ kN} \\ &= 525 \text{ kN} \end{aligned}$$

STEP 5 Compute the unit toe resistance, q_t (kPa).

$$q_t = N_t p_t$$

- a. Use local experience to select N_t coefficient.

Assume no local experience.

- b. In the absence of local experience, estimate N_t coefficient from Table 9-6 or Figure 9.21 based on ϕ' angle.

Table 9-6 or Figure 9.21 are a function of soil type and the ϕ' angle. The soil type for each layer can be obtained from the soil boring. The ϕ' angle for each layer can be obtained from laboratory tests or in-situ data. In the absence of either laboratory or in-situ test data, the ϕ' angle should be estimated from Table 4-6 in Chapter 4 using the average corrected SPT N' value, \bar{N}' , over the zone from the pile toe to 3 diameter below the pile toe (1.065 meters). The soil near the pile toe is a dense sand and gravel.

$$\bar{N}'_{toe} = 33 \rightarrow \phi'_{toe} = 35^\circ$$

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.21 to estimate the N_t coefficient.

$$N_t = 58 \quad (\text{For dense sand and gravel with } \phi'_{toe} = 35^\circ)$$

- c. Calculate the effective overburden pressure at the pile toe, p_t .

The effective overburden pressure at the pile toe, p_t , has been computed in a previous example (Section F.2.3.1, Step 1):

$$p_t = 143.8 \text{ kPa}$$

STEP 5 (continued)

The unit toe resistance, q_t is:

$$\begin{aligned} q_t &= N_t p_t \\ &= 58 (143.8 \text{ kPa}) = 8,340 \text{ kPa} \end{aligned}$$

STEP 6 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} R_t &= q_t A_t \\ &= 8,340 (0.356 \text{ m}) (0.356 \text{ m}) = 1,059 \text{ kN} \end{aligned}$$

STEP 7 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 525 \text{ kN} + 1,059 \text{ kN} = 1,584 \text{ kN} \end{aligned}$$

Note: The ultimate capacity according to the Effective Stress method is less than the required 1780 kN ultimate capacity. As discussed in the Nordlund method, in reality the pile toe will not be stopped at the top of the bearing stratum. The pile toe will be driven further into the dense sand and gravel bearing stratum, and therefore, the ultimate toe resistance of the pile is expected to be higher than 1,059 kN. The Effective Stress method would require a pile penetration depth of 14.0 meters for a 1780 kN capacity.

STEP 8 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,584 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.3.3 Static Axial Pile Capacity Calculations by Driven Computer Program

Note: In the following tables, the depth corresponding to the pile tip is 15 m. The “driving strength loss (%)” factor used in Driven for Boring S-2 was selected based on Table 9-20. For the cohesionless silts, sands and gravels, the soil set-up factor selected was 1.0, which leads to a driving strength loss of 0%. For the cohesive silty clay layers, the selected soil set-up factor selected was 2.0, which leads to a driving strength loss of 50%. In the Driven results, the “Driving” tables reflect the lost resistance in the clay layers due to driving. The “Restrike” tables reflect a time when the clay layers have regained that resistance after pore water pressure dissipation. The “Ultimate” tables consider the removal of the silty upper 2 m of the soil profile due to scour. Note the minor loss of 29 kN between the “Restrike” and “Ultimate” results due to the loss of the silty material.

DRIVEN 1.2 **GENERAL PROJECT INFORMATION**

Filename: C:\DRIVEN\S3.DVN
Project Name: BORING S-3 Project Date: 09/11/2003
Project Client: FHWA Manual
Computed By: BRR
Project Manager:

PILE INFORMATION

Pile Type: Concrete Pile
Top of Pile: 2.00 m
Length of Square Side: 356.00 mm

ULTIMATE CONSIDERATIONS

| | | |
|-------------------------------|---------------------|--------|
| Water Table Depth At Time Of: | - Drilling: | 0.00 m |
| | - Driving/Restrike: | 0.00 m |
| | - Ultimate: | 0.00 m |
| Ultimate Considerations: | - Local Scour: | 0.00 m |
| | - Long Term Scour: | 2.00 m |
| | - Soft Soil: | 0.00 m |

ULTIMATE PROFILE

| Layer | Type | Thickness | Driving Loss | Unit Weight | Strength | Ultimate Curve |
|-------|--------------|-----------|--------------|-------------------------|------------|----------------|
| 1 | Cohesionless | 2.00 m | 0.00% | 14.90 kN/m ³ | 31.0/31.0 | Nordlund |
| 2 | Cohesionless | 1.00 m | 0.00% | 20.40 kN/m ³ | 36.0/36.0 | Nordlund |
| 3 | Cohesive | 3.00 m | 50.00% | 19.60 kN/m ³ | 106.00 kPa | T-80 Sand |
| 4 | Cohesive | 9.00 m | 50.00% | 20.20 kN/m ³ | 155.00 kPa | T-79 Concrete |
| 5 | Cohesionless | 5.00 m | 0.00% | 20.10 kN/m ³ | 36.0/36.0 | Nordlund |

RESTRIKE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|------------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 1.99 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.01 m | Cohesionless | 10.25 kPa | 30.32 | N/A | 0.14 kN |
| 2.99 m | Cohesionless | 15.44 kPa | 30.32 | N/A | 21.44 kN |
| 3.01 m | Cohesive | N/A | N/A | 106.00 kPa | 23.24 kN |
| 5.99 m | Cohesive | N/A | N/A | 106.00 kPa | 473.03 kN |
| 6.01 m | Cohesive | N/A | N/A | 47.10 kPa | 475.21 kN |
| 9.01 m | Cohesive | N/A | N/A | 54.64 kPa | 708.74 kN |
| 12.01 m | Cohesive | N/A | N/A | 62.19 kPa | 1006.71 kN |
| 14.99 m | Cohesive | N/A | N/A | 67.79 kPa | 1342.35 kN |
| 15.01 m | Cohesionless | 143.83 kPa | 30.32 | N/A | 1345.34 kN |
| 18.01 m | Cohesionless | 159.28 kPa | 30.32 | N/A | 2015.65 kN |
| 19.99 m | Cohesionless | 169.47 kPa | 30.32 | N/A | 2529.26 kN |

RESTRIKE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 35.20 | 125.39 kN | 0.00 kN |
| 1.99 m | Cohesionless | 0.00 kPa | 35.20 | 125.39 kN | 0.00 kN |
| 2.01 m | Cohesionless | 10.30 kPa | 77.60 | 919.89 kN | 70.25 kN |
| 2.99 m | Cohesionless | 20.69 kPa | 77.60 | 919.89 kN | 141.07 kN |
| 3.01 m | Cohesive | N/A | N/A | N/A | 120.90 kN |
| 5.99 m | Cohesive | N/A | N/A | N/A | 120.90 kN |
| 6.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 9.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 12.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 14.99 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 15.01 m | Cohesionless | 143.88 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 18.01 m | Cohesionless | 174.78 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 19.99 m | Cohesionless | 195.17 kPa | 77.60 | 919.89 kN | 919.89 kN |

RESTRIKE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.99 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.01 m | 0.14 kN | 70.25 kN | 70.39 kN |
| 2.99 m | 21.44 kN | 141.07 kN | 162.51 kN |
| 3.01 m | 23.24 kN | 120.90 kN | 144.14 kN |
| 5.99 m | 473.03 kN | 120.90 kN | 593.93 kN |
| 6.01 m | 475.21 kN | 176.79 kN | 652.00 kN |
| 9.01 m | 708.74 kN | 176.79 kN | 885.53 kN |
| 12.01 m | 1006.71 kN | 176.79 kN | 1183.50 kN |
| 14.99 m | 1342.35 kN | 176.79 kN | 1519.14 kN |
| 15.01 m | 1345.34 kN | 919.89 kN | 2265.22 kN |
| 18.01 m | 2015.65 kN | 919.89 kN | 2935.54 kN |
| 19.99 m | 2529.26 kN | 919.89 kN | 3449.15 kN |

DRIVING - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|------------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 1.99 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.01 m | Cohesionless | 10.25 kPa | 30.32 | N/A | 0.14 kN |
| 2.99 m | Cohesionless | 15.44 kPa | 30.32 | N/A | 21.44 kN |
| 3.01 m | Cohesive | N/A | N/A | 106.00 kPa | 22.34 kN |
| 5.99 m | Cohesive | N/A | N/A | 106.00 kPa | 247.24 kN |
| 6.01 m | Cohesive | N/A | N/A | 47.10 kPa | 248.33 kN |
| 9.01 m | Cohesive | N/A | N/A | 54.64 kPa | 365.09 kN |
| 12.01 m | Cohesive | N/A | N/A | 62.19 kPa | 514.08 kN |
| 14.99 m | Cohesive | N/A | N/A | 67.79 kPa | 681.90 kN |
| 15.01 m | Cohesionless | 143.83 kPa | 30.32 | N/A | 684.88 kN |
| 18.01 m | Cohesionless | 159.28 kPa | 30.32 | N/A | 1355.20 kN |
| 19.99 m | Cohesionless | 169.47 kPa | 30.32 | N/A | 1868.81 kN |

DRIVING - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 35.20 | 125.39 kN | 0.00 kN |
| 1.99 m | Cohesionless | 0.00 kPa | 35.20 | 125.39 kN | 0.00 kN |
| 2.01 m | Cohesionless | 10.30 kPa | 77.60 | 919.89 kN | 70.25 kN |
| 2.99 m | Cohesionless | 20.69 kPa | 77.60 | 919.89 kN | 141.07 kN |
| 3.01 m | Cohesive | N/A | N/A | N/A | 120.90 kN |
| 5.99 m | Cohesive | N/A | N/A | N/A | 120.90 kN |
| 6.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 9.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 12.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 14.99 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 15.01 m | Cohesionless | 143.88 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 18.01 m | Cohesionless | 174.78 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 19.99 m | Cohesionless | 195.17 kPa | 77.60 | 919.89 kN | 919.89 kN |

DRIVING - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.99 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.99 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.00 m | 0.00 kN | 27.42 kN | 27.42 kN |
| 2.01 m | 0.14 kN | 70.25 kN | 70.39 kN |
| 2.99 m | 21.44 kN | 141.07 kN | 162.51 kN |
| 3.01 m | 22.34 kN | 120.90 kN | 143.24 kN |
| 5.99 m | 247.24 kN | 120.90 kN | 368.14 kN |
| 6.01 m | 248.33 kN | 176.79 kN | 425.12 kN |
| 9.01 m | 365.09 kN | 176.79 kN | 541.88 kN |
| 12.01 m | 514.08 kN | 176.79 kN | 690.87 kN |
| 14.99 m | 681.90 kN | 176.79 kN | 858.69 kN |
| 15.01 m | 684.88 kN | 919.89 kN | 1604.77 kN |
| 18.01 m | 1355.20 kN | 919.89 kN | 2275.08 kN |
| 19.99 m | 1868.81 kN | 919.89 kN | 2788.69 kN |

ULTIMATE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|--------------|---------------------------------|---------------------------|------------|------------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 1.99 m | Cohesionless | 0.00 kPa | 0.00 | N/A | 0.00 kN |
| 2.01 m | Cohesionless | 0.05 kPa | 30.32 | N/A | 0.00 kN |
| 2.99 m | Cohesionless | 5.25 kPa | 30.32 | N/A | 7.28 kN |
| 3.01 m | Cohesive | N/A | N/A | 106.00 kPa | 8.94 kN |
| 5.99 m | Cohesive | N/A | N/A | 106.00 kPa | 458.73 kN |
| 6.01 m | Cohesive | N/A | N/A | 47.10 kPa | 460.91 kN |
| 9.01 m | Cohesive | N/A | N/A | 54.64 kPa | 694.45 kN |
| 12.01 m | Cohesive | N/A | N/A | 62.19 kPa | 992.41 kN |
| 14.99 m | Cohesive | N/A | N/A | 67.79 kPa | 1328.05 kN |
| 15.01 m | Cohesionless | 133.63 kPa | 30.32 | N/A | 1330.89 kN |
| 18.01 m | Cohesionless | 149.08 kPa | 30.32 | N/A | 1958.31 kN |
| 19.99 m | Cohesionless | 159.28 kPa | 30.32 | N/A | 2443.61 kN |

ULTIMATE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|--------------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesionless | 0.00 kPa | 0.00 | 0.00 kN | 0.00 kN |
| 1.99 m | Cohesionless | 0.00 kPa | 0.00 | 0.00 kN | 0.00 kN |
| 2.01 m | Cohesionless | 0.11 kPa | 77.60 | 919.89 kN | 0.72 kN |
| 2.99 m | Cohesionless | 10.49 kPa | 77.60 | 919.89 kN | 71.54 kN |
| 3.01 m | Cohesive | N/A | N/A | N/A | 120.90 kN |
| 5.99 m | Cohesive | N/A | N/A | N/A | 120.90 kN |
| 6.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 9.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 12.01 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 14.99 m | Cohesive | N/A | N/A | N/A | 176.79 kN |
| 15.01 m | Cohesionless | 133.69 kPa | 77.60 | 919.89 kN | 905.23 kN |
| 18.01 m | Cohesionless | 164.58 kPa | 77.60 | 919.89 kN | 919.89 kN |
| 19.99 m | Cohesionless | 184.97 kPa | 77.60 | 919.89 kN | 919.89 kN |

ULTIMATE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.99 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 2.01 m | 0.00 kN | 0.72 kN | 0.72 kN |
| 2.99 m | 7.28 kN | 71.54 kN | 78.83 kN |
| 3.01 m | 8.94 kN | 120.90 kN | 129.84 kN |
| 5.99 m | 458.73 kN | 120.90 kN | 579.63 kN |
| 6.01 m | 460.91 kN | 176.79 kN | 637.70 kN |
| 9.01 m | 694.45 kN | 176.79 kN | 871.23 kN |
| 12.01 m | 992.41 kN | 176.79 kN | 1169.20 kN |
| 14.99 m | 1328.05 kN | 176.79 kN | 1504.84 kN |
| 15.01 m | 1330.89 kN | 905.23 kN | 2236.12 kN |
| 18.01 m | 1958.31 kN | 919.89 kN | 2878.20 kN |
| 19.99 m | 2443.61 kN | 919.89 kN | 3363.50 kN |

F.2.3.4 Static Axial Pile Capacity Calculations by LPC CPT Method - Computer Program

L.P.C. CPT Method Page 1/2
Peach Freeway CPT-3 at Pier 3 -- 356 mm-square PCPS Concrete Pile

Installation Method: 9 - Driven Prefabricated Piles (Concrete)
Depth to Water Table: 0.0 meter

| Pile No. | Toe Area (m ²) | Perimeter (m) |
|----------|-------------------------------|------------------|
| 1 | 0.127 | 1.424 |

| Depth to Bottom of Layer (m) | Soil Type |
|---------------------------------|-----------|
| 1.9 | 4 |
| 3.0 | 7 |
| 15.0 | 2 |
| 20.0 | 7 |

| Depth (m) | Cone Tip Resistance (kPa) |
|--------------|------------------------------|
| 0.0 | 1,244.9 |
| 2.0 | 1,244.9 |
| 3.0 | 33,228.7 |
| 7.0 | 3,715.5 |
| 11.0 | 2,848.9 |
| 12.0 | 4,117.7 |
| 13.0 | 4,237.4 |
| 14.0 | 4,472.0 |
| 15.0 | 4,256.5 |
| 16.0 | 17,715.6 |
| 17.0 | 18,816.8 |
| 18.0 | 20,588.4 |
| 19.0 | 19,056.2 |
| 19.5 | 19,678.7 |
| 20.0 | 23,940.0 |

Peach Freeway CPT-3 at Pier 3 -- 356 mm-square PCPS Concrete Pile

| Depth (m) | Unit Friction (kPa) | Toe Bearing (kPa) | Shaft Resistance (kN) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|------------------------|----------------------|-----------------------------|---------------------------|------------------------------|
| 0.00 | 38.21 | 746.93 | 0.0 | 94.3 | 94.3 |
| 2.00 | 11.54 | 2508.91 | 105.4 | 317.1 | 422.6 |
| 3.00 | 70.38 | 2796.19 | 163.7 | 353.6 | 517.3 |
| 7.00 | 60.14 | 2231.21 | 505.7 | 282.0 | 787.7 |
| 11.00 | 58.03 | 1972.66 | 842.0 | 249.5 | 1091.5 |
| 12.00 | 61.14 | 2236.00 | 926.5 | 282.9 | 1209.4 |
| 13.00 | 61.43 | 2537.64 | 1013.7 | 320.7 | 1334.4 |
| 14.00 | 62.00 | 4108.10 | 1101.3 | 519.5 | 1621.3 |
| 15.00 | 61.48 | 6655.32 | 1189.4 | 841.1 | 2030.5 |
| 16.00 | 64.49 | 5860.51 | 1281.0 | 740.6 | 2021.6 |
| 17.00 | 64.93 | 7124.54 | 1373.1 | 900.7 | 2273.8 |
| 18.00 | 65.60 | 7306.49 | 1465.6 | 923.8 | 2389.5 |
| 19.00 | 65.02 | 7847.53 | 1558.6 | 991.9 | 2549.6 |
| 19.50 | 65.26 | 8062.99 | 1604.8 | 1019.5 | 2624.3 |
| 20.00 | 66.84 | 8259.30 | 1652.0 | 1044.4 | 2696.4 |

Note: Depth is referenced from the original ground surface.

F.2.3.5 Static Axial Pile Capacity Calculations by Schmertmann Method

Location: Peach Freeway CPT-3 at Pier 3.

| Depth (m) | fs(avg) (bars) | Unit Friction (bars) | Increment Friction (kN) | Shaft Resistance (kN) | qc(avg) (bars) | qc1(min) (bars) | qc2 (bars) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|-------------------|----------------------------|-------------------------------|-----------------------------|-------------------|--------------------|---------------|---------------------------|------------------------------|
| 10.00 | 1.99 | 0.80 | 27.77 | 1,050 | 32.87 | | | | |
| 10.25 | 1.93 | 0.77 | 26.93 | 1,077 | 29.15 | | | | |
| 10.50 | 2.13 | 0.85 | 29.76 | 1,107 | 31.50 | | | | |
| 10.75 | 2.36 | 0.94 | 32.86 | 1,140 | 33.35 | | | | |
| 11.00 | 2.24 | 0.90 | 31.29 | 1,171 | 35.10 | 38.88 | 29.68 | 416 | 1,587 |
| 11.25 | 2.20 | 0.88 | 30.63 | 1,202 | 42.65 | | | | |
| 11.50 | 2.29 | 0.92 | 31.95 | 1,234 | 44.30 | 42.19 | 21.49 | 386 | 1,620 |
| 11.75 | 2.45 | 0.98 | 34.12 | 1,268 | 43.50 | | | | |
| 12.00 | 2.54 | 1.02 | 35.44 | 1,303 | 41.33 | 42.34 | 33.71 | 461 | 1,764 |
| 12.25 | 2.22 | 0.89 | 30.91 | 1,334 | 43.35 | 43.86 | 34.25 | 474 | 1,808 |
| 12.50 | 2.21 | 0.88 | 30.79 | 1,365 | 45.03 | 44.03 | 35.44 | 482 | 1,847 |
| 12.75 | 2.17 | 0.87 | 30.20 | 1,395 | 45.00 | | | | |
| 13.00 | 2.26 | 0.91 | 31.58 | 1,427 | 43.53 | 43.32 | 37.30 | 489 | 1,916 |
| 13.25 | 2.74 | 1.10 | 38.23 | 1,465 | 46.50 | | | | |
| 13.50 | 2.84 | 1.14 | 39.67 | 1,504 | 47.27 | 43.39 | 39.34 | 502 | 2,006 |
| 13.75 | 2.59 | 1.04 | 36.14 | 1,541 | 47.30 | | | | |
| 14.00 | 2.47 | 0.99 | 34.51 | 1,575 | 45.80 | 42.46 | 40.82 | 505 | 2,080 |
| 14.25 | 2.13 | 0.85 | 29.66 | 1,605 | 41.35 | | | | |
| 14.50 | 2.21 | 0.88 | 30.84 | 1,636 | 43.07 | 44.93 | 41.35 | 523 | 2,159 |
| 14.75 | 2.21 | 0.88 | 30.84 | 1,666 | 46.80 | | | | |
| 15.00 | 2.05 | 1.74 | 60.69 | 1,727 | 130.90 | 161.05 | 41.95 | 1231 | 2,958 |
| 15.25 | 1.62 | 1.37 | 47.88 | 1,775 | 191.20 | | | | |
| 15.50 | 1.48 | 1.26 | 43.79 | 1,819 | 195.97 | | | | |
| 15.75 | 1.16 | 0.98 | 34.25 | 1,853 | 180.90 | | | | |
| 16.00 | 1.15 | 0.98 | 34.19 | 1,887 | 170.97 | | | | |

Note: Depth is referenced from the original ground surface.

F.2.3.6 Summary of Pier 3 Capacity Calculation Results

Summary of Pile Capacity Estimates with an Embedded Pile Length of 13.0 meters

| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity* (kN) |
|--|--|--|--|
| Norlund and α Method - SPT Data | 1,171 | 635 | 1,806 |
| Effective Stress Method | 525 | 1,059 | 1,584 |
| Driven Program - SPT Data | 1,345 | 920 | 2,265 |
| LPC CPT Program - CPT Data | 1,189 | 841 | 2,030 |
| Schmertmann Method - CPT Data | 1,727 | 1,231 | 2,958 |

*Scour was not included in these analysis, but the Driven analysis shows it has little effect

Summary of Pile Length Estimates for the 1,780 kN Ultimate Pile Capacity

| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity Prior to Scour |
|--|--|
| Norlund and α Method - SPT Data | 13.0 meters for 1,806 kN |
| Effective Stress Method | 14.0 meters for 1,980 kN |
| Driven Program - SPT Data | 13.0 meters for 2,265 kN |
| LPC CPT Program - CPT Data | 12.5 meters for 1,826 kN |
| Schmertmann Method - CPT Data | 10.2 meters for 1,808 kN |

The ultimate pile group capacity at Pier 3 should be calculated based on Steps 1 to 3 of the design recommendations presented in Section 9.8.1.2, since most of the soil along the pile embedded length is cohesive type. One of the design recommendations for estimating the ultimate pile group capacity in cohesive soil is to calculate the ultimate pile group capacity against block failure using the procedure described in Section 9.8.1.3. The ultimate pile group capacity should be governed by the lesser of the ultimate pile group capacity calculated from steps 1 to 3 of the design recommendations presented in Section 9.8.1.3. An example calculations of the ultimate pile group capacity against block failure for the South Abutment is presented in Section F.2.4.1 - Step 8.

F.2.4 South Abutment - Soil Boring S-4 (Cohesive Soil)

F.2.4.1 Static Axial Pile Capacity Calculations by α -Method

For the soil profile interpreted from Soil Boring S-4 as shown in Figure F.11. Perform the α -method pile capacity calculation for an embedded length of 17.5 meters. Use the step-by-step method outlined in Section 9.7.1.2a.

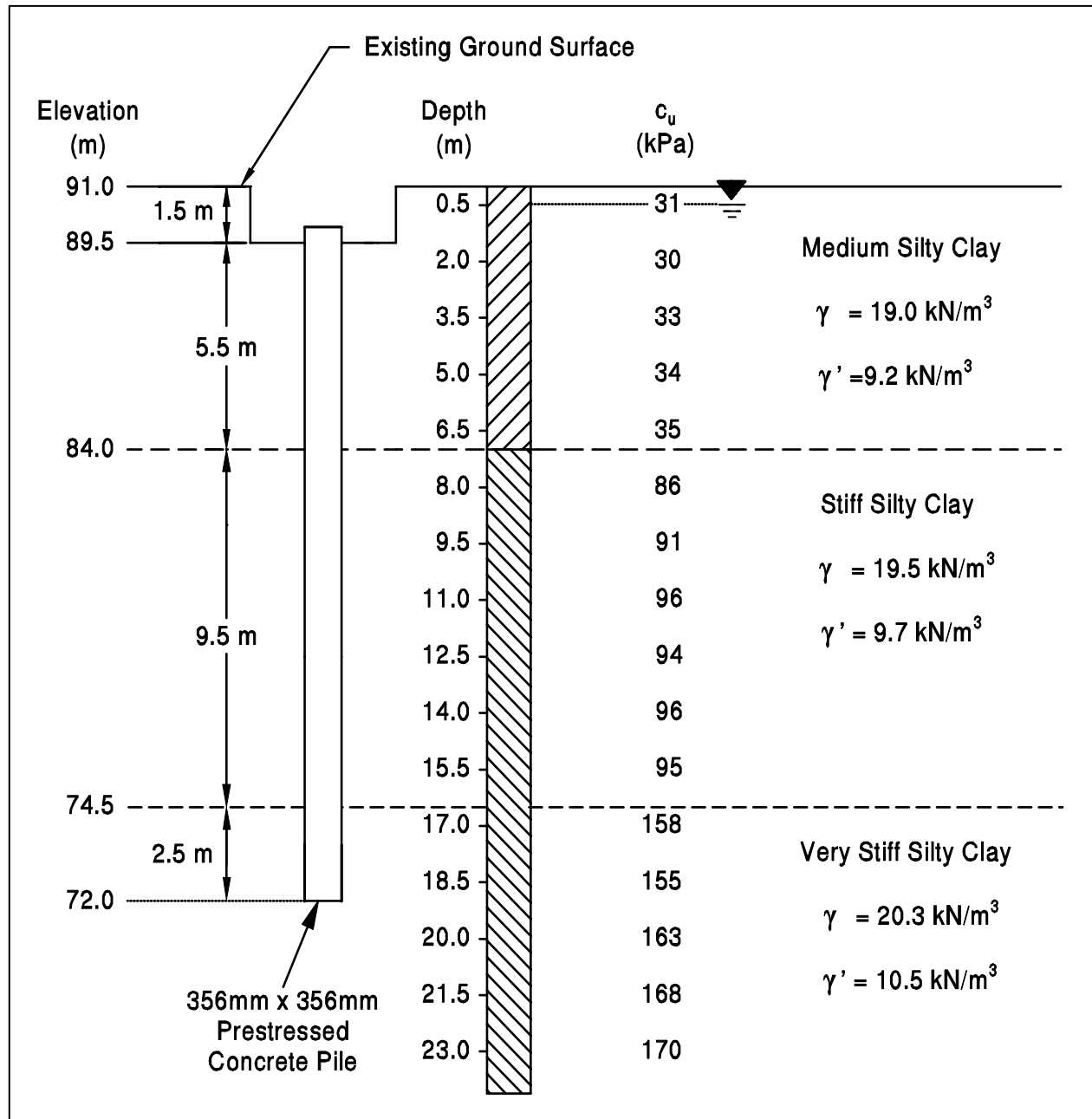


Figure F.11 Interpreted Soil Profile from Soil Boring S-4 at the South Abutment

STEP 1 Delineate the soil profile into layers and determine the adhesion, c_a from Figure 9.18 or adhesion factor, α from Figure 9.19 for each layer.

Enter appropriate figure (based on soil stratigraphy) with the undrained shear strength of the soil, c_u , and determine adhesion or adhesion factor based on the ratio of embedded pile length in clay, D , and pile diameter, b .

Along the pile embedded length, the soil profile is delineated into three layers. Layer 1 is medium silty clay that is 5.5 meters thick, layer 2 is stiff silty clay that is 9.5 meters thick, and layer 3 is very stiff silty clay that is 2.5 meters thick.

Determine the average undrained shear strength, c_u for each soil layer.

$$\text{Layer 1: } c_{u1} = \frac{31 + 30 + 33 + 34 + 35}{5} = 33 \text{ kPa}$$

(Layer 1 - depth 1.5 to 7 m;
Medium silty clay)

$$\text{Layer 2: } c_{u2} = \frac{86 + 91 + 96 + 94 + 96 + 95}{6} = 93 \text{ kPa}$$

(Layer 2 - depth 7 to 16.5 m;
Stiff silty clay)

$$\text{Layer 3: } c_{u3} = \frac{158 + 155}{2} = 157 \text{ kPa}$$

(Layer 3 - depth 16.5 to 19.0 m;
Very stiff silty clay)

The soil stratigraphy of layers 1, 2, and 3 matches that of Figures 9.19c or 9.18. In fact, for concrete piles, the adhesion obtained from Figure 9.18 should be the same as the adhesion factor from Figure 9.19c times the undrained shear strength. Figure 9.18 and the depth to pile diameter ratio, D/b , will be used here to determine the adhesion for soil layers 1, 2, and 3.

STEP 1 (continued)

For soil layer 1:

$$(D/b) = (5.5 \text{ m}) / (0.356 \text{ m}) = 15.45$$

Interpolating from Figure 9.18 for $c_{u1} = 33 \text{ kPa}$ and $(D/b) = 15.45$:

$$c_{a1} = 33 \text{ kPa}$$

For soil layer 2:

$$(D/b) = (15 \text{ m}) / (0.356 \text{ m}) = 42.13$$

Interpolating from Figure 9.18, for $c_{u2} = 93 \text{ kPa}$ and $(D/b) = 42.13$:

$$c_{a2} = 85 \text{ kPa}$$

For soil layer 3:

$$(D/b) = (17.5 \text{ m}) / (0.355 \text{ m}) = 49.16$$

Interpolating from Figure 9.18, for $c_{u3} = 157 \text{ kPa}$ and $(D/b) = 49.16$:

$$c_{a3} = 67 \text{ kPa}$$

STEP 2 For each soil layer, compute the unit shaft resistance, f_s (kPa).

$$f_s = c_a$$

$$\text{Layer 1: } f_{s1} = c_{a1} = 33 \text{ kPa}$$

$$\text{Layer 2: } f_{s2} = c_{a2} = 85 \text{ kPa}$$

$$\text{Layer 3: } f_{s3} = c_{a3} = 67 \text{ kPa}$$

STEP 3 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s (kN) from the sum of the shaft resistance from each layer.

$$R_s = f_s A_s$$

where A_s = Pile-soil surface area from perimeter and length

$$\begin{aligned}\text{Layer 1: } R_{s1} &= 33 \text{ kPa } (4)(0.356 \text{ m})(5.5 \text{ m}) \\ &= 259 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Layer 2: } R_{s2} &= 85 \text{ kPa } (4)(0.356 \text{ m})(9.5 \text{ m}) \\ &= 1,150 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Layer 3: } R_{s3} &= 67 \text{ kPa } (4)(0.356 \text{ m})(2.5 \text{ m}) \\ &= 239 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Total: } R_s &= R_{s1} + R_{s2} + R_{s3} \\ &= 259 \text{ kN} + 1,150 \text{ kN} + 239 \text{ kN} = 1,648 \text{ kN}\end{aligned}$$

STEP 4 Compute the unit toe resistance, q_t (kPa).

$$q_t = 9 c_u$$

Where: c_u = undrained shear strength of soil at the pile toe.

$$\text{At the pile toe } c_u = \frac{155 + 163}{2} = 159 \text{ kPa}$$

STEP 4 (continued)

Therefore, the unit toe resistance is:

$$\begin{aligned} q_t &= 9 (159 \text{ kPa}) \\ &= 1,431 \text{ kPa} \end{aligned}$$

STEP 5 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} R_t &= q_t A_t \\ &= 1,431 \text{ kPa } (0.356 \text{ m})(0.356 \text{ m}) \\ &= 182 \text{ kN} \end{aligned}$$

STEP 6 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 1,648 \text{ kN} + 182 \text{ kN} \\ &= 1,830 \text{ kN} \end{aligned}$$

STEP 7 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,830 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

The group capacity in a cohesive soil should be checked for block failure.

STEP 8 Investigate the possibility of a block failure of pile groups as discussed in Section 9.8.1.3.

Block failure of pile groups should be considered in the design of pile groups in soft cohesive soils or in cohesionless soils underlain by a weak cohesive layer. For a pile group in cohesive soil, the ultimate capacity of the pile group against block failure can be expressed as:

$$Q_{ug} = 2D (B+Z) c_{u1} + B Z c_{u2} N_c$$

Where:

D = embedded lengths of piles = 17.5 m.

B = width of pile group = 3.36 m.

Z = length of pile group = 10.86 m

c_{u1} = the weighted average of the undrained shear strength over the depth of pile embedment for the cohesive soils along the pile group perimeter

Layer 1: $c_{u1-1} = 33$ kPa

Layer 2: $c_{u1-2} = 93$ kPa

Layer 3: $c_{u1-3} = 157$ kPa

c_{u2} = average undrained shear strength of the cohesive soils at the base of the pile group to a depth of 2B below pile toe level

$$= \frac{155 + 162 + 168}{3} = 162 \text{ kPa}$$

N_c = bearing capacity factor = 9

STEP 8 (continued)

The group shaft resistance against block failure is $2D (B+Z) c_{u1}$:

$$\text{Layer 1: } 2 (5.5 \text{ m}) (3.36 \text{ m} + 10.86 \text{ m}) (33 \text{ kPa}) = 5,162 \text{ kN}$$

$$\text{Layer 2: } 2 (9.5 \text{ m}) (3.36 \text{ m} + 10.86 \text{ m}) (93 \text{ kPa}) = 25,127 \text{ kN}$$

$$\text{Layer 3: } 2 (2.5 \text{ m}) (3.36 \text{ m} + 10.86 \text{ m}) (157 \text{ kPa}) = 11,163 \text{ kN}$$

The group toe resistance against block failure is:

$$\begin{aligned} B Z c_{u2} N_c &= 3.36 \text{ m} (10.86 \text{ m}) (162 \text{ kPa}) (9) \\ &= 53,202 \text{ kN} \end{aligned}$$

Therefore,

$$\begin{aligned} Q_{ug} &= 5,162 \text{ kN} + 25,127 \text{ kN} + 11,163 \text{ kN} + 53,202 \text{ kN} \\ &= 94,654 \text{ kN} \end{aligned}$$

The ultimate pile group capacity in cohesive soil should be taken as the lesser of the ultimate pile group capacity calculated from Steps 1 to 4 as described in Section 9.8.1.2. Steps 1 and 2 take into account the pile center to center spacing and the undrained shear strength of the cohesive soil. For the South Abutment soil strength and pile spacing, this results in a group efficiency of 1.0. Therefore, the ultimate pile group capacity is the calculated ultimate pile capacity of 1,830 kN time the 24 piles in the group or 43,920 kN. The ultimate pile group capacity against block failure, Q_{ug} , calculated above is equal to 94,654 kN. Therefore, block failure is not a problem. The ultimate pile group capacity of 43,920 kN is in excess of the required ultimate pile group capacity of 42,720 kN.

F.2.4.2 Static Axial Pile Capacity Calculations by Effective Stress Method

For the soil profile interpreted from Soil Boring S-4 as shown in Figure F.11. Perform an Effective Stress method pile capacity calculation for an embedded length of 17.5 meters. Use the step-by-step method outlined in Section 9.7.1.3.

STEP 1 Delineate the soil profile into layers and determine ϕ' angle for each layer.

- a. Use the procedure described in Section 9.4 to construct a p_o diagram.

For Soil Boring S-4, the p_o diagram is presented below in Figure F.12.

- b. Divide the soil profile throughout the pile penetration depth into layers and determine the effective overburden pressure, p_o , at the midpoint of each layer.

As the example in Section F.2.4.1, the soil profile along the pile embedded length is delineated into three layers of 5.5, 9.5, and 2.5 meter thick. The average effective overburden pressure of each layer is equal to the effective overburden pressure at the midpoint of that layer as follows.

Layer 1: $p_{o1} = 44.0 \text{ kPa}$ (at depth of 4.25 meters)

Layer 2: $p_{o2} = 115.4 \text{ kPa}$ (at depth of 11.75 meters)

Layer 3: $p_{o3} = 174.6 \text{ kPa}$ (at depth of 17.75 meters)

- c. Determine the ϕ' angle for each soil layer from laboratory or in-situ test data.

The effective frictional angle for each layer was obtained from the laboratory triaxial test.

Layer 1: $\phi_1' = 27^\circ$

Layer 2: $\phi_2' = 29^\circ$

Layer 3: $\phi_3' = 30^\circ$

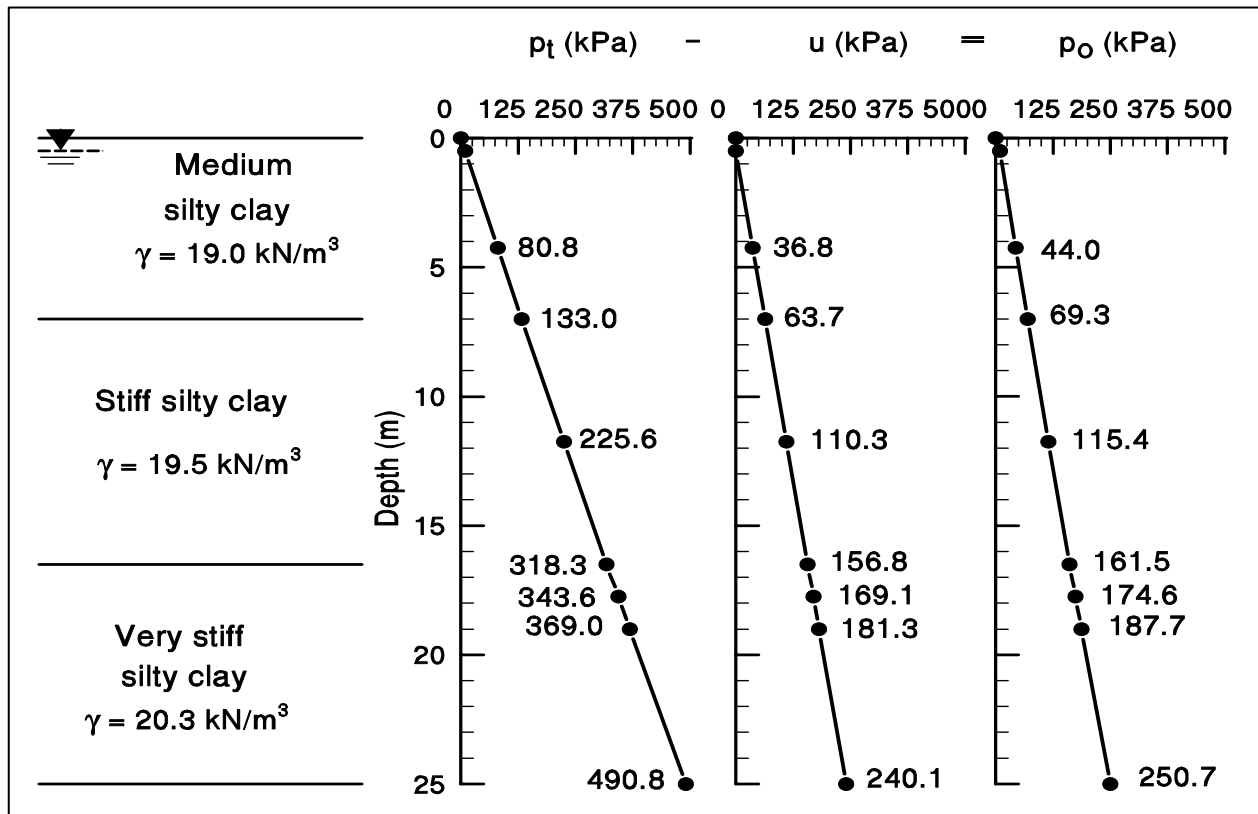


Figure F.12 Effective Overburden Pressure Diagram – South Abutment

STEP 2 Select the β coefficient for each soil layer.

a. Use local experience to select β coefficient for each layer.

Assume no local experience.

b. In the absence of local experience, use Table 9-6 or Figure 9.20 to estimate β coefficient from ϕ' angle for each layer.

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.20 to estimate the β coefficient for each soil layer.

Layer 1: $\beta_1 = 0.30$ (For medium silty clay with $\phi'_1 = 27^\circ$)

Layer 2: $\beta_2 = 0.35$ (For stiff silty clay with $\phi'_2 = 29^\circ$)

Layer 3: $\beta_3 = 0.40$ (For very stiff silty clay with $\phi'_3 = 30^\circ$)

STEP 3 For each soil layer, compute the unit shaft resistance, f_s (kPa).

$$f_s = \beta p_o$$

$$\text{Layer 1: } f_{s1} = 0.30 (44.0 \text{ kPa}) = 13.20 \text{ kPa}$$

$$\text{Layer 2: } f_{s2} = 0.35 (115.4 \text{ kPa}) = 40.39 \text{ kPa}$$

$$\text{Layer 3: } f_{s3} = 0.40 (174.6 \text{ kPa}) = 69.84 \text{ kPa}$$

STEP 4 Compute the shaft resistance in each soil layer and the ultimate shaft resistance, R_s (kN) from the sum of the shaft resistance from each soil layer.

$$R_s = f_s A_s$$

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 13.20 (4) (0.356 \text{ m}) (5.5 \text{ m}) \\ &= 103 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 40.39 (4) (0.356 \text{ m}) (9.5 \text{ m}) \\ &= 546 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 3: } R_{s3} &= 69.84 (4) (0.356 \text{ m}) (2.5 \text{ m}) \\ &= 249 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total: } R_s &= R_{s1} + R_{s2} + R_{s3} \\ &= 103 \text{ kN} + 546 \text{ kN} + 249 \text{ kN} \\ &= 898 \text{ kN} \end{aligned}$$

STEP 5 Compute the unit toe resistance, q_t (kPa).

$$q_t = N_t p_t$$

- a. Use local experience to select N_t coefficient.

Assume no local experience.

- b. In the absence of local experience, estimate N_t coefficient from Table 9-6 or Figure 9.21 based on ϕ' angle.

Based on the laboratory triaxial test, the undrained frictional angle is:

$$\phi'_{\text{toe}} = 30^\circ$$

Use the soil type, the estimated ϕ' angle, and Table 9-6 or Figure 9.21 to estimate the N_t coefficient.

$$N_t = 30$$

- c. Calculate the effective overburden pressure at the pile toe, p_t .

The effective overburden pressure at the pile toe, p_t , has been computed in Figure F.12:

$$p_t = 187.7 \text{ kPa}$$

The unit toe resistance, q_t is:

$$\begin{aligned} q_t &= N_t p_t \\ &= 30 (187.7 \text{ kPa}) \\ &= 5,631 \text{ kPa} \end{aligned}$$

STEP 6 Compute the ultimate toe resistance, R_t (kN).

$$\begin{aligned} R_t &= q_t A_t \\ &= 5,631 \text{ kPa } (0.356 \text{ m }) (0.356 \text{ m }) \\ &= 715 \text{ kN} \end{aligned}$$

STEP 7 Compute the ultimate pile capacity, Q_u (kN).

$$\begin{aligned} Q_u &= R_s + R_t \\ &= 898 \text{ kN } + 715 \text{ kN} \\ &= 1,613 \text{ kN} \end{aligned}$$

STEP 8 Compute the allowable design load, Q_a (kN).

$$Q_a = \frac{Q_u}{\text{Factor of Safety}} = \frac{1,613 \text{ kN}}{\text{Factor of Safety}}$$

Note: Factor of Safety should be selected based on the construction control method to be specified. Recommended factors of safety are described in Section 9.6.

F.2.4.3 Static Axial Pile Capacity Calculations by the Driven Computer Program

Note: In the following tables, the depth corresponding to the pile tip is 15 m. The “driving strength loss (%)” factor used in Driven for Boring S-2 was selected based on Table 9-20. For the cohesive silty clay layers, the selected soil set-up factor selected was 2.0, which leads to a driving strength loss of 50%. In the Driven results, the “Driving” tables reflect the lost resistance in the clay layers due to driving. The “Restrike” and “Ultimate” tables reflect a time when the clay layers have regained that resistance after pore water pressure dissipation.

DRIVEN 1.2 **GENERAL PROJECT INFORMATION**

Filename: C:\DOCUME~1\BRENT\DESKTOP\FHWAMA~1\APPFDR~1\S4.DVN
Project Name: Boring S-4 Project Date: 09/11/2003
Project Client: FHWA Manual
Computed By: BRR
Project Manager:

PILE INFORMATION

Pile Type: Concrete Pile
Top of Pile: 1.50 m
Length of Square Side: 356.00 mm

ULTIMATE CONSIDERATIONS

| | | |
|-------------------------------|--------------------|--------|
| Water Table Depth At Time Of: | - Drilling: | 0.50 m |
| | - Driving/Restrike | 0.50 m |
| | - Ultimate: | 0.50 m |
| Ultimate Considerations: | - Local Scour: | 0.00 m |
| | - Long Term Scour: | 0.00 m |
| | - Soft Soil: | 0.00 m |

ULTIMATE PROFILE

| Layer | Type | Thickness | Driving Loss | Unit Weight | Strength | Ultimate Curve |
|-------|----------|-----------|--------------|-------------------------|------------|----------------|
| 1 | Cohesive | 7.00 m | 50.00% | 19.00 kN/m ³ | 33.00 kPa | T-79 Concrete |
| 2 | Cohesive | 9.50 m | 50.00% | 19.50 kN/m ³ | 93.00 kPa | T-79 Concrete |
| 3 | Cohesive | 2.50 m | 50.00% | 20.30 kN/m ³ | 157.00 kPa | T-79 Concrete |
| 4 | Cohesive | 4.00 m | 50.00% | 20.30 kN/m ³ | 167.00 kPa | T-79 Concrete |

RESTRIKE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|-----------|---------------------------------|---------------------------|-----------|------------------|
| 0.01 m | Cohesive | N/A | N/A | 0.00 kPa | 0.00 kN |
| 1.49 m | Cohesive | N/A | N/A | 0.00 kPa | 0.00 kN |
| 1.50 m | Cohesive | N/A | N/A | 32.24 kPa | 0.00 kN |
| 3.01 m | Cohesive | N/A | N/A | 32.24 kPa | 69.33 kN |
| 6.01 m | Cohesive | N/A | N/A | 32.31 kPa | 207.51 kN |
| 6.99 m | Cohesive | N/A | N/A | 32.38 kPa | 253.14 kN |
| 7.01 m | Cohesive | N/A | N/A | 71.76 kPa | 254.63 kN |
| 10.01 m | Cohesive | N/A | N/A | 77.24 kPa | 584.68 kN |
| 13.01 m | Cohesive | N/A | N/A | 82.73 kPa | 961.57 kN |
| 16.01 m | Cohesive | N/A | N/A | 84.97 kPa | 1343.80 kN |
| 16.49 m | Cohesive | N/A | N/A | 84.97 kPa | 1401.88 kN |
| 16.51 m | Cohesive | N/A | N/A | 67.30 kPa | 1404.05 kN |
| 18.99 m | Cohesive | N/A | N/A | 67.30 kPa | 1641.71 kN |
| 19.01 m | Cohesive | N/A | N/A | 65.12 kPa | 1643.60 kN |
| 22.01 m | Cohesive | N/A | N/A | 65.12 kPa | 1921.76 kN |
| 22.99 m | Cohesive | N/A | N/A | 65.12 kPa | 2012.63 kN |

RESTRIKE - END BEARING

| Depth | Soil Type | Effective Stress At Tip Factor | Bearing Cap. | Limiting End Bearing | End Bearing |
|---------|-----------|-----------------------------------|--------------|-------------------------|----------------|
| 0.01 m | Cohesive | N/A | N/A | N/A | 0.00 kN |
| 1.49 m | Cohesive | N/A | N/A | N/A | 0.00 kN |
| 1.50 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 3.01 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 6.01 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 6.99 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 7.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 10.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 13.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.49 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.51 m | Cohesive | N/A | N/A | N/A | 179.07 kN |
| 18.99 m | Cohesive | N/A | N/A | N/A | 179.07 kN |
| 19.01 m | Cohesive | N/A | N/A | N/A | 190.48 kN |
| 22.01 m | Cohesive | N/A | N/A | N/A | 190.48 kN |
| 22.99 m | Cohesive | N/A | N/A | N/A | 190.48 kN |

RESTRIKE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.49 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.50 m | 0.00 kN | 37.64 kN | 37.64 kN |
| 3.01 m | 69.33 kN | 37.64 kN | 106.97 kN |
| 6.01 m | 207.51 kN | 37.64 kN | 245.15 kN |
| 6.99 m | 253.14 kN | 37.64 kN | 290.78 kN |
| 7.01 m | 254.63 kN | 106.07 kN | 360.70 kN |
| 10.01 m | 584.68 kN | 106.07 kN | 690.75 kN |
| 13.01 m | 961.57 kN | 106.07 kN | 1067.64 kN |
| 16.01 m | 1343.80 kN | 106.07 kN | 1449.87 kN |
| 16.49 m | 1401.88 kN | 106.07 kN | 1507.95 kN |
| 16.51 m | 1404.05 kN | 179.07 kN | 1583.12 kN |
| 18.99 m | 1641.71 kN | 179.07 kN | 1820.78 kN |
| 19.01 m | 1643.60 kN | 190.48 kN | 1834.07 kN |
| 22.01 m | 1921.76 kN | 190.48 kN | 2112.24 kN |
| 22.99 m | 2012.63 kN | 190.48 kN | 2203.11 kN |

DRIVING - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|-----------|---------------------------------|---------------------------|-----------|------------------|
| 0.01 m | Cohesive | N/A | N/A | 0.00 kPa | 0.00 kN |
| 1.49 m | Cohesive | N/A | N/A | 0.00 kPa | 0.00 kN |
| 1.50 m | Cohesive | N/A | N/A | 32.24 kPa | 0.00 kN |
| 3.01 m | Cohesive | N/A | N/A | 32.24 kPa | 34.67 kN |
| 6.01 m | Cohesive | N/A | N/A | 32.31 kPa | 103.75 kN |
| 6.99 m | Cohesive | N/A | N/A | 32.38 kPa | 126.57 kN |
| 7.01 m | Cohesive | N/A | N/A | 71.76 kPa | 127.31 kN |
| 10.01 m | Cohesive | N/A | N/A | 77.24 kPa | 292.34 kN |
| 13.01 m | Cohesive | N/A | N/A | 82.73 kPa | 480.78 kN |
| 16.01 m | Cohesive | N/A | N/A | 84.97 kPa | 671.90 kN |
| 16.49 m | Cohesive | N/A | N/A | 84.97 kPa | 700.94 kN |
| 16.51 m | Cohesive | N/A | N/A | 67.30 kPa | 702.02 kN |
| 18.99 m | Cohesive | N/A | N/A | 67.30 kPa | 820.86 kN |
| 19.01 m | Cohesive | N/A | N/A | 65.12 kPa | 821.80 kN |
| 22.01 m | Cohesive | N/A | N/A | 65.12 kPa | 960.88 kN |
| 22.99 m | Cohesive | N/A | N/A | 65.12 kPa | 1006.32 kN |

DRIVING - END BEARING

| Depth | Soil Type | Effective Stress At Tip Factor | Bearing Cap. | Limiting End Bearing | End Bearing |
|---------|-----------|-----------------------------------|--------------|-------------------------|----------------|
| 0.01 m | Cohesive | N/A | N/A | N/A | 0.00 kN |
| 1.49 m | Cohesive | N/A | N/A | N/A | 0.00 kN |
| 1.50 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 3.01 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 6.01 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 6.99 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 7.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 10.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 13.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.49 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.51 m | Cohesive | N/A | N/A | N/A | 179.07 kN |
| 18.99 m | Cohesive | N/A | N/A | N/A | 179.07 kN |
| 19.01 m | Cohesive | N/A | N/A | N/A | 190.48 kN |
| 22.01 m | Cohesive | N/A | N/A | N/A | 190.48 kN |
| 22.99 m | Cohesive | N/A | N/A | N/A | 190.48 kN |

DRIVING - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.49 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.50 m | 0.00 kN | 37.64 kN | 37.64 kN |
| 3.01 m | 34.67 kN | 37.64 kN | 72.30 kN |
| 6.01 m | 103.75 kN | 37.64 kN | 141.39 kN |
| 6.99 m | 126.57 kN | 37.64 kN | 164.21 kN |
| 7.01 m | 127.31 kN | 106.07 kN | 233.39 kN |
| 10.01 m | 292.34 kN | 106.07 kN | 398.41 kN |
| 13.01 m | 480.78 kN | 106.07 kN | 586.86 kN |
| 16.01 m | 671.90 kN | 106.07 kN | 777.97 kN |
| 16.49 m | 700.94 kN | 106.07 kN | 807.01 kN |
| 16.51 m | 702.02 kN | 179.07 kN | 881.09 kN |
| 18.99 m | 820.86 kN | 179.07 kN | 999.93 kN |
| 19.01 m | 821.80 kN | 190.48 kN | 1012.27 kN |
| 22.01 m | 960.88 kN | 190.48 kN | 1151.36 kN |
| 22.99 m | 1006.32 kN | 190.48 kN | 1196.79 kN |

ULTIMATE - SKIN FRICTION

| Depth | Soil Type | Effective Stress At Midpoint | Sliding Friction Angle | Adhesion | Skin Friction |
|---------|-----------|---------------------------------|---------------------------|-----------|------------------|
| 0.01 m | Cohesive | N/A | N/A | 0.00 kPa | 0.00 kN |
| 1.49 m | Cohesive | N/A | N/A | 0.00 kPa | 0.00 kN |
| 1.50 m | Cohesive | N/A | N/A | 32.24 kPa | 0.00 kN |
| 3.01 m | Cohesive | N/A | N/A | 32.24 kPa | 69.33 kN |
| 6.01 m | Cohesive | N/A | N/A | 32.31 kPa | 207.51 kN |
| 6.99 m | Cohesive | N/A | N/A | 32.38 kPa | 253.14 kN |
| 7.01 m | Cohesive | N/A | N/A | 71.76 kPa | 254.63 kN |
| 10.01 m | Cohesive | N/A | N/A | 77.24 kPa | 584.68 kN |
| 13.01 m | Cohesive | N/A | N/A | 82.73 kPa | 961.57 kN |
| 16.01 m | Cohesive | N/A | N/A | 84.97 kPa | 1343.80 kN |
| 16.49 m | Cohesive | N/A | N/A | 84.97 kPa | 1401.88 kN |
| 16.51 m | Cohesive | N/A | N/A | 67.30 kPa | 1404.05 kN |
| 18.99 m | Cohesive | N/A | N/A | 67.30 kPa | 1641.71 kN |
| 19.01 m | Cohesive | N/A | N/A | 65.12 kPa | 1643.60 kN |
| 22.01 m | Cohesive | N/A | N/A | 65.12 kPa | 1921.76 kN |
| 22.99 m | Cohesive | N/A | N/A | 65.12 kPa | 2012.63 kN |

ULTIMATE - END BEARING

| Depth | Soil Type | Effective Stress At Tip | Bearing Cap. Factor | Limiting End Bearing | End Bearing |
|---------|-----------|----------------------------|------------------------|-------------------------|----------------|
| 0.01 m | Cohesive | N/A | N/A | N/A | 0.00 kN |
| 1.49 m | Cohesive | N/A | N/A | N/A | 0.00 kN |
| 1.50 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 3.01 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 6.01 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 6.99 m | Cohesive | N/A | N/A | N/A | 37.64 kN |
| 7.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 10.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 13.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.01 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.49 m | Cohesive | N/A | N/A | N/A | 106.07 kN |
| 16.51 m | Cohesive | N/A | N/A | N/A | 179.07 kN |
| 18.99 m | Cohesive | N/A | N/A | N/A | 179.07 kN |
| 19.01 m | Cohesive | N/A | N/A | N/A | 190.48 kN |
| 22.01 m | Cohesive | N/A | N/A | N/A | 190.48 kN |
| 22.99 m | Cohesive | N/A | N/A | N/A | 190.48 kN |

ULTIMATE - SUMMARY OF CAPACITIES

| Depth | Skin Friction | End Bearing | Total Capacity |
|---------|---------------|-------------|----------------|
| 0.01 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.49 m | 0.00 kN | 0.00 kN | 0.00 kN |
| 1.50 m | 0.00 kN | 37.64 kN | 37.64 kN |
| 3.01 m | 69.33 kN | 37.64 kN | 106.97 kN |
| 6.01 m | 207.51 kN | 37.64 kN | 245.15 kN |
| 6.99 m | 253.14 kN | 37.64 kN | 290.78 kN |
| 7.01 m | 254.63 kN | 106.07 kN | 360.70 kN |
| 10.01 m | 584.68 kN | 106.07 kN | 690.75 kN |
| 13.01 m | 961.57 kN | 106.07 kN | 1067.64 kN |
| 16.01 m | 1343.80 kN | 106.07 kN | 1449.87 kN |
| 16.49 m | 1401.88 kN | 106.07 kN | 1507.95 kN |
| 16.51 m | 1404.05 kN | 179.07 kN | 1583.12 kN |
| 18.99 m | 1641.71 kN | 179.07 kN | 1820.78 kN |
| 19.01 m | 1643.60 kN | 190.48 kN | 1834.07 kN |
| 22.01 m | 1921.76 kN | 190.48 kN | 2112.24 kN |
| 22.99 m | 2012.63 kN | 190.48 kN | 2203.11 kN |

F.2.4.4 Static Axial Pile Capacity Calculations by LPC CPT Method - Computer Program

L.P.C. CPT Method Page 1/2
 Peach Freeway CPT-4 at South Abutment -- 356 mm-square PCPS Concrete Pile

Installation Method: 9 - Driven Prefabricated Piles (Concrete)
 Depth to Water Table: 1.00 meter

| Pile No. | Toe Area (m ²) | Perimeter (m) |
|----------|-------------------------------|------------------|
| 1 | 0.127 | 1.424 |

| Depth to Bottom of Layer (m) | Soil Type |
|------------------------------------|-----------|
| 7.0 | 1 |
| 29.0 | 2 |
| 30.0 | 8 |

| Depth (m) | Cone Tip Resistance (kPa) |
|--------------|---------------------------------|
| 0.0 | 1,149.1 |
| 3.5 | 1,149.1 |
| 7.0 | 1,053.4 |
| 10.0 | 3,255.8 |
| 15.0 | 2,872.8 |
| 16.0 | 4,438.5 |
| 17.0 | 3,433.0 |
| 18.0 | 4,989.1 |
| 19.0 | 4,141.6 |
| 20.0 | 4,021.9 |
| 21.0 | 3,361.2 |
| 22.0 | 3,064.3 |
| 23.0 | 6,875.6 |
| 24.0 | 5,266.8 |
| 26.0 | 4,979.5 |
| 28.0 | 5,027.4 |
| 28.5 | 4,309.2 |
| 29.0 | 20,492.6 |
| 30.0 | 48,981.2 |

| Depth (m) | Unit Friction (kPa) | Toe Bearing (kPa) | Shaft Resistance (kN) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|------------------------|----------------------|-----------------------------|---------------------------|------------------------------|
| 0.00 | 35.81 | 689.47 | 0.0 | 87.2 | 87.2 |
| 3.50 | 35.81 | 689.47 | 178.4 | 87.2 | 265.6 |
| 7.00 | 31.22 | 1292.76 | 345.2 | 163.2 | 508.4 |
| 10.00 | 59.04 | 1953.50 | 596.9 | 246.9 | 843.8 |
| 5.00 | 58.08 | 2025.32 | 1013.3 | 256.2 | 1269.5 |
| 16.00 | 61.91 | 2164.18 | 1098.7 | 273.6 | 1372.2 |
| 17.00 | 59.47 | 2542.43 | 1185.0 | 321.2 | 1506.1 |
| 18.00 | 63.25 | 2513.70 | 1272.1 | 318.0 | 1590.2 |
| 19.00 | 61.19 | 2590.31 | 1360.6 | 327.8 | 1688.5 |
| 20.00 | 60.90 | 2312.60 | 1447.4 | 292.2 | 1739.6 |
| 21.00 | 59.28 | 2168.96 | 1532.8 | 274.4 | 1807.2 |
| 22.00 | 58.56 | 2666.92 | 1616.4 | 337.6 | 1954.0 |
| 23.00 | 67.85 | 3011.65 | 1706.3 | 380.8 | 2087.0 |
| 24.00 | 63.92 | 3385.12 | 1800.1 | 427.9 | 2228.0 |
| 26.00 | 63.20 | 3026.02 | 1981.1 | 382.5 | 2363.7 |
| 28.00 | 63.35 | 8637.55 | 2160.8 | 1092.4 | 3253.3 |
| 28.50 | 61.57 | 9576.00 | 2205.3 | 1210.8 | 3416.1 |
| 29.00 | 101.07 | 9576.00 | 2263.1 | 1210.8 | 3473.9 |
| 30.00 | 76.37 | 9576.00 | 2371.7 | 1210.8 | 3582.4 |

Note: Depth is referenced from the original ground surface.

F.2.4.5 Static Axial Pile Capacity Calculations by Schmertmann Method

Location: Peach Freeway CPT-4 at South Abutment.

| Depth (m) | fs(avg) (bars) | Unit Friction (bars) | Increment Friction (kN) | Shaft Resistance (kN) | q _c (avg) (bars) | q _{c1} (min) (bars) | q _{c2} (bars) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|-------------------|----------------------------|-------------------------------|-----------------------------|--------------------------------|---------------------------------|---------------------------|---------------------------|------------------------------|
| 15.00 | 2.24 | 0.90 | 31.22 | 1,191 | 45.20 | | | | |
| 15.25 | 3.19 | 1.28 | 44.44 | 1,235 | 54.84 | | | | |
| 15.50 | 2.53 | 1.01 | 35.27 | 1,271 | 44.96 | 33.90 | 20.38 | 29 | 1,599 |
| 15.75 | 2.41 | 0.96 | 33.57 | 1,304 | 43.12 | | | | |
| 16.00 | 2.49 | 1.00 | 34.76 | 1,339 | 42.38 | 32.13 | 25.23 | 347 | 1,686 |
| 16.25 | 1.82 | 0.73 | 25.37 | 1,364 | 33.98 | | | | |
| 16.50 | 1.29 | 0.58 | 20.26 | 1,385 | 29.10 | 31.80 | 27.41 | 358 | 1,743 |
| 16.75 | 1.97 | 0.79 | 27.43 | 1,412 | 34.50 | 40.16 | 28.48 | 416 | 1,828 |
| 17.00 | 2.35 | 0.94 | 32.78 | 1,445 | 45.82 | 43.94 | 29.55 | 445 | 1,890 |
| 17.25 | 3.07 | 1.23 | 42.80 | 1,488 | 55.86 | | | | |
| 17.50 | 2.69 | 1.08 | 37.49 | 1,525 | 53.16 | 40.59 | 29.83 | 426 | 1,951 |
| 17.75 | 2.60 | 1.04 | 36.27 | 1,561 | 62.30 | | | | |
| 18.00 | 2.15 | 0.86 | 29.97 | 1,591 | 37.04 | 34.39 | 28.94 | 383 | 1,975 |
| 18.25 | 2.26 | 0.91 | 31.56 | 1,623 | 46.56 | | | | |
| 18.50 | 3.08 | 1.23 | 42.96 | 1,666 | 64.02 | 33.90 | 28.94 | 380 | 2,046 |
| 18.75 | 1.84 | 0.74 | 25.71 | 1,692 | 32.00 | | | | |
| 19.00 | 1.77 | 0.72 | 25.26 | 1,717 | 30.44 | 29.32 | 28.94 | 353 | 2,070 |
| 19.25 | 1.53 | 0.66 | 22.99 | 1,740 | 28.94 | | | | |
| 19.50 | 2.22 | 0.89 | 30.98 | 1,771 | 42.22 | 30.27 | 28.94 | 358 | 2,129 |
| 19.75 | 1.48 | 0.62 | 21.69 | 1,793 | 30.34 | | | | |
| 20.00 | 1.33 | 0.60 | 20.80 | 1,813 | 27.26 | 29.92 | 27.26 | 346 | 2,160 |
| 20.25 | 1.94 | 0.78 | 27.10 | 1,841 | 36.50 | | | | |
| 20.50 | 1.48 | 0.62 | 21.69 | 1,862 | 30.50 | 23.62 | 18.54 | 255 | 2,117 |
| 20.75 | 1.94 | 0.77 | 26.99 | 1,889 | 33.60 | | | | |
| 21.00 | 2.35 | 0.94 | 32.73 | 1,922 | 39.78 | 22.78 | 18.54 | 250 | 2,172 |
| 21.25 | 1.59 | 0.67 | 23.30 | 1,945 | 27.36 | | | | |
| 21.50 | 1.06 | 0.52 | 18.17 | 1,963 | 22.38 | 19.50 | 18.54 | 230 | 2,194 |
| 21.75 | 0.78 | 0.45 | 15.53 | 1,979 | 18.54 | | | | |

Note: Depth is referenced from the original ground surface.

Location: Peach Freeway CPT-4 at South Abutment (continued).

| Depth (m) | fs(avg) (bars) | Unit Friction (bars) | Increment Friction (kN) | Shaft Resistance (kN) | q _c (avg) (bars) | q _{c1} (min) (bars) | q _{c2} (bars) | Toe Resistance (kN) | Ultimate Capacity (kN) |
|--------------|-------------------|----------------------------|-------------------------------|-----------------------------|--------------------------------|---------------------------------|---------------------------|---------------------------|------------------------------|
| 22.00 | 2.12 | 0.85 | 29.61 | 2,090 | 46.92 | 47.34 | 18.54 | 399 | 2,407 |
| 22.25 | 5.48 | 4.65 | 162.21 | 2,171 | 116.78 | | | | |
| 22.50 | 3.78 | 3.21 | 111.91 | 2,283 | 71.18 | 42.20 | 22.26 | 390 | 2,673 |
| 22.75 | 2.86 | 1.14 | 39.81 | 2,323 | 61.10 | | | | |
| 23.00 | 1.96 | 0.78 | 27.35 | 2,350 | 38.18 | 34.17 | 22.38 | 342 | 2,692 |
| 23.25 | 1.90 | 0.76 | 26.46 | 2,376 | 33.42 | | | | |
| 23.50 | 2.79 | 1.12 | 38.87 | 2,415 | 46.08 | 34.99 | 24.30 | 359 | 2,774 |

Note: Depth is referenced from the original ground surface.

F.2.4.6 Summary of South Abutment Capacity Calculation Results

Summary of Pile Capacity Estimates with an Embedded Pile Length of 17.5 meters

| Method Used for Estimation of Pile Capacity | Calculated Pile Shaft Resistance (kN) | Calculated Pile Toe Resistance (kN) | Calculated Ultimate Pile Capacity (kN) |
|--|--|--|---|
| α Method | 1,648 | 182 | 1,830 |
| Effective Stress Method | 898 | 715 | 1,613 |
| Driven Program - SPT Data | 1,644 | 190 | 1,834 |
| LPC CPT Program - CPT Data | 1,361 | 328 | 1,689 |
| Schmertmann Method - CPT Data | 1,717 | 353 | 2,070 |

Summary of Pile Length Estimates for the 1,780 kN Ultimate Pile Capacity

| Method Used for Estimation of Pile Capacity | Calculated Pile Length for the 1,780 kN Ultimate Pile Capacity |
|--|---|
| α Method | 17.5 meters for 1,830 kN |
| Effective Stress Method | 18.7 meters for 1,800 kN |
| Driven Program - SPT Data | 17.5 meters for 1,834 kN |
| LPC CPT Program - CPT Data | 19.5 meters for 1,807 kN |
| Schmertmann Method - CPT Data | 15.2 meters for 1,828 kN |

The ultimate pile group capacity at the South Abutment should be calculated based on the lesser of the ultimate pile group capacity calculated from Steps 1 to 4 of the design recommendations presented in Section 9.8.1.2. The ultimate pile group capacity based on the design recommendations is equal to 43,920 kN which is in excess of the required ultimate pile group capacity of 42,720 kN.

F.3 GROUP SETTLEMENT CALCULATIONS

The substructure of the bridge is designed to be supported on a pile group having three rows of piles with 8 piles in each row. The piles are arranged at 1.5 m center to center spacing with a total pile group area of 3.36 m by 10.86 m. Piles in a group are combined with a pile cap having a dimension of 4.5 m by 12 m.

The bridge division has estimated that the maximum compression loads per substructure unit are 12,600 kN. The maximum pile group settlement should be less than 25 mm under the compression loads.

Calculations of pile group settlement will be demonstrated for pile groups embedded in both cohesionless, cohesive, and combined layers of cohesionless and cohesive soils. The pile groups at the North Abutment and Pier 2 has a cohesionless soil profile. The pile groups at Pier 3 has a combined layers of cohesionless and cohesive soils, and the pile groups at the South Abutment has a cohesive soil profile.

F.3.1 North Abutment - Meyerhof Method Based on SPT Test Data

The soil profile interpreted from Soil Boring S-1 for the pile group at the North Abutment was shown in Figure F.3. Calculate the immediate settlement of pile group using the Meyerhof method based on SPT test data for an embedded pile length of 11.5 meters. Use the method outlined in Section 9.8.2.2a.

STEP 1 Calculate total pile group settlement due to soil compression.

Meyerhof recommended that the settlement of a pile group in a homogeneous sand deposit not underlain by a more compressible soil at a greater depth may be conservatively estimated by the following expression:

STEP 1 (continued)

Where:

p_f = foundation pressure (kPa). Group load divided by group area.

Notes: settlement should be calculated for the design load to be imposed on the pile group, and not the ultimate or allowable pile group capacities.

$$= \frac{12,600 \text{ kN}}{(3.36 \text{ m})(10.86 \text{ m})} = 345 \text{ kPa}$$

B = the width of pile group = 3.36 m

\bar{N}' = average corrected SPT N' value within a depth B below pile toe level.

$$= \frac{34 + 32 + 33}{3} = 33$$

D = pile embedment depth = 11.5 m

I_f = influence factor for group embedment.

$$= 1 - [D / 8B] \geq 0.5$$

$$= 1 - [(11.5 \text{ m}) / 8(3.36 \text{ m})] = 0.572$$

Therefore,

s = estimated total pile group settlement due to soil compression.

$$= \frac{0.96(345 \text{ kPa})\sqrt{3.36(0.572)}}{33} = 10.52 \text{ mm}$$

Note: For silty sand, a different equation should be used as indicated in Section 9.8.2.2a.

STEP 2 Calculate the elastic compression of pile material under design load on each pile as described in Section 9.8.2.1.

The design load on each pile = 890 kN. The elastic compression of each pile can be calculated with the following expression:

$$\Delta = \frac{Q_a L}{A E}$$

Where:

L = Length of pile (mm) = 11,500 mm

A = Pile cross sectional area (m²) = 0.127 m²

E = Modulus of elasticity of pile material (kPa) = 27.8 x 10⁶ kPa

Q_a = Design axial load in pile (kN), as discussed below.

Because of the shaft resistance, the axial load transferred to the pile varies along the pile length. For this reason, the average axial load in each pile segment should be calculated. The pile is divided into four segments according to the number of soil layers used in shaft resistance computations presented in Section F.2.1.2 (Nordlund Method). The first segment is 1 meter length, the second is 3 meters, the third is 7 meters, and the fourth is 0.5 meters. The shaft resistance as calculated using the Nordlund method for the first, second, third, and fourth segment is 37 kN, 146 kN, 615 kN, and 100 kN, respectively. The average axial load transferred to each pile segment is equal to the axial load transferred to the mid length of each pile segment as shown in Figure F.13. The average axial load transferred is used to calculate the elastic compression of the pile segment. The total elastic compression of the pile is equal to the sum of elastic compression from each pile segment.

$$\text{Pile segment 1a: } \Delta_{1a} = \frac{(872 \text{ kN})(1000 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.247 \text{ mm}$$

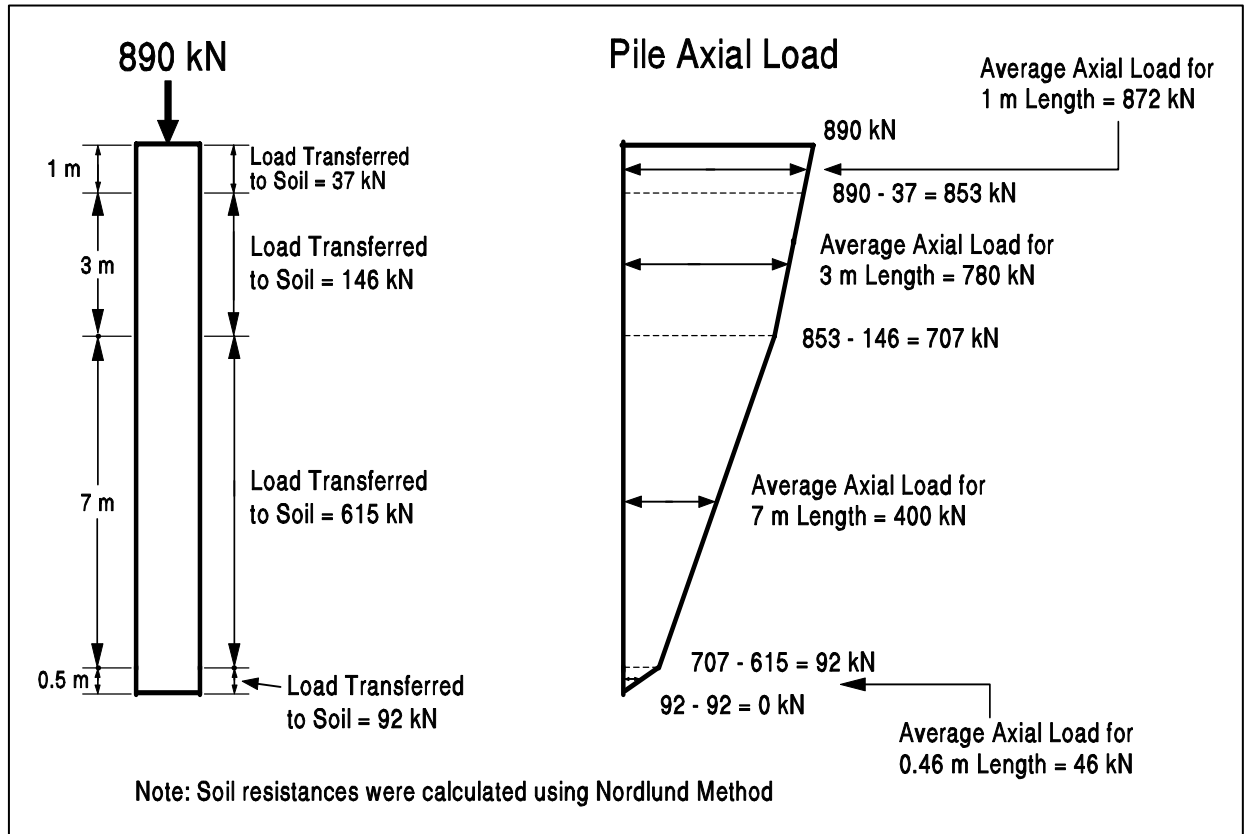


Figure F.13 Calculation of Axial Load Transfer to the Pile at the North Abutment

STEP 2 (continued)

Pile segment 1b: $\Delta_{1b} = \frac{(780 \text{ kN})(3000 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.663 \text{ mm}$

Pile segment 2: $\Delta_2 = \frac{(400 \text{ kN})(7000 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.793 \text{ mm}$

Pile segment 3: $\Delta_3 = \frac{(46 \text{ kN})(460 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.006 \text{ mm}$

Total: $\Delta = \Delta_{1a} + \Delta_{1b} + \Delta_2 + \Delta_3$

$= 0.247 \text{ mm} + 0.663 \text{ mm} + 0.793 \text{ mm} + 0.006 \text{ mm} = 1.709 \text{ mm}$

STEP 3 Compute total pile group settlement.

$$\begin{aligned}\Delta(\text{ total }) &= \Delta (\text{ soil compression }) + \Delta (\text{ elastic pile compression }) \\ &= 10.52 \text{ mm} + 1.709 \text{ mm} \\ &= 12.23 \text{ mm} \quad \text{or} \quad 0.012 \text{ m}\end{aligned}$$

Note: Total pile group settlement is less than the maximum allowable settlement of 25 mm.

F.3.2 Pier 2 - Meyerhof Method Based on SPT Test Data

The soil profile interpreted from Soil Boring S-2 for the pile group at Pier 2 was shown in Figure F.5. Calculate the immediate settlement of pile group using the Meyerhof method based on SPT test data for an embedded pile length of 10 meters. Use the method outlined in Section 9.8.2.2a.

STEP 1 Calculate total pile group settlement due to soil compression.

Meyerhof recommended that the settlement of a pile group in a homogeneous sand deposit not underlain by a more compressible soil at a greater depth may be conservatively estimated by the following expression:

$$s = \frac{0.96 p_f \sqrt{B} I_f}{\bar{N}'}$$

Where:

p_f = foundation pressure (kPa). Group load divided by group area.
Notes: settlement should be calculated for the design load to be imposed on the pile group, and not the ultimate or allowable pile group capacities.

$$= \frac{12,600 \text{ kN}}{(3.36 \text{ m})(10.86 \text{ m})} = 345 \text{ kPa}$$

B = the width of pile group = 3.36 m

\bar{N}' = average corrected SPT N' value within a depth B below pile toe level

$$= \frac{34 + 30 + 32}{3} = 32$$

D = pile embedment depth = 10 m

STEP 1 (continued)

I_f = influence factor for group embedment

$$= 1 - [D / 8B] \geq 0.5$$

$$= 1 - [(10 \text{ m}) / 8 (3.36 \text{ m})] = 0.628$$

Therefore,

s = estimated total pile group settlement due to soil compression

$$= \frac{0.96 (345 \text{ kPa}) \sqrt{.36 (0.628)}}{32} = 11.91 \text{ mm}$$

Note: For silty sand, a different equation should be used as indicated in Section 9.8.2.2a.

STEP 2 Calculate the elastic compression of pile material under design load on each pile.

The design load on each pile = 890 kN. The elastic compression of each pile can be calculated with the following expression:

$$\Delta = \frac{Q_a L}{A E}$$

Where:

L = Length of pile (mm) = 10,000 mm

A = Pile cross sectional area (m^2) = 0.127 m^2

E = Modulus of elasticity of pile material (kPa) = 27.8 x 10⁶ kPa

Q_a = Design axial load in pile (kN), as discussed below.

Because of the shaft resistance, the axial load transferred to the pile varies along the pile length. For this reason, the average axial load in each pile segment should be calculated. The pile is divided into two segments according to the number of soil layers presented in Figure F.5. The first segment is 4

STEP 2 (continued)

meters length and the second is 6 meters. The shaft resistance as calculated using the Nordlund method (as presented in Section F.2.2.2) for the first and second segment is 267 kN and 717 kN, respectively. The average axial load transferred to each pile segment is equal to the axial load transferred to the mid length of each pile segment as described earlier in Section F.3.1 and shown in Figure F.14. The average axial load transferred is used to calculate the elastic compression of the pile segment. The total elastic compression of the pile is equal to the sum of elastic compression from each pile segment.

$$\text{Pile segment 1: } \Delta_1 = \frac{(757 \text{ kN})(4000 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.858 \text{ mm}$$

$$\text{Pile segment 2: } \Delta_2 = \frac{(312 \text{ kN})(5213 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.461 \text{ mm}$$

$$\begin{aligned} \text{Total: } \Delta &= \Delta_1 + \Delta_2 \\ &= 0.858 \text{ mm} + 0.461 \text{ mm} = 1.319 \text{ mm} \end{aligned}$$

STEP 3 Compute total pile group settlement.

$$\begin{aligned} \Delta (\text{total}) &= \Delta (\text{soil compression}) + \Delta (\text{elastic pile compression}) \\ &= 11.91 \text{ mm} + 1.319 \text{ mm} \\ &= 13.23 \text{ mm} \quad \text{or} \quad 0.013 \text{ m} \end{aligned}$$

Note: Total pile group settlement is less than the maximum allowable settlement of 25 mm.

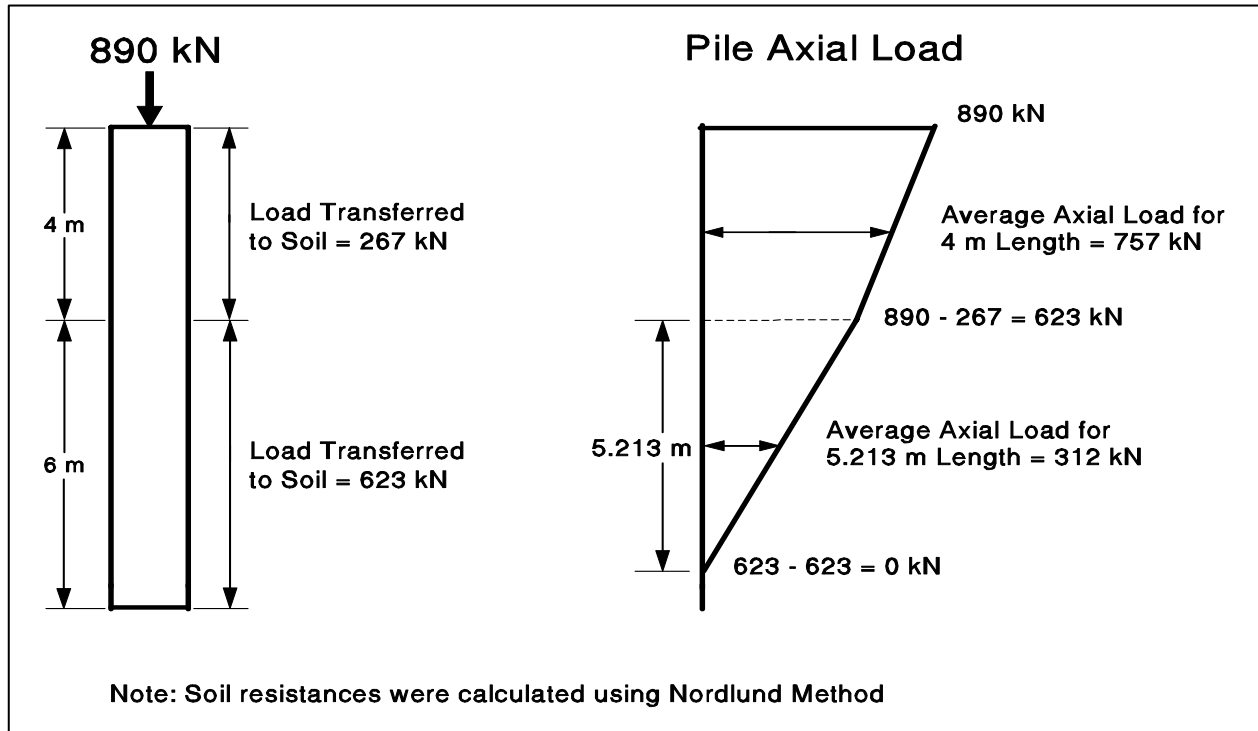


Figure F.14 Calculation of Axial Load Transfer to the Pile at Pier 2

F.3.3 Pier 3 - Equivalent Footing Method for Layered Soils

For the pile group at Pier 3 and the soil profile interpreted from Soil Boring S-3 as shown in Figure F.9. Calculate the immediate settlements of pile groups using the equivalent footing method for layered soils for an embedded pile length of 13 meters. Use the step-by-step method outlined in Section 9.8.2.5.

STEP 1 Determine the new load imposed on soil by the pile group.

a. Determine the location of the equivalent footing.

The location of the equivalent footing is based on the shaft and toe resistance condition and the soil profile. Figure 9.62 should be used to determine the location of the equivalent footing and the pressure distribution. The soil profile for Soil Boring S-3, and the shaft and toe resistance combination match that in Figure 9.62(d), and therefore the equivalent footing is placed at depth of $\frac{2}{3} D$ from the bottom of the pile cap as shown in the figure.

STEP 1 (continued)

Depth of Equivalent Footing:

- below the pile cap $= \frac{2}{3} (13.0 \text{ m}) = 8.67 \text{ m}$
- or below the existing ground $= 8.67 \text{ m} + 2.0 \text{ m} = 10.67 \text{ m}$

b. Determine the dimensions of the equivalent footing.

All the piles in the pile group are vertical, and the pile group has a dimension of 3.36 meters by 10.86 meters. To account for load transfer, the equivalent footing has a modified dimension that spreads as a pyramid with a side slope of 1H:4V, as shown in Figure 9.44(d). Since the equivalent footing is 8.67 meters below the pile cap, the equivalent footing dimensions are:

$$\begin{aligned}\text{The width of the equivalent footing, } B_1 &= 3.36 \text{ m} + 2 \left(\frac{8.67 \text{ m}}{4} \right) \\ &= 7.70 \text{ m}\end{aligned}$$

$$\begin{aligned}\text{The length of the equivalent footing, } Z_1 &= 10.86 \text{ m} + 2 \left(\frac{8.67 \text{ m}}{4} \right) \\ &= 15.20 \text{ m}\end{aligned}$$

c. Determine the pressure distribution to soil layers below the equivalent footing up to the depth at which the pressure increase from the equivalent footing is less than 10% of existing effective overburden pressure at that depth.

The pressure distribution diagram below the equivalent footing is presented in Figure F.15. Note, the pressure distribution area increases with depth below the equivalent footing which results in a pressure reduction with depth below the equivalent footing. The dimension of the pressure distribution surface also spreads as a pyramid with depth but with a side slope of 1H:2V.

For example, at depth of 0.67 meter below the equivalent footing (or 11.34 meters below the existing ground surface), the pressure distribution surface has the following dimensions:

STEP 1 (continued)

Width of pressure distribution surface, $B_2 = 7.70 \text{ m} + 2 \left(\frac{0.67 \text{ m}}{2} \right) = 8.37 \text{ m}$

Length of pressure distribution surface, $Z_2 = 15.20 \text{ m} + 2 \left(\frac{0.67 \text{ m}}{2} \right) = 15.87 \text{ m}$

Area of pressure distribution surface, $A_2 = (B_2) (Z_2) = (8.37 \text{ m}) (15.87 \text{ m})$
 $= 132.8 \text{ m}^2$

Therefore, at depth of 0.67 meter below the equivalent footing the pressure increase due to the imposed design load is:

$$\Delta p = \left(\frac{12,600 \text{ kN}}{132.8 \text{ m}^2} \right) = 94.88 \text{ kPa}$$

The pressure increase at other locations below the equivalent footing is summarized in Table F-1. The limestone bedrock was reached before the imposed pressure increase becomes less than 10% of existing effective overburden pressure. Therefore for settlement calculation, the total soil thickness up to the bedrock will be used.

- d. Divide the cohesive soil layers in the affected pressure increase zone into several thinner layers of 1.5 to 3 meter thickness. The thickness of each layer is the thickness H for the settlement computation for that layer.

For this example, the soil is divided into 1.5 meter thick layers as presented in column 3 of Table F-2. The soil layer boundaries are presented in column 2 of Table F-2.

- e. Determine the existing effective overburden pressure, p_o , at the midpoint of each layer.

The midpoint location of each soil layer below the existing ground is presented in column 4 of Table F-2. The effective overburden pressure, p_o , at the midpoint of each layer is presented in column 5 of Table F-2.

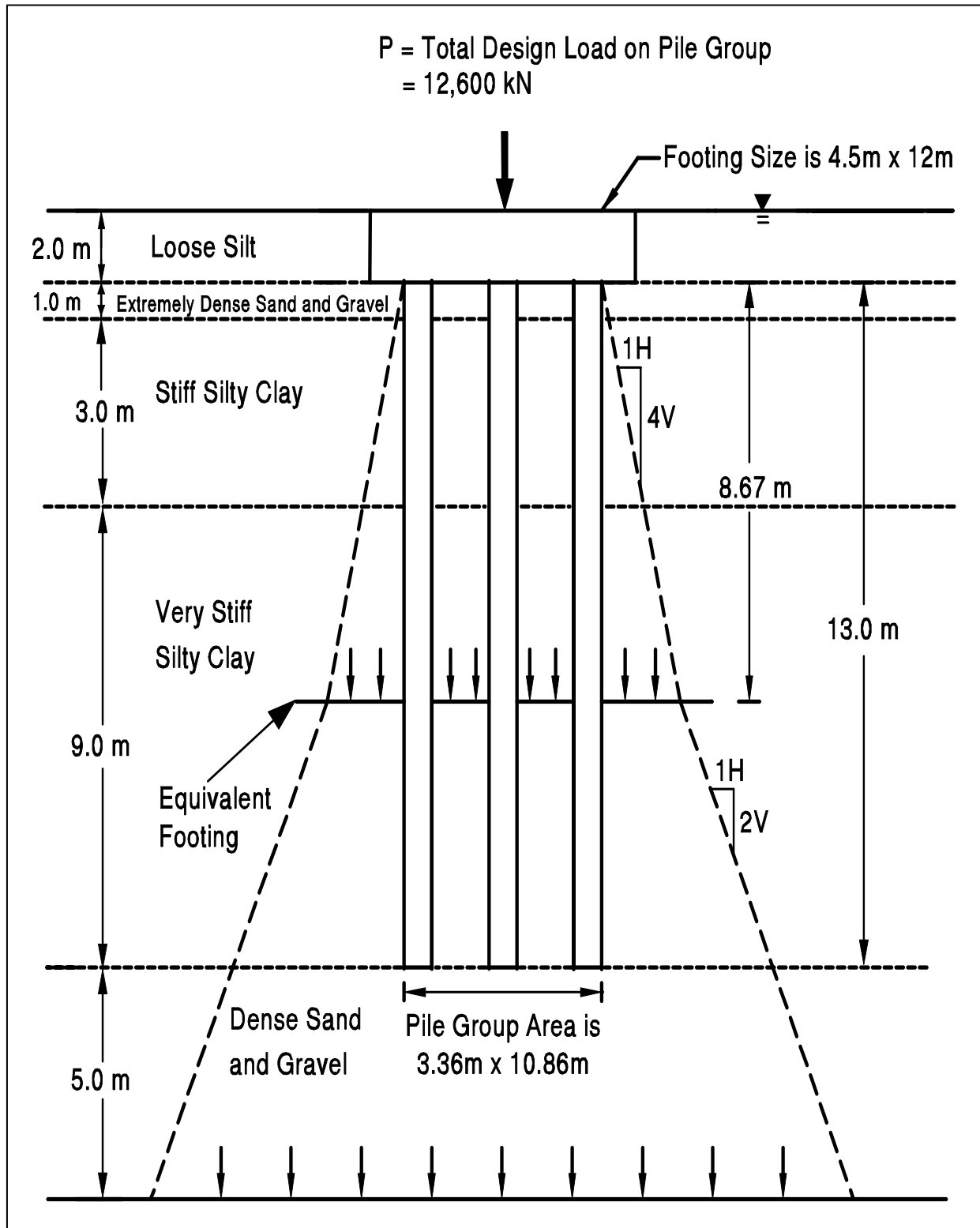


Figure F.15 Pressure Distribution Below Equivalent Footing for Pile Group at Pier 3

| Table F-1 Summary of Pressure Distribution Below Equivalent Footing | | | | | | | |
|---|--|-------------------------------|--------------------------------|---|--|---|--|
| Depth Below Existing Ground (m) | Depth Below Equivalent Footing (m) | Load Distribution Surface | | | Imposed Pressure Increase Δp (kPa) | Effective Overburden Pressure p_o (kPa) | $\left(\frac{\Delta p}{p_o}\right) 100\%$ (%) |
| | | Width B_2 (m) | Length Z_2 (m) | Area $(B_2)(Z_2)$ (m ²) | | | |
| 10.67 | 0.00 | 7.70 | 15.20 | 117.0 | 107.66 | 98.77 | 109.0 |
| 11.34 | 0.67 | 8.37 | 15.87 | 132.8 | 94.88 | 105.74 | 89.7 |
| 12.75 | 2.08 | 9.78 | 17.28 | 169.0 | 74.56 | 120.40 | 61.9 |
| 14.25 | 3.58 | 11.28 | 18.78 | 211.8 | 59.48 | 136.00 | 43.7 |
| 15.75 | 5.08 | 12.78 | 20.28 | 259.2 | 48.62 | 151.53 | 32.1 |
| 17.25 | 6.58 | 14.28 | 21.78 | 311.0 | 40.51 | 166.98 | 24.3 |
| 18.75 | 8.08 | 15.78 | 23.28 | 367.4 | 34.30 | 182.43 | 18.8 |
| 19.75 | 9.08 | 16.78 | 24.28 | 407.4 | 30.93 | 192.73 | 16.1 |

Note: Equivalent Footing is at 10.67 meters below existing ground.

STEP 1 (continued)

- f. Determine the imposed pressure increase, Δp , at the midpoint of each affected soil layer based on the appropriate pressure distribution surface.

The imposed pressure increase, Δp , at the midpoint of each affected soil layer is presented in column 6 of Table F-2. Calculations of the imposed pressure increase based on the pressure distribution area were presented earlier in Step 1c.

STEP 2 Determine consolidation test parameters for the cohesive soil layer.

The laboratory consolidation test results on the undisturbed samples of stiff silty clay from layer 2 and very stiff silty clay from layer 3 were plotted on the "log pressure, p versus void ratio, e " (similar to Figure 9.43).

[illegible]

STEP 2 (continued)

The following consolidation test parameters were obtained from the plot.

Soil Layer 3 (very stiff silty clay):

| | | |
|----------------------------------|---|---------|
| Preconsolidation pressure, p_c | = | 297 kPa |
| Initial void ratio, e_0 | = | 0.54 |
| Compression index, C_c | = | 0.20 |
| Recompression index, C_{cr} | = | 0.020 |

STEP 3 Determine bearing capacity index for each cohesionless layer.

Determine the average corrected SPT N' value, \bar{N}' , for each cohesionless layer.

Use \bar{N}' for the appropriate SPT hammer type in Figure 9.63 to obtain the bearing capacity index for each layer.

Soil Layer 4:

| | |
|--------------------|---|
| Layer 15.0 - 16.5: | $\bar{N}'=33$ from Safety Hammer; $C'=146$ from Figure 9.63 |
| Layer 16.5 - 18.0: | $\bar{N}'=38$ from Safety Hammer; $C'=173$ from Figure 9.63 |
| Layer 18.0 - 19.5: | $\bar{N}'=33$ from Safety Hammer; $C'=146$ from Figure 9.63 |
| Layer 19.5 - 20.0: | $\bar{N}'=39$ from Safety Hammer; $C'=180$ from Figure 9.63 |

STEP 4 Compute settlement due to soil compression.

Compute settlement of each cohesive soil layer using the following equations:

$$s = H \left[\frac{C_{cr}}{1 + e_0} \log \frac{p_o + \Delta p}{p_o} \right] \quad \text{when } p_o + \Delta p \leq p_c$$
$$= H \left[\frac{C_{cr}}{1 + e_0} \log \frac{p_c}{p_o} \right] + H \left[\frac{C_c}{1 + e_0} \log \frac{p_o + \Delta p}{p_o} \right] \quad \text{when } p_o + \Delta p > p_c$$

For example, the soil layer increment 10.67 m to 12.00 m corresponds to:

$$(p_o + \Delta p) = 200.62 \text{ kPa} < p_c = 297 \text{ kPa}$$

STEP 4 (continued)

Therefore, layer settlement as shown in column 8 of settlement calculations table:

$$\begin{aligned} s &= H \left[\frac{C_{cr}}{1 + e_0} \log \frac{p_o + \Delta p}{p_o} \right] \\ &= 1.33 \left[\frac{0.020}{(1 + 0.54)} \log \left(\frac{200.62}{105.74} \right) \right] = 0.0048 \text{ m} \end{aligned}$$

Compute settlement of each cohesionless soil layer using the following equations:

$$s = H \left[\frac{1}{C'} \log \frac{p_o + \Delta p}{p_o} \right]$$

For the soil layer increment 15.0 m to 16.5 m corresponds to soil layer 3:

Therefore, the settlement for the soil layer increment as shown in column 8 of Table F-2 is:

$$s = 1.50 \left[\frac{1}{146} \log \left(\frac{200.15}{151.53} \right) \right] = 0.0012 \text{ m}$$

Following similar procedures, the total estimated pile group settlement due to soil compression is equal to the sum of settlements of all layers, or the sum of column 8 of Table F-2 and is equal to 0.0150 meter or 15.0 mm.

STEP 5 Calculate the elastic compression of pile material under design load on each pile. (See Section 9.8.2.1)

Note, for elastic compression calculations, it is assumed that all piles in the group are loaded with the 890 kN design load. This assumption is conservative because piles in the middle and rear rows have smaller loads. The elastic compression of each pile can be calculated with the following expression:

$$\Delta = \frac{Q_a L}{A E}$$

STEP 5 (continued)

Where:

L = Length of pile (mm) = 13,000 mm

A = Pile cross sectional area (m^2) = 0.127 m^2

E = Modulus of elasticity of pile material (kPa) = 27.8×10^6 kPa

Q_a = Design axial load in pile (kN), as discussed below.

Because of shaft resistances, the axial load transferred to the pile varies along the length of the pile. Therefore, for elastic compression calculations the pile should be divided into segments with the average axial load in each segment calculated. For this example, the pile is divided into three segments based on the soil layers presented in Figure F.9. The first segment is 1.0 meter length, the second is 3.0 meters, and the third is 9.0 meters. The shaft resistance as calculated using the Nordlund method for the cohesionless soil layer and the α -method for the cohesive soil layer (as presented in Section F.2.3.1) for the first, second, and third segment is 22 kN, 453 kN, and 696 kN, respectively.

The average axial load transferred to each pile segment is equal to the axial load transferred to the mid-length of the segment, as shown in Figure F.16. The average axial load is used to calculate the elastic compression of each pile segment. Figure F.16 also shows that there is 868 kN to be transferred to soil layer 2, and 415 kN to be transferred to soil layer 3 which is capable of supporting up to 696 kN over the 9.0 meter layer thickness. Therefore, the 415 kN load will be fully transferred to the soil at depth of (415 kN / 696 kN) times (9.0 meters), or 5.366 meters below the top of layer 3, or the 890 kN total load will be fully transferred to the soil at depth of 9.366 meters below the pile cap. In other words, the lower 3.634 meters of the pile will not be subjected to any load or elastic compression.

$$\text{Pile segment 1: } \Delta_1 = \frac{(879 \text{ kN})(1,000 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.249 \text{ mm}$$

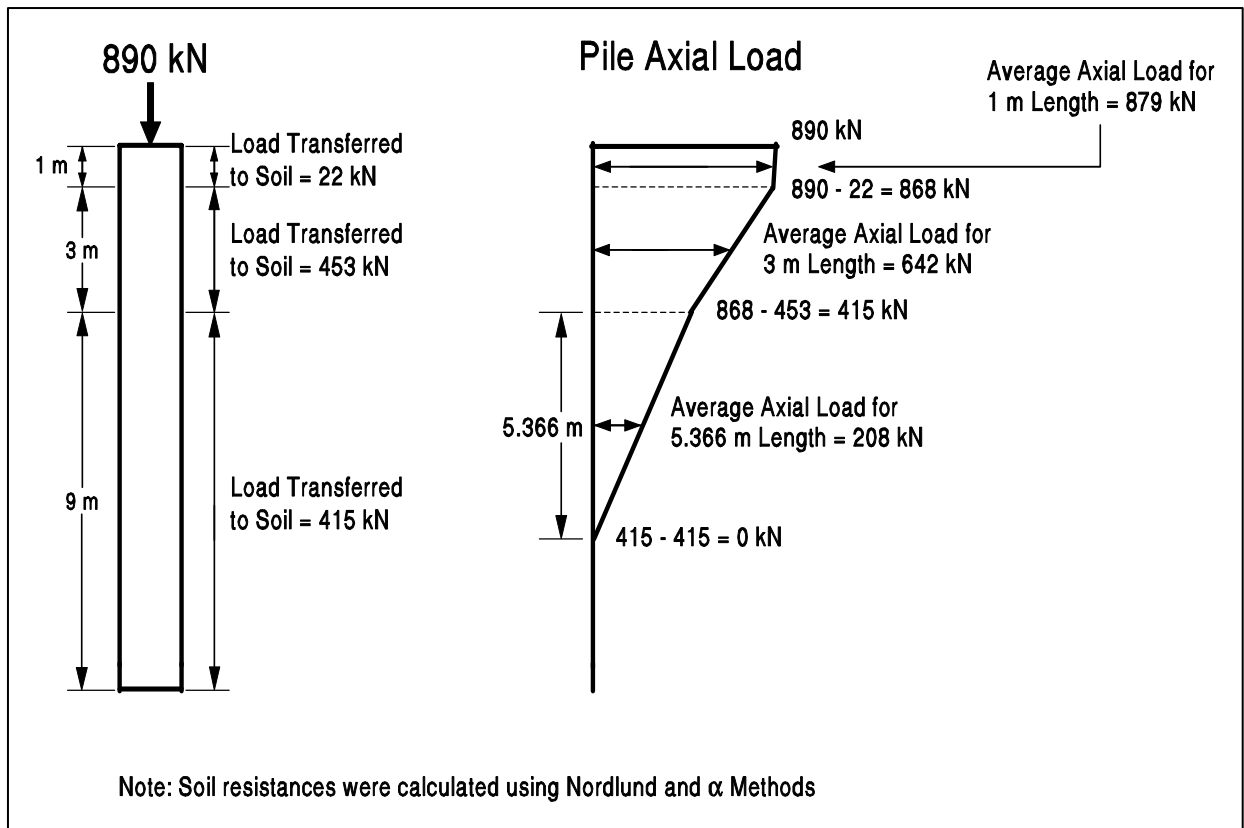


Figure F.16 Calculation of Axial Load Transfer to the Pile at Pier 3

STEP 5 (continued)

Pile segment 2: $\Delta_2 = \frac{(642 \text{ kN})(3,000 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.546 \text{ mm}$

Pile segment 3: $\Delta_3 = \frac{(208 \text{ kN})(5,366 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.316 \text{ mm}$

Total: $\Delta = \Delta_1 + \Delta_2 + \Delta_3$

$= 0.249 \text{ mm} + 0.546 \text{ mm} + 0.316 = 1.111 \text{ mm}$

Note: The elastic pile compression is small relative to the soil compression (15.0 mm), and therefore it is usually ignored.

STEP 6 Compute total pile group settlement.

$$\begin{aligned}\Delta(\text{ total }) &= \Delta(\text{ soil compression }) + \Delta(\text{ elastic pile compression }) \\ &= 15.0 \text{ mm} + 1.111 \text{ mm} = 16.111 \text{ mm or } 0.016 \text{ m}\end{aligned}$$

The total pile group settlement is smaller than the maximum allowable pile group settlement of 25 mm.

The Meyerhof method for settlement calculations based on SPT test data (Section 9.8.2.2a) will be performed on the following to compare with settlement calculated above.

STEP 1 Calculate total pile group settlement due to soil compression.

Meyerhof recommended that the settlement of a pile group in a homogeneous sand deposit not underlain by a more compressible soil at greater depth may be conservatively estimated by the following expression:

$$s = \frac{0.96 p_f \sqrt{B} I_f}{\bar{N}'}$$

Where:

p_f = foundation pressure (kPa). Group load divided by group area.

Notes: settlement should be calculated for the design load to be imposed on the pile group, and not the ultimate or allowable pile group capacities.

$$= \frac{12,600 \text{ kN}}{(3.36 \text{ m})(10.86 \text{ m})} = 345 \text{ kPa}$$

B = the width of pile group = 3.36 m

\bar{N}' = average corrected SPT N' value within a depth B below pile toe level

$$= \frac{33 + 38 + 33}{3} = 35$$

STEP 1 (continued)

$$D = \text{pile embedment depth} = 13 \text{ m}$$

$$I_f = \text{influence factor for group embedment}$$

$$= 1 - [D / 8B] \geq 0.5$$

$$= 1 - [(13 \text{ m}) / 8 (3.36 \text{ m})] = 0.516$$

Therefore,

$$s = \text{estimated total pile group settlement due to soil compression}$$

$$= \frac{0.96 (345 \text{ kPa}) \sqrt{.36 (0.516)}}{35} = 8.95 \text{ mm}$$

The settlement estimated using the Meyerhof method (8.95 mm) is less than the settlement calculated based on the equivalent method (15.2 mm). In this soil profile, the equivalent footing method calculates most of the foundation settlement (12 mm) to occur in the clay layer with minimal settlement of the underlying sand layer in which the piles are founded. It is unlikely that the magnitude of settlement calculated in the clay layer would occur due to the lack of strain compatibility between the layers. Therefore, the Meyerhof method is a better estimate of group settlement in this profile.

F.3.4 South Abutment - Equivalent Footing Method

For the pile group at the South Abutment and the soil profile interpreted from Soil Boring S-4 as shown in Figure F.11. Calculate the immediate settlements of pile groups using the equivalent footing method for an embedded pile length of 17.5 meters. Use the step-by-step method outlined in Section 9.8.2.3.

STEP 1 Determine the new load imposed on soil by the pile group.

- a. Determine the location of the equivalent footing.

The location of the equivalent footing is based on the shaft and toe resistance condition and the soil profile. Figure 9.62 should be used to determine the location of the equivalent footing and the pressure distribution. The soil profile for Soil Boring S-4 matches Figure 9.62(b), and therefore the equivalent footing is placed at depth of $\frac{2}{3}$ D from the bottom of the pile cap as shown in the figure.

Depth of Equivalent Footing:

- below the pile cap $= \frac{2}{3} (17.5 \text{ m}) = 11.67 \text{ m}$
- or below the existing ground $= 11.67 \text{ m} + 1.50 \text{ m} = 13.17 \text{ m}$

- b. Determine the dimensions of the equivalent footing.

All the piles in the pile group are vertical, and the pile group has a dimension of 3.36 meters by 10.86 meters. To account for load transfer, the equivalent footing has a modified dimension that spreads as a pyramid with a side slope of 1H:4V, as shown in Figure 9.62(b). Since the equivalent footing is 11.67 meters below the pile cap, the equivalent footing dimensions are:

$$\begin{aligned}\text{The width of the equivalent footing, } B_1 &= 3.36 \text{ m} + 2 \left(\frac{11.67 \text{ m}}{4} \right) \\ &= 9.20 \text{ m}\end{aligned}$$

STEP 1 (continued)

$$\begin{aligned}\text{The length of the equivalent footing, } Z_1 &= 10.86 \text{ m} + 2 \left(\frac{11.67 \text{ m}}{4} \right) \\ &= 16.70 \text{ m}\end{aligned}$$

- c. Determine the pressure distribution to soil layers below the equivalent footing up to the depth at which the pressure increase from the equivalent footing is less than 10% of existing effective overburden pressure at that depth.

The pressure distribution diagram below the equivalent footing is presented in Figure F.17. Note, the pressure distribution area increases with depth below the equivalent footing which results in a pressure reduction with depth below the equivalent footing. The dimension of the pressure distribution surface also spreads as a pyramid with depth but with a side slope of 1H:2V.

For example, at depth of 0.17 meter below the equivalent footing (or 13.34 meters below the existing ground surface), the pressure distribution surface has the following dimensions:

$$\text{Width of pressure distribution surface, } B_2 = 9.20 \text{ m} + 2 \left(\frac{0.17 \text{ m}}{2} \right) = 9.37 \text{ m}$$

$$\text{Length of pressure distribution surface, } Z_2 = 16.70 \text{ m} + 2 \left(\frac{0.17 \text{ m}}{2} \right) = 16.87 \text{ m}$$

$$\begin{aligned}\text{Area of pressure distribution surface, } A_2 &= (B_2) (Z_2) = (9.37 \text{ m}) (16.87 \text{ m}) \\ &= 158.1 \text{ m}^2\end{aligned}$$

Therefore, at depth of 0.17 meter below the equivalent footing the pressure increase due to the imposed design load is:

$$\Delta p = \left(\frac{12,600 \text{ kN}}{158.1 \text{ m}^2} \right) = 79.71 \text{ kPa}$$

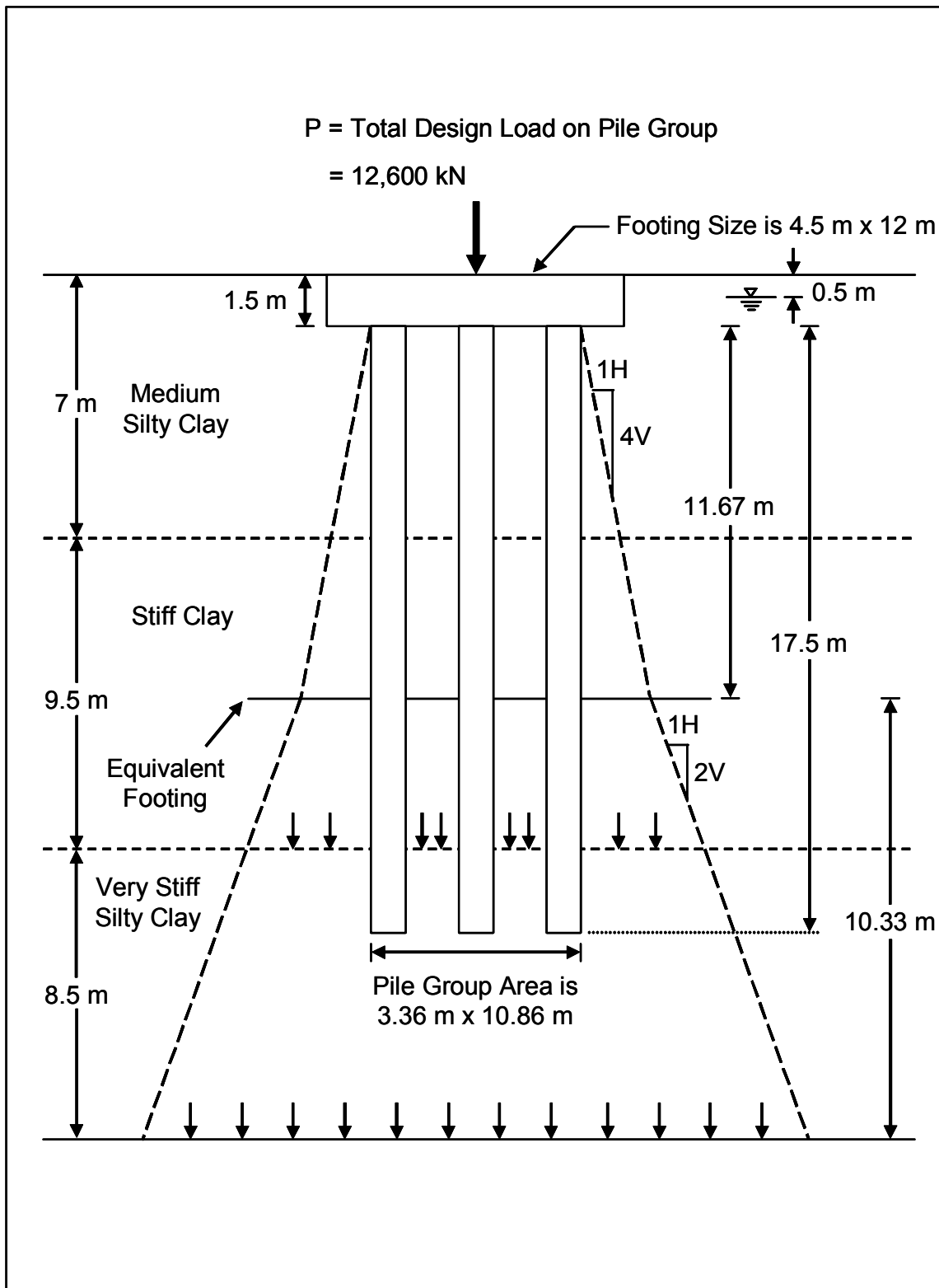


Figure F.17 Pressure Distribution Below Equivalent Footing for Pile Group at the South Abutment

STEP 1 (continued)

The pressure increase at other locations below the equivalent footing is summarized in Table F-3. The imposed pressure increase becomes less than 10% of existing effective overburden pressure at depth of 11.58 meters below the equivalent footing or 24.75 meters below the existing ground.

- d. Divide the cohesive soil layers in the affected pressure increase zone into several thinner layers of 1.5 to 3 meter thickness. The thickness of each layer is the thickness H for the settlement computation for that layer.

For this example, the soil is divided into 1.5 meter thick layers as presented in column 3 of Table F-4. The soil layer boundaries are presented in column 2 of Table F-4.

- e. Determine the existing effective overburden pressure, p_o , at the midpoint of each layer.

The midpoint location of each soil layer below the existing ground is presented in column 4 of Table F-4. The effective overburden pressure, p_o , at the midpoint of each layer is presented in column 5 of Table F-4.

- f. Determine the imposed pressure increase, Δp , at the midpoint of each affected soil layer based on the appropriate pressure distribution surface.

The imposed pressure increase, Δp , at the midpoint of each affected soil layer is presented in column 6 of Table F-4. Calculations of the imposed pressure increase based on the pressure distribution area were presented earlier in Step 1c.

| Table F-3 Summary of Pressure Distribution Below Equivalent Footing | | | | | | | |
|---|--|-------------------------------|--------------------------------|---|--|---|--|
| Depth Below Existing Ground (m) | Depth Below Equivalent Footing (m) | Load Distribution Surface | | | Imposed Pressure Increase Δp (kPa) | Effective Overburden Pressure p_o (kPa) | $\left(\frac{\Delta p}{p_o}\right) 100\%$ (%) |
| | | Width B_2 (m) | Length Z_2 (m) | Area $(B_2)(Z_2)$ (m ²) | | | |
| 13.17 | 0.00 | 9.20 | 16.70 | 153.5 | 82.08 | 129.15 | 63.6 |
| 13.34 | 0.17 | 9.37 | 16.87 | 158.1 | 79.71 | 130.80 | 60.9 |
| 14.25 | 1.08 | 10.28 | 17.78 | 182.8 | 68.94 | 139.63 | 49.4 |
| 15.75 | 2.58 | 11.78 | 19.28 | 227.1 | 55.48 | 154.18 | 36.0 |
| 17.25 | 4.08 | 13.28 | 20.78 | 276.0 | 45.66 | 169.33 | 27.0 |
| 8.75 | 5.58 | 14.78 | 22.28 | 329.3 | 38.26 | 185.08 | 20.7 |
| 20.25 | 7.08 | 16.28 | 23.78 | 387.1 | 32.55 | 200.83 | 16.2 |
| 21.75 | 8.58 | 17.78 | 25.28 | 449.5 | 28.03 | 216.58 | 12.9 |
| 23.25 | 10.08 | 19.28 | 26.78 | 516.3 | 24.40 | 232.33 | 10.5 |
| 24.75 | 11.58 | 20.78 | 28.28 | 587.7 | 21.44 | 248.08 | 8.6 |

Note: Equivalent Footing is at 13.17 meters below existing ground.

STEP 2 Determine consolidation test parameters.

The laboratory consolidation test results on the undisturbed samples of stiff silty clay from layer 2 and very stiff silty clay from layer 3 were plotted on the "log pressure, p versus void ratio, e " (similar to Figure 9.61). The following consolidation test parameters were obtained from the plot.

Soil Layer 2:

Preconsolidation pressure, $p_c = 200$ kPa

Initial void ratio, $e_0 = 0.80$

Compression index, $C_c = 0.30$

Recompression index, $C_{cr} = 0.030$

Table F-4 Settlement Calculations

[illegible]

STEP 2 (continued)

Soil Layer 3:

Preconsolidation pressure, $p_c = 297$ kPa

Initial void ratio, $e_0 = 0.54$

Compression index, $C_c = 0.20$

Recompression index, $C_{cr} = 0.020$

STEP 3 Compute settlement due to soil compression.

Compute settlement of each soil layer using the following equations:

$$s = H \left[\frac{C_{cr}}{1+e_0} \log \frac{p_o + \Delta p}{p} \right] \quad \text{when } p_o + \Delta p \leq p_c$$

$$= H \left[\frac{C_{cr}}{1+e_0} \log \frac{p_c}{p_o} \right] + H \left[\frac{C_c}{1+e_0} \log \frac{p_o + \Delta p}{p_c} \right] \quad \text{when } p_o + \Delta p > p_c$$

For example, the soil layer increment 13.17 m to 13.50 m corresponds to:

$$(p_o + \Delta p) = 210.51 \text{ kPa} > p_c = 200 \text{ kPa}$$

Therefore, layer settlement as shown in column 8 of settlement calculations table:

$$\begin{aligned} s &= H \left[\frac{C_{cr}}{1+e_0} \log \frac{p_c}{p_o} \right] + H \left[\frac{C_c}{1+e_0} \log \frac{p_o + \Delta p}{p_c} \right] \\ &= 0.33 \left[\frac{0.030}{(1+0.80)} \log \left(\frac{200}{130.80} \right) \right] + 0.33 \left[\frac{0.30}{(1+0.80)} \log \left(\frac{210.51}{200} \right) \right] = 0.0022 \text{ m} \end{aligned}$$

For the soil layer increment 16.50 m to 18.00 m corresponds to soil layer 3:

$$(p_o + \Delta p) = 214.99 \text{ kPa} < p_c = 297 \text{ kPa}$$

STEP 3 (continued)

Therefore, the settlement for the soil layer increment as shown in column 8 of Table F-4 is:

$$\begin{aligned} s &= H \left[\frac{C_{cr}}{1+e_0} \log \frac{p_o + \Delta p}{p_o} \right] \\ &= 1.5\text{m} \left[\frac{0.020}{(1+0.54)} \log \left(\frac{214.99}{169.33} \right) \right] = 0.0020\text{m} \end{aligned}$$

Following similar procedures, the total estimated pile group settlement due to soil compression is equal to the sum of settlements of all layers, or the sum of column 8 of Table F-4 and is equal to 0.0260 meter or 26.0 mm.

STEP 4 Calculate the elastic compression of pile material under design load on each pile as described in Section 9.8.2.1a.

Note, for elastic compression calculations, it is assumed that all piles in the group are loaded with the 890 kN design load. This assumption is conservative because piles in the middle and rear rows have smaller loads. The elastic compression of each pile can be calculated with the following expression:

$$\Delta = \frac{Q_a L}{A E}$$

Where:

L = Length of pile (mm) = 17,500 mm

A = Pile cross sectional area (m^2) = 0.127 m^2

E = Modulus of elasticity of pile material (kPa) = 27.8 x 10⁶ kPa

Q_a = Design axial load in pile (kN), as discussed below.

STEP 4 (continued)

Because of shaft resistances, the axial load transferred to the pile varies along the length of the pile. Therefore, for elastic compression calculations the pile should be divided into segments with the average axial load in each segment calculated. For this example, the pile is divided into three segments based on the soil layers presented in Figure F.11. The first segment is 5.5 meters length, the second is 9.5 meters, and the third is 2.5 meters. The shaft resistance as calculated using the α -method (as presented in Section F.2.4.1) for the first, second, and third segment is 259 kN, 1,150 kN, and 239 kN, respectively.

The average axial load transferred to each pile segment is equal to the axial load transferred to the mid-length of the segment, as shown in Figure F.18. The average axial load is used to calculate the elastic compression of each pile segment. Figure F.18 also shows that there is 631 kN to be transferred to soil layer 2 which is capable of supporting up to 1,150 kN over the 9.5 meter layer thickness. Therefore, the 631 kN load will be fully transferred to the soil at depth of $(631 \text{ kN} / 1,150 \text{ kN})$ times (9.5 meters) , or 5.213 meters below the top of layer 2, or the 890 kN total load will be fully transferred to the soil at depth of 10.713 meters below the pile cap. In other words, the lower 6.787 meters of the pile will not be subjected to any load or elastic compression.

$$\text{Pile segment 1: } \Delta_1 = \frac{(761 \text{ kN})(5,500 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 1.186 \text{ mm}$$

$$\text{Pile segment 2: } \Delta_2 = \frac{(316 \text{ kN})(5,213 \text{ mm})}{(0.127 \text{ m}^2)(27,800,000 \text{ kPa})} = 0.467 \text{ mm}$$

$$\begin{aligned} \text{Total: } \Delta &= \Delta_1 + \Delta_2 \\ &= 1.186 \text{ mm} + 0.467 \text{ mm} = 1.653 \text{ mm} \end{aligned}$$

Note: The elastic pile compression is small relative to the soil compression (26.0 mm), and therefore it is usually ignored.

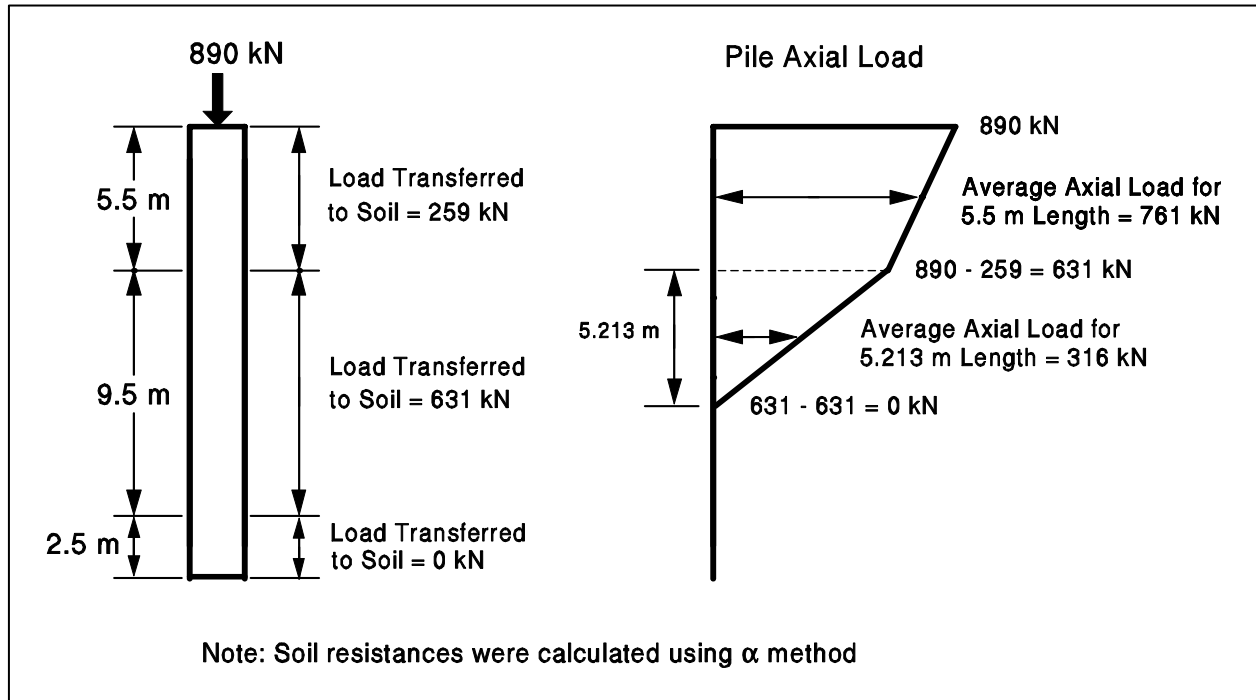


Figure F.18 Calculation of Axial Load Transfer to the Pile at South Abutment

STEP 5 Compute total pile group settlement.

$$\begin{aligned}
 \Delta(\text{total}) &= \Delta(\text{soil compression}) + \Delta(\text{elastic pile compression}) \\
 &= 26.0 \text{ mm} + 1.653 \text{ mm} \\
 &= 27.653 \text{ mm} \quad \text{or} \quad 0.028 \text{ m}
 \end{aligned}$$

The total pile group settlement is larger than the maximum allowable pile group settlement of 25 mm. The total settlement will even be larger after the placement of the approach embankment fill materials behind the abutment wall, as discussed in Section F.6. Therefore, preloading of the South Abutment should be performed prior to pile installation. The interaction of the approach embankment fill with the South Abutment foundation is discussed in greater detail in Section F.6.

F.4 LATERAL PILE CAPACITY ANALYSIS

The bridge division estimated that the group lateral loads range from 600 kN at the interior pile groups to 900 kN at the abutment pile groups. The maximum lateral load per pile is limited to 40 kN. A horizontal deflection of up to 10 mm is permissible under lateral loading.

F.4.1 Broms' Method - North Abutment

Perform a lateral pile capacity analysis for a pile at the North Abutment using Soil Boring S-1 as shown in Figure F.3. Perform the analysis based on an embedded pile length of 11.5 meters. Use the step by step procedure for the Broms' method outlined in Section 9.7.3.2.

STEP 1 Determine the general soil type within the critical depth below ground surface (about 4 or 5 pile diameters).

For pile diameter of 0.356 meter, the critical depth below the ground surface is about 1.42 to 1.78 meters. Based on the soil conditions for the North Abutment shown in Figure F.3, the general soil type within the critical depth below the ground surface is a loose silty fine sand cohesionless soil.

STEP 2 Determine the coefficient of horizontal subgrade reaction, K_h , within the critical depth based on cohesive or cohesionless soils.

For cohesionless soils, choose the K_h from Table 9-14 based on soil density and ground water table. For a loose silty fine sand, K_h is either 1,086 or 1,900 kN/m³ depending on whether the ground water table is below or above the critical depth, respectively. When the ground water table is within the critical depth region, a linear interpolation between these two values should be used to calculate K_h .

Assuming the critical depth is at 1.60 meters depth below the bottom of the excavation. Based on Figure F.3, the ground water table is at 1.0 meter below the bottom of the excavation. Therefore, using a linear interpolation, the coefficient of horizontal subgrade reaction, K_h , is:

STEP 2 (continued)

$$K_h = 1,086 + \frac{1.00}{1.60} (1,900 - 1,086) = 1,595 \text{ kN/ m}^3$$

STEP 3 Adjust K_h for loading and soil conditions.

Assuming that a cyclic loading exists at the site. For cyclic loading in loose cohesionless soils:

$$\begin{aligned} K_h &= \frac{1}{4} K_h \\ &= \frac{1}{4} (1,595) = 399 \text{ kN/m}^3 \end{aligned}$$

STEP 4 Determine pile parameters.

- a. Modulus of elasticity, E = 27,800 MPa
- b. Moment of inertia, I = $1.32 \times 10^{-3} \text{ m}^4$
- c. Section modulus, S = $7.46 \times 10^{-3} \text{ m}^3$
- d. Ultimate compressive strength, f'_c = 34.5 MPa
- e. Embedded pile length, D = 11.5 m
- f. Pile width, b = 0.356 m
- g. Eccentricity of applied load, e_c = 0 for fixed-headed pile
- h. Dimensionless shape factor, C_s , applied only to steel piles.
- i. Resisting moment of pile, M_y = $f'_c S$ for concrete piles
= 34.5 MPa ($7.46 \times 10^{-3} \text{ m}^3$)
= 257.4 kN-m

STEP 5 Determine η for cohesionless soils.

$$\begin{aligned}\eta &= \sqrt[5]{K_h/EI} = \sqrt[5]{\frac{399 \text{ kN/m}^3}{(27.8 \times 10^6 \text{ kN/m}^2) (1.32 \times 10^{-3} \text{ m}^4)}} \\ &= 0.405 \text{ m}^{-1}\end{aligned}$$

STEP 6 Determine the dimensionless length factor for cohesionless soil.

$$\eta D = 0.405 \text{ m}^{-1} (11.5 \text{ m}) = 4.66$$

STEP 7 Determine if pile is long or short according to the cohesionless soil criteria.

Since $\eta D = 4.66$ is greater than 4.0, the pile is long.

STEP 8 Determine other soil parameters.

a. Rankine passive pressure coefficient for cohesionless soil, K_p , is:

$$K_p = \tan^2 (45 + \phi/2)$$

where ϕ is the average soil friction angle along the embedded pile length.

As shown in Figure F.3, the soil profile along the embedded pile length is divided into three layers. As discussed in Section F.2.1.2, the soil friction angle, ϕ , from each layer is calculated using the corrected SPT N' value and Table 4-6.

$$\text{Layer 1 (4 m depth):} \quad \bar{N}_1' = 8 \quad \rightarrow \quad \phi_1 = 29^\circ$$

$$\text{Layer 2 (7 m depth):} \quad \bar{N}_2' = 14 \quad \rightarrow \quad \phi_2 = 31^\circ$$

$$\text{Layer 3 (0.5 m depth):} \quad \bar{N}_3' = 34 \quad \rightarrow \quad \phi_3 = 36^\circ$$

The average ϕ angle is calculated from the weighted ϕ angle based on the thickness of each layer.

STEP 8 (continued)

The average ϕ angle is:

$$\phi = \frac{29^\circ (4 \text{ m}) + 31^\circ (7 \text{ m}) + 36^\circ (0.5 \text{ m})}{11.5 \text{ m}} = 30.5^\circ$$

Therefore, the Rankine passive pressure coefficient, K_p , is:

$$\begin{aligned} K_p &= \tan^2 (45 + \phi/2) \\ &= \tan^2 (45 + 30.5/2) = 3.06 \end{aligned}$$

- b. Average effective soil unit weight over embedded length of pile, γ (kN/m^3).

The average effective soil unit weight, γ , will also be calculated from the weighted γ of each layer based on the thickness of each layer.

$$\begin{aligned} \gamma &= \frac{16.5 \text{ kN/m}^3 (1 \text{ m}) + 6.7 \text{ kN/m}^3 (3 \text{ m}) + 7.8 \text{ kN/m}^3 (7 \text{ m}) + 9.8 \text{ kN/m}^3 (0.5 \text{ m})}{11.5 \text{ m}} \\ &= 8.36 \text{ kN/m}^3 \end{aligned}$$

STEP 9 Determine the ultimate (failure) lateral load, Q_u , for a single pile.

The pile will be used in a group under a pile cap, therefore it is considered a fixed headed pile. For a long fixed headed pile in a cohesionless soil, Figure 9.40 should be used to calculate the ultimate load. First $M_y / (b^4 \gamma K_p)$ must be calculated.

$$\frac{M_y}{b^4 \gamma K_p} = \frac{257.4 \text{ kN-m}}{(0.356 \text{ m})^4 (8.36 \text{ kN/m}^3) (3.06)} = 626$$

Enter Figure 9.40 with this value to the fixed head curve to obtain $Q_u / K_p b^3 \gamma = 190$.

STEP 9 (continued)

So,

$$\begin{aligned}Q_u &= 190 K_p b^3 \gamma \\&= 190 (3.06) (0.356 \text{ m})^3 (8.36 \text{ kN/m}^3) \\&= 219 \text{ kN}\end{aligned}$$

STEP 10 Calculate the maximum allowable working load for a single pile, Q_m , from the ultimate load, Q_u , determined in Step 9, as shown in Figure 9.41.

$$Q_m = \frac{Q_u}{2.5} = \frac{219 \text{ kN}}{2.5} = 88 \text{ kN}$$

STEP 11 Calculate the deflection, y , corresponding to the desired design load, Q_a of 40 kN.

For fixed headed pile in cohesionless soil, enter Figure 9.43 with $\eta D = 4.66$ to obtain $y(EI)^{3/5} K_h^{2/5} / Q_a D$. This results in

$$y(EI)^{3/5} K_h^{2/5} / Q_a D = 0.21$$

The calculated deflection y is:

$$\begin{aligned}y &= 0.21 Q_a D / (EI)^{3/5} K_h^{2/5} \\&= 0.21(40 \text{ kN})(11.5 \text{ m}) / (27.8 \times 10^6 \text{ kN/m}^2)^{3/5} (1.32 \times 10^{-3} \text{ m}^4)^{3/5} (399 \text{ kN/m}^3)^{2/5} \\&= 0.016 \text{ m} \quad \text{or} \quad 16 \text{ mm}\end{aligned}$$

Therefore, the desired design load of 40 kN will cause the pile head to deflect 16 mm at the ground surface which exceeds the bridge division's allowable deflection of 10 mm. Therefore, the maximum design load that will not exceed the 10 mm deflection should be determined.

STEP 11 (continued)

$$y = 0.21 Q_a D / (EI)^{3/5} K_n^{2/5}$$

$$.01 = 0.21 (Q_a) (11.5 \text{ m}) / (21 \times 10^6 \text{ kN/m}^2)^{3/5} (1.32 \times 10^{-3} \text{ m}^4)^{3/5} (399 \text{ kN/m}^3)^{2/5}$$

$$\begin{aligned} Q_a &= 0.01 (27.8 \times 10^6 \text{ kN/m}^2)^{3/5} (1.32 \times 10^{-3} \text{ m}^4)^{3/5} (399 \text{ kN/m}^3)^{2/5} / (0.21)(11.5 \text{ m}) \\ &= 24.9 \text{ kN} \end{aligned}$$

STEP 12 Compare the design load Q_a , and design deflection, y , with the maximum allowable working load, Q_m , and deflection, y_m .

The maximum design load of 24.9 kN determined from the design deflection is less than the maximum allowable working load of 87 kN.

STEP 13 Reduce the maximum allowable load to account for group effects and method of installation.

a. Group effects.

The center to center pile spacing, z , is designed to be 1.5 meters.

$$(z/b) = (1.5 \text{ m}) / (0.356 \text{ m}) = 4.21$$

Using the reduction factor table and linear interpolation:

$$\text{reduction factor} = 0.532$$

$$\text{So, } Q_m = 0.532 Q_a = 0.532 (88 \text{ kN}) = 47 \text{ kN}$$

b. Method of installation.

No reduction is required for driven piles. So, $Q_m = 47 \text{ kN}$.

STEP 14 Compute the total lateral load capacity of the pile group.

The total lateral load capacity of the pile group is equal to the adjusted allowable load per pile from Step 13b times the number of piles.

$$\text{Total Pile Group Lateral Load Capacity} = 24 (47 \text{ kN}) = 1,128 \text{ kN}$$

However, this group lateral load cannot be achieved at the deflection limit required by the bridge division and therefore a lower group load must be used.

To meet the 10 mm deflection requirements, a design lateral load of 25 kN per pile must be used. This lateral load is less than desired. Therefore, the group capacity of 600 kN (24 piles at 25 kN/pile) is insufficient, and more piles would be required.

F.4.2 LPILE Analysis - North Abutment

A LPILE analysis was performed to evaluate the lateral load capacity of the 356 mm square prestressed concrete pile at the North Abutment. The concrete pile was driven 11.5 m into the dense sand and gravel stratum as depicted in Figure F.3.

The North Abutment concrete pile was analyzed considering full fixity at the base of the pile cap. The geometric and elastic properties of the pile were input along with the relevant soil properties and stratigraphic information. Soil input parameters were obtained from Table 9-12. Moment-dependent flexural rigidity (concrete cracking effects) are included explicitly in the analyses. In order to rigorously evaluate the moment-stiffness relationship, the longitudinal reinforcement (4 No. 8 bars) was also characterized with respect to cross-section geometry and steel properties using LPILE analysis type 4 – “Computation of Ultimate Bending Moment and Pile Response with User Specified EI.” The p-y curves were generated by the program assuming cyclic loading conditions were applied. The program calculated internally the flexural rigidity along the pile as a function of bending moment and axial force (assumed full 890 kN compression load) for each applied lateral load level. Ten equal 20 kN increments of load were applied to a maximum of 200 kN. The graphical output contains all ten increments; the numeric summaries are abridged.

An echo print of the input file is presented on the following page. LPILE generated summaries of the problem input and output are provided including nonlinear bending stiffness calculations. For selected lateral loads, Figures F.19 to F.22 provide graphical presentations of deflection, movement, shear, and soil reaction versus depth.

The LPILE solutions for the North abutment indicate the pile deflection under the 40 kN design load will be 3.2 mm. The corresponding maximum moment and shear stress are - 54.2 m-kN and 14,500 kN/m², respectively. The deflection, moment and shear stress under the design load are acceptable. Hence, the more rigorous LPILE analysis indicates a 40 kN design lateral load could be used whereas the Broms' method indicated only a 24.9 kN design load. Additional LPILE analyses should be performed to evaluate group response using the p-multiplier approach described in Section 9.8.4.

```

LPILEP4
FWA North Abut. - 355 mm-sq PSC Fixed-Head/Cyclic/Crack Modeled
2      3      0      0      0      0
100    2      0      11.5  0
0      0.355  0.0013      0.126 27800000
11.5   0.355  0.0013      0.126 27800000
4      8      8      0      0
4      0      1      6790 6790
4      1      4      5430 5430
4      4      11     16300 16300
4      11     11.5   33900 33900
0      16.5
1      16.5
1      6.7
4      6.7
4      7.8
11     7.8
11     9.8
11.5   9.8
0      0      29      0      0
1      0      29      0      0
1      0      29      0      0
4      0      29      0      0
4      0      30      0      0
11     0      30      0      0
11     0      36      0      0
11.5   0      36      0      0
0      0      20
10
2      20      0      890
2      40      0      890
2      60      0      890
2      80      0      890
2      100     0      890
2      120     0      890
2      140     0      890
2      160     0      890
2      180     0      890
2      200     0      890
0
1      1      0
100    1E-6  1
1      1
890
41370 262000      413685.52 2.0685E8
0.355 0.355 0      0      0
0.0005      4      2      0.0762
0.102 0.0006
-0.102      0.0006

```

North Abutment - Echo of Input File

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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=====

Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 4:

- Computation of Nonlinear Bending Stiffness and Ultimate Bending Moment Capacity with Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis does not use p-y multipliers (individual pile or shaft action only)
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 10.000E-06 m
- Maximum allowable deflection = 1.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 1

Pile Structural Properties and Geometry

Pile Length = 11.50 m
 Depth of ground surface below top of pile = .00 m
 Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35500000 | .001300 | .1260 | 27800000.000 |
| 2 | 11.5000 | .35500000 | .001300 | .1260 | 27800000.000 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of moment of inertia and modulus of are not used for any computations other than total stress due to combined axial loading and bending.

Soil and Rock Layering Information

The soil profile is modelled using 4 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 1.000 m
 p-y subgrade modulus k for top of soil layer = 6790.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 6790.000 kN/ m**3

Layer 2 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 1.000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 5430.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 5430.000 kN/ m**3

Layer 3 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 11.000 m
 p-y subgrade modulus k for top of soil layer = 16300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 16300.000 kN/ m**3

Layer 4 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 11.000 m
 Distance from top of pile to bottom of layer = 11.500 m
 p-y subgrade modulus k for top of soil layer = 33900.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 33900.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth
is defined using 8 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|--------------|--------------|------------------------------|
| 1 | .00 | 16.50000 |
| 2 | 1.00 | 16.50000 |
| 3 | 1.00 | 6.70000 |
| 4 | 4.00 | 6.70000 |
| 5 | 4.00 | 7.80000 |
| 6 | 11.00 | 7.80000 |
| 7 | 11.00 | 9.80000 |
| 8 | 11.50 | 9.80000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth
defined using 8 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|--------------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 29.00 | ----- | ----- |
| 2 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 3 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 4 | 4.000 | .00000 | 29.00 | ----- | ----- |
| 5 | 4.000 | .00000 | 30.00 | ----- | ----- |
| 6 | 11.000 | .00000 | 30.00 | ----- | ----- |
| 7 | 11.000 | .00000 | 36.00 | ----- | ----- |
| 8 | 11.500 | .00000 | 36.00 | ----- | ----- |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 20.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

.
 . [Abridged]
 .

Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 200.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computations of Ultimate Moment Capacity and Nonlinear Bending Stiffness

Pile Description:

The pile shape is a rectangular solid pile.

Width = .355 m
 Depth = .355 m

Material Properties:

Compressive Strength of Concrete = 41370.000 kN/ m**2
 Yield Stress of Reinforcement = 262000. kN/ m**2
 Modulus of Elasticity of Reinforcement = 206850000. kN/ m**2
 Number of Reinforcing Bars = 4
 Area of Single Bar = .00050 m**2
 Number of Rows of Reinforcing Bars = 2
 Cover Thickness (edge to bar center) = .076 m

Ultimate Axial Squash Load Capacity = 4703.81 kN

Distribution and Area of Steel Reinforcement

| Row Number | Area of Reinforcement m**2 | Distance to Centroidal Axis m |
|---------------|----------------------------------|-------------------------------------|
| 1 | .000600 | .1020 |
| 2 | .000600 | -.1020 |

Axial Thrust Force = 890.00 kN

| Bending Moment kN-m | Bending Stiffness kN-m2 | Bending Curvature rad/m | Maximum Strain m/m | Neutral Axis Position m |
|--|-------------------------------|-------------------------------|--------------------------|-------------------------------|
| 1.54295127 | 39190.962 | .00003937 | .00023366 | 5.93486814 |
| 7.71444547 | 39189.382 | .00019685 | .00026170 | 1.32942587 |
| 13.885 | 39185.750 | .00035433 | .00028986 | .81803677 |
| 20.053 | 39179.988 | .00051181 | .00031813 | .62158314 |
| 26.218 | 39172.157 | .00066929 | .00034653 | .51775257 |
| 32.378 | 39162.188 | .00082677 | .00037504 | .45362225 |
| 38.534 | 39150.185 | .00098425 | .00040367 | .41013020 |
| 44.683 | 39136.085 | .00114173 | .00043242 | .37873943 |
| 50.825 | 39119.844 | .00129921 | .00046129 | .35505146 |
| 56.988 | 39121.516 | .00145669 | .00049033 | .33660160 |
| 63.049 | 39059.507 | .00161417 | .00051931 | .32172146 |
| 69.110 | 39008.681 | .00177165 | .00054844 | .30956600 |
| 75.155 | 38958.023 | .00192913 | .00057769 | .29945812 |
| 81.088 | 38861.083 | .00208661 | .00060684 | .29082363 |
| 81.088 | 36133.990 | .00224409 | .00061495 | .27403133 |
| 81.088 | 33764.548 | .00240157 | .00063793 | .26562977 |
| 81.469 | 31835.639 | .00255906 | .00066017 | .25797573 |
| 83.923 | 30893.279 | .00271654 | .00068196 | .25104214 |
| 86.229 | 30003.115 | .00287402 | .00070333 | .24472065 |
| 88.411 | 29164.014 | .00303150 | .00072433 | .23893543 |
| 90.481 | 28372.973 | .00318898 | .00074498 | .23361065 |
| 92.458 | 27628.502 | .00334646 | .00076533 | .22869755 |
| 94.358 | 26929.177 | .00350394 | .00078544 | .22415821 |
| 96.109 | 26249.199 | .00366142 | .00080493 | .21984097 |
| 97.855 | 25623.877 | .00381890 | .00082447 | .21589207 |
| 99.561 | 25038.090 | .00397638 | .00084391 | .21223026 |
| 110.590 | 21442.569 | .00515748 | .00098201 | .19040569 |
| 120.077 | 18943.856 | .00633858 | .00111351 | .17567181 |
| 128.620 | 17104.480 | .00751969 | .00124079 | .16500599 |
| 136.481 | 15686.050 | .00870079 | .00136470 | .15684818 |
| 143.755 | 14547.283 | .00988189 | .00148690 | .15046711 |
| 145.817 | 13180.644 | .01106299 | .00158671 | .14342518 |
| 147.540 | 12049.856 | .01224409 | .00168395 | .13753162 |
| 148.999 | 11098.438 | .01342520 | .00177927 | .13253185 |
| 150.255 | 10286.974 | .01460630 | .00187345 | .12826336 |
| 151.236 | 9579.525 | .01578740 | .00196414 | .12441196 |
| 152.156 | 8966.965 | .01696850 | .00205603 | .12116726 |
| 153.062 | 8433.379 | .01814961 | .00214772 | .11833424 |
| 153.569 | 7944.317 | .01933071 | .00223691 | .11571789 |
| 154.075 | 7511.548 | .02051181 | .00232536 | .11336697 |
| 154.597 | 7126.607 | .02169291 | .00242001 | .11155773 |
| 154.870 | 6770.554 | .02287402 | .00250841 | .10966183 |
| 155.085 | 6447.050 | .02405512 | .00259871 | .10803135 |
| 155.264 | 6152.428 | .02523622 | .00269049 | .10661213 |
| 155.477 | 5885.409 | .02641732 | .00278965 | .10559917 |
| 155.534 | 5635.593 | .02759843 | .00288088 | .10438580 |
| 155.547 | 5404.764 | .02877953 | .00297346 | .10331867 |
| 155.550 | 5191.809 | .02996063 | .00306693 | .10236530 |
| 155.550 | 4994.901 | .03114173 | .00316169 | .10152569 |
| 155.550 | 4812.383 | .03232283 | .00325744 | .10077816 |
| 155.550 | 4642.734 | .03350394 | .00336721 | .10050190 |
| 155.550 | 4484.639 | .03468504 | .00346243 | .09982479 |
| 155.550 | 4336.956 | .03586614 | .00355857 | .09921810 |
| 155.550 | 4198.689 | .03704724 | .00365529 | .09866558 |
| 155.550 | 4068.967 | .03822835 | .00375256 | .09816181 |
| 155.550 | 3947.020 | .03940945 | .00418210 | .10611919 |
| Ultimate Moment Capacity at a Concrete Strain of 0.003 = | | | | 155.548 m- kN |

 Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 20.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .001561 | -26.8503 | 20.0000 | 1.60E-17 | 1.07E+04 | 36140.000 | 0.000 |
| .115 | .001556 | -24.5459 | 19.9447 | -8.18E-05 | 1.04E+04 | 36140.000 | -.962181 |
| .230 | .001542 | -22.2463 | 19.7509 | -1.56E-04 | 1.01E+04 | 36140.000 | -2.408 |
| .345 | .001520 | -19.9712 | 19.4077 | -2.23E-04 | 9790.3 | 36140.000 | -3.560 |
| .460 | .001491 | -17.7368 | 18.9353 | -2.83E-04 | 9485.2 | 36140.000 | -4.656 |
| .575 | .001455 | -15.5581 | 18.3410 | -3.36E-04 | 9187.8 | 36140.000 | -5.680 |
| .690 | .001413 | -13.4495 | 17.6338 | -3.83E-04 | 8899.9 | 36140.000 | -6.621 |
| .805 | .001367 | -11.4241 | 16.8235 | -4.22E-04 | 8623.3 | 36140.000 | -7.470 |
| .920 | .001316 | -9.4937 | 15.9212 | -4.55E-04 | 8359.7 | 36140.000 | -8.221 |
| 1.035 | .001262 | -7.6690 | 15.0394 | -4.83E-04 | 8110.6 | 36140.000 | -7.115 |
| . | . | . | . | . | . | . | . |
| . [ABRIDGED] | | | | | | | |
| . | . | . | . | . | . | . | . |
| 11.040 | -4.48E-08 | 3.34E-03 | -1.23E-02 | -2.50E-07 | 7063.9 | 36140.000 | .011567 |
| 11.155 | -7.28E-08 | 2.03E-03 | -1.05E-02 | -2.41E-07 | 7063.8 | 36140.000 | .019107 |
| 11.270 | -1.00E-07 | 9.65E-04 | -7.91E-03 | -2.36E-07 | 7063.6 | 36140.000 | .026670 |
| 11.385 | -1.27E-07 | 2.55E-04 | -4.40E-03 | -2.34E-07 | 7063.5 | 36140.000 | .034350 |
| 11.500 | -1.54E-07 | 0.0 | 0.0 | -2.34E-07 | 7063.5 | 36140.000 | .042215 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00156072 m
 Computed slope at pile head = 1.60273E-17
 Maximum bending moment = -26.850 kN- m
 Maximum shear force = 20.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 5
 Number of zero deflection points = 3

[ABRIDGED—ADDITIONAL LOAD CASES OMITTED]

Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m

M = pile-head moment, kN- m

V = pile-head shear force, kN

S = pile-head slope, radians

R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|----------------------------|----------------------------|---------------------|------------------------------|----------------------------|------------------------|
| 2 | V= 20.000 | S= 0.000 | 890.0000 | .001561 | -26.8503 | 20.0000 |
| 2 | V= 40.000 | S= 0.000 | 890.0000 | .003153 | -54.1631 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .004853 | -82.7732 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .006807 | -113.7237 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .009130 | -147.3525 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .011611 | -181.8318 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .014199 | -216.8237 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .017001 | -253.3626 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .020117 | -291.9951 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .023611 | -332.8377 | 200.0000 |

The analysis ended normally.

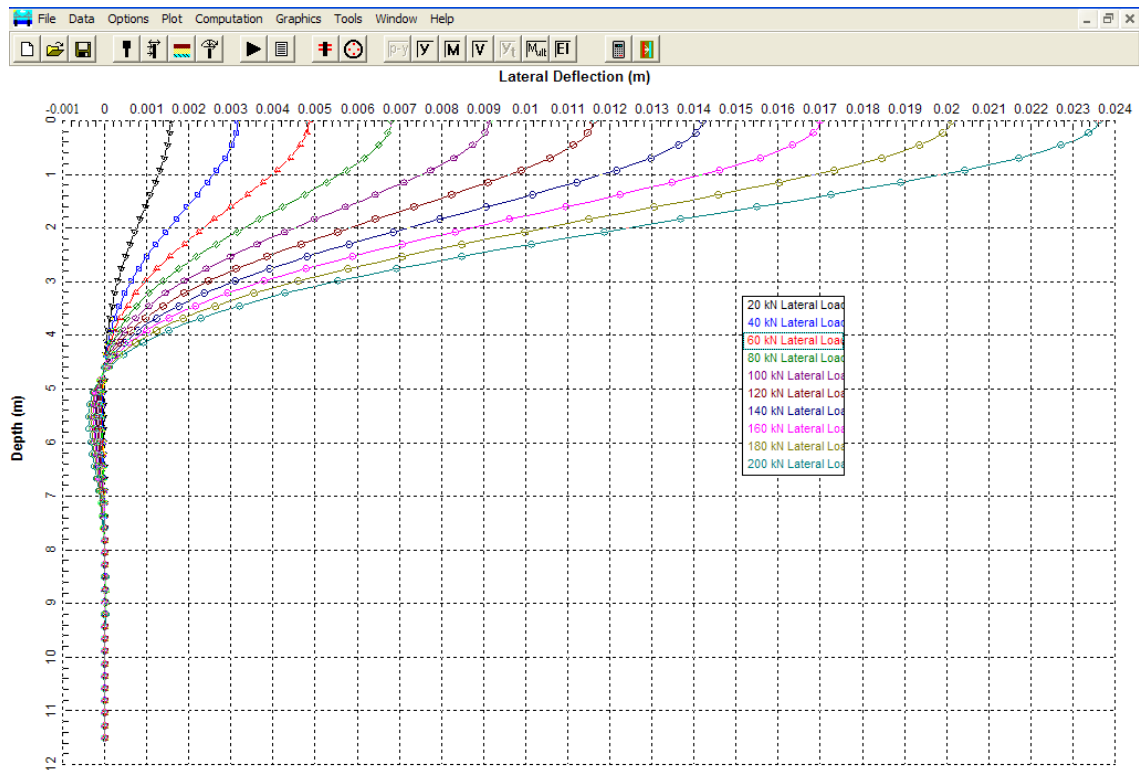


Figure F.19: North Abutment - Plot of Deflection vs. Depth as a Function of Lateral Load

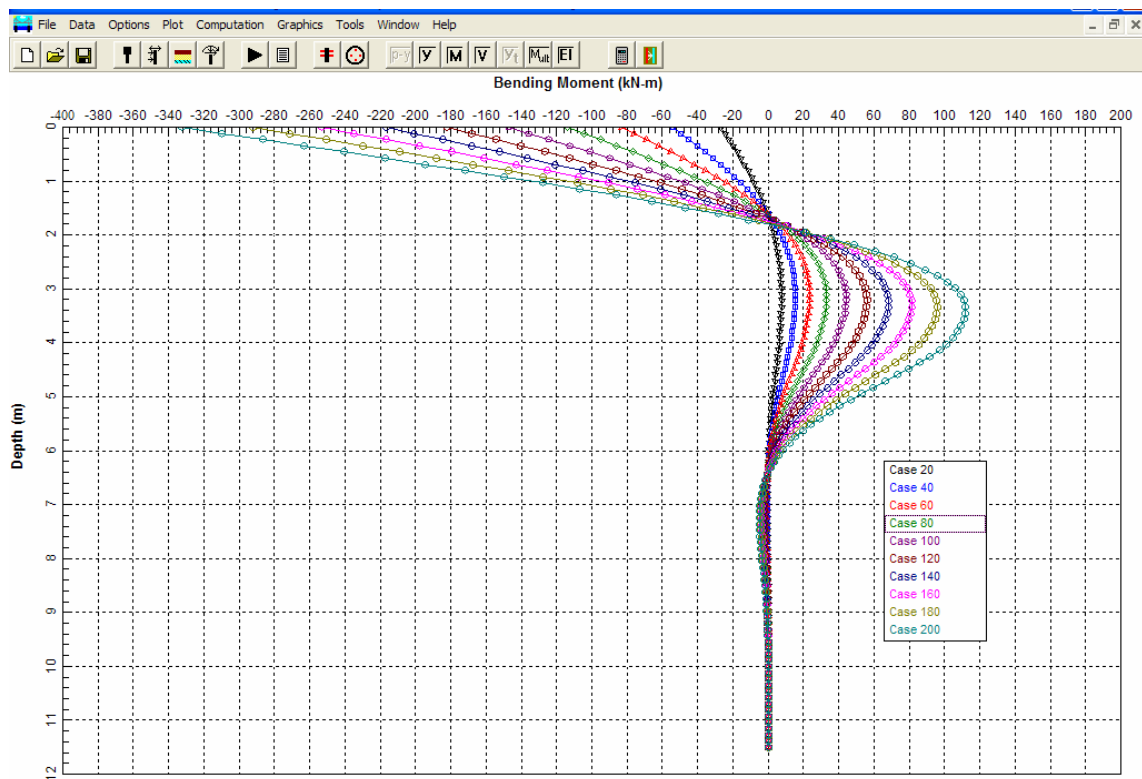


Figure F.20: North Abutment – Plot of Moment *versus* Depth as a Function of Lateral Load

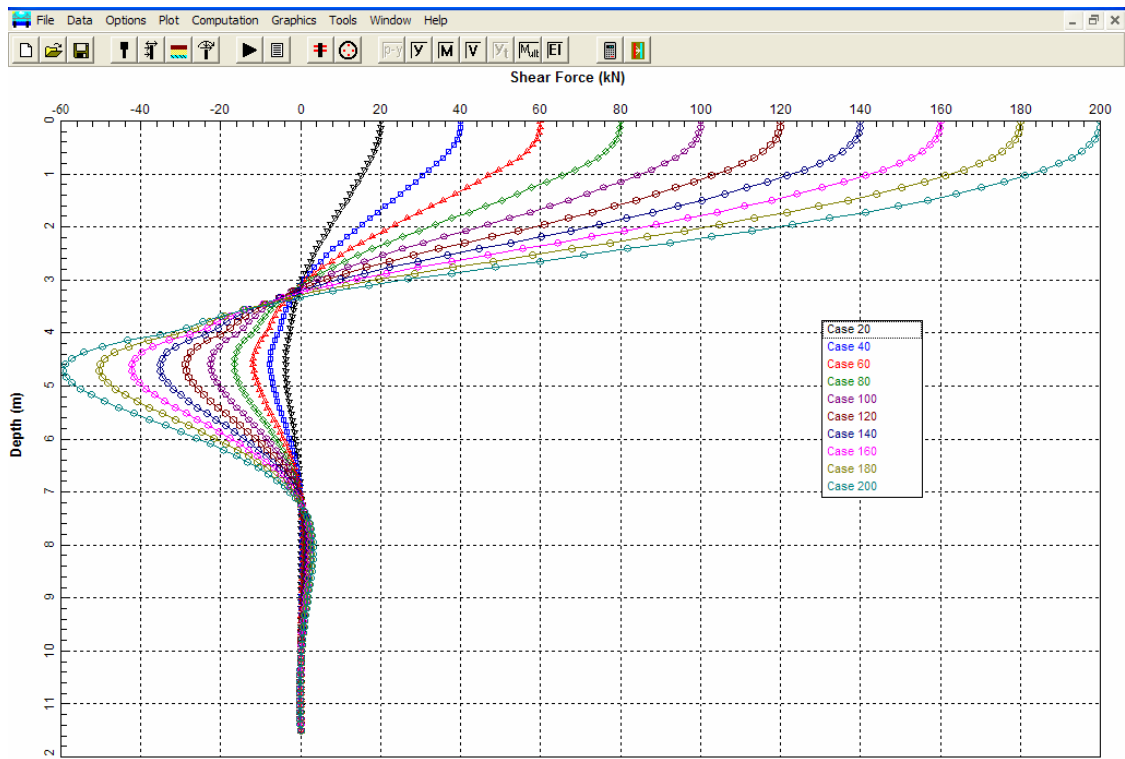


Figure F.21: North Abutment – Plot of Shear *versus* Depth as a Function of Lateral Load

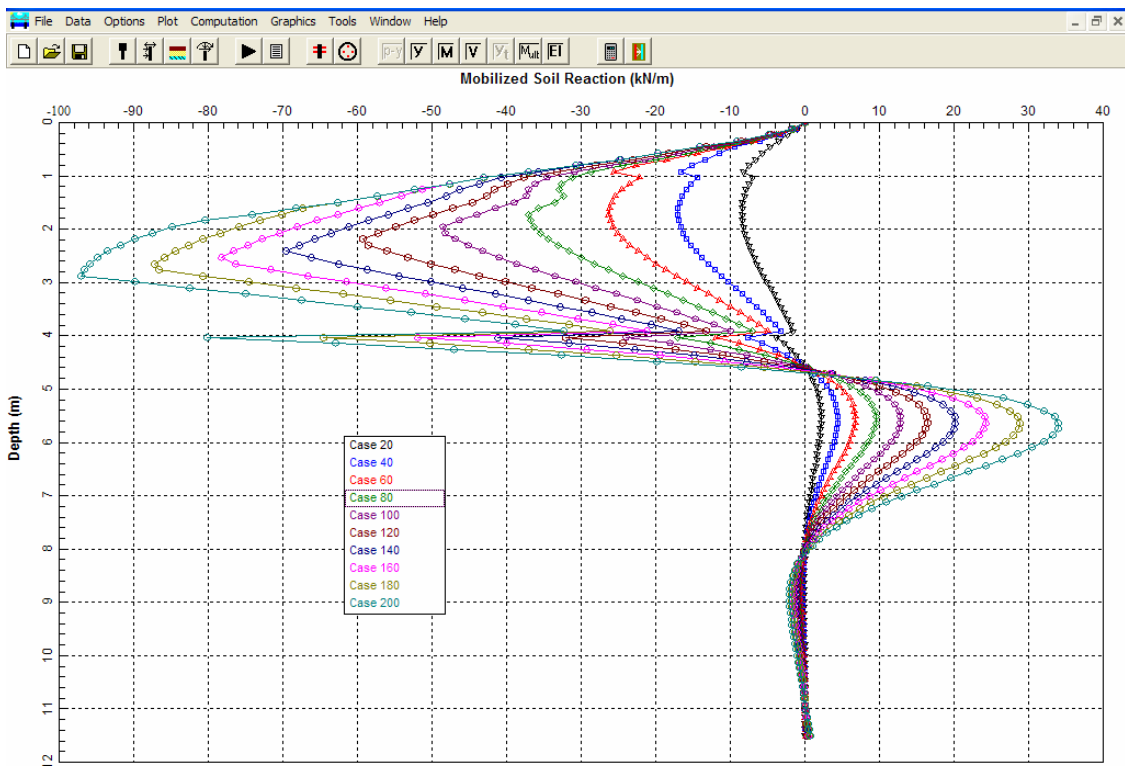


Figure F.22: North Abutment - Plot of Soil Reaction vs. Depth as a Function of Lateral Load

F.4.3 LPILE - Pier 2 H-pile, X-X Axis and Y-Y Axis

As discussed in Chapter 12, wave equation driveability analyses at the internal piers indicated a potential driveability problem for 356 mm concrete piles. Therefore, low displacement HP 360x152 H-piles were chosen for the pile foundations at the interior piers.

For the selected H-pile section at Pier 2, LPILE solutions for lateral loading in the major (X-X) and minor (Y-Y) axis directions were obtained. These analyses again assumed full fixity at the base of the pier. At Pier 2, it was assumed that near-surface scour protection prevented removal of materials below the pier base in this case. In the full design process a number of other variables such as partial rotational constraint or extreme scour depth could be evaluated. The presence of the extremely dense sand and gravel stratum in the upper 4 m of the soil profile introduced a considerably stiffer soil response in comparison with that modeled at the North Abutment. Table 9-16 only has dense sand, therefore the slope of soil modulus for this extremely dense sand and gravel was assumed to be 50,000 kN/m³. As in the previous example, the detailed results were saved only for every other lateral load increment up to the maximum lateral load evaluated of 220 kN.

LPILE analysis of lateral loading in the X-X and Y-Y axis are presented on the following pages. The analysis output includes an echo print of the input file followed by the LPILE generated summaries of the problem input and output. The output includes a summary table of deflection, moment, shear, and soil reaction versus lateral load. For selected lateral loads in the X-X axis, Figures F.23 to F.26 provide graphical presentations of deflection, moment, shear, and soil reaction versus depth. These graphical presentations for loads in the Y-Y axis are presented in Figure F.27 to F.30.

The LPILE analyses indicate the performance of the H-pile is acceptable when laterally loaded in either axis. The maximum deflection under the 40 kN design load is less than 2 mm.

Additional LPILE analyses should be performed to evaluate group response using the p-multiplier approach described in Section 9.8.4.

```

LPFILEP4
FHWA Pier 2, HP360x152 X-X Axis/Fixed-Head Cyclic
2      1      0      0      0      0
100    2      0      14     0
0      0.3565    0.0004    0.0194    2.1E8
14     0.3565    0.0004    0.0194    2.1E8
2      4      4      0      0
4      0      4      50000  50000
4      4      14     33900  33900
0      11.4
4      11.4
4      9.8
14     9.8
0      0      36     0      0
4      0      36     0      0
4      0      35     0      0
14     0      35     0      0
0      0      20
10
2      40     0      890
2      60     0      890
2      80     0      890
2      100    0      890
2      120    0      890
2      140    0      890
2      160    0      890
2      180    0      890
2      200    0      890
2      220    0      890
0
1      1      0
100    1E-5  2

```

Pier 2 X-X Axis - Echo of Input File

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LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
 Subjected to Lateral Loading Using the p-y Method

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Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 1:

- Computation of Lateral Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis does not use p-y multipliers (individual pile or shaft action only)
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 1.0000E-05 m
- Maximum allowable deflection = 2.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

Pile Structural Properties and Geometry

Pile Length = 14.00 m
 Depth of ground surface below top of pile = .00 m
 Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35650000 | 4.00000E-04 | .019400 | 210000000.000 |
| 2 | 14.0000 | .35650000 | 4.00000E-04 | .019400 | 210000000.000 |

Soil and Rock Layering Information

The soil profile is modelled using 2 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 50000.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 50000.000 kN/ m**3

Layer 2 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 14.000 m
 p-y subgrade modulus k for top of soil layer = 33900.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 33900.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth
 is defined using 4 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|--------------|--------------|------------------------------|
| 1 | .00 | 11.40000 |
| 2 | 4.00 | 11.40000 |
| 3 | 4.00 | 9.80000 |
| 4 | 14.00 | 9.80000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth
 defined using 4 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|--------------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 36.00 | ----- | ----- |
| 2 | 4.000 | .00000 | 36.00 | ----- | ----- |
| 3 | 4.000 | .00000 | 35.00 | ----- | ----- |
| 4 | 14.000 | .00000 | 35.00 | ----- | ----- |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 40.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

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[ABRIDGED]

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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 220.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

 Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 40.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. Y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|------------------------|
| 0.000 | 8.14E-04 | -47.1053 | 40.0000 | 3.872E-18 | 66867.5983 | 0.0000 |
| .700 | 7.02E-04 | -19.7659 | 35.8968 | -2.770E-04 | 54684.4589 | -15.0633 |
| 1.400 | 4.72E-04 | .9085 | 22.5879 | -3.490E-04 | 46281.1434 | -15.2146 |
| 2.100 | 2.44E-04 | 12.5820 | 9.0945 | -2.864E-04 | 51483.1390 | -23.1076 |
| 2.800 | 8.34E-05 | 14.0092 | -3.8300 | -1.695E-04 | 52119.1374 | -11.6742 |
| 3.500 | 2.11E-06 | 9.5302 | -7.7446 | -6.956E-05 | 50123.1883 | -.3700 |
| 4.200 | -2.37E-05 | 4.5520 | -6.0892 | -1.173E-05 | 47904.7646 | 3.4722 |
| 4.900 | -2.22E-05 | 1.2138 | -3.4091 | 1.103E-05 | 46417.1981 | 3.7781 |
| 5.600 | -1.28E-05 | -.3423 | -1.1795 | 1.362E-05 | 46028.8109 | 2.4745 |
| 6.300 | -4.75E-06 | -.6881 | .029271 | 8.762E-06 | 46182.9277 | 1.0342 |
| 7.000 | -5.14E-07 | -.5017 | .3994 | 3.635E-06 | 46099.8680 | .1241 |
| 7.700 | 8.31E-07 | -.2293 | .3395 | 6.193E-07 | 45978.4487 | -.2201 |
| 8.400 | 7.90E-07 | -.050297 | .1710 | -4.656E-07 | 45898.7024 | -.2283 |
| 9.100 | 4.05E-07 | .021177 | .045222 | -5.281E-07 | 45885.7257 | -.1267 |
| 9.800 | 1.15E-07 | .029767 | -.010279 | -2.901E-07 | 45889.5534 | -.038599 |
| 10.500 | -1.14E-08 | .017431 | -.019934 | -8.921E-08 | 45884.0563 | .004092 |
| 11.200 | -3.52E-08 | .005695 | -.012507 | 3.540E-09 | 45878.8264 | .013493 |
| 11.900 | -2.27E-08 | 2.281E-05 | -.004217 | 2.346E-08 | 45876.2988 | .009270 |
| 12.600 | -8.09E-09 | -.001152 | 1.660E-04 | 1.672E-08 | 45876.8019 | .003489 |
| 13.300 | 6.64E-10 | -5.244E-04 | .001173 | 9.275E-09 | 45876.5223 | -3.022E-04 |
| 14.000 | 6.30E-09 | 0.0000 | 0.0000 | 7.638E-09 | 45876.2887 | -.003015 |

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00081352 m
 Computed slope at pile head = 3.87215E-18
 Maximum bending moment = -47.105 kN- m
 Maximum shear force = 40.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 6
 Number of zero deflection points = 4

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[ABRIDGED]

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 Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m
 M = pile-head moment, kN- m
 V = pile-head shear force, kN
 S = pile-head slope, radians
 R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition | | Boundary Condition | | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|-----------------------|---------|-----------------------|-------|---------------------|------------------------------|----------------------------|------------------------|
| | 1 | | 2 | | | | | |
| 2 | V= | 40.000 | S= | 0.000 | 890.0000 | 8.135E-04 | -47.1053 | 40.0000 |
| 2 | V= | 60.000 | S= | 0.000 | 890.0000 | .001507 | -77.1836 | 60.0000 |
| 2 | V= | 80.000 | S= | 0.000 | 890.0000 | .002311 | -108.9651 | 80.0000 |
| 2 | V= | 100.000 | S= | 0.000 | 890.0000 | .003214 | -142.1167 | 100.0000 |
| 2 | V= | 120.000 | S= | 0.000 | 890.0000 | .004192 | -176.2173 | 120.0000 |
| 2 | V= | 140.000 | S= | 0.000 | 890.0000 | .005244 | -211.2150 | 140.0000 |
| 2 | V= | 160.000 | S= | 0.000 | 890.0000 | .006356 | -246.8856 | 160.0000 |
| 2 | V= | 180.000 | S= | 0.000 | 890.0000 | .007523 | -283.1503 | 180.0000 |
| 2 | V= | 200.000 | S= | 0.000 | 890.0000 | .008739 | -319.8726 | 200.0000 |
| 2 | V= | 220.000 | S= | 0.000 | 890.0000 | .009996 | -356.9209 | 220.0000 |

The analysis ended normally.

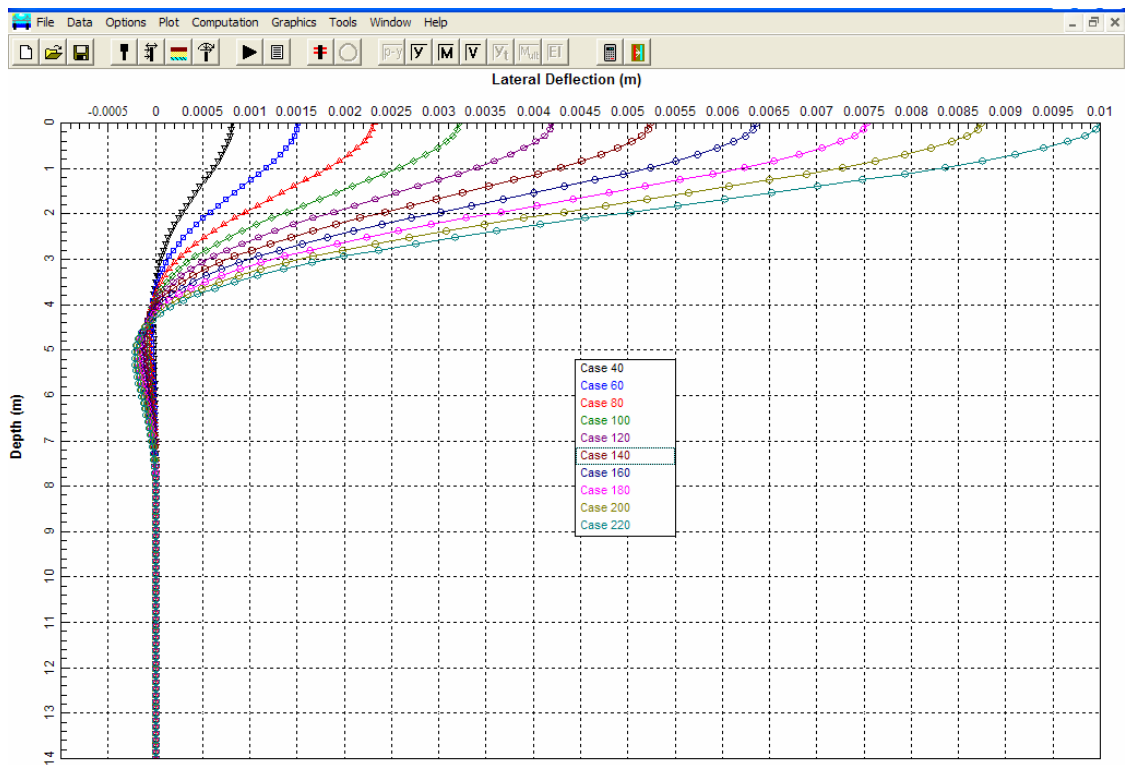


Figure F.23: Pier 2 – Plot of Deflection *versus* Depth as a Function on Lateral Load on X-X Axis

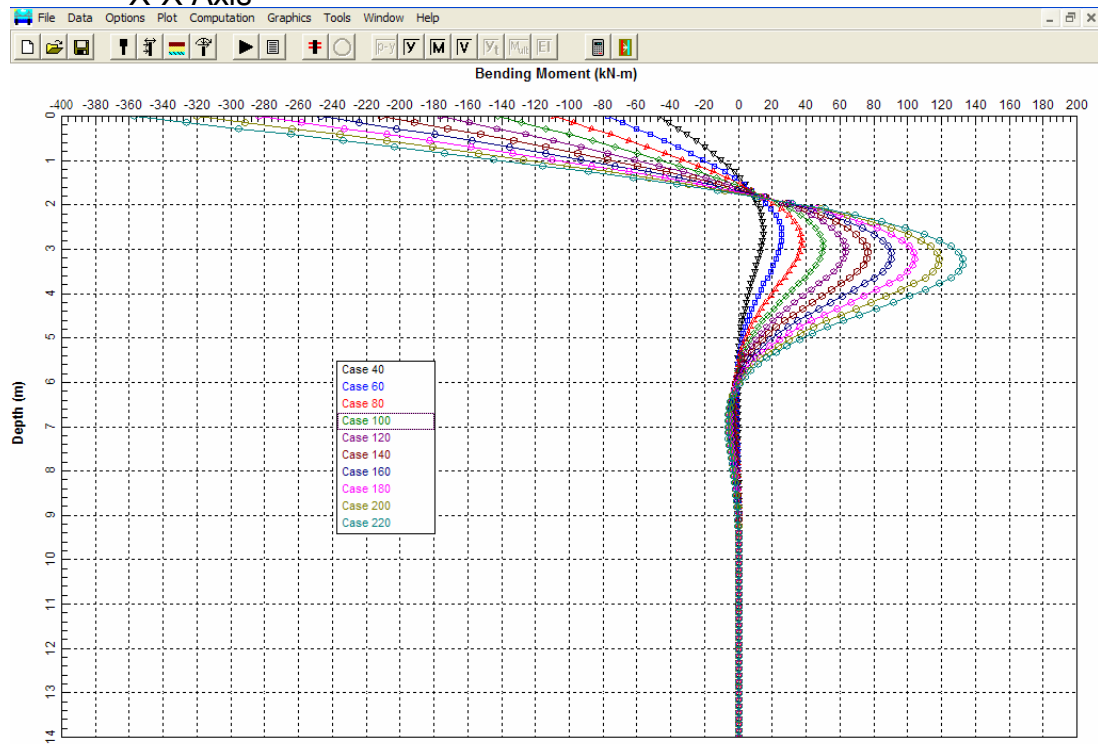


Figure F.24: Pier 2 – Plot of Moment *versus* Depth as a Function of Lateral Load on X-X Axis

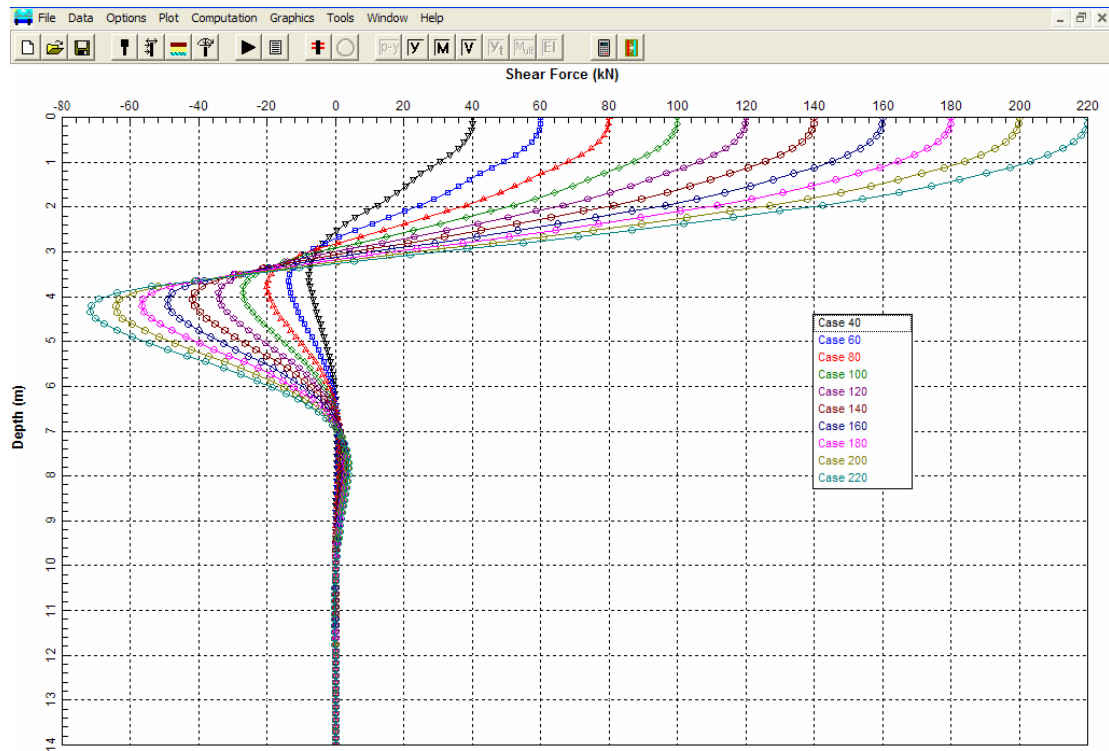


Figure F.25: Pier 2 – Plot of Shear *versus* Depth as a Function of Lateral Load on X-X Axis

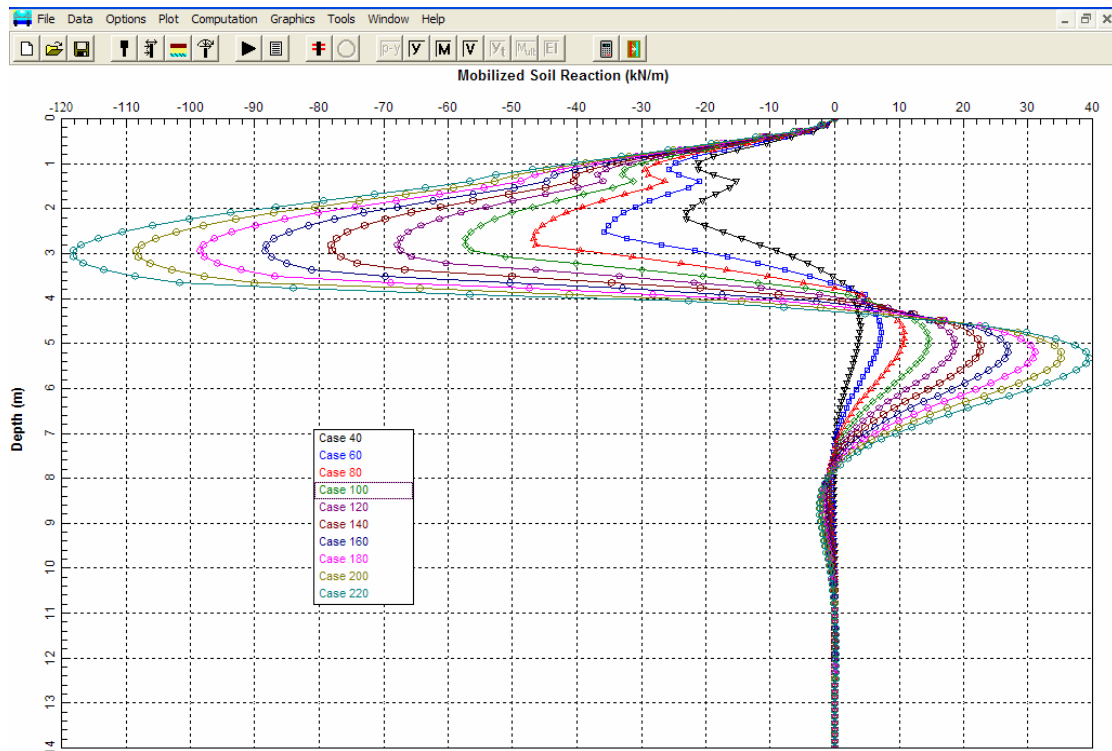


Figure F.26: Pier 2 – Plot of Soil Reaction *versus* Depth as a Function of Lateral Load on X-X Axis

```

LPFILEP4
FHWA Pier 2, HP360x152 Y-Y Axis/Fixed-Head Cyclic
2 1 0 0 0 0
100 2 0 14 0
0 0.376 0.0002 0.0194 2.1E8
14 0.376 0.0002 0.0194 2.1E8
2 4 4 0 0
4 0 4 50000 50000
4 4 14 33900 33900
0 11.4
4 11.4
4 9.8
14 9.8
0 0 36 0 0
4 0 36 0 0
4 0 35 0 0
14 0 35 0 0
0 0 20
10
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
2 220 0 890
0
1 1 0
100 1E-5 2

```

Pier 2 Y-Y Axis - Echo of Input File

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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=====

Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 1:

- Computation of Lateral Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis does not use p-y multipliers (individual pile or shaft action only)
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 1.0000E-05 m
- Maximum allowable deflection = 2.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

File Structural Properties and Geometry

Pile Length = 14.00 m
Depth of ground surface below top of pile = .00 m
Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .37600000 | 2.00000E-04 | .019400 | 210000000.000 |
| 2 | 14.0000 | .37600000 | 2.00000E-04 | .019400 | 210000000.000 |

Soil and Rock Layering Information

The soil profile is modelled using 2 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
Distance from top of pile to bottom of layer = 4.000 m
p-y subgrade modulus k for top of soil layer = 50000.000 kN/ m**3
p-y subgrade modulus k for bottom of layer = 50000.000 kN/ m**3

Layer 2 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 4.000 m
Distance from top of pile to bottom of layer = 14.000 m
p-y subgrade modulus k for top of soil layer = 33900.000 kN/ m**3
p-y subgrade modulus k for bottom of layer = 33900.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth is defined using 4 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|-----------|--------------|------------------------------|
| 1 | .00 | 11.40000 |
| 2 | 4.00 | 11.40000 |
| 3 | 4.00 | 9.80000 |
| 4 | 14.00 | 9.80000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth defined using 4 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|-----------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 36.00 | ----- | ----- |
| 2 | 4.000 | .00000 | 36.00 | ----- | ----- |
| 3 | 4.000 | .00000 | 35.00 | ----- | ----- |
| 4 | 14.000 | .00000 | 35.00 | ----- | ----- |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 40.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 220.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 40.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|------------------------|
| 0.000 | .001216 | -43.1920 | 40.0000 | -6.970E-18 | 86476.7805 | 0.0000 |
| .700 | .001016 | -15.8536 | 35.4883 | -4.886E-04 | 60778.6640 | -16.3858 |
| 1.400 | 6.24E-04 | 3.9838 | 19.6133 | -5.719E-04 | 49621.0522 | -20.6143 |
| 2.100 | 2.69E-04 | 13.1367 | 4.9083 | -4.155E-04 | 58224.7945 | -23.8423 |
| 2.800 | 5.65E-05 | 11.7234 | -7.2107 | -1.967E-04 | 56896.3012 | -7.9139 |
| 3.500 | -2.32E-05 | 5.9570 | -7.9588 | -4.867E-05 | 51475.8564 | 4.0609 |
| 4.200 | -3.18E-05 | 1.6998 | -4.2171 | 1.145E-05 | 47474.0619 | 4.6506 |
| 4.900 | -1.83E-05 | -.2112 | -1.4064 | 2.121E-05 | 46074.8505 | 3.1201 |
| 5.600 | -5.95E-06 | -.6057 | .061142 | 1.303E-05 | 46445.6693 | 1.1540 |
| 6.300 | -8.76E-08 | -.3937 | .4168 | 4.381E-06 | 46246.3472 | .019053 |
| 7.000 | 1.21E-06 | -.1352 | .2868 | 1.014E-07 | 46003.3342 | -.2915 |
| 7.700 | 7.99E-07 | -.002966 | .1004 | -8.736E-07 | 45879.0767 | -.2119 |
| 8.400 | 2.60E-07 | .027293 | .002072 | -5.794E-07 | 45901.9443 | -.075033 |
| 9.100 | 3.31E-09 | .017820 | -.020495 | -1.832E-07 | 45893.0391 | -.001035 |
| 9.800 | -4.67E-08 | .005368 | -.013161 | 2.693E-09 | 45881.3345 | .015703 |
| 10.500 | -2.72E-08 | -3.015E-04 | -.003765 | 3.604E-08 | 45876.5720 | .009803 |
| 11.200 | -6.80E-09 | -.001184 | 3.805E-04 | 1.983E-08 | 45877.4020 | .002608 |
| 11.900 | 1.08E-09 | -6.030E-04 | 9.201E-04 | 4.479E-09 | 45876.8555 | -4.405E-04 |
| 12.600 | 1.76E-09 | -1.242E-04 | 4.126E-04 | -1.087E-09 | 45876.4054 | -7.605E-04 |
| 13.300 | 6.60E-10 | 1.115E-05 | 3.019E-05 | -1.669E-09 | 45876.2991 | -3.003E-04 |
| 14.000 | -4.51E-10 | 0.0000 | 0.0000 | -1.548E-09 | 45876.2887 | 2.157E-04 |

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00121631 m
 Computed slope at pile head = -6.96987E-18
 Maximum bending moment = -43.192 kN- m
 Maximum shear force = 40.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 7
 Number of zero deflection points = 5

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Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m
 M = pile-head moment, kN- m
 V = pile-head shear force, kN
 S = pile-head slope, radians
 R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|----------------------------|----------------------------|---------------------|------------------------------|----------------------------|------------------------|
| 2 | V= 40.000 | S= 0.000 | 890.0000 | .001216 | -43.1920 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .002322 | -71.2590 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .003623 | -101.0843 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .005082 | -132.1560 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .006679 | -164.2676 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .008387 | -197.1322 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .010186 | -230.5318 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .012058 | -264.2880 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .013984 | -298.2736 | 200.0000 |
| 2 | V= 220.000 | S= 0.000 | 890.0000 | .015974 | -332.7162 | 220.0000 |

The analysis ended normally.

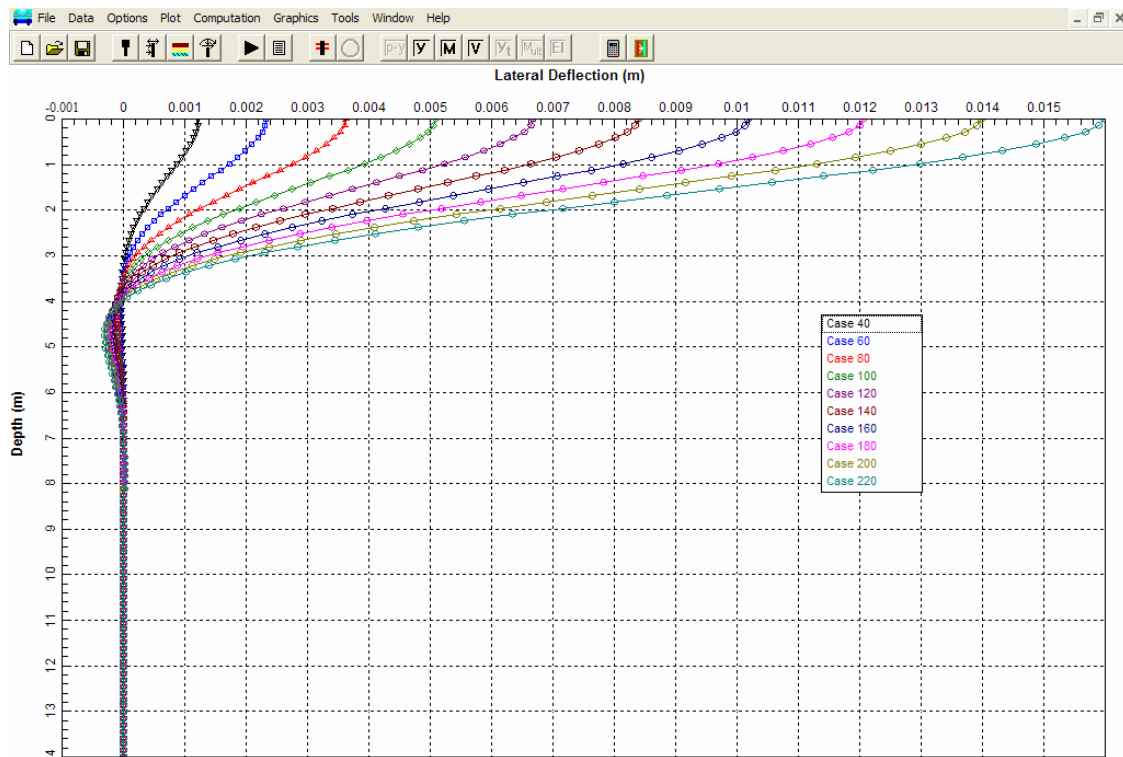


Figure F.27: Pier 2 – Plot of Deflection *versus* Depth as a Function of Lateral Load on Y- Y Axis

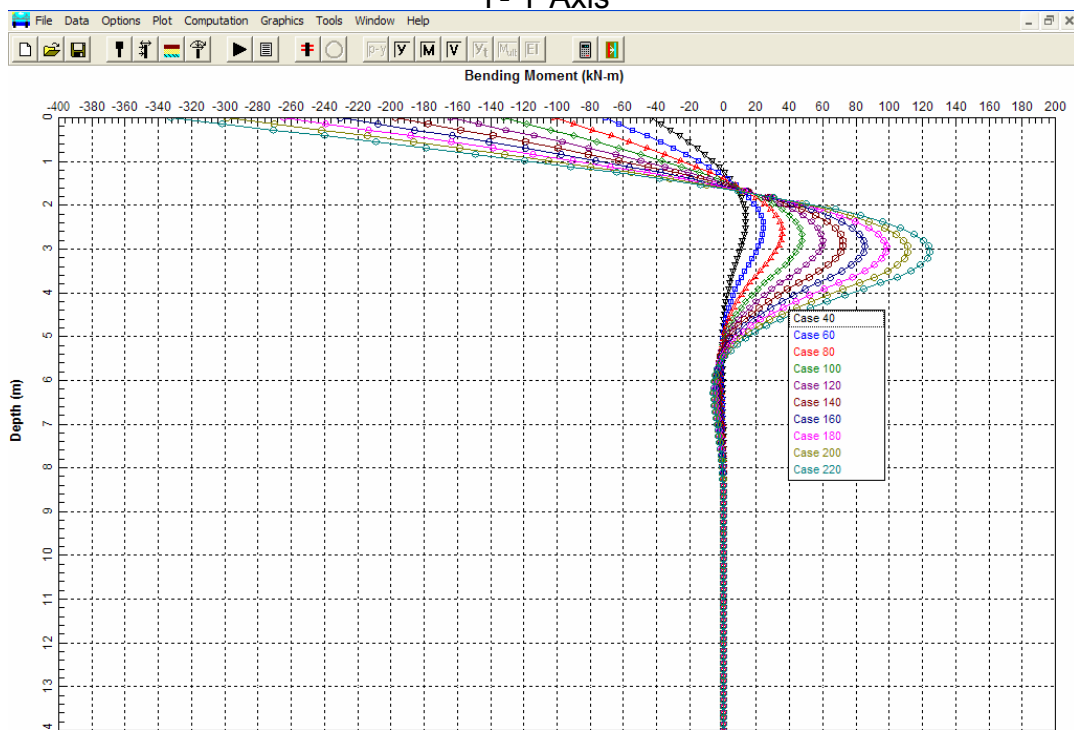


Figure F.28: Pier 2 – Plot of Moment *versus* Depth as a Function of Lateral Load on Y- Y Axis

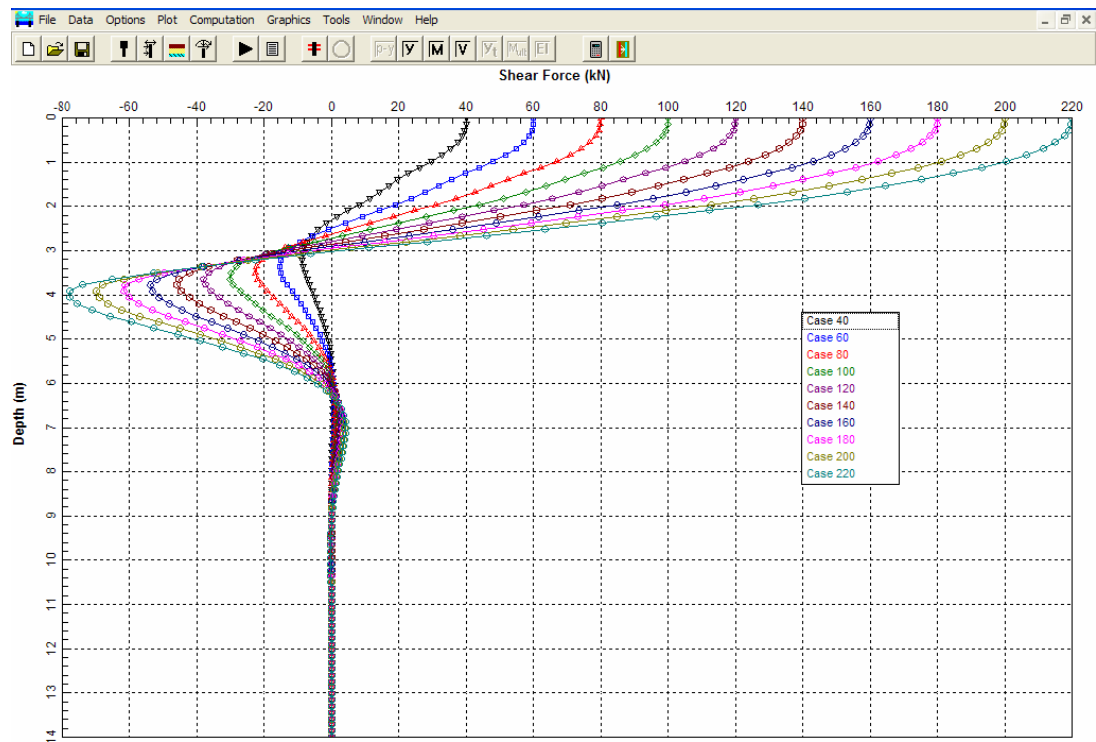


Figure F.29: Pier 2 – Plot of Shear *versus* Depth as a Function of Lateral Load on Y-Y Axis

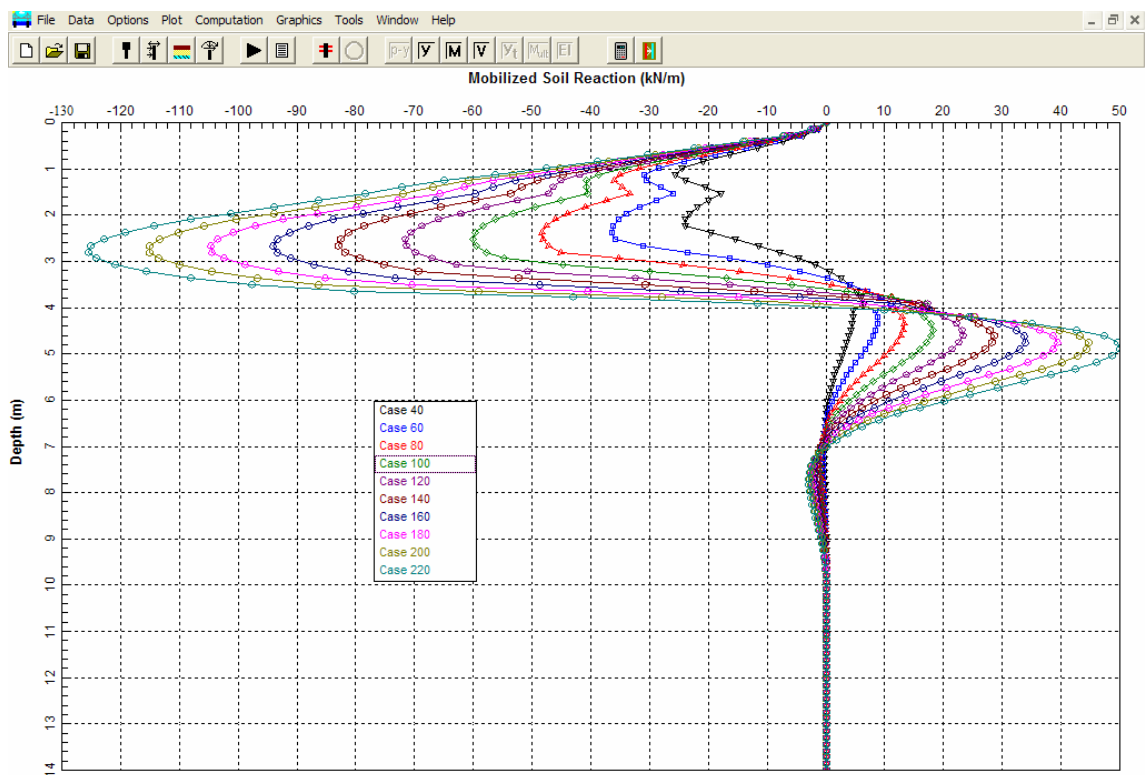


Figure F.30: Pier 2 – Plot of Soil Reaction *versus* Depth as a Function of Lateral Load on Y-Y Axis

F.4.4 LPILE - Pier 3 H-pile, X-X Axis and Y-Y Axis

As discussed in Chapter 12, wave equation driveability analyses at the internal piers indicated a potential driveability problem for 356 mm concrete piles. Therefore, low displacement HP 360x152 H-piles were chosen for the pile foundations at the interior piers.

LPILE solutions for lateral loading of the selected H-pile section at Pier 3 in both the major (X-X) and minor (Y-Y) axes directions were also obtained. The same assumptions used for Pier 2 also apply to Pier 3. The four meter extremely dense sand and gravel layer at Pier 2 decreases to one meter at Pier 3 location. The same assumed slope soil modulus (50,000 kN/m³) was used for the extremely dense sand and gravel layer. Soil parameters for the cohesive soil layers were obtained from Tables 9-15 and 9-16.

LPILE analysis of lateral loading in the X-X and Y-Y axes are presented on the following pages. The analysis output includes an echo print of the input file followed by the LPILE generated summaries of the problem input and output. The output includes a summary table of deflection, moment, shear, and soil reaction versus lateral load. For selected lateral loads in the X-X axis, Figures F.31 to F.34 provide graphical presentations of deflection, moment, shear, and soil reaction versus depth. These graphical presentations for loads in the Y-Y axis are presented in Figure F.35 to F.38.

The LPILE analyses indicate the performance of the H-pile subjected to lateral loading is acceptable in either axis. The maximum deflection under the 40 kN design load is less than 1 mm.

Additional LPILE analyses should be performed to evaluate group response using the p-multiplier approach described in Section 9.8.4.

```

LPFILEP4
FHWA Pier 3, HP360x152 X-X Axis/Fixed-Head Cyclic
2 1 0 0 0 0
100 2 0 13 0
0 0.3565 0.0004 0.0194 2.1E8
14 0.3565 0.0004 0.0194 2.1E8
3 6 6 0 0
4 0 1 50000 50000
3 1 4 54300 54300
3 4 13 108500 108500
0 10.6
1 10.6
1 9.8
4 9.8
4 10.4
13 10.4
0 0 36 0 0
1 0 36 0 0
1 106 0 0.005 0
4 106 0 0.005 0
4 155 0 0.005 0
13 155 0 0.005 0
0 0 20
10
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
2 220 0 890
0
1 1 0
100 1E-5 2

```

Pier 3 X-X Axis - Echo of Input File

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LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 1:

- Computation of Lateral Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis does not use p-y multipliers (individual pile or shaft action only)
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 1.0000E-05 m
- Maximum allowable deflection = 2.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

Pile Structural Properties and Geometry

Pile Length = 13.00 m
Depth of ground surface below top of pile = .00 m
Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35650000 | 4.00000E-04 | .019400 | 210000000.000 |
| 2 | 14.0000 | .35650000 | 4.00000E-04 | .019400 | 210000000.000 |

Soil and Rock Layering Information

The soil profile is modelled using 3 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 1.000 m
 p-y subgrade modulus k for top of soil layer = 50000.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 50000.000 kN/ m**3

Layer 2 is stiff clay without free water

Distance from top of pile to top of layer = 1.000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 54300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 54300.000 kN/ m**3

Layer 3 is stiff clay without free water

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 13.000 m
 p-y subgrade modulus k for top of soil layer = 108500.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 108500.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth
 is defined using 6 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|--------------|--------------|------------------------------|
| 1 | .00 | 10.60000 |
| 2 | 1.00 | 10.60000 |
| 3 | 1.00 | 9.80000 |
| 4 | 4.00 | 9.80000 |
| 5 | 4.00 | 10.40000 |
| 6 | 13.00 | 10.40000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth
 defined using 6 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|--------------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 36.00 | ----- | ----- |
| 2 | 1.000 | .00000 | 36.00 | ----- | ----- |
| 3 | 1.000 | 106.00000 | .00 | .00500 | .0 |
| 4 | 4.000 | 106.00000 | .00 | .00500 | .0 |
| 5 | 4.000 | 155.00000 | .00 | .00500 | .0 |
| 6 | 13.000 | 155.00000 | .00 | .00500 | .0 |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 40.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

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.[**ABRIDGED**]

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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 220.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

 Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 40.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. Y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|------------------------|
| 0.000 | 4.82E-04 | -41.4026 | 40.0000 | -4.170E-19 | 64326.3147 | 0.0000 |
| .650 | 3.99E-04 | -15.7980 | 37.2719 | -2.204E-04 | 52916.2782 | -10.7758 |
| 1.300 | 2.34E-04 | 5.0149 | 23.7742 | -2.566E-04 | 48111.0717 | -28.4179 |
| 1.950 | 9.01E-05 | 14.5288 | 5.1555 | -1.734E-04 | 52350.6850 | -27.9604 |
| 2.600 | 1.44E-05 | 12.4030 | -11.0138 | -6.262E-05 | 51403.3740 | -20.2403 |
| 3.250 | -2.32E-06 | 3.0988 | -11.7209 | -2.124E-06 | 47257.1964 | 19.4326 |
| 3.900 | -4.41E-07 | -.7026 | -.7681 | 2.671E-06 | 46189.3708 | 12.4916 |
| 4.550 | 2.19E-09 | .019768 | .1542 | -3.208E-08 | 45885.0978 | -3.4451 |
| 5.200 | 1.42E-18 | 7.313E-09 | 2.526E-06 | -5.670E-15 | 45876.2887 | -3.972E-05 |
| 5.850 | 0.000 | 7.528E-22 | -2.804E-18 | 0.0000 | 45876.2887 | 4.305E-17 |
| 6.500 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 7.150 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 7.800 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 8.450 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 9.100 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 9.750 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 10.400 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 11.050 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 11.700 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 12.350 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 13.000 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00048191 m
 Computed slope at pile head = -4.17001E-19
 Maximum bending moment = -41.403 kN- m
 Maximum shear force = 40.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 6
 Number of zero deflection points = 35

Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m

M = pile-head moment, kN- m

V = pile-head shear force, kN

S = pile-head slope, radians

R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|----------------------------|----------------------------|---------------------|------------------------------|----------------------------|------------------------|
| 2 | V= 40.000 | S= 0.000 | 890.0000 | 4.819E-04 | -41.4026 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | 9.860E-04 | -68.6692 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .001653 | -98.6945 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .002501 | -131.2477 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .003507 | -165.6023 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .004670 | -201.7577 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .005986 | -239.3866 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .007455 | -278.4169 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .009050 | -318.4934 | 200.0000 |
| 2 | V= 220.000 | S= 0.000 | 890.0000 | .010785 | -359.6486 | 220.0000 |

The analysis ended normally.

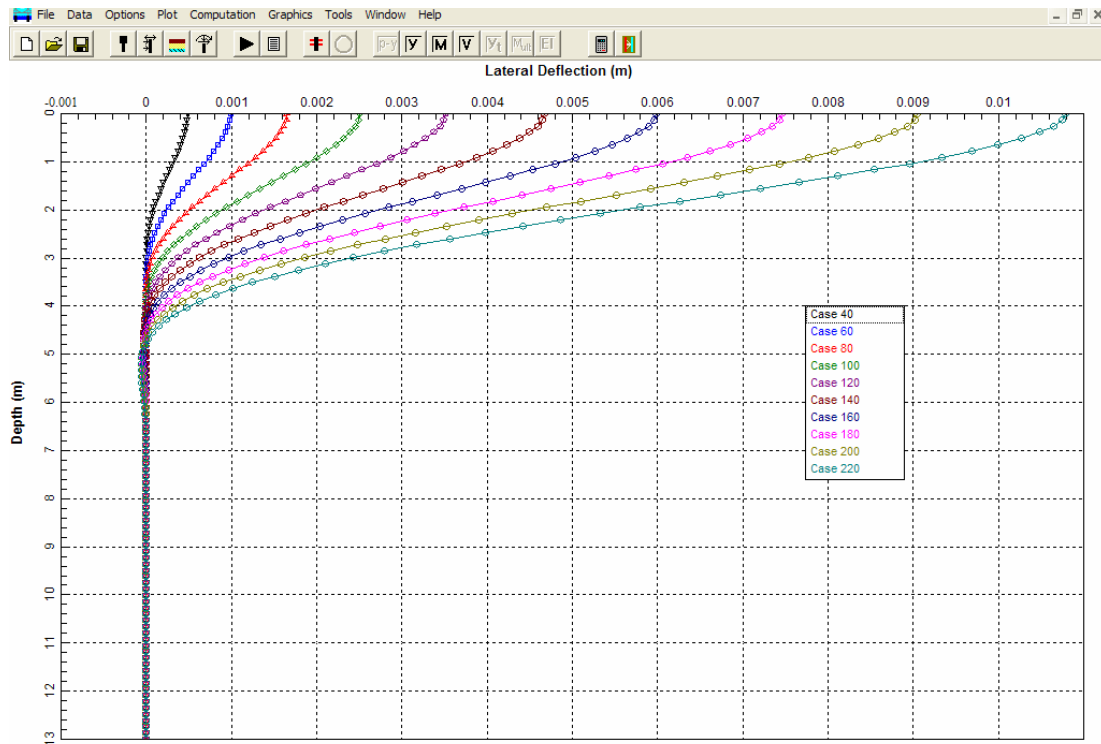


Figure F.31: Pier 3 – Plot Deflection *versus* Depth as a Function on Lateral Load on X-X Axis

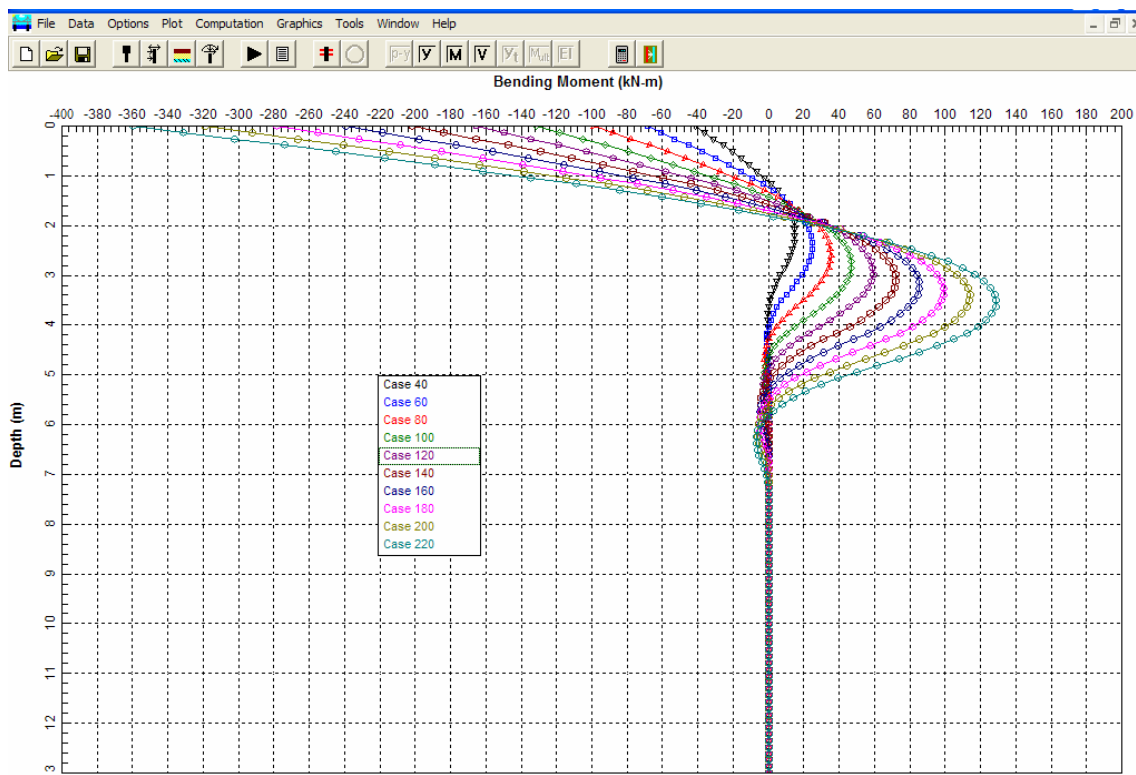


Figure F.32: Pier 3 – Plot of Moment *versus* Depth as a Function of Lateral Load on X-X Axis

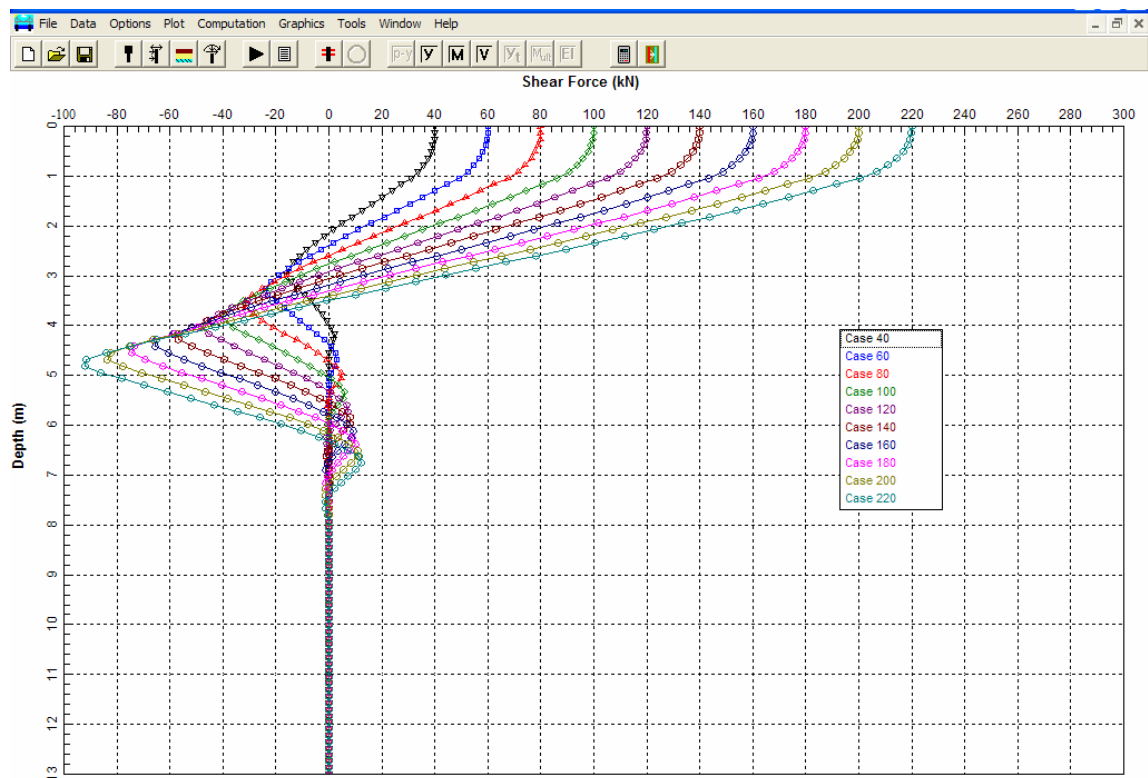


Figure F.33: Pier 3 – Plot of Shear *versus* Depth as a Function of Lateral Load on X-X Axis

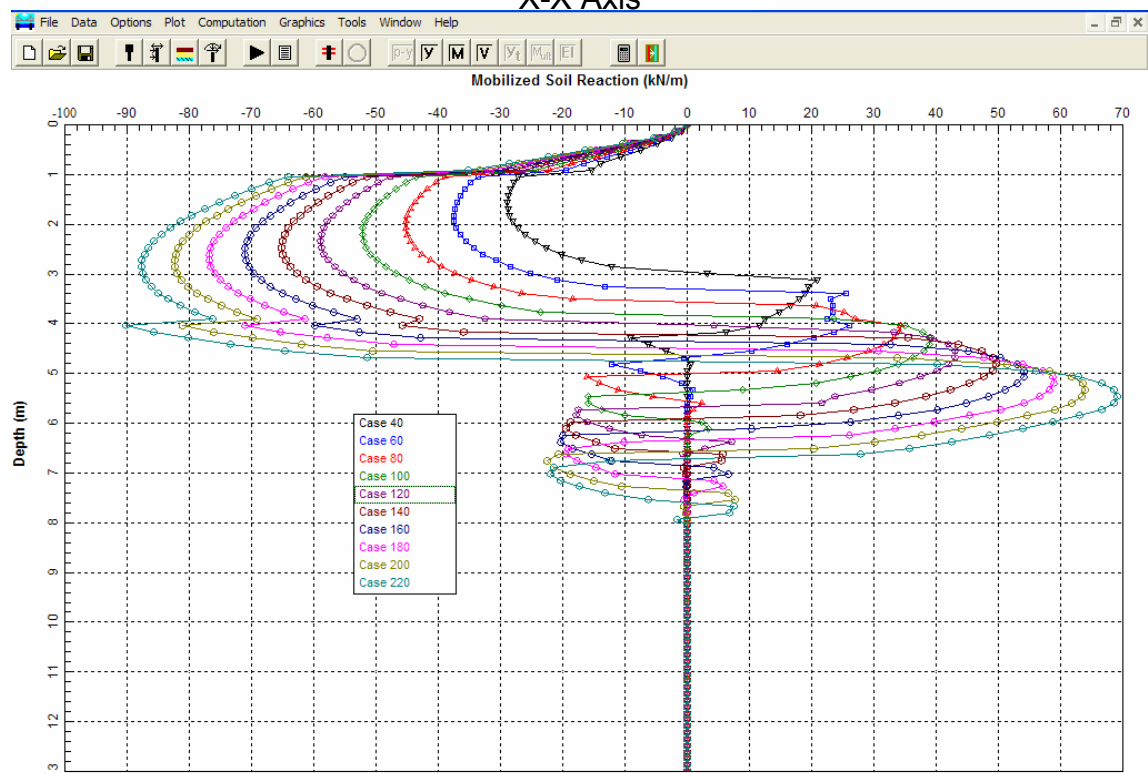


Figure F.34: Pier 3 – Plot of Soil Reaction *versus* Depth as a Function of Lateral Load on X-X Axis

```

LPFILEP4
FHWA Pier 3, HP360x152 Y-Y Axis/Fixed-Head Cyclic
2 1 0 0 0 0
100 2 0 13 0
0 0.3755 0.0002 0.0194 2.1E8
14 0.3755 0.0002 0.0194 2.1E8
3 6 6 0 0
4 0 1 50000 50000
3 1 4 54300 54300
3 4 13 108500 108500
0 10.6
1 10.6
1 9.8
4 9.8
4 10.4
13 10.4
0 0 36 0 0
1 0 36 0 0
1 106 0 0.005 0
4 106 0 0.005 0
4 155 0 0.005 0
13 155 0 0.005 0
0 0 20
10
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
2 220 0 890
0
5 1 0
100 1E-5 2

```

Pier 3 Y-Y Axis - Echo of Input File

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
 Subjected to Lateral Loading Using the p-y Method

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Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 1:

- Computation of Lateral Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis does not use p-y multipliers (individual pile or shaft action only)
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 1.0000E-05 m
- Maximum allowable deflection = 2.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

Pile Structural Properties and Geometry

Pile Length = 13.00 m
 Depth of ground surface below top of pile = .00 m
 Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .37550000 | 2.00000E-04 | .019400 | 210000000.000 |
| 2 | 14.0000 | .37550000 | 2.00000E-04 | .019400 | 210000000.000 |

Soil and Rock Layering Information

The soil profile is modelled using 3 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 1.000 m
 p-y subgrade modulus k for top of soil layer = 50000.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 50000.000 kN/ m**3

Layer 2 is stiff clay without free water

Distance from top of pile to top of layer = 1.000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 54300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 54300.000 kN/ m**3

Layer 3 is stiff clay without free water

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 13.000 m
 p-y subgrade modulus k for top of soil layer = 108500.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 108500.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth is defined using 6 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|-----------|-----------|---------------------------|
| 1 | .00 | 10.60000 |
| 2 | 1.00 | 10.60000 |
| 3 | 1.00 | 9.80000 |
| 4 | 4.00 | 9.80000 |
| 5 | 4.00 | 10.40000 |
| 6 | 13.00 | 10.40000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth defined using 6 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|-----------|-----------|---------------------|------------------------|-------------|-------|
| 1 | .000 | .00000 | 36.00 | ----- | ----- |
| 2 | 1.000 | .00000 | 36.00 | ----- | ----- |
| 3 | 1.000 | 106.00000 | .00 | .00500 | .0 |
| 4 | 4.000 | 106.00000 | .00 | .00500 | .0 |
| 5 | 4.000 | 155.00000 | .00 | .00500 | .0 |
| 6 | 13.000 | 155.00000 | .00 | .00500 | .0 |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
 - (2) Values of E50 are reported for clay strata.
 - (3) Default values will be generated for E50 when input values are 0.
 - (4) RQD and k_rm are reported only for weak rock strata.
-

Loading Type

Cyclic loading criteria was used for computation of p-y curves
 Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 40.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 220.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computed Values of Load Distribution and Deflection for Lateral Loading for Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 40.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|------------------------|
| 0.000 | 7.76E-04 | -38.7573 | 40.0000 | -1.251E-18 | 82259.6833 | 0.0000 |
| .650 | 6.23E-04 | -13.1536 | 36.9218 | -3.997E-04 | 58224.2592 | -12.0373 |
| 1.300 | 3.33E-04 | 6.9774 | 21.3244 | -4.347E-04 | 52426.2873 | -32.3114 |
| 1.950 | 1.03E-04 | 14.2468 | .6777 | -2.536E-04 | 59250.4846 | -30.0090 |
| 2.600 | 5.75E-06 | 9.0549 | -15.3582 | -5.998E-05 | 54376.5658 | -16.0991 |
| 3.250 | -3.82E-06 | .7024 | -6.9571 | 6.951E-06 | 46535.6511 | 18.8813 |
| 3.900 | -8.27E-08 | -.4808 | 1.7088 | 1.465E-06 | 46327.6789 | 4.9423 |
| 4.550 | -1.17E-10 | .002128 | -.049741 | -2.468E-09 | 45878.2865 | .4849 |
| 5.200 | -1.97E-20 | -1.959E-10 | -2.093E-09 | 3.033E-16 | 45876.2887 | 5.537E-08 |
| 5.850 | 0.000 | -1.458E-24 | 2.344E-20 | 0.0000 | 45876.2887 | -3.604E-19 |
| 6.500 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 7.150 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 7.800 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 8.450 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 9.100 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 9.750 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 10.400 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 11.050 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 11.700 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 12.350 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |
| 13.000 | 0.000 | 0.0000 | 0.0000 | 0.0000 | 45876.2887 | 0.0000 |

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00077584 m
 Computed slope at pile head = -1.25100E-18
 Maximum bending moment = -38.757 kN- m
 Maximum shear force = 40.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 5
 Number of zero deflection points = 36

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Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m
 M = pile-head moment, kN- m
 V = pile-head shear force, kN
 S = pile-head slope, radians
 R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|----------------------------|----------------------------|---------------------|------------------------------|----------------------------|------------------------|
| 2 | V= 40.000 | S= 0.000 | 890.0000 | 7.758E-04 | -38.7573 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .001595 | -64.4761 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .002701 | -92.8759 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .004081 | -123.4155 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .005726 | -155.7800 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .007628 | -189.7682 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .009763 | -225.0271 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .012132 | -261.4188 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .014712 | -298.8351 | 200.0000 |
| 2 | V= 220.000 | S= 0.000 | 890.0000 | .017626 | -338.3204 | 220.0000 |

The analysis ended normally.

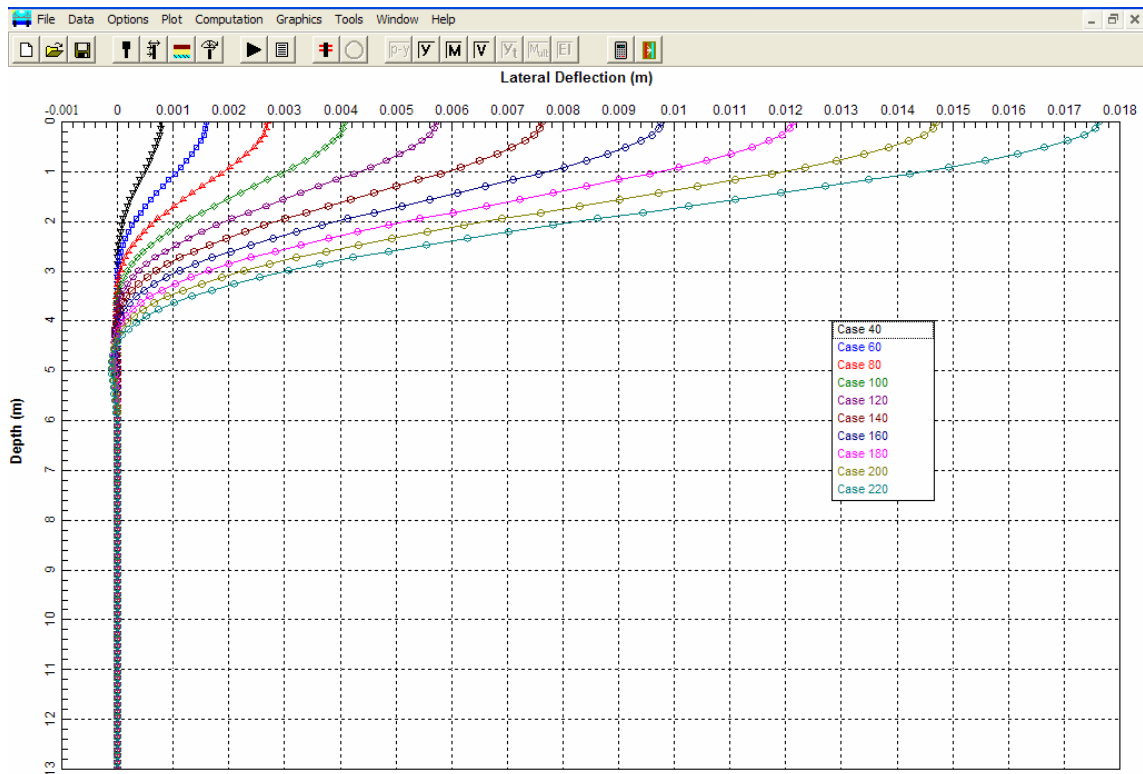


Figure F.35: Pier 3 – Plot of Deflection *versus* Depth as a Function of Lateral Load on Y-Y Axis

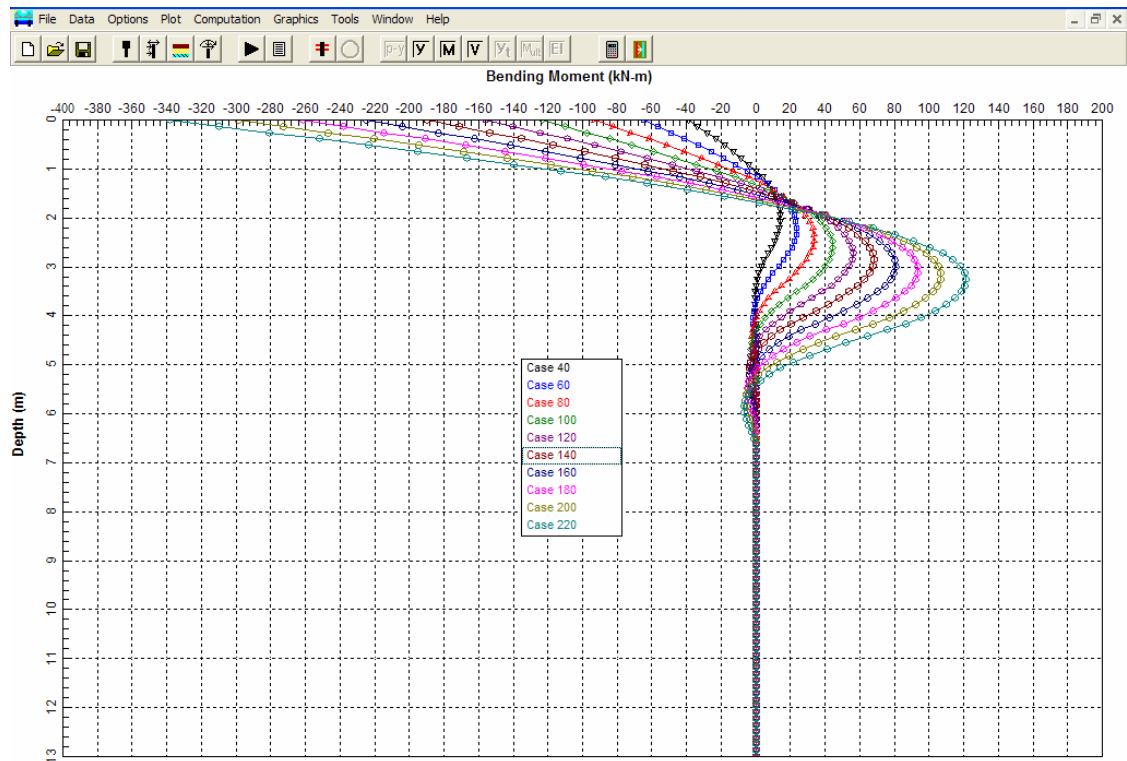


Figure F.36: Pier 3 – Plot of Moment *versus* Depth as a Function of Lateral Load on Y-Y Axis

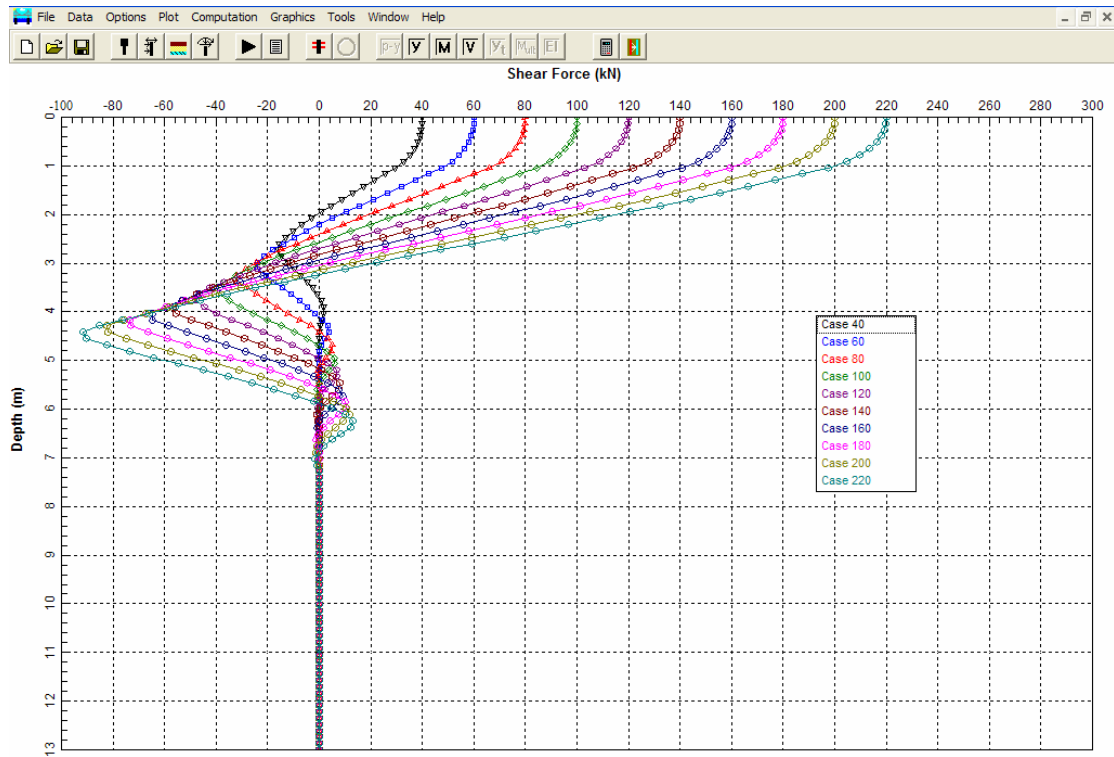


Figure F.37: Pier 3 – Plot of Shear *versus* Depth as a Function of Lateral Load on Y-Y Axis

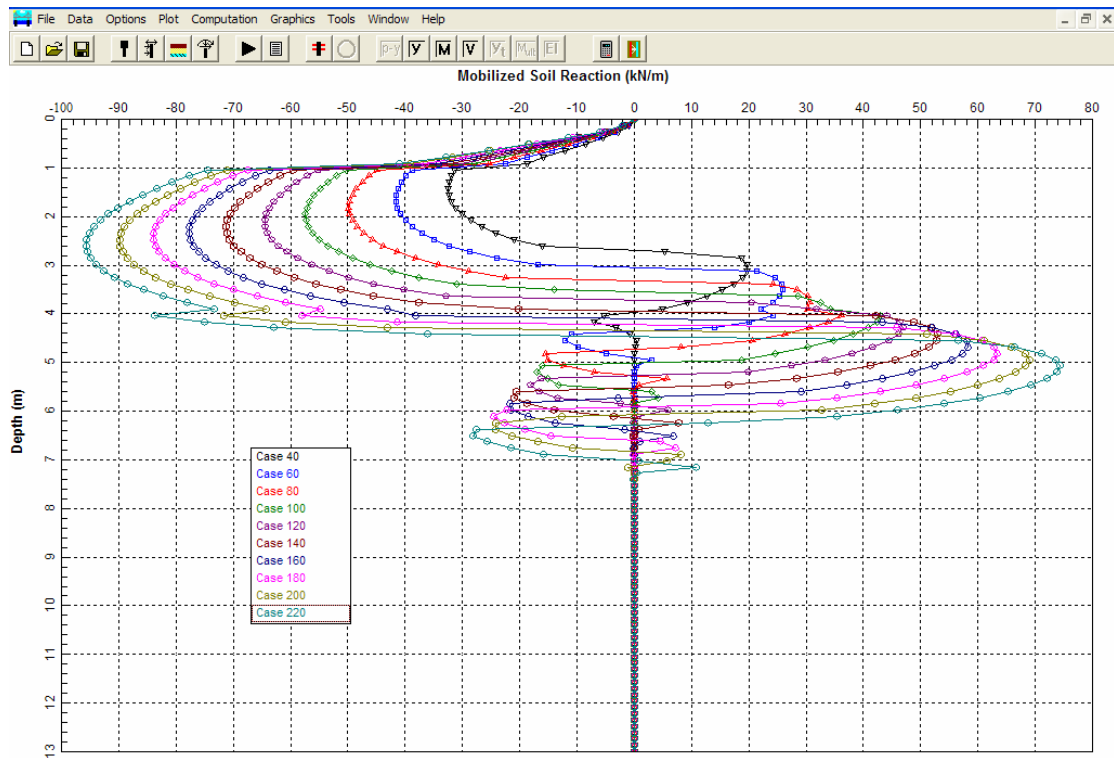


Figure F.38: Pier 3 – Plot of Soil Reaction *versus* Depth as a Function of Lateral Load on Y-Y Axis

F.4.5 LPILE Analysis - South Abutment

A LPILE analysis was performed to evaluate the performance of the 356 mm square prestressed concrete pile under lateral load at the South abutment. Unlike the North Abutment, the soil at the South abutment consists of only cohesive type. Again, soil parameters were obtained from Tables 9-15 and 9-16.

The same assumptions and analysis options as the North abutment were used. Ten lateral loads were analyzed from 20 to 200 kN in 20 kN increments.

An echo print of the input file is presented on the following page. LPILE generated summaries of the problem input and output are provided. For selected lateral loads, Figures F.39 to F.42 provide graphical presentations of deflection, movement, shear, and soil reaction versus depth.

The LPILE solutions for the South abutment indicate the pile deflection under the 40 kN design load will be 1.9 mm. The corresponding maximum moment and shear stress are - 44.4 m-kN and 13,100 kN/m², respectively. The deflection, moment and shear stress under the design load are acceptable.

Additional LPILE analyses should be performed to evaluate group response using the p-multiplier approach described in Section 9.8.4.

```

LPILEP4
FWA South Abut. - 355 mm-sq PSC Fixed-Head/Cyclic/Crack Modeled
2 3 0 0 0 0
100 2 0 21 0
0 0.355 0.0013 0.126 27800000
21 0.355 0.0013 0.126 27800000
3 6 6 0 0
1 0 5.5 0 0
3 5.5 15 54300 54300
3 15 21 108500 108500
0 9.2
5.5 9.2
5.5 9.7
15 9.7
15 10.5
21 10.5
0 33 0 0.01 0
5.5 33 0 0.01 0
5.5 93 0 0.007 0
15 93 0 0.007 0
15 161 0 0.005 0
21 161 0 0.005 0
0 0 20
10
2 20 0 890
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
0
1 1 0
100 1E-6 1
1 1
890
41370 248220 413685.52 2.0685E8
0.355 0.355 0 0 0
0.0005 4 2 0.0762
0.102 0.0006
-0.102 0.0006

```

South Abutment - Echo of Input File

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 4:

- Computation of Nonlinear Bending Stiffness and Ultimate Bending Moment Capacity with Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis does not use p-y multipliers (individual pile or shaft action only)
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 10.000E-06 m
- Maximum allowable deflection = 1.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 1

Pile Structural Properties and Geometry

Pile Length = 21.00 m
Depth of ground surface below top of pile = .00 m
Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35500000 | .001300 | .1260 | 27800000.000 |
| 2 | 21.0000 | .35500000 | .001300 | .1260 | 27800000.000 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of moment of inertia and modulus of are not used for any computations other than total stress due to combined axial loading and bending.

Soil and Rock Layering Information

The soil profile is modelled using 3 layers

Layer 1 is soft clay, p-y criteria by Matlock, 1970

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 5.500 m

Layer 2 is stiff clay without free water

Distance from top of pile to top of layer = 5.500 m
 Distance from top of pile to bottom of layer = 15.000 m
 p-y subgrade modulus k for top of soil layer = 54300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 54300.000 kN/ m**3

Layer 3 is stiff clay without free water

Distance from top of pile to top of layer = 15.000 m
 Distance from top of pile to bottom of layer = 21.000 m
 p-y subgrade modulus k for top of soil layer = 108500.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 108500.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth is defined using 6 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|-----------|--------------|------------------------------|
| 1 | .00 | 9.20000 |
| 2 | 5.50 | 9.20000 |
| 3 | 5.50 | 9.70000 |
| 4 | 15.00 | 9.70000 |
| 5 | 15.00 | 10.50000 |
| 6 | 21.00 | 10.50000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth defined using 6 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|-----------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | 33.00000 | .00 | .01000 | .0 |
| 2 | 5.500 | 33.00000 | .00 | .01000 | .0 |
| 3 | 5.500 | 93.00000 | .00 | .00700 | .0 |
| 4 | 15.000 | 93.00000 | .00 | .00700 | .0 |
| 5 | 15.000 | 161.00000 | .00 | .00500 | .0 |
| 6 | 21.000 | 161.00000 | .00 | .00500 | .0 |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 20.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

•
 .[ABRIDGED]

•
 Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 200.000 kN
 Slope at pile head = .000 m/ m
 Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computations of Ultimate Moment Capacity and Nonlinear Bending Stiffness

File Description:

The pile shape is a rectangular solid pile.

Width = .355 m
 Depth = .355 m

Material Properties:

Compressive Strength of Concrete = 41370.000 kN/ m**2
 Yield Stress of Reinforcement = 248220. kN/ m**2
 Modulus of Elasticity of Reinforcement = 206850000. kN/ m**2
 Number of Reinforcing Bars = 4
 Area of Single Bar = .00050 m**2
 Number of Rows of Reinforcing Bars = 2
 Cover Thickness (edge to bar center) = .076 m

Ultimate Axial Squash Load Capacity = 4687.27 kN

Distribution and Area of Steel Reinforcement

| Row Number | Area of Reinforcement m**2 | Distance to Centroidal Axis m |
|---------------|----------------------------------|-------------------------------------|
| 1 | .000600 | .1020 |
| 2 | .000600 | -.1020 |

Axial Thrust Force = 890.00 kN

| Bending Moment kN-m | Bending Stiffness kN-m2 | Bending Curvature rad/m | Maximum Strain m/m | Neutral Axis Position m |
|---------------------------|-------------------------------|-------------------------------|--------------------------|-------------------------------|
| 1.54295127 | 39190.962 | .00003937 | .00023366 | 5.93486814 |
| 7.71444547 | 39189.382 | .00019685 | .00026170 | 1.32942587 |
| 13.885 | 39185.750 | .00035433 | .00028986 | .81803677 |
| 20.053 | 39179.988 | .00051181 | .00031813 | .62158314 |
| 26.218 | 39172.157 | .00066929 | .00034653 | .51775257 |
| 32.378 | 39162.188 | .00082677 | .00037504 | .45362225 |
| 38.534 | 39150.185 | .00098425 | .00040367 | .41013020 |
| 44.683 | 39136.085 | .00114173 | .00043242 | .37873943 |
| 50.825 | 39119.844 | .00129921 | .00046129 | .35505146 |
| 56.988 | 39121.516 | .00145669 | .00049033 | .33660160 |
| 63.049 | 39059.507 | .00161417 | .00051931 | .32172146 |
| 69.110 | 39008.681 | .00177165 | .00054844 | .30956600 |
| 75.155 | 38958.023 | .00192913 | .00057769 | .29945812 |
| 81.088 | 38861.083 | .00208661 | .00060684 | .29082363 |
| 81.088 | 36133.990 | .00224409 | .00061495 | .27403133 |
| 81.088 | 33764.548 | .00240157 | .00063793 | .26562977 |
| 81.469 | 31835.639 | .00255906 | .00066017 | .25797573 |
| 83.923 | 30893.279 | .00271654 | .00068196 | .25104214 |
| 86.229 | 30003.115 | .00287402 | .00070333 | .24472065 |
| 88.411 | 29164.014 | .00303150 | .00072433 | .23893543 |
| 90.481 | 28372.973 | .00318898 | .00074498 | .23361065 |
| 92.458 | 27628.502 | .00334646 | .00076533 | .22869755 |
| 94.358 | 26929.177 | .00350394 | .00078544 | .22415821 |
| 96.109 | 26249.199 | .00366142 | .00080493 | .21984097 |
| 97.855 | 25623.877 | .00381890 | .00082447 | .21589207 |
| 99.561 | 25038.090 | .00397638 | .00084391 | .21223026 |
| 110.590 | 21442.569 | .00515748 | .00098201 | .19040569 |
| 120.077 | 18943.856 | .00633858 | .00111351 | .17567181 |
| 128.620 | 17104.480 | .00751969 | .00124079 | .16500599 |
| 136.481 | 15686.050 | .00870079 | .00136470 | .15684818 |
| 142.143 | 14384.225 | .00988189 | .00148005 | .14977375 |
| 144.188 | 13033.330 | .01106299 | .00157940 | .14276432 |
| 145.892 | 11915.286 | .01224409 | .00167612 | .13689243 |
| 147.331 | 10974.243 | .01342520 | .00177083 | .13190350 |
| 148.579 | 10172.279 | .01460630 | .00186443 | .12764584 |
| 149.683 | 9481.177 | .01578740 | .00195798 | .12402195 |
| 150.467 | 8867.434 | .01696850 | .00204601 | .12057682 |
| 151.314 | 8337.066 | .01814961 | .00213887 | .11784672 |
| 151.873 | 7856.558 | .01933071 | .00222570 | .11513828 |
| 152.385 | 7429.115 | .02051181 | .00231392 | .11280903 |
| 152.897 | 7048.226 | .02169291 | .00240709 | .11096188 |
| 153.186 | 6696.962 | .02287402 | .00249515 | .10908222 |
| 153.411 | 6377.467 | .02405512 | .00258529 | .10747341 |
| 153.715 | 6091.050 | .02523622 | .00268420 | .10636295 |
| 153.799 | 5821.896 | .02641732 | .00277391 | .10500332 |
| 153.865 | 5575.122 | .02759843 | .00286459 | .10379536 |
| 153.883 | 5346.955 | .02877953 | .00295694 | .10274448 |
| 153.894 | 5136.551 | .02996063 | .00305021 | .10180737 |
| 153.894 | 4941.739 | .03114173 | .00314448 | .10097317 |
| 153.894 | 4761.164 | .03232283 | .00325113 | .10058315 |
| 153.894 | 4593.320 | .03350394 | .00334652 | .09988438 |
| 153.894 | 4436.907 | .03468504 | .00344120 | .09921268 |
| 153.894 | 4290.796 | .03586614 | .00353701 | .09861683 |
| 153.894 | 4154.001 | .03704724 | .00363341 | .09807514 |
| 153.894 | 4025.660 | .03822835 | .00373041 | .09758221 |
| 153.894 | 3905.010 | .03940945 | .00415798 | .10550709 |

Ultimate Moment Capacity at a Concrete Strain of 0.003 = 153.888 m- kN

 Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 1

File-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 20.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. Y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | 5.22E-04 | -18.0043 | 20.0000 | -5.16E-19 | 9521.8 | 36140.000 | -6.843 |
| .210 | 5.11E-04 | -13.9454 | 18.4837 | -9.28E-05 | 8967.6 | 36140.000 | -7.598 |
| .420 | 4.83E-04 | -10.2065 | 16.8203 | -1.63E-04 | 8457.1 | 36140.000 | -8.244 |
| .630 | 4.43E-04 | -6.8200 | 15.0334 | -2.12E-04 | 7994.7 | 36140.000 | -8.773 |
| .840 | 3.94E-04 | -3.8130 | 13.1488 | -2.43E-04 | 7584.1 | 36140.000 | -9.175 |
| 1.050 | 3.41E-04 | -1.2066 | 11.1938 | -2.58E-04 | 7228.2 | 36140.000 | -9.443 |
| 1.260 | 2.86E-04 | .9848 | 9.1977 | -2.59E-04 | 7198.0 | 36140.000 | -9.568 |
| 1.470 | 2.32E-04 | 2.7531 | 7.1907 | -2.48E-04 | 7439.4 | 36140.000 | -9.546 |
| 1.680 | 1.82E-04 | 4.0975 | 5.2045 | -2.28E-04 | 7623.0 | 36140.000 | -9.370 |
| 1.890 | 1.36E-04 | 5.0242 | 3.2720 | -2.01E-04 | 7749.5 | 36140.000 | -9.035 |
| 2.100 | 9.73E-05 | 5.5470 | 1.4272 | -1.71E-04 | 7820.9 | 36140.000 | -8.535 |
| 2.310 | 6.48E-05 | 5.6874 | -.2945 | -1.38E-04 | 7840.0 | 36140.000 | -7.862 |
| 2.520 | 3.93E-05 | 5.4749 | -1.8551 | -1.06E-04 | 7811.0 | 36140.000 | -7.001 |
| 2.730 | 2.05E-05 | 4.9477 | -3.2110 | -7.53E-05 | 7739.0 | 36140.000 | -5.913 |
| 2.940 | 7.73E-06 | 4.1544 | -4.3014 | -4.88E-05 | 7630.7 | 36140.000 | -4.471 |
| 3.150 | 1.07E-08 | 3.1593 | -4.8212 | -2.76E-05 | 7494.9 | 36140.000 | -.479385 |
| 3.360 | -3.85E-06 | 2.1397 | -4.4661 | -1.22E-05 | 7355.6 | 36140.000 | 3.862 |
| 3.570 | -5.10E-06 | 1.2881 | -3.5982 | -2.21E-06 | 7239.4 | 36140.000 | 4.404 |
| 3.780 | -4.78E-06 | .6293 | -2.6832 | 3.36E-06 | 7149.4 | 36140.000 | 4.310 |
| 3.990 | -3.69E-06 | .1599 | -1.8154 | 5.66E-06 | 7085.3 | 36140.000 | 3.955 |
| 4.200 | -2.40E-06 | -.1352 | -1.0398 | 5.73E-06 | 7082.0 | 36140.000 | 3.431 |
| 4.410 | -1.28E-06 | -.2789 | -.3870 | 4.53E-06 | 7101.6 | 36140.000 | 2.787 |
| 4.620 | -4.99E-07 | -.2995 | .1202 | 2.85E-06 | 7104.4 | 36140.000 | 2.044 |
| 4.830 | -8.46E-08 | -.2295 | .4558 | 1.31E-06 | 7094.8 | 36140.000 | 1.152 |
| 5.040 | 5.01E-08 | -.1085 | .4794 | 3.26E-07 | 7078.3 | 36140.000 | -.927970 |
| 5.250 | 5.25E-08 | -2.83E-02 | .2814 | -7.10E-08 | 7067.4 | 36140.000 | -.957485 |
| 5.460 | 2.03E-08 | 9.71E-03 | .1069 | -1.25E-07 | 7064.8 | 36140.000 | -.704314 |
| 5.670 | 5.60E-12 | 1.66E-02 | -2.31E-02 | -4.84E-08 | 7065.8 | 36140.000 | -.534327 |
| 5.880 | -1.56E-12 | 7.14E-06 | -3.96E-02 | -1.33E-11 | 7063.5 | 36140.000 | .377189 |
| 6.090 | -1.50E-17 | -1.27E-06 | -1.70E-05 | 3.70E-12 | 7063.5 | 36140.000 | 2.20E-04 |
| 6.300 | 1.89E-18 | -1.54E-11 | 3.03E-06 | 3.56E-17 | 7063.5 | 36140.000 | -2.89E-05 |
| 6.510 | 2.64E-23 | 1.55E-12 | 3.66E-11 | -4.51E-18 | 7063.5 | 36140.000 | -4.19E-10 |
| 6.720 | -2.14E-24 | 2.52E-17 | -3.70E-12 | -6.30E-23 | 7063.5 | 36140.000 | 3.52E-11 |
| 6.930 | 0.000 | -1.76E-18 | -6.00E-17 | 5.10E-24 | 7063.5 | 36140.000 | 6.51E-16 |
| 7.140 | 0.000 | -3.58E-23 | 4.18E-18 | 0.000 | 7063.5 | 36140.000 | -3.98E-17 |
| 7.350 | 0.000 | 1.95E-24 | 8.51E-23 | 0.000 | 7063.5 | 36140.000 | -8.99E-22 |
| 7.560 | 0.000 | 0.0 | -4.64E-24 | 0.000 | 7063.5 | 36140.000 | 4.42E-23 |
| 7.770 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 7.980 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 8.190 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 8.400 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 8.610 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 8.820 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 9.030 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 9.240 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 9.450 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 9.660 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 9.870 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 10.080 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 10.290 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 10.500 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 10.710 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 10.920 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |

| | | | | | | | |
|--------|-------|-----|-----|-------|--------|-----------|-------|
| 11.130 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 11.340 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 11.550 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 11.760 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 11.970 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 12.180 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 12.390 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 12.600 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 12.810 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 13.020 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 13.230 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 13.440 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 13.650 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 13.860 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 14.070 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 14.280 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 14.490 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 14.700 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 14.910 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 15.120 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 15.330 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 15.540 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 15.750 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 15.960 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 16.170 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 16.380 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 16.590 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 16.800 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 17.010 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 17.220 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 17.430 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 17.640 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 17.850 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 18.060 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 18.270 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 18.480 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 18.690 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 18.900 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 19.110 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 19.320 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 19.530 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 19.740 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 19.950 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 20.160 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 20.370 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 20.580 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 20.790 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |
| 21.000 | 0.000 | 0.0 | 0.0 | 0.000 | 7063.5 | 36140.000 | 0.000 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

| | | | |
|----------------------------------|---|--------------|-------|
| Pile-head deflection | = | .00052244 | m |
| Computed slope at pile head | = | -5.16287E-19 | |
| Maximum bending moment | = | -18.004 | kN- m |
| Maximum shear force | = | 20.000 | kN |
| Depth of maximum bending moment | = | 0.000 | m |
| Depth of maximum shear force | = | 0.000 | m |
| Number of iterations | = | 10 | |
| Number of zero deflection points | = | 39 | |

Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m

M = pile-head moment, kN- m

V = pile-head shear force, kN

S = pile-head slope, radians

R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|----------------------------|----------------------------|---------------------|------------------------------|----------------------------|------------------------|
| 2 | V= 20.000 | S= 0.000 | 890.0000 | 5.224E-04 | -18.0043 | 20.0000 |
| 2 | V= 40.000 | S= 0.000 | 890.0000 | .001897 | -44.4270 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .004016 | -75.2557 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .006833 | -109.3218 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .010330 | -146.0260 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .014498 | -185.0004 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .019306 | -226.0812 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .024733 | -269.0181 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .031494 | -318.1544 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .041557 | -381.1517 | 200.0000 |

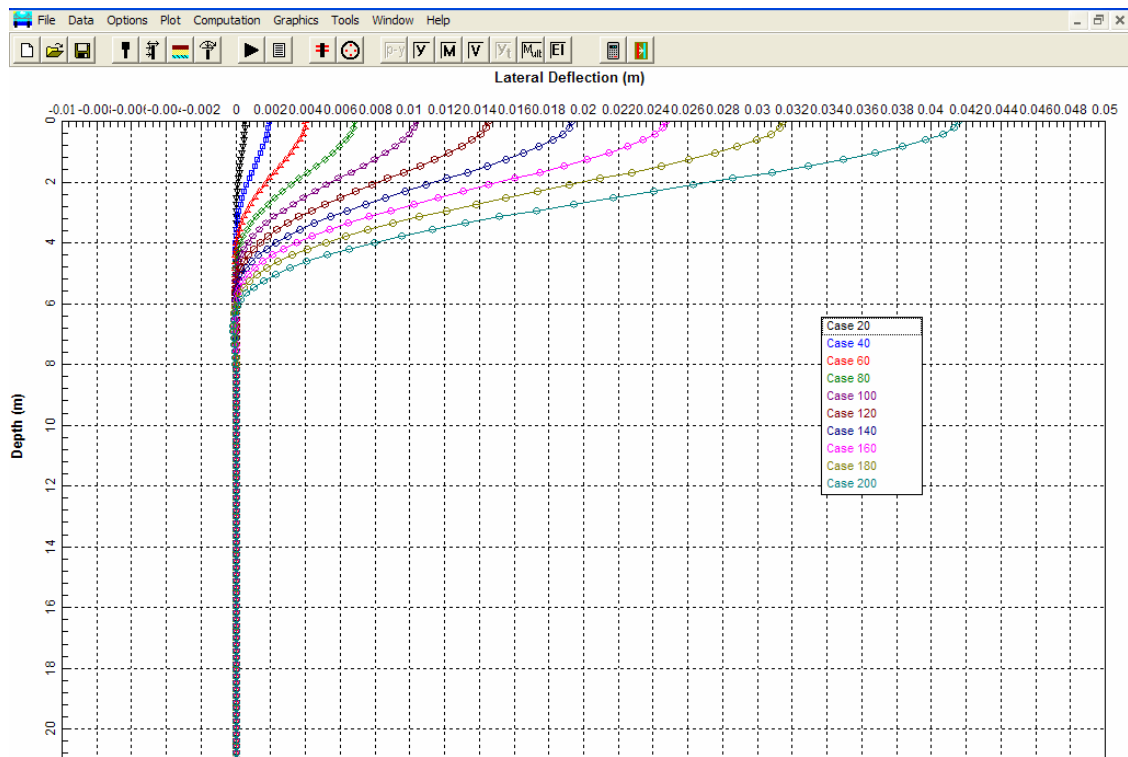


Figure F.39: South Abutment – Plot of Deflection *versus* Depth as a Function of Lateral Load

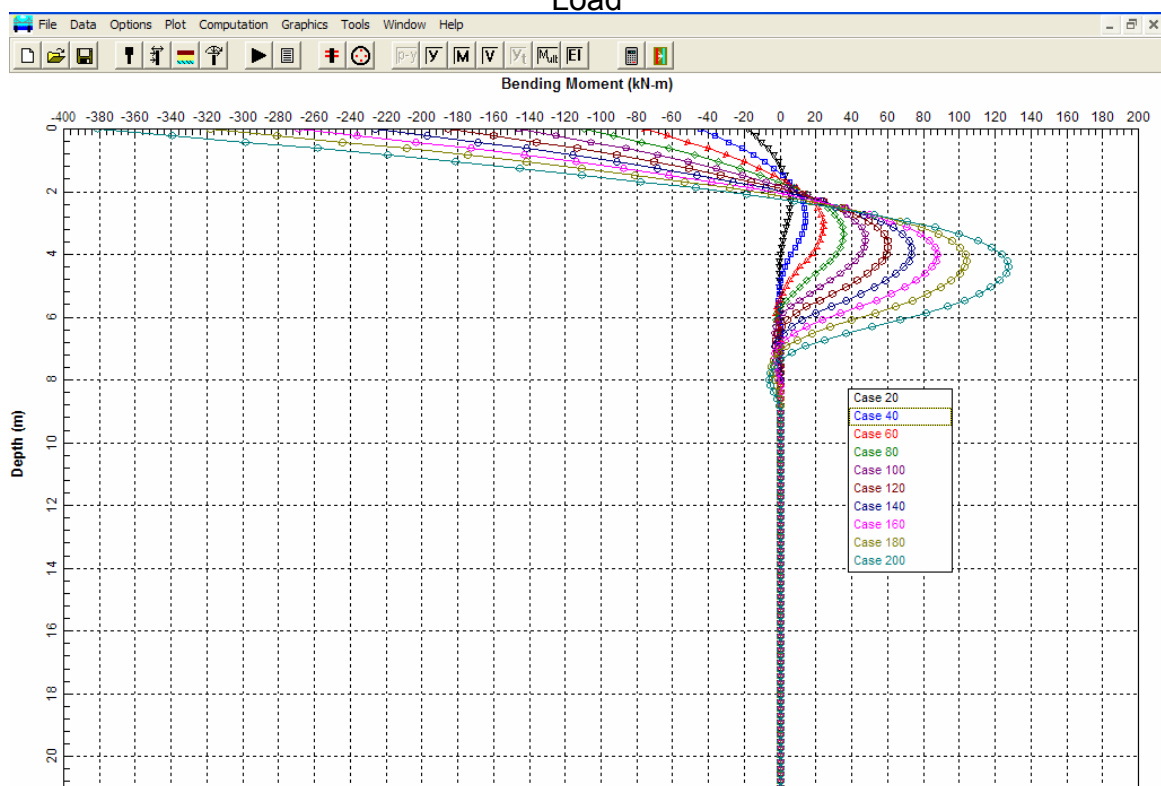


Figure F.40: South Abutment – Plot of Moment *versus* Depth as a Function of Lateral Load

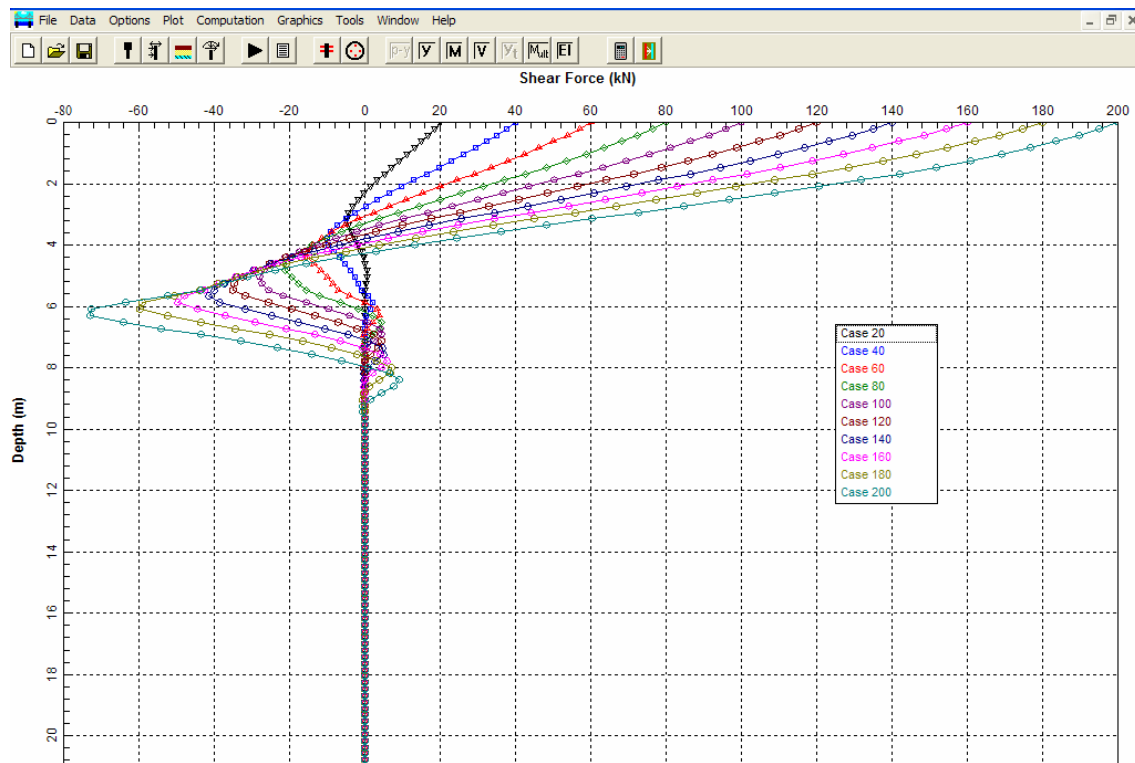


Figure F.41: South Abutment – Plot of Shear *versus* Depth as a Function of Lateral Load

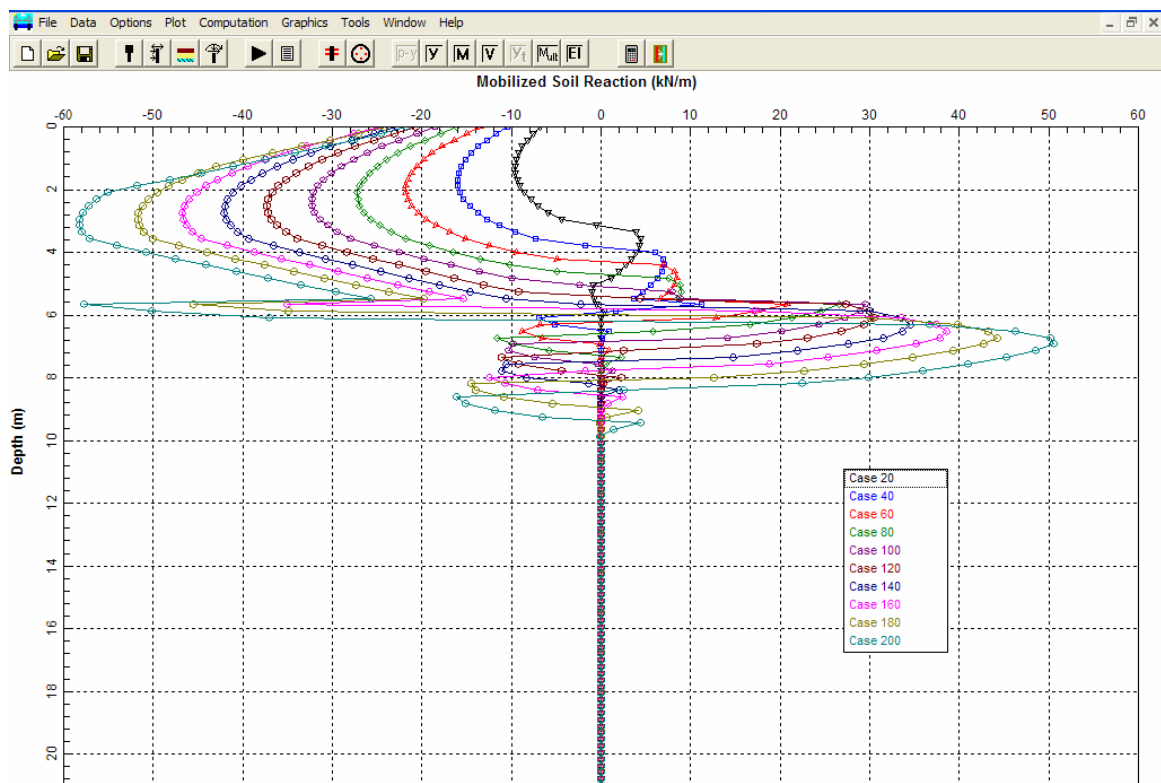


Figure F.42: South Abutment – Plot of Soil Reaction *versus* Depth as a Function of Lateral Load

F.5 GROUP UPLIFT LOAD CALCULATIONS

The maximum uplift load on a pile group is estimated to be 1,800 kN with a maximum uplift load per pile of 100 kN.

F.5.1 North Abutment - AASHTO Code (2002)

For the pile group at the North Abutment and the soil profile interpreted from Soil Boring S-1 as shown in Figure F.3. Perform an uplift capacity calculations based on the AASHTO Code for service load design. Use the method outlined in Section 9.8.3.1.

According to AASHTO specifications (2002), the uplift capacity of a pile group should be limited to the lesser value determined from any of the following.

1. The design uplift capacity of a single pile times the number of piles in a pile group. The design uplift capacity of a single pile is specified as $\frac{1}{3}$ the ultimate shaft resistance calculated in a static analysis method or $\frac{1}{2}$ the failure load determined from an uplift load test.

The ultimate shaft resistance for a single pile as calculated from a static analysis using the Nordlund method is 898 kN. The design uplift capacity is:

$$= \frac{1}{3} \text{ (ultimate shaft resistance)}$$

$$= \frac{1}{3} \text{ (898 kN)}$$

$$= 299 \text{ kN}$$

The design group uplift capacity based on criterion 1 is:

$$= \text{(uplift capacity of a single pile) (number of piles in a group)}$$

$$= 299 \text{ kN (24)}$$

$$= 7,176 \text{ kN}$$

North Abutment - AASHTO Code (2002) (continued)

2. Two-thirds ($\frac{2}{3}$) of the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the piles.

$$\text{Buoyant unit weight of concrete} = 24 \text{ kN/m}^3 - 9.8 \text{ kN/m}^3 = 14.2 \text{ kN/m}^3$$

Effective weight of pile group (24 piles):

$$\begin{aligned} &= 24 (0.356 \text{ m}) (0.356 \text{ m}) (11.5 \text{ m}) (24 \text{ kN/m}^3 - 9.8 \text{ kN/m}^3) \\ &= 497 \text{ kN} \end{aligned}$$

Effective weight of soil:

$$\begin{aligned} &= (\text{Layer 1} + \text{Layer 2} + \text{Layer 3}) (\text{Gross Area of Pile Group} - \text{Pile Area}) \\ &= [16.5 \text{ kN/m}^3 (1.0 \text{ m}) + 6.7 \text{ kN/m}^3 (3.0 \text{ m}) + 7.8 \text{ kN/m}^3 (7.0 \text{ m}) + \\ &\quad 9.8 \text{ kN/m}^3 (0.5 \text{ m})] \{ (3.36 \text{ m}) (10.86 \text{ m}) - 24 (0.356 \text{ m}) (0.356 \text{ m}) \} \\ &= [16.5 \text{ kN/m}^2 + 20.1 \text{ kN/m}^2 + 54.6 \text{ kN/m}^2 + 4.9 \text{ kN/m}^2] \{ 36.49 \text{ m}^2 - 3.04 \text{ m}^2 \} \\ &= [96.1 \text{ kN/m}^2] \{ 33.45 \text{ m}^2 \} = 3,215 \text{ kN} \end{aligned}$$

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the pile is equal to 497 kN plus 3,215 kN, or 3,712 kN.

The design group uplift capacity based on criterion 2 is:

$$\begin{aligned} &= \frac{2}{3} (3,712 \text{ kN}) \\ &= 2,475 \text{ kN} \end{aligned}$$

North Abutment - AASHTO Code (2002) (continued)

3. One-half ($\frac{1}{2}$) the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded pile length plus $\frac{1}{2}$ the total soil shear resistance on the peripheral surface of the pile group.

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group, as calculated in criteria 2 above, is equal to 3,712 kN.

The total soil shear resistance on the peripheral surface of the pile group is calculated from the following equation.

$$\text{Unit shear resistance of cohesionless soil} = p_d \tan \phi$$

Where:

p_d is the effective overburden stress at depth d , and

ϕ is the friction angle of the soil.

Note: $p_d \tan \phi$ is used for a soil-to-soil failure.

As calculated in Section F.2.1.2:

$$\text{Layer 1a: } p_{d1a} = 57.8 \text{ kPa} \quad (\text{midpoint of layer 1a - 1 m thick})$$

$$\phi_{1a} = 29^\circ$$

$$\text{Layer 1b: } p_{d1b} = 76.1 \text{ kPa} \quad (\text{midpoint of layer 1b - 3 m thick})$$

$$\phi_{1b} = 29^\circ$$

$$\text{Layer 2: } p_{d2} = 113.4 \text{ kPa} \quad (\text{midpoint of layer 2 - 7 m thick})$$

$$\phi_2 = 31^\circ$$

North Abutment - AASHTO Code (2002) (continued)

$$\text{Layer 3: } p_{d3} = 143.1 \text{ kPa (midpoint of layer 3 - 0.5 m thick)}$$

$$\phi_3 = 36^\circ$$

Thus,

$$\begin{aligned} \text{Layer 1a: } R_{s1a} &= 57.8 \text{ kPa } (\tan 29^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (1 \text{ m}) (2) \\ &= 911 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 1b: } R_{s1a} &= 76.1 \text{ kPa } (\tan 29^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (3 \text{ m}) (2) \\ &= 3,599 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 113.4 \text{ kPa } (\tan 31^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (7 \text{ m}) (2) \\ &= 13,565 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 3: } R_{s3} &= 143.1 \text{ kPa } (\tan 36^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (0.5 \text{ m}) (2) \\ &= 1,478 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Total soil shear resistance} &= R_{s1a} + R_{s1b} + R_{s2} + R_{s3} \\ &= 911 \text{ kN} + 3,599 \text{ kN} + 13,565 \text{ kN} + 1,478 \text{ kN} \\ &= 19,553 \text{ kN} \end{aligned}$$

The design group uplift capacity based on criterion 3 is:

$$\begin{aligned} &= \frac{1}{2} (3,712 \text{ kN}) + \frac{1}{2} (19,553 \text{ kN}) \\ &= 1,856 \text{ kN} + 9,777 \text{ kN} = 11,633 \text{ kN} \end{aligned}$$

According to AASHTO specifications (2002), the uplift capacity of this pile group is limited to 2,475 kN. This is greater than the maximum uplift load in the pile group of 1,800 kN.

F.5.2 Pier 2 - AASHTO Code (2002)

For the pile group at Pier 2 and the soil profile interpreted from Soil Boring S-2 as shown in Figure F.5. Perform an uplift capacity calculations based on the AASHTO Code for service load design. Use the method outlined in Section 9.8.3.1.

According to AASHTO specifications (2002), the uplift capacity of a pile group should be limited to the lesser value determined from any of the following.

1. The design uplift capacity of a single pile times the number of piles in a pile group. The design uplift capacity of a single pile is specified as $\frac{1}{3}$ the ultimate shaft resistance calculated in a static analysis method or $\frac{1}{2}$ the failure load determined from an uplift load test.

The ultimate shaft resistance for a single pile as calculated from a static analysis using the Nordlund method is 984 kN. The design uplift capacity is:

$$= \frac{1}{3} \text{ (ultimate shaft resistance)}$$

$$= \frac{1}{3} \text{ (984 kN)}$$

$$= 328 \text{ kN}$$

The design group uplift capacity based on criterion 1 is:

$$= \text{(uplift capacity of a single pile) (number of piles in a group)}$$

$$= 328 \text{ kN (24)}$$

$$= 7,872 \text{ kN}$$

Pier 2 - AASHTO Code (2002)(continued)

2. Two-thirds ($\frac{2}{3}$) of the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the piles.

Effective weight of pile group (24 piles):

$$\begin{aligned} &= 24 (0.356 \text{ m}) (0.356 \text{ m}) (10.0 \text{ m}) (24 \text{ kN/m}^3 - 9.8 \text{ kN/m}^3) \\ &= 432 \text{ kN} \end{aligned}$$

Effective weight of soil:

$$\begin{aligned} &= (\text{Layer 1} + \text{Layer 2}) (\text{Gross Area of Pile Group} - \text{Pile Area}) \\ &= [11.4 \text{ kN/m}^3 (4.0 \text{ m}) + 9.8 \text{ kN/m}^3 (6.0 \text{ m})] \\ &\quad \{ (3.36 \text{ m}) (10.86 \text{ m}) - 24 (0.356 \text{ m}) (0.356 \text{ m}) \} \\ &= [45.6 \text{ kN/m}^2 + 58.8 \text{ kN/m}^2] \{ 36.49 \text{ m}^2 - 3.04 \text{ m}^2 \} \\ &= [104.4 \text{ kN/m}^2] \{ 33.45 \text{ m}^2 \} \\ &= 3,492 \text{ kN} \end{aligned}$$

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the pile is equal to 432 kN plus 3,492 kN, or 3,924 kN.

The design group uplift capacity based on criterion 2 is:

$$\begin{aligned} &= \frac{2}{3} (3,924 \text{ kN}) \\ &= 2,616 \text{ kN} \end{aligned}$$

Pier 2 - AASHTO Code (2002)(continued)

3. One-half ($\frac{1}{2}$) the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded pile length plus $\frac{1}{2}$ the total soil shear resistance on the peripheral surface of the pile group.

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group, as calculated in criteria 2 above, is equal to 3,924 kN.

The total soil shear resistance on the peripheral surface of the pile group is calculated from the following equation.

$$\text{Unit shear resistance of cohesionless soil} = p_d \tan \phi$$

Where:

p_d is the effective overburden stress at depth d , and

ϕ is the friction angle of the soil.

Note: $p_d \tan \phi$ is used for a soil-to-soil failure.

As calculated in Section F.2.2.2:

$$\text{Layer 1: } p_{d1} = 48.3 \text{ kPa} \quad (\text{midpoint of layer 1 - 4 m thick})$$

$$\phi_1 = 36^\circ$$

$$\text{Layer 2: } p_{d2} = 100.5 \text{ kPa} \quad (\text{midpoint of layer 2 - 6 m thick})$$

$$\phi_2 = 35^\circ$$

Pier 2 - AASHTO Code (2002)(continued)

Thus,

$$\begin{aligned}\text{Layer 1: } R_{s1} &= 48.3 \text{ kPa } (\tan 36^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (4 \text{ m}) (2) \\ &= 3,992 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Layer 2: } R_{s2} &= 100.5 \text{ kPa } (\tan 35^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (6 \text{ m}) (2) \\ &= 12,008 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Total soil shear resistance} &= R_{s1} + R_{s2} \\ &= 3,992 \text{ kN} + 12,008 \text{ kN} \\ &= 16,000 \text{ kN}\end{aligned}$$

The design group uplift capacity based on criterion 3 is:

$$\begin{aligned}&= \frac{1}{2} (3,924 \text{ kN}) + \frac{1}{2} (16,000 \text{ kN}) \\ &= 9,962 \text{ kN}\end{aligned}$$

According to AASHTO specifications (2002), the uplift capacity of this pile group is limited to 2,616 kN. This is greater than the maximum uplift load in the pile group of 1,800 kN.

F.5.3 Pier 3 - AASHTO Code (2002)

For the pile group at Pier 3 and the soil profile interpreted from Soil Boring S-3 as shown in Figure F.9. Perform an uplift capacity calculations based on the AASHTO Code for service load design. Use the method outlined in Section 9.8.3.1.

According to AASHTO specifications (2002), the uplift capacity of a pile group should be limited to the lesser value determined from any of the following.

1. The design uplift capacity of a single pile times the number of piles in a pile group. The design uplift capacity of a single pile is specified as $\frac{1}{3}$ the ultimate shaft resistance calculated in a static analysis method or $\frac{1}{2}$ the failure load determined from an uplift load test.

The ultimate shaft resistance for a single pile as calculated from a static analysis using the Nordlund method and α -Method is 1,171 kN. The design uplift capacity is:

$$= \frac{1}{3} \text{ (ultimate shaft resistance)}$$

$$= \frac{1}{3} (1,171 \text{ kN})$$

$$= 390 \text{ kN}$$

The design group uplift capacity based on criterion 1 is:

$$= \text{(uplift capacity of a single pile)} \text{ (number of piles in a group)}$$

$$= 390 \text{ kN (24)}$$

$$= 9,360 \text{ kN}$$

Pier 3 - AASHTO Code (2002)(continued)

2. Two-thirds ($\frac{2}{3}$) of the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the piles.

Effective weight of pile group (24 piles):

$$\begin{aligned} &= 24 (0.356 \text{ m}) (0.356 \text{ m}) (13.0 \text{ m}) (24 \text{ kN/m}^3 - 9.8 \text{ kN/m}^3) \\ &= 562 \text{ kN} \end{aligned}$$

Effective weight of soil:

$$\begin{aligned} &= (\text{Layer 1} + \text{Layer 2} + \text{Layer 3}) (\text{Gross Area of Pile Group} - \text{Pile Area}) \\ &= [10.6 \text{ kN/m}^3 (1.0 \text{ m}) + 9.8 \text{ kN/m}^3 (3.0 \text{ m}) + 10.4 \text{ kN/m}^3 (9.0 \text{ m})] \\ &\quad \{ (3.36 \text{ m}) (10.86 \text{ m}) - 24 (0.356 \text{ m}) (0.356 \text{ m}) \} \\ &= [10.6 \text{ kN/m}^2 + 29.4 \text{ kN/m}^2 + 93.6 \text{ kN/m}^2] \{ 36.49 \text{ m}^2 - 3.04 \text{ m}^2 \} \\ &= [133.6 \text{ kN/m}^2] \{ 33.45 \text{ m}^2 \} \\ &= 4,469 \text{ kN} \end{aligned}$$

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the pile is equal to 562 kN plus 4,469 kN, or 5,031 kN.

The design group uplift capacity based on criterion 2 is:

$$\begin{aligned} &= \frac{2}{3} (5,031 \text{ kN}) \\ &= 3,354 \text{ kN} \end{aligned}$$

Pier 3 - AASHTO Code (2002)(continued)

- 3 One-half ($\frac{1}{2}$) the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded pile length plus $\frac{1}{2}$ the total soil shear resistance on the peripheral surface of the pile group.

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group, as calculated in criteria 2 above, is equal to 5,031 kN.

The total soil shear resistance on the peripheral surface of the pile group is calculated from the following equation.

$$\text{Unit shear resistance of cohesionless soil} = p_d \tan \phi$$

$$\text{Unit shear resistance of cohesive soil} = c_u$$

Where:

p_d is the effective overburden stress at depth d ,

ϕ is the friction angle of the soil, and

c_u is the average undrained shear strength of the soil.

Note: $p_d \tan \phi$ is used for a soil-to-soil failure.

As calculated in Section F.2.3.1:

$$\text{Layer 1: } p_{d1} = 15.5 \text{ kPa} \quad (\text{midpoint of layer 1 - 1 m thick})$$

$$\phi_1 = 36^\circ$$

$$\text{Layer 2: } c_{u2} = 106 \text{ kPa} \quad (\text{layer 2 - 3 m thick})$$

$$\text{Layer 3: } c_{u3} = 155 \text{ kPa} \quad (\text{layer 3 - 9 m thick})$$

Pier 3 - AASHTO Code (2002)(continued)

Thus,

$$\begin{aligned}\text{Layer 1: } R_{s1} &= 15.5 \text{ kPa } (\tan 36^\circ) (3.36 \text{ m} + 10.86 \text{ m}) (1 \text{ m}) (2) \\ &= 320 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Layer 2: } R_{s2} &= 106 \text{ kPa } (3.36 \text{ m}) (10.86 \text{ m}) (3 \text{ m}) (2) \\ &= 9,044 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Layer 3: } R_{s3} &= 155 \text{ kPa } (3.36 \text{ m}) (10.86 \text{ m}) (9 \text{ m}) (2) \\ &= 39,674 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Total soil shear resistance} &= R_{s1} + R_{s2} + R_{s3} \\ &= 320 \text{ kN} + 9,044 \text{ kN} + 39,674 \text{ kN} \\ &= 49,038 \text{ kN}\end{aligned}$$

The design group uplift capacity based on criterion 3 is:

$$\begin{aligned}&= \frac{1}{2} (5,031 \text{ kN}) + \frac{1}{2} (49,038 \text{ kN}) \\ &= 27,035 \text{ kN}\end{aligned}$$

According to AASHTO specifications (2002), the uplift capacity of this pile group is limited to 3,354 kN. This is greater than the maximum uplift load in the pile group of 1,800 kN.

F.5.4 South Abutment - AASHTO Code (2002)

For the pile group at the South Abutment and the soil profile interpreted from Soil Boring S-4 as shown in Figure F.11. Perform an uplift capacity calculations based on the AASHTO Code for service load design. Use the method outlined in Section 9.8.3.1.

According to AASHTO specifications (2002), the uplift capacity of a pile group should be limited to the lesser value determined from any of the following.

1. The design uplift capacity of a single pile times the number of piles in a pile group. The design uplift capacity of a single pile is specified as $\frac{1}{3}$ the ultimate shaft resistance calculated in a static analysis method or $\frac{1}{2}$ the failure load determined from an uplift load test.

The ultimate shaft resistance for a single pile as calculated from a static analysis using the α -Method is 1,648 kN. The design uplift capacity is:

$$= \frac{1}{3} \text{ (ultimate shaft resistance)}$$

$$= \frac{1}{3} (1,648 \text{ kN})$$

$$= 549 \text{ kN}$$

The design group uplift capacity based on criterion 1 is:

$$= \text{(uplift capacity of a single pile)} \text{ (number of piles in a group)}$$

$$= 549 \text{ kN} (24)$$

$$= 13,176 \text{ kN}$$

South Abutment - AASHTO Code (2002) (continued)

2. Two-thirds ($\frac{2}{3}$) of the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the piles.

Effective weight of pile group (24 piles):

$$\begin{aligned} &= 24 (0.356 \text{ m}) (0.356 \text{ m}) (17.5 \text{ m}) (24 \text{ kN/m}^3 - 9.8 \text{ kN/m}^3) \\ &= 756 \text{ kN} \end{aligned}$$

Effective weight of soil:

$$\begin{aligned} &= (\text{Layer 1} + \text{Layer 2} + \text{Layer 3}) (\text{Gross Area of Pile Group} - \text{Pile Area}) \\ &= [9.2 \text{ kN/m}^3 (5.5 \text{ m}) + 9.7 \text{ kN/m}^3 (9.5 \text{ m}) + 10.5 \text{ kN/m}^3 (2.5 \text{ m})] \\ &\quad \{ (3.36 \text{ m}) (10.86 \text{ m}) - 24 (0.356 \text{ m}) (0.356 \text{ m}) \} \\ &= [50.6 \text{ kN/m}^2 + 92.2 \text{ kN/m}^2 + 26.3 \text{ kN/m}^2] \{ 36.49 \text{ m}^2 - 3.04 \text{ m}^2 \} \\ &= [169.1 \text{ kN/m}^2] \{ 33.45 \text{ m}^2 \} \\ &= 5,656 \text{ kN} \end{aligned}$$

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded length of the pile is equal to 756 kN plus 5,656 kN, or 6,412 kN.

The design group uplift capacity based on criterion 2 is:

$$\begin{aligned} &= \frac{2}{3} (6,412 \text{ kN}) \\ &= 4,275 \text{ kN} \end{aligned}$$

South Abutment - AASHTO Code (2002) (continued)

3. One-half ($\frac{1}{2}$) the effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group and the embedded pile length plus $\frac{1}{2}$ the total soil shear resistance on the peripheral surface of the pile group.

The effective weight of the pile group and the soil contained within a block defined by the perimeter of the pile group, as calculated in criteria 2 above, is equal to 6,412 kN.

The total soil shear resistance on the peripheral surface of the pile group is calculated from the following equation.

$$\text{Unit shear resistance of cohesive soil} = c_u$$

Where: c_u is the average undrained shear strength of the soil.

As calculated in Section F.2.4.1:

$$\text{Layer 1: } c_{u1} = 33 \text{ kPa} \quad (\text{layer 1 - 5.5 m thick})$$

$$\text{Layer 2: } c_{u2} = 93 \text{ kPa} \quad (\text{layer 2 - 9.5 m thick})$$

$$\text{Layer 3: } c_{u3} = 157 \text{ kPa} \quad (\text{layer 3 - 2.5 m thick})$$

Thus,

$$\begin{aligned} \text{Layer 1: } R_{s1} &= 33 \text{ kPa} (3.36 \text{ m} + 10.86 \text{ m}) (5.5 \text{ m}) (2) \\ &= 5,162 \text{ kN} \end{aligned}$$

$$\begin{aligned} \text{Layer 2: } R_{s2} &= 93 \text{ kPa} (3.36 \text{ m} + 10.86 \text{ m}) (9.5 \text{ m}) (2) \\ &= 25,127 \text{ kN} \end{aligned}$$

South Abutment - AASHTO Code (2002) (continued)

$$\begin{aligned}\text{Layer 3: } R_{s3} &= 157 \text{ kPa } (3.36 \text{ m} + 10.86 \text{ m}) (2.5 \text{ m}) (2) \\ &= 11,163 \text{ kN}\end{aligned}$$

$$\begin{aligned}\text{Total soil shear resistance} &= R_{s1} + R_{s2} + R_{s3} \\ &= 5,162 \text{ kN} + 25,127 \text{ kN} + 11,163 \text{ kN} \\ &= 41,452 \text{ kN}\end{aligned}$$

The design group uplift capacity based on criterion 3 is:

$$\begin{aligned}&= \frac{1}{2} (6,412 \text{ kN}) + \frac{1}{2} (41,452 \text{ kN}) \\ &= 23,932 \text{ kN}\end{aligned}$$

According to AASHTO specifications (2002), the uplift capacity of this pile group is limited to 4,275 kN. This is greater than the maximum uplift load in the pile group of 1,800 kN.

F.6 NEGATIVE SHAFT RESISTANCE CALCULATIONS

F.6.1 South Abutment – α -Method

Piles at the South Abutment will be subjected to negative shaft resistance due to soil settlement following the placement of 10 m of approach embankment material behind the abutment after pile installation. This settlement needs to be estimated prior to determining the location of the negative and positive shaft resistances along the pile. The α -method is used to estimate both the positive and negative shaft resistance components. The step-by-step procedure for the analysis of downdrag loading is outlined in Section 9.9.1.1a. The soil profile for the South Abutment interpreted from Soil Boring S-4 is presented in Figure F.11.

STEP 1 Establish the simplified soil profile and soil properties for computing settlement.

Schematic of the South Abutment showing the approach embankment backfill material and the soil profile is presented in Figure F.43.

STEP 2 Determine the overburden pressure increase, Δp , due to the approach embankment fill placed behind the abutment.

The overburden pressure increase, Δp , is calculated using the pressure coefficient, K_f , determined from the pressure distribution chart presented in Figure F.44. The pressure distribution chart calculates the pressure coefficient, K_f , at various depths below the bottom of the fill (xb_f), and also at various distances from the centerline of the fill. The depth below the bottom of the fill is given as a multiple of “ b_f ”, where b_f is the distance from the centerline of the fill to the midpoint of the fill slope, as shown in Figure F.44. Given:

The top width of the fill = 12 m

Side slope of the fill = 2H:1V

The height of the fill, h_f = 10 m

$$\text{Thus, } b_f = \left(\frac{12 \text{ m}}{2} \right) + \left(\frac{10 \text{ m}}{2} \right) 2 = 16 \text{ m}$$

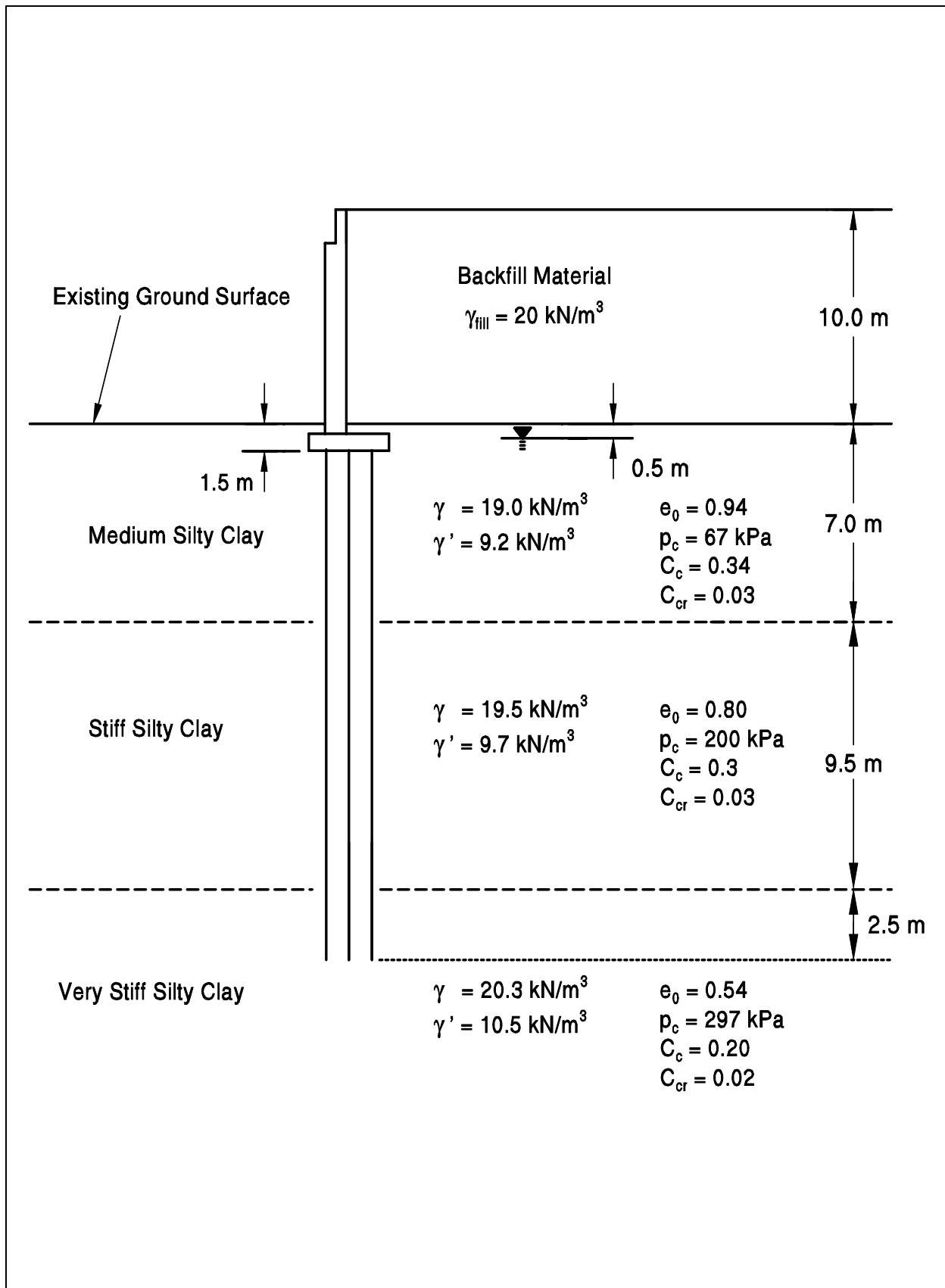


Figure F.43: Schematic of South Abutment Showing the Backfill Material and Soil Profile

The diagram illustrates the flow of water through a rectangular channel with a sluice gate. The top part shows the flow from a reservoir with water level Q above the gate, through the gate opening of height b_f , with flow area A . The bottom part shows the channel bed profile with a sloped section and a vertical section, with water level h_f above the bed and flow area Q and b_f .

Chart Legend:
Pressure Under Centerline
Pressure Under Midpoint of
Side Slope

$$p = K_f \gamma_f h_f$$

Where: h_f = Height of the Fill
 γ = Unit Weight of the Fill Material

PRESSURE COEFFICIENTS BENEATH THE END OF A FILL

b_f = Distance from Mid-Point of Slope to Q_L

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STEP 2 (continued)

For settlement calculations, the overburden pressure increase, Δp , at various depths beneath the centerline of the fill needs to be calculated. The overburden pressure increase is equal to the pressure coefficient, K_f , multiplied by the unit weight of the fill, γ_f , and the height of the fill, h_f . The unit weight of the fill, γ_f , is 20 kN/m^3 . The height of the fill, h_f , is 10 meters. Table F-5 shows the overburden pressure increase, Δp , at various depths beneath the bottom of the fill. The effective overburden pressure diagram in Figure F.45 shows the effective overburden pressure, p_o , before the backfill is placed, and the effective pressure, $p_o + \Delta p$, after the backfill placement.

For example at depth 3.2 meters below existing ground, the overburden pressure increase, Δp , is equal to:

$$\Delta p = 0.5 (20 \text{ kN/m}^3) (10 \text{ m}) = 100 \text{ kPa}$$

| Table F-5 Overburden Pressure Increase Computations - South Abutment | | |
|--|-------------------------------|--|
| Depth Below Existing Ground (m) | Pressure Coefficient K_f | $\Delta p = K_f \gamma_f h_f$ (kPa) |
| Existing Ground Surface = 0 | 0.50 | 100.0 |
| $0.2b_f = 3.2 \text{ m}$ | 0.50 | 100.0 |
| $0.4b_f = 6.4 \text{ m}$ | 0.50 | 100.0 |
| $0.6b_f = 9.6 \text{ m}$ | 0.50 | 100.0 |
| $0.8b_f = 12.8 \text{ m}$ | 0.40 | 80.0 |
| $1.0b_f = 16.0 \text{ m}$ | 0.40 | 80.0 |
| $1.2b_f = 19.2 \text{ m}$ | 0.35 | 70.0 |
| $1.6b_f = 25.6 \text{ m}$ | 0.30 | 60.0 |

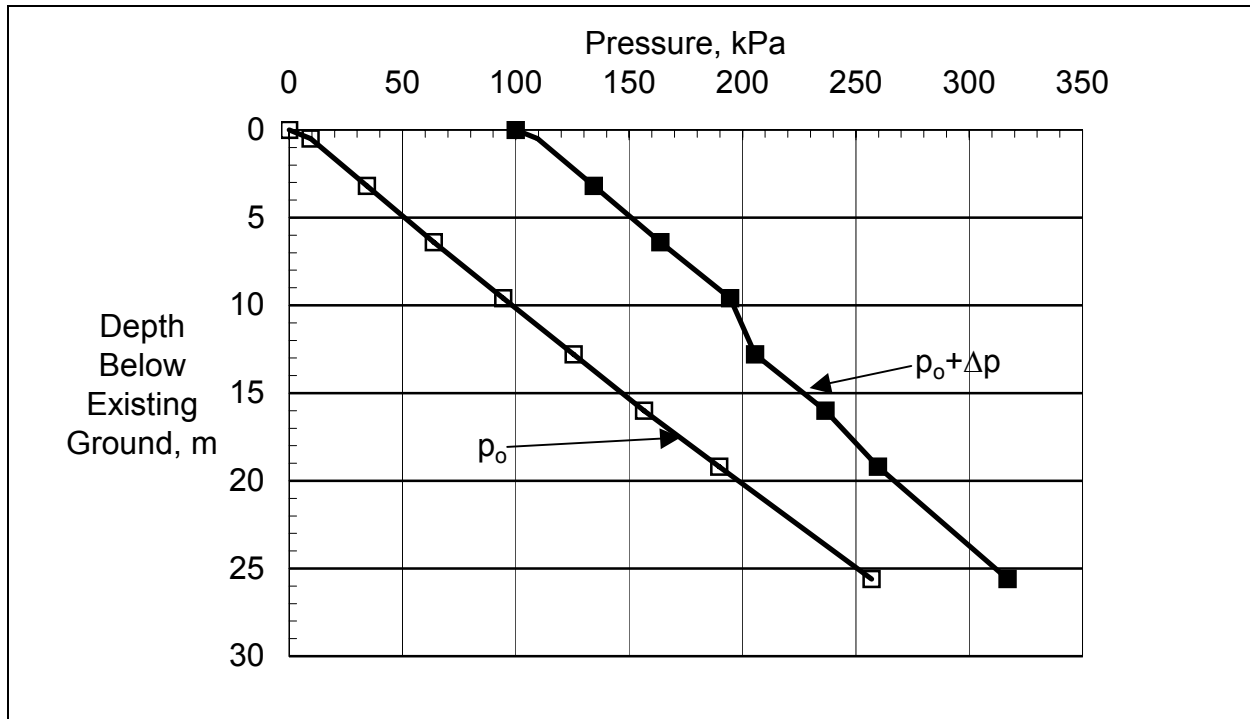


Figure F.45 Effective Overburden Diagram – Original and Original + Increase

STEP 3 Perform settlement computations for the soil layers along the embedded pile length.

- Determine consolidation test parameters for each soil layer from laboratory consolidation test results.

The laboratory consolidation test results on the undisturbed samples were plotted on the "log pressure, p versus void ratio, e " (similar to Figure 9.61). The following consolidation test parameters were obtained from the plot.

Soil Layer 1: Preconsolidation pressure, $p_c = 67$ kPa
 Initial void ratio, $e_0 = 0.94$
 Compression index, $C_c = 0.34$
 Recompression index, $C_{cr} = 0.030$

Soil Layer 2: Preconsolidation pressure, $p_c = 200$ kPa
 Initial void ratio, $e_0 = 0.80$
 Compression index, $C_c = 0.30$
 Recompression index, $C_{cr} = 0.030$

STEP 3 (continued)

Soil Layer 3: Preconsolidation pressure, $p_c = 297 \text{ kPa}$
Initial void ratio, $e_0 = 0.54$
Compression index, $C_c = 0.20$
Recompression index, $C_{cr} = 0.020$

- b. Compute settlement of each soil layer using the appropriate settlement equation provided in Section 9.8.2.3 for cohesive layers or Section 9.8.2.5 for cohesionless layers.

The following equations apply to cohesive layers (see Section 9.8.2.3):

$$s = H \left[\frac{C_{cr}}{1 + e_0} \right] \log \frac{p_o + \Delta p}{p_o} \quad \text{when } p_o + \Delta p \leq p_c$$

$$= H \left[\frac{C_{cr}}{1 + e_0} \log \frac{p_c}{p_o} \right] + H \left[\frac{C_c}{1 + e_0} \log \frac{p_o + \Delta p}{p_c} \right] \quad \text{when } p_o + \Delta p > p_c$$

The settlement of each layer is summarized in the settlement computations in Table F-6. An example of settlement calculation has been presented earlier in Section F.3.

- b. Compute the total settlement over the embedded pile length which is equal to the sum of the settlement from each soil layer.

Based on the settlement calculation table, the calculated settlement is 0.499 meters. Because the total long term settlement of the clay is very high (0.499 m), it is assumed that preloading of soil will be performed by placing additional temporary surcharge for the necessary time period prior to pile installation. It is also assumed that 90% consolidation of clay will be achieved prior to pile installation. Therefore, after installation, the piles will only be subjected to the 10% consolidation settlement left as shown in column 9 of the settlement calculation table, or a total settlement of 0.0499 meter or 49.9 mm.

Table F-6: Settlement Calculations Table - South Abutment

| 1 Soil Type | 2 Soil Layer Below Existing Ground (m) | 3 Soil Layer Thick- ness (m) | 4 Depth of Midpoint Below Existing Ground (m) | 5 Effective Overburden Pressure at Midpoint p_o (kPa) | 6 Imposed Pressure Increase at Midpoint Δp (kPa) | 7 $(p_o + \Delta p)$ (kPa) | 8 Layer Settle- ment (m) | 9 10% of Layer Settle- ment (m) | 10 Depth Below Existing Ground (m) | 11 Relative Soil Movement due to 10% Settlement (m) |
|--|--|---|---|---|--|----------------------------------|--------------------------------------|---|---|---|
| Layer 1 $p_c=67\text{kPa}$; $e_0=0.94$ $C_c=0.34$; $C_{cr}=0.030$ | | | | | | | | | 0.0 | 0.0499 |
| | 0.0 - 3.0 | 3.0 | 1.50 | 18.7 | 100.0 | 118.7 | 0.156 | 0.0156 | 3.0 | 0.0343 |
| | 3.0 - 7.0 | 4.0 | 5.00 | 50.9 | 100.0 | 150.9 | 0.255 | 0.0255 | 7.0 | 0.0088 |
| Layer 2 $p_c=200\text{kPa}$; $e_0=0.80$ $C_c=0.30$; $C_{cr}=0.030$ | 7.0 - 10.5 | 3.5 | 7.75 | 76.6 | 100.0 | 176.6 | 0.021 | 0.0021 | 10.5 | 0.0067 |
| | 10.5 - 13.5 | 3.0 | 12.00 | 117.8 | 85.0 | 202.8 | 0.015 | 0.0015 | 13.5 | 0.0052 |
| | 13.5 - 16.5 | 3.0 | 15.00 | 146.9 | 80.0 | 226.9 | 0.034 | 0.0034 | 16.5 | 0.0018 |
| Layer 3 $p_c=297\text{kPa}$; $e_0=0.54$ $C_c=0.20$; $C_{cr}=0.020$ | 16.5 - 19.5 | 3.0 | 18.00 | 177.2 | 73.8 | 251.0 | 0.006 | 0.0006 | 19.5 | 0.0012 |
| | 19.5 - 22.5 | 3.0 | 21.00 | 208.7 | 67.2 | 275.9 | 0.005 | 0.0005 | 22.5 | 0.0007 |
| | 22.5 - 25.5 | 3.0 | 24.00 | 240.2 | 62.5 | 302.7 | 0.007 | 0.0007 | 25.5 | 0.0000 |
| Total Settlement = | | | | | | | | 0.499 | 0.0499 | |

STEP 4 Determine the pile length that will experience negative shaft resistance.

Negative shaft resistance occurs due to the settlement between soil and pile. The amount of settlement between soil and pile necessary to mobilize the negative shaft resistance is about 10 mm. Therefore, negative shaft resistance will occur on the pile shaft in each soil layer or portion of a soil layer with a settlement greater than 10 mm.

Column 11 of Table F-6 presents the settlement between soil and pile due to the 10% consolidation settlement at various locations along the pile embedded length. The existing ground surface will experience a total consolidation settlement of 0.0499 meter. At a depth of 3 meters below the existing ground surface, a lesser total settlement will occur which is equal to the total settlement at the existing ground surface minus the consolidation settlement of the top 3 meter soil layer, or 0.0343 meter, as shown in column 11 of the table.

The table also shows that the settlement between soil and pile due the 10% consolidation settlement at 7 meters depth below existing ground is already less than 10 mm which is the minimum required to mobilized the negative shaft resistance. The 7 meter depth also happens to be the end of soil layer 1. Therefore, the pile segment above the 7 meter depth will be subjected to the negative shaft resistances (downdrag) from soil layer 1 while the pile segment below the 7 meter depth will provide the positive shaft resistances (or capacity) to sustain loads from the structure and the negative shaft resistances (downdrag).

STEP 5 Determine magnitude of negative shaft resistance, Q_s^- .

The method used to calculate the ultimate negative shaft resistance over the pile length determined in Step 4 should be the same method used to calculate the ultimate positive shaft resistance, except that it will act in the opposite direction.

As calculated in Step 4 above, the negative shaft resistance will be caused by soil layer 1 which is a medium silty clay. The pile length in soil layer 1 is 5.5 meters. The ultimate positive shaft resistance in soil layer 1 has been calculated with the α -method in Section F.2.4.1 and is equal to:

$$R_{s1} = 259 \text{ kN}$$

STEP 5 (continued)

Therefore, the ultimate negative shaft resistance is equal to:

$$Q_s^- = 259 \text{ kN}$$

STEP 6 Calculate the ultimate pile capacity provided by the positive shaft resistance and the toe resistance, Q_u^+ .

Positive shaft and toe resistances will develop below the depth where the relative pile-soil movements are less than 10 mm. The positive soil resistances can be calculated on the pile length remaining below the negative shaft resistance depth from Step 4 using an appropriate static analysis method for the soil type.

The ultimate pile capacity will be provided by the shaft resistance from soil layers 2 and 3, and the toe resistance, as calculated in Section F.2.4.1. The shaft resistance provided by each of soil layer and the ultimate positive shaft resistance is as follows:

$$\text{Layer 2: } R_{s2}^+ = 1,150 \text{ kN}$$

$$\text{Layer 3: } R_{s3}^+ = 239 \text{ kN}$$

$$\begin{aligned} \text{Total: } R_s^+ &= R_{s2}^+ + R_{s3}^+ \\ &= 1,150 \text{ kN} + 239 \text{ kN} \\ &= 1,389 \text{ kN} \end{aligned}$$

Also as calculated in Section F.2.4.1, the ultimate toe resistance is equal to:

$$R_t = 182 \text{ kN}$$

STEP 6 (continued)

Hence, the ultimate pile capacity is equal to:

$$\begin{aligned} Q_u^+ &= R_s^+ + R_t \\ &= 1,389 \text{ kN} + 182 \text{ kN} = 1,571 \text{ kN} \end{aligned}$$

STEP 7 Calculate the net ultimate pile capacity, Q_u^{NET} , available to resist imposed loads.

$$\begin{aligned} Q_u^{\text{NET}} &= Q_u^+ - Q_s^- \\ &= 1,571 \text{ kN} - 259 \text{ kN} = 1,312 \text{ kN} \end{aligned}$$

The net ultimate pile capacity is smaller than the required ultimate pile capacity of 1780 kN. Therefore, alternatives to obtain higher pile capacities must be considered.

STEP 8 Consider alternatives to obtain higher net ultimate pile capacity.

Alternatives are described in Section 9.9.1.2 and include use of preloading or wick drains to reduce settlements prior to pile installation, use of lightweight fills to reduce settlements that cause downdrag loads, use of friction reducers to reduce downdrag loads, use of higher allowable material stress, and isolation of pile from consolidating soil.

Three alternatives will be further investigated on the following.

Alternate 1: Use bitumen coating on piles to reduce negative shaft resistance.

According to Goudreau and Fellenius (2002), the maximum pile adhesion, c_a , used in the static pile capacity calculation should be limited to 10 kPa when the pile is coated with bitumen.

STEP 8 (continued)

According to the α -method presented in Section F.2.4.1, the pile adhesion from soil layer 1, c_{a1} , is equal to 33 kPa. If the 5.5 m pile length in layer 1 is coated with bitumen, the pile adhesion will become 10 kPa, and therefore the positive or negative shaft resistance is equal to:

$$\begin{aligned} R_{s1}^+ &= Q_s^- = 10 \text{ kPa} (4) (0.356 \text{ m}) (5.5 \text{ m}) \\ &= 78 \text{ kN} \end{aligned}$$

The net ultimate pile capacity available to resist imposed loads is equal to:

$$\begin{aligned} Q_u^{\text{NET}} &= Q_u^+ - Q_s^- \\ &= 1,571 \text{ kN} - 78 \text{ kN} = 1,493 \text{ kN} \end{aligned}$$

This is still less than the required ultimate bearing capacity (1780 kN).

- Notes: 1. Bitumen coating should be applied only to the top 5.5 m of the pile.
2. Batter piles should be avoided if possible.

Alternate 2: Use longer piles driven to a stiffer or denser noncompressible layer.

Try an extra pile embedded length of 3.5 meters or a total pile embedded length of 21.0 meters. This extra pile embedded length will increase the shaft resistance from soil layer 3 and the toe resistance.

The average undrained shear strength of soil layer 3 is equal to:

$$c_{u3} = \frac{158 + 155 + 163 + 168}{4} = 161 \text{ kPa}$$

$$(D/b) = (20.5 \text{ m}) / (0.356 \text{ m}) = 57.58$$

STEP 8 (continued)

Using Figure 9.18 and for $c_{u3} = 161$ kPa and $(D/b) = 57.58$, the pile adhesion is:

$$c_{a3} = 66 \text{ kPa} \quad \text{and therefore } f_{s3} = 66 \text{ kPa}$$

Hence,

$$\begin{aligned} R_{s3} &= 66 \text{ kPa } (4) (0.356 \text{ m}) (6.0 \text{ m}) \\ &= 564 \text{ kN} \end{aligned}$$

The ultimate positive shaft resistance:

$$\begin{aligned} R_s^+ &= R_{s2}^+ + R_{s3}^+ \\ &= 1,150 \text{ kN} + 564 \text{ kN} \\ &= 1,714 \text{ kN} \end{aligned}$$

The average undrained shear strength of soil at the pile toe is equal 170 kPa.

The unit toe resistance, q_t , is:

$$\begin{aligned} q_t &= 9 c_u \\ &= 9 (170 \text{ kPa}) = 1,530 \text{ kPa} \end{aligned}$$

The ultimate toe resistance, R_t , is equal to:

$$\begin{aligned} R_t &= 1,530 \text{ kPa } (0.356 \text{ m}) (0.356 \text{ m}) \\ &= 194 \text{ kN} \end{aligned}$$

STEP 8 (continued)

The ultimate pile capacity is equal to:

$$\begin{aligned} Q_u^+ &= R_s^+ + R_t \\ &= 1,714 \text{ kN} + 194 \text{ kN} \\ &= 1,908 \text{ kN} \end{aligned}$$

The net ultimate pile capacity available to resist imposed loads, with an increased pile length to 20.5 meters and a bitumen coating on the top 5.5 meter of the pile:

$$\begin{aligned} Q_u^{NET} &= Q_u^+ - Q_s^- \\ &= 1,908 \text{ kN} - 78 \text{ kN} \\ &= 1,830 \text{ kN} \end{aligned}$$

This alternate provides the required ultimate capacity, but a cost analysis of alternatives 1 and 2 and a combination of both alternatives should be performed before making the selection.

Alternate 3: A stub abutment instead of a full height abutment may be a better choice for the south abutment. The stub abutment could be supported on a spread footing with specified embankment material and density control in the foundation area. A stub abutment with pile foundation is another alternative available for consideration.

This design problem illustrates the difficulties encountered in designing pile foundations in clay where substantial settlements occur and large downdrag loads are encountered by piles.

F.7 LATERAL SQUEEZE CALCULATIONS

F.7.1 South Abutment - Investigation of Lateral Squeeze

Use the guidelines presented in Section 9.9.3 of Chapter 9.

STEP 1 Determine if abutment tilting can occur.

The backfill material properties:

$$\gamma_f = 20 \text{ kN/m}^3.$$

$$h_f = 10 \text{ meters.}$$

Any tilting which may occur will take place on the top soil layer which is the medium silty clay. The average undrained shear strength, c_u , of the medium silty clay layer is 33 kPa.

Abutment tilting will occur if the following condition govern:

$$\gamma_f h_f > 3 c_u$$

$$20 \text{ kN/m}^3 (10 \text{ m}) > 3 (33 \text{ kPa})$$

$$200 \text{ kPa} > 99 \text{ kPa}$$

Hence, abutment tilting can occur.

STEP 2 Determine the magnitude of horizontal movement.

Two cases will be investigated on the following.

Case 1: If piles are placed before any soil compression occurs.

The computations performed previously for negative shaft resistance indicated the vertical fill settlement is equal to 0.495 meter.

Estimated horizontal movement = $0.25 (0.495 \text{ m}) = 0.124 \text{ m}$

This horizontal movement is not tolerable as it is greater than the 10 mm allowable by the bridge division.

Case 2: If piles are driven after 90% of vertical settlement has occurred.

Estimated vertical fill settlement after 90% settlement has occurred is 0.0495 meter.

Estimated horizontal movement = $0.25 (0.0495 \text{ m}) = 0.0124 \text{ m}$

This movement is also larger than the 10 mm allowed by the bridge division. Because the estimated movement is close, provisions can be made in the bridge shoe and expansion joint design so this movement is tolerable.

F.8 LATERALLY LOADED PILE GROUP CALCULATIONS

As noted in section F.4, the bridge division estimated that group lateral loads range from 600 kN at the interior pile groups to 900 kN at the abutment pile groups. The maximum lateral load per pile is limited to 40kN.

F.8.1 Laterally Loaded Pile Group, North Abutment Example Calculation

Perform a lateral pile group capacity analysis for the 24 pile layout at the North Abutment using the single pile LPILE analyses from section F.4.2 as a starting point. The piles will be laid out in three rows of eight piles (see Figure F.2), with the lateral loading acting along the three pile axis. Prestressed concrete piles, 356 mm square are planned and will be spaced 1.5 meters on center. Piles are embedded 11.5 meters. Use the step by step procedure outlined in Section 9.8.4.

STEP 1 Develop p-y curves for a single pile.

In section F.4.2, p-y curves were assumed based on general soil type used in the LPILE program.

STEP 2 Perform LPILE analyses.

- a. Using the LPILE analysis for the North Abutment in F.4.2 (with nonlinear flexural rigidity effects), edit the input file and use the P_m value for the first row to develop load-deflection and load-moment data. Section 9.8.4 suggests using P_m values of 0.8 for the first row. The p-multiplier can be entered by clicking the Options menu, then selecting "Include p-y Modification Factors." p-multipliers can then be entered by clicking the Data menu, then selecting "Modification Factors for p-y Curves" option. In this screen, p-multipliers can be varied by depth. The input file and abridged numerical output follows.

```

LPILEP4
FHWA North Abut. - 355 mm-sq PSC - Group lateral, Row 1
2 3 0 0 0 0
100 2 0 11.5 0
0 0.355 0.0013 0.126 27800000
11.5 0.355 0.0013 0.126 27800000
4 8 8 0 2
4 0 1 6790 6790
4 1 4 5430 5430
4 4 11 16300 16300
4 11 11.5 33900 33900
0 16.5
1 16.5
1 6.7
4 6.7
4 7.8
11 7.8
11 9.8
11.5 9.8
0 0 29 0 0
1 0 29 0 0
1 0 29 0 0
4 0 29 0 0
4 0 30 0 0
11 0 30 0 0
11 0 36 0 0
11.5 0 36 0 0
0 0.8 1
11.5 0.8 1
0 0 20
10
2 20 0 890
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
0
1 1 0
100 1E-6 1
1 1
890
41370 262000 413685.52 2.0685E8
0.355 0.355 0 0 0
0.0005 4 2 0.0762
0.102 0.0006
-0.102 0.0006

```

North Abutment, Front Row Lateral Analysis—Echo Input

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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All Rights Reserved

=====

Problem Title

FHWA North Abut. - 355 mm-sq PSC - Group lateral, Row 1

Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 4:

- Computation of Nonlinear Bending Stiffness and Ultimate Bending Moment Capacity with Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis uses p-y multipliers for group action
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 10.000E-06 m
- Maximum allowable deflection = 1.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

Pile Structural Properties and Geometry

Pile Length = 11.50 m
 Depth of ground surface below top of pile = .00 m
 Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35500000 | .001300 | .1260 | 27800000.000 |
| 2 | 11.5000 | .35500000 | .001300 | .1260 | 27800000.000 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of moment of inertia and modulus of are not used for any computations other than total stress due to combined axial loading and bending.

Soil and Rock Layering Information

The soil profile is modelled using 4 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 1.000 m
 p-y subgrade modulus k for top of soil layer = 6790.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 6790.000 kN/ m**3

Layer 2 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 1.000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 5430.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 5430.000 kN/ m**3

Layer 3 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 11.000 m
 p-y subgrade modulus k for top of soil layer = 16300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 16300.000 kN/ m**3

Layer 4 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 11.000 m
 Distance from top of pile to bottom of layer = 11.500 m
 p-y subgrade modulus k for top of soil layer = 33900.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 33900.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth
is defined using 8 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|--------------|--------------|------------------------------|
| 1 | .00 | 16.50000 |
| 2 | 1.00 | 16.50000 |
| 3 | 1.00 | 6.70000 |
| 4 | 4.00 | 6.70000 |
| 5 | 4.00 | 7.80000 |
| 6 | 11.00 | 7.80000 |
| 7 | 11.00 | 9.80000 |
| 8 | 11.50 | 9.80000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth
defined using 8 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|--------------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 29.00 | ----- | ----- |
| 2 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 3 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 4 | 4.000 | .00000 | 29.00 | ----- | ----- |
| 5 | 4.000 | .00000 | 30.00 | ----- | ----- |
| 6 | 11.000 | .00000 | 30.00 | ----- | ----- |
| 7 | 11.000 | .00000 | 36.00 | ----- | ----- |
| 8 | 11.500 | .00000 | 36.00 | ----- | ----- |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

p-y Modification Factors

Distribution of p-y multipliers with depth defined using 2 points

| Point No. | Depth X m | p-mult | y-mult |
|--------------|--------------|--------|--------|
| 1 | .000 | .8000 | 1.0000 |
| 2 | 11.500 | .8000 | 1.0000 |

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

File-head Loading and File-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 20.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Load Case Number 2

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 40.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

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.[ABRIDGED]

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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 200.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computations of Ultimate Moment Capacity and Nonlinear Bending Stiffness

File Description:

The pile shape is a rectangular solid pile.

Width = .355 m
Depth = .355 m

Material Properties:

Compressive Strength of Concrete = 41370.000 kN/ m**2
Yield Stress of Reinforcement = 262000. kN/ m**2
Modulus of Elasticity of Reinforcement = 206850000. kN/ m**2
Number of Reinforcing Bars = 4
Area of Single Bar = .00050 m**2
Number of Rows of Reinforcing Bars = 2
Cover Thickness (edge to bar center) = .076 m

Ultimate Axial Squash Load Capacity = 4703.81 kN

Distribution and Area of Steel Reinforcement

| Row Number | Area of Reinforcement m**2 | Distance to Centroidal Axis m |
|---------------|----------------------------------|-------------------------------------|
| 1 | .000600 | .1020 |
| 2 | .000600 | -.1020 |

Axial Thrust Force = 890.00 kN

| Bending Moment kN-m | Bending Stiffness kN-m2 | Bending Curvature rad/m | Maximum Strain m/m | Neutral Axis Position m |
|---------------------------|-------------------------------|-------------------------------|--------------------------|-------------------------------|
| 1.54295127 | 39190.962 | .00003937 | .00023366 | 5.93486814 |
| 7.71444547 | 39189.382 | .00019685 | .00026170 | 1.32942587 |
| 13.885 | 39185.750 | .00035433 | .00028986 | .81803677 |
| 20.053 | 39179.988 | .00051181 | .00031813 | .62158314 |
| 26.218 | 39172.157 | .00066929 | .00034653 | .51775257 |
| 32.378 | 39162.188 | .00082677 | .00037504 | .45362225 |
| 38.534 | 39150.185 | .00098425 | .00040367 | .41013020 |
| 44.683 | 39136.085 | .00114173 | .00043242 | .37873943 |
| 50.825 | 39119.844 | .00129921 | .00046129 | .35505146 |
| 56.988 | 39121.516 | .00145669 | .00049033 | .33660160 |
| 63.049 | 39059.507 | .00161417 | .00051931 | .32172146 |
| 69.110 | 39008.681 | .00177165 | .00054844 | .30956600 |
| 75.155 | 38958.023 | .00192913 | .00057769 | .29945812 |
| 81.088 | 38861.083 | .00208661 | .00060684 | .29082363 |
| 81.088 | 36133.990 | .00224409 | .00061495 | .27403133 |
| 81.088 | 33764.548 | .00240157 | .00063793 | .26562977 |
| 81.469 | 31835.639 | .00255906 | .00066017 | .25797573 |
| 83.923 | 30893.279 | .00271654 | .00068196 | .25104214 |
| 86.229 | 30003.115 | .00287402 | .00070333 | .24472065 |
| 88.411 | 29164.014 | .00303150 | .00072433 | .23893543 |
| 90.481 | 28372.973 | .00318898 | .00074498 | .23361065 |

| | | | | |
|---------|-----------|-----------|-----------|-----------|
| 92.458 | 27628.502 | .00334646 | .00076533 | .22869755 |
| 94.358 | 26929.177 | .00350394 | .00078544 | .22415821 |
| 96.109 | 26249.199 | .00366142 | .00080493 | .21984097 |
| 97.855 | 25623.877 | .00381890 | .00082447 | .21589207 |
| 99.561 | 25038.090 | .00397638 | .00084391 | .21223026 |
| 110.590 | 21442.569 | .00515748 | .00098201 | .19040569 |
| 120.077 | 18943.856 | .00633858 | .00111351 | .17567181 |
| 128.620 | 17104.480 | .00751969 | .00124079 | .16500599 |
| 136.481 | 15686.050 | .00870079 | .00136470 | .15684818 |
| 143.755 | 14547.283 | .00988189 | .00148690 | .15046711 |
| 145.817 | 13180.644 | .01106299 | .00158671 | .14342518 |
| 147.540 | 12049.856 | .01224409 | .00168395 | .13753162 |
| 148.999 | 11098.438 | .01342520 | .00177927 | .13253185 |
| 150.255 | 10286.974 | .01460630 | .00187345 | .12826336 |
| 151.236 | 9579.525 | .01578740 | .00196414 | .12441196 |
| 152.156 | 8966.965 | .01696850 | .00205603 | .12116726 |
| 153.062 | 8433.379 | .01814961 | .00214772 | .11833424 |
| 153.569 | 7944.317 | .01933071 | .00223691 | .11571789 |
| 154.075 | 7511.548 | .02051181 | .00232536 | .11336697 |
| 154.597 | 7126.607 | .02169291 | .00242001 | .11155773 |
| 154.870 | 6770.554 | .02287402 | .00250841 | .10966183 |
| 155.085 | 6447.050 | .02405512 | .00259871 | .10803135 |
| 155.264 | 6152.428 | .02523622 | .00269049 | .10661213 |
| 155.477 | 5885.409 | .02641732 | .00278965 | .10559917 |
| 155.534 | 5635.593 | .02759843 | .00288088 | .10438580 |
| 155.547 | 5404.764 | .02877953 | .00297346 | .10331867 |
| 155.550 | 5191.809 | .02996063 | .00306693 | .10236530 |
| 155.550 | 4994.901 | .03114173 | .00316169 | .10152569 |
| 155.550 | 4812.383 | .03232283 | .00325744 | .10077816 |
| 155.550 | 4642.734 | .03350394 | .00336721 | .10050190 |
| 155.550 | 4484.639 | .03468504 | .00346243 | .09982479 |
| 155.550 | 4336.956 | .03586614 | .00355857 | .09921810 |
| 155.550 | 4198.689 | .03704724 | .00365529 | .09866558 |
| 155.550 | 4068.967 | .03822835 | .00375256 | .09816181 |
| 155.550 | 3947.020 | .03940945 | .00418210 | .10611919 |

Ultimate Moment Capacity at a Concrete Strain of 0.003 = 155.548 m- kN

 Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 20.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .001791 | -28.2073 | 20.0000 | 1.70E-17 | 1.09E+04 | 36140.000 | 0.000 |
| .575 | .001678 | -16.8808 | 18.4825 | -3.58E-04 | 9368.4 | 36140.000 | -5.242 |
| 1.150 | .001411 | -7.0773 | 14.6306 | -5.46E-04 | 8029.8 | 36140.000 | -7.067 |
| 1.725 | .001076 | .3865 | 10.1909 | -5.96E-04 | 7116.3 | 36140.000 | -8.081 |
| 2.300 | 7.44E-04 | 5.2214 | 5.6633 | -5.48E-04 | 7776.4 | 36140.000 | -7.441 |
| 2.875 | 4.57E-04 | 7.5841 | 1.8469 | -4.43E-04 | 8099.0 | 36140.000 | -5.714 |
| 3.450 | 2.38E-04 | 8.0079 | -.8275 | -3.17E-04 | 8156.9 | 36140.000 | -3.574 |
| 4.025 | 9.18E-05 | 7.1809 | -2.4876 | -1.95E-04 | 8044.0 | 36140.000 | -4.901 |
| 4.600 | 1.02E-05 | 5.2666 | -3.9801 | -9.47E-05 | 7782.6 | 36140.000 | -.621689 |
| 5.175 | -2.34E-05 | 3.0487 | -3.6091 | -2.88E-05 | 7479.8 | 36140.000 | 1.602 |
| 5.750 | -2.88E-05 | 1.2915 | -2.4598 | 4.94E-06 | 7239.8 | 36140.000 | 2.187 |
| 6.325 | -2.19E-05 | .2216 | -1.2787 | 1.61E-05 | 7093.7 | 36140.000 | 1.825 |
| 6.900 | -1.25E-05 | -.2555 | -.4235 | 1.52E-05 | 7098.4 | 36140.000 | 1.135 |
| 7.475 | -5.16E-06 | -.3534 | 4.07E-02 | 1.00E-05 | 7111.7 | 36140.000 | .507519 |
| 8.050 | -9.29E-07 | -.2747 | .2039 | 4.92E-06 | 7101.0 | 36140.000 | .098348 |
| 8.625 | 8.16E-07 | -.1554 | .1969 | 1.50E-06 | 7084.7 | 36140.000 | -.092513 |
| 9.200 | 1.12E-06 | -6.14E-02 | .1264 | -1.74E-07 | 7071.9 | 36140.000 | -.135321 |
| 9.775 | 8.29E-07 | -9.87E-03 | 5.51E-02 | -6.89E-07 | 7064.8 | 36140.000 | -.106451 |
| 10.350 | 4.23E-07 | 7.09E-03 | 7.75E-03 | -6.76E-07 | 7064.5 | 36140.000 | -.057485 |
| 10.925 | 6.78E-08 | 4.93E-03 | -1.14E-02 | -5.67E-07 | 7064.2 | 36140.000 | -.009720 |
| 11.500 | -2.45E-07 | 0.0 | 0.0 | -5.35E-07 | 7063.5 | 36140.000 | .053636 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00179060 m
 Computed slope at pile head = 1.69701E-17
 Maximum bending moment = -28.207 kN- m
 Maximum shear force = 20.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 5
 Number of zero deflection points = 3

 Computed Values of Load Distribution and Deflection
 for Lateral Loading for Load Case Number 3

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 60.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .005659 | -87.8505 | 60.0000 | -1.89E-17 | 1.91E+04 | 36140.000 | 0.000 |
| .575 | .005308 | -53.4721 | 57.2204 | -.001123 | 1.44E+04 | 36140.000 | -12.004 |
| 1.150 | .004465 | -22.6370 | 46.3629 | -.001721 | 1.02E+04 | 36140.000 | -22.368 |
| 1.725 | .003410 | 1.0387 | 32.3826 | -.001882 | 7205.3 | 36140.000 | -25.597 |
| 2.300 | .002357 | 16.4098 | 18.0357 | -.001733 | 9304.1 | 36140.000 | -23.587 |
| 2.875 | .001450 | 23.9456 | 5.9335 | -.001403 | 1.03E+04 | 36140.000 | -18.127 |
| 3.450 | 7.57E-04 | 25.3316 | -2.5545 | -.001004 | 1.05E+04 | 36140.000 | -11.350 |
| 4.025 | 2.92E-04 | 22.7462 | -7.8311 | -6.18E-04 | 1.02E+04 | 36140.000 | -15.597 |
| 4.600 | 3.31E-05 | 16.7006 | -12.5925 | -3.01E-04 | 9343.8 | 36140.000 | -2.015 |
| 5.175 | -7.39E-05 | 9.6778 | -11.4364 | -9.17E-05 | 8384.9 | 36140.000 | 5.052 |
| 5.750 | -9.13E-05 | 4.1071 | -7.8031 | 1.53E-05 | 7624.3 | 36140.000 | 6.923 |
| 6.325 | -6.94E-05 | .7112 | -4.0612 | 5.09E-05 | 7160.6 | 36140.000 | 5.786 |
| 6.900 | -3.97E-05 | -.8053 | -1.3491 | 4.82E-05 | 7173.4 | 36140.000 | 3.603 |
| 7.475 | -1.64E-05 | -1.1186 | .1249 | 3.18E-05 | 7216.2 | 36140.000 | 1.613 |
| 8.050 | -2.98E-06 | -.8707 | .6445 | 1.56E-05 | 7182.4 | 36140.000 | .314985 |
| 8.625 | 2.57E-06 | -.4931 | .6237 | 4.78E-06 | 7130.8 | 36140.000 | -.291558 |
| 9.200 | 3.54E-06 | -.1953 | .4011 | -5.38E-07 | 7090.2 | 36140.000 | -.428395 |
| 9.775 | 2.63E-06 | -3.17E-02 | .1750 | -2.18E-06 | 7067.8 | 36140.000 | -.337492 |
| 10.350 | 1.34E-06 | 2.23E-02 | 2.49E-02 | -2.14E-06 | 7066.5 | 36140.000 | -.182478 |
| 10.925 | 2.17E-07 | 1.56E-02 | -3.60E-02 | -1.80E-06 | 7065.6 | 36140.000 | -.031051 |
| 11.500 | -7.75E-07 | 0.0 | 0.0 | -1.70E-06 | 7063.5 | 36140.000 | .169800 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 3:

Pile-head deflection = .00565918 m
 Computed slope at pile head = -1.88557E-17
 Maximum bending moment = -87.850 kN- m
 Maximum shear force = 60.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 6
 Number of zero deflection points = 3

Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m

M = pile-head moment, kN- m

V = pile-head shear force, kN

S = pile-head slope, radians

R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|---------|----------------------|----------------------|---------------|------------------------|----------------------|------------------|
| 2 | V= 20.000 | S= 0.000 | 890.0000 | .001791 | -28.2073 | 20.0000 |
| 2 | V= 40.000 | S= 0.000 | 890.0000 | .003632 | -57.0762 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .005659 | -87.8505 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .008105 | -121.7768 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .010847 | -157.4910 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .013734 | -193.8464 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .016845 | -231.7067 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .020361 | -272.0828 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .024357 | -314.9833 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .028850 | -360.1588 | 200.0000 |

The analysis ended normally.

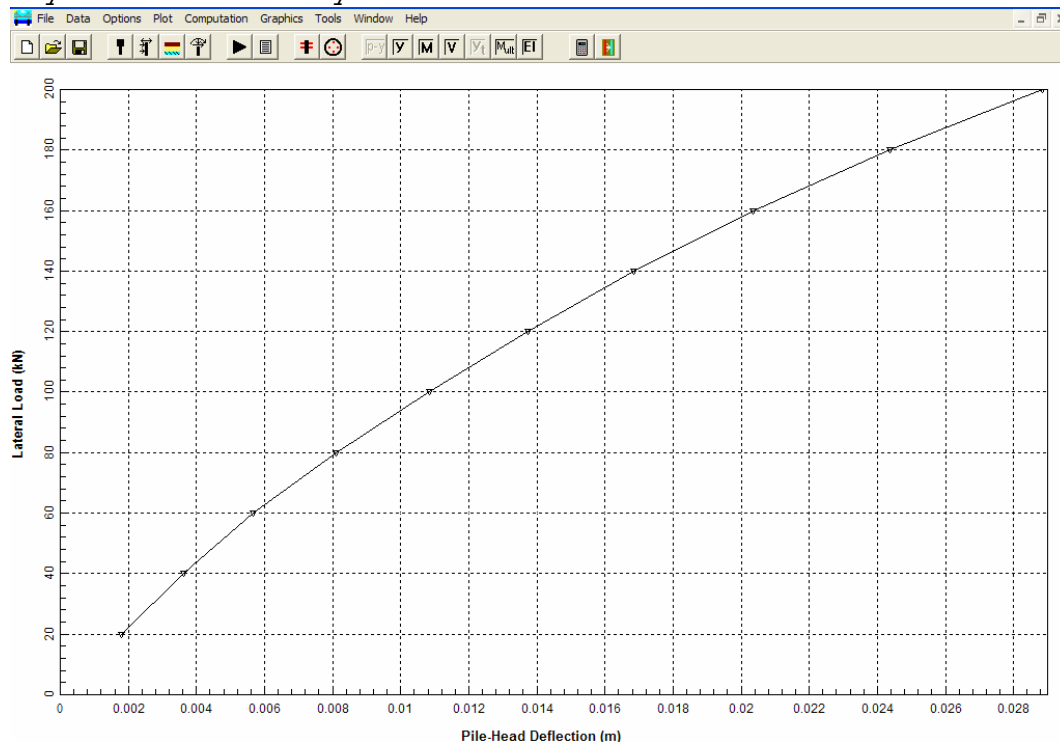


Figure F.46 North Abutment LPILE analysis—Front Row Lateral Load vs Pile Head Deflection

STEP 2 (cont.)

- b. Adjust the LPILE analysis for the first row, using the P_m value for the second row to develop load-deflection and load-moment data. Section 9.8.4 suggests using P_m values of 0.4 for the second row. The input file and abridged numerical output follows.

```

LPILEP4
FHWA North Abut. - 355 mm-sq PSC - Group lateral, Row 2
2 3 0 0 0 0
100 2 0 11.5 0
0 0.355 0.0013 0.126 27800000
11.5 0.355 0.0013 0.126 27800000
4 8 8 0 2
4 0 1 6790 6790
4 1 4 5430 5430
4 4 11 16300 16300
4 11 11.5 33900 33900
0 16.5
1 16.5
1 6.7
4 6.7
4 7.8
11 7.8
11 9.8
11.5 9.8
0 0 29 0 0
1 0 29 0 0
1 0 29 0 0
4 0 29 0 0
4 0 30 0 0
11 0 30 0 0
11 0 36 0 0
11.5 0 36 0 0
0 0.4 1
11.5 0.4 1
0 0 20
10
2 20 0 890
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
0
1 1 0
100 1E-6 1
1 1
890
41370 262000 413685.52 2.0685E8
0.355 0.355 0 0 0
0.0005 4 2 0.0762
0.102 0.0006
-0.102 0.0006

```

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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Problem Title

FHWA North Abut. - 355 mm-sq PSC - Group lateral, Row 2

Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 4:

- Computation of Nonlinear Bending Stiffness and Ultimate Bending Moment Capacity with Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis uses p-y multipliers for group action
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 10.000E-06 m
- Maximum allowable deflection = 1.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

Pile Structural Properties and Geometry

Pile Length = 11.50 m
 Depth of ground surface below top of pile = .00 m
 Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35500000 | .001300 | .1260 | 27800000.000 |
| 2 | 11.5000 | .35500000 | .001300 | .1260 | 27800000.000 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of moment of inertia and modulus of are not used for any computations other than total stress due to combined axial loading and bending.

Soil and Rock Layering Information

The soil profile is modelled using 4 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 1.000 m
 p-y subgrade modulus k for top of soil layer = 6790.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 6790.000 kN/ m**3

Layer 2 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 1.000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 5430.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 5430.000 kN/ m**3

Layer 3 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 11.000 m
 p-y subgrade modulus k for top of soil layer = 16300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 16300.000 kN/ m**3

Layer 4 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 11.000 m
 Distance from top of pile to bottom of layer = 11.500 m
 p-y subgrade modulus k for top of soil layer = 33900.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 33900.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth
is defined using 8 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|--------------|--------------|------------------------------|
| 1 | .00 | 16.50000 |
| 2 | 1.00 | 16.50000 |
| 3 | 1.00 | 6.70000 |
| 4 | 4.00 | 6.70000 |
| 5 | 4.00 | 7.80000 |
| 6 | 11.00 | 7.80000 |
| 7 | 11.00 | 9.80000 |
| 8 | 11.50 | 9.80000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth
defined using 8 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|--------------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 29.00 | ----- | ----- |
| 2 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 3 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 4 | 4.000 | .00000 | 29.00 | ----- | ----- |
| 5 | 4.000 | .00000 | 30.00 | ----- | ----- |
| 6 | 11.000 | .00000 | 30.00 | ----- | ----- |
| 7 | 11.000 | .00000 | 36.00 | ----- | ----- |
| 8 | 11.500 | .00000 | 36.00 | ----- | ----- |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

p-y Modification Factors

Distribution of p-y multipliers with depth defined using 2 points

| Point No. | Depth X m | p-mult | y-mult |
|--------------|--------------|--------|--------|
| 1 | .000 | .4000 | 1.0000 |
| 2 | 11.500 | .4000 | 1.0000 |

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

Pile-head Loading and Pile-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 20.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

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.[ABRIDGED]
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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 200.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computations of Ultimate Moment Capacity and Nonlinear Bending Stiffness

Pile Description:

The pile shape is a rectangular solid pile.

Width = .355 m

Depth = .355 m

Material Properties:

Compressive Strength of Concrete = 41370.000 kN/ m**2

Yield Stress of Reinforcement = 262000. kN/ m**2

Modulus of Elasticity of Reinforcement = 206850000. kN/ m**2

Number of Reinforcing Bars = 4

Area of Single Bar = .00050 m**2

Number of Rows of Reinforcing Bars = 2

Cover Thickness (edge to bar center) = .076 m

Ultimate Axial Squash Load Capacity = 4703.81 kN

Distribution and Area of Steel Reinforcement

| Row Number | Area of Reinforcement m**2 | Distance to Centroidal Axis m |
|---------------|----------------------------------|-------------------------------------|
| 1 | .000600 | .1020 |
| 2 | .000600 | -.1020 |

Axial Thrust Force = 890.00 kN

| Bending Moment kN-m | Bending Stiffness kN-m2 | Bending Curvature rad/m | Maximum Strain m/m | Neutral Axis Position m |
|---------------------------|-------------------------------|-------------------------------|--------------------------|-------------------------------|
| 1.54295127 | 39190.962 | .00003937 | .00023366 | 5.93486814 |
| 7.71444547 | 39189.382 | .00019685 | .00026170 | 1.32942587 |
| 13.885 | 39185.750 | .00035433 | .00028986 | .81803677 |
| 20.053 | 39179.988 | .00051181 | .00031813 | .62158314 |
| 26.218 | 39172.157 | .00066929 | .00034653 | .51775257 |
| 32.378 | 39162.188 | .00082677 | .00037504 | .45362225 |
| 38.534 | 39150.185 | .00098425 | .00040367 | .41013020 |
| 44.683 | 39136.085 | .00114173 | .00043242 | .37873943 |
| 50.825 | 39119.844 | .00129921 | .00046129 | .35505146 |
| 56.988 | 39121.516 | .00145669 | .00049033 | .33660160 |
| 63.049 | 39059.507 | .00161417 | .00051931 | .32172146 |
| 69.110 | 39008.681 | .00177165 | .00054844 | .30956600 |
| 75.155 | 38958.023 | .00192913 | .00057769 | .29945812 |
| 81.088 | 38861.083 | .00208661 | .00060684 | .29082363 |
| 81.088 | 36133.990 | .00224409 | .00061495 | .27403133 |
| 81.088 | 33764.548 | .00240157 | .00063793 | .26562977 |
| 81.469 | 31835.639 | .00255906 | .00066017 | .25797573 |
| 83.923 | 30893.279 | .00271654 | .00068196 | .25104214 |
| 86.229 | 30003.115 | .00287402 | .00070333 | .24472065 |
| 88.411 | 29164.014 | .00303150 | .00072433 | .23893543 |
| 90.481 | 28372.973 | .00318898 | .00074498 | .23361065 |
| 92.458 | 27628.502 | .00334646 | .00076533 | .22869755 |
| 94.358 | 26929.177 | .00350394 | .00078544 | .22415821 |
| 96.109 | 26249.199 | .00366142 | .00080493 | .21984097 |
| 97.855 | 25623.877 | .00381890 | .00082447 | .21589207 |
| 99.561 | 25038.090 | .00397638 | .00084391 | .21223026 |
| 110.590 | 21442.569 | .00515748 | .00098201 | .19040569 |
| 120.077 | 18943.856 | .00633858 | .00111351 | .17567181 |
| 128.620 | 17104.480 | .00751969 | .00124079 | .16500599 |
| 136.481 | 15686.050 | .00870079 | .00136470 | .15684818 |
| 143.755 | 14547.283 | .00988189 | .00148690 | .15046711 |
| 145.817 | 13180.644 | .01106299 | .00158671 | .14342518 |
| 147.540 | 12049.856 | .01224409 | .00168395 | .13753162 |
| 148.999 | 11098.438 | .01342520 | .00177927 | .13253185 |
| 150.255 | 10286.974 | .01460630 | .00187345 | .12826336 |
| 151.236 | 9579.525 | .01578740 | .00196414 | .12441196 |
| 152.156 | 8966.965 | .01696850 | .00205603 | .12116726 |
| 153.062 | 8433.379 | .01814961 | .00214772 | .11833424 |
| 153.569 | 7944.317 | .01933071 | .00223691 | .11571789 |
| 154.075 | 7511.548 | .02051181 | .00232536 | .11336697 |
| 154.597 | 7126.607 | .02169291 | .00242001 | .11155773 |
| 154.870 | 6770.554 | .02287402 | .00250841 | .10966183 |
| 155.085 | 6447.050 | .02405512 | .00259871 | .10803135 |
| 155.264 | 6152.428 | .02523622 | .00269049 | .10661213 |

| | | | | |
|---------|----------|-----------|-----------|-----------|
| 155.477 | 5885.409 | .02641732 | .00278965 | .10559917 |
| 155.534 | 5635.593 | .02759843 | .00288088 | .10438580 |
| 155.547 | 5404.764 | .02877953 | .00297346 | .10331867 |
| 155.550 | 5191.809 | .02996063 | .00306693 | .10236530 |
| 155.550 | 4994.901 | .03114173 | .00316169 | .10152569 |
| 155.550 | 4812.383 | .03232283 | .00325744 | .10077816 |
| 155.550 | 4642.734 | .03350394 | .00336721 | .10050190 |
| 155.550 | 4484.639 | .03468504 | .00346243 | .09982479 |
| 155.550 | 4336.956 | .03586614 | .00355857 | .09921810 |
| 155.550 | 4198.689 | .03704724 | .00365529 | .09866558 |
| 155.550 | 4068.967 | .03822835 | .00375256 | .09816181 |
| 155.550 | 3947.020 | .03940945 | .00418210 | .10611919 |

Ultimate Moment Capacity at a Concrete Strain of 0.003 = 155.548 m- kN

Computed Values of Load Distribution and Deflection
for Lateral Loading for Load Case Number 1

File-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 20.000 kN
Specified slope at pile head = 0.000E+00 m/ m
Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. Y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .002734 | -33.0244 | 20.0000 | 1.89E-18 | 1.16E+04 | 36140.000 | 0.000 |
| .575 | .002600 | -21.5836 | 18.9224 | -4.34E-04 | 1.00E+04 | 36140.000 | -4.060 |
| 1.150 | .002267 | -11.2392 | 15.8860 | -6.93E-04 | 8598.1 | 36140.000 | -5.680 |
| 1.725 | .001831 | -2.7351 | 12.2183 | -8.01E-04 | 7436.9 | 36140.000 | -6.872 |
| 2.300 | .001367 | 3.5533 | 8.2239 | -7.92E-04 | 7548.7 | 36140.000 | -6.841 |
| 2.875 | 9.35E-04 | 7.5783 | 4.5408 | -7.01E-04 | 8098.2 | 36140.000 | -5.845 |
| 3.450 | 5.70E-04 | 9.6255 | 1.6140 | -5.62E-04 | 8377.7 | 36140.000 | -4.278 |
| 4.025 | 2.93E-04 | 10.1847 | -.6518 | -4.02E-04 | 8454.1 | 36140.000 | -7.811 |
| 4.600 | 1.07E-04 | 8.9405 | -3.7787 | -2.48E-04 | 8284.2 | 36140.000 | -3.250 |
| 5.175 | 1.79E-06 | 6.5126 | -4.6611 | -1.24E-04 | 7952.7 | 36140.000 | -.061164 |
| 5.750 | -4.37E-05 | 3.9721 | -4.1388 | -4.12E-05 | 7605.8 | 36140.000 | 1.658 |
| 6.325 | -5.25E-05 | 1.9153 | -2.9883 | 4.78E-06 | 7325.0 | 36140.000 | 2.187 |
| 6.900 | -4.32E-05 | .5457 | -1.7704 | 2.35E-05 | 7138.0 | 36140.000 | 1.964 |
| 7.475 | -2.85E-05 | -.1881 | -.7952 | 2.56E-05 | 7089.2 | 36140.000 | 1.402 |
| 8.050 | -1.52E-05 | -.4580 | -.1642 | 2.00E-05 | 7126.0 | 36140.000 | .803476 |
| 8.625 | -5.84E-06 | -.4551 | .1542 | 1.25E-05 | 7125.6 | 36140.000 | .330933 |
| 9.200 | -5.76E-07 | -.3344 | .2513 | 6.15E-06 | 7109.1 | 36140.000 | .034826 |
| 9.775 | 1.64E-06 | -.1953 | .2249 | 1.95E-06 | 7090.2 | 36140.000 | -.105163 |
| 10.350 | 2.04E-06 | -8.66E-02 | .1511 | -2.35E-07 | 7075.3 | 36140.000 | -.138800 |
| 10.925 | 1.62E-06 | -2.15E-02 | 7.62E-02 | -1.04E-06 | 7066.4 | 36140.000 | -.116361 |
| 11.500 | 9.75E-07 | 0.0 | 0.0 | -1.15E-06 | 7063.5 | 36140.000 | -.106891 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00273403 m
 Computed slope at pile head = 1.88557E-18
 Maximum bending moment = -33.024 kN- m
 Maximum shear force = 20.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 5
 Number of zero deflection points = 2

----- Computed Values of Load Distribution and Deflection for Lateral Loading for Load Case Number 2 -----

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 40.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .005698 | -68.0143 | 40.0000 | -2.26E-17 | 1.64E+04 | 36140.000 | 0.000 |
| .575 | .005421 | -44.9851 | 38.6053 | -8.99E-04 | 1.32E+04 | 36140.000 | -6.030 |
| 1.150 | .004731 | -23.5969 | 33.0520 | -.001440 | 1.03E+04 | 36140.000 | -11.850 |
| 1.725 | .003822 | -5.8593 | 25.5797 | -.001669 | 7863.5 | 36140.000 | -14.347 |
| 2.300 | .002856 | 7.3083 | 17.2380 | -.001652 | 8061.4 | 36140.000 | -14.290 |
| 2.875 | .001954 | 15.7486 | 9.5423 | -.001463 | 9213.8 | 36140.000 | -12.216 |
| 3.450 | .001193 | 20.0561 | 3.4233 | -.001173 | 9801.9 | 36140.000 | -8.947 |
| 4.025 | 6.13E-04 | 21.2525 | -1.3176 | -8.41E-04 | 9965.3 | 36140.000 | -16.352 |
| 4.600 | 2.24E-04 | 18.6733 | -7.8684 | -5.19E-04 | 9613.1 | 36140.000 | -6.819 |
| 5.175 | 4.36E-06 | 13.6119 | -9.7263 | -2.60E-04 | 8922.0 | 36140.000 | -.148874 |
| 5.750 | -9.10E-05 | 8.3082 | -8.6447 | -8.66E-05 | 8197.9 | 36140.000 | 3.450 |
| 6.325 | -1.10E-04 | 4.0107 | -6.2462 | 9.73E-06 | 7611.1 | 36140.000 | 4.564 |
| 6.900 | -9.03E-05 | 1.1472 | -3.7036 | 4.89E-05 | 7220.1 | 36140.000 | 4.102 |
| 7.475 | -5.96E-05 | -.3888 | -1.6658 | 5.35E-05 | 7116.6 | 36140.000 | 2.931 |
| 8.050 | -3.18E-05 | -.9547 | -.3463 | 4.18E-05 | 7193.8 | 36140.000 | 1.681 |
| 8.625 | -1.22E-05 | -.9502 | .3203 | 2.61E-05 | 7193.2 | 36140.000 | .693609 |
| 9.200 | -1.23E-06 | -.6988 | .5242 | 1.29E-05 | 7158.9 | 36140.000 | .074330 |
| 9.775 | 3.41E-06 | -.4084 | .4699 | 4.10E-06 | 7119.3 | 36140.000 | -.218832 |
| 10.350 | 4.26E-06 | -.1812 | .3160 | -4.77E-07 | 7088.2 | 36140.000 | -.289682 |
| 10.925 | 3.39E-06 | -4.51E-02 | .1594 | -2.16E-06 | 7069.7 | 36140.000 | -.243269 |
| 11.500 | 2.05E-06 | 0.0 | 0.0 | -2.40E-06 | 7063.5 | 36140.000 | -.224200 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 2:

Pile-head deflection = .00569808 m
 Computed slope at pile head = -2.26268E-17
 Maximum bending moment = -68.014 kN- m
 Maximum shear force = 40.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 6
 Number of zero deflection points = 2

.
 .[ABRIDGED]
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Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m
 M = pile-head moment, kN- m
 V = pile-head shear force, kN
 S = pile-head slope, radians
 R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition 1 | Boundary Condition 2 | Axial Load kN | Pile Head Deflection m | Maximum Moment m- kN | Maximum Shear kN |
|------------|----------------------------|----------------------------|---------------------|------------------------------|----------------------------|------------------------|
| 2 | V= 20.000 | S= 0.000 | 890.0000 | .002734 | -33.0244 | 20.0000 |
| 2 | V= 40.000 | S= 0.000 | 890.0000 | .005698 | -68.0143 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .009400 | -107.5652 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .013487 | -148.7898 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .018066 | -192.3571 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .023574 | -240.1437 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .030126 | -291.7676 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .037798 | -346.9042 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .046752 | -405.5691 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .057086 | -467.6713 | 200.0000 |

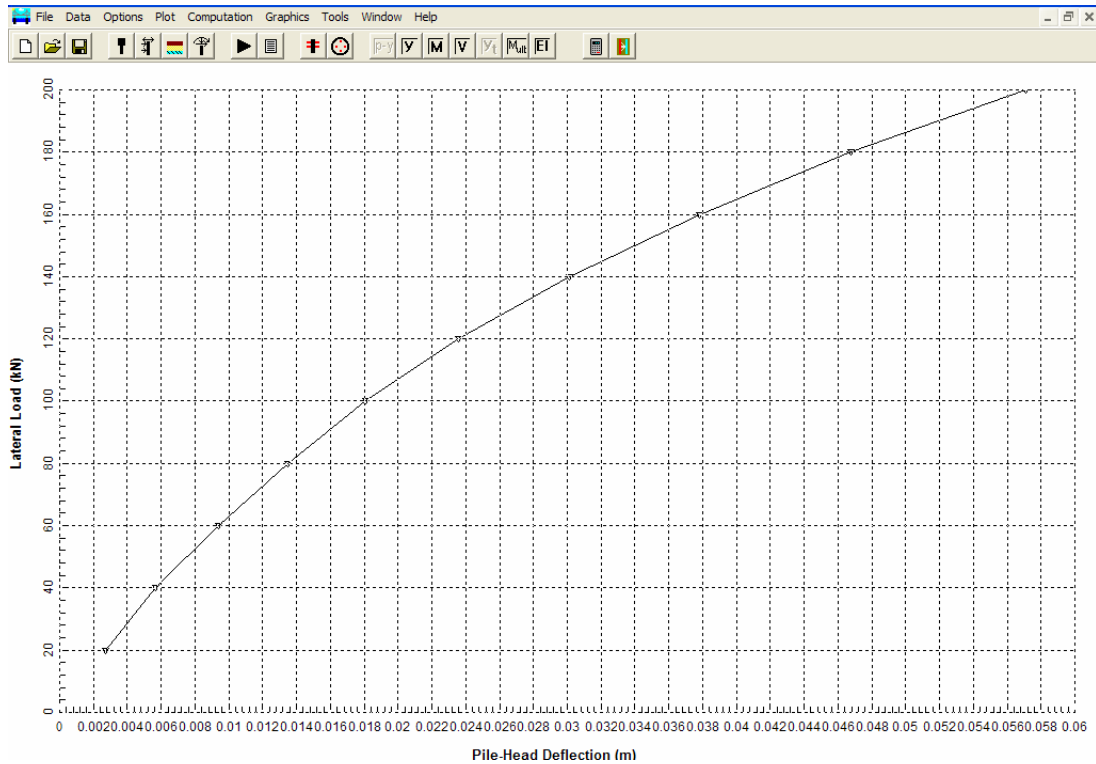


Figure F.47 North Abutment LPILE analysis—Second Row Lateral Load vs Pile Head Deflection

STEP 2 (cont.)

- c. Using the LPILE analysis for second row as a starting point, edit the input file using the P_m value for the third row to develop load-deflection and load-moment data. Section 9.8.4 suggests using P_m values of 0.3 for the third row. The input file and abridged numerical output follows.

```

LPILEP4
FHWA North Abut. - 355 mm-sq PSC - Group lateral, Row 3
2 3 0 0 0 0
100 2 0 11.5 0
0 0.355 0.0013 0.126 27800000
11.5 0.355 0.0013 0.126 27800000
4 8 8 0 2
4 0 1 6790 6790
4 1 4 5430 5430
4 4 11 16300 16300
4 11 11.5 33900 33900
0 16.5
1 16.5
1 6.7
4 6.7
4 7.8
11 7.8
11 9.8
11.5 9.8
0 0 29 0 0
1 0 29 0 0
1 0 29 0 0
4 0 29 0 0
4 0 30 0 0
11 0 30 0 0
11 0 36 0 0
11.5 0 36 0 0
0 0.3 1
11.5 0.3 1
0 0 20
10
2 20 0 890
2 40 0 890
2 60 0 890
2 80 0 890
2 100 0 890
2 120 0 890
2 140 0 890
2 160 0 890
2 180 0 890
2 200 0 890
0
1 1 0
100 1E-6 1
1 1
890
41370 262000 413685.52 2.0685E8
0.355 0.355 0 0 0
0.0005 4 2 0.0762
0.102 0.0006
-0.102 0.0006

```

Row 3 Group Lateral Analysis-LPILE Echo Input

=====

LPILE Plus for Windows, Version 4.0 (4.0.7)

Analysis of Individual Piles and Drilled Shafts
Subjected to Lateral Loading Using the p-y Method

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=====

Problem Title

FHWA North Abut. - 355 mm-sq PSC - Group lateral, Row 3

Program Options

Units Used in Computations - SI Units, meters, kilopascals

Basic Program Options:

Analysis Type 4:

- Computation of Nonlinear Bending Stiffness and Ultimate Bending Moment Capacity with Pile Response Using User-specified Constant EI

Computation Options:

- Only internally-generated p-y curves used in analysis
- Analysis uses p-y multipliers for group action
- Analysis assumes no shear resistance at pile tip
- Analysis for fixed-length pile or shaft only
- No computation of foundation stiffness matrix elements
- Output pile response for full length of pile
- Analysis assumes no soil movements acting on pile
- No additional p-y curves to be computed at user-specified depths

Solution Control Parameters:

- Number of pile increments = 100
- Maximum number of iterations allowed = 100
- Deflection tolerance for convergence = 10.000E-06 m
- Maximum allowable deflection = 1.0000E+00 m

Printing Options:

- Values of pile-head deflection, bending moment, shear force, and soil reaction are printed for full length of pile.
- Printing Increment (spacing of output points) = 5

Pile Structural Properties and Geometry

Pile Length = 11.50 m
 Depth of ground surface below top of pile = .00 m
 Slope angle of ground surface = .00 deg.

Structural properties of pile defined using 2 points

| Point | Depth X m | Pile Diameter m | Moment of Inertia m**4 | Pile Area Sq. m | Modulus of Elasticity kN/Sq. m |
|-------|-----------------|-----------------------|------------------------------|-----------------------|--------------------------------------|
| 1 | 0.0000 | .35500000 | .001300 | .1260 | 27800000.000 |
| 2 | 11.5000 | .35500000 | .001300 | .1260 | 27800000.000 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of moment of inertia and modulus of are not used for any computations other than total stress due to combined axial loading and bending.

Soil and Rock Layering Information

The soil profile is modelled using 4 layers

Layer 1 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = .000 m
 Distance from top of pile to bottom of layer = 1.000 m
 p-y subgrade modulus k for top of soil layer = 6790.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 6790.000 kN/ m**3

Layer 2 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 1.000 m
 Distance from top of pile to bottom of layer = 4.000 m
 p-y subgrade modulus k for top of soil layer = 5430.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 5430.000 kN/ m**3

Layer 3 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 4.000 m
 Distance from top of pile to bottom of layer = 11.000 m
 p-y subgrade modulus k for top of soil layer = 16300.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 16300.000 kN/ m**3

Layer 4 is sand, p-y criteria by Reese et al., 1974

Distance from top of pile to top of layer = 11.000 m
 Distance from top of pile to bottom of layer = 11.500 m
 p-y subgrade modulus k for top of soil layer = 33900.000 kN/ m**3
 p-y subgrade modulus k for bottom of layer = 33900.000 kN/ m**3

(Depth of lowest layer extends .00 m below pile tip)

Effective Unit Weight of Soil vs. Depth

Distribution of effective unit weight of soil with depth
is defined using 8 points

| Point No. | Depth X m | Eff. Unit Weight kN/ m**3 |
|--------------|--------------|------------------------------|
| 1 | .00 | 16.50000 |
| 2 | 1.00 | 16.50000 |
| 3 | 1.00 | 6.70000 |
| 4 | 4.00 | 6.70000 |
| 5 | 4.00 | 7.80000 |
| 6 | 11.00 | 7.80000 |
| 7 | 11.00 | 9.80000 |
| 8 | 11.50 | 9.80000 |

Shear Strength of Soils

Distribution of shear strength parameters with depth
defined using 8 points

| Point No. | Depth X m | Cohesion c kN/ m**2 | Angle of Friction Deg. | E50 or k_rm | RQD % |
|--------------|--------------|------------------------|---------------------------|----------------|----------|
| 1 | .000 | .00000 | 29.00 | ----- | ----- |
| 2 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 3 | 1.000 | .00000 | 29.00 | ----- | ----- |
| 4 | 4.000 | .00000 | 29.00 | ----- | ----- |
| 5 | 4.000 | .00000 | 30.00 | ----- | ----- |
| 6 | 11.000 | .00000 | 30.00 | ----- | ----- |
| 7 | 11.000 | .00000 | 36.00 | ----- | ----- |
| 8 | 11.500 | .00000 | 36.00 | ----- | ----- |

Notes:

- (1) Cohesion = uniaxial compressive strength for rock materials.
- (2) Values of E50 are reported for clay strata.
- (3) Default values will be generated for E50 when input values are 0.
- (4) RQD and k_rm are reported only for weak rock strata.

p-y Modification Factors

Distribution of p-y multipliers with depth defined using 2 points

| Point No. | Depth X m | p-mult | y-mult |
|--------------|--------------|--------|--------|
| 1 | .000 | .3000 | 1.0000 |
| 2 | 11.500 | .3000 | 1.0000 |

Loading Type

Cyclic loading criteria was used for computation of p-y curves

Number of cycles of loading = 20.

File-head Loading and File-head Fixity Conditions

Number of loads specified = 10

Load Case Number 1

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 20.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

.
[ABRIDGED]
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Load Case Number 10

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Shear force at pile head = 200.000 kN

Slope at pile head = .000 m/ m

Axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head condition)

Computations of Ultimate Moment Capacity and Nonlinear Bending Stiffness

Pile Description:

The pile shape is a rectangular solid pile.

Width = .355 m

Depth = .355 m

Material Properties:

Compressive Strength of Concrete = 41370.000 kN/ m**2

Yield Stress of Reinforcement = 262000. kN/ m**2

Modulus of Elasticity of Reinforcement = 206850000. kN/ m**2

Number of Reinforcing Bars = 4

Area of Single Bar = .00050 m**2

Number of Rows of Reinforcing Bars = 2

Cover Thickness (edge to bar center) = .076 m

Ultimate Axial Squash Load Capacity = 4703.81 kN

Distribution and Area of Steel Reinforcement

| Row Number | Area of Reinforcement m**2 | Distance to Centroidal Axis m |
|------------|-------------------------------|----------------------------------|
| 1 | .000600 | .1020 |
| 2 | .000600 | -.1020 |

Axial Thrust Force = 890.00 kN

| Bending Moment kN-m | Bending Stiffness kN-m2 | Bending Curvature rad/m | Maximum Strain m/m | Neutral Axis Position m |
|------------------------|----------------------------|----------------------------|-----------------------|----------------------------|
| 1.54295127 | 39190.962 | .00003937 | .00023366 | 5.93486814 |
| 7.71444547 | 39189.382 | .00019685 | .00026170 | 1.32942587 |
| 13.885 | 39185.750 | .00035433 | .00028986 | .81803677 |
| 20.053 | 39179.988 | .00051181 | .00031813 | .62158314 |
| 26.218 | 39172.157 | .00066929 | .00034653 | .51775257 |
| 32.378 | 39162.188 | .00082677 | .00037504 | .45362225 |
| 38.534 | 39150.185 | .00098425 | .00040367 | .41013020 |
| 44.683 | 39136.085 | .00114173 | .00043242 | .37873943 |
| 50.825 | 39119.844 | .00129921 | .00046129 | .35505146 |
| 56.988 | 39121.516 | .00145669 | .00049033 | .33660160 |
| 63.049 | 39059.507 | .00161417 | .00051931 | .32172146 |
| 69.110 | 39008.681 | .00177165 | .00054844 | .30956600 |
| 75.155 | 38958.023 | .00192913 | .00057769 | .29945812 |
| 81.088 | 38861.083 | .00208661 | .00060684 | .29082363 |
| 81.088 | 36133.990 | .00224409 | .00061495 | .27403133 |
| 81.088 | 33764.548 | .00240157 | .00063793 | .26562977 |
| 81.469 | 31835.639 | .00255906 | .00066017 | .25797573 |
| 83.923 | 30893.279 | .00271654 | .00068196 | .25104214 |
| 86.229 | 30003.115 | .00287402 | .00070333 | .24472065 |
| 88.411 | 29164.014 | .00303150 | .00072433 | .23893543 |
| 90.481 | 28372.973 | .00318898 | .00074498 | .23361065 |
| 92.458 | 27628.502 | .00334646 | .00076533 | .22869755 |
| 94.358 | 26929.177 | .00350394 | .00078544 | .22415821 |
| 96.109 | 26249.199 | .00366142 | .00080493 | .21984097 |
| 97.855 | 25623.877 | .00381890 | .00082447 | .21589207 |
| 99.561 | 25038.090 | .00397638 | .00084391 | .21223026 |
| 110.590 | 21442.569 | .00515748 | .00098201 | .19040569 |
| 120.077 | 18943.856 | .00633858 | .00111351 | .17567181 |
| 128.620 | 17104.480 | .00751969 | .00124079 | .16500599 |
| 136.481 | 15686.050 | .00870079 | .00136470 | .15684818 |
| 143.755 | 14547.283 | .00988189 | .00148690 | .15046711 |
| 145.817 | 13180.644 | .01106299 | .00158671 | .14342518 |
| 147.540 | 12049.856 | .01224409 | .00168395 | .13753162 |
| 148.999 | 11098.438 | .01342520 | .00177927 | .13253185 |
| 150.255 | 10286.974 | .01460630 | .00187345 | .12826336 |
| 151.236 | 9579.525 | .01578740 | .00196414 | .12441196 |
| 152.156 | 8966.965 | .01696850 | .00205603 | .12116726 |
| 153.062 | 8433.379 | .01814961 | .00214772 | .11833424 |
| 153.569 | 7944.317 | .01933071 | .00223691 | .11571789 |
| 154.075 | 7511.548 | .02051181 | .00232536 | .11336697 |
| 154.597 | 7126.607 | .02169291 | .00242001 | .11155773 |

| | | | | |
|---------|----------|-----------|-----------|-----------|
| 154.870 | 6770.554 | .02287402 | .00250841 | .10966183 |
| 155.085 | 6447.050 | .02405512 | .00259871 | .10803135 |
| 155.264 | 6152.428 | .02523622 | .00269049 | .10661213 |
| 155.477 | 5885.409 | .02641732 | .00278965 | .10559917 |
| 155.534 | 5635.593 | .02759843 | .00288088 | .10438580 |
| 155.547 | 5404.764 | .02877953 | .00297346 | .10331867 |
| 155.550 | 5191.809 | .02996063 | .00306693 | .10236530 |
| 155.550 | 4994.901 | .03114173 | .00316169 | .10152569 |
| 155.550 | 4812.383 | .03232283 | .00325744 | .10077816 |
| 155.550 | 4642.734 | .03350394 | .00336721 | .10050190 |
| 155.550 | 4484.639 | .03468504 | .00346243 | .09982479 |
| 155.550 | 4336.956 | .03586614 | .00355857 | .09921810 |
| 155.550 | 4198.689 | .03704724 | .00365529 | .09866558 |
| 155.550 | 4068.967 | .03822835 | .00375256 | .09816181 |
| 155.550 | 3947.020 | .03940945 | .00418210 | .10611919 |

Ultimate Moment Capacity at a Concrete Strain of 0.003 = 155.548 m- kN

Computed Values of Load Distribution and Deflection
for Lateral Loading for Load Case Number 1

File-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 20.000 kN
Specified slope at pile head = 0.000E+00 m/ m
Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. Y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .003250 | -35.2968 | 20.0000 | -4.34E-17 | 1.19E+04 | 36140.000 | 0.000 |
| .575 | .003105 | -23.8112 | 19.1013 | -4.70E-04 | 1.03E+04 | 36140.000 | -3.637 |
| 1.150 | .002742 | -13.2527 | 16.3651 | -7.63E-04 | 8873.0 | 36140.000 | -5.151 |
| 1.725 | .002256 | -4.3402 | 13.0075 | -9.00E-04 | 7656.1 | 36140.000 | -6.353 |
| 2.300 | .001730 | 2.5372 | 9.2691 | -9.12E-04 | 7409.9 | 36140.000 | -6.490 |
| 2.875 | .001225 | 7.2732 | 5.7183 | -8.31E-04 | 8056.6 | 36140.000 | -5.741 |
| 3.450 | 7.84E-04 | 10.0685 | 2.7802 | -6.91E-04 | 8438.2 | 36140.000 | -4.413 |
| 4.025 | 4.35E-04 | 11.3297 | .3509 | -5.19E-04 | 8610.4 | 36140.000 | -8.714 |
| 4.600 | 1.88E-04 | 10.5547 | -3.3539 | -3.42E-04 | 8504.6 | 36140.000 | -4.300 |
| 5.175 | 3.68E-05 | 8.2444 | -4.8036 | -1.92E-04 | 8189.2 | 36140.000 | -.942768 |
| 5.750 | -3.97E-05 | 5.5210 | -4.6914 | -8.22E-05 | 7817.3 | 36140.000 | 1.129 |
| 6.325 | -6.54E-05 | 3.0951 | -3.7318 | -1.43E-05 | 7486.1 | 36140.000 | 2.046 |
| 6.900 | -6.24E-05 | 1.2977 | -2.5025 | 1.98E-05 | 7240.7 | 36140.000 | 2.126 |
| 7.475 | -4.70E-05 | .1798 | -1.3792 | 3.07E-05 | 7088.0 | 36140.000 | 1.733 |
| 8.050 | -2.95E-05 | -.3714 | -.5423 | 2.86E-05 | 7114.2 | 36140.000 | 1.171 |
| 8.625 | -1.51E-05 | -.5317 | -2.56E-02 | 2.10E-05 | 7136.1 | 36140.000 | .642715 |
| 9.200 | -5.45E-06 | -.4717 | .2232 | 1.28E-05 | 7127.9 | 36140.000 | .247101 |
| 9.775 | -3.63E-08 | -.3222 | .2882 | 6.45E-06 | 7107.5 | 36140.000 | .001749 |
| 10.350 | 2.44E-06 | -.1663 | .2487 | 2.59E-06 | 7086.2 | 36140.000 | -.124069 |
| 10.925 | 3.36E-06 | -4.82E-02 | .1591 | 9.52E-07 | 7070.1 | 36140.000 | -.180467 |
| 11.500 | 3.79E-06 | 0.0 | 0.0 | 6.87E-07 | 7063.5 | 36140.000 | -.311409 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 1:

Pile-head deflection = .00324962 m
 Computed slope at pile head = -4.33681E-17
 Maximum bending moment = -35.297 kN- m
 Maximum shear force = 20.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 5
 Number of zero deflection points = 2

----- Computed Values of Load Distribution and Deflection for Lateral Loading for Load Case Number 2 -----

Pile-head boundary conditions are Shear and Slope (BC Type 2)

Specified shear force at pile head = 40.000 kN
 Specified slope at pile head = 0.000E+00 m/ m
 Specified axial load at pile head = 890.000 kN

(Zero slope for this load indicates fixed-head conditions)

| Depth X m | Deflect. y m | Moment M kN- m | Shear V kN | Slope S Rad. | Total Stress kN/ m**2 | Flx. Rig. EI kN- m**2 | Soil Res p kN/ m |
|-----------------|--------------------|----------------------|------------------|--------------------|-----------------------------|-----------------------------|------------------------|
| 0.000 | .006955 | -73.7808 | 40.0000 | 2.64E-17 | 1.71E+04 | 36140.000 | 0.000 |
| .575 | .006651 | -50.6821 | 38.9019 | -9.90E-04 | 1.40E+04 | 36140.000 | -4.743 |
| 1.150 | .005883 | -28.7626 | 34.3624 | -.001619 | 1.10E+04 | 36140.000 | -10.163 |
| 1.725 | .004850 | -9.8239 | 28.0662 | -.001922 | 8404.8 | 36140.000 | -12.580 |
| 2.300 | .003723 | 5.0753 | 20.1427 | -.001954 | 7756.5 | 36140.000 | -13.970 |
| 2.875 | .002640 | 15.3748 | 12.4934 | -.001785 | 9162.7 | 36140.000 | -12.378 |
| 3.450 | .001694 | 21.4927 | 6.1543 | -.001487 | 9998.1 | 36140.000 | -9.530 |
| 4.025 | 9.43E-04 | 24.3000 | .9020 | -.001119 | 1.04E+04 | 36140.000 | -18.861 |
| 4.600 | 4.10E-04 | 22.7003 | -7.1296 | -7.39E-04 | 1.02E+04 | 36140.000 | -9.348 |
| 5.175 | 8.19E-05 | 17.7659 | -10.2970 | -4.15E-04 | 9489.2 | 36140.000 | -2.099 |
| 5.750 | -8.39E-05 | 11.9193 | -10.0883 | -1.79E-04 | 8690.9 | 36140.000 | 2.387 |
| 6.325 | -1.40E-04 | 6.6980 | -8.0415 | -3.20E-05 | 7978.0 | 36140.000 | 4.382 |
| 6.900 | -1.34E-04 | 2.8221 | -5.4030 | 4.18E-05 | 7448.8 | 36140.000 | 4.570 |
| 7.475 | -1.01E-04 | .4063 | -2.9853 | 6.58E-05 | 7119.0 | 36140.000 | 3.733 |
| 8.050 | -6.37E-05 | -.7887 | -1.1804 | 6.14E-05 | 7171.2 | 36140.000 | 2.528 |
| 8.625 | -3.27E-05 | -1.1400 | -6.35E-02 | 4.52E-05 | 7219.2 | 36140.000 | 1.391 |
| 9.200 | -1.19E-05 | -1.0146 | .4762 | 2.77E-05 | 7202.0 | 36140.000 | .538343 |
| 9.775 | -1.65E-07 | -.6943 | .6193 | 1.40E-05 | 7158.3 | 36140.000 | .007951 |
| 10.350 | 5.21E-06 | -.3589 | .5359 | 5.66E-06 | 7112.5 | 36140.000 | -.265151 |
| 10.925 | 7.23E-06 | -.1042 | .3436 | 2.12E-06 | 7077.7 | 36140.000 | -.388693 |
| 11.500 | 8.20E-06 | 0.0 | 0.0 | 1.55E-06 | 7063.5 | 36140.000 | -.673827 |

Please note that because this analysis makes computations of ultimate moment capacity and pile response using nonlinear bending stiffness that the above values of total stress due to combined axial stress and bending may not be representative of actual conditions.

Output Verification:

Computed forces and moments are within specified convergence limits.

Output Summary for Load Case No. 2:

Pile-head deflection = .00695511 m
 Computed slope at pile head = 2.63980E-17
 Maximum bending moment = -73.781 kN- m
 Maximum shear force = 40.000 kN
 Depth of maximum bending moment = 0.000 m
 Depth of maximum shear force = 0.000 m
 Number of iterations = 7
 Number of zero deflection points = 2

.[ABRIDGED]

Summary of Pile-head Response

Definition of symbols for pile-head boundary conditions:

y = pile-head displacement, m

M = pile-head moment, kN- m

V = pile-head shear force, kN

S = pile-head slope, radians

R = rotational stiffness of pile-head, m- kN/rad

| BC Type | Boundary Condition | Boundary Condition | Axial Load | Pile Head Deflection | Maximum Moment | Maximum Shear |
|------------|-----------------------|-----------------------|---------------|-------------------------|-------------------|------------------|
| | 1 | 2 | kN | m | m- kN | kN |
| 2 | V= 20.000 | S= 0.000 | 890.0000 | .003250 | -35.2968 | 20.0000 |
| 2 | V= 40.000 | S= 0.000 | 890.0000 | .006955 | -73.7808 | 40.0000 |
| 2 | V= 60.000 | S= 0.000 | 890.0000 | .011498 | -116.6035 | 60.0000 |
| 2 | V= 80.000 | S= 0.000 | 890.0000 | .016553 | -161.2939 | 80.0000 |
| 2 | V= 100.000 | S= 0.000 | 890.0000 | .022735 | -210.8144 | 100.0000 |
| 2 | V= 120.000 | S= 0.000 | 890.0000 | .030344 | -265.1962 | 120.0000 |
| 2 | V= 140.000 | S= 0.000 | 890.0000 | .039597 | -324.1805 | 140.0000 |
| 2 | V= 160.000 | S= 0.000 | 890.0000 | .050707 | -387.6993 | 160.0000 |
| 2 | V= 180.000 | S= 0.000 | 890.0000 | .063563 | -455.0322 | 180.0000 |
| 2 | V= 200.000 | S= 0.000 | 890.0000 | .078336 | -526.1806 | 200.0000 |

The analysis ended normally.

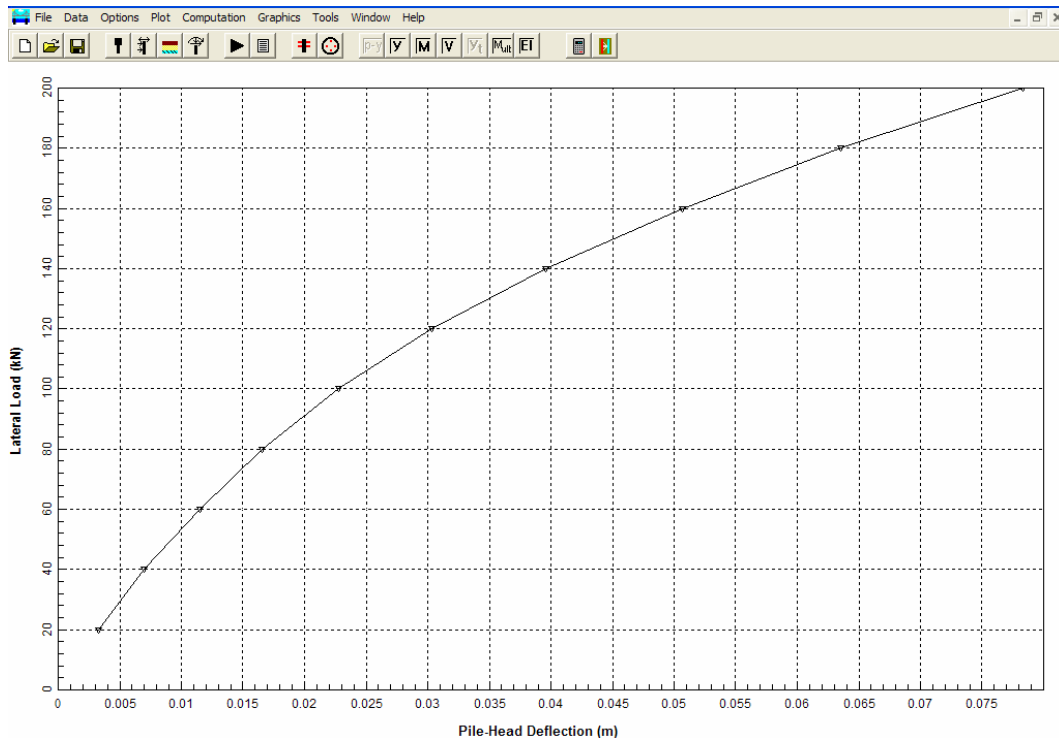


Figure F.48 North Abutment LPILE analysis—Third Row Lateral Load vs Pile Head Deflection

STEP 3 Estimate group deflection under lateral load.

- a. Plot the Lateral Load vs. Pile Head Deflection Curves for each Row (shown in Figures F.46, F.47 and F.48) on the same plot. Average the loads for a given deflection to determine the average group response to a lateral load as shown in Figure F.49.
- b. Divide the lateral load to be resisted (900 kN) by number of piles (24) to determine the average lateral load resisted per pile. Estimate the group deflection from the average group deflection curve at this load. From Figure F.49, the average group deflection for an approximately 40 kN per pile lateral load is 5.4 mm.

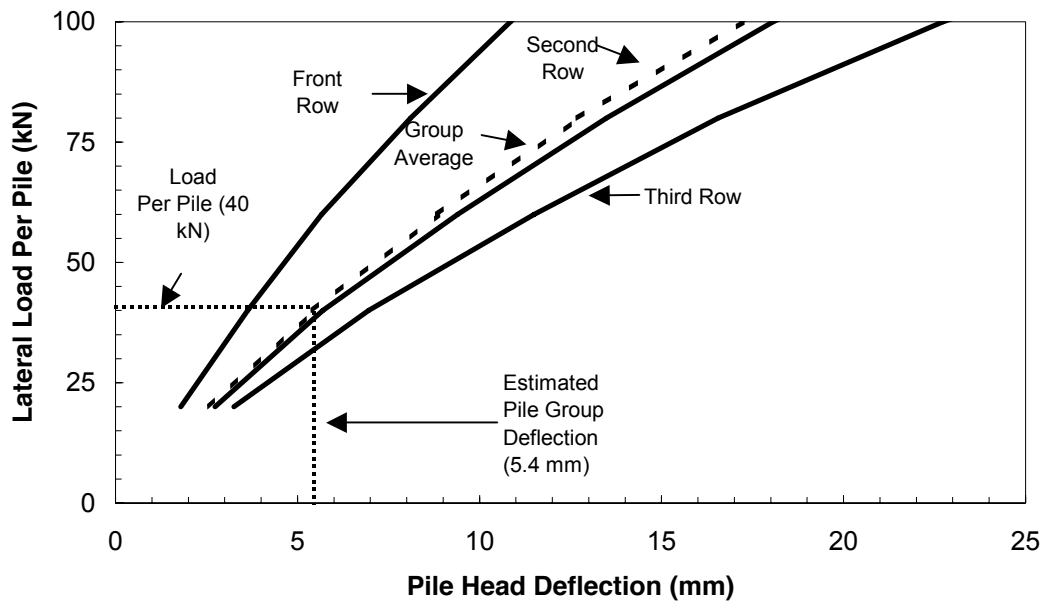


Figure F.49 Average Group Deflection vs. Lateral Load Curves

STEP 4. Evaluate pile structural acceptability.

- Plot the maximum bending moment versus deflection for each row of piles as shown in Figure F.50. This plot can be constructed from the “Summary of Pile Head Response” tables shown in the LPILE numeric summaries.
- Check the structural adequacy for each row of piles. Using the 5.4 mm estimated group deflection, determine the maximum bending moment. In this example, the graphs show maximum bending moments of 84, 64 and 58 kN-m for the front, second and third rows, respectively.
- In the LPILE “Load Case Number...” output tables, find the maximum bending moment and determine the maximum pile stress associated with it. For the North abutment, maximum bending moments of 84, 64 and 58 kN-m in rows 1, 2 and 3, respectively, correspond to Total Stresses of 19,000; 16,000; and 14,500 kPa.
- Compare maximum pile stresses to the pile yield stress. Assuming a 34,500 kPa compressive strength and a prestress level of 6,900 kPa, the maximum total stress of 19,000 kPa is within normally recommended limits.

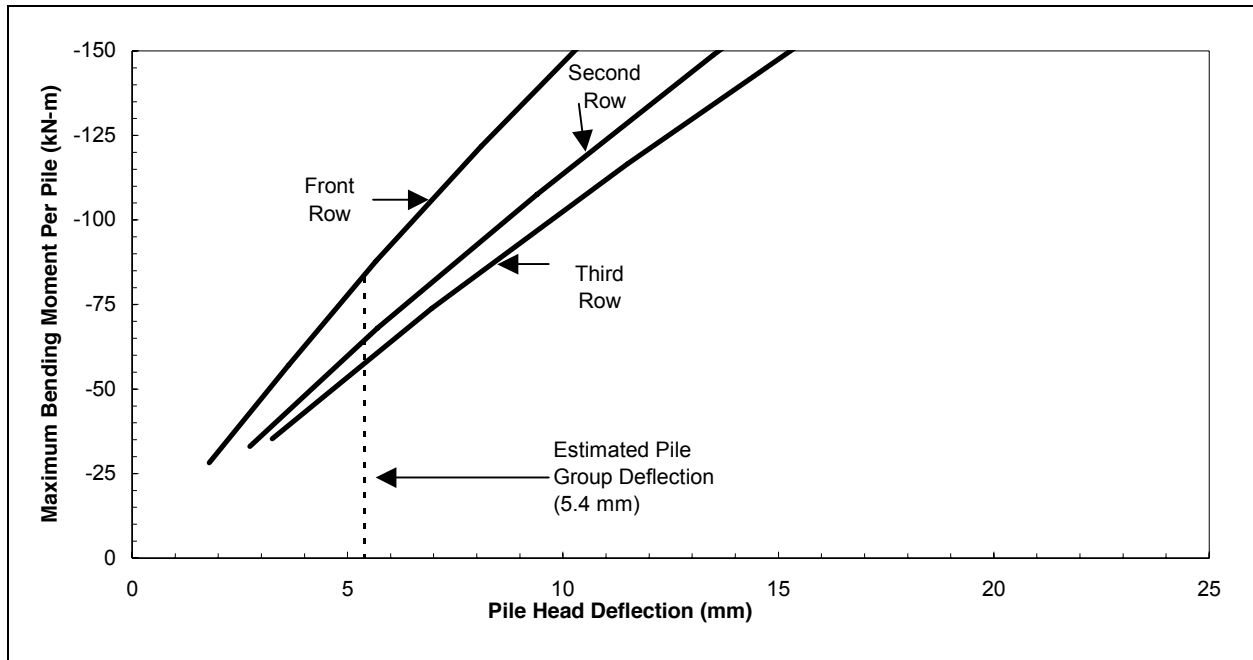


Figure F.50 Maximum Bending Moment vs Pile Head Deflection

- STEP 5 Perform refined pile group evaluation that considers superstructure-substructure interaction. These analyses are not shown here, but can be performed with FBPIER or other methods.
- STEP 6 Repeat for each Pier and the South Abutment. These analyses are not included in this discussion.

F.9 PRECONSTRUCTION DRIVEABILITY ANALYSES WITH GRLWEAP

As noted in Chapter 12.11, the proposed pile sections and minimum pile penetrations should be evaluated by using a wave equation program to ensure the piles can be safely installed. Using the static soil analyses calculated by Driven in sections F.2.1.4, F.2.2.7, F.2.3.3, and F.2.4.3., GRLWEAP driveability files are generated. The hammer and driving system data is input, the depths to be analyzed are refined, and the analysis is run. The input and output results will be summarized here.

For each soil profile, the following hammer was selected based on local availability. It is used to evaluate installation penetration resistance and stresses with a “typical” hammer; once a contractor is selected, further wave equation studies should be performed or submitted to check the hammer that will actually be used to install the piles on the site.

| | |
|-----------------------|---|
| Hammer | Conmaco 140 (single acting air) 56.9 kJ rated energy; 62.2 kN ram, 0.91 m stroke |
| Hammer Cushion | 152 mm Blue Nylon |
| Helmet | 18.09 kN |
| Pile Cushion | 254 mm Plywood (Concrete Piles only) |

F.9.1 North Abutment Preconstruction Driveability

This analysis was initially generated from the Soil Boring S-1 file in Driven. Driven created a GRLWEAP input file that included the general pile properties, a detailed soil resistance distribution and soil damping, quake and set-up parameters based on the soil type. The hammer and driving system parameters were entered, the gain/loss factor was selected as 1.0 for both shaft and toe (per Table 9-20), and the depths for analysis were set every 0.5 m to the pile penetration. The analysis was run, and the results follow. In this case, penetration resistance is greater than 25 blows per 0.25 m, and the pile compressive and tensile stresses are with FHWA limits for typical prestressed concrete piles.

File Settings View Options Tools Window Help

SI Variable Resistance Distr Uniform Pile Driveability

Boring S-1: 09/19/2003: BRR

Hammer Information
Select from following list [8/5/2003-2003]: ID: 182

| ID | Name | Type | Ram Wt | Energy/Power |
|-----|-----------------|------|---------|--------------|
| 181 | CONMACO C 125E5 | ECH | 55.6250 | 84.773 |
| 182 | CONMACO C 140 | ECH | 62.3000 | 56.967 |
| 183 | CONMACO C 160 | ECH | 72.3125 | 66.123 |

Hammer parameters
Efficiency: 0.670
Stroke: 0.91 m
Type: ECH Fixed

Pile material
☒ Concrete ☐ Steel ☐ Timber

Cushion Information

| | Hammer | Pile | Unit |
|-----------------|--------|--------|-----------------|
| Area | 1596.8 | 1264.6 | cm ² |
| Elastic Modulus | 1207.0 | 207.0 | MPa |
| Thickness | 152.0 | 254.0 | mm |
| C.O.R. | 0.92 | 0.5 | |
| Stiffness | 0.0 | 0.0 | kN/mm |
| Helmet Weight | 18.09 | | kN |

Pile Information

| | | | | |
|----------------|---------|-------------------|------|----------|
| Length | 14.5 | m | Auto | Segments |
| Penetration | 14.5 | m | Auto | S-Length |
| Section Area | 1267.36 | cm ² | Auto | S-St, Wt |
| Elast Modulus | 34500.0 | MPa | | |
| Spec Weight | 23.6 | kN/m ³ | | |
| Strength/Yield | 28.0 | MPa | 0 | Splices |

Resistance Gain/Loss Factors

| Shaft | | Toe | |
|-------|-----|-----|-----|
| 1 | 1.0 | 1 | 1.0 |
| 2 | 0.0 | 2 | 0.0 |
| 3 | 0.0 | 3 | 0.0 |
| 4 | 0.0 | 4 | 0.0 |
| 5 | 0.0 | 5 | 0.0 |

Incr: 0 Action >>

Toe Area: 1.0 cm²
Top Circum: 1.42 m

Soil Parameters

Quake
Shaft: 0.0 mm Const
Toe: 0.0 mm

Damping
Shaft: 0.0 s/m Const
Toe: 0.0 s/m Smith

Shaft Resistance
Percentage: 0 %
Dist. Shape Num: 0.0

Residual Stress Analysis: No

CONMACO C 14
152.00 mm
18.09 kN
254.00 mm

0
2
4
6
8
10
12
14
14.5

Press F1 for General Help Topics or F3 for Specific Help on Current Parameters

The new depth, 19.500, must be equal to or less than NUM

Figure F 51 GRLWEAP Main Input Screen

Input File Contents

Boring S-1 : 09/19/2003 : BRR

| OUT | OSG | HAM | STR | FUL | PEL | N | SPL | N-U | P-D | %SK | ISM | 0 | PHI | RSA | ITR | H-D | MXT | DEx |
|------|-----|-----|-----|-----|-----|---|-----|-----|-----|-----|-----|---|-----|-----|-----|-----|-----|-------|
| -100 | 0 | 182 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000 |

File g Hammer g
9.810 9.810

| W Cp | A Cp | E Cp | T Cp | CoR | ROut | StCp |
|--------|----------|--------|---------|-------|-------|------|
| 18.090 | 1596.800 | 1207.0 | 152.000 | 0.920 | 3.000 | 0.0 |

| A Cu | E Cu | T Cu | CoR | ROut | StCu |
|----------|-------|---------|-------|-------|------|
| 1264.500 | 207.0 | 254.000 | 0.500 | 3.000 | 0.0 |

| LPle | APle | EPle | WPle | Circ | Strg | CoR | ROut |
|--------|----------|-----------|--------|-------|--------|-------|-------|
| 14.500 | 1267.360 | 34500.000 | 23.600 | 1.420 | 28.000 | 1.000 | 0.010 |

Manufac Hmr Name HmrType No Seg-s
CONMACO C 140 3 1

| Ram Wt | Ram L | Ram Dia | MaxStrk | RtdStrk | Efficy |
|--------|---------|---------|---------|---------|--------|
| 62.30 | 1397.00 | 612.65 | 0.91 | 0.91 | 0.67 |

No. Assmbly Segs
2

<---- Assembly Masses ----><----Assembly Stiffnesses---->

| Stroke | Effic. | Pressure | R-Weight | T-Delay | Exp-Coeff | Eps-Str | Qs | Qt | Js | Jt | Qx | Jx | Rati | Dept |
|--------|--------|----------|----------|---------|-----------|---------|-------|-------|-------|-------|-------|-------|-------|--------|
| 37.291 | 37.291 | 0.000 | 12540.6 | 12540.6 | 0.0 | 0.0100 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.0000 |

Research Soil Model: Atoe, Plug, Gap, Q-fac
0.000 0.000 0.000 0.000

Research Soil Model: RD-skn: m, d, toe: m, d
0.000 0.000 0.000 0.000

Res. Distribution

| Dpth | Rskn | Rtoe | Qs | Qt | Js | Jt | SU F | RelE | SU T |
|-------|--------|--------|------|------|------|------|------|------|------|
| 0.01 | 0.00 | 0.00 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 2.49 | 0.00 | 0.00 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 2.50 | 18.34 | 77.01 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 3.01 | 22.08 | 80.82 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 3.99 | 29.28 | 80.82 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 4.01 | 29.38 | 80.82 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 6.99 | 38.26 | 80.82 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 7.01 | 47.44 | 125.39 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 10.01 | 60.33 | 125.39 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 13.01 | 73.21 | 125.39 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 13.99 | 77.41 | 125.39 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 14.01 | 138.65 | 919.89 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 14.49 | 143.29 | 919.89 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |
| 14.51 | 143.48 | 919.89 | 2.54 | 2.97 | 0.16 | 0.50 | 1.00 | 0.00 | 0.00 |

Gain/Loss factors: shaft and toe

| Dpth | L | Wait | Strk | Pmx% | Eff. | Stff | CoR |
|------|-------|------|-------|-------|-------|-------|-------|
| 0.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

. [ABRIDGED]

| Dpth | L | Wait | Strk | Pmx% | Eff. | Stff | CoR |
|-------|-------|------|-------|-------|-------|-------|-------|
| 10.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 10.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 11.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 11.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 13.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 13.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14.00 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14.50 | 14.50 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.00 | 0.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

GRLWEAP: WAVE EQUATION ANALYSIS OF PILE FOUNDATIONS
Version 2003
SI Units

Boring S-1 : 09/19/2003 : BRR

| | | | | | | |
|-------------------|--------------|-----------------|-------|-------------|-----------------|---------|
| Hammer Model: | | C 140 | | Made by: | | CONMACO |
| No. | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | Dampg kN/m/s | |
| 1 | 62.300 | | | | | |
| Helmet | 18.090 | 1231.0 | 0.920 | 3.0000 | 111.8 | |
| Cushion | | 103.1 | 0.500 | 3.0000 | | |
| Combined Pile Top | | 100.8 | | | | |
| Assembly | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | | |
| 1 | 37.291 | 12540.6 | | | | |
| 2 | 37.291 | 12540.6 | 0.800 | 3.0480 | | |

HAMMER OPTIONS:

| | | | |
|--------------------|-----|-------------|-----------|
| Hammer File ID No. | 182 | Hammer Type | Ext.Comb. |
|--------------------|-----|-------------|-----------|

HAMMER DATA:

| | | | | | |
|---------------------|------|-------|--------------------|------|---------|
| Ram Weight | (kN) | 62.30 | Ram Length | (mm) | 1397.00 |
| Maximum (Eq) Stroke | (m) | 0.91 | Actual (Eq) Stroke | (m) | 0.91 |
| Efficiency | | 0.670 | | | |

| | | | | | |
|----------------|------|-------|------------------|-------|-------|
| Rated Energy | (kJ) | 56.97 | Potential Energy | (kJ) | 56.69 |
| Kinetic Energy | (kJ) | 37.98 | Impact Velocity | (m/s) | 3.46 |

HAMMER CUSHION

| | | | | | |
|----------------------|---------|---------|----------------------|---------|---------|
| Cross Sect. Area | (cm2) | 1596.80 | PILE CUSHION | | |
| Elastic-Modulus | (MPa) | 1207.0 | Cross Sect. Area | (cm2) | 1264.50 |
| Thickness | (mm) | 152.00 | Elastic-Modulus | (MPa) | 207.0 |
| Coeff of Restitution | | 0.920 | Thickness | (mm) | 254.00 |
| RoundOut | (mm) | 3.0 | Coeff of Restitution | | 0.500 |
| Stiffness | (kN/mm) | 1268.0 | RoundOut | (mm) | 3.0 |
| | | | Stiffness | (kN/mm) | 103.1 |

Boring S-1 : 09/19/2003 : BRR
GRL Engineers, Inc.

2003/09/24
GRLWEAP(TM) Version 2003

Depth (m) 0.5
Shaft Gain/Loss Factor 1.000 Toe Gain/Loss Factor 1.000

PILE PROFILE:

| L b Top | Area | E-Mod | Spec Wt | Circmf | Strength | Wave Sp | EA/c |
|---------|--------|--------|---------|--------|----------|---------|---------|
| m | cm2 | MPa | kN/m3 | m | MPa | m/s | kN/m/s |
| 0.00 | 1267.4 | 34500. | 23.60 | 1.420 | 28.00 | 3787. | 1154.60 |
| 14.50 | 1267.4 | 34500. | 23.60 | 1.420 | 28.00 | 3787. | 1154.60 |

Wave Travel Time 2L/c (ms) 7.658

| Pile and Soil Model | | | | | | Total Capacity Rut | | | (kN) | | | 0.0 |
|---------------------|--------|--------|-------|-------|------|--------------------|--------|-------|-------|-------|--------|-----|
| No. | Weight | Stiffn | C-Slk | T-Slk | CoR | Soil-S | Soil-D | Quake | LbTop | Circm | Area | |
| | kN | kN/mm | mm | mm | | kN | s/m | mm | m | m | cm2 | |
| 1 | 2.891 | 4523. | 3.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.54 | 0.97 | 1.4 | 1267.4 | |
| 2 | 2.891 | 4523. | 0.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.54 | 1.93 | 1.4 | 1267.4 | |
| 15 | 2.891 | 4523. | 0.000 | 0.000 | 1.00 | 0.0 | 0.160 | 2.54 | 14.50 | 1.4 | 1267.4 | |
| Toe | | | | | | 0.0 | 0.500 | 2.97 | | | | |

PILE, SOIL, ANALYSIS OPTIONS:

Uniform pile
No. of Slacks/Splices 0
File Segments: Automatic
File Damping (%) 3
File Damping Fact.(kN/m/s) 69.276

Driveability Analysis

Soil Damping Option Smith
Max No Analysis Iterations 0 Time Increment/Critical 160
Output Time Interval 1 Analysis Time-Input (ms) 0
Output Level: Normal
Gravity Mass, Pile, Hammer: 9.810 9.810 9.810
Output Segment Generation: Automatic

| Depth | Stroke | Efficy | PileC.St. | PileC.CoR |
|-------|--------|--------|-----------|-----------|
| m | m | | kN/mm | |
| 0.50 | 0.91 | 0.670 | 103. | 0.500 |

INITIAL STATIC ANALYSIS: Total Wt, Sum(R) 136.0 0.0
Hammer+Pile Weight > Rult: Pile Runs

The remainder of the output file was omitted.

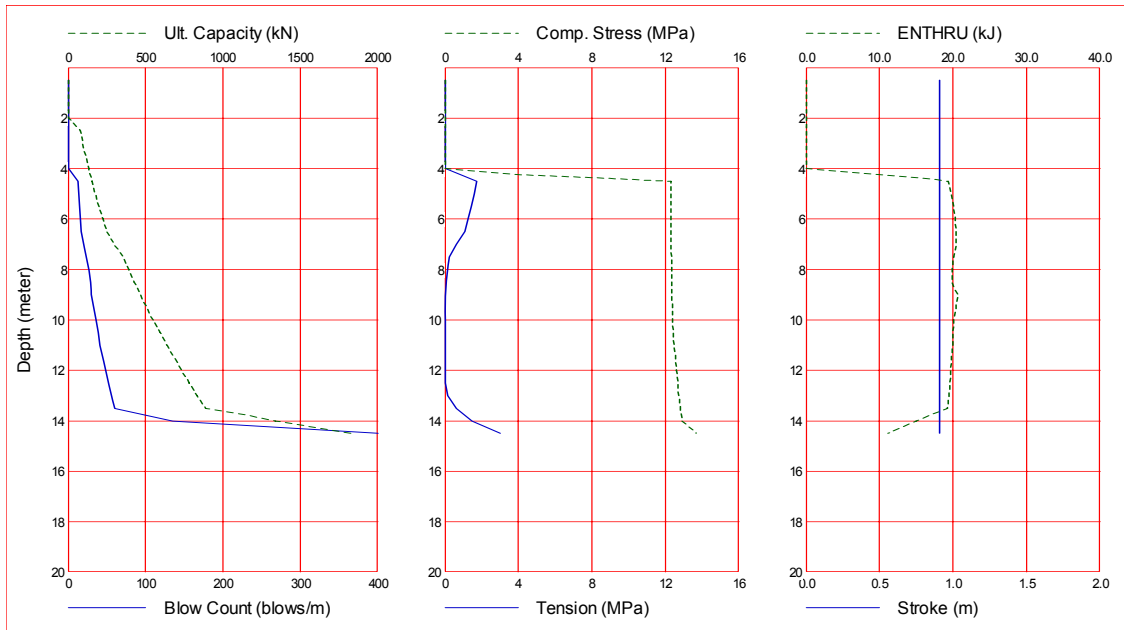


Figure F 52 North Abutment Graphical Driveability Results

Gain/Loss 1 at Shaft and Toe 1.000 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.5 | 77.1 | 0.1 | 77.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.0 | 95.2 | 14.5 | 80.7 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.5 | 112.2 | 31.4 | 80.8 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 4.0 | 131.7 | 50.9 | 80.8 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 4.5 | 153.1 | 72.3 | 80.8 | 13.0 | 12.316 | -1.725 | 0.91 | 19.4 |
| 5.0 | 175.5 | 94.7 | 80.8 | 13.8 | 12.316 | -1.587 | 0.91 | 19.8 |
| 5.5 | 199.0 | 118.2 | 80.8 | 14.6 | 12.317 | -1.439 | 0.91 | 20.1 |
| 6.0 | 223.6 | 142.7 | 80.8 | 15.5 | 12.319 | -1.272 | 0.91 | 20.3 |
| 6.5 | 249.1 | 168.3 | 80.8 | 16.5 | 12.321 | -1.087 | 0.91 | 20.4 |
| 7.0 | 298.1 | 195.0 | 103.1 | 19.4 | 12.325 | -0.625 | 0.91 | 20.4 |
| 7.5 | 354.8 | 229.4 | 125.4 | 23.7 | 12.332 | -0.222 | 0.91 | 20.1 |
| 8.0 | 390.7 | 265.3 | 125.4 | 26.4 | 12.341 | -0.139 | 0.91 | 19.9 |
| 8.5 | 428.2 | 302.8 | 125.4 | 28.7 | 12.350 | -0.054 | 0.91 | 19.9 |
| 9.0 | 467.2 | 341.8 | 125.4 | 29.9 | 12.363 | -0.003 | 0.91 | 20.6 |
| 9.5 | 507.7 | 382.3 | 125.4 | 33.0 | 12.379 | 0.000 | 0.91 | 20.4 |
| 10.0 | 549.7 | 424.3 | 125.4 | 36.0 | 12.413 | -0.005 | 0.91 | 20.1 |
| 10.5 | 593.3 | 467.9 | 125.4 | 38.7 | 12.454 | -0.010 | 0.91 | 20.0 |
| 11.0 | 638.4 | 513.0 | 125.4 | 41.5 | 12.501 | -0.015 | 0.91 | 20.0 |
| 11.5 | 685.0 | 559.6 | 125.4 | 44.6 | 12.550 | -0.023 | 0.91 | 19.8 |
| 12.0 | 733.1 | 607.7 | 125.4 | 48.2 | 12.606 | 0.000 | 0.91 | 19.7 |
| 12.5 | 782.8 | 657.4 | 125.4 | 52.0 | 12.672 | 0.000 | 0.91 | 19.6 |
| 13.0 | 834.0 | 708.6 | 125.4 | 55.9 | 12.740 | -0.136 | 0.91 | 19.5 |
| 13.5 | 886.7 | 761.3 | 125.4 | 59.9 | 12.807 | -0.637 | 0.91 | 19.3 |
| 14.0 | 1338.3 | 815.7 | 522.5 | 135.0 | 12.910 | -1.460 | 0.91 | 15.0 |
| 14.5 | 1835.5 | 915.6 | 919.9 | 445.4 | 13.671 | -3.005 | 0.91 | 11.1 |

Total Number of Blows: 487

Driving Time (min): 16 12 9 8 6 6 5 4 4 4

@Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

Table F.7 North Abutment Driveability Results

F.9.2 Pier 2 Preconstruction Driveability Analyses

The analyses performed for Pier 2 were discussed in detail in Chapter 16, Example 5 (Section 16.5.5). The input and output files are printed here.

F.9.2.1 Pier 2, Single Concrete Pile Example

FHWA - GRLWEAP EXAMPLE #5 - First Pile

Hammer Information
Select from following list [8/5/2003-2003]: ID: 182

| ID | Name | Type | Ram Wt | Energy/Power |
|-----|-----------------|------|--------|--------------|
| 181 | CONMACO C 125E5 | ECH | 55.625 | 84.773 |
| 182 | CONMACO C 140 | ECH | 62.300 | 56.967 |
| 183 | CONMACO C 160 | ECH | 72.313 | 66.123 |

Hammer parameters
Efficiency: 0.670
Stroke: 0.91 m
ECH
Fixed

Pile material
☒ Concrete ☐ Steel ☐ Timber

Cushion Information

| | Hammer | Pile | |
|-----------------|--------|--------|-----------------|
| Area | 1596.8 | 1264.5 | cm ² |
| Elastic Modulus | 1207.0 | 207.0 | MPa |
| Thickness | 152.0 | 254.0 | mm |
| C.O.R. | 0.92 | 0.5 | |
| Stiffness | 0.0 | 0.0 | kN/mm |
| Helmet Weight | 18.09 | | kN |

Pile Information

| | | | | |
|----------------|---------|-------------------|------|----------|
| Length | 14.5 | m | Auto | Segments |
| Penetration | 14.5 | m | Auto | S-Length |
| Section Area | 1260.3 | cm ² | Auto | S-St, Wt |
| Elast Modulus | 40000.0 | MPa | | |
| Spec Weight | 24.0 | kN/m ³ | | |
| Strength/Yield | 0.0 | MPa | 0 | Splices |

Resistance Gain/Loss Factors

| | 1 | 2 | 3 | 4 | 5 |
|---|-----|-----|---|---|---|
| 1 | 1.0 | 1.0 | | | |
| 2 | 0.0 | 0.0 | | | |
| 3 | 0.0 | 0.0 | | | |
| 4 | 0.0 | 0.0 | | | |
| 5 | 0.0 | 0.0 | | | |

Incr. 0 Action >>

Toe Area 1.0 cm²
Top Circum. 1.42 m

Soil Parameters

Quake
Shaft 2.5 mm Const
Toe 2.5 mm

Damping
Shaft 0.15 s/m Const
Toe 0.5 s/m Smith

Shaft Resistance
Percentage 0.0 %
Dist. Shape Num 0.0

Output the result for current input

The new depth, 19.500, must be equal to or less than NUM

Figure F 53 GRLWEAP Main Input Screen, Pier 2 Single Concrete

Input File Contents

```

FHWA - GRLWEAP EXAMPLE #5 - First Pile
OUT  OSG HAM STR FUL PEL  N  SPL N-U P-D %SK ISM  0  PHI RSA ITR H-D MXT      DEx
0    0 182  0  0  0  0  0  0  3  0  1  0  0  0  0  0  0  0.000
  File g  Hammer g
  9.810    9.810
    W Cp    A Cp          E Cp      T Cp          CoR      ROut      StCp
18.090 1596.800    1207.0 152.000    0.920    3.000    0.0
    A Cu    E Cu      T Cu      CoR      ROut      StCu
1264.500    207.0 254.000    0.500    3.000    0.0
    LPle    APle      EPle      WPle      Circ      Strg      CoR      ROut
14.500 1260.300 40000.000    24.000    1.420    0.000    0.850    3.000
Manufac Hmr Name HmrType No Seg-s
CONMACO C 140          3          1
  Ram Wt    Ram L      Ram Dia    MaxStrk    RtdStrk    Effic
62.30    1397.00    612.65      0.91      0.91      0.67
  No. Assmby Segs
2
<---- Assembly Masses ----><----Assembly Stiffnesses---->
37.291 37.291    0.000 12540.6 12540.6    0.0
Stroke  Effic.  Pressure  R-Weight  T-Delay  Exp-Coeff  Eps-Str
0.9100 0.6700    0.0000 0.0000 0.0000 0.0000 0.0100 0.0000
  Qs      Qt      Js      Jt      Qx      Jx      Rati  Dept
2.500 2.500    0.150 0.500 0.000 0.000 0.000 0.000
Research Soil Model: Atoe, Plug, Gap, Q-fac
0.000 0.000    0.000 0.000
Research Soil Model: RD-skn: m, d, toe: m, d
0.000 0.000    0.000 0.000
Res. Distribution
Dpth  Rskn  Rtoe    Qs    Qt    Js    Jt    SU F    RelE    SU T
0.00  0.00  0.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
0.50  28.17  954.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
3.50  44.87 1995.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
4.00  47.71  570.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
6.00  68.18  838.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
7.50  74.47  769.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
9.00  80.57  864.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
10.50 86.77 1147.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
12.00 92.97  844.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
13.50 99.21 1060.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
15.00 105.41 1127.00    0.00  0.00  0.00  0.00  0.00  0.00  0.00
Gain/Loss factors: shaft and toe
1.00000 0.00000 0.00000 0.00000 0.00000
1.00000 0.00000 0.00000 0.00000 0.00000
  Dpth  L      Wait    Strk    Pmx%    Eff.    Stff    CoR
  0.50  0.00  0.00    0.000  0.000  0.000  1.000  0.000
  1.00  0.00  0.00    0.000  0.000  0.000  1.500  0.000
  1.50  0.00  0.00    0.000  0.000  0.000  2.500  0.000
  2.00  0.00  0.00    0.000  0.000  0.000  2.750  0.000
  2.50  0.00  0.00    0.000  0.000  0.000  3.000  0.000
  2.75  0.00  0.00    0.000  0.000  0.000  3.250  0.000
  3.00  0.00  0.00    0.000  0.000  0.000  3.500  0.000
  3.25  0.00  0.00    0.000  0.000  0.000  3.600  0.000
  3.50  0.00  0.00    0.000  0.000  0.000  3.600  0.000
  3.60  0.00  0.00    0.000  0.000  0.000  3.700  0.000
  3.75  0.00  0.00    0.000  0.000  0.000  3.700  0.000
  3.80  0.00  0.00    0.000  0.000  0.000  3.700  0.000
  4.00  0.00  0.00    0.000  0.000  0.000  3.700  0.000
  4.25  0.00  0.00    0.000  0.000  0.000  3.750  0.000
.
.[ABRIDGED]
.
  10.00  0.00  0.00    0.000  0.000  0.000  3.960  0.000
  10.50  0.00  0.00    0.000  0.000  0.000  3.970  0.000
  11.00  0.00  0.00    0.000  0.000  0.000  3.970  0.000
  11.50  0.00  0.00    0.000  0.000  0.000  3.980  0.000
  12.00  0.00  0.00    0.000  0.000  0.000  3.980  0.000
  12.50  0.00  0.00    0.000  0.000  0.000  4.000  0.000
  13.00  0.00  0.00    0.000  0.000  0.000  3.990  0.000
  13.50  0.00  0.00    0.000  0.000  0.000  4.000  0.000
  14.00  0.00  0.00    0.000  0.000  0.000  4.000  0.000

```

GRLWEAP: WAVE EQUATION ANALYSIS OF PILE FOUNDATIONS
Version 2003
SI Units

FHWA - GRLWEAP EXAMPLE #5 - First Pile

| Hammer Model: | | | C 140 | Made by: | | CONMACO |
|----------------------|--------------|-----------------|--------------|----------------------|-----------------|---------------|
| No. | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | Dampg kN/m/s | |
| 1 | 62.300 | | | | | |
| Helmet | 18.090 | 1231.0 | 0.920 | 3.0000 | 111.8 | |
| Cushion | | 103.1 | 0.500 | 3.0000 | | |
| Combined Pile Top | | 101.1 | | | | |
| Assembly | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | | |
| 1 | 37.291 | 12540.6 | | | | |
| 2 | 37.291 | 12540.6 | 0.800 | 3.0480 | | |
| HAMMER OPTIONS: | | | | | | |
| Hammer File ID No. | | 182 | Hammer Type | | Ext.Comb. | |
| HAMMER DATA: | | | | | | |
| Ram Weight | | (kN) | 62.30 | Ram Length | | (mm) 1397.00 |
| Maximum (Eq) Stroke | | (m) | 0.91 | Actual (Eq) Stroke | | (m) 0.91 |
| Efficiency | | | 0.670 | | | |
| Rated Energy | | (kJ) | 56.97 | Potential Energy | | (kJ) 56.69 |
| Kinetic Energy | | (kJ) | 37.98 | Impact Velocity | | (m/s) 3.46 |
| HAMMER CUSHION | | | PILE CUSHION | | | |
| Cross Sect. Area | | (cm2) | 1596.80 | Cross Sect. Area | | (cm2) 1264.50 |
| Elastic-Modulus | | (MPa) | 1207.0 | Elastic-Modulus | | (MPa) 207.0 |
| Thickness | | (mm) | 152.00 | Thickness | | (mm) 254.00 |
| Coeff of Restitution | | | 0.920 | Coeff of Restitution | | 0.500 |
| RoundOut | | (mm) | 3.0 | RoundOut | | (mm) 3.0 |
| Stiffness | | (kN/mm) | 1268.0 | Stiffness | | (kN/mm) 103.1 |

Depth (m) 0.5
Shaft Gain/Loss Factor 1.000 Toe Gain/Loss Factor 1.000

PILE PROFILE:

| L b Top | Area | E-Mod | Spec Wt | Circmf | Strength | Wave Sp | EA/c |
|---------|--------|--------|---------|--------|----------|---------|---------|
| m | cm2 | MPa | kN/m3 | m | MPa | m/s | kN/m/s |
| 0.00 | 1260.3 | 40000. | 24.00 | 1.420 | 1.00 | 4044. | 1246.74 |
| 14.50 | 1260.3 | 40000. | 24.00 | 1.420 | 1.00 | 4044. | 1246.74 |

Wave Travel Time 2L/c (ms) 7.172

| Pile and Soil Model | | | | | | Total Capacity Rut | | | (kN) 964.0 | | |
|---------------------|--------|--------|-------|-------|------|--------------------|--------|-------|------------|-------|--------|
| No. | Weight | Stiffn | C-Slk | T-Slk | CoR | Soil-S | Soil-D | Quake | LbTop | Circm | Area |
| | kN | kN/mm | mm | mm | | kN | s/m | mm | m | m | cm2 |
| 1 | 2.924 | 5215. | 3.000 | 0.000 | 0.85 | 0.0 | 0.000 | 2.50 | 0.97 | 1.4 | 1260.3 |
| 2 | 2.924 | 5215. | 0.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.50 | 1.93 | 1.4 | 1260.3 |
| 15 | 2.924 | 5215. | 0.000 | 0.000 | 1.00 | 10.0 | 0.150 | 2.50 | 14.50 | 1.4 | 1260.3 |
| Toe | | | | | | 954.0 | 0.500 | 2.50 | | | |

PILE, SOIL, ANALYSIS OPTIONS:

Uniform pile
No. of Slacks/Splices 0
File Segments: Automatic
File Damping (%) 3
File Damping Fact. (kN/m/s) 74.804

Driveability Analysis

Soil Damping Option Smith
Max No Analysis Iterations 0 Time Increment/Critical 160
Output Time Interval 1 Analysis Time-Input (ms) 0
Output Level: Normal
Gravity Mass, Pile, Hammer: 9.810 9.810 9.810
Output Segment Generation: Automatic

| Depth | Stroke | Efficy | PileC.St. | PileC.CoR |
|-------|--------|--------|-----------|-----------|
| m | m | | kN/mm | |
| 0.50 | 0.91 | 0.670 | 103. | 0.500 |

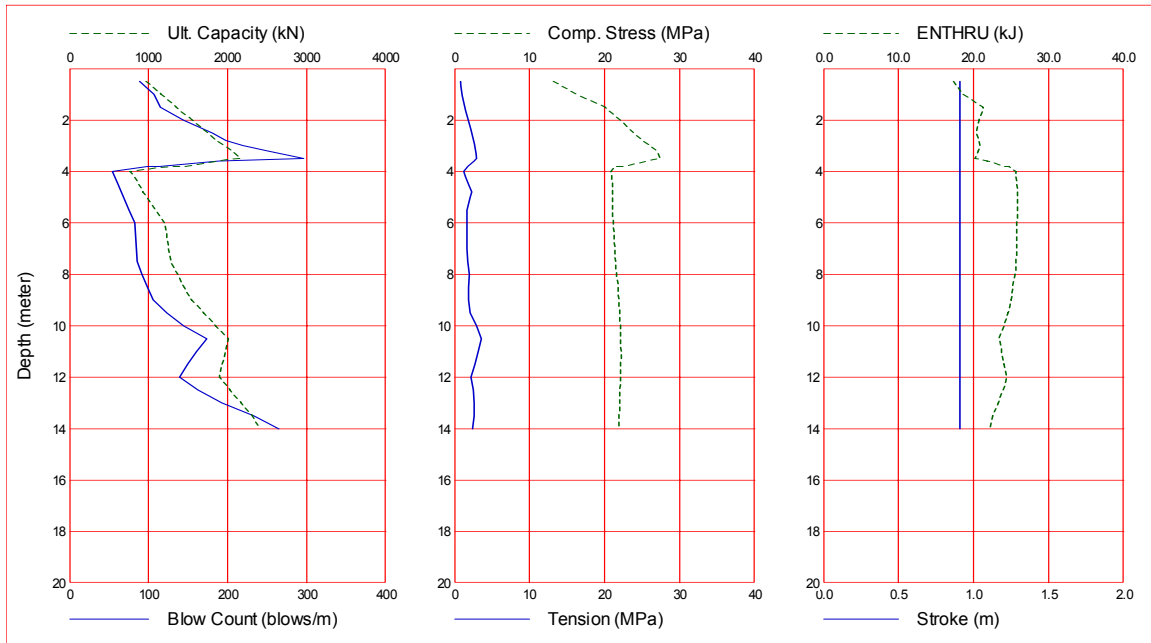


Figure F 54 GRLWEAP Driveability Results, Pier 2 Single Concrete

Gain/Loss 1 at Shaft and Toe 1.000 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 964.0 | 10.0 | 954.0 | 88.3 | 13.205 | -0.832 | 0.91 | 17.3 |
| 1.0 | 1158.5 | 31.0 | 1127.5 | 106.8 | 16.253 | -1.027 | 0.91 | 18.6 |
| 1.5 | 1355.0 | 54.0 | 1301.0 | 114.9 | 20.154 | -1.343 | 0.91 | 21.3 |
| 2.0 | 1553.4 | 78.9 | 1474.5 | 143.9 | 22.142 | -1.857 | 0.91 | 20.7 |
| 2.5 | 1753.8 | 105.8 | 1648.0 | 180.6 | 23.981 | -2.302 | 0.91 | 20.4 |
| 2.8 | 1854.8 | 120.0 | 1734.7 | 198.0 | 25.085 | -2.506 | 0.91 | 20.7 |
| 3.0 | 1956.2 | 134.7 | 1821.5 | 219.0 | 26.124 | -2.672 | 0.91 | 20.9 |
| 3.2 | 2058.1 | 149.9 | 1908.2 | 251.1 | 26.922 | -2.793 | 0.91 | 20.6 |
| 3.5 | 2160.6 | 165.6 | 1995.0 | 296.7 | 27.458 | -2.891 | 0.91 | 20.2 |
| 3.6 | 1882.0 | 172.0 | 1710.0 | 189.0 | 25.658 | -2.646 | 0.91 | 21.8 |
| 3.8 | 1464.3 | 181.8 | 1282.5 | 114.2 | 22.496 | -1.796 | 0.91 | 23.9 |
| 3.8 | 1325.1 | 185.1 | 1140.0 | 98.8 | 21.264 | -1.762 | 0.91 | 24.7 |
| 4.0 | 768.4 | 198.4 | 570.0 | 53.9 | 20.828 | -1.183 | 0.91 | 25.6 |
| 4.2 | 819.3 | 215.8 | 603.5 | 57.5 | 20.924 | -1.439 | 0.91 | 25.7 |
| 4.5 | 871.1 | 234.1 | 637.0 | 61.4 | 21.017 | -1.881 | 0.91 | 25.8 |
| 4.8 | 923.8 | 253.3 | 670.5 | 65.1 | 21.023 | -2.258 | 0.91 | 25.9 |
| 5.0 | 977.5 | 273.5 | 704.0 | 68.3 | 21.031 | -2.099 | 0.91 | 25.9 |
| 5.5 | 1087.4 | 316.4 | 771.0 | 75.1 | 21.041 | -1.605 | 0.91 | 25.9 |
| 6.0 | 1201.0 | 363.0 | 838.0 | 82.7 | 21.157 | -1.618 | 0.91 | 25.8 |
| 6.5 | 1227.2 | 412.2 | 815.0 | 83.5 | 21.301 | -1.664 | 0.91 | 25.8 |
| 7.0 | 1254.8 | 462.8 | 792.0 | 84.5 | 21.364 | -1.655 | 0.91 | 25.8 |
| 7.5 | 1283.9 | 514.9 | 769.0 | 85.7 | 21.476 | -1.764 | 0.91 | 25.7 |
| 8.0 | 1369.2 | 568.5 | 800.7 | 91.9 | 21.611 | -1.993 | 0.91 | 25.5 |
| 8.5 | 1455.9 | 623.6 | 832.3 | 98.5 | 21.849 | -1.873 | 0.91 | 25.2 |
| 9.0 | 1544.0 | 680.0 | 864.0 | 106.2 | 21.959 | -1.898 | 0.91 | 25.0 |
| 9.5 | 1696.3 | 738.0 | 958.3 | 123.0 | 22.060 | -2.117 | 0.91 | 24.6 |
| 10.0 | 1850.1 | 797.4 | 1052.7 | 144.8 | 22.160 | -2.884 | 0.91 | 24.0 |
| 10.5 | 2005.3 | 858.3 | 1147.0 | 173.3 | 22.129 | -3.564 | 0.91 | 23.4 |
| 11.0 | 1966.6 | 920.6 | 1046.0 | 160.5 | 22.193 | -3.172 | 0.91 | 23.7 |
| 11.5 | 1929.4 | 984.4 | 945.0 | 149.3 | 22.133 | -2.707 | 0.91 | 24.1 |
| 12.0 | 1893.7 | 1049.7 | 844.0 | 139.1 | 22.126 | -2.190 | 0.91 | 24.4 |
| 12.5 | 2032.4 | 1116.4 | 916.0 | 162.3 | 22.073 | -2.540 | 0.91 | 23.9 |
| 13.0 | 2172.7 | 1184.7 | 988.0 | 192.8 | 22.035 | -2.631 | 0.91 | 23.3 |
| 13.5 | 2314.4 | 1254.4 | 1060.0 | 233.2 | 21.948 | -2.599 | 0.91 | 22.6 |
| 14.0 | 2407.9 | 1325.5 | 1082.3 | 264.4 | 21.912 | -2.404 | 0.91 | 22.2 |

Total Number of Blows: 1802

Driving Time (min): 60 45 36 30 25 22 20 18 16 15
 @Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

Table F.8 GRLWEAP Driveability Results, Pier 2 Single Concrete

F.9.2.2 Pier 2, Concrete Pile Example Considering Soil Densification

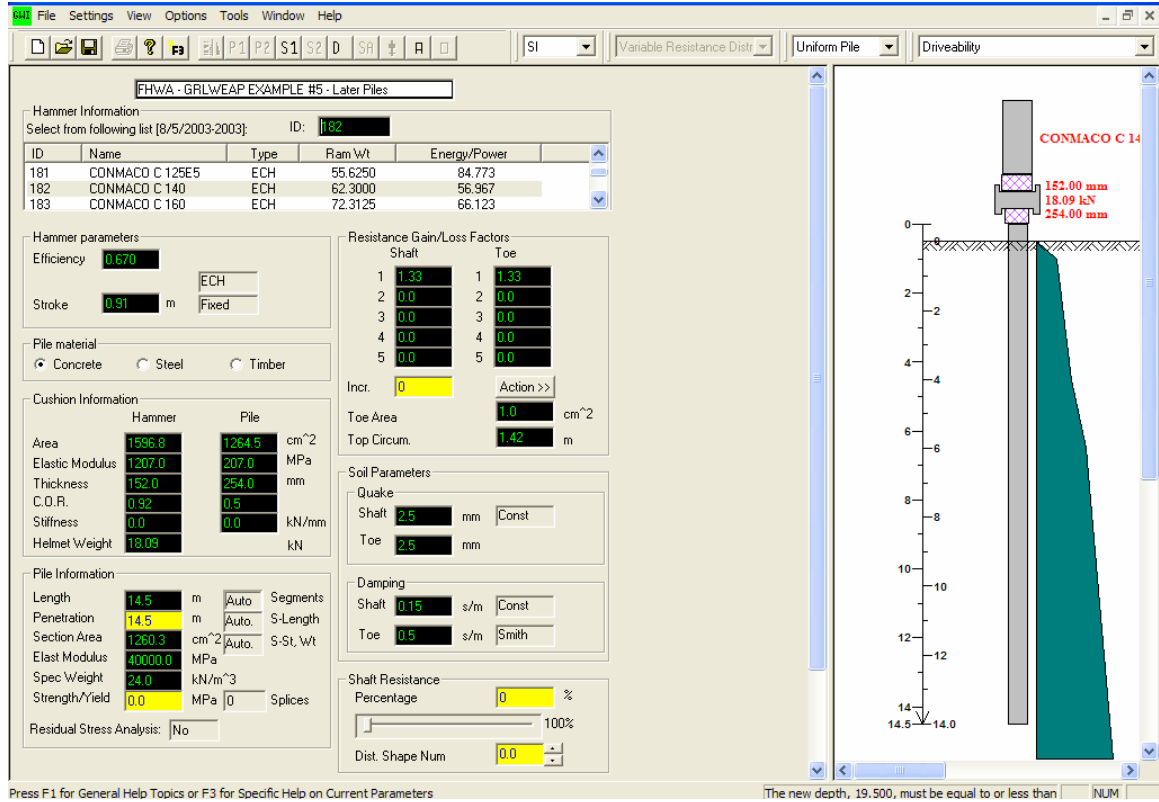


Figure F 55 GRLWEAP Driveability Input, Pier 2 with Soil Densification

Input File Contents

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FHWA - GRLWEAP EXAMPLE #5 - Later Piles
OUT OSG HAM STR FUL PEL N SPL N-U P-D %SK ISM 0 PHI RSA ITR H-D MXT DEx
0 0 182 0 0 0 0 0 3 0 0 0 0 0 0 0 0 0.000
  File g Hammer g
  9.810 9.810
    W Cp A Cp E Cp T Cp CoR ROut StCp
    18.090 1596.800 1207.0 152.000 0.920 3.000 0.0
    A Cu E Cu T Cu CoR ROut StCu
    1264.500 207.0 254.000 0.500 3.000 0.0
    LPle APle EPle WPle Circ Strg CoR ROut
    14.500 1260.300 40000.000 24.000 1.420 0.000 0.850 3.000
Manufac Hmr Name HmrType No Seg-s
CONMACO C 140 3 1
  Ram Wt Ram L Ram Dia MaxStrk RtdStrk Effic
  62.30 1397.00 612.65 0.91 0.91 0.67
  No. Assmbly Segs
  2
<---- Assembly Masses <---->----Assembly Stiffnesses---->
37.291 37.291 0.000 12540.6 12540.6 0.0
Stroke Effic. Pressure R-Weight T-Delay Exp-Coeff Eps-Str
0.9100 0.6700 0.0000 0.0000 0.0000 0.0000 0.0100 0.0000
  Qs Qt Js Jt Qx Jx Rati Dept
  2.500 2.500 0.150 0.500 0.000 0.000 0.000 0.000
Research Soil Model: Atoe, Plug, Gap, Q-fac
0.000 0.000 0.000 0.000
Research Soil Model: RD-skn: m, d, toe: m, d
0.000 0.000 0.000 0.000
Res. Distribution
Dpth Rskn Rtoe Qs Qt Js Jt SU F RelE SU T
0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
0.50 28.17 954.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
3.50 44.87 1995.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
4.00 47.71 570.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
6.00 68.18 838.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
7.50 74.47 769.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
9.00 80.57 864.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
10.50 86.77 1147.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
12.00 92.97 844.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
13.50 99.21 1060.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
15.00 105.41 1127.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Gain/Loss factors: shaft and toe
1.33000 0.00000 0.00000 0.00000 0.00000
1.33000 0.00000 0.00000 0.00000 0.00000
  Dpth L Wait Strk Pmx% Eff. Stff CoR
  0.50 0.00 0.00 0.000 0.000 0.000 1.000 0.000
  1.00 0.00 0.00 0.000 0.000 0.000 1.500 0.000
  1.50 0.00 0.00 0.000 0.000 0.000 2.500 0.000
  2.00 0.00 0.00 0.000 0.000 0.000 2.750 0.000
  2.50 0.00 0.00 0.000 0.000 0.000 3.000 0.000
  2.75 0.00 0.00 0.000 0.000 0.000 3.250 0.000
  3.00 0.00 0.00 0.000 0.000 0.000 3.500 0.000
  3.25 0.00 0.00 0.000 0.000 0.000 3.600 0.000
  3.50 0.00 0.00 0.000 0.000 0.000 3.600 0.000
  3.60 0.00 0.00 0.000 0.000 0.000 3.700 0.000
  3.75 0.00 0.00 0.000 0.000 0.000 3.700 0.000
  3.80 0.00 0.00 0.000 0.000 0.000 3.700 0.000
.
. [ABRIDGED]
.
  9.50 0.00 0.00 0.000 0.000 0.000 3.960 0.000
 10.00 0.00 0.00 0.000 0.000 0.000 3.960 0.000
 10.50 0.00 0.00 0.000 0.000 0.000 3.970 0.000
 11.00 0.00 0.00 0.000 0.000 0.000 3.970 0.000
 11.50 0.00 0.00 0.000 0.000 0.000 3.980 0.000
 12.00 0.00 0.00 0.000 0.000 0.000 3.980 0.000
 12.50 0.00 0.00 0.000 0.000 0.000 4.000 0.000
 13.00 0.00 0.00 0.000 0.000 0.000 3.990 0.000
 13.50 0.00 0.00 0.000 0.000 0.000 4.000 0.000
 14.00 0.00 0.00 0.000 0.000 0.000 4.000 0.000

```


GRLWEAP: WAVE EQUATION ANALYSIS OF PILE FOUNDATIONS
Version 2003
SI Units

FHWA - GRLWEAP EXAMPLE #5 - Later Piles

| Hammer Model: C 140 | | | Made by: | | CONMACO | | |
|----------------------|--------------|-----------------|--------------|----------------------|-----------------|---------|---------|
| No. | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | Dampg kN/m/s | | |
| 1 | 62.300 | | | | | | |
| Helmet | 18.090 | 1231.0 | 0.920 | 3.0000 | 111.8 | | |
| Cushion | | 103.1 | 0.500 | 3.0000 | | | |
| Combined Pile Top | | 101.1 | | | | | |
| Assembly | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | | | |
| 1 | 37.291 | 12540.6 | | | | | |
| 2 | 37.291 | 12540.6 | 0.800 | 3.0480 | | | |
| HAMMER OPTIONS: | | | | | | | |
| Hammer File ID No. | | 182 | Hammer Type | | Ext.Comb. | | |
| HAMMER DATA: | | | | | | | |
| Ram Weight | | (kN) | 62.30 | Ram Length | | (mm) | 1397.00 |
| Maximum (Eq) Stroke | | (m) | 0.91 | Actual (Eq) Stroke | | (m) | 0.91 |
| Efficiency | | | 0.670 | | | | |
| Rated Energy | | (kJ) | 56.97 | Potential Energy | | (kJ) | 56.69 |
| Kinetic Energy | | (kJ) | 37.98 | Impact Velocity | | (m/s) | 3.46 |
| HAMMER CUSHION | | | PILE CUSHION | | | | |
| Cross Sect. Area | | (cm2) | 1596.80 | Cross Sect. Area | | (cm2) | 1264.50 |
| Elastic-Modulus | | (MPa) | 1207.0 | Elastic-Modulus | | (MPa) | 207.0 |
| Thickness | | (mm) | 152.00 | Thickness | | (mm) | 254.00 |
| Coeff of Restitution | | | 0.920 | Coeff of Restitution | | | 0.500 |
| RoundOut | | (mm) | 3.0 | RoundOut | | (mm) | 3.0 |
| Stiffness | | (kN/mm) | 1268.0 | Stiffness | | (kN/mm) | 103.1 |

Depth (m) 0.5
Shaft Gain/Loss Factor 1.330 Toe Gain/Loss Factor 1.330

PILE PROFILE:

| L b Top | Area | E-Mod | Spec Wt | Circmf | Strength | Wave Sp | EA/c |
|---------|--------|--------|---------|--------|----------|---------|---------|
| m | cm2 | MPa | kN/m3 | m | MPa | m/s | kN/m/s |
| 0.00 | 1260.3 | 40000. | 24.00 | 1.420 | 1.00 | 4044. | 1246.74 |
| 14.50 | 1260.3 | 40000. | 24.00 | 1.420 | 1.00 | 4044. | 1246.74 |

Wave Travel Time 2L/c (ms) 7.172

| Pile and Soil Model | | | | | | Total Capacity Rut (kN) | | | | 1282.1 | |
|---------------------|--------|--------|-------|-------|------|-------------------------|--------|-------|-------|--------|--------|
| No. | Weight | Stiffn | C-Slk | T-Slk | CoR | Soil-S | Soil-D | Quake | LbTop | Circm | Area |
| | kN | kN/mm | mm | mm | | kN | s/m | mm | m | m | cm2 |
| 1 | 2.924 | 5215. | 3.000 | 0.000 | 0.85 | 0.0 | 0.000 | 2.50 | 0.97 | 1.4 | 1260.3 |
| 2 | 2.924 | 5215. | 0.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.50 | 1.93 | 1.4 | 1260.3 |
| 15 | 2.924 | 5215. | 0.000 | 0.000 | 1.00 | 13.3 | 0.150 | 2.50 | 14.50 | 1.4 | 1260.3 |
| Toe | | | | | | 1268.8 | 0.500 | 2.50 | | | |

PILE, SOIL, ANALYSIS OPTIONS:

Uniform pile
No. of Slacks/Splices 0
File Segments: Automatic
File Damping (%) 3
File Damping Fact. (kN/m/s) 74.804

Driveability Analysis

Soil Damping Option Smith
Max No Analysis Iterations 0 Time Increment/Critical 160
Output Time Interval 1 Analysis Time-Input (ms) 0
Output Level: Normal
Gravity Mass, Pile, Hammer: 9.810 9.810 9.810
Output Segment Generation: Automatic

| Depth | Stroke | Efficy | PileC.St. | PileC.CoR |
|-------|--------|--------|-----------|-----------|
| m | m | | kN/mm | |
| 0.50 | 0.91 | 0.670 | 103. | 0.500 |

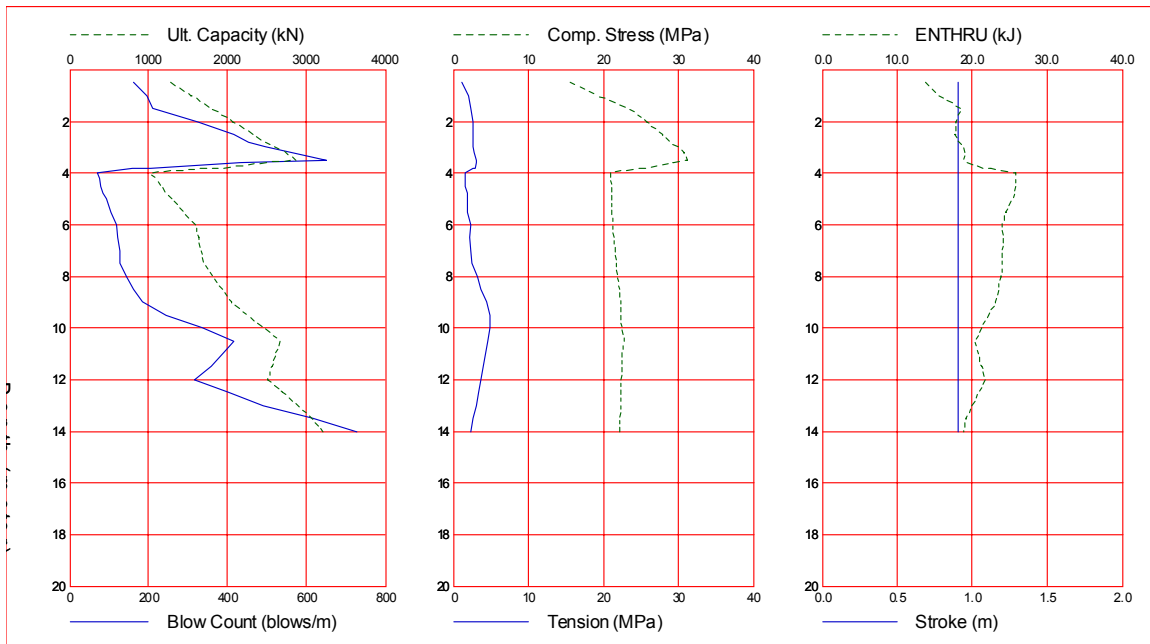


Figure F 56 GRLWEAP Driveability Results, Pier 2 with Soil Densification

Gain/Loss 1 at Shaft and Toe 1.330 / 1.330

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 1282.1 | 13.3 | 1268.8 | 161.5 | 15.522 | -1.120 | 0.91 | 13.8 |
| 1.0 | 1540.8 | 41.2 | 1499.6 | 196.3 | 19.038 | -1.979 | 0.91 | 15.5 |
| 1.5 | 1802.1 | 71.8 | 1730.3 | 212.0 | 23.447 | -2.309 | 0.91 | 18.6 |
| 2.0 | 2066.0 | 104.9 | 1961.1 | 324.4 | 25.779 | -2.538 | 0.91 | 17.9 |
| 2.5 | 2332.6 | 140.7 | 2191.8 | 416.0 | 27.766 | -2.476 | 0.91 | 17.7 |
| 2.8 | 2466.8 | 159.6 | 2307.2 | 454.4 | 28.898 | -2.555 | 0.91 | 18.3 |
| 3.0 | 2601.8 | 179.2 | 2422.6 | 497.8 | 29.973 | -2.657 | 0.91 | 18.8 |
| 3.2 | 2737.3 | 199.4 | 2538.0 | 561.8 | 30.690 | -2.755 | 0.91 | 19.0 |
| 3.5 | 2873.6 | 220.2 | 2653.3 | 650.6 | 31.142 | -2.888 | 0.91 | 18.9 |
| 3.6 | 2503.1 | 228.7 | 2274.3 | 432.8 | 29.393 | -3.028 | 0.91 | 19.4 |
| 3.8 | 1947.5 | 241.7 | 1705.7 | 203.6 | 25.779 | -2.873 | 0.91 | 21.6 |
| 3.8 | 1762.3 | 246.1 | 1516.2 | 158.7 | 24.536 | -2.645 | 0.91 | 22.6 |
| 4.0 | 1022.0 | 263.9 | 758.1 | 71.7 | 20.831 | -1.539 | 0.91 | 25.8 |
| 4.2 | 1089.7 | 287.1 | 802.7 | 76.0 | 20.929 | -1.495 | 0.91 | 25.8 |
| 4.5 | 1158.6 | 311.4 | 847.2 | 80.6 | 21.031 | -1.496 | 0.91 | 25.8 |
| 4.8 | 1228.7 | 336.9 | 891.8 | 85.8 | 21.035 | -1.742 | 0.91 | 25.6 |
| 5.0 | 1300.0 | 363.7 | 936.3 | 91.5 | 21.037 | -1.822 | 0.91 | 25.3 |
| 5.5 | 1446.3 | 420.8 | 1025.4 | 104.7 | 21.072 | -1.763 | 0.91 | 24.5 |
| 6.0 | 1597.3 | 482.8 | 1114.5 | 120.9 | 21.323 | -2.141 | 0.91 | 24.1 |
| 6.5 | 1632.1 | 548.2 | 1084.0 | 122.9 | 21.385 | -2.075 | 0.91 | 24.2 |
| 7.0 | 1668.9 | 615.5 | 1053.4 | 125.7 | 21.517 | -2.256 | 0.91 | 24.1 |
| 7.5 | 1707.6 | 684.9 | 1022.8 | 128.6 | 21.676 | -2.420 | 0.91 | 24.1 |
| 8.0 | 1821.0 | 756.1 | 1064.9 | 144.1 | 21.844 | -3.132 | 0.91 | 23.8 |
| 8.5 | 1936.3 | 829.3 | 1107.0 | 162.3 | 22.133 | -3.688 | 0.91 | 23.5 |
| 9.0 | 2053.6 | 904.5 | 1149.1 | 185.7 | 22.281 | -4.282 | 0.91 | 23.1 |
| 9.5 | 2256.1 | 981.5 | 1274.6 | 244.9 | 22.336 | -4.739 | 0.91 | 22.2 |
| 10.0 | 2460.6 | 1060.5 | 1400.0 | 336.1 | 22.484 | -4.716 | 0.91 | 21.3 |
| 10.5 | 2667.0 | 1141.5 | 1525.5 | 416.4 | 22.635 | -4.540 | 0.91 | 20.4 |
| 11.0 | 2615.6 | 1224.4 | 1391.2 | 387.6 | 22.496 | -4.210 | 0.91 | 20.8 |
| 11.5 | 2566.1 | 1309.3 | 1256.9 | 359.5 | 22.410 | -3.921 | 0.91 | 21.3 |
| 12.0 | 2518.6 | 1396.1 | 1122.5 | 317.8 | 22.399 | -3.549 | 0.91 | 21.7 |
| 12.5 | 2703.1 | 1484.9 | 1218.3 | 401.4 | 22.319 | -3.214 | 0.91 | 20.9 |
| 13.0 | 2889.6 | 1575.6 | 1314.0 | 491.5 | 22.261 | -2.914 | 0.91 | 20.0 |
| 13.5 | 3078.1 | 1668.3 | 1409.8 | 616.9 | 22.152 | -2.562 | 0.91 | 19.2 |
| 14.0 | 3202.5 | 1763.0 | 1439.5 | 729.0 | 22.107 | -2.154 | 0.91 | 18.9 |

Total Number of Blows: 3815

Driving Time (min): 127 95 76 63 54 47 42 38 34 31
 @Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

Table F 9 GRLWEAP Driveability Results, Pier 2 with Soil Densification

F.9.2.3 Pier 2, H-Pile Example

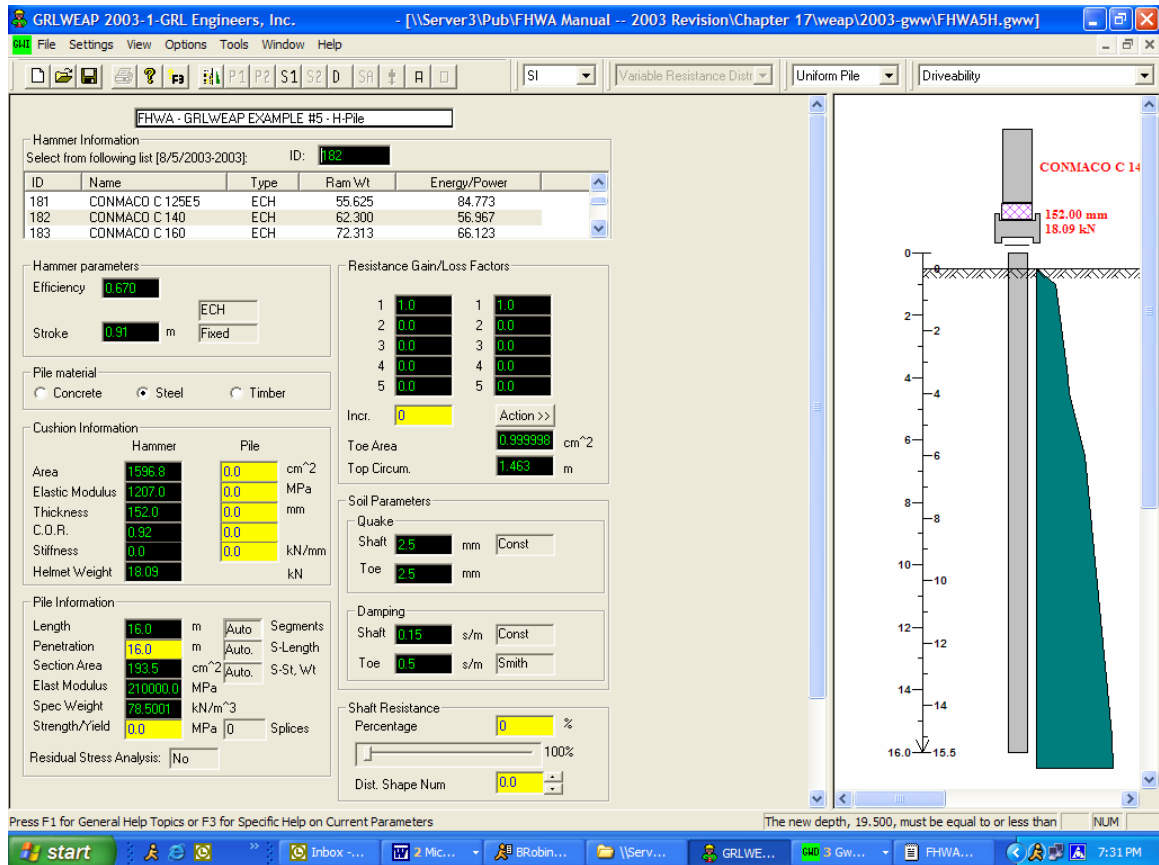


Figure F 57 GRLWEAP Driveability Results, Pier 2 H-Pile

```

Input File Contents
FHWA - GRLWEAP EXAMPLE #5 - H-Pile
OUT OSG HAM STR FUL PEL N SPL N-U P-D %SK ISM 0 PHI RSA ITR H-D MXT Dex
0 0 0 182 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0.000
  Pile g Hammer g
  9.810 9.810
    W Cp A Cp E Cp T Cp CoR ROut StCp
    18.090 1596.800 1207.0 152.000 0.920 3.000 0.0
    A Cu E Cu T Cu CoR ROut StCu
    0.000 0.0 0.000 0.000 0.000 0.0
    LPle APle EPle WPle Circ Strg CoR ROut
    16.000 193.500 210000.000 78.500 1.463 0.000 0.850 3.000
Manufac Hmr Name HmrType No Seg-s
CONMACO C 140 3 1
  Ram Wt Ram L Ram Dia MaxStrk RtdStrk Effic
  62.30 1397.00 612.65 0.91 0.91 0.67
  No. Assmbly Segs
  2
<---- Assembly Masses ----><----Assembly Stiffnesses---->
  37.291 37.291 0.000 12540.6 12540.6 0.0
  Stroke Effic. Pressure R-Weight T-Delay Exp-Coeff Eps-Str
  0.9100 0.6700 0.0000 0.0000 0.0000 0.0000 0.0100 0.0000
    Qs Qt Js Jt Qx Jx Rati Dept
    2.500 2.500 0.150 0.500 0.000 0.000 0.000 0.000
Research Soil Model: Atoe, Plug, Gap, Q-fac
0.000 0.000 0.000 0.000
Research Soil Model: RD-skn: m, d, toe: m, d
0.000 0.000 0.000 0.000
Res. Distribution
  Dpth Rskn Rtoe Qs Qt Js Jt SU F RelE SU T
  0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  0.50 20.36 681.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  3.50 32.42 1425.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  4.00 34.44 407.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  6.00 50.59 598.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  7.50 55.19 550.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  9.00 59.79 617.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  10.50 64.39 820.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  12.00 68.99 603.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  13.50 73.63 757.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  15.00 78.23 805.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
  16.00 79.76 20000.00 0.00 0.00 0.00 0.00 0.00 0.00 0.00
Gain/Loss factors: shaft and toe
1.00000 0.00000 0.00000 0.00000 0.00000
1.00000 0.00000 0.00000 0.00000 0.00000
  Dpth L Wait Strk Pmx% Eff. Stiff CoR
  0.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  1.00 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  1.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  2.00 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  2.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  2.75 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  3.00 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  3.25 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  3.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  3.60 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  3.75 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  3.80 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  4.00 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  4.25 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  4.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
.
. [ABRIDGED]
.
  13.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  14.00 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  14.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  15.00 0.00 0.00 0.000 0.000 0.000 0.000 0.000
  15.50 0.00 0.00 0.000 0.000 0.000 0.000 0.000

```

GRLWEAP: WAVE EQUATION ANALYSIS OF PILE FOUNDATIONS
Version 2003
SI Units

FHWA - GRLWEAP EXAMPLE #5 - H-Pile

| Hammer Model: C 140 | | | Made by: | | CONMACO | |
|----------------------|--------------|-----------------|--------------|----------------------|-----------------|--------------|
| No. | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | Dampg kN/m/s | |
| 1 | 62.300 | | | | | |
| Helmet | 18.090 | 1231.0 | 0.920 | 3.0000 | 111.8 | |
| Combined Pile Top | | 4063.5 | | | | |
| Assembly | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | | |
| 1 | 37.291 | 12540.6 | | | | |
| 2 | 37.291 | 12540.6 | 0.800 | 3.0480 | | |
| HAMMER OPTIONS: | | | | | | |
| Hammer File ID No. | | 182 | Hammer Type | | Ext.Comb. | |
| HAMMER DATA: | | | | | | |
| Ram Weight | | (kN) | 62.30 | Ram Length | | (mm) 1397.00 |
| Maximum (Eq) Stroke | | (m) | 0.91 | Actual (Eq) Stroke | | (m) 0.91 |
| Efficiency | | | 0.670 | | | |
| Rated Energy | | (kJ) | 56.97 | Potential Energy | | (kJ) 56.69 |
| Kinetic Energy | | (kJ) | 37.98 | Impact Velocity | | (m/s) 3.46 |
| HAMMER CUSHION | | | PILE CUSHION | | | |
| Cross Sect. Area | | (cm2) | 1596.80 | Cross Sect. Area | | (cm2) 0.00 |
| Elastic-Modulus | | (MPa) | 1207.0 | Elastic-Modulus | | (MPa) 0.0 |
| Thickness | | (mm) | 152.00 | Thickness | | (mm) 0.00 |
| Coeff of Restitution | | | 0.920 | Coeff of Restitution | | 1.000 |
| RoundOut | | (mm) | 3.0 | RoundOut | | (mm) 0.0 |
| Stiffness | | (kN/mm) | 1268.0 | Stiffness | | (kN/mm) 0.0 |

Depth (m) 0.5
Shaft Gain/Loss Factor 1.000 Toe Gain/Loss Factor 1.000

PILE PROFILE:

| L b Top | Area | E-Mod | Spec Wt | Circmf | Strength | Wave Sp | EA/c |
|---------|-----------------|---------|-------------------|--------|----------|---------|--------|
| m | cm ² | MPa | kN/m ³ | m | MPa | m/s | kN/m/s |
| 0.00 | 193.5 | 210000. | 78.50 | 1.463 | 1.00 | 5123. | 793.21 |
| 16.00 | 193.5 | 210000. | 78.50 | 1.463 | 1.00 | 5123. | 793.21 |

Wave Travel Time 2L/c (ms) 6.247

| Pile and Soil Model | | | | | | Total Capacity | | | Rut | | | 688.4 | |
|---------------------|--------|--------|-------|-------|------|----------------|--------|-------|-------|-------|-----------------|-------|--|
| No. | Weight | Stiffn | C-Slk | T-Slk | CoR | Soil-S | Soil-D | Quake | LbTop | Circm | Area | | |
| | kN | kN/mm | mm | mm | | kN | s/m | mm | m | m | cm ² | | |
| 1 | 1.519 | 4063. | 3.000 | 0.000 | 0.85 | 0.0 | 0.000 | 2.50 | 1.00 | 1.5 | 193.5 | | |
| 2 | 1.519 | 4063. | 0.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.50 | 2.00 | 1.5 | 193.5 | | |
| 16 | 1.519 | 4063. | 0.000 | 0.000 | 1.00 | 7.4 | 0.150 | 2.50 | 16.00 | 1.5 | 193.5 | | |
| Toe | | | | | | 681.0 | 0.500 | 2.50 | | | | | |

PILE, SOIL, ANALYSIS OPTIONS:

Uniform pile
No. of Slacks/Splices 0
File Segments: Automatic
File Damping (%) 1
File Damping Fact. (kN/m/s) 15.864

Driveability Analysis

Soil Damping Option Smith
Max No Analysis Iterations 0 Time Increment/Critical 160
Output Time Interval 1 Analysis Time-Input (ms) 0
Output Level: Normal
Gravity Mass, Pile, Hammer: 9.810 9.810 9.810
Output Segment Generation: Automatic

| Depth | Stroke | Effic |
|-------|--------|-------|
| m | m | |
| 0.50 | 0.91 | 0.670 |

FHWA - GRLWEAP EXAMPLE #5 - H-Pile Gain/Loss 1 at Shaft and Toe 1.000 / 1.000 GRLWEAP(TM) Version 2003

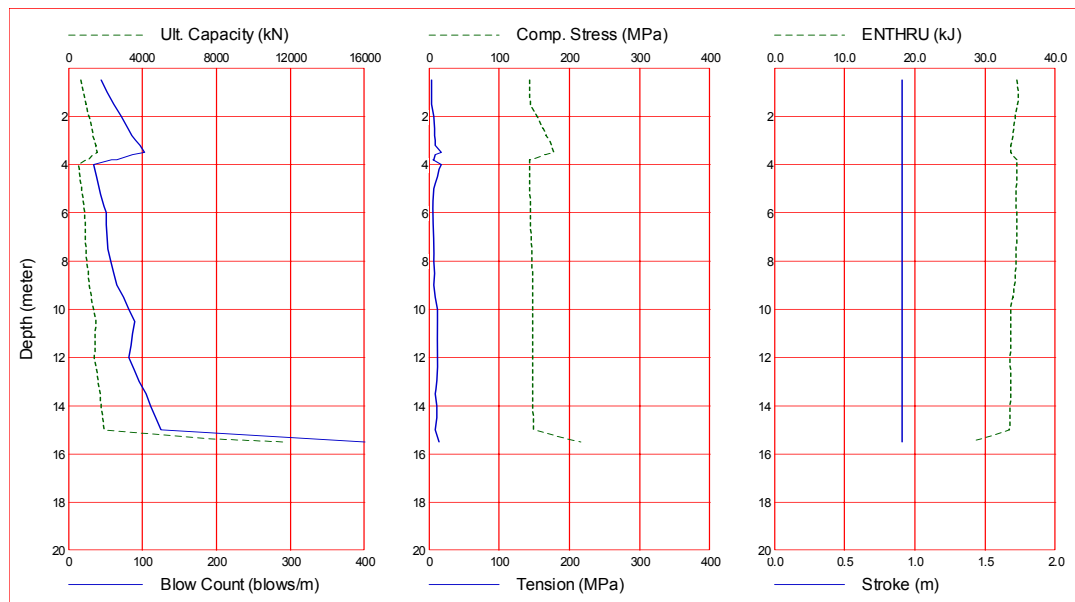


Figure F 58 GRLWEAP Driveability Results, Pier 2 H-Piles

Gain/Loss 1 at Shaft and Toe 1.000 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 688.4 | 7.4 | 681.0 | 44.2 | 143.839 | -4.233 | 0.91 | 34.5 |
| 1.0 | 828.1 | 23.1 | 805.0 | 52.4 | 143.841 | -3.504 | 0.91 | 34.7 |
| 1.5 | 969.2 | 40.2 | 929.0 | 61.4 | 144.000 | -4.140 | 0.91 | 34.6 |
| 2.0 | 1111.7 | 58.7 | 1053.0 | 71.0 | 154.053 | -6.587 | 0.91 | 34.3 |
| 2.5 | 1255.8 | 78.8 | 1177.0 | 80.5 | 163.144 | -8.007 | 0.91 | 34.1 |
| 2.8 | 1328.4 | 89.4 | 1239.0 | 85.5 | 166.754 | -8.432 | 0.91 | 34.0 |
| 3.0 | 1401.3 | 100.3 | 1301.0 | 90.9 | 170.902 | -8.858 | 0.91 | 33.9 |
| 3.2 | 1474.6 | 111.6 | 1363.0 | 96.7 | 174.264 | -9.574 | 0.91 | 33.7 |
| 3.5 | 1548.3 | 123.3 | 1425.0 | 102.9 | 177.535 | -17.974 | 0.91 | 33.6 |
| 3.6 | 1349.4 | 128.0 | 1221.4 | 86.5 | 165.496 | -9.311 | 0.91 | 33.9 |
| 3.8 | 1051.3 | 135.3 | 916.0 | 65.6 | 145.174 | -6.976 | 0.91 | 34.5 |
| 3.8 | 952.0 | 137.8 | 814.2 | 58.6 | 143.851 | -5.952 | 0.91 | 34.6 |
| 4.0 | 554.7 | 147.7 | 407.0 | 33.7 | 143.849 | -17.499 | 0.91 | 34.5 |
| 4.2 | 591.6 | 160.7 | 430.9 | 35.8 | 143.854 | -14.533 | 0.91 | 34.5 |
| 4.5 | 629.1 | 174.4 | 454.8 | 37.6 | 143.885 | -11.832 | 0.91 | 34.5 |
| 4.8 | 667.5 | 188.8 | 478.6 | 39.5 | 143.920 | -9.151 | 0.91 | 34.5 |
| 5.0 | 706.5 | 204.0 | 502.5 | 41.5 | 143.957 | -6.460 | 0.91 | 34.4 |
| 5.5 | 786.8 | 236.6 | 550.2 | 46.2 | 144.086 | -5.429 | 0.91 | 34.4 |
| 6.0 | 870.1 | 272.1 | 598.0 | 50.8 | 144.462 | -5.989 | 0.91 | 34.5 |
| 6.5 | 891.7 | 309.7 | 582.0 | 51.6 | 144.987 | -6.248 | 0.91 | 34.5 |
| 7.0 | 914.4 | 348.4 | 566.0 | 52.5 | 145.634 | -6.867 | 0.91 | 34.5 |
| 7.5 | 938.2 | 388.2 | 550.0 | 53.5 | 146.332 | -7.181 | 0.91 | 34.4 |
| 8.0 | 1001.5 | 429.1 | 572.3 | 57.2 | 147.090 | -7.172 | 0.91 | 34.4 |
| 8.5 | 1065.8 | 471.2 | 594.7 | 61.3 | 147.332 | -7.586 | 0.91 | 34.3 |
| 9.0 | 1131.4 | 514.4 | 617.0 | 65.7 | 147.690 | -7.398 | 0.91 | 34.2 |
| 9.5 | 1243.3 | 558.7 | 684.7 | 74.0 | 147.974 | -9.159 | 0.91 | 34.0 |
| 10.0 | 1356.4 | 604.1 | 752.3 | 81.5 | 147.831 | -12.000 | 0.91 | 33.7 |
| 10.5 | 1470.6 | 650.6 | 820.0 | 89.3 | 148.113 | -12.746 | 0.91 | 33.6 |
| 11.0 | 1445.9 | 698.3 | 747.7 | 86.7 | 147.823 | -12.558 | 0.91 | 33.6 |
| 11.5 | 1422.4 | 747.1 | 675.3 | 84.1 | 148.097 | -12.331 | 0.91 | 33.6 |
| 12.0 | 1400.0 | 797.0 | 603.0 | 81.5 | 147.814 | -12.131 | 0.91 | 33.5 |
| 12.5 | 1502.3 | 848.0 | 654.3 | 88.5 | 148.095 | -11.902 | 0.91 | 33.6 |
| 13.0 | 1605.8 | 900.2 | 705.7 | 96.2 | 147.852 | -10.705 | 0.91 | 33.7 |
| 13.5 | 1710.5 | 953.5 | 757.0 | 104.9 | 148.186 | -8.599 | 0.91 | 33.6 |
| 14.0 | 1780.9 | 1007.9 | 773.0 | 110.9 | 148.077 | -11.058 | 0.91 | 33.5 |
| 14.5 | 1852.4 | 1063.4 | 789.0 | 117.5 | 148.577 | -11.363 | 0.91 | 33.5 |
| 15.0 | 1925.1 | 1120.1 | 805.0 | 124.8 | 148.659 | -9.243 | 0.91 | 33.4 |
| 15.5 | 11580.1 | 1177.6 | 10402.5 | 9999.0 | 215.986 | -14.843 | 0.91 | 28.0 |

Refusal occurred; no driving time output possible

Table F 10 GRLWEAP Driveability Results, Pier 2 H-Piles

F.9.3.1 Pier 3 H-Pile Preconstruction Driveability Analysis

This analysis was initially generated from the Soil Boring S-3 file in Driven. Driven created a GRLWEAP input file that included the general pile properties, a detailed soil resistance distribution and soil damping, quake and set-up parameters based on the soil type. The hammer and driving system parameters were entered, the gain/loss factor was selected as 0.5 and 1.0 for the shaft (per cohesive soils in Table 9-20), and the depths for analysis were set every 0.5 m to the pile penetration. The analysis was run, and the results follow.

In this case, penetration resistance is less than 25 blows per 0.25 m when the hammer is run at full stroke. If the stroke can be reduced on this hammer, the analysis should be re-run at a lower stroke. The resulting penetration resistance will be higher and the stresses lower. The pile compressive and tensile stresses are with FHWA limits for steel piles.

File Settings View Options Tools Window Help

SI Variable Resistance Distr Uniform Pile Driveability

BORING S-3 --H-Pile

Hammer Information
Select from following list [8/5/2003-2003]: ID: 182

| ID | Name | Type | Ram Wt | Energy/Power |
|-----|-----------------|------|--------|--------------|
| 181 | CONMACO C 125E5 | ECH | 55.625 | 84.773 |
| 182 | CONMACO C 140 | ECH | 62.300 | 56.967 |
| 183 | CONMACO C 160 | ECH | 72.313 | 66.123 |

Hammer parameters
Efficiency: 0.670
Stroke: 0.91 m
Type: ECH Fixed

Pile material
☒ Concrete ☒ Steel ☐ Timber

Cushion Information

| | Hammer | Pile | Unit |
|-----------------|--------|------|-----------------|
| Area | 1596.8 | 0.0 | cm ² |
| Elastic Modulus | 1207.0 | 0.0 | MPa |
| Thickness | 152.0 | 0.0 | mm |
| C.O.R. | 0.92 | 0.0 | |
| Stiffness | 0.0 | 0.0 | kN/mm |
| Helmet Weight | 18.09 | | kN |

Pile Information
Length: 15.0 m Auto Segments
Penetration: 15.0 m Auto S-Length
Section Area: 133.5 cm² Auto S-St, Wt
Elast Modulus: 210000.0 MPa
Spec Weight: 77.5 kN/m³
Strength/Yield: 248.0 MPa 0 Splices
Residual Stress Analysis: No

Resistance Gain/Loss Factors

| Shaft | Toe |
|-------|-------|
| 1 0.5 | 1 1.0 |
| 2 1.0 | 2 1.0 |
| 3 0.0 | 3 0.0 |
| 4 0.0 | 4 0.0 |
| 5 0.0 | 5 0.0 |

Incr: 0 Action >>

Toe Area: 1.0 cm²
Top Circum: 1.42 m

Soil Parameters
Quake
Shaft: 0.0 mm Const
Toe: 0.0 mm

Damping
Shaft: 0.0 s/m Const
Toe: 0.0 s/m Smith

Shaft Resistance
Percentage: 0 %
Dist. Shape Num: 0.0

CONMACO C 140
152.00 mm
18.09 kN

0 2 4 6 8 10 12 14 15.0

Press F1 for General Help Topics or F3 for Specific Help on Current Parameters

The new depth, 19.500, must be equal to or less than NUM

Input File Contents

```

BORING S-3 --H-Pile
OUT OSG HAM STR FUL PEL N SPL N-U P-D %SK ISM 0 PHI RSA ITR H-D MXT DEx
-100 0 182 0 0 0 0 0 0 1 0 0 0 0 0 0 0 0.000
File g Hammer g
9.810 9.810
W Cp A Cp E Cp T Cp CoR ROut StCp
18.090 1596.800 1207.0 152.000 0.920 3.000 0.0
A Cu E Cu T Cu CoR ROut StCu
0.000 0.0 0.000 0.000 0.000 0.0
LPle APle EPle WPle Circ Strg CoR ROut
15.000 193.500210000.000 77.500 1.420 248.000 0.850 0.010
Manufac Hmr Name HmrType No Seg-s
CONMACO C 140 3 1
Ram Wt Ram L Ram Dia MaxStrk RtdStrk Effic
62.30 1397.00 612.65 0.91 0.91 0.67
No. Assmby Segs
2
<---- Assembly Masses ----><----Assembly Stiffnesses---->
37.291 37.291 0.000 12540.6 12540.6 0.0
Stroke Effic. Pressure R-Weight T-Delay Exp-Coeff Eps-Str
0.9100 0.6700 0.0000 0.0000 0.0000 0.0000 0.0100 0.0000
Qs Qt Js Jt Qx Jx Rati Dept
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
Research Soil Model: Atoe, Plug, Gap, Q-fac
0.000 0.000 0.000 0.000
Research Soil Model: RD-skn: m, d, toe: m, d
0.000 0.000 0.000 0.000
Res. Distribution
Dpth Rskn Rtoe Qs Qt Js Jt SU F RelE SU T
0.01 0.00 0.00 2.54 2.97 0.16 0.50 1.00 0.00 0.00
1.99 0.00 0.00 2.54 2.97 0.16 0.50 1.00 0.00 0.00
1.99 0.00 0.00 2.54 2.97 0.16 0.50 1.00 0.00 0.00
2.00 5.61 27.42 2.54 2.97 0.16 0.50 1.00 0.00 0.00
2.01 10.15 70.25 2.54 2.97 0.16 0.50 1.00 0.00 0.00
2.99 20.38 141.00 2.54 2.97 0.16 0.50 1.00 0.00 0.00
3.01 106.00 120.90 2.54 2.97 0.65 0.50 2.00 0.00 0.00
5.99 106.00 120.90 2.54 2.97 0.65 0.50 2.00 0.00 0.00
6.01 47.10 176.79 2.54 2.97 0.65 0.50 2.00 0.00 0.00
9.01 54.64 176.79 2.54 2.97 0.65 0.50 2.00 0.00 0.00
12.01 62.19 176.79 2.54 2.97 0.65 0.50 2.00 0.00 0.00
14.99 67.79 176.79 2.54 2.97 0.65 0.50 2.00 0.00 0.00
15.01 141.70 919.89 2.54 2.97 0.16 0.50 1.00 0.00 0.00
Gain/Loss factors: shaft and toe
0.50000 1.00000 0.00000 0.00000 0.00000
1.00000 1.00000 0.00000 0.00000 0.00000
Dpth L Wait Strk Pmx% Eff. Stff CoR
0.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
1.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
1.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
2.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
2.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
3.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
3.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
4.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
4.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
5.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
5.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
6.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
.
. [ABRIDGED]
.
13.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
14.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000
14.50 15.00 0.00 0.000 0.000 0.000 0.000 0.000
15.00 15.00 0.00 0.000 0.000 0.000 0.000 0.000

```

GRLWEAP: WAVE EQUATION ANALYSIS OF PILE FOUNDATIONS
Version 2003
SI Units

BORING S-3 --H-Pile

| | | | | | | |
|-------------------|--------------|-----------------|-------|-------------|-----------------|---------|
| Hammer Model: | | C 140 | | Made by: | | CONMACO |
| No. | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | Dampg kN/m/s | |
| 1 | 62.300 | | | | | |
| Helmet | 18.090 | 1231.0 | 0.920 | 3.0000 | 111.8 | |
| Combined Pile Top | | 4063.5 | | | | |
| Assembly | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | | |
| 1 | 37.291 | 12540.6 | | | | |
| 2 | 37.291 | 12540.6 | 0.800 | 3.0480 | | |

HAMMER OPTIONS:

| | | | |
|--------------------|-----|-------------|-----------|
| Hammer File ID No. | 182 | Hammer Type | Ext.Comb. |
|--------------------|-----|-------------|-----------|

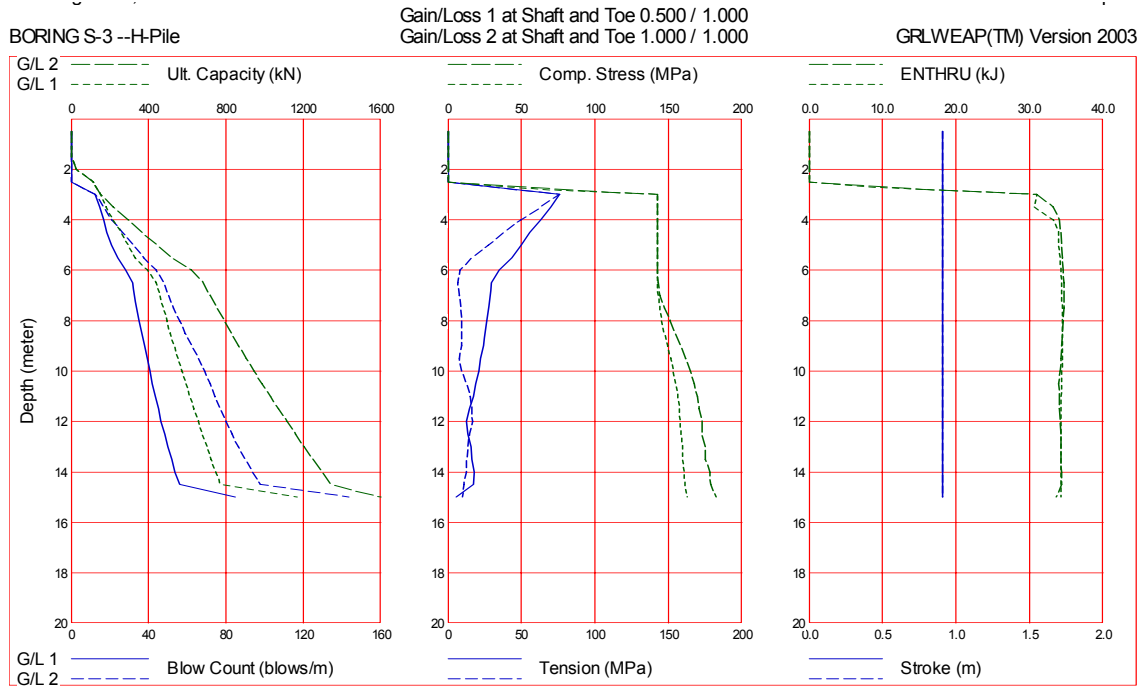
HAMMER DATA:

| | | | | | |
|---------------------|------|-------|--------------------|------|---------|
| Ram Weight | (kN) | 62.30 | Ram Length | (mm) | 1397.00 |
| Maximum (Eq) Stroke | (m) | 0.91 | Actual (Eq) Stroke | (m) | 0.91 |
| Efficiency | | 0.670 | | | |

| | | | | | |
|----------------|------|-------|------------------|-------|-------|
| Rated Energy | (kJ) | 56.97 | Potential Energy | (kJ) | 56.69 |
| Kinetic Energy | (kJ) | 37.98 | Impact Velocity | (m/s) | 3.46 |

HAMMER CUSHION

| | | | | | |
|----------------------|---------|---------|----------------------|---------|-------|
| Cross Sect. Area | (cm2) | 1596.80 | Cross Sect. Area | (cm2) | 0.00 |
| Elastic-Modulus | (MPa) | 1207.0 | Elastic-Modulus | (MPa) | 0.0 |
| Thickness | (mm) | 152.00 | Thickness | (mm) | 0.00 |
| Coeff of Restitution | | 0.920 | Coeff of Restitution | | 1.000 |
| RoundOut | (mm) | 3.0 | RoundOut | (mm) | 0.0 |
| Stiffness | (kN/mm) | 1268.0 | Stiffness | (kN/mm) | 0.0 |



Gain/Loss 1 at Shaft and Toe 0.500 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.0 | 27.5 | 0.0 | 27.4 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.5 | 114.6 | 9.0 | 105.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.0 | 152.9 | 21.9 | 130.9 | 12.3 | 142.675 | -76.224 | 0.91 | 31.0 |
| 3.5 | 180.5 | 59.6 | 120.9 | 14.7 | 142.676 | -69.887 | 0.91 | 30.7 |
| 4.0 | 218.1 | 97.2 | 120.9 | 16.9 | 142.677 | -63.117 | 0.91 | 33.2 |
| 4.5 | 255.8 | 134.9 | 120.9 | 18.6 | 142.680 | -55.726 | 0.91 | 34.0 |
| 5.0 | 293.3 | 172.4 | 120.9 | 21.0 | 142.683 | -50.084 | 0.91 | 34.0 |
| 5.5 | 331.0 | 210.1 | 120.9 | 24.0 | 142.707 | -43.651 | 0.91 | 34.2 |
| 6.0 | 396.4 | 247.6 | 148.8 | 28.2 | 142.750 | -34.911 | 0.91 | 34.3 |
| 6.5 | 441.5 | 264.7 | 176.8 | 31.6 | 142.908 | -29.849 | 0.91 | 34.4 |
| 7.0 | 458.8 | 282.0 | 176.8 | 32.6 | 143.298 | -28.832 | 0.91 | 34.4 |
| 7.5 | 476.7 | 299.9 | 176.8 | 34.0 | 144.224 | -27.440 | 0.91 | 34.5 |
| 8.0 | 494.9 | 318.1 | 176.8 | 35.2 | 145.499 | -26.440 | 0.91 | 34.5 |
| 8.5 | 513.7 | 336.9 | 176.8 | 36.7 | 147.693 | -25.158 | 0.91 | 34.5 |
| 9.0 | 532.8 | 356.0 | 176.8 | 37.9 | 149.569 | -24.177 | 0.91 | 34.5 |
| 9.5 | 552.5 | 375.7 | 176.8 | 39.5 | 151.736 | -22.348 | 0.91 | 34.5 |
| 10.0 | 572.5 | 395.7 | 176.8 | 40.7 | 153.518 | -20.979 | 0.91 | 34.4 |
| 10.5 | 593.0 | 416.2 | 176.8 | 42.1 | 154.832 | -19.062 | 0.91 | 34.4 |
| 11.0 | 613.9 | 437.1 | 176.8 | 43.4 | 156.377 | -17.394 | 0.91 | 34.3 |
| 11.5 | 635.4 | 458.6 | 176.8 | 45.0 | 157.613 | -14.711 | 0.91 | 34.3 |
| 12.0 | 657.1 | 480.4 | 176.8 | 46.5 | 158.176 | -12.457 | 0.91 | 34.3 |
| 12.5 | 679.5 | 502.7 | 176.8 | 48.3 | 158.828 | -13.766 | 0.91 | 34.3 |
| 13.0 | 702.0 | 525.2 | 176.8 | 49.9 | 159.549 | -15.769 | 0.91 | 34.3 |
| 13.5 | 724.9 | 548.1 | 176.8 | 51.9 | 159.924 | -16.370 | 0.91 | 34.3 |
| 14.0 | 748.1 | 571.3 | 176.8 | 53.7 | 160.872 | -18.042 | 0.91 | 34.3 |
| 14.5 | 771.7 | 595.0 | 176.8 | 55.9 | 161.529 | -17.233 | 0.91 | 34.3 |
| 15.0 | 1167.4 | 619.1 | 548.3 | 84.8 | 162.863 | -5.707 | 0.91 | 34.3 |

Total Number of Blows: 451

Driving Time (min): 15 11 9 7 6 5 5 4 4 3
 @Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

Gain/Loss 2 at Shaft and Toe 1.000 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.0 | 27.5 | 0.0 | 27.4 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.5 | 114.6 | 9.0 | 105.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.0 | 152.9 | 22.0 | 130.9 | 12.4 | 142.675 | -76.217 | 0.91 | 31.0 |
| 3.5 | 217.8 | 96.9 | 120.9 | 16.9 | 142.677 | -63.209 | 0.91 | 33.2 |
| 4.0 | 293.1 | 172.2 | 120.9 | 21.0 | 142.679 | -49.650 | 0.91 | 34.1 |
| 4.5 | 368.4 | 247.5 | 120.9 | 26.4 | 142.683 | -37.880 | 0.91 | 34.3 |
| 5.0 | 443.6 | 322.7 | 120.9 | 32.0 | 142.687 | -27.211 | 0.91 | 34.4 |
| 5.5 | 518.9 | 398.0 | 120.9 | 37.5 | 142.731 | -16.424 | 0.91 | 34.5 |
| 6.0 | 621.9 | 473.0 | 148.8 | 43.8 | 142.793 | -8.516 | 0.91 | 34.6 |
| 6.5 | 683.9 | 507.1 | 176.8 | 47.8 | 143.322 | -6.929 | 0.91 | 34.7 |
| 7.0 | 718.7 | 541.9 | 176.8 | 50.3 | 144.259 | -7.491 | 0.91 | 34.7 |
| 7.5 | 754.3 | 577.5 | 176.8 | 53.0 | 147.346 | -8.902 | 0.91 | 34.7 |
| 8.0 | 790.9 | 614.1 | 176.8 | 55.9 | 151.032 | -9.133 | 0.91 | 34.6 |
| 8.5 | 828.3 | 651.5 | 176.8 | 59.0 | 154.961 | -9.500 | 0.91 | 34.5 |
| 9.0 | 866.6 | 689.8 | 176.8 | 62.4 | 158.810 | -9.166 | 0.91 | 34.4 |
| 9.5 | 905.9 | 729.1 | 176.8 | 66.0 | 161.663 | -7.739 | 0.91 | 34.3 |
| 10.0 | 946.0 | 769.2 | 176.8 | 69.2 | 165.110 | -9.465 | 0.91 | 34.2 |
| 10.5 | 987.0 | 810.2 | 176.8 | 71.7 | 167.670 | -12.443 | 0.91 | 34.0 |
| 11.0 | 1028.9 | 852.1 | 176.8 | 74.3 | 169.994 | -15.204 | 0.91 | 34.1 |
| 11.5 | 1071.7 | 894.9 | 176.8 | 77.1 | 171.142 | -16.379 | 0.91 | 34.1 |
| 12.0 | 1115.4 | 938.6 | 176.8 | 80.0 | 173.189 | -16.563 | 0.91 | 34.2 |
| 12.5 | 1159.8 | 983.1 | 176.8 | 83.2 | 173.156 | -14.500 | 0.91 | 34.3 |
| 13.0 | 1205.0 | 1028.2 | 176.8 | 86.5 | 175.406 | -13.689 | 0.91 | 34.3 |
| 13.5 | 1250.8 | 1074.0 | 176.8 | 90.1 | 175.406 | -12.761 | 0.91 | 34.3 |
| 14.0 | 1297.3 | 1120.5 | 176.8 | 93.8 | 178.310 | -12.610 | 0.91 | 34.4 |
| 14.5 | 1344.4 | 1167.6 | 176.8 | 97.9 | 179.132 | -10.871 | 0.91 | 34.4 |
| 15.0 | 1764.0 | 1215.7 | 548.3 | 143.4 | 182.879 | -9.694 | 0.91 | 33.7 |

Total Number of Blows: 738

Driving Time (min): 24 18 14 12 10 9 8 7 6 6
 @Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

F.9.4.1 South Abutment, Concrete Pile

This analysis was initially generated from the Soil Boring S-4 file in Driven. Driven created a GRLWEAP input file that included the general pile properties, a detailed soil resistance distribution and soil damping, quake and set-up parameters based on the soil type. The hammer and driving system parameters were entered, the gain/loss factor was selected as 0.5 and 1.0 for the shaft (per cohesive soils in Table 9-20) and 1.0 for the toe. The depths for analysis were set every 0.5 m to the pile penetration. The analysis was run, and the results follow.

In this case, penetration resistance is less than 25 blows per 0.25 m when the hammer is run at full stroke. If the stroke can be reduced on this hammer, the analysis should be re-run at a lower stroke. The resulting penetration resistance will be higher and the stresses lower. The pile compressive and tensile stresses are with FHWA limits for typical prestressed concrete piles.

Boring S-4 : 09/11/2003 : BRR

Hammer Information
Select from following list [8/5/2003-2003]: ID: 182

| ID | Name | Type | Ram Wt | Energy/Power |
|-----|-----------------|------|---------|--------------|
| 181 | CONMACO C 125E5 | ECH | 55.6250 | 84.773 |
| 182 | CONMACO C 140 | ECH | 62.3000 | 56.967 |
| 183 | CONMACO C 160 | ECH | 72.3125 | 66.123 |

Hammer parameters
Efficiency: 0.670
Stroke: 0.91 m
Fixed

Pile material
☒ Concrete ☐ Steel ☐ Timber

Cushion Information

| | Hammer | Pile | Unit |
|-----------------|--------|--------|-----------------|
| Area | 1596.8 | 1264.5 | cm ² |
| Elastic Modulus | 1207.0 | 207.0 | MPa |
| Thickness | 152.0 | 254.0 | mm |
| C.O.R. | 0.92 | 0.5 | |
| Stiffness | 0.0 | 0.0 | kN/mm |
| Helmet Weight | 18.09 | | kN |

Pile Information

| | | | | |
|----------------|---------|-------------------|------|----------|
| Length | 19.0 | m | Auto | Segments |
| Penetration | 19.0 | m | Auto | S-Length |
| Section Area | 1267.36 | cm ² | Auto | S-St, Wt |
| Elast Modulus | 40000.0 | MPa | | |
| Spec Weight | 24.0 | kN/m ³ | | |
| Strength/Yield | 28.0 | MPa | 0 | Splices |

Resistance Gain/Loss Factors

| | Shaft | Toe |
|---|-------|-----|
| 1 | 0.5 | 1.0 |
| 2 | 1.0 | 1.0 |
| 3 | 0.0 | 0.0 |
| 4 | 0.0 | 0.0 |
| 5 | 0.0 | 0.0 |

Incr: 0 Action >>

Toe Area: 1.0 cm²
Top Circum: 1.42 m

Soil Parameters

Quake
Shaft: 0.0 mm Const
Toe: 0.0 mm

Damping
Shaft: 0.0 s/m Const
Toe: 0.0 s/m Smith

Shaft Resistance
Percentage: 0 %
Dist. Shape Num: 0.0

CONMACO C 14
152.00 mm
18.09 kN
254.00 mm

Press F1 for General Help Topics or F3 for Specific Help on Current Parameters

The new depth, 19.500, must be equal to or less than NUM

Input File Contents

Boring S-4 : 09/11/2003 : BRR

| OUT | OSG | HAM | STR | FUL | PEL | N | SPL | N-U | P-D | %SK | ISM | 0 | PHI | RSA | ITR | H-D | MXT | DEX |
|------|-----|-----|-----|-----|-----|---|-----|-----|-----|-----|-----|---|-----|-----|-----|-----|-----|-------|
| -100 | 0 | 182 | 0 | 0 | 0 | 0 | 0 | 0 | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0.000 |

File g Hammer g
9.810 9.810

| W Cp | A Cp | E Cp | T Cp | CoR | ROut | StCp |
|--------|----------|--------|---------|-------|-------|------|
| 18.090 | 1596.800 | 1207.0 | 152.000 | 0.920 | 3.000 | 0.0 |

| A Cu | E Cu | T Cu | CoR | ROut | StCu |
|----------|-------|---------|-------|-------|------|
| 1264.500 | 207.0 | 254.000 | 0.500 | 3.000 | 0.0 |

| LPle | APle | EPle | WPle | Circ | Strg | CoR | ROut |
|--------|----------|-----------|--------|-------|--------|-------|-------|
| 19.000 | 1267.360 | 40000.000 | 24.000 | 1.420 | 28.000 | 1.000 | 0.010 |

Manufac Hmr Name HmrType No Seg-s
CONMACO C 140 3 1

| Ram Wt | Ram L | Ram Dia | MaxStrk | RtdStrk | Efficy |
|--------|---------|---------|---------|---------|--------|
| 62.30 | 1397.00 | 612.65 | 0.91 | 0.91 | 0.67 |

No. Assmbly Segs
2

<---- Assembly Masses ----><----Assembly Stiffnesses---->

| Stroke | Effic. | Pressure | R-Weight | T-Delay | Exp-Coeff | Eps-Str | Qs | Qt | Js | Jt | Qx | Jx | Rati | Dept |
|--------|--------|----------|----------|---------|-----------|---------|-------|-------|-------|-------|-------|-------|-------|--------|
| 37.291 | 37.291 | 0.000 | 12540.6 | 12540.6 | 0.0 | 0.0100 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 | 0.0000 |

Research Soil Model: Atoe, Plug, Gap, Q-fac
0.000 0.000 0.000 0.000

Research Soil Model: RD-skn: m, d, toe: m, d
0.000 0.000 0.000 0.000

Res. Distribution

| Dpth | Rskn | Rtoe | Qs | Qt | Js | Jt | SU F | RelE | SU T |
|-------|-------|--------|------|------|------|------|------|------|------|
| 0.01 | 0.00 | 0.00 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 1.49 | 0.00 | 0.00 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 1.50 | 32.24 | 37.64 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 3.01 | 32.24 | 37.64 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 6.01 | 32.31 | 37.64 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 6.99 | 32.38 | 37.64 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 7.01 | 71.76 | 106.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 10.01 | 77.24 | 106.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 13.01 | 82.73 | 106.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 16.01 | 84.97 | 106.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 16.49 | 84.97 | 106.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 16.51 | 67.30 | 179.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 18.99 | 67.30 | 179.07 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |
| 19.01 | 65.12 | 190.48 | 2.54 | 2.97 | 0.65 | 0.50 | 2.00 | 0.00 | 0.00 |

Gain/Loss factors: shaft and toe

| Dpth | L | Wait | Strk | Pmx% | Eff. | Stff | CoR |
|------|-------|------|-------|-------|-------|-------|-------|
| 0.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 1.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 2.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 3.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 5.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 5.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

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.[ABRIDGED]
.

| Dpth | L | Wait | Strk | Pmx% | Eff. | Stff | CoR |
|-------|-------|------|-------|-------|-------|-------|-------|
| 14.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 14.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 15.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 16.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 16.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 17.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 17.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 18.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

| | | | | | | | |
|-------|-------|------|-------|-------|-------|-------|-------|
| 18.50 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 19.00 | 19.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 0.00 | 0.00 | 0.00 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |

GRLWEAP: WAVE EQUATION ANALYSIS OF PILE FOUNDATIONS
Version 2003
SI Units

Boring S-4 : 09/11/2003 : BRR

| | | | | | | |
|-------------------|--------------|-----------------|-------|-------------|-----------------|---------|
| Hammer Model: | | C 140 | | Made by: | | CONMACO |
| No. | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | Dampg kN/m/s | |
| 1 | 62.300 | | | | | |
| Helmet | 18.090 | 1231.0 | 0.920 | 3.0000 | 111.8 | |
| Cushion | | 103.1 | 0.500 | 3.0000 | | |
| Combined Pile Top | | 101.0 | | | | |
| Assembly | Weight kN | Stiffn kN/mm | CoR | C-Slk mm | | |
| 1 | 37.291 | 12540.6 | | | | |
| 2 | 37.291 | 12540.6 | 0.800 | 3.0480 | | |

HAMMER OPTIONS:

| | | | |
|--------------------|-----|-------------|-----------|
| Hammer File ID No. | 182 | Hammer Type | Ext.Comb. |
|--------------------|-----|-------------|-----------|

HAMMER DATA:

| | | | | | |
|---------------------|------|-------|--------------------|------|---------|
| Ram Weight | (kN) | 62.30 | Ram Length | (mm) | 1397.00 |
| Maximum (Eq) Stroke | (m) | 0.91 | Actual (Eq) Stroke | (m) | 0.91 |
| Efficiency | | 0.670 | | | |

| | | | | | |
|----------------|------|-------|------------------|-------|-------|
| Rated Energy | (kJ) | 56.97 | Potential Energy | (kJ) | 56.69 |
| Kinetic Energy | (kJ) | 37.98 | Impact Velocity | (m/s) | 3.46 |

HAMMER CUSHION

| | | | | | |
|----------------------|---------|---------|----------------------|---------|---------|
| Cross Sect. Area | (cm2) | 1596.80 | PILE CUSHION | | |
| Elastic-Modulus | (MPa) | 1207.0 | Cross Sect. Area | (cm2) | 1264.50 |
| Thickness | (mm) | 152.00 | Elastic-Modulus | (MPa) | 207.0 |
| Coeff of Restitution | | 0.920 | Thickness | (mm) | 254.00 |
| RoundOut | (mm) | 3.0 | Coeff of Restitution | | 0.500 |
| Stiffness | (kN/mm) | 1268.0 | RoundOut | (mm) | 3.0 |
| | | | Stiffness | (kN/mm) | 103.1 |

Boring S-4 : 09/11/2003 : BRR
GRL Engineers, Inc.

2003/09/24
GRLWEAP(TM) Version 2003

Depth (m) 0.5
Shaft Gain/Loss Factor 0.500 Toe Gain/Loss Factor 1.000

PILE PROFILE:

| L b Top | Area | E-Mod | Spec Wt | Circmf | Strength | Wave Sp | EA/c |
|---------|--------|--------|---------|--------|----------|---------|---------|
| m | cm2 | MPa | kN/m3 | m | MPa | m/s | kN/m/s |
| 0.00 | 1267.4 | 40000. | 24.00 | 1.420 | 28.00 | 4044. | 1253.72 |
| 19.00 | 1267.4 | 40000. | 24.00 | 1.420 | 28.00 | 4044. | 1253.72 |

Wave Travel Time 2L/c (ms) 9.398

| Pile and Soil Model | | | | | | Total Capacity Rut (kN) | | | | 0.0 | |
|---------------------|--------|--------|-------|-------|------|-------------------------|--------|-------|-------|-------|--------|
| No. | Weight | Stiffn | C-Slk | T-Slk | CoR | Soil-S | Soil-D | Quake | LbTop | Circm | Area |
| | kN | kN/mm | mm | mm | | kN | s/m | mm | m | m | cm2 |
| 1 | 3.042 | 5069. | 3.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.54 | 1.00 | 1.4 | 1267.4 |
| 2 | 3.042 | 5069. | 0.000 | 0.000 | 1.00 | 0.0 | 0.000 | 2.54 | 2.00 | 1.4 | 1267.4 |
| 19 | 3.042 | 5069. | 0.000 | 0.000 | 1.00 | 0.0 | 0.650 | 2.54 | 19.00 | 1.4 | 1267.4 |
| Toe | | | | | | 0.0 | 0.500 | 2.97 | | | |

PILE, SOIL, ANALYSIS OPTIONS:

Uniform pile
No. of Slacks/Splices 0
File Segments: Automatic
Pile Damping (%) 3
Pile Damping Fact. (kN/m/s) 75.223

Driveability Analysis

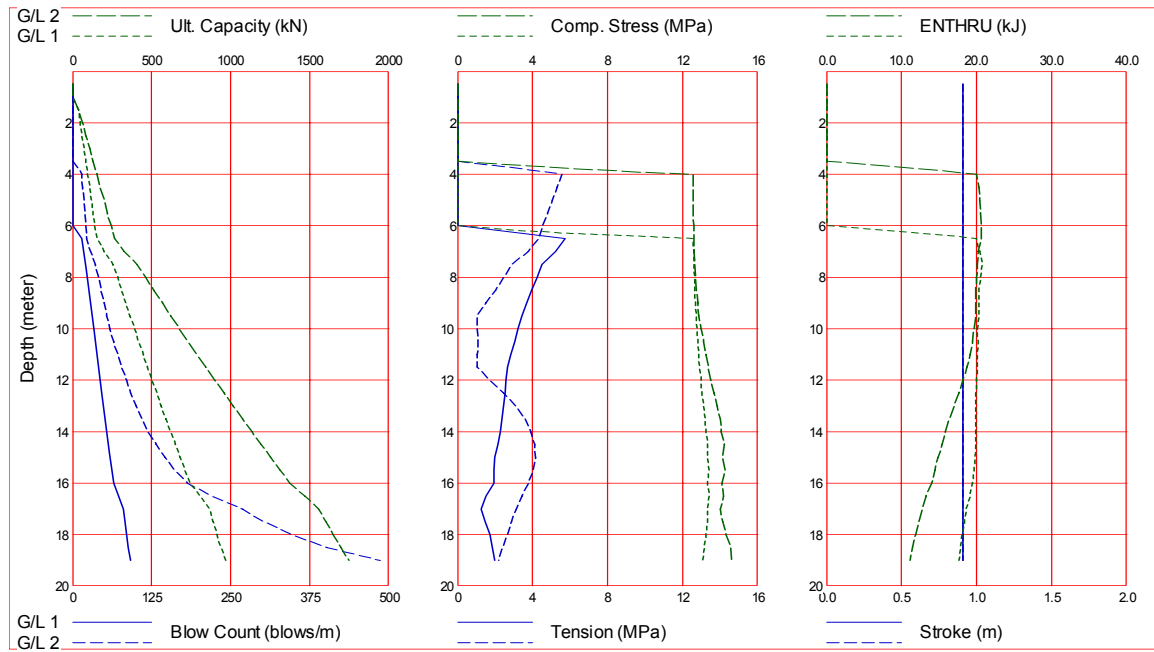
Soil Damping Option Smith
Max No Analysis Iterations 0 Time Increment/Critical 160
Output Time Interval 1 Analysis Time-Input (ms) 0
Output Level: Normal
Gravity Mass, Pile, Hammer: 9.810 9.810 9.810
Output Segment Generation: Automatic

| Depth | Stroke | Efficy | PileC.St. | PileC.CoR |
|-------|--------|--------|-----------|-----------|
| m | m | | kN/mm | |
| 0.50 | 0.91 | 0.670 | 103. | 0.500 |

Boring S-4 : 09/11/2003 : BRR

Gain/Loss 1 at Shaft and Toe 0.500 / 1.000
Gain/Loss 2 at Shaft and Toe 1.000 / 1.000

GRLWEAP(TM) Version 2003



Gain/Loss 1 at Shaft and Toe 0.500 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.5 | 37.8 | 0.1 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.0 | 49.2 | 11.6 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.5 | 60.6 | 23.0 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.0 | 72.1 | 34.5 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.5 | 83.5 | 45.9 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 4.0 | 95.0 | 57.4 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 4.5 | 106.5 | 68.8 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 5.0 | 117.9 | 80.3 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 5.5 | 129.4 | 91.7 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 6.0 | 140.8 | 103.2 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 6.5 | 152.3 | 114.7 | 37.6 | 15.0 | 12.583 | -5.741 | 0.91 | 20.0 |
| 7.0 | 198.1 | 126.2 | 71.9 | 17.5 | 12.600 | -5.241 | 0.91 | 20.4 |
| 7.5 | 257.9 | 151.8 | 106.1 | 20.8 | 12.609 | -4.509 | 0.91 | 20.7 |
| 8.0 | 283.8 | 177.8 | 106.1 | 23.2 | 12.630 | -4.224 | 0.91 | 20.5 |
| 8.5 | 310.1 | 204.0 | 106.1 | 26.0 | 12.650 | -3.948 | 0.91 | 20.3 |
| 9.0 | 336.7 | 230.6 | 106.1 | 28.9 | 12.682 | -3.687 | 0.91 | 20.3 |
| 9.5 | 363.6 | 257.6 | 106.1 | 31.3 | 12.716 | -3.442 | 0.91 | 20.3 |
| 10.0 | 390.9 | 284.8 | 106.1 | 34.1 | 12.759 | -3.224 | 0.91 | 20.1 |
| 10.5 | 418.5 | 312.4 | 106.1 | 36.5 | 12.805 | -3.031 | 0.91 | 20.2 |
| 11.0 | 446.4 | 340.3 | 106.1 | 39.2 | 12.854 | -2.846 | 0.91 | 20.1 |
| 11.5 | 474.6 | 368.5 | 106.1 | 41.7 | 12.913 | -2.679 | 0.91 | 20.1 |
| 12.0 | 503.2 | 397.1 | 106.1 | 44.2 | 12.974 | -2.584 | 0.91 | 20.0 |
| 12.5 | 532.0 | 426.0 | 106.1 | 46.5 | 13.045 | -2.544 | 0.91 | 19.9 |
| 13.0 | 561.2 | 455.2 | 106.1 | 48.9 | 13.112 | -2.472 | 0.91 | 19.9 |
| 13.5 | 590.7 | 484.6 | 106.1 | 51.3 | 13.193 | -2.382 | 0.91 | 19.9 |
| 14.0 | 620.2 | 514.2 | 106.1 | 53.9 | 13.267 | -2.269 | 0.91 | 19.9 |
| 14.5 | 649.9 | 543.9 | 106.1 | 56.5 | 13.354 | -2.138 | 0.91 | 19.9 |
| 15.0 | 679.8 | 573.7 | 106.1 | 59.3 | 13.353 | -1.981 | 0.91 | 19.8 |
| 15.5 | 709.7 | 603.6 | 106.1 | 62.3 | 13.430 | -1.961 | 0.91 | 19.7 |
| 16.0 | 739.8 | 633.7 | 106.1 | 65.4 | 13.351 | -1.934 | 0.91 | 19.5 |
| 16.5 | 806.4 | 663.9 | 142.6 | 72.9 | 13.407 | -1.518 | 0.91 | 19.1 |
| 17.0 | 866.9 | 687.8 | 179.1 | 79.8 | 13.327 | -1.260 | 0.91 | 18.6 |
| 17.5 | 890.8 | 711.7 | 179.1 | 82.4 | 13.313 | -1.481 | 0.91 | 18.4 |
| 18.0 | 914.7 | 735.6 | 179.1 | 85.2 | 13.231 | -1.723 | 0.91 | 18.1 |
| 18.5 | 938.5 | 759.5 | 179.1 | 88.1 | 13.178 | -1.860 | 0.91 | 17.9 |
| 19.0 | 968.1 | 783.4 | 184.8 | 91.9 | 13.089 | -1.997 | 0.91 | 17.6 |

Total Number of Blows: 629

Driving Time (min): 20 15 12 10 8 7 6 6 5 5
 @Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

Gain/Loss 2 at Shaft and Toe 1.000 / 1.000

| Depth m | Ultimate Capacity kN | Friction kN | End Bearing kN | Blow Count blows/m | Comp. Stress MPa | Tension Stress MPa | Stroke m | ENTHRU kJ |
|------------|----------------------------|----------------|----------------------|--------------------------|------------------------|--------------------------|-------------|--------------|
| 0.5 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 1.5 | 37.9 | 0.2 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.0 | 60.8 | 23.1 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 2.5 | 83.7 | 46.0 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.0 | 106.6 | 68.9 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 3.5 | 129.4 | 91.8 | 37.6 | 0.0 | 0.000 | 0.000 | 0.91 | 0.0 |
| 4.0 | 152.4 | 114.7 | 37.6 | 15.1 | 12.569 | -5.585 | 0.91 | 20.0 |
| 4.5 | 175.3 | 137.6 | 37.6 | 16.4 | 12.573 | -5.310 | 0.91 | 20.3 |
| 5.0 | 198.2 | 160.5 | 37.6 | 17.8 | 12.578 | -5.051 | 0.91 | 20.4 |
| 5.5 | 221.1 | 183.5 | 37.6 | 19.3 | 12.582 | -4.792 | 0.91 | 20.5 |
| 6.0 | 244.1 | 206.4 | 37.6 | 20.7 | 12.592 | -4.564 | 0.91 | 20.6 |
| 6.5 | 267.0 | 229.4 | 37.6 | 22.1 | 12.604 | -4.339 | 0.91 | 20.6 |
| 7.0 | 324.3 | 252.5 | 71.9 | 27.9 | 12.628 | -3.757 | 0.91 | 20.2 |
| 7.5 | 409.7 | 303.6 | 106.1 | 35.9 | 12.649 | -2.888 | 0.91 | 20.1 |
| 8.0 | 461.6 | 355.5 | 106.1 | 40.8 | 12.692 | -2.455 | 0.91 | 20.0 |
| 8.5 | 514.2 | 408.1 | 106.1 | 45.3 | 12.731 | -2.006 | 0.91 | 19.9 |
| 9.0 | 567.4 | 461.3 | 106.1 | 49.6 | 12.804 | -1.505 | 0.91 | 19.9 |
| 9.5 | 621.2 | 515.1 | 106.1 | 54.2 | 12.885 | -1.060 | 0.91 | 19.9 |
| 10.0 | 675.7 | 569.7 | 106.1 | 59.3 | 12.989 | -1.046 | 0.91 | 19.7 |
| 10.5 | 730.9 | 624.8 | 106.1 | 64.9 | 13.106 | -1.083 | 0.91 | 19.5 |
| 11.0 | 786.7 | 680.6 | 106.1 | 71.2 | 13.227 | -1.042 | 0.91 | 19.1 |
| 11.5 | 843.1 | 737.1 | 106.1 | 78.3 | 13.367 | -1.049 | 0.91 | 18.7 |
| 12.0 | 900.2 | 794.2 | 106.1 | 85.1 | 13.513 | -1.686 | 0.91 | 18.2 |
| 12.5 | 958.0 | 851.9 | 106.1 | 92.3 | 13.677 | -2.468 | 0.91 | 17.6 |
| 13.0 | 1016.4 | 910.3 | 106.1 | 100.5 | 13.831 | -3.079 | 0.91 | 17.0 |
| 13.5 | 1075.2 | 969.2 | 106.1 | 109.7 | 14.005 | -3.590 | 0.91 | 16.4 |
| 14.0 | 1134.4 | 1028.3 | 106.1 | 120.2 | 14.072 | -3.885 | 0.91 | 15.8 |
| 14.5 | 1193.8 | 1087.7 | 106.1 | 132.0 | 14.232 | -4.100 | 0.91 | 15.4 |
| 15.0 | 1253.4 | 1147.4 | 106.1 | 145.9 | 14.151 | -4.146 | 0.91 | 14.9 |
| 15.5 | 1313.4 | 1207.3 | 106.1 | 161.9 | 14.288 | -4.034 | 0.91 | 14.5 |
| 16.0 | 1373.6 | 1267.5 | 106.1 | 181.1 | 14.117 | -3.784 | 0.91 | 14.0 |
| 16.5 | 1470.3 | 1327.8 | 142.6 | 220.7 | 14.192 | -3.435 | 0.91 | 13.3 |
| 17.0 | 1554.7 | 1375.6 | 179.1 | 268.6 | 14.023 | -3.122 | 0.91 | 12.7 |
| 17.5 | 1602.5 | 1423.4 | 179.1 | 303.0 | 14.153 | -2.884 | 0.91 | 12.3 |
| 18.0 | 1650.2 | 1471.2 | 179.1 | 346.4 | 14.330 | -2.657 | 0.91 | 11.9 |
| 18.5 | 1698.0 | 1519.0 | 179.1 | 401.9 | 14.585 | -2.429 | 0.91 | 11.5 |
| 19.0 | 1751.5 | 1566.7 | 184.8 | 486.4 | 14.621 | -2.202 | 0.91 | 11.1 |

Total Number of Blows: 1775

Driving Time (min): 59 44 35 29 25 22 19 17 16 14
 @Blow Rate (b/min): 30 40 50 60 70 80 90 100 110 120

Driving Time for continuously running hammer; any wait times not included

APPENDIX G

Driven Pile Foundation Design by LRFD

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APPENDIX G

DRIVEN PILE FOUNDATION DESIGN BY LRFD

G.1 INTRODUCTION

In 1994, the AASHTO Subcommittee on Bridges adopted a Bridge Design Specification based on the use of the Load and Resistance Factor (LRFD) method (AASHTO, 1994). The geotechnical parts of the new specification had been developed by an NCHRP Research Project (Barker et al). The driven pile part of the 1994 version of the specification was then extensively edited in the Second Edition of 1998 (AASHTO, 1998). In general, the new specification has generated considerable resistance to its implementation from many parts of bridge design community including the driven pile part. A very few States implemented it immediately while many still have made little progress in its implementation (2005). The purpose here is to provide the necessary basis for preparing the deep foundation designer to use this new method in driven pile design.

The geotechnical portion of the specification has proven to be one of the most difficult to implement. This includes shallow and deep foundations, and earth retaining systems. Considerable effort has been spent, since the adoption in 1994, to modify the document to satisfy the concerns of the users. In the driven pile area, it was extensively modified in the Second Edition (AASHTO 1998), but those modifications failed to satisfy many of the criticisms. This Appendix is being written using that Second Edition version of the Code. Basic concepts of LRFD will be presented, the application to driven pile design will be discussed and examples will be solved using the requirements of that Code with the application of some imagination.

G.2 BASIC CONCEPTS OF ASD AND LRFD

In order for the designer to understand and appreciate LRFD for the design of driven pile foundations, it is necessary to briefly summarize the fundamental basis for allowable stress design (ASD) and then to review the history of the development of the LRFD and its early implementation. The history of the development of LRFD is particularly interesting in view of what has happened recently and, in addition, it places the changes wrought by LRFD in proper perspective.

Allowable Stress Design (ASD) grew out of the development of methods of structural analysis during the nineteenth century. These methods were based on the assumption that the structure behaved elastically and they produced a rational evaluation of structural behavior that satisfied both equilibrium and compatibility. Prior to these developments, structures were designed based entirely on experience and sets of rules. But, the analyses only explained structural behavior. It was desirable that a rational design approach be developed and it was logical to limit the calculated stresses in a structure to some fraction of the structural material strength. Gradually, structural loads appropriate for design were defined and then codified. So, if member stresses could be calculated it was logical to limit those stresses and values of allowable stresses were gradually accepted based on the experience that the structure did not fail. These limiting stress values became known “design stresses” or “allowable stresses.” For instance, the allowable stresses in steel beams in bending have been limited to between about 0.4 and 0.66 times the steel yield strength.

But, linear elastic behavior is not universally observed in all structural elements. For example, the failure strength of a column is related the slenderness ratio of the member and methods are available to calculate the failure load with considerable confidence. Similar considerations affect the design of other structural elements. The approach that came to be used in some applications during the development of ASD was to apply a “safety factor” to the calculated ultimate member capacity.

Geotechnical engineering has the universal problem that a linear elastic analysis will not represent the strength of a soil structure. Therefore, the use of factors of safety applied to the strength is universal in geotechnical design. So, in ASD foundation design the superstructure is analyzed using an elastic analysis. From this analysis, the element forces including the foundations are determined. Then the elements are selected so that they will carry the elastically calculated loads with the required factor of safety.

Factors of safety were selected so that failures were very unlikely, based on experience, but the magnitudes of the factors of safety were based only on experience. The geotechnical engineer should understand that he does not “own” all of the factor of safety. It must be adequate to deal with the variability of the loads and the inadequacy of the analysis in addition to the strength variability.

Until 1956, the analysis of a concrete section subject to bending was performed assuming that the compression stress in the concrete was linearly distributed on the cross section with the further assumption that concrete could carry no tension. Designs were limited by placing limits on the calculated stress in both the concrete in compression and in the steel in both tension and compression (if compression steel was present). In other words, the element strength was treated as if the materials were elastic and, to perform the analysis, the steel was then “transformed” into concrete based on the relative moduli of the two materials. The result of these assumptions produced quite conservative results, particularly if compression reinforcement was present as is always the case with columns. The time dependent deformation of concrete subjected to compression causes its effective modulus to be time dependent. Extensive research was performed in the first half of the twentieth century to understand what the actual stress distribution was and how it could be used in design.

These fundamental problems with the use of ASD caused the American Concrete Institute (ACI) in 1956 to adopt a new edition of their Building Code for the design of concrete structures and in that code an Appendix was included that used a strength design approach (ACI 1956) to replace the allowable stress method described above. The ultimate strength of the element in bending was calculated using a prescribed, nonlinear concrete stress distribution on the section at failure. The computational procedure was quite simple and the result was element strength not stress. The Appendix of ACI 318-56 achieved little use.

The ACI Committee that prepared this method then took another major step. Instead of selecting a factor of safety for particular failure modes they broke the factor of safety into parts. They realized that the limiting value of ultimate load should depend on the variability of the particular load types. So they specified different “load factors” for the various types of loads and, indirectly, they applied an additional multiplier to provide structural safety for the strength variability of member types and failure modes.

ACI 318-63, adopted in 1963, made extensive changes from the 1956 Code and the result had the form that we now know as LRFD (ACI 1963).

$$\sum \gamma_{ij} Q_{ij} \leq \phi_k R_{nk} \quad (1)$$

Where, γ is the load factor, Q is the load effect (this refers the element load calculated from the applied loads by a linear elastic structural analysis. The subscripts i and j refer

to the load condition (dead, live, wind, etc.) and the load combination, respectively. ϕ is the resistance factor for a given limit state (failure mode), R_{nk} is the nominal resistance in the k^{th} limit state. The term nominal resistance was adopted to define the element strength determined by some specified method. (It should be noted that in the AASHTO LRFD Code the term nominal resistance is used instead of nominal strength.) The summation on the left side of Expression (1) is known as the factored load. A generally used name for the right side of the expression has not been accepted. The term factored resistance will be used here.

The version of Expression (1) used in the AASHTO LRFD Design Specification is somewhat different. It has the form

$$\sum \eta_{ij} Q_{ij} \leq \phi_k R_{nk} \quad (2)$$

where η is a factor related to the ductility, redundancy and operational importance.

When ACI 318-63 was adopted the load and resistance factors were generated based on judgment followed by extensive comparative designs. By 1965, the designers of concrete structures in the private sector had almost universally adopted the ACI LRFD Code. There were a few minor changes in the load factors in the next edition of the Code in 1968 (ACI 1968) and the ASD section was dropped completely. The ACI LRFD Building Code was then essentially unchanged until 2002 (ACI 2002) when extensive changes were made primarily to the load and resistance factors. During this entire development period the design method was known as “Ultimate Strength Design”.

The LRFD procedure adopted by ACI 318-63 was applicable to structural concrete elements for buildings only. It did not apply to the geotechnical aspects of foundation design. This produced a considerable anomaly for reinforced concrete building designers. For example, in the design process the geotechnical engineer recommended an allowable bearing pressure for a spread footing. The structural designer then had to size the footing using allowable loads – and that implied the use of a different set of loads - but perform the structural design of the reinforced concrete footing with factored loads.

Driven pile cap design was even more absurd. The geotechnical engineer selected an ultimate pile capacity based on subsurface conditions. Most of the methods that are used to establish pile capacity produce ultimate capacity. Those methods include wave

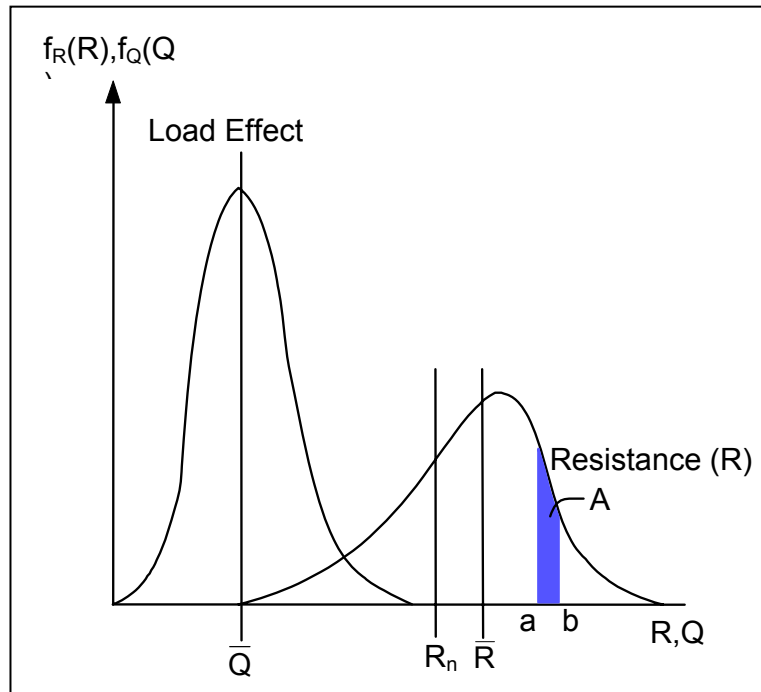
equation analysis, dynamic testing or static load testing. The one exception is the use of a dynamic formula and most formulas usually give allowable loads. The Gates Formula is an exception in that it produces a predicted ultimate load. The geotechnical engineer then selected a factor of safety to arrive at an allowable load. Again, the structural engineer had to use allowable loads to do the pile group selection and layout but then factored loads to design the pile cap. Private sector designers have been dealing with this inconsistency for forty years.

In 1969, Cornell published a paper in the ACI Journal (Cornell 1969) showing that the load and resistance factors could be determined rationally using a probabilistic analysis. As input to that analysis the variability of both the loads and the resistance was required. The National Bureau of Standards (NBS) completed a research project to collect the necessary information for buildings and they generated the associated factors (Ellingwood et al 1980). At that time the only LRFD Design Code in use was the ACI Code and the NBS factors were quite different than those contained in the ACI Code. These differences continued until 2002.

Today, LRFD design specifications are available for both steel and concrete buildings. Beginning with the 2002 ACI Building Code the load factors for both steel and concrete structures became the same. All concrete buildings are designed using LRFD but in the case of steel buildings the implementation of LRFD is not complete and an ASD design specification is still available and widely used for steel structures.

G.3 CALIBRATION OF PROBABILITY BASED LRFD

The original work of Cornell (1969) produced a major research effort to develop a probabilistic approach to structural design based on the load and resistance factor concept. The fundamental concept held that, since neither the loads nor the resistance are deterministic, it is appropriate to treat both load and resistance as random variables and to develop an approach to the design of structures based on probability theory. The concept is illustrated in Figure G.1 where probability density functions are shown for both the load effect, Q , and the resistance, R . The area under the resistance curve between a and b represents the probability of the resistance being between a and b . The region where the two curves overlap represents cases of “failure.” Probability-based design is founded on the concept that the design be selected so that the probability of failure is equal to, or less than, some prescribed value. The limiting failure probability was originally established from laboratory test data on structural elements.



**Figure G.1: Example of Probability Density Functions
for both Load and Resistance**

The load effect in Figure G.1 has been shown much narrower than the resistance for illustrative purposes, indicating that, in this case, the load has less variability than the resistance. The variability is defined by the standard deviation of the distribution. (The standard deviations are not shown in Figure G.1.) In Figure G.1, the mean values are denoted by \bar{Q} and \bar{R} . The nominal resistance, R_n is not necessarily the same as the mean resistance as illustrated in Figure G.1, but is the resistance that would be determined by the specified analysis method.

If distributions are available for both the load effect and the resistance, then the probability of failure can be determined. One approach that has been used is to consider the combined probability density function for $R-Q$ and this is illustrated in Figure G.2. Failure is defined when $R-Q$ is less than zero and the region is shaded in Figure G.2. The probability of failure is the area of the shaded portion under the curve. The basis for design is to require that the mean of that distribution, $\bar{R} - \bar{Q}$, be greater than the value of $R-Q = 0$. The distance of that mean above zero is taken as a multiple, β , of the standard deviation of the distribution. β is known as the safety index or

reliability index. There are other approaches to establishing a measure of safety. A more detailed discussion of probabilistic code calibration has been presented by Kulicki (1998).

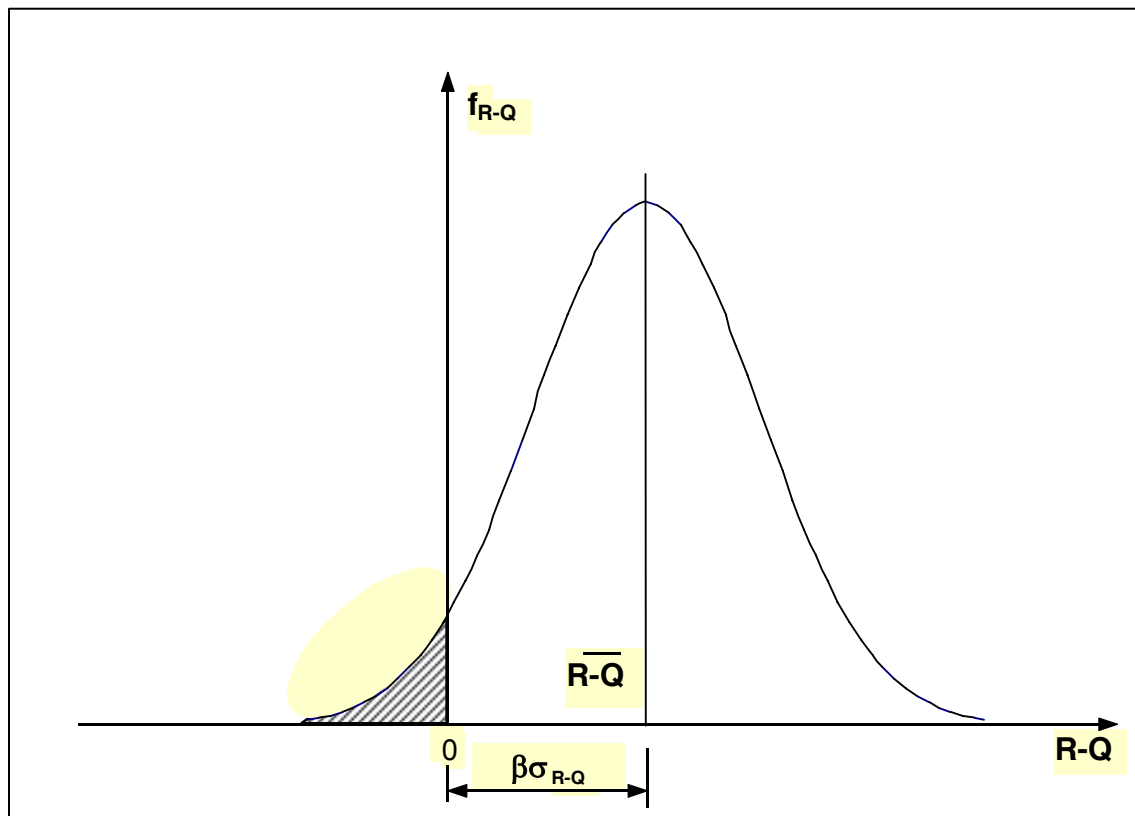


Figure G.2: Probability Density Function for R-Q

Existing structures that have performed satisfactorily have been analyzed to determine safety indices and from these analyses recommended values have been determined. Then, with knowledge of the load and the strength variabilities it is possible to select load and resistance factors to produce the required safety index. Structural engineers have established load factors for the various load types in the AASHTO Bridge Code and most of these values are probably not subject to change today. So the geotechnical resistance factors must be selected to achieve the required appropriate safety index.

Geotechnical strength measurement is very difficult to describe statistically due to the lack of standardized procedures for material characterization of soils. But, load and resistance factors can be calibrated based on a direct comparison with existing design practice. Load factors have been selected for the AASHTO LRFD Bridge Code so resistance factors can be directly determined to produce designs similar to those obtained in current ASD practice. For example, the AASHTO Strength I case is considered since it is commonly critical in design. The equality condition is used to obtain a unique and limiting expression. The expression can be stated in a simplified fashion as

$$\gamma_D Q_D + \gamma_L Q_L = \phi_k R_{nk} \quad (3)$$

where the subscript D refers to dead load and L refers to live load. Values are available for the dead and live load factors for Strength I in the AASHTO LRFD Bridge Code and Expression (3) becomes

$$1.25 Q_D + 1.75 Q_L = \phi_k R_{nk} \quad (4)$$

The equivalent ASD relationship can be stated

$$(Q_D + Q_L) FS = R_{nk} \quad (5)$$

where FS is the ASD factor of safety. For the equality condition, R_{nk} can be eliminated from Expressions (4) and (5) and this results in a single relationship for ϕ_k , in terms of FS and the Q_L/Q_D ratio.

$$\phi_k = \frac{FS(1 + Q_L / Q_D)}{(1.25 + 1.75 Q_L / Q_D)} \quad (6)$$

Figure G.3 shows resistance factors for various factors of safety as a function of Q_L/Q_D ratio for the AASHTO LRFD Code. Regardless of the source of resistance factors they must be checked against existing ASD practice. For example, if the probability analysis produced smaller resistance factors than the equivalent ASD factors of safety this would imply an unnecessary increase in conservatism in the design.

The factor η in Expression (2) has been ignored in the above discussion. The primary concern with η in foundation design comes when only a very few deep foundation

elements are used so that the foundation is non-redundant. While it is not so clear how redundancy can be determined since it is to some degree controlled by the superstructure geometry it can be critical and must be evaluated. Certainly a single deep foundation element will be non-redundant. Of course, most driven pile foundations will have enough piles to be redundant.

G.4 LRFD DETAILS

Now let us look at what we have to do to verify the safety of an LRFD-based design. We will consider the issue, “Does the structural element (pile) have adequate axial strength.” We have spoken at some length about the fundamental concepts on which LRFD is based. Now, how do we actually use this concept that has often been presented as a radical new approach? It is best to consider the details. First, consider the determination of the loads that would be used in bridge design. There are five strength limit states, two extreme event limit states, four serviceability limit states and one fatigue limit state given in Table 3.4.1-1 of the AASHTO LRFD Bridge Code. We will consider only the strength limit states here. The factored loads for those five cases are

Strength I

$$\gamma_p D + 1.75 L + 1.0 WA + 1.0 FR$$

Strength II

$$\gamma_p D + 1.35 L + 1.0 WA + 1.0 FR$$

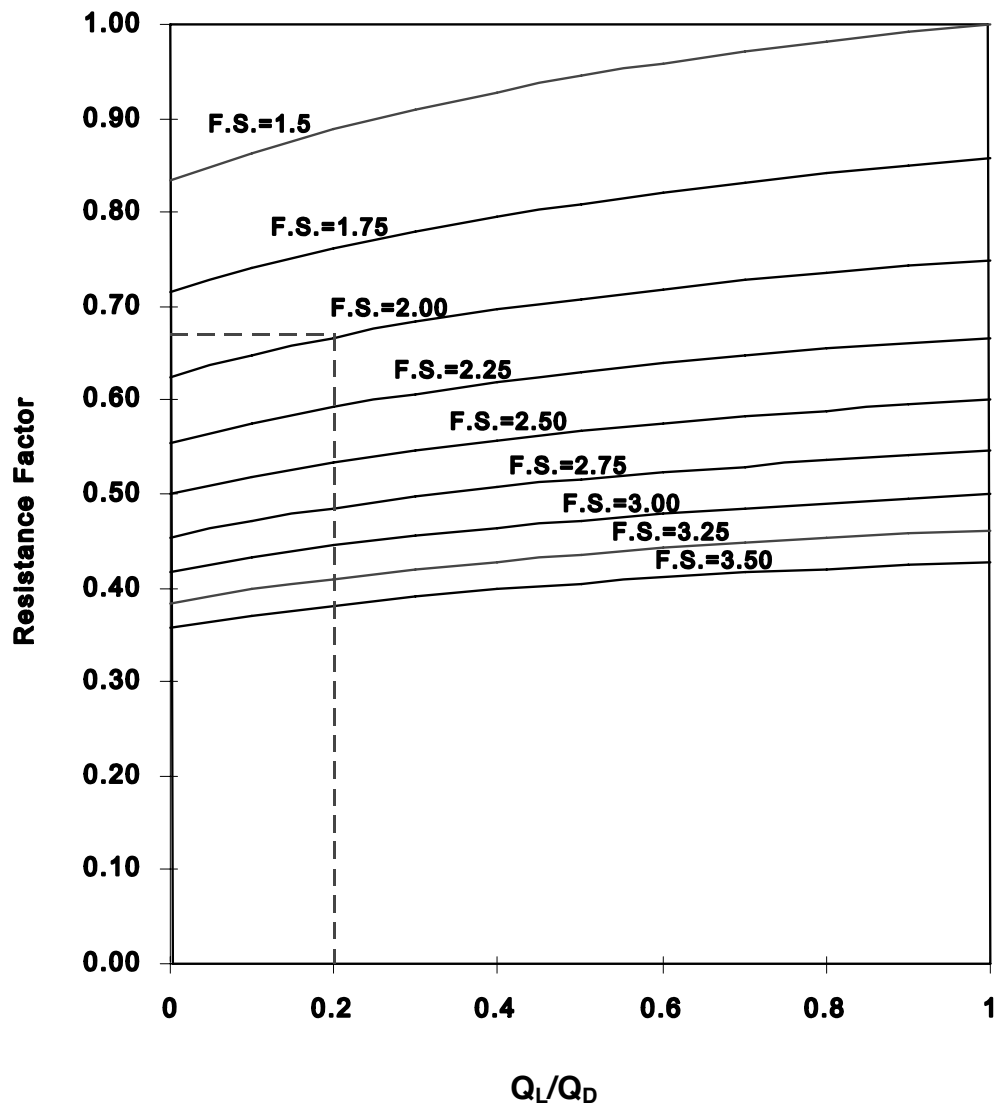


Figure G.3: Resistance Factor as a Function of Q_L/Q_D for Various Factors of Safety for the AASHTO LRFD Bridge Code

Strength III

$$\gamma_p D + 1.0 \text{ WA} + 1.4 \text{ WS} + 1.0 \text{ FR}$$

Strength IV

$$\gamma_p D + 1.0 \text{ WA} + 1.0 \text{ FR}$$

but for dead load due to structural components only

$$1.5 D$$

Strength V

$$\gamma_p D + 1.35 L + 1.0 WA + 0.4 WS + 1.0 WL + 1.0 FR$$

These load combinations have been somewhat simplified for this discussion. The notation can be defined as follows:

γ_p – load factor for the various types of dead load. For the superstructure dead load γ_p is 1.25, but other values are specified for other types of dead load.

D – dead load.

L – live load

WA – water and stream load

FR – friction load

WS – wind load on the structure

WL – wind load on the live load

Since the load combinations have been somewhat simplified, the reader is encouraged to review Sections 3.3 through 3.6 of the AASHTO LRFD Bridge Design Specifications. Probably geotechnical engineers that are responsible for driven pile design will not be required to determine the factored loads, but a general understanding of those loads provides a better understanding of the entire design process. While the above loads and load combinations have differences from that of previous AASHTO Specifications the general structure of the loads is unchanged. Since there may be several different sets of loads (for instance, maximum and minimum) for each of the strength limit states the final set of factored loads will usually be larger than the five given above and sometimes much larger, particularly if extreme event conditions must be considered.

So now, in the foundation design process, the factored loads will be determined by the structural designer and with the exception of the downdrag case it is unlikely that these loads or load combinations will change in future AASHTO Codes. We have now completed a review of the left side of Expression (2).

The right side of Expression (2) is of greater concern for the geotechnical foundation designer. He must determine values of ϕ_k , the resistance factor, and R_{nk} , the nominal

strength. Values for ϕ_k must be defined by code. It has often been implied that resistance factors may be determined in the design process using a probability analysis. This is not realistic and certainly not necessary for driven pile design. At the present, the resistance factors contained in the AASHTO Bridge Code are poorly defined and not always unique. They will not be discussed here since the entire document may soon be replaced. However, it is quite clear what resistance factors are needed, only their values are not clearly defined. Methods must be available to determine the nominal strength, R_{nk} .

G.5 THE DESIGN PROCESS

The design process for LRFD will now be reviewed. The Flow Chart for LRFD-based design is given in Figure G.4. This flow chart is very similar to that given in Figure 2.1 to show the process for ASD-based design. All of the Blocks are similar through Block 7. Requirements must be determined and the subsurface must be investigated and evaluated to obtain the necessary geotechnical design quantities. A driven pile type is selected. Then in Block 8 the factored loads are determined. In Blocks 10 or 12 the resistance factor is selected based on the capacity verification procedure and the quality control method that has been selected. In the ASD method, a factor of safety is selected based on the information in Table 4.5.6.2.1A of the AASHTO Standard Specification. The resistance factor for LRFD is given in the Table 10.5.5-2 of the AASHTO LRFD Specification. Selection of the proper value for resistance factor from the LRFD Specification will not be discussed here.

The rest of the Design Flow chart is similar to the one for ASD. It can be seen that there is little difference in the design process for LRFD composed to ASD.

G.6 A SIMPLE EXAMPLE

A very simple numerical design example will be solved to illustrate the differences between ASD and LRFD. Only strength will be considered since those limitations are the only ones that are different for the two methods. The example uses the soil of Example 1, of Chapter 16, Section 16.5.1 of this manual. The soil

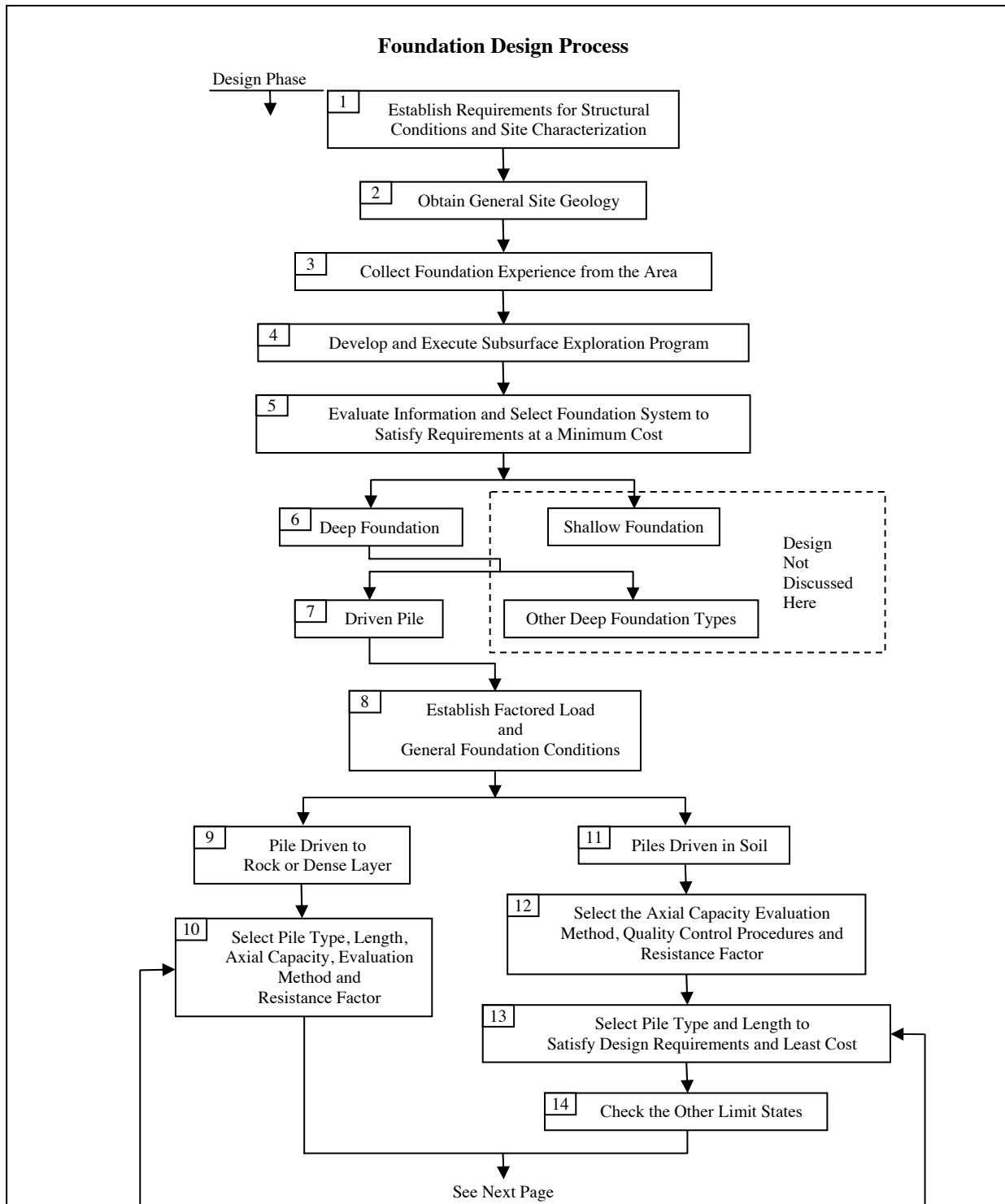


Figure G.4: Driven Pile Design and Construction Process by LRFD

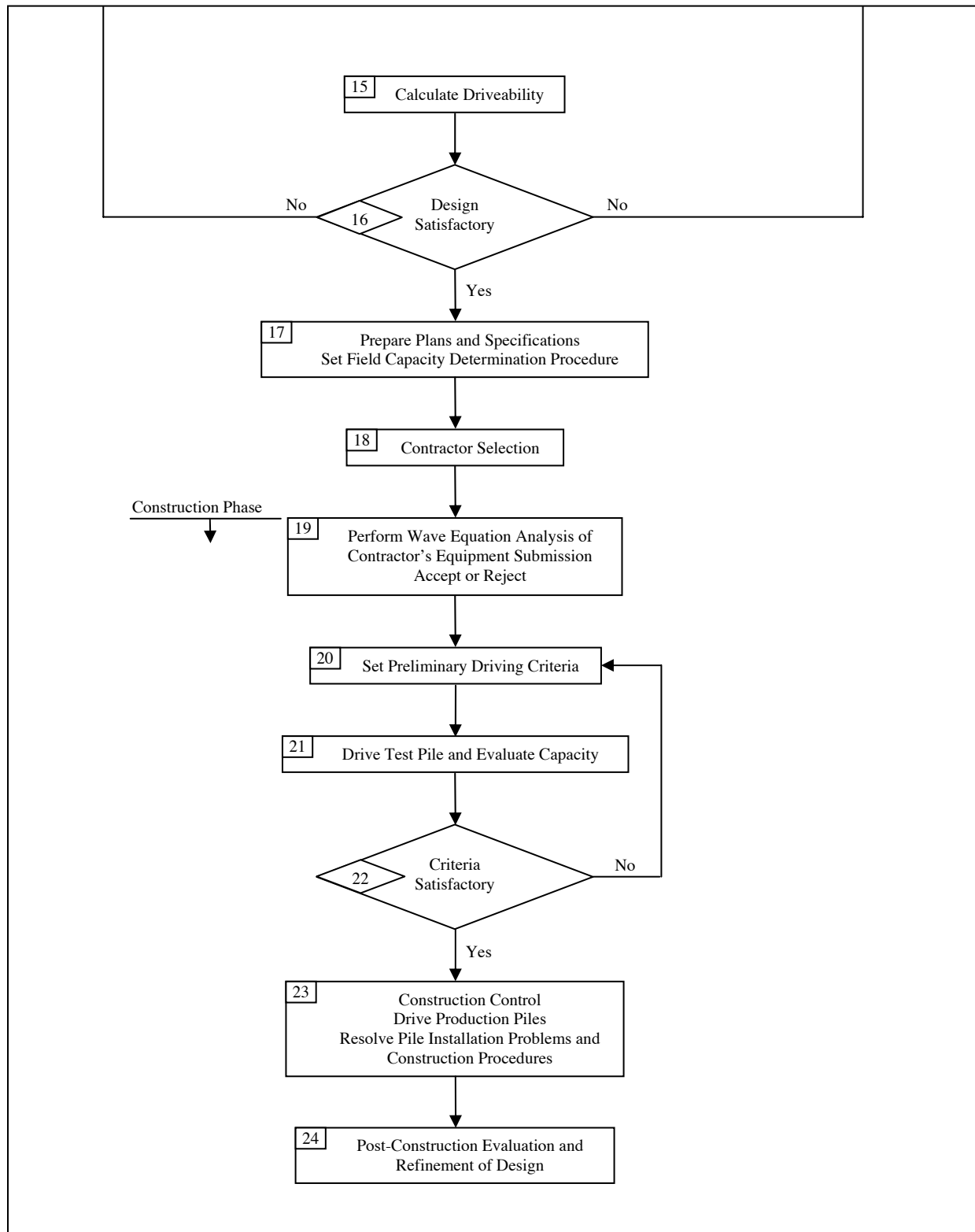


Figure G.5: Driven Pile Design and Construction Process by LRFD (Continued)

is a medium dense sand with an adjusted N-value of 20 and a friction angle of 33 degrees. In this trial design, a closed end steel pile having a length of 20 m (66.7 feet) and a cross section 356 mm x 8 mm (14 inches x 5/16 inches) has been selected and a geotechnical analysis indicates a nominal resistance of 1480 kN (330 kips). The working load on the foundation will be taken as 2225 kN (500 kips) dead load and 3560 kN (800 kips) live load including impact.

G.6.1 ASD

According to Table 3.22.1A of the Standard Bridge Code for the service load Case I, the design load is

$$2225 + 3560 = 5785 \text{ kN (1300 k)}$$

First, assume that a static load test will be used in addition to a drivability analysis by wave equation with subsurface investigation and static analysis to verify the driving criteria. Therefore, the factor of safety specified in Table 4.5.6.2A is 2.0 and the required nominal axial resistance is 11,570 kN (2600 k). Now if the pile nominal resistance is 1480 kN (333 k), then the total required number of piles will be

$$11,570/1480 = 7.8 \text{ piles, 8 piles}$$

If dynamic measurement and analysis is used the specified factor of safety is 2.25, giving a required ultimate axial resistance of 13,016 kN (2924 k). In this case the required number of piles will be

$$13,016/1480 = 8.8 \text{ piles, 9 piles}$$

G.6.2 LRFD

First, determine the factored load. In this very simple example, only Strength I of Table 3.4.1-1 of the LRFD Bridge Code will be considered.

$$1.25 \times 2250 + 1.75 \times 3560 = 9,042 \text{ kN (2032 k)}$$

The specified resistance factor to be used with a static load test is given in Table 10.5.5-2. It is interpreted to be $0.8\lambda_v$ for static load test. The value of λ_v with a wave equation analysis used in the field is 0.85. The resistance factor is.

$$0.80 \times 0.85 = 0.68$$

The required nominal resistance is

$$9,042/0.68 = 13,297 \text{ kN (2988 k)}$$

The required number of piles is

$$13,297/1480 = 9.0 \text{ piles}$$

The required value of resistance factor for the case of dynamic measurement and analysis cannot be interpreted from the current AASHTO LRFD Specification.

G.6.3 Comments

This very simple example illustrates the difference between ASD and LRFD. Of course, only one failure mode limit state was considered. In a real design problem, several load combinations would be included, the loads would include overturning loads and all aspects of the problem would be much more complex. This simple example illustrates the total difference between ASD and LRFD clearly and simply. No conclusions should be made regarding the fact that the LRFD design was more conservative in this case. However, the importance of live-dead load ratio becomes clear. For short span bridges the live load may be much larger than the dead load which is the case here while for very long spans structures the live loads can be almost inconsequential. In the latter case, Condition Strength IV would become critical and fewer piles would be required.

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