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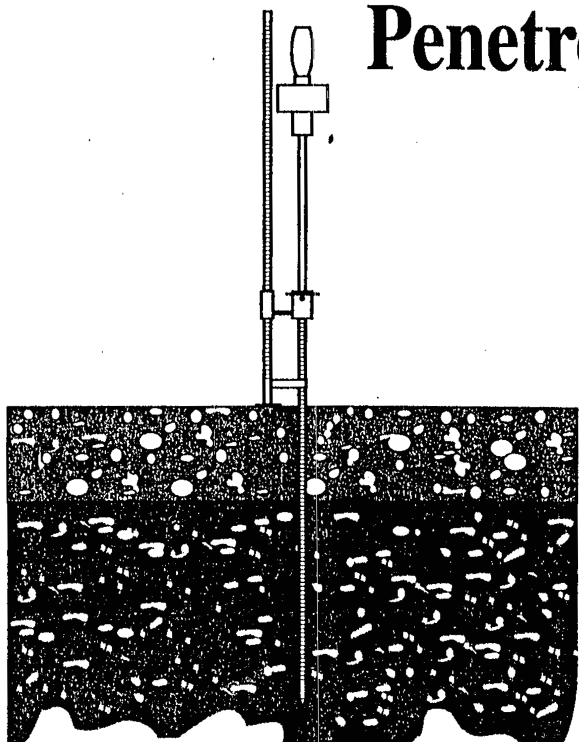
Physical Research

In Situ Foundation Characterization Using the Dynamic Cone Penetrometer



IN SITU FOUNDATION CHARACTERIZATION USING THE DYNAMIC CONE PENETROMETER

Final Report

By
Tom Burnham
Research Testing Engineer
and
Dave Johnson
Research Operations Engineer

Minnesota Department of Transportation
Office of Research Administration
200 Ford Bldg., 117 University Ave.
St. Paul, MN 55155

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16. Abstract (Limit: 200 words)

The Dynamic Cone Penetrometer (DCP) is a test device used for measuring the strength and variability of unbound layers of soil and granular material. The DCP is not a new test device but transportation organizations in Canada and the United States, including the Strategic Highway Research Program (SHRP), have shown a renewed interest in its unique capability of measuring a profile of in situ foundation characteristics. A desire to more fully characterize subsurface conditions on the Minnesota Road Research Project (Mn/ROAD) led to the initial use of DCP's by Mn/DOT. From an operational perspective it is very attractive because the DCP is both portable and simple to use.

The objective of this research was to explore ways that DCP's could effectively be used by Minnesota pavement and materials engineers and to perform the testing, analysis, and learning necessary for establishing relationships between DCP test results and other commonly used foundation parameters.

This report describes the design and operation of the DCP as well as an overview of the theoretical basis for use of the device. In addition, correlation results, data profiles, case histories and related information are presented.

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Background

Characterizing field material properties by using laboratory tests is an ongoing problem in the discipline of pavement design. This problem has two aspects. First it is difficult to collect and test representative samples. Because of the large variability of typical pavement materials a large number of random samples must be collected and tested to generate results with good statistical significance. Second it is difficult to quantify, much less reproduce, the in situ sample condition and environment in a laboratory. This problem is particularly acute for subgrade material layers which are a product of a seemingly random glaciation process rather than of a controlled manufacturing process.

Two papers presented at the Transportation Research Board Annual Meeting in January 1993 highlight the inherent difficulties in using laboratory testing to characterize field subgrade conditions.

Daleiden et al[1] performed a preliminary investigation of the 1986 American Association of State Highway and Transportation Officials (AASHTO) flexible pavement design equation using data from Strategic Highway Research Program (SHRP) Long Term Pavement Performance (LTPP) test sections. They compared the subgrade resilient modulus (Mr) back calculated from field tests to the Mr determined from laboratory testing. They determined from the data available for their study that the sample average of the ratios of field to corresponding laboratory results was 5.06. Furthermore the standard deviation of the sample of these ratios was 3.28.

Forsyth[2] contacted 11 states that currently are not using the 1986 AASHTO pavement design procedure and asked them what criteria they use for selecting a subgrade strength value for a project. He found that 8 of these states select a very conservative subgrade strength value, one being less than or equal to 85 to 100 percent of the samples. In addition "laboratory strength tests are conducted on saturated disturbed samples reflecting a more [harsh] environment than will likely occur in the design life of the pavement". As a result of an ever increasing conservatism in selecting subgrade strength values, "permanent subgrade deformation is virtually non existent in California, even on badly cracked flexible pavement." He goes on to recommend that "Whenever possible, pavement designs should be based upon in situ subgrade strength measurements ...".

The cost implications of conservative pavement designs resulting from our inability to adequately characterize field subgrade strengths have to be staggering. Certainly the 1986 AASHTO pavement design procedures take steps in the right direction by allowing the incorporation of non destructive testing (NDT) deflection data and reliability factors into the design process. However, as we begin to move away from empirical methods and move toward mechanistic and statistically based design methods we need to continue to look for tools that will give us the information we need to support such a move.

The Dynamic Cone Penetrometer (DCP) is one such tool. It is a simple test device that is inexpensive, portable, easy to operate, and easy to understand. It does not take extensive experience to interpret results and several correlations to more widely known strength measurements have been published. The DCP quickly generates a continuous profile of in situ subgrade and base strength measurements.

Description of the Test

The dynamic cone penetrometer (DCP) described in this paper is based on the Central African Standard as modified by the Transvaal Road Department[3]. The device consists of two 0.63 in. (16 mm) diameter rods, with the lower rod containing an anvil, a replaceable 60° pointed tip, and depth markings every 0.2 inches (5.1 mm). The upper rod contains an 17.6 lbs. (8 kg) drop hammer with a 22.6 inch (575 mm) drop distance, an end plug for connection to the lower rod, and a top grab handle (Fig. 1). All materials (except the drop hammer) are stainless steel for corrosion resistance. An optional depth reading device can be attached, as shown in Fig. 1, to eliminate the need to measure penetration depth at ground level.

Operation of the DCP requires two persons, one to drop the hammer and the other to record the depth of penetration. The test begins with the operator "seating" the cone tip by dropping the hammer until the widest part of the cone is just below the testing surface. At this point the other person records this initial penetration as "Blow 0". The operator then lifts and drops the hammer either one or more times depending upon the strength of the soil at that test location. Following each sequence of hammer drops, a penetration reading is taken. This process continues until the desired depth of testing is reached, or the full length of the lower rod is buried. At that time, a specially adapted jack is used to extract the device.

Data from a DCP test is processed to produce a penetration index (PI), which is simply the distance the cone penetrates with each drop of the hammer. The PI is expressed in terms of inches per blow or millimeters per blow. The penetration index can be plotted on a layer strength diagram (Fig. 2), or directly correlated with a number of common pavement design parameters. Some of these correlations will be described in more detail later in this paper.

Since its introduction to Mn/DOT in June 1991, the DCP has undergone some minor modifications in its design, with the most significant change occurring at the connection between the upper and lower rods. Originally a threaded connection, a simple slip plug and bolt connection is now used. Other notable modifications include an increase in the weld size at all junctions (for prolonged device life) and the addition of a hand safety guard on the anvil.

History

Soil penetration testing devices like the DCP have a long, but subdued history. Perhaps the earliest penetration testing devices were driven piles. On a project requiring piles, a builder would install "test" piles to determine their required length. These "test" piles would be driven until a certain rate of penetration rate was achieved. Once that rate was reached, it was assumed that future installation of the same length piles would be satisfactory[4].

The earliest record of a subsoil penetration testing device similar to the DCP is a "ram penetrometer," developed in Germany at the end of 17th century by Nicholaus Goldmann. The next major development again came from Germany, when Künzel in 1936 developed what was known as a "Prüfstab". This device was later used by Paproth in 1943, and eventually become standardized in 1964 as the "Light Penetrometer", German Standard DIN 4094[4].

Concurrent with the German standardization of the "Light Penetrometer", several other countries developed their own standard penetration devices. The DCP used by Mn/DOT, and several other DOT's in the United States and Canada, was originally developed by Scala (1956) in Australia. Following its adoption as the Central African Standard DCP, it was later simplified and modified by van Vuuren (1969) in South Africa[3,4]. Interest in the U.S. mainly originated from research conducted by Marshall Thompson at the University of Illinois[5]. Mn/DOT obtained specifications from the University of Illinois and constructed two DCPs for research on the Minnesota Road Research Project (Mn/ROAD).

Theory

As a cone penetration device, the DCP provides some measurement of the shear strength of a soil. Research has been conducted looking at both the forces imparted by a DCP cone tip, and the behavior of the soil caused by the application of these forces.

Most DCP tip to soil interaction behavior models are variations of models developed to analyze soil failure caused by air-dropped projectiles. While projectiles begin with velocities of several hundred feet per second, DCP tip penetrations are considered "slow" penetrations.

Chua(6) formulates his modeling solution by considering the penetration of an axisymmetric soil disc with a thickness equal to the height of the cone, similar to work by Yankelevsky and Adin(7) for projectiles. Using stresses and strains from the model, Chua developed a correlation of penetration index (PI) versus elastic modulus for various types of soils. Chua and Lytton(8) performed a "structural system" type dynamic analysis including both the DCP and its soil interaction. In the analysis, the DCP is modeled as a series of springs and masses, and the soil as a dashpot. Acceleration and damping analysis' were conducted, along with measuring the peak acceleration of the device (1400 *G*). It was also shown that it is possible to determine damping properties of in-situ pavement materials through DCP testing.

Applications

DCP testing can be applied to the characterization of subgrade and base material properties in many ways. Perhaps the greatest strength of the DCP device lies in its ability to provide a continuous record of relative soil strength with depth. By plotting a graph of penetration index (PI) versus depth below the testing surface, a user can observe a profile showing layer depths, thicknesses, and strength conditions (Fig. 2). This can be particularly helpful in cases where the original as-built plans for a project were lost, never created, or found to be inaccurate.

The DCP's other strength lies in its small and relatively lightweight design. It can be used in confined areas such as inside buildings to evaluate foundation settlements, or used on congested sites (trees, steep topography, soft soils, etc...) that would prevent larger testing equipment from being used. The DCP is ideal for testing through core holes in existing pavements.

The following applications outline either existing or proposed uses of DCP testing.

a) <u>Preliminary Soils Surveys</u>

DCP testing can be done during preliminary soil investigations to quickly map out areas of weak material. Some have used it to locate potentially collapsible soils. By running an initial DCP test, and then flooding the location with water and running another test, a noticeable increase in the PI (less shear strength) might indicate a potentially collapsible or moisture sensitive soil that would warrant a more detailed investigation(4).

b) <u>Construction Control</u>

The DCP is an ideal tool for monitoring all aspects of the construction of a pavement subgrade and base. It can be used to verify the level and uniformity of compaction over a project. It can also be used to define problem areas that develop due to unavoidable soil conditions brought on by inclement weather. Some have suggested it would be a good tool to use in lieu of test rolling on projects that are too short (to justify expense of test rolling) or have shallow utilities (which would prevent test rolling).

An excellent example of the usefulness of DCP testing was demonstrated in 1989 during the construction of a new cargo apron on the southeast side of the Greater Peoria Regional Airport in Illinois. It was determined that lime modification (not stabilization) was necessary to obtain adequate compaction of the grade. The lime was applied to the upper 12 inches (30.5 cm) of the grade, but heavy rains prevented hauling traffic from reaching the treated areas, so they remained undisturbed for several weeks. When construction resumed on those areas, the subgrade was found to be yielding under construction traffic. To test whether the lime modification was effective, eight DCP tests were run. It was found that the lime had modified the upper 12 inches soil, and the actual cause of the rutting was a very soft layer 30 to 40 inches (76 to 102 cm) below the surface (Fig. 3)[(5)].

c) Structural Evaluation of Existing Pavements

One of the major applications of DCP testing has been in the structural evaluation of existing pavements. South Africa has used DCP testing extensively in conjunction with their Heavy Vehicle Simulator (HVS) to investigate both shallow and deep pavements with light cementitious gravel layers. The effects of traffic molding caused by HVS loading were also evaluated by DCP tests[(9)]. Prior to this study, de Beer et al.[(10)], had developed a pavement strength-balance classification system based on Standard Pavement Balance Curves (SPBCs) as determined from DCP testing. Kleyn describes the strength balance of a pavement as "the change in the strength of the pavement layers with depth. Normally, the strength ... decreases with depth,...and if this decrease is smooth and without discontinuities, and conforms with one of the SPBCs, the pavement is regarded as balanced or in a state of balance[(11)]."

Using the above system, an empirical DCP-based model for the prediction of pavement life expectancy was developed using DCP results. Finally, overlay test strips were constructed to study the feasibility of light pavement design based on the same model.

Thompson and Herrin[(5)] reported on the use of DCP testing in a 1988 non-destructive rehabilitation study at Illinois' Palwaukee Municipal Airport. In the study, DCP testing was conducted following Falling Weight Deflectometer (FWD) testing to further evaluate "weak" areas that were found. FWD testing showed the northern 1000 feet of one runway to have weaker pavement sections than the rest. Since this weaker area was near a drainage ditch, a subsurface investigation, including DCP testing, was conducted. Both soil borings and DCP results indicated weaker granular material was underlying the pavement near the ditch. Based on these findings, properly designed bituminous overlays were then determined following the FAA design procedure.

d) Future Applications

Due to the DCP's small size and simplicity of operation, there is no doubt new applications will be found for its use. One of these applications may be as mentioned before, a substitute for final testing rolling of grades before pavement placement. Yet another might be its use in measuring the frost/thaw depth in cold climate pavements during the spring months. This could enhance an engineer's decision to invoke or remove load restrictions.

Data Analysis

DCP testing results are expressed in terms of the penetration index (PI), which is defined as the downward vertical movement of the DCP cone produced by one drop of the sliding hammer (inches/blow or mm/blow). Stiffer or stronger soils require a higher number of blows or drops of the hammer to achieve a given penetration.

Test results are typically processed using a spreadsheet as shown in Fig. 4. Data for the first two columns (blow number and depth of penetration) is transferred directly from a field data collection form. The third column is an average of the present and previous DCP depth readings. By averaging the readings in this manner, the strength of a soil layer between DCP readings is represented by a uniform PI located at the midpoint of the layer. The fourth column is the PI, which is calculated by dividing the difference in the present and previous DCP depth readings by the number of hammer blows between these readings.

Once the results are processed, a graph of penetration index (column 4) versus penetration below the surface (column 3) can be prepared (Fig. 5) . The graph will clearly show a profile of the different strength layers. It should be noted that the results can easily become unrealistic if the DCP encountered a rock or debris during a test (one or two points with near zero penetration index).

The penetration index can be correlated with a known pavement design parameter in order to understand the actual material strength. The following section describes some of the more commonly published PI correlations.

Published Correlations

a) California Bearing Ratio (CBR)

The most common correlation of the PI is to the California Bearing Ratio (CBR). The CBR is defined as the ratio of the resistance to penetration developed by a subgrade soil to that developed by a specimen of standard crushed-rock base material. Many graphs of PI-CBR correlation can be found (Fig. 6)[12], with the equation for the line typically in the form:[3,13,14]

$$\mathrm{Log}\,CBR = \mathrm{A} - \mathrm{B}\ \mathrm{Log}\,PI$$

Although moisture content and dry density can have great effects on shear strength in fine soils, these properties are typically neglected in this correlation since they were found to have a similar effect on both CBR and PI results[3].

During the studies of the correlation of PI and CBR, it was found that DCP testing can be an excellent substitute for field CBR determination. This is based on the fact that the coefficient of variation (CV) in field CBR test results for a particular material can be of the order of 60%, while that of CBR determined by DCP testing can be of the order of 40%[3,14]. The CV of a test is an indication of the repeatability of a test (lower values mean higher degree of repeatability). However, some researchers caution against PI-CBR correlations since CBR is a measurement of soil performance in the elastic range, whereas a DCP test causes material failure[6]. Is his studies, Klimochko[21] found that correlating the PI and CBR for base course materials can lead to unusually high and misleading results.

b) Unconfined Compressive Strength (UCS)

Another published correlation is that of PI versus unconfined compressive strength (UCS). The UCS is a measure of the cohesive strength of a soil. Several graphs of the correlation between UCS and PI can be found in the literature (Fig. 6[12]).

c) Standard Penetration Resistance

Sowers and Hedges[16], and later Livneh and Ishai[17], developed a correlation between PI and standard penetration test (SPT, ASTM D1586-64) results (Fig. 7a[17]). The correlation equation took the form:

$$\text{Log(PI)} = -A + B\ \text{Log(SPT)}$$

(Valid for SPT < 0.40 inches/blow (10mm/blow)

It should be noted that both studies involved the use of DCP's of slightly different design, but which still fit the classification "light penetrometer".

d) Elastic Modulus

Some research has been conducted to find a correlation between PI and the elastic modulus of a soil. Chua[6] presented a model and preliminary findings for several types of soil, and expects final analysis to be complete by fall of 1993. Others[15] have examined this correlation and propose equations of a form similar to CBR equations (Fig. 7b[15]):

$$\text{Log}(Eeff) = A - B\ \text{Log}(PI)$$

Investigation into the correlation of PI versus resilient modulus (Mr), as back calculated from Falling Weight Deflectometer (FWD) testing on the Mn/ROAD research project, will be pursued by Mn/DOT in the future.

e) Shear Strength of Cohesionless Granular Materials

Ayers et al[18] performed a laboratory study to determine relationships between the PI and the shear strength (cohesion (c) and the angle of internal friction (Φ)) properties of cohesionless granular materials. Prediction equations of the form:

$$DS = A - B(PI) \qquad \text{where DS = Deviator stress at failure}$$

for confining pressures of 5, 15, and 30 psi (35, 103, and 207 kPa) were developed (Fig. 8). The selection of the appropriate prediction equation requires an estimate of the confining pressure under field loading conditions, which was stated to require further investigation.

f) Clegg-hammer and Benkelman Beam

Trial roadway sections were constructed in Botswana to study the use of sub-standard pavement materials for low volume roads[(20)]. A comparison in pavement strength was then carried out using a DCP, a Clegg-hammer, and a Benkelman Beam. The researchers found good correlation between the test methods for base level materials, with result comparisons deteriorating rapidly with depth. Clegg-hammer CBR values were found to be roughly 1.6 to 2.2 times higher than CBR values determined with a DCP. Useful correlations were found between PI and deflection as measured by the Benkelman Beam for base, subbase, and upper subgrade layers.

Saskatchewan Highways and Transportation researchers also report beneficial results using the DCP to supplement Benkelman Beam test results[(21)].

h) General Comments

At the First International Symposium on Penetration Testing (ISOPT-1), the ISSMFE Technical Committee submitted an international reference test procedure for dynamic probing[(22)]. In their document No. 2, *Reviewing The Present Practice*, a current state of practice for interpreting penetration testing results was overviewed. A long list describing typical test behaviors, such as the affect material properties have on penetration resistance, was given for many types of penetration testing.

Finally, future DCP users may be interested in following the Australian practice of recalibrating the DCP for each soil on a specific construction job, and then using it as a control instrument based on localized PI parameters[23].

Examples of DCP Usage in Mn/DOT

The purpose of the following examples are to stimulate the readers' insight as to the potential and versatility of the DCP. Since its introduction to Mn/DOT in 1991, the DCP has been evaluated by the department for several different applications. These examples outline how this instrument has been used successfully by Mn/DOT. Further details about these examples are available from the authors upon request.

a) Locating High Strength Layers in Pavement Structures

A byproduct (spray dryer residue) from Northern States Power's coal burning power plant at Becker, Minnesota was used experimentally to stabilize aggregate layers in a haul road at the plant site in October of 1991. DCP testing was selected to measure the relative strengths of stabilized and unstabilized road layers.

The measurements from a test section with no treated layers (Fig. 9) show that the PI of the aggregate gradually decreases (relative strength increases) with depth. This can be explained by increased densification in the lower layers because of the overburden. However, measurements for a test section with a treated layer (Fig. 10) show a sudden and drastic reduction in the PI starting at a depth of about 7.5 inches (190 mm). Testing was terminated at a depth of about 10 inches (254 mm) because the drop hammer was bouncing up from the anvil after each drop.

b) Identifying Weak Spots in Constructed Embankments

In October of 1991 DCP testing was done on a TH 212 bridge embankment west of Sacred Heart, MN. At that site the contractor was having difficulty meeting embankment density requirements. Measurements at this site demonstrated the utility of the DCP to map out weak spots and to highlight how variable the "same" material can be under real world construction conditions. All measurements were made at station 3+93, but at different offsets. One test (Fig. 11) depicted an embankment with an average PI of about 2 inches (51 mm) per blow with a range from .5 to 3.6 inches (13 to 91 mm) per blow. A mere 40 feet (12 m) away (Fig. 12) the average PI was about 1 inch (25 mm) per blow with a range from .4 to 1.6 inches (10 to 41 mm) per blow. Typically with plastic soils, a PI over 2 inches (50 mm/blow) per blow is cause for concern, and additional soil testing is warranted.

At the Mn/ROAD pavement research facility DCP testing showed an extremely weak spot in the lower layers in one of the test section embankments. PI's were as high as an astounding 11.7 inches (297 mm) per blow at a depth of 30 inches (762 mm) while PI's near the surface averaged under 2 inches (51 mm) per blow (Fig. 13). Additional tests in this area showed that the weak spot was quite limited in size but the cause was still not understood. Finally someone noticed a stripe on the shoulder of nearby westbound I-94 marking an edge drain outlet. Unfortunately, the outlet had been covered during the construction of the new test section embankment. Water was being drained directly into the embankment causing the weak spot! The outlet was excavated and proper drainage was restored.

There is an expectation among Mn/DOT Materials and Soils Engineers that the DCP in a construction environment can perform much the same function as test rolling and can be used to delineate weak subgrade locations when pavements fail during construction. Both the Duluth and Rochester districts have used DCP testing to investigate the latter situation.

c) Measuring the Uniformity of In Situ Base Material

After the base material was placed at Mn/ROAD in 1992 we started DCP testing at the same rate that we had on the subgrade, that is at two offsets every 100 feet (30 m). We soon reduced our DCP testing rate because the compacted base materials were giving surprisingly uniform results at different depths, and at different locations. Figure 2 illustrates the strength, about 0.2 inches (5 mm) per blow, and uniformity of a relatively poor Class 3 special base material as compared to the more variable subgrade layer.

Heavy rains saturated a 4 inch (100 mm) base on I-35 near Faribault, MN, on a July 1991 night. DCP testing confirmed the decision not to begin concrete paving operations the next day because of the weakened state of the base (Fig. 14).

d) Supplementing Foundation Testing for Design Purposes

A DCP test can provide additional qualitative and quantitative in situ foundation information during normal soil survey sampling operations. By conducted a DCP test through a drill hole or near a thinwall hole, supplemental information can be gathered for comparison with laboratory results. It is felt that this additional information will lead to better design decisions.

In October of 1991 a DCP was used on TH 212 near Sacred Heart, MN, to evaluate the strength of the subgrade under a cracked full depth AC pavement. This section of roadway was being evaluated for rehabilitation options. Results of testing at 9 locations showed a quantitative difference in subgrade strengths immediately below the 12 inch (305 mm) pavement. The average PI under the wheel path was 0.9 inches (23 mm) per blow with a standard deviation of 0.17 inches (4 mm) per blow while readings NOT under the wheel path averaged 1.34 inches (34 mm) per blow with a standard deviation of 0.4 inches (10 mm) per blow. For these same 9 tests the average PI under a crack was 1.38 inches (35 mm) per blow with a standard deviation of 0.35 inches (9 mm) per blow while readings NOT under a crack averaged 0.83 inches (21 mm) per blow with a standard deviation of 0.15 inches (4 mm) per blow.

e) Compaction Testing of Back Fill in Edge Drain Trenches

Mn/DOT's typical pavement edge drain design (Fig.15) is back filled with a uniform fine filter aggregate (FFA). There has been an occasional problem with the settlement of the shoulder surface above the these edge drains. This problem led Mn/DOT's Geotechnical Section to investigate the compaction requirements and methods for the FFA. Their goal was to find a procedure for obtaining a compacted density of at least 95% of the maximum density defined by the standard Proctor test (ASTM T-99).

Investigators determined that the moisture content of the FFA had little effect on the compacted densities that it could attain. With this in mind the investigators set up a field test to correlate DCP tests of the FFA to its density for various compaction methods. They performed DCP and sand cone density tests in trenches ranging in depth from 12 inches (305 mm) shown in Fig. 16 to 48 inches (1220 mm) shown in Fig. 17. Their conclusions indicated that "the DCP can be easily and quickly used by construction inspectors to evaluate and approve the use of different types of compaction equipment based on field test installations."[19] As a result, Mn/DOT specifications now call for the use of the DCP for this purpose, and each Mn/DOT district now has a minimum of 2 DCP's.

Future Activities

While a fair amount of research has been done on DCP testing, new applications and correlations appear frequently. In an effort to further the understanding and use of the DCP for in-situ foundation characterization, Mn/DOT has chosen to conduct over 800 tests on the various materials and layers at the Mn/ROAD research project. (Some of the preliminary results were discussed earlier). What should also be mentioned is the significant amount of material sampling that is coinciding with this DCP testing. By analyzing the moisture content, soil type, and compaction density Mn/DOT hopes to develop more refined correlations for the DCP. Correlation with FWD results will also continue to be pursued.

Other future concerns include determining the appropriate frequency of DCP testing on a particular project. While this depends greatly on the type of investigation, developing guidelines seems feasible. As an example, the Mn/Road DCP testing frequency is listed on the next page.

Location:
- Every 100 feet (30.5m)
- Offset of +9.8' & -9.8' (Outer wheel paths)
- Top of subgrade
- Top of Base

Maximum depth: 42" (1067mm)

Moisture sample: 1 sample every 500 ft. (152 m) at depths: 6,18,30,42" (152,457,762,1067mm).

These guidelines were based on a number of factors including construction schedule limitations, sensor location, and having an adequate amount of test results for a good statistical analysis.

Finally, two well known problems with the DCP are its labor intensive operation and its requirement of two people to operate it. On larger sites testing work becomes repetitive, monotonous, and physically tiring. These factors can lead to improper testing procedures, injury, and less accurate results. The idea of an automated DCP (ADCP) was formulated in hopes of developing better working conditions and to take advantage of improved efficiencies on larger test sites.

While other organizations throughout the world have attempted to automate the DCP, success has been limited. On March 31, 1992, Mn/DOT's Breakthrough Innovation Program Committee awarded $50,000 for the design and construction of an ADCP. Managing Technology, Inc. of Overland Park, Kansas successfully responded to a Request for Proposal and began design of the ADCP in August 1992. Early demonstrations of the concept and design have been extremely encouraging. Delivery and acceptance testing is expected in May 1993.

Summary

The DCP, and soon the ADCP, can efficiently and effectively provide a view of strength characteristics throughout a soil or roadbed structure. This type and breadth of information will allow engineers to perform better analysis and consequently make more cost effective design and ad hoc decisions of the kind described above. Some correlations to other material characterization parameters are available but more work in this area is needed. Correlation to specific pavement response measurements may be possible. The Mn/ROAD pavement research facility and staff will continue to provide data and resources for this effort.

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Appendix

of

Figures

DCP (Mn/DOT DESIGN)

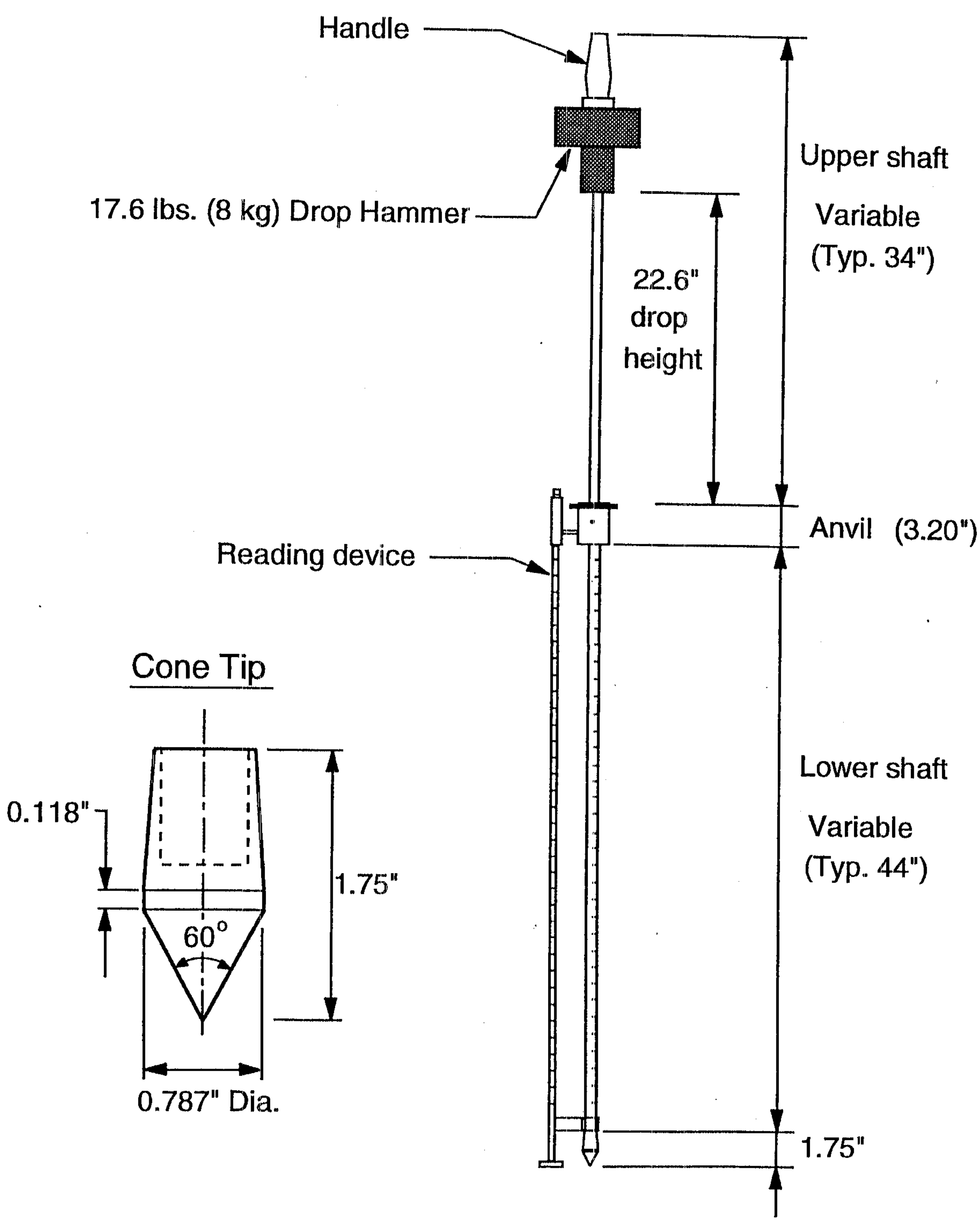
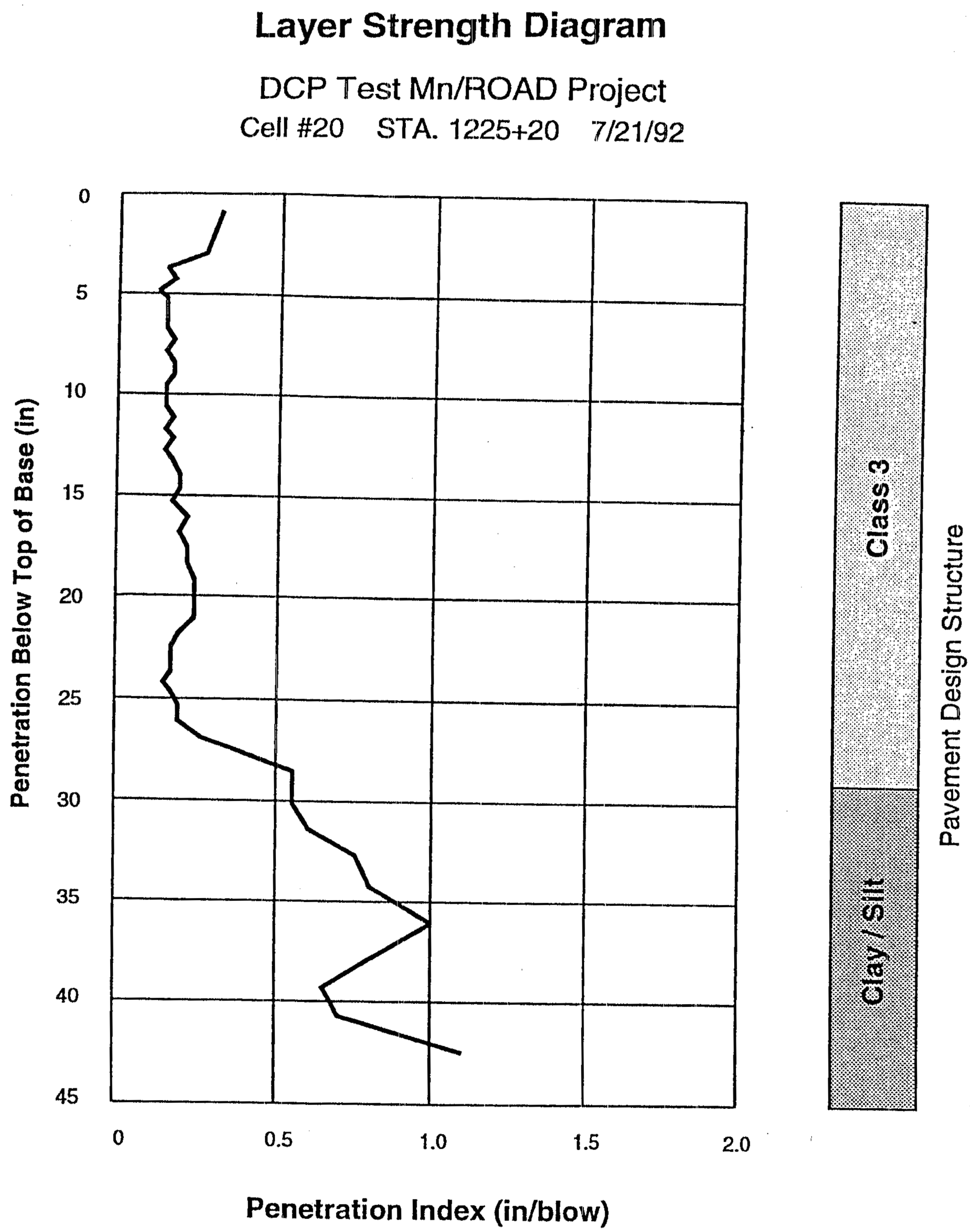


Fig. 1



Layer Strength Diagram
DCP Test Mn/ROAD Project
Cell #20 STA. 1225+20 7/21/92
Penetration Below Top of Base (in)
0
5
10
15
20
25
30
35
40
45
0
0.5
1.0
1.5
2.0
Penetration Index (in/blow)
Class 3
Clay / Silt
Pavement Design Structure

Fig. 2

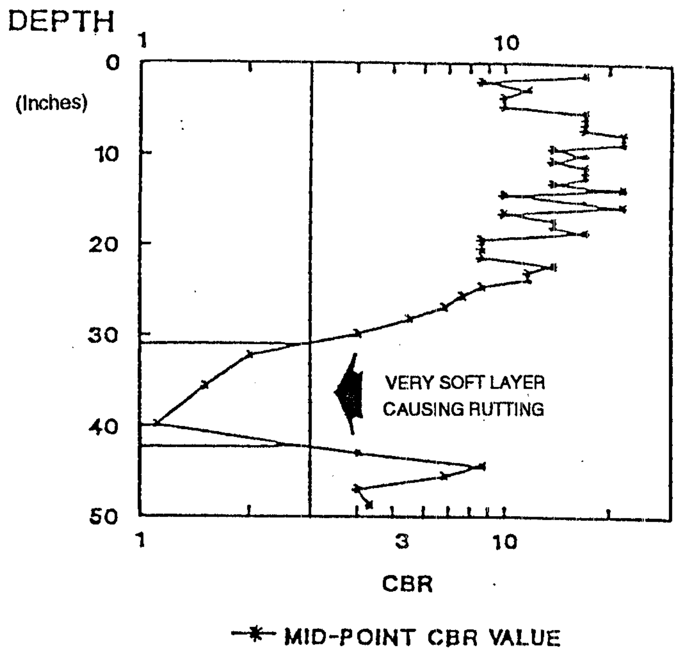


Fig. 3 Typical DCP mid-point plot
Greater Peoria Airport Cargo Apron

DCP Test @ Mn/ROAD Site 6/24/92 SUBGRADE
Sta. 1112+80 W. TEST File: DCP_2E
Offset = 9.8'

# of Blow	DCP Reading (in)	Midrange Depth of DCP Reading (in.)	Penetration Index (in/blow)
0	0.0		0
1	1.8	0.9	1.80
2	3.9	2.9	2.10
3	5.1	4.5	1.20
5	6.5	5.8	0.70
6	7.2	6.9	0.70
8	9.0	8.1	0.90
10	11.6	10.3	1.30
12	13.8	12.7	1.10
13	15.3	14.6	1.50
14	17.1	16.2	1.80
15	18.6	17.9	1.50
16	20.1	19.4	1.50
17	21.6	20.9	1.50
18	23.3	22.5	1.70
19	24.7	24.0	1.40
20	26.2	25.5	1.50
22	29.1	27.7	1.45
24	32.4	30.8	1.65
26	34.3	33.4	0.95
28	35.5	34.9	0.60
30	37.7	36.6	1.10
32	39.6	38.7	0.95
34	41.2	40.4	0.80

Fig. 4 Processed DCP data

DCP Test Mn/ROAD Project

Cell #2 Station 1112+80 W. Test 6/24/92

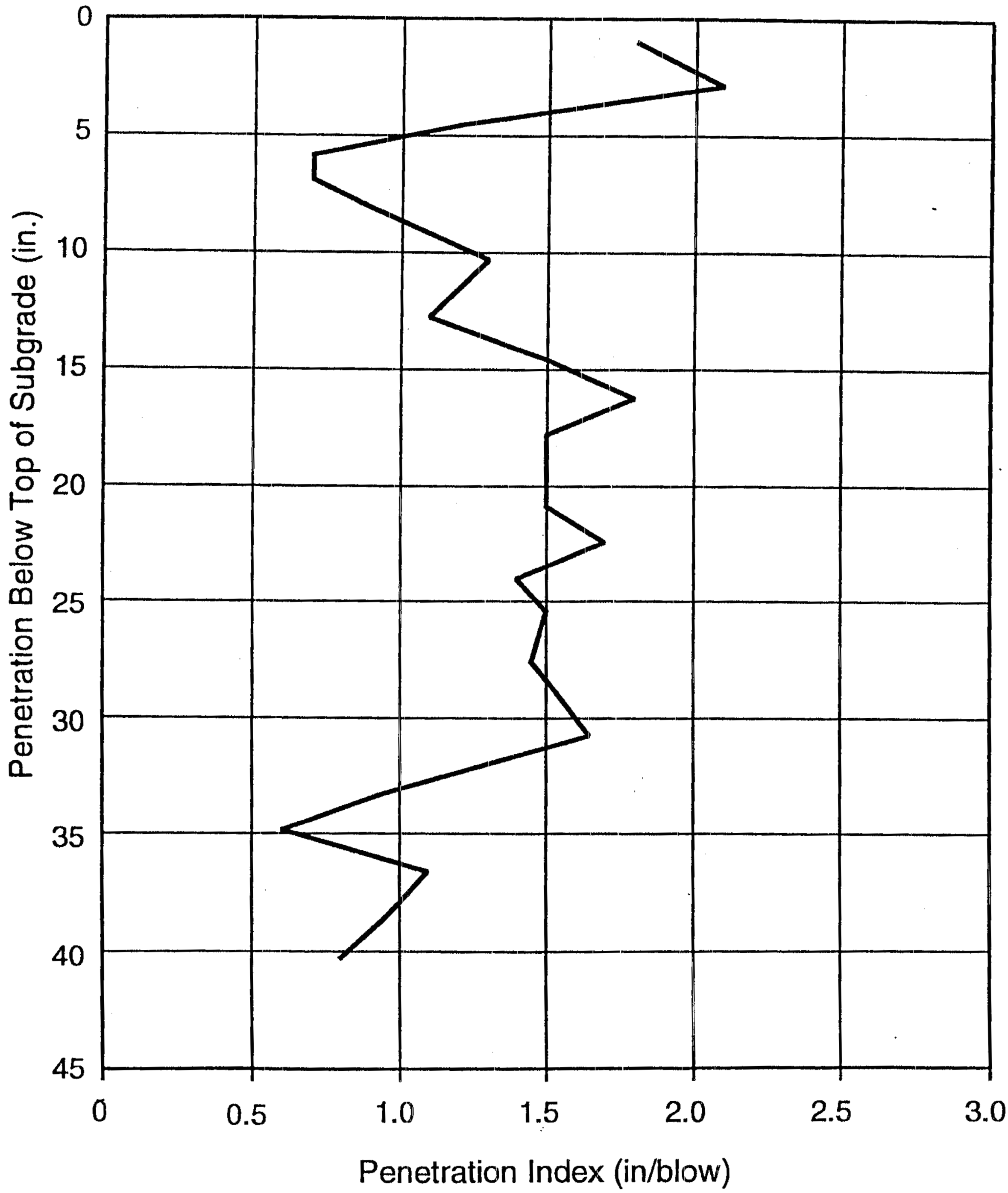


Fig. 5

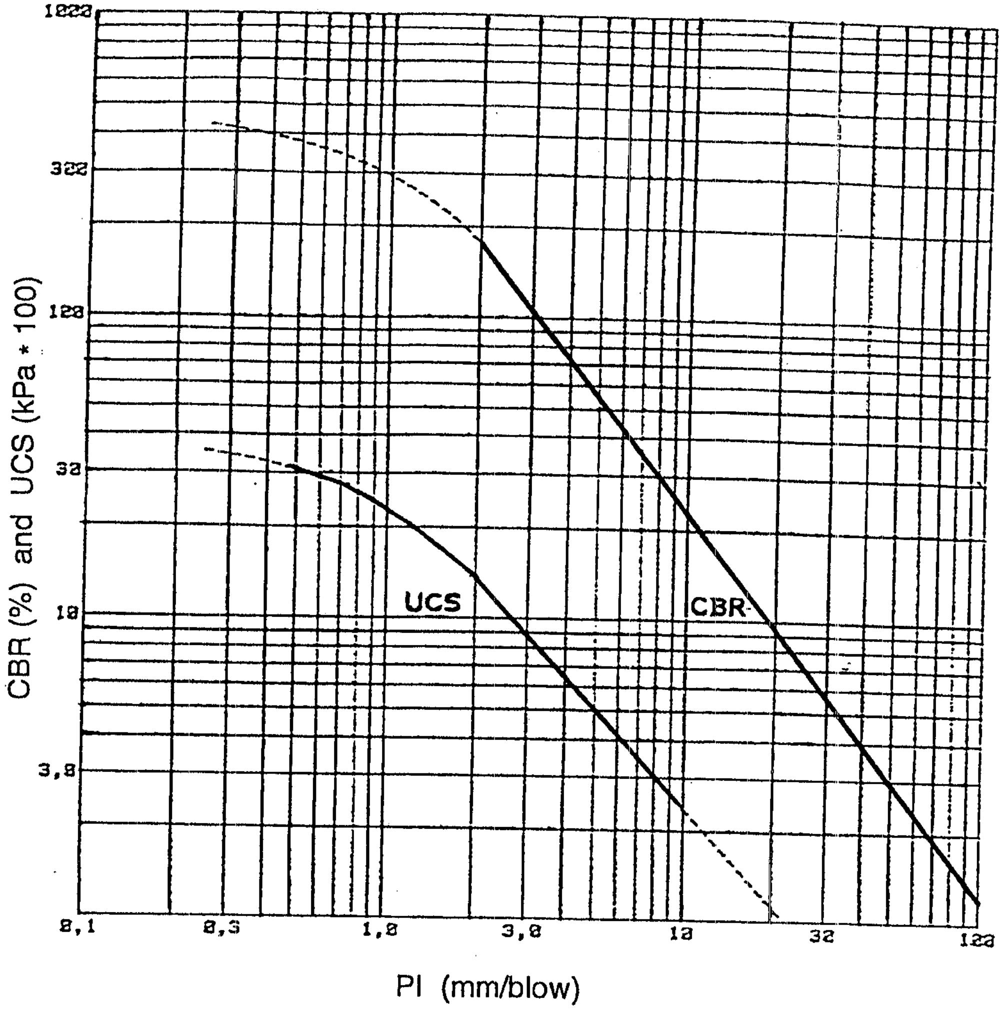


Fig. 6 Relationship between PI, CBR and UCS

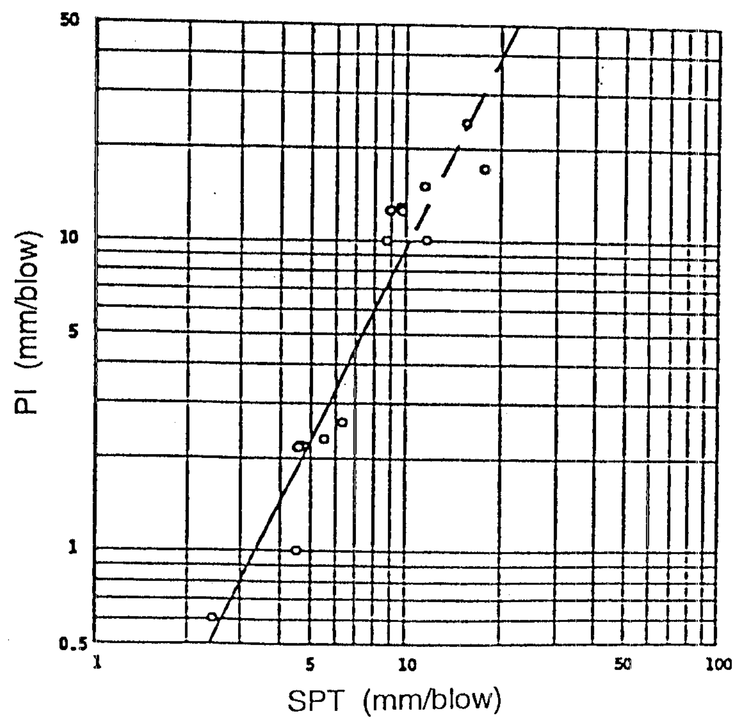


Fig. 7a Relationship between PI and SPT

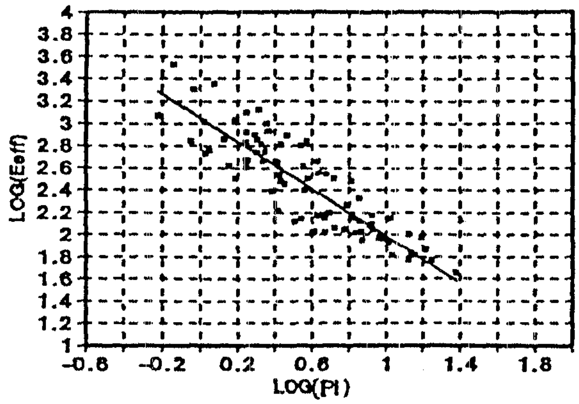


Fig. 7b Tentative empirical relationship between effective elastic moduli (Eeff, MPa) and DCP penetration rate (PI, mm/blow)

ONE VARIABLE LINEAR REGRESSION EQUATIONS

MATERIAL	CONFINING PRESSURE (PSI)	EQUATION	CORRELATION COEFFICIENT (R)	STANDARD ERROR OF ESTIMATE	DATA BASE PR RANGE
SAND	5	DS - 41.3-12.8 PR	-.999	.3	.5 - 1.2
	15	DS - 100.4-23.4 PR	-.999	.5	.5 - 1.2
	30	DS - 149.6-12.7 PR	-.989	.9	.5 - 1.2
CA-10 SANDY-GRAVEL (ROKEY)	5	DS - 51.3-13.6 PR	-.992	1.9	.55-2.15
	15	DS - 62.9- 3.6 PR	-.997	.3	.55-2.15
	30	DS - 90.7- 5.8 PR	-.975	1.5	.55-2.15
CRUSHED DOLO-MITIC BALLAST	5	DS - 64.1-13.3 PR	-.991	1.4	.7 - 1.8
	15	DS - 139.0-40.6 PR	-.867	18.9	.7 - 1.8
	30	DS - 166.3-16.2 PR	-.934	5.0	.7 - 1.8
BALLAST WITH 7.5% FA-20	5	DS - 87.2-78.7 PR	-.881	7.5	.4 - .65
	15	DS - 216.1-213.9 PR	-.958	11.3	.4 - .65
	30	DS - 282.1-233.2 PR	-.994	4.4	.4 - .65
BALLAST WITH 15% FA-20	5	DS - 47.5- .45 PR	-.902	12.4	.25 - .55
	15	DS - 184.2-215.5 PR	-.943	16.3	.25 - .55
	30	DS - 206.4-135.7 PR	-.922	12.3	.25 - .55
BALLAST WITH 22.5% FA-20	5	DS - 49.7-23.1 PR	-.991	.9	.2 - .6
	15	DS - 133.1-68.6 PR	-.976	4.5	.2 - .6
	30	DS - 192.1-95.8 PR	-.971	6.9	.2 - .6
ALL BALLAST MATERIALS*	5	DS - 50.8- 6.3 PR	-.281	9.7	.2 - 1.8
	15	DS - 122.5-34.2 PR	-.617	19.8	.2 - 1.8
	30	DS - 169.1-23.1 PR	-.517	17.3	.2 - 1.8
ALL MATERIALS**	5	DS - 51.5-12.5 PR	-.580	9.6	.2 - 2.2
	15	DS - 115.9-32.8 PR	-.668	19.9	.2 - 2.2
	30	DS - 168.6-36.9 PR	-.626	25.1	.2 - 2.2

NOTE: DS - DEVIATOR STRESS (PSI) AT FAILURE
PR - PENETRATION RATE (INCHES/BLOW)=PI
SIGNIFICANT VALUE OF CORRELATION COEFFICIENT (R)

(α)	(R)
.05	.997
*.05	.576
**.05	.468
.10	.988
*.10	.497
**.10	.400

Fig. 8 DCP shear strength prediction equations

DCP Test Becker Pilot Project

Sta. 2+35 Offset 9.0' 10/07/91

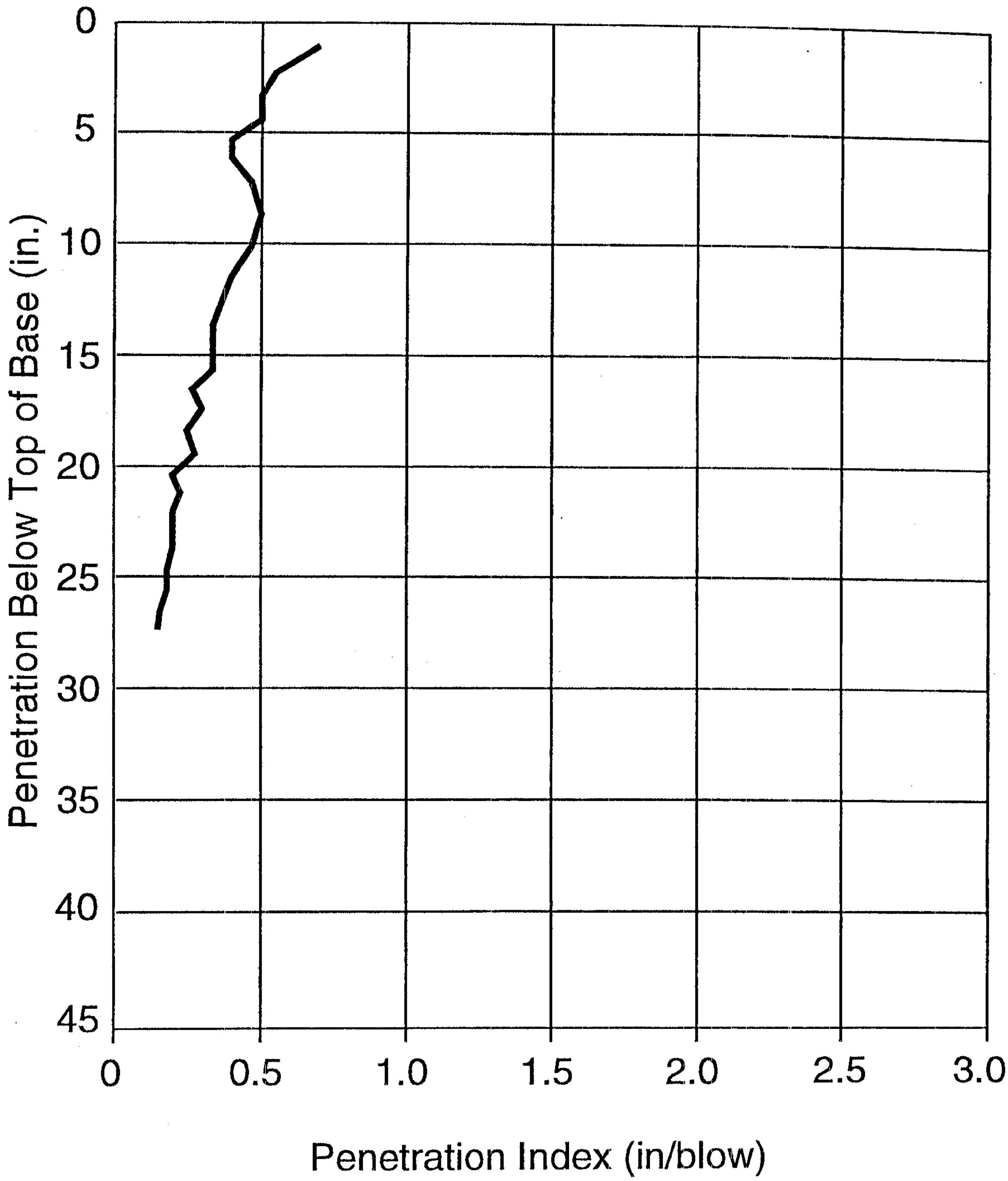


Fig. 9

DCP Test Becker Pilot Project

Sta. 4+64 Offset 9.0' 10/07/91

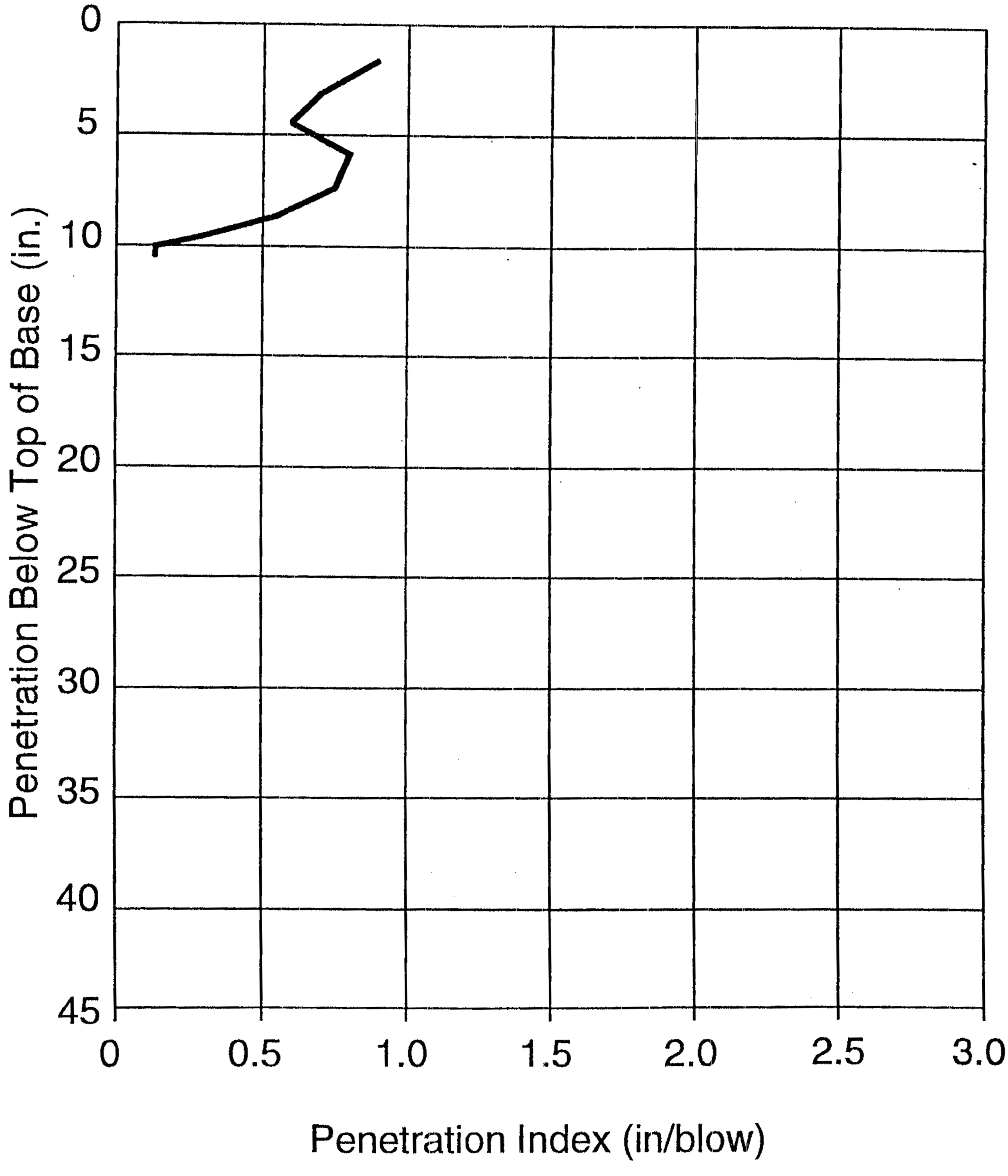


Fig. 10

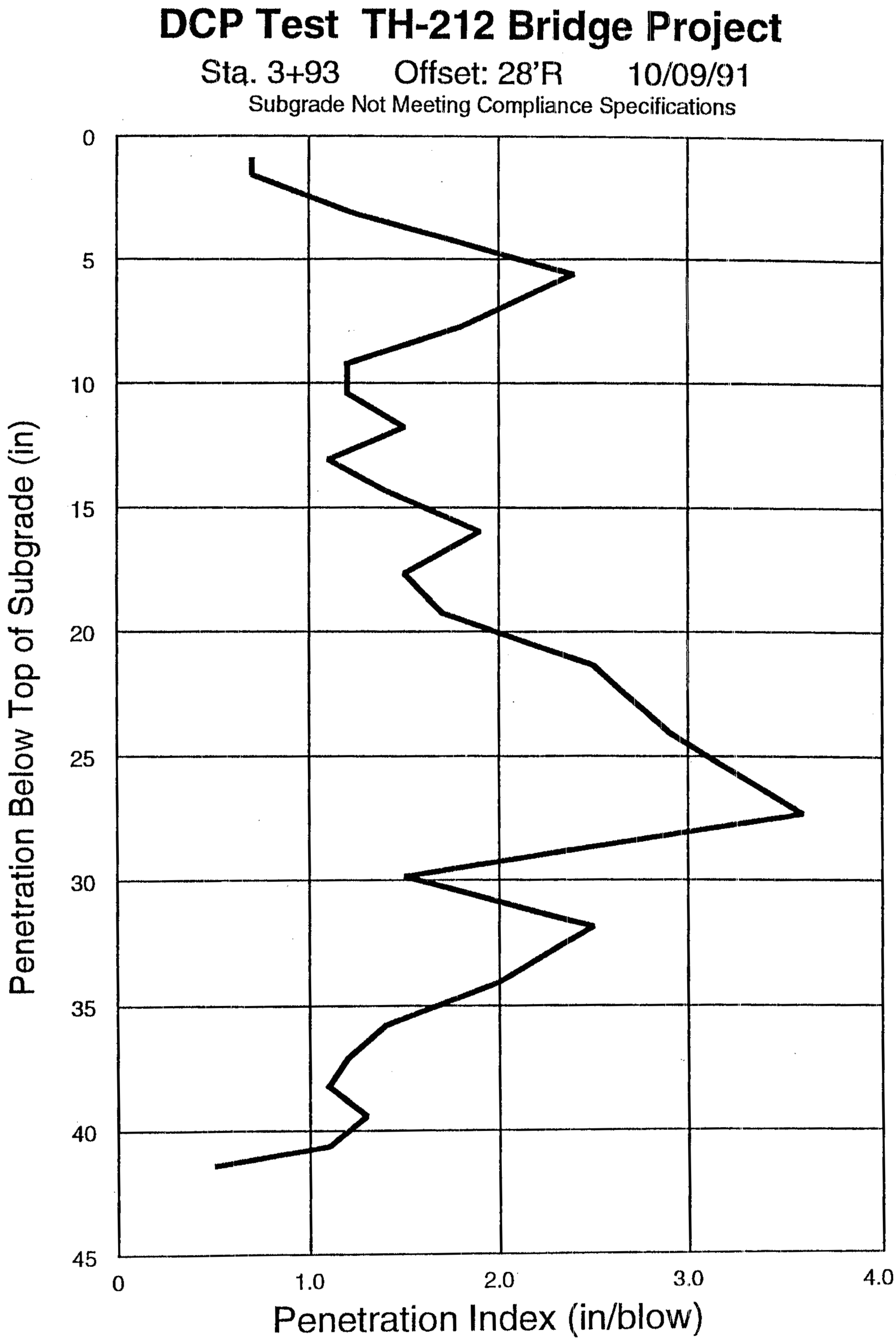

DCP Test TH-212 Bridge Project
Sta. 3+93 Offset: 28'R 10/09/91
Subgrade Not Meeting Compliance Specifications
0
5
10
15
20
25
30
35
40
45
Penetration Below Top of Subgrade (in)
0
1.0
2.0
3.0
4.0
Penetration Index (in/blow)

Fig. 11

DCP Test TH-212 Bridge Project

Sta. 3+93 Offset: 12'L 10/09/91

Subgrade Not Meeting Compliance Specifications

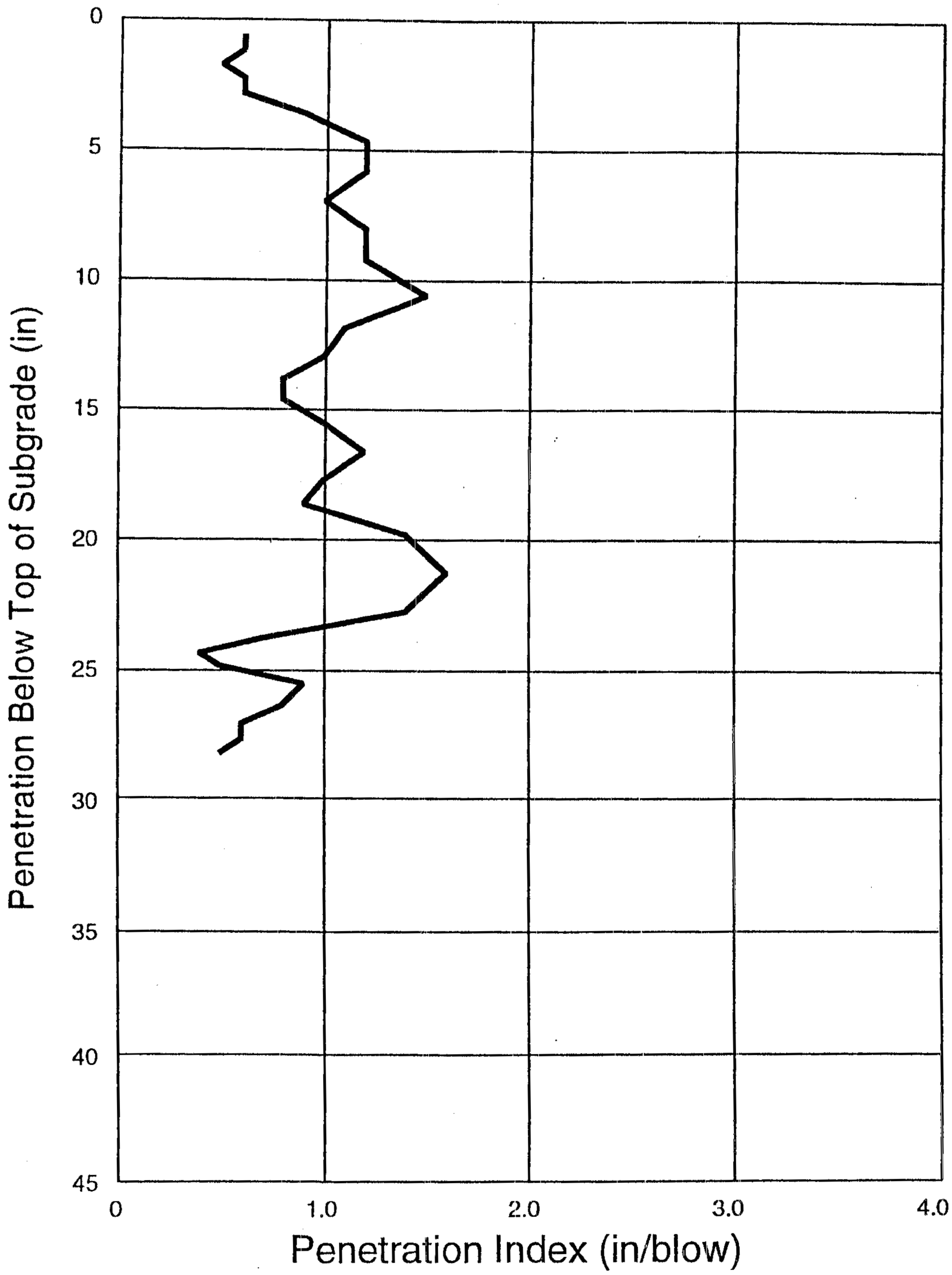
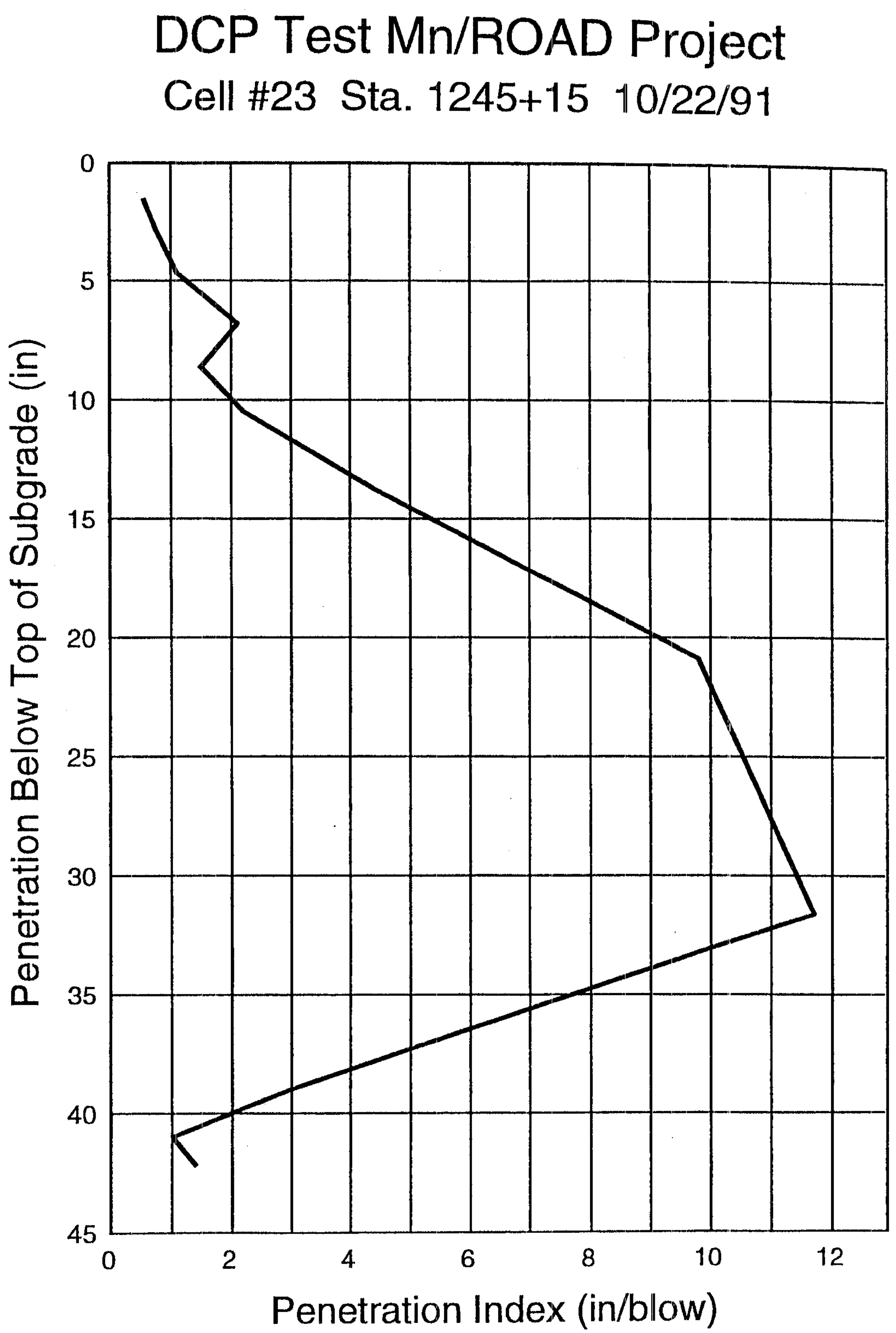


Fig. 12



DCP Test Mn/ROAD Project
Cell #23 Sta. 1245+15 10/22/91
Penetration Below Top of Subgrade (in)
0
5
10
15
20
25
30
35
40
45
0
2
4
6
8
10
12
Penetration Index (in/blow)

Fig. 13

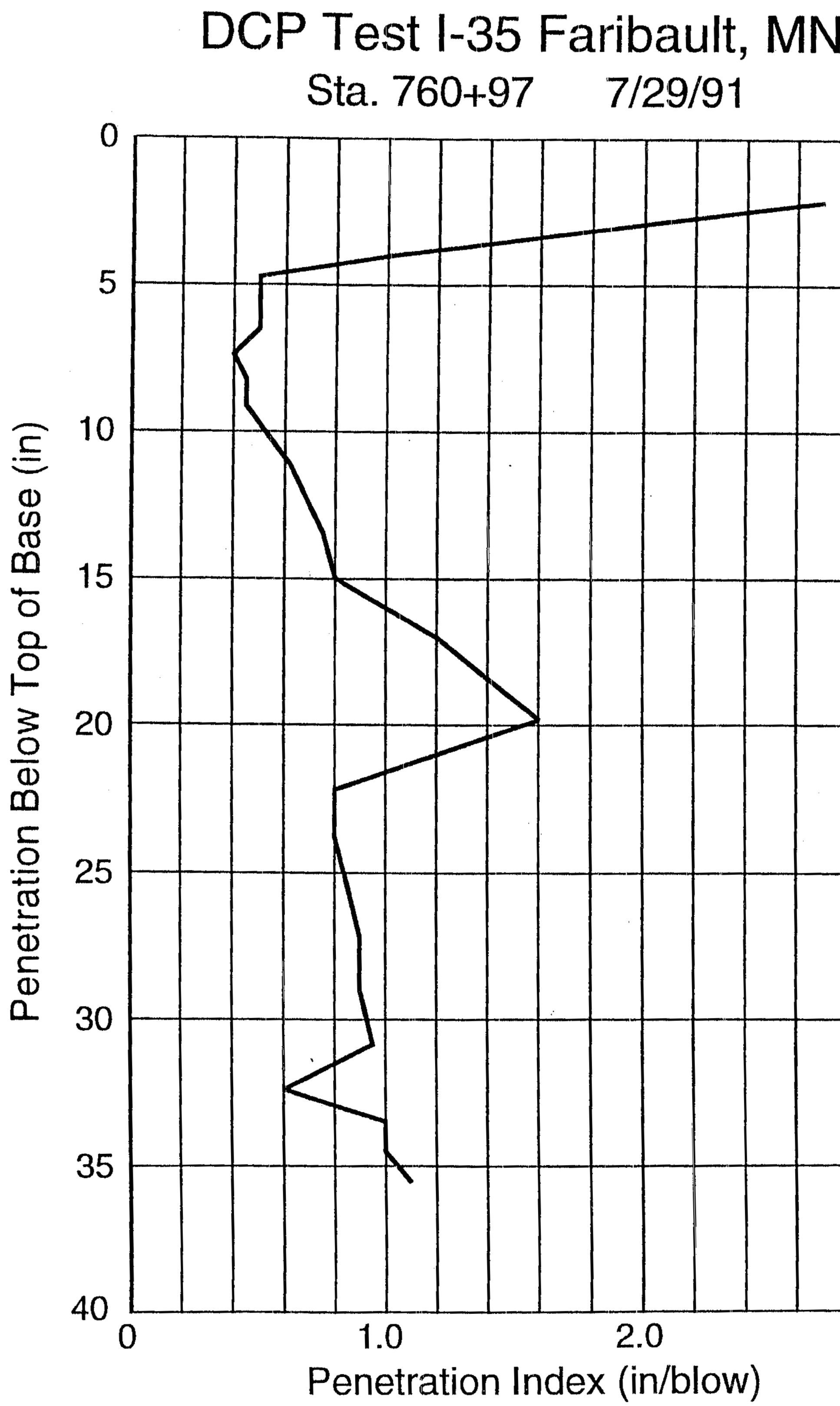

DCP Test I-35 Faribault, MN
Sta. 760+97 7/29/91
0
5
10
15
20
25
30
35
40
Penetration Below Top of Base (in)
0
1.0
2.0
3.0
Penetration Index (in/blow)

Fig. 14

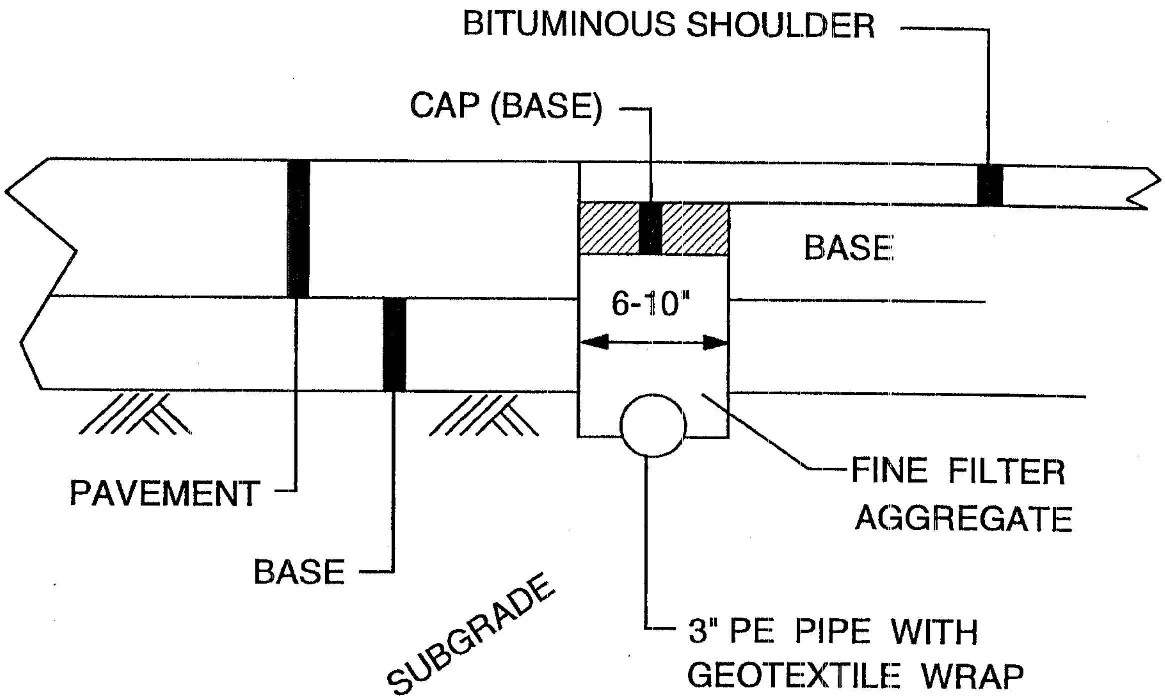


Fig. 15 Mn/DOT typical edge drain design

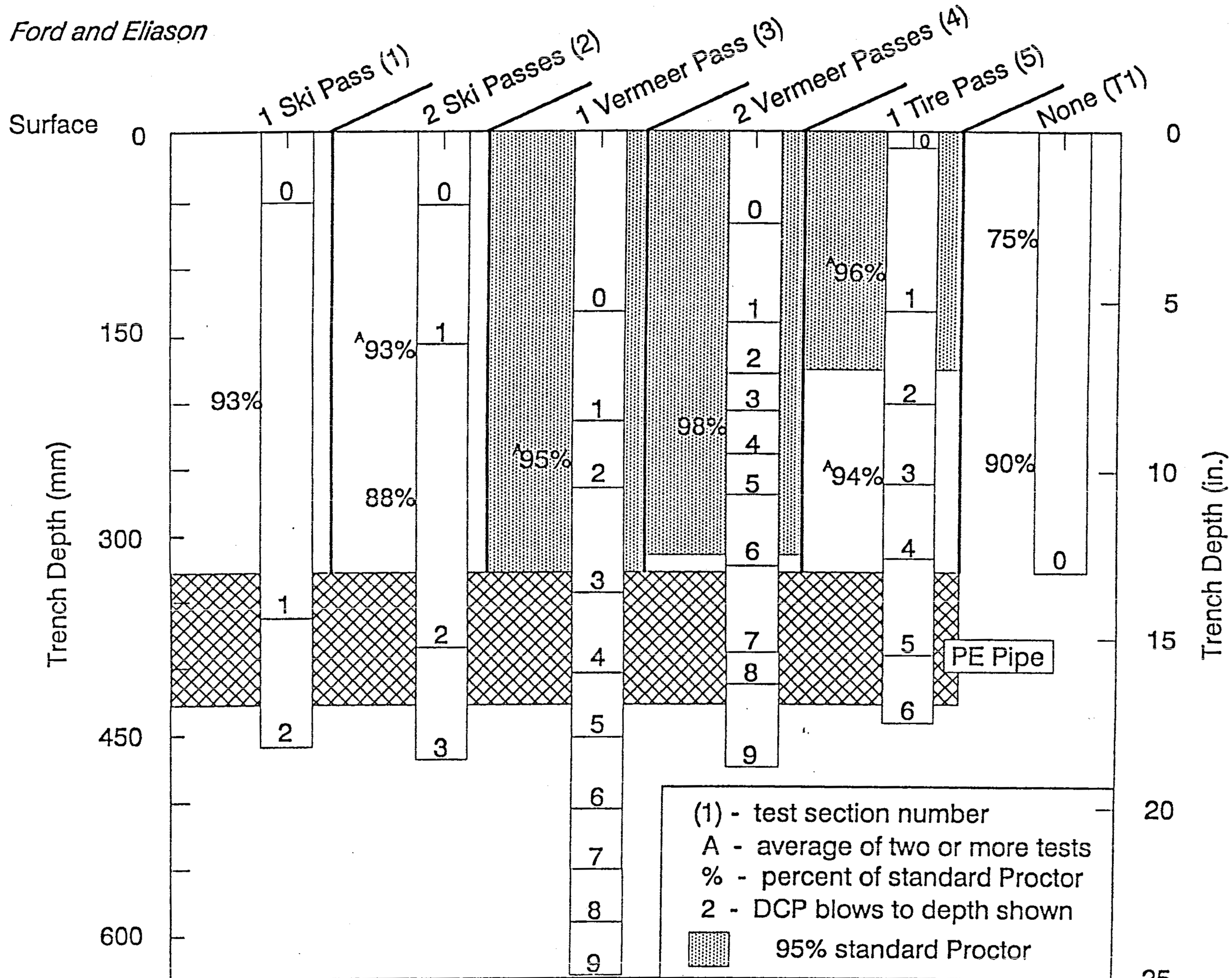


Fig. 16 Field compaction results for 12 in. (300 mm) trench depth

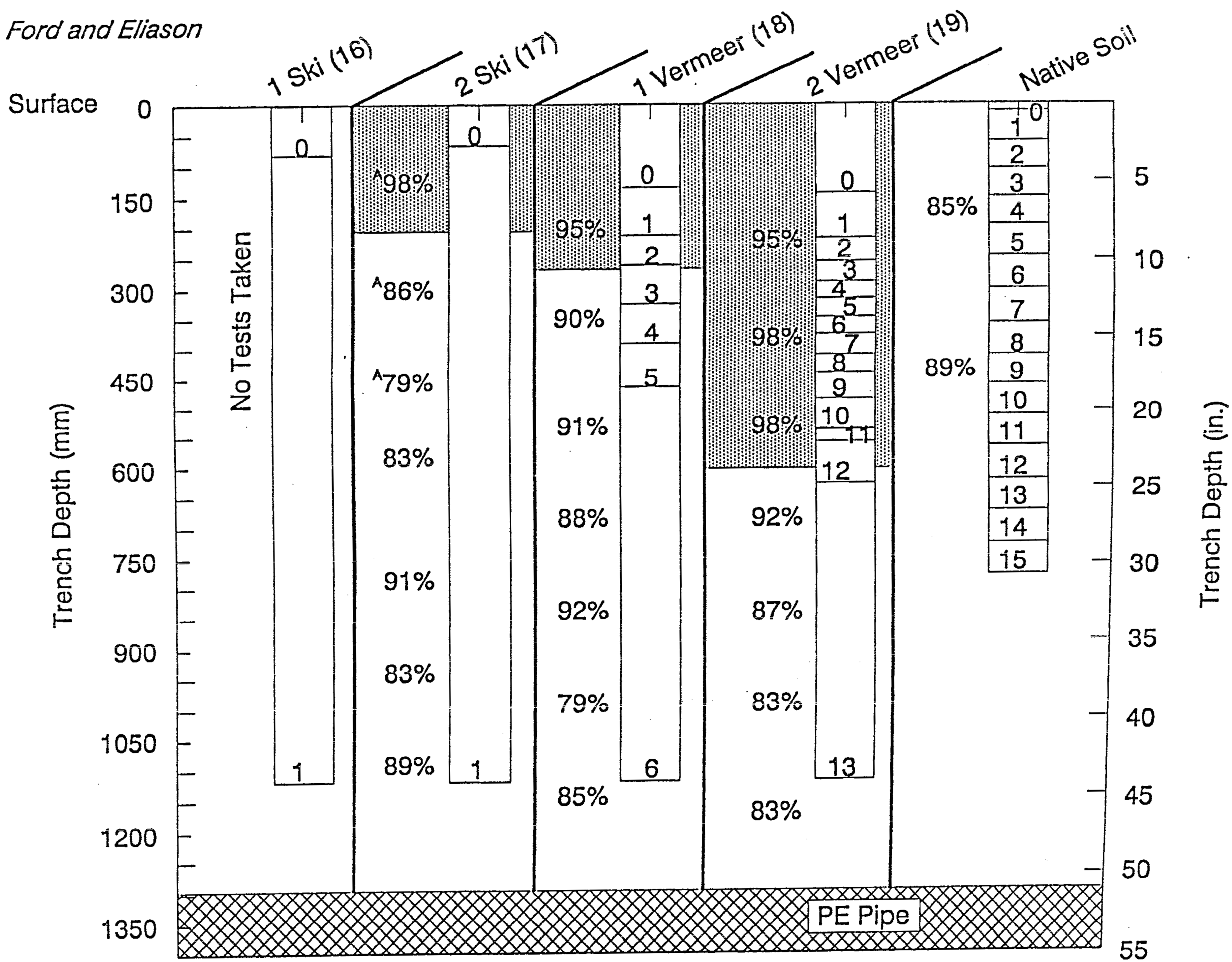


Fig. 17 Field compaction results for 48 in. (1200 mm) trench depth