Final Report

# STANDARD PENETRATION TEST ENERGY CALIBRATIONS

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**FLORIDA DEPARTMENT OF TRANSPORTATION**


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16. Abstract

The Standard Penetration Test (SPT) is the most common in-situ test used for foundation design and other geotechnical applications in Florida. The results of the test, the N-value, are used with many empirical correlations to determine important soil properties used in design. Contrary to the implication of its name, the SPT is not all that standard, and test results may vary even for identical soil conditions.

While many variables affect the N-value, a strong relationship exists between N-value and the energy that the SPT hammer transfers to the drill rods. If the energy transfer characteristics of an SPT system (the drill rig, hammer, operator, etc.) are known, then the N-values recovered by that system may be corrected to a standardized energy and more appropriately used in design.

This report documents a field testing program in which energy transfer measurements were performed for 58 SPT systems. Energy measurements were made using the SPT Analyzer™. Drilling operations were not controlled but were performed under normal operating conditions. The resulting data are presented, and assessments are made of the effects of automatic versus safety hammer type, drill rig type, drill rod length, drill rod type, hammer drop height, hammer blow rate, number of rope turns, N-value, and two energy calculation methods.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | square millimeters | $mm^2$ |
| $ft^2$ | square feet | 0.093 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.836 | square meters | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | square kilometers | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | ml |
| gal | gallons | 3.785 | liters | l |
| $ft^3$ | cubic feet | 0.028 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | cubic meters | $m^3$ |

NOTE: Volumes greater than 1000 l shall be shown in $m^3$.

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 or (F-32)/1.8 | Celcius temperature | °C |
| | | **ILLUMINATION** | | |
| fc | foot-candles | 10.76 | lux | l |
| fl | foot-Lamberts | 3.426 | candela/m² | cd/m² |
| | | **FORCE and PRESSURE or STRESS** | | |
| lbf | poundforce | 4.45 | newtons | N |
| psi | poundforce per square inch | 6.89 | kilopascals | kPa |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.039 | inches | in |
| m | meters | 3.28 | feet | ft |
| m | meters | 1.09 | yards | yd |
| km | kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | square millimeters | 0.0016 | square inches | $in^2$ |
| $m^2$ | square meters | 10.764 | square feet | $ft^2$ |
| $m^2$ | square meters | 1.195 | square yards | $yd^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | square kilometers | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| ml | milliliters | 0.034 | fluid ounces | fl oz |
| l | liters | 0.264 | gallons | gal |
| $m^3$ | cubic meters | 35.71 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.307 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.202 | pounds | lb |
| Mg | megagrams | 1.103 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |
| | | **ILLUMINATION** | | |
| lx | lux | 0.0929 | foot-candles | fc |
| cd/m² | candela/m² | 0.2919 | foot-Lamberts | fl |
| | | **FORCE and PRESSURE or STRESS** | | |
| N | newtons | 0.225 | poundforce | lbf |
| kPa | kilopascals | 0.145 | poundforce per square inch | psi |

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised August 1992)

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$$dW = Fdx \tag{1}$$

$$W = \int Fdx \tag{2}$$

$$E(t) = W(t) = \int F(t)\frac{dx}{dt}dt = \int F(t)v(t)dt \tag{3}$$

$$E = \int_{0}^{t_{E(max)}} F(t)v(t)dt = EFV \tag{4}$$

$$F(t) = v(t)Z = v(t)\frac{EA}{c} \tag{5}$$

$$v(t) = F(t)\frac{c}{EA} \tag{6}$$

$$E(t) = \frac{c}{EA}\int F^2 dt = EF2 \tag{7}$$

$$ER_{FV} = \frac{EFV}{350 ft-lb} \tag{8}$$

$$ER_{F2} = \frac{EF2}{350 ft-lb} \tag{9}$$

$$RAT = \frac{2L'/c_{measured}}{2L'/c_{theoretical}} \tag{10}$$

$$N_{60}E_{60} = N_{field}E_{measured} \tag{11}$$

## LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| **A** | = cross-sectional area |
| **ASCE** | = American Society of Civil Engineers |
| **ASTM** | = American Society for Testing and Materials |
| **BPM** | = blows per minute |
| **c** | = wave speed |
| **CME** | = Central Mine Equipment Company |
| **dt** | = increment of time |
| **dW** | = increment of work |
| **dx** | = increment of distance |
| **E** | = Modulus of Elasticity |
| **E or E(t)** | = energy or energy as a function of time |
| $E_{60}$ | = standardized energy |
| $E_{measured}$ | = energy measured during testing |
| **EF2** | = transmitted energy (Force-Squared Method) |
| **EFV** | = transmitted energy (Force-Velocity Method) |
| **ER** | = energy transfer ratio (or efficiency), no method specified |
| $ER_{F2}$ | = energy transfer ratio (or efficiency) by the Force-Squared Method |
| $ER_{FV}$ | = energy transfer ratio (or efficiency) by the Force-Velocity Method |
| **ESOPT-I** | = First European Symposium on Penetration Testing |

**ESOPT-II** = Second European Symposium on Penetration Testing

**F or F(t)** = force or force as a function of time

**$F^2$** = Force-Squared Method

**FDOT** = Florida Department of Transportation

**Fv** = Force-Velocity Method

**$Fv_{corr}$** = Force-Velocity Corrected Method

**GRL & Associates, Inc.** = Goble Rausche Likins and Associates, Inc.

**GRLWEAP™** = GRL Wave Equation Analysis Program

**HPA** = Hammer Performance Analyzer™

**ICSSMFE** = International Conference of the Society for Soil Mechanics and Foundation Engineering

**ISOPT-I** = First International Symposium on Penetration Testing

**ISSMFE** = International Society for Soil Mechanics and Foundation Engineering

**L** = length from anvil impact surface to rod/sampler tip

**L'** = length of rod from sensor location to rod/sampler tip

**MnDOT** = Minnesota Department of Transportation

**$N_{60}$** = standardized N-value

**$N_{field}$** = N-value measured during testing

**pcf** = pounds per cubic foot

**PDA** = Pile Driving Analyzer®

**R** = Coefficient of Correlation

**$R^2$** = Coefficient of Determination

**RAT** = length ratio

**SPT** = Standard Penetration Test

**$t_{E(max)}$** = limit of integration (maximum time of force trace)

**v(t)** = velocity as a function of time

**W or W(t)** = work or work as a function of time

**Z** = impedance

# CHAPTER 1
# INTRODUCTION

## 1.1 Background

Despite the variability of the test, the Standard Penetration Test (SPT) is the most common in-situ test used for foundation design and other geotechnical applications (Kovacs and Salomone, 1982). The SPT is used extensively by the Florida Department of Transportation (FDOT) and its consultants. Many researchers contend that the SPT is not "standard," as the name implies. However, because the test is relatively simple to conduct, produces an indicator of soil resistance (the N-value), and yields a soil sample for visual identification and laboratory testing, the test retains its popularity with geotechnical engineers worldwide. A number of correlations relate the N-value to such parameters as relative density, friction angle, allowable bearing capacity, and pile skin friction. Because of the frequent use of such correlations, it is important for the geotechnical community to study the dynamics of the test and strive for standardization.

## 1.2 Problem

Reliance on SPT N-values and the historically derived correlations may not provide an engineer with reasonable soil parameters unless the source and characteristics of the SPT hammer system (the hammer type, drill rig type, driller, etc.) providing the N-values are considered. Although ASTM D1586 does provide a "standard" for the performance of the SPT, it allows for a variety of equipment to be used. As a result there are a variety of hammer types in use, ranging from donut and safety hammers using a cathead and rope system to the more recently developed automatic trip hammers. Additionally, safety hammers operate on different platforms such as CME, Diedrich, Mobile, Acker, and Failing where the cathead diameters and the rope pulley systems are different. Also, the various automatic hammers manufactured by CME and Diedrich operate differently. These factors, as well as numerous others, result in different SPT systems introducing different amounts of energy per blow into the drill rods. As a result, for SPTs performed in identical soil conditions, different driller-rig-hammer systems will likely record different N-values. These differences can be great.

Most of the correlations developed from the results of the SPT originated before the emergence of the automatic hammer and are therefore based on the cathead and safety hammer system. These safety hammer systems are generally found to have efficiencies of about 60% which means 60% (or 210 ft-lbs) of the theoretically available energy (350 ft-lbs) is transferred from the hammer to the drill rods. The N-values from systems operating at 60% efficiency are referred to as $N_{60}$. If an SPT hammer-rig-driller system is not operating at 60% efficiency, then the correlations will not hold. The newer automatic hammers, for instance, typically have much higher efficiencies; N-values taken from these hammers may not be appropriate for use with "$N_{60}$ correlations."

## 1.3 Objectives

In order to reduce the significant variability and uncertainty associated with the N-value, it is recommended that all N-values be standardized to $N_{60}$. This correction would be equal to the N-value obtained in the field, multiplied by the ratio of that SPT system's energy input to the standard 60% energy of 210 ft-lbs. If an engineer can accurately make this correction, then the variables in hammer-rig-driller systems will be minimized, and the corrected N-value can be more appropriately used with existing correlations.

The key to making the necessary corrections to the N-value is an accurate measurement of the energy efficiency of the driller-rig-hammer system. Equipment for performing the energy measurement is commercially available.

The objectives of this research included the following:

1. Measure the energy transferred from the hammer to the drill rods for a variety of SPT systems operating in the state of Florida.
2. Identify and assess the effect that SPT system variables have on Energy Transfer.
3. Assess the general trends of SPT system performance for Florida-based systems performing work for FDOT.
4. Recommend how the findings of this research may be used to improve our understanding and use of SPT results, and what future additional research may be worthwhile.

The research has consisted of conducting energy testing for a total of 58 SPT drill-rig-hammer systems, 15 FDOT-owned and 43 consultant-owned SPT rigs commonly contracted by FDOT. The research was not intended to simply evaluate a hammer's energy transfer characteristics under ideal and controlled conditions. Rather, these tests were performed under field conditions to provide a measure of "real world" performance of complete SPT hammer systems.

Chapter 2 details the history of the test, development of the related ASTM standards and the transmission of energy during the SPT. Also covered are the methods used to calculate energy and existing research related to the scope of this project.

Chapter 3 presents a general discussion of the primary hammer system types in use in Florida. Chapter 4 presents a discussion of the energy measurement equipment used in this research.

Chapter 5 contains a description of how the testing program was developed and conducted. Chapter 6 discusses how the data recovered in the field were evaluated and reduced for inclusion in the project index.

A discussion of testing results and analyses is presented in Chapter 7, while conclusions and recommendations for further research are presented in Chapter 8. Test data, energy calculations, and computer outputs are contained in the appendices.

# CHAPTER 2
# REVIEW OF LITERATURE

## 2.1 History of SPT

### 2.1.1 Early Test Developments

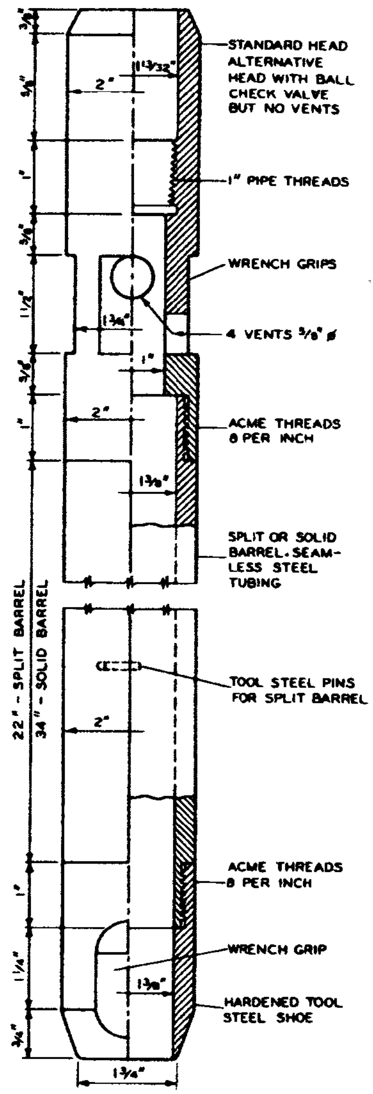
In March 1988, the First International Symposium on Penetration Testing (ISOPT-I) was held in Orlando, Florida. For this symposium, the SPT Working Party (whose origination is discussed in Section 2.1.2) prepared a comprehensive paper that documented the origin of the test and the development of the test method (ISSMFE, 1988).

The SPT Working Party paper records that initially Lt. Col. Charles R. Gow, whose company became a subsidiary of the Raymond Concrete Pile Company in 1922, drove one-inch diameter pipes into the ground for soil sampling. Riggs (1986), as well as Broms and Flodin (1988), reports that the actual work by Charles Gow dates as far back as 1902 and that the one-inch pipe served both as the sampler and the sampling rod column. A 100 lb falling weight was used to drive the rods. Riggs states that Gow used this method to estimate pile-driving resistances.

In 1927, the two-inch outside diameter sampling spoon was developed based on fieldwork by G.F.A. Fletcher, a consulting engineer in foundations and construction, and research by H.A. Mohr, who was then District Manager of the Gow Company in New England, USA. (Documentation of the early development of the SPT is contained in a paper by Mohr (1937) and a paper by Fletcher (1965) with a discussion from Mohr (Lo

Pinto and Mohr, 1966).) According to Fletcher, "the original purpose [of the test] was to measure the density of soil formations by a standard procedure, thereby providing a correlation with experience in the design and installation of caisson foundations." Mohr's publication from 1937 contains a copy of a test boring log dated February 1929 from the Gow Division of the Raymond Concrete Pile Company. This boring log contains a note that the test was performed by recording the number of blows required to advance the sampling pipe one foot using a 140 lb weight falling from a height of 30 inches. In his discussion of Fletcher's paper, Mohr (1966) elaborates that the drive weight consisted of a square concrete block with hardwood inset, mounted on a guide spike. This method of using the 140 lb hammer falling 30 inches to advance the sampler 12 inches appeared in specifications as early as 1930. Despite the growing popularity of this method, Mohr (1966) stated that his experience proves "these data should be used with great restraint."

Hvorslev documented the configuration and exact dimensions of the two-inch sampler in 1949. Hvorslev's diagram of the *Raymond sampler*, Figure 2-1, shows both a 22-inch long split barrel and a 34-inch solid steel tubing barrel. The sampler had a hardened tool steel shoe and a vented sampler head, but no ball check valve. The inside diameter was 1 3/8-inch throughout the barrel and shoe. A liner is not shown, though liners in some samplers had been used as far back as 1932. Later split spoon sampler improvements included the addition of a ball valve to improve sample recovery during retrieval of the spoon.




RAYMOND SAMPLER

Figure 2-1. Raymond Sampler

Hvorslev credits Mohr with establishing the SPT as a regular procedure for determining dynamic penetration resistance in soils (about 1927). However, the SPT Working Party documents that Terzaghi, in a 1947 paper presented to the 7th Texas Conference on Soil Mechanics and Foundation Engineering, was the first to call the method the "Standard Penetration Test." The first textbook reference to the SPT occurred in the 1948 edition of Terzaghi and Peck's *Soil Mechanics in Engineering*

*Practice.* Both the 1947 paper and the textbook make reference to the six-inch initial seating drive. Hvorslev documents that the Gow Division of the Raymond Concrete Pile Company continued to use a one-inch section of extra heavy pipe as both sampler and drill rod and the penetration resistance was measured from the depth to which the sampler sank under its own weight. However, the other company divisions used the Raymond sampler and incorporated the six-inch seating drive to lessen the influence of the disturbed zone at the bottom of the borehole.

### 2.1.2 European/International Test Standardization

In 1957, at the 4th International Conference on Soil Mechanics and Foundation Engineering in London, a committee was formed to study dynamic, as well as static, penetration testing in an effort to develop testing "standards." Agreement was not reached within the committee on a suitable standard for the SPT. In 1965, at the 6th International Conference, another committee was formed and tasked with developing a European SPT standard. In 1973, the Swedish Committee on Penetration Testing suggested that a European symposium on penetration testing be held in Stockholm in 1974 in order to document penetration testing methods in different countries and continue the task of standardizing commonly used testing methods.

At the 1974 symposium (ESOPT-I), "state-of-the-art" papers were submitted by twenty-five engineers documenting current testing practices in their countries. The papers were published as part of the symposium proceedings, along with two additional volumes of papers concerning penetration testing. In 1977, the European Sub-Committee on Standardization of Penetration Testing published recommendations for a European

SPT standard and presented these recommendations to the ISSMFE. As a result, an ISSMFE Technical Committee on Penetration Testing was formed at the Second European Symposium on Penetration Testing (ESOPT-II) in 1982 in order to foster international cooperation for the development of reference test procedures. Four working parties were also established to develop proposed Reference Test Procedures for the four major classes of penetration testing, the Standard Penetration Test (SPT), the Cone Penetration Test (CPT), Dynamic probing (DPA, DPB, DPL), and the Weight Sounding Test (WST).

At ESOPT-II, the ISSMFE Technical Committee on Penetration Testing was greatly encouraged by the interest in penetration testing from the world-wide geotechnical community. The call for papers resulted in 142 symposium papers by authors from more than 30 countries. As a result, the Technical Committee decided to continue these specialty conferences on penetration testing by holding a truly international conference, the ISOPT-I in Orlando in 1988. The SPT Working Party presented a draft of its International Reference Test Procedure at this symposium, with the final version published in the proceedings. The aim of the committee was to convey as simply as possible all of the factors that affect SPT results, with variations to suit the particular needs of a given country. The intention was not to institute an international "standard," which might be disruptive to years of successful application of individual test methods.

### 2.1.3 Development of ASTM Standards

ASTM D 1586-58 T. In April of 1958, the American Society for Testing and Materials (ASTM) Committee D-18 on Soils for Engineering Purposes published the "Tentative Method for Penetration Test and Split-Barrel Sampling of Soils" as information in a compilation entitled *Procedures for Testing Soils*. In June of the same year, ASTM adopted the "tentative" method at their annual meeting for use pending adoption as a standard.

The scope of the test method, which remains unchanged through the present day, is to "describe a test procedure for making soil borings with a split-barrel sampler in order to obtain representative samples of soil for identification purposes and other laboratory tests and obtain a record of the resistance of the soil to penetration of the sampler."

Apparatus. In this section, the user is allowed to perform the test using any type of drilling method that "provides a reasonably clean hole" before inserting the sampler to ensure that the test is conducted in undisturbed soil. If needed, both casing and drilling mud are permitted to keep the hole open. However, the hole is limited in diameter to between 2.25 and 6 inches. The method is also not specific about the drive weight assembly, other than it shall consist of a 140-pound weight with a 30-inch free-fall drop. The method is specific about the split-barrel sampler which is described in detail, including a figure with dimensions.

Procedure. The test procedure covers such areas as cleaning the hole, obtaining the samples, removing and labeling the samples, and field observations during testing. Instructions for cleaning the hole are rather general in nature. However, the use of bottom-discharging bits and sampling intervals greater than five feet are not permissible. The user is directed to record the number of blows required to drive the sampler the last two 6-inch increments of the 18-inch run. *Refusal* is defined as penetration of less than one foot for 100 blows. Finally, under this section, the user is instructed on how to remove the samples from the sampler and store for laboratory testing, as well as how and when to record the groundwater level on the field logs.

Report. The boring log should include such information as date of boring, reference datum, job number, boring number, drilling method, sample elevations, strata limits, water data, soil identification, penetration records, and casing used. The final form shall include a soil profile showing the extent of the strata over the area under consideration.

ASTM D 1586-64 T. In 1963 and 1964, the tentative method from 1958 was revised. The method reissued in 1964, still *tentative*, suggests that the stiffness of the drill rod used during sampling has an effect on the N-value. Therefore, the method calls for drill rods with a stiffness equal to or greater than the A-rod. For holes deeper than 50 feet, a stiffer rod is recommended. Unlike the previous version, the revised method specifically directs the reader to record the number of blows required to drive all three six-inch increments, even the first six inch seating drive. As in the previous version, the N-value is taken as the total number of blows to drive the last 12 inches. In the 1964 revision, it is noted that if the sampler is driven less than 18 inches total, the N-value is calculated for the last foot of penetration. If less than one foot is penetrated, the logs shall show the fraction of a foot penetrated and the number of blows. Refusal was redefined as the condition when the rate of penetration is less than one inch for 50 blows.

ASTM D 1586-67. In October 1967, the tentative method from 1964 was revised and adopted as a *standard* method, "Standard Method for Penetration Test and Split-Barrel Sampling of Soils." With this revision, the dimensions of the A-rod are given, as well as a figure of the slightly modified split-barrel sampler. Metric equivalents for all weights and dimensions are introduced. While this version did not produce significant changes to the procedure, it does elaborate on the logging of samples and the data reported on the boring log. The reader is instructed to describe the composition, structure, consistency, color, and condition of samples. In addition to the requirements from the previous version, the boring log should also include boring coordinates, lengths of recovered samples, type and size of sampler, rig identification, names of drilling personnel, weather remarks, and blowcounts for each six-inch increment. The 1967 version was reapproved in 1974 without revision.

ASTM D 1586-84 (Reapproved 1992). In September 1984, the 1967 version of the test method was revised significantly and approved by ASTM Committee D-18. The scope was expanded to include a disclaimer regarding safety during testing. In addition, sections entitled *Referenced Documents* and *Terminology* were introduced. Three of the referenced documents are ASTM Standards pertaining to soil samples. The fourth document, "Test Method for Stress Wave Energy Measurement for Dynamic Penetrometer Testing Systems," is an ASTM standard developed specifically to address energy transmission and measurement during the SPT and will be discussed in more detail in the following section.

Unlike previous versions, the standard now specifies a variety of drilling equipment for advancing the hole, such as different types of drill bits and augers. Several types of acceptable drilling methods are listed, along with applicable restrictions. In addition, the split-barrel sampler is no longer restricted to one size, but can vary according to the dimensions shown in the standard.

Perhaps the most significant change to ASTM D 1586 is the section on sampling and testing. The sequence of operations is given in much more detail than prior versions. For the first time, the standard addresses the lifting and dropping mechanism for the hammer. Either a trip (automatic or semi-automatic) mechanism or a cathead and rope system can be used. Even though a number of restrictions are given for the cathead and rope method, the standard still allows a great deal of flexibility in execution of the test – thereby contributing to the variability that many engineers are trying to eliminate. In the section entitled *Precision and Bias*, the variation in N-values is addressed. The authors introduce the concept of adjusting the N-value based on comparative energies and refer the reader to the method for energy measurement contained in ASTM D 4633.

ASTM D 4633-86. The new "Standard Test Method for Stress Wave Energy Measurement for Dynamic Penetrometer Testing Systems" was developed to address energy transmission variability. The test method describes the procedure for measuring the kinetic energy that enters the drill rod string from the hammer impact and is applied to the comparative evaluation of different hammer systems.

The testing apparatus in the current standard consists of a load cell, processing instrument, digital timer, and an oscilloscope. Both the apparatus and the testing procedure are based on the early tests conducted by Schmertmann and others (refer to Section 2.4.3 for details). The energy computation method specified is the *Stress Wave Integration Method,* which is more commonly referred to as the *Force-Squared ($F^2$) Method.* Section 2.3 of this chapter contains a detailed description of both the $F^2$ method and the newer *Force-Velocity (Fv) Method.* This latter method will be included in the next version of ASTM D 4633, which is currently under revision.

The Fv method was used for this FDOT testing program and is discussed in detail throughout this report.

## 2.2 Energy Transmission in the SPT

In order to understand, and ultimately measure, the energy transmitted during the SPT, the components of the SPT system must be defined. In the SPT the split spoon sampler, attached to a string of drill rods, is driven into the bottom of a prepared borehole using a 140 lb hammer free falling a distance of 30 inches. The hammer strikes an anvil attached to the drill rods. Upon impact, the hammer's energy of 350 foot-pounds is transmitted to the drill rods in the form of a compression wave that propagates down the rods to the sampler, where soil penetration occurs.

Because the SPT replicates the dynamic nature of pile driving, it is often modeled in the same manner, using one-dimensional wave mechanics. Fischer (1984) provides a derivation of wave theory as applied to pile driving. Abou-matar and Goble (1997) have justified the use of this theory as a basis for their evaluation of energy measurements on SPT systems.

As documented by Fischer, in order to explain energy transmission due to impact, it is necessary to consider a rigid mass impacting an elastic, uniform rod. The impact on the top of the rod creates a stress wave that propagates through the rod with a wave speed "c." When the wave front reaches the tip of the rod, it is reflected upwards. The character of the reflected wave depends on the soil resistance encountered at the tip. High resistance will generate a compressive reflection, while low soil resistance results in a tensile reflection.

As the wave passes by a particle in the rod, the particle moves with a certain velocity. This particle velocity is different from and should not be confused with the wave speed, "c." The sign convention for wave propagation and particle velocity is given in the following table:

Table 2-1. Sign Convention

| | Stress Wave | Particle Velocity |
|---|---|---|
| Positive | Compression | Downward |
| Negative | Tension | Upward |

(source: Pile Driving Analyzer™ Manual, 1990)

For a compression wave, the particle velocity is in the same direction as the wave. For a tension wave, the opposite is true, the particle velocity is in a direction opposite to that of the wave propagation. Therefore, for a downward traveling compression wave or an upward traveling tension wave, the particle velocity is positive.

When studying energy transfer during the SPT, two situations are of primary importance: 1) the reflection of the wave at the bottom of the rod (sampler) and 2) wave reflection and transmission where there is a sudden change in rod properties (i.e. cross-sectional area, modulus of elasticity, etc.).

When the rod rests against a rigid bottom (N-values>about 50), the compression wave traveling through the rod reaches the bottom at time L/c and reflects as an identical compression wave traveling back up the rod. When this wave reaches the top of the rod at time 2L/c, the hammer is pushed upwards. A portion of the wave is reflected downward in the rod for a second trip. This process continues with a decaying of the stress wave. At the first moment of reflection, the compressive pulse traveling upwards will be superimposed on the compressive pulse traveling downwards, thereby doubling the compressive force at the tip.

Fischer explains that for the case of a reflection at a free rod tip, the compression wave is reflected as a mirror image tension wave. The upward traveling tension wave is associated with downward traveling particle velocities. Therefore, at the tip, the velocity doubles due to the downward particle velocities associated with both the compression and tension waves.

As in the case of a rigid bottom, when the reflected wave reaches the top of the rods, the hammer is separated from the rods by the upward traveling wave. Only in this case, the upward traveling tension wave does not push the hammer away, but actually pulls the rod top downward. The tension wave is then reflected at the rod top as a compression wave and the process begins again.

The theoretical model of a rigid mass impacting an elastic rod is a good representation of wave transmission during the SPT. However, in reality, the situation is not so "ideal." For the time between impact and 2L/c, force and velocity at the top of the rod are directly proportional (Butler, 1997). However, after the initial arrival of the reflected wave at the rod top, proportionality between force and velocity no longer holds. Wave reflections and transmissions occur which create a complex wave propagation pattern. As mentioned previously, the complexity is increased when the wave encounters a sudden change in rod properties. Changes in cross section, due to the presence of rod connectors or slack in rod joints, cause partial reflections that disturb force/velocity proportionality. These reflections also occur at the interface between the rods and the sampler. A past study by Kovacs and Salomone (1982) also indicates that anvil shape has a definite impact on energy transmission, as of course does the amount of resistance at the bottom of the hole. Because all of these variables affect the force and velocity waves, they also influence the methods of energy measurement. The following section details the methods used to calculate energy during the SPT.

## 2.3 Method of Energy Calculation

Similar to pile driving, the SPT is dynamic in nature. The transmission of energy from the hammer system to the sampler, via the drill string, can be modeled using one-dimensional wave mechanics. Butler (1997) presents a simple derivation of the energy equations. The transferred energy is a function of the work done when a force is applied to a body that moves some distance. Thus the incremental work is defined as

$$dW = Fdx \qquad (1)$$

where,

$dW$ = increment of work
$F$ = force
$dx$ = incremental distance

Therefore, the total work is equal to

$$W = \int F dx \tag{2}$$

Work, expressed as a function of time, is equal to energy. Therefore, energy is defined as the following:

$$E(t) = W(t) = \int F(t)\frac{dx}{dt}dt = \int F(t)v(t)dt \tag{3}$$

where,

$E(t)$ = energy as a function of time
$dt$ = incremental time
$v(t)$ = velocity as a function of time

For the Force-Velocity (Fv) Method, energy is calculated using both force and velocity. Velocity is obtained by integrating acceleration, which is measured in the field. Therefore, the energy equation for the Fv Method is defined as follows

$$E(t) = \int_0^{t_{E(max)}} F(t)v(t)dt = EFV \tag{4}$$

where,

$t_{E(max)}$ = time of the entire force and velocity record

In order to obtain the maximum value of energy, equation (4) is integrated over the entire force and velocity record. Sophisticated accelerometers are used successfully to measure acceleration from which velocity is computed. However, in the early days of measuring energy during performance of the SPT, acceleration measurements were difficult to obtain for steel to steel impacts. Therefore, the older energy computation method, the $F^2$ method, is based on force measurements alone. The $F^2$ method is related to the Fv method by the following

$$F(t) = v(t)Z = v(t)\frac{EA}{c} \tag{5}$$

therefore,

$$v(t) = F(t)\frac{c}{EA} \tag{6}$$

where,

$Z$ = impedance
$E$ = modulus of elasticity of steel
$A$ = cross-sectional area of the rod
$c$ = wave speed in steel

Substituting equation (6) into equation (4) yields the following

$$E(t) = \frac{c}{EA}\int F^2 dt = EF2 \tag{7}$$

The limits of integration for equation (7) are from 0 to time 2L/c, where L is equal to the rod length. The 2L/c time is significant for several reasons. First, 2L/c marks the arrival of the initial compression wave as it is reflected from the toe. According to Schmertmann and Palacios (1979), the hammer separates from the rods with the arrival of the reflected wave. They contend that by the time the separation occurs, the majority of the energy has already entered the rods. Subsequent pulses from the hammer would have very little kinetic energy relative to the first compression wave to enter the rods. However, Nixon (1982) and others have stressed that for short rod lengths (<20 feet), there is a significant reduction in energy for the first compression pulse because of the early separation of the hammer from the rods. Therefore, the 2L/c time may not be indicative of the amount of energy entering the drill string.

When relating the two equations, velocity in the Fv method is replaced by a force term multiplied by a constant in the $F^2$ method. Therefore, force and velocity must be proportional for the $F^2$ method to remain valid. Studies by Butler (1997) and Abou-matar and Goble (1997) indicate that when the transmitted wave reaches a change in cross-section (connector, slack joint, etc.), a portion of the transmitted wave is reflected in the opposite direction. A change in area causes a change in the impedance; therefore, the $F * \frac{1}{Z}$ term is no longer proportional to the velocity term and the $F^2$ method is no longer valid. Proportionality between velocity and force is also violated after a time 2L/c because of the cycling of waves back and forth in the rods.

Because energy is only computed from time 0 to 2L/c, the current ASTM standard (ASTM D 4633, 1986) requires that certain corrections be made to the energy value. The correction factors are $K_1$, $K_2$, and $K_c$. Because the sensor is not located immediately at the point of hammer impact, $K_1$ is a correction factor to account for the location of the sensor on the drill rod. $K_2$ is applied for rod lengths less than 45 feet. $K_c$ is a ratio of the actual wave speed to the theoretical value.

ASTM D 4633 is currently being revised. In the draft revision, $K_1$ is a correction to be applied when the rod-ram weight ratio is less than 0.7, which accounts for the fact that some of the first compression wave energy is cut off prematurely. $K_2$ is an empirical factor used to correct for wave speed differences between theoretical and wave form reflections that violate the force-velocity proportionality.

Equations (8) and (9) represent the *energy transfer ratios* or *energy transfer efficiency* for the Fv and $F^2$ methods, respectively. The term in the denominator, 350 ft-lb, represents the maximum potential energy of a hammer system.

$$ER_{FV} = \frac{EFV}{350 ft - lb} \quad (8)$$

$$ER_{F2} = \frac{EF2}{350 ft - lb} \quad (9)$$

Equation (10) is a ratio of the measured 2L'/c time to the theoretical, where L' is the distance from the measuring gages to the tip of the sampler.

$$RAT = \frac{2L'/c_{measured}}{2L'/c_{theoretical}} \quad (10)$$

According to ASTM D 4633, if the measured 2L'/c time is outside of the limits of (0.9 to 1.2) times the theoretical 2L'/c, then the data from the $F^2$ method should not be used.

Finally, there has been considerable discussion about standardizing the N-value to account for a reduced energy transmission from the hammer to the sampler. The following equation, taken from the SPT Analyzer Users Manual (Pile Dynamics, Inc., 1995), modifies the blowcount determined in the field to a standard $N_{60}$ value.

$$N_{60} E_{60} = N_{field} E_{measured} \quad (11)$$

where,

$E_{60}$ = 60% of the theoretical potential energy
$N_{field}$ = N-value observed in the field
$E_{measured}$ = measured energy

Section 2.4 contains more information regarding standardization of SPT data.

## 2.4 Previous Work by Others

### 2.4.1 Background

In the geotechnical community, it is not uncommon to hear engineers refer to the standard penetration test as anything but "standard." While writing about SPT testing, many individuals (Lamb, 1997; Schmertmann, 1978; Kovacs, 1979, 1981; and others) have stressed that the SPT has great variability between equipment, operators, and testing practices and its N-values have poor reproducibility in similar soil conditions. As previously noted, interested parties have formally gathered to discuss the SPT and work together to develop a "standard." One individual who is credited by many for his groundbreaking work in the standardization of the SPT is Dr. John H. Schmertmann, principal of Schmertmann & Crapps, Inc. and former professor of Civil Engineering at the University of Florida. His work or that of the graduate students under his direction was referenced in almost 75 percent of the papers reviewed as part of this research. Dr. Schmertmann recognized that the test is widely used by engineers without proper control of several variables that greatly affect the blowcount obtained during testing (Schmertmann, 1974). In the following section, a short discussion is presented of those variables considered by researchers to have the most effect on the N-value obtained during testing.

### 2.4.2 Variables Affecting Standard Penetration Testing

The fact that certain variables have an impact on the results of the SPT has not gone unnoticed, not even by those responsible for the earliest use of the test. As far back as 1965, Fletcher documented 13 variables inherent in the performance of the test, due to both human and method- and equipment-related influences. Fletcher's variables were:

- Inadequate cleaning of the borehole
- Failure to maintain sufficient hydrostatic head in the boring
- Variations from an exact 30-inch drop of the drive weight
- Use of drill rods heavier than 1-inch extra heavy pipe or A rods

- Extreme length of drill rods (over 175 feet)
- Interference with free-fall of the drive weight from any cause
- Use of 140 lb weight without hardwood cushion, block, or guide rod
- Use of sliding weight that can strike the drive cap eccentrically
- Use of deformed tip on the sample spoon
- Excessive driving of sample spoon before the blow count
- Failure to seat sample spoon on undisturbed material
- Driving of sample spoon above bottom of casing
- Carelessness in counting the blows and measuring penetration

In his discussion of the paper by Fletcher, Mohr (1966) added eight additional variables inherent in the test. Like Mohr, others have added to or expanded on the list originated by Fletcher. Schmertmann (1978) not only documented 11 detailed causes of variability in the test, but also provided an estimated percentage by which the variable can change the N-value.

While variables such as the use of drilling mud versus casing and water, as well as borehole diameter, have a significant effect on test results, only variables related to energy will be considered in this report. Five of the 11 variables documented by Schmertmann are a function of the dynamic energy reaching the sampler. Number of turns of rope on the cathead, anvil size, rod length, drop height, and rod size are considered by Schmertmann to change the N-value from ±10 percent to 100 percent, with number of turns of rope having the greatest effect. The following Table 2-2 was adapted from Schmertmann.

Table 2-2. Factors Affecting the N-Value of the Standard Penetration Test

| CAUSE | | ESTIMATED % BY WHICH "CAUSE" CAN CHANGE N-VALUE |
|---|---|---|
| BASIC | DETAILED | |
| Dynamic Energy Reaching Sampler (All Soils) | 2 to 3 turns of rope on the cathead versus free drop | +100% |
| | large versus small anvil | +50% |
| | <u>length of rods:</u> | -- |
| | less than 10 feet | +50% |
| | 30 to 80 feet | 0% |
| | more than 100 feet | +10% |
| | variations in height drop | ±10% |
| | A-rods versus NW-rods | ±10% |

<u>Source</u>: Adapted from Schmertamnn (1978).

Many researchers have specifically addressed energy transmission from the hammer to the sampler. The Working Party from the Orlando Symposium of 1988 concluded that the greatest cause of variability of penetration resistance was the variation in the amount of energy delivered to the drive rod system. They attributed the variation to the shape of the hammer, as well as the number of turns of rope around the cathead. Based on a thorough review of numerous papers, it appears that a common thread is the variability of energy transmission during the test. Many authors (Lamb, 1997; Broms and Flodin, 1988; Skempton, 1986; Jamiolkowski et al., 1988; Nixon, 1982; and Seed et al., 1985) document causes for the variability of transmitted energy. The following is a summary of the variables mentioned most often by the above referenced authors and as observed by the authors during this research:

- Hammer system
    - Lifting and dropping mechanism (cathead and rope versus trip)
        - Ram drop height
        - Number of turns of rope on the cathead
        - Cathead speed
    - Type of hammer and anvil shape
- Operator techniques
    - Plumbness of drill rods and hammer
    - Operator's rope "throw"
- Drill rod size
- Drill rod length

In 1981, Kovacs presented the results of a survey conducted by ASTM Headquarters. Kovacs and others felt that because the ASTM standard did not address some of the variables that control the energy during testing, wide variations occur in test results. Therefore, the purpose of the survey was to obtain information on current (at the time of the survey) practice with respect to hammer types used, number of turns of rope around the cathead, and other test specifics. Almost 95 percent of the respondents used a cathead and rope mechanism. The number of wraps used by those surveyed varied from one to three, with the majority specifying two wraps. Of those using the cathead, 65 percent used it in conjunction with the safety hammer. A smaller percentage of respondents were still using the donut hammer. Many of the companies surveyed had a free-fall type hammer, but did not use it on a routine basis. It was concluded from the study that ASTM should provide more education to acquaint engineers with the "fine details" of performing the SPT, in order to reduce the differences in energy reaching the samplers.

Based on information presented by engineers such as Kovacs and Schmertmann, the geotechnical engineering profession was enlightened about variability associated with the very popular SPT. In an effort to quantify the effect that the variables mentioned above have on the transmission of energy during the SPT, many individuals have conducted field tests and/or computer simulations where variables were isolated for in-depth study. In the following section, the significant studies and their findings are documented.

### 2.4.3 Prior Energy Measurements and Computer Simulations

In an effort to predict the energy efficiency of a given rig and hammer system, taking into account a matrix of variables, numerous field tests and computer simulations have been conducted. A recent publication by Butler (1997) contains a summary of energy efficiencies, as predicted by a number of researchers. Table 2-3 was taken from Butler and modified to 1) exclude data pertaining to hammer systems not covered in this report, and 2) include additional data related to safety and automatic trip hammer systems.

As seen from Table 2-3, these studies indicate that the energy transfer ratio for safety hammers with cathead and rope hoisting mechanisms can vary considerably. The range of reported values is from 30 to 96 percent. For automatic trip hammers, the range is smaller, with a low of 60 percent and a high of 90 percent.

Table 2-3. Summary of Average Energy Transfer Ratios

| Study | SPT System -- Hammer, Hoist and Release | Energy Ratios [a] (%) |
|---|---|---|
| Schmertmann, Smith, Ho (1978) | Safety, rope & cathead | 45 – 70 |
| Goble, Ruchti (1981) | Safety, rope & cathead | 76 – 96 |
| Kovacs, Salomone, Yokel (1981) | Safety, rope & cathead | 34 – 83 |
| Riggs, Mathes, Rassieur (1984) | Safety, rope & cathead<br>Automatic trip | 80 (3 operators)<br>88 |
| Seed et al. (1985) | Safety, rope & cathead<br>Automatic trip | 63 – 72<br>76 – 90 |
| Riggs (1986) | Safety, rope & cathead | 65 – 90 |
| Skempton (1986) | Safety, rope & cathead | 55 |
| Clayton (1990) | Safety, rope & cathead<br>Automatic trip | 55 – 60<br>60 – 73 |
| Lamb (1997) | Safety, rope & cathead<br>Automatic trip | 67<br>80 |
| Batchelor, Goble, Berger, Miner (no date) | Safety, rope & cathead<br>Automatic trip | 51<br>69 – 81 |

Source: Adapted from Butler (1997).
Note: (a) Rounded to the nearest whole percent.

Schmertmann. Schmertmann is credited with being the first researcher to experimentally investigate the dynamic behavior of the SPT (Schmertmann, 1978). Schmertmann and his University of Florida graduate students performed energy calibrations on drill rigs owned by the FDOT. The purpose of the research was to reduce the variability of N-values between different rigs and crews by calibrating the drill rigs so that they all supplied the same energy to the sampler. The method of accomplishing this task was to find the height of hammer drop for each rig that would produce an average energy transfer ratio of 50 percent. In order to calibrate each rig, Schmertmann placed a dynamic load cell into the string of drill rods as close to the hammer as possible. A trigger switch was clamped to the drill rods between the load cell and the hammer. Tripping of the switch by the hammer started a single-sweep trace on an oscilloscope connected to the load cell. A Polaroid® photograph was taken of the force-time record stored on the oscilloscope screen. In order to determine the energy for that hammer blow, an electronic graphics digitizer (connected to the university's main frame computer system) was used to digitize the photograph. Then, the waveform was automatically integrated using the $F^2$ method of energy computation (refer to Section 2.3 for an explanation of the energy computation methods). Figure 2-2 is a reproduction from the appendix to an energy calibration report prepared for FDOT Rig 2503.

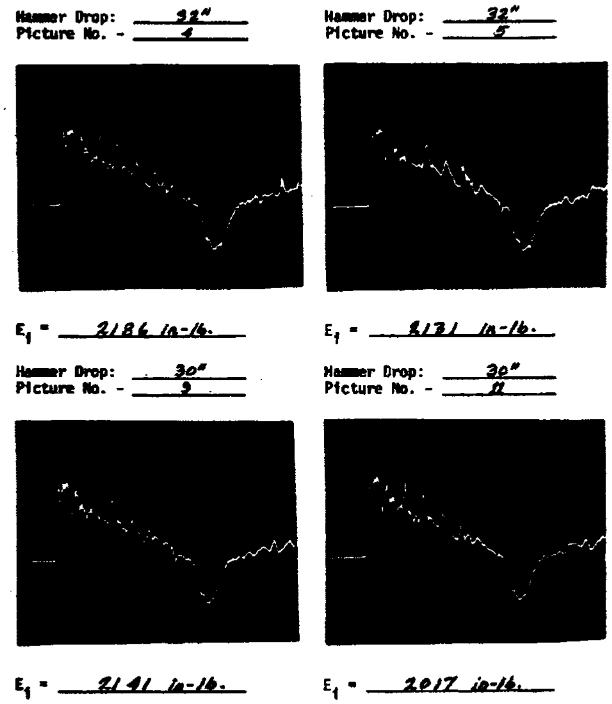



Figure 2-2. Digitized Wave Form

As expected, system efficiency was found to increase linearly with an increase in drop height. Based on these energy measurements, a drop height was recommended for each rig in order to achieve the desired efficiency of 50 percent under routine conditions.

Kovacs et al. Shortly after Schmertmann began investigating the dynamics of the SPT through field testing, Kovacs and his colleagues (Kovacs, Griffith, and Evans, 1978) began performing similar types of testing. They found that when using the cathead and rope to lift and release the hammer, the energy reaching the anvil was substantially less than the theoretical free-fall value. They also found that great variability existed in N-values obtained by different rigs under similar soil conditions. Therefore, the researchers proposed the use of a new lifting device, a hydraulic motor-operated spool with a wire line that raises the hammer and then reverses the direction of the spool (by means of a hydraulic control valve) to permit free-fall. In the manual mode, the equipment is operated similar to the rope and cathead. The operator raises and drops the hammer by moving a lever switch back and forth. The drop height is determined visually as with the cathead and rope mechanism. In the automatic mode, the operator merely engages an electrical switch on the control panel to begin the automatic sequence.

The researchers were interested in the up and down travel of the hammer during any given stroke. By using a light beam recorder with reflective scanners, they were able to calculate the velocity of the drive weight system knowing the distance between scanners and the time between recorded pulses. They were also able to determine how high the hammer was raised during each stroke. During testing, several parameters were varied in order to study their effects on the velocity of the hammer. The test variables were hammer drop height, drill stem inclination, and automatic versus manual mode of operation.

Based on the test results, Kovacs et al. concluded that the lifting device and hammer system yielded less than the 100 percent free-fall energy. However, the resulting energy transfer ratios were essentially the same as those of the cathead and rope system using two turns of new rope. The researchers found that similar results were obtained with both the automatic and manual modes of operation. In addition, they concluded that the inclination of the drill string up to 3 degrees from the vertical did not significantly affect test results. However, the height of fall was found to have a significant effect on the velocity at impact. Kovacs and his colleagues recommended careful control of the height of fall during testing. They also stressed that a standardized energy ratio is needed. They recommended using an energy ratio of 68 percent until a "standard" energy is adopted.

Four years later, Kovacs and Salomone (1982) reported on yet another test to measure the energy delivered by a drill rig system. The purpose of their test program was to study the factors that affect delivered energy. Their instrumentation consisted of two light beam sensors used to measure fall height and hammer velocity and a load cell to measure the stress wave generated by the hammer blow. Such variables as number of turns of rope around the cathead, fall height, drill rig type, hammer type, and operator characteristics were studied on four drill rigs, using both donut and safety hammers. During each test, a tape recording was made of the data from each scanner and the load cell for each blow of the hammer. The method of data reduction was the same as used by Kovacs in previous studies. Energy was calculated using the $F^2$ method.

Based on their test results, Kovacs and Salomone determined that velocity increases as fall height increases. Also, as the number of turns around the cathead increases from one to three, the velocity and the efficiency of the hammer system decrease. The effect was more pronounced for 2-3 turns than for 1-2 turns.

Kovacs and Salomone calculated the energy ratio both as a function of kinetic energy (using velocity) and as a function of force (integrating the force-time relationship from the load cell measurements). Differences between the two computations were attributed to errors in digitizing and integrating the force-time curve, squaring the force term, and possible inaccuracies in the load cell measurements. As discussed in a later section, questions relating to the accuracy of the $F^2$ method of energy computation have surfaced. After carefully evaluating the data, the investigators concluded that operators tended to have a stroke slightly greater than 30 inches, but based on their statistical analysis of the data, assuming a fall height of 30 inches in the computation of the energy ratio is acceptable.

Finally, Kovacs and Salomone made an important observation. They concluded that the safety hammer was more efficient than the donut hammer. Researchers previously attributed the difference in energy efficiency to hammer geometry. However, Kovacs and Salomone referenced a study by Hanskat (1978) where anvil type was studied using a computer model and thought to be the primary cause for the energy difference.

<u>Riggs et al</u>. Shortly after Kovacs and his colleagues documented the results of their energy measurement studies, Charles O. Riggs, research engineer for Central Mine Equipment Company (CME), along with several of his associates, published papers documenting a new automatic SPT hammer system developed and tested by CME (Riggs, Schmidt, and Rassieur, 1983, and Riggs, Mathes, and Rassieur, 1984). The new system was designed with three objectives in mind: 1) provide reproducible SPT results within a narrow range, 2) provide optimum safety during operation of the hammer, and 3) provide a system economically comparable to the cathead and rope system.

Not only was the hammer system technologically advanced over other systems in use, but the test instrumentation was also an improvement over equipment used in previous tests. A Binary Instruments Model 102 SPT calibrator with load cell and digital readout was used to record peak impact force and compute energy according to the $F^2$ method. Therefore, the investigator was no longer required to photograph and digitize wave forms, leading to more accurate results. After testing the automatic trip hammer and comparing the results to tests conducted using a safety hammer, Riggs et al. concluded that automatic hammer and the safety hammer (when tested in free-fall) have practically the same mean peak force and mean driving energy. They stated that the automatic hammer should produce N-values at the lower end of the range of N-values that are produced using the cathead and rope system.

Later field testing by Riggs, Mathes, and Rassieur was conducted to evaluate the N-values obtained using an automatic trip hammer versus a safety hammer with cathead and rope system. Certain variables were held constant during testing. By using the same CME safety hammer, clean and dry hemp ropes, AW rods assembled in the same order for each test, advancing all 14 borings using the same hollow stem auger, and obtaining the N-value at the same depth (± 1.0 inch) for each test, a comparison of the N-values obtained using each method became more reliable. Based on the test data, the researchers concluded that the difference in the mean N-values and measured stress wave energies of the two methods was approximately 10 percent. This difference in N-values was considered by the researchers to be statistically insignificant, because a difference of 10 percent is not discernable in engineering practice.

Lamb. All of the studies discussed above highlight the questions that geotechnical engineers have had about the SPT for many years. A recent study by the Minnesota Department of Transportation (MnDOT) shows that engineers are still attempting to clarify and quantify the variables that make the SPT less than standard (Lamb, 1997). The purpose of Lamb's study was truly a practical one, similar to one of the objectives of this report. The MnDOT began testing their rigs in 1996 after noticing significantly different N-values on projects using drill rigs with different hammer systems sampling in similar soil conditions. Their inventory consists of semi- and fully automatic SPT hammer systems, as well as the older cathead and rope systems. All of their hammer systems operate differently and have different levels of operator involvement. Using the Pile Driving Analyzer® (PDA) and an instrumented section of drill rod, the MnDOT found that their hammer systems delivered between 27 and 82 percent of the maximum energy. Unlike their predecessors, the MnDOT used the Fv method to calculate the energy transferred from the hammer to the drill rods (refer to Section 2.3 for information on energy calculation methods).

As shown in Table 2-3, the only cathead and rope system included in the test had an average energy efficiency of 67 percent. Two of the three CME automatic hammers had an average efficiency of approximately 80 percent, with a standard deviation of only two percent. The standard deviation of the third CME hammer was as high as 11 percent. The MnDOT determined that this hammer was not working properly and credited the testing program with uncovering the malfunction. In addition to specific energies, it was observed that the alignment of the hammer system affected the energy transfer. An anvil or rod not struck squarely results in reduced energy. Based on the test results, a correction factor was established for each hammer system to normalize the data to an energy transfer ratio of 60 percent. However, they felt that to apply the correction factor to each blowcount on every log would create extra work for office personnel. Similar to Schmertmann, MnDOT personnel decided that adjusting the hammer stroke in the field to deliver 60 percent of the potential energy of the hammer would be the best option for providing more standardized SPT data.

Batchelor, Goble, Berger, and Miner. In Lamb's report from 1997, he referenced a study similar to his own. The Seattle Branch of the American Society of Civil Engineers (ASCE) sponsored a voluntary testing program to conduct energy measurements on Seattle area drill rigs (Batchelor, Goble, Berger, and Miner, 1995). Using the PDA, Goble Rausche Likins and Associates, Inc. (GRL & Associates, Inc.) tested drill rigs supplied by the Washington State Department of Transportation and local drilling companies. The test program included three drill rigs using safety hammers with cathead and rope systems and three automatic hammers. The results from this testing program were consistent with test results from other researchers. The average energy efficiency values are listed in Table 2.3.

Morgano and Liang. A study by Morgano and Liang (1992) included both numerical modeling using the GRL Wave Equation Analysis Program (GRLWEAP™) and field tests utilizing the PDA and the Hammer Performance Analyzer™ (HPA). As in other studies, the PDA was used to measure energy transfer. The HPA measured the kinetic energy from the hammer impact, replacing the light beam recorder and reflective scanners used in the past to measure hammer velocity. The purpose of the project was to determine the effects of rod length on energy transfer. Based on the field testing and the computer modeling, Morgano and Liang concluded that transferred energy is independent of rod length for lengths greater than 50 feet. However, for rod lengths less than 50 feet, the energy transfer is less than 100 percent. Figure 2-3 is a graph of average transfer efficiency versus rod length. The curve is non-linear, especially for rod lengths ranging from 10 to 30 feet.

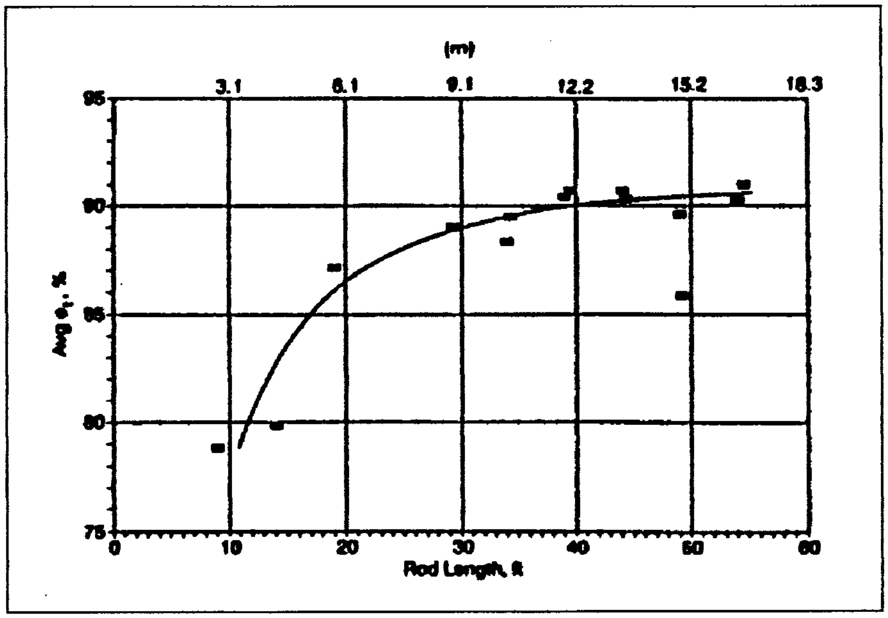



Figure 2-3. Transfer Efficiency versus Rod Length

Because the energy transfer is reduced for rod lengths less than 50 feet, artificially high blowcounts result. Therefore, Morgano and Liang recommend correcting the blowcounts determined in the field by a correction factor to account for rod length effects. The required modification factor is determined from Figure 2-4 and then applied to the field N-value ($N_f$) to yield the corrected N-value ($N_c$). As confirmed by Morgano, the ratio shown on the x-axis, $N_c/N_f$, is a typographical error and should read $N_f/N_c$. Because a reduced energy is transmitted due to the short rod length, the field N-values are artificially high. Therefore, application of the correction factor shown in Figure 2-4 will result in a lower corrected N-value.

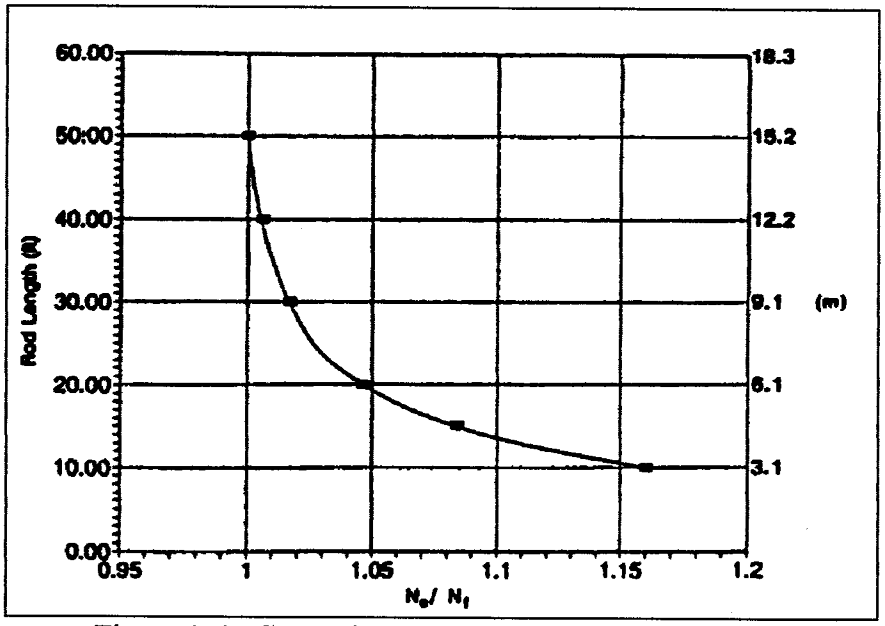



Figure 2-4. Correction Factor for Rod Length Effects

Abou-matar and Goble. The use of equipment such as the PDA and the HPA has become very important in the measurement of energy transmission. While this equipment is manufactured by Pile Dynamics, Inc., it was developed by its sister company, GRL & Associates, Inc. Dr. George Goble, a principal in the company, and his colleagues have been deeply involved in the standardization of the SPT and have worked extensively to understand and quantify the energy transmission process. In their recent paper, Abou-matar and Goble contend that to accurately quantify energy, measurements of both force and velocity must be obtained (Abou-matar and Goble, 1997). Based on laboratory measurements, wave mechanics, and the use of a wave equation analysis program, they have concluded that acceleration and force can be accurately measured during standard penetration testing and that the energy measurement method specified by

ASTM D4633-86 can produce large errors. This work is significant, because the results are directly applicable to the project documented in this report.

For their study, laboratory tests were run using both a safety hammer and an automatic trip hammer system, both manufactured by CME. The testing system consisted of a Hammer Performance Analyzer™ to measure impact velocity, a section of AW drill rod instrumented with foil resistance strain gages and piezoresistive accelerometers, and an RC Electronics A/D recorder to digitally sample the data and store it in a personal computer. The instrumented drill rod is identical to the one used for the tests documented in this report.

As seen from Figure 2-5, the laboratory measurements on the safety hammer compared well with the theoretical analysis from points A to F. At point F, the reflection from the toe of the drill rod arrived at the sensor location.

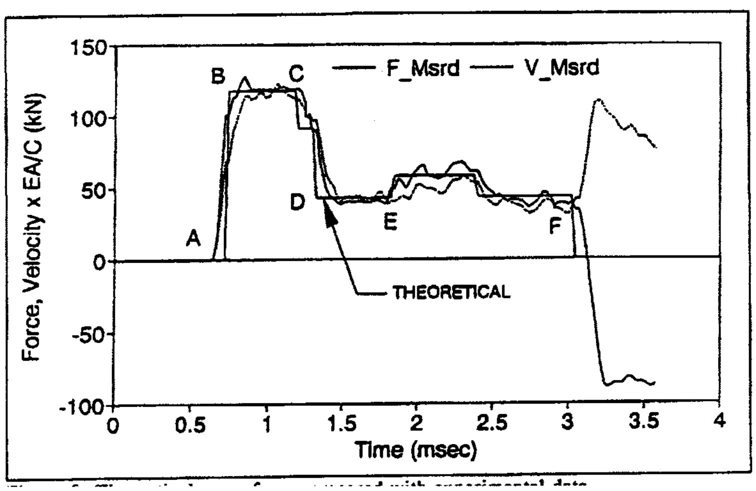



Figure 2-5. Laboratory Measurements versus Theoretical Computations

Force and velocity were calculated using the wave equation analysis program GRLWEAP™ and compared with the same laboratory measurements shown in Figure 2-5. As seen from Figure 2-6, the results compared well. There is a slight departure from proportionality at Point C, attributed to the reflection from the first connector in the drill string. A reflection from a second connector is evident at Point E. Overall, the researchers felt that the wave equation analysis can be effectively used to model SPT operations, if the system is modeled correctly.

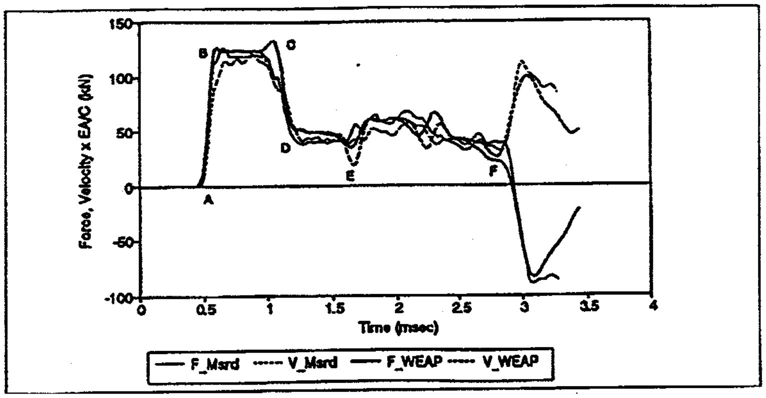



Figure 2-6. Laboratory Measurements versus GRLWEAP™ Analysis

The same comparisons were made for the CME automatic trip hammer. As with the safety hammer, the wave mechanics solution gave peak stresses and velocities that supported the measured values. In addition, the researchers concluded that the wave equation analyses also agreed well with the values obtained in the laboratory. Abou-matar and Goble also modeled the effect of changes in drill rod cross section. As discussed in Section 2.2, at the point of cross section change, a portion of the wave is reflected and disturbs the proportionality between force and velocity. Therefore, they concluded that even small changes in cross section due to connectors in a typical AW drill string could produce an error of 10 percent when using the $F^2$ method to calculate energy. However, the Fv method yields good results, because it does not rely on proportionality between force and velocity.

<u>Butler</u>. As mentioned often in this chapter, there are two accepted methods for calculating the energy transferred from the hammer to the drill string, the $F^2$ and Fv

methods. Joshua Butler, who recently received a Master of Science degree from Utah State University, prepared a thesis containing an evaluation of each method (Butler, 1997). In addition, Butler developed a third hybrid method – the $Fv_{corr}$ method. The project data were collected from various sites located across the United States using the PDA and instrumented drill rods, identical to the instrumentation used in other more recent studies. Butler evaluated the force and velocity measurements, calculated the energy from each blow using the three methods, and analyzed the data with statistical software. In addition, a wave equation analysis was performed using GRLWEAP™. The purpose of the GRLWEAP™ analysis was to evaluate the effects of connectors and slack in the rod string on wave transmission.

Butler's database consisted of 273 records, where a record was a set of blows taken at a particular sample depth. A total of 9,919 individual blows were analyzed. The majority of these blows were collected by GRL & Associates. Based on a qualitative analysis of the data, Butler assigned a data quality rating to each record. The rating was used to "weight" the data during quantitative and statistical analyses.

For the quantitative analysis, Butler calculated energy values using the two standard methods and his new $Fv_{corr}$ method. Energy values were calculated using this latter method by manually scaling the energy computed by the Fv method off the computer screen at the 2L/c cutoff time. Three values were scaled at random from the blows in each record and then averaged. The averaged value was multiplied by the ASTM correction factor, $K_2$.

The purpose of the statistical analysis was to compare the energy computation methods and determine relationships and trends in the data. Taking the data from the quantitative analysis, Butler numerical encoded the database and read it into a statistical program. Qualitative data, such as type of drilling method, were analyzed as independent variables. Numerical values were analyzed as dependent variables. Output from the program included histograms, which were used primarily to visually describe the distribution of values for independent variables, such as hammer type. Output data also included correlations, which showed a relationship (or lack thereof) among dependent variables; analysis of variance, which was used to determine relationships between independent and dependent variables; and a matched paired comparison between the three energy computation methods.

For the wave equation analysis, four models were used: 1) uniform AW rod; 2) AW rod with connectors only; 3) AW rod with a slack only; and 4) AW rod with connectors and a slack. The SPT system was modeled with a CME automatic hammer and anvil and a standard split spoon sampler. The computer results were evaluated numerically by comparing the energy transfer values for each model. Graphically, the wave traces for each model were compared. Butler found that for the model with connectors, reflections were evident in the force trace. These reflections caused a substantial amount of disproportionality in the force and velocity wave traces within the first 2L/c time, lending itself to questions about the validity of $F^2$ measurements. For the model depicting slack joints, there was an overall decrease in EF2 measurements compared to the uniform rod model.

Based on the analyses described above, Butler reached a number of significant conclusions. Some of his conclusions, along with those from other studies, are documented in the following section.

### 2.4.4 Conclusions Based on Previous Work

In Section 2.4.3, significant studies related to energy measurements during the SPT were discussed. Some of the important results from those studies, as well as from several studies not previously mentioned, are summarized in this section. The conclusions reached and the responsible investigators are listed below. These conclusions will be used as a basis of comparison between previous work and the results of this study. Note, the purpose of a number of studies was to determine energy efficiencies for different hammer systems. Those results were summarized in Table 2-3.

Comparison between $F^2$ and Fv Methods.

1. Short rod lengths result in the energy measured by the $F^2$ method being too low, because not all of the energy is transmitted in the shorter 2L/c time. Therefore, the energy value must be corrected by the ASTM correction factor $K_2$. Short rod lengths do not affect the Fv method (Butler, 1997).
2. Changes in SPT rod cross-sectional area from connectors or slack joints result in wave reflections that disrupt the force/velocity proportionality within the time interval of 2L/c. When proportionality is violated, the energy measured by the $F^2$ method is inaccurate. Disruptions in force/velocity proportionality do not affect the Fv method (Butler, 1997). A similar statement is made by Abou-matar and Goble, 1997.
3. The difference between the energy transfer ratios of the $F^2$ and Fv methods can be as high as 15 percent (Butler, 1997).

4. The $F^2$ method gives higher energy values than the Fv method for high blow counts (>50). The opposite is true for the case of low blowcounts (<10). The two methods are almost the same within the intermediate range of blows (Butler, 1997).

5. If the first zero force is not within the time range of 0.9 to1.2 times 2L/c, the $F^2$ method can not be used (Butler, 1997; ASTM, 1986). Also, if the velocity measurement for the Fv method does not slope toward the zero axis late in the record, the energy measurement will be erroneously high (Butler, 1997).

6. Reflections from rod connectors cause a substantial amount of disproportionality in the force and velocity wave traces within the first 2L/c time, affecting the validity of $F^2$ measurements (Butler, 1997).

7. The Fv method is generally more reliable than the $F^2$ method; however, values for both methods are within 10 percent of each other (Robertson, Woeller, and Addo, 1993).

Energy Standardization/Use of Current Correlations

8. The use of blowcounts from tests preformed using free-fall hammers should be used with caution when comparison is made with engineering correlations based on SPT results where present practice produces substantially less energy (Kovacs, 1979).

9. Use an energy ratio of 68 percent until a standard is adopted (equates to two turns of rope around the cathead) (Kovacs, Griffith, and Evans, 1978).

10. The average energy ratio (in terms of percentage of theoretical free-fall energy) for a safety hammer used with two wraps around the cathead is approximately 60

percent. Therefore, correction of field data would be minimized if an energy ratio of 60 percent is adopted as standard (Seed, Tokimatsu, Harder, and Chung, 1985).

<u>Variables that Affect Energy Transfer</u>

11. An inclination of the drill string up to 3 degrees from the vertical did not influence the velocity at impact (Kovacs, Griffith, and Evans, 1978).

12. It is not necessary to measure the actual fall height in the computation of the energy ratio if the operator can achieve the fall height within one inch (Kovacs and Salomone, 1982).

13. Transferred energy is independent of rod length for lengths greater than 50 feet. For lengths less than 50 feet, the energy transfer is reduced and non-linear in distribution. A correction factor should be applied to the field blowcounts to account for rod length effects (Morgano and Liang, 1992).

14. In a comparison of the automatic and safety hammer (tested in free-fall) systems, the mean peak force and the mean driving energy were practically the same for both systems (Riggs, Schmidt, and Rassieur, 1985).

15. According to Goble and Ruchti (1981), most operators “overpull” the hammer (Riggs, Schmidt, and Rassieur, 1985).

16. System efficiency increases linearly with an increase in drop height (Schmertmann, 1978).

17. As the number of turns around the cathead increases from one to three, the velocity and the efficiency of the hammer system decrease. The effect is more pronounced for 2-3 turns than for 1-2 turns. (Kovacs and Salomone, 1982).

# CHAPTER 3
# SPT HAMMER SYSTEMS

An SPT hammer system is comprised of the hammer itself, the mechanism that lifts and drops the hammer, and the operator. Because there are several types of hammers, and even more types of lifting and dropping mechanisms, the combination of these variables results in a matrix of systems. Fortunately, the FDOT uses the two most common systems – the safety hammer with cathead and rope mechanism and the automatic trip hammer system. Therefore, only these two systems were tested under the scope of this project and are discussed in this report.

## 3.1 Safety Hammer

The safety hammer, shown in Figure 3-1, is one of the two most common hammers used in the United States because of its internal striking ram that greatly reduces the risk of injuries (Lamb, 1997). When the hammer is lifted to the prescribed height, the outer barrel and the enclosed hammer move together as one piece. When released, the hammer falls, striking the internal anvil and creating an energy wave. The kinetic energy of the system, in the form of the wave, is transmitted through the anvil to the center rod. Because the center rod is threaded into the drill rod string, the wave is then transmitted through the drill rod string and into the split-spoon sampler.

In this study, the mechanism used to lift the safety hammer is the cathead and rope system. A rope is tied to the outer barrel of the safety hammer and strung through a pulley, or crown sheave, where it is wrapped around a rotating cathead. The free end of the rope is held by the operator. To conduct the test, the operator pulls the rope to raise the hammer and then "throws" the rope quickly to release the tension holding the hammer at the 30-inch drop height, thereby causing the hammer to fall. The raising and dropping of the hammer is conducted repeatedly until the sampler penetrates the required depth of 18 inches.

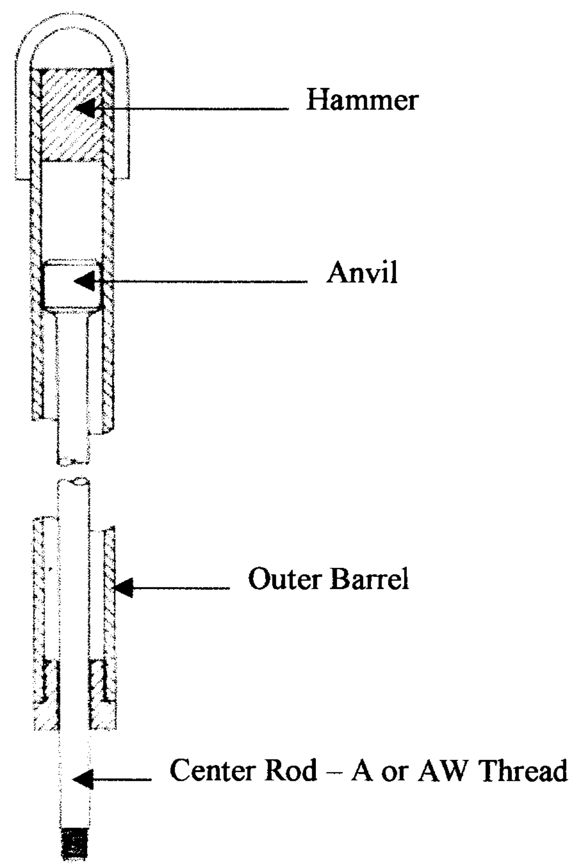



Figure 3-1. Safety Hammer (adapted from Riggs, Schmidt, and Rassieur, 1983)

## 3.2 Automatic-Trip Hammer

The second most commonly used hammer in the United States is the automatic trip hammer. Two automatic trip hammer types were encountered during this research: one manufactured by Central Mining Equipment (CME) and one manufactured by Diedrich Drill, Inc.

### 3.2.1 CME Automatic Hammer

The CME automatic hammer, Figure 3-2, consists of a cylindrical 140 lb drive weight, a cylindrical anvil, a guide tube, a lifting chain drive, and an automatic lowering and aligning assembly (Riggs, Schmidt, and Rassieur, 1983). While the safety hammer relies on the operator to pull the hammer to the required 30-inch height, the automatic hammer can be calibrated to repeatedly drop the drive weight from that height. The anvil is separate from the hammer and is screwed onto the top of the drill string. The lowering and alignment assembly allows the hammer to be positioned and lowered over the anvil and then rotated out of the way when not in use. The assembly also keeps the hammer drop in alignment with the axis of the borehole and transmits the lifting thrust of the drive weight to the drill rig rather than the drill rods. When the test is being performed, a hydraulically driven chain lifts the drive weight and releases it at the appropriate location for a 30-inch drop. When the weight falls, strikes the anvil and drives the drill rods downward, the entire hammer assembly follows the hammer anvil downward. Since the entire assembly moves downward as the SPT advances, each hammer stroke should rise to the same point on the hammer assembly for a consistent 30-inch stroke. A slot on the side of the guide tube allows observation of the drive weight to verify the correct drop height.

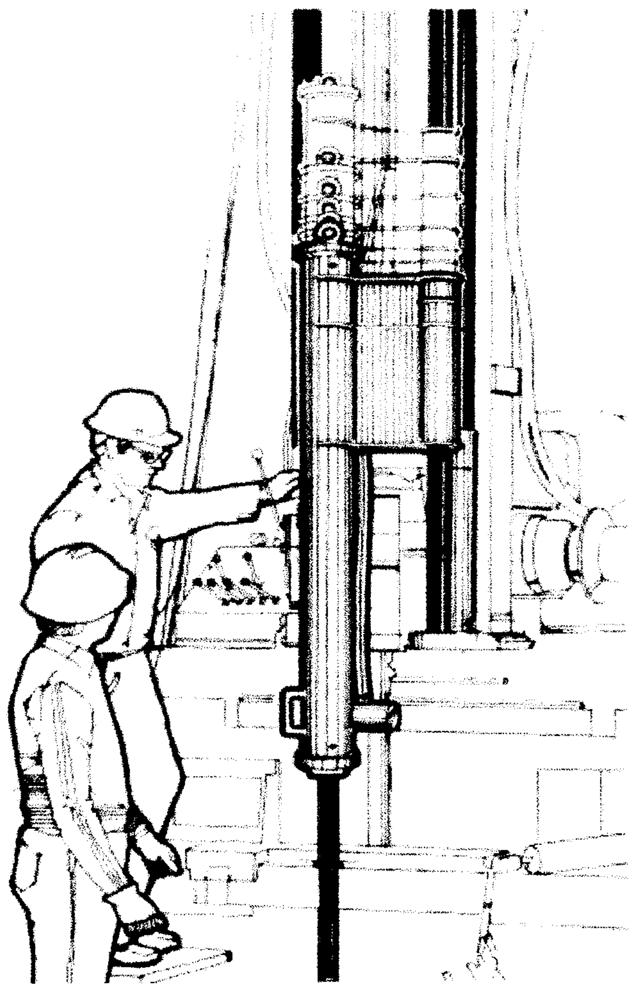


Figure 3-2. CME Automatic Hammer (Riggs, Schmidt, and Rassieur, 1983).

3.2.2 Diedrich Automatic Hammer

The Diedrich automatic hammer consists of a cylindrical 140 lb drive weight, a cylindrical anvil, a guide rail, a chain-mounted lifting device, and a hydraulic lowering and aligning assembly (Frost, 1992). As with the CME automatic hammer, the Diedrich automatic hammer can be calibrated to repeatedly drop the drive weight from a 30-inch height. The anvil is separate from the hammer and is screwed onto the top of the drill string. The lowering and alignment assembly allows the hammer to be positioned and lowered over the anvil and then rotated out of the way when not in use. The assembly also keeps the hammer drop in alignment with the axis of the borehole and transmits the lifting thrust of the drive weight to the drill rig rather than the drill rods. When the test is being performed, a cam on a hydraulically driven chain catches and lifts the drive weight and releases it at the appropriate location for a 30-inch drop. When the weight falls, strikes the anvil and drives the rods downward, the hammer assembly remains stationary while the hammer follows the anvil and drill string downward. Since the hammer assembly does not follow, each stroke of the hammer will rise to a different point relative to the assembly making it difficult to visually assess the drop height. In addition to this, a safety cover on the hammer precludes this difficult observation.

# CHAPTER 4
# ENERGY MEASURING SYSTEMS

## 4.1 Background

To accurately measure the energy transmitted from the hammer to the drill string, some form of instrumented equipment is required. As discussed in Chapter 2, Schmertmann (1978) and others set the precedent by using a dynamic load cell in the string of drill rods to obtain dynamic force measurements. As the hammer impact tripped the switch clamped to the drill rods, a single-sweep trace was produced on an oscilloscope connected to the load cell. A Polaroid® photograph was taken of the force-time record stored on the oscilloscope screen. In order to determine the energy for that hammer blow, an electronic graphics digitizer was used to digitize the photograph. Then, the waveform was automatically integrated using the $F^2$ method of energy computation.

In the late 1970s, Kovacs was interested in determining kinetic energy just prior to hammer impact. Using a reflective scanner with a target of reflective light and dark strips mounted on the hammer, he was able to measure the velocity of the falling hammer. As the interest in obtaining accurate velocity measurements increased, technology responded by producing equipment with the sophistication to accurately measure acceleration, thereby obtaining velocity. With growing confidence in the ability to obtain accurate force and velocity measurements, researchers promoted the Fv method of energy computation (Abou-matar and Goble, 1997).

Present day instrumentation includes foil strain gages attached to the SPT rod for obtaining force measurements and accelerometers, also attached to the rod, for obtaining acceleration data. The output from these sensors is transmitted via cables to the processing instrument. These instruments are capable of recording and displaying the velocity and force waveforms, as well as calculating energy values using both the $F^2$ and Fv methods. According to Butler (1997), the capabilities of the processing instruments range from simply squaring the force reading and displaying the energy value, to calculating the energy by either method, and displaying quantities such as maximum velocity, force, stroke, and displacement. The force and velocity traces are usually displayed on the screen with the data stored in the memory of the instrument until downloaded into a computer.

## 4.2 Selection of System

To conduct the testing described in this report, it was first necessary to purchase the appropriate testing equipment. After researching current trends in energy measurement systems and developing some understanding of the type of equipment required to accomplish the work, an evaluation was made of available products in order to select the most suitable system. After reviewing recent publications related to the project, searching the Internet for manufacturers' literature, and gathering information by "word of mouth," the equipment search was narrowed to two manufacturers – Pile Dynamics, Inc. and TNO Building and Construction Research (TNO).

The features of the SPT Analyzer™ (Pile Dynamics, Inc.) and the SPT Controller (TNO) were evaluated and comparisons made, as documented in Table 4-1.

Table 4-1. Comparison of Energy Measurement Systems.

| Parameter | Pile Dynamics, Inc.<br>GRL, Inc.<br>*SPT Analyzer* | TNO<br>William F. Loftus Assoc.<br>*SPT Controller* |
|---|---|---|
| **Cost** | $_ _,_ _ _<br>(includes 3 days of training)<br>(includes 2 rods) | $_ _,_ _ _<br>(includes 3 days training @ $1200/day but not extra $1000 for the 2nd rod) |
| **Training** | 3 days<br>(theoretical, operational, & field) | 3 days<br>(theoretical, operational, & field) |
| **Technical Support** | Orlando<br>(continuous consultant to FL DOT)<br>Support comes directly from manufacturer<br>Representative involved in revising ASTM<br>30 years specialized experience<br>GRL, Inc. invented PDA in 1964 | New Jersey<br>(limited to 1 yr. @ no add. Charge)<br>support comes from intermediary<br>unsure of representative's qualifications |
| **Measurements** | F2, Fv methods<br>wave equation soil constants | F2, v2, Fv methods<br>wave equation soil constants |
| **Hardware** | SPT Analyzer<br>(rugged)<br>(monitor designed for use in sunlight) | laptop (Compaq or Toshiba)<br>(much less rugged)<br>(monitor difficult to see in sunlight) |
| **Power Supply** | generator or car battery | generator or cigarette lighter outlet |
| **Software** | menu driven | menu driven |
| **Warranty** | repairs in-house | repairs contracted out<br>1 year on tech. Support<br>1 year on equipment |
| **Delivery** | 30 days | 30 days |
| **Use in Florida** | > 13 PDAs in FL DOT alone | 2 PDAs – private companies |

Adding $1000 to the cost of the SPT Controller for a second instrumented drill rod results in costs for the two systems within $200. Eliminating cost, the energy measuring capability was the most important point of comparison. Both systems were manufactured optimizing the latest technology in sensors and data processing. Both systems consisted of an instrumented drill rod with foil strain gages and piezoresistive accelerometers connected via cables to a data control unit.

One of the most significant differences between the two systems was the data control unit. For the SPT Controller, the data signals are stored directly on the hard drive of a laptop computer. Because the SPT Analyzer™ has a separate data control unit, the data must be downloaded into a computer before the data files can be used. While the downloading process is time consuming and somewhat of a disadvantage, the SPT Analyzer™ unit, shown in Figure 4-1, is compact and more rugged than a laptop computer. Considering the harshness of the testing environment, the sturdiness of the equipment was a major consideration in the evaluation.

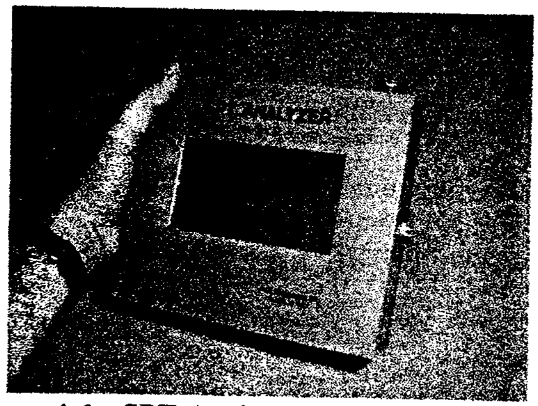


Figure 4-1. SPT Analyzer™ Data Control Unit

Another important factor in comparing the two systems was the technical support. While the technical representative for TNO was very knowledgeable about the equipment and appeared committed to providing complete support, Pile Dynamics, Inc. (GRL & Associates) personnel had the advantage of an established relationship with the FDOT, serving as a consultant for a large number of projects. Because the FDOT already uses other Pile Dynamics, Inc. equipment and software, their personnel are familiar with the products and can easily incorporate the SPT Analyzer™ into their drill rig maintenance program. Finally, the principals in Pile Dynamics, Inc, and its sister company, GRL & Associates, are actively involved in the revision of ASTM D 4633 and have contributed greatly to the advancement of the SPT through many years of research. Therefore, based on the reasons presented herein, the decision was made to purchase the SPT Analyzer™

from Pile Dynamics, Inc. Appendix A contains manufacturers' literature for the SPT Analyzer™.

## 4.3 SPT Analyzer™

The SPT Analyzer™, manufactured and marketed by Piled Dynamics, Inc. (PDI), was purchased by the FDOT for use in this research. This equipment allows for the measure of energy transfer by both the Fv and $F^2$ methods. The energy according to the Fv method, EFV, is calculated by integrating from the beginning of the energy input to the end of the record. The EF2 is calculated by integrating from the beginning of the energy input to the force=0 cutoff time. The ASTM specified corrections for the F2 method are not automatically applied to the EF2 value.

The equipment is similar to the Pile Driving Analyzer® (PDA) that is frequently used in Florida in conjunction with pile driving. The equipment purchased consisted of: two instrumented 2-foot long drill rod sections, one AW rod and one NW rod, on which are permanently affixed two strain gauges; three piezoresistive accelerometers; the hand-held SPT Analyzer™ unit (the analyzer); the necessary wiring to connect the gauges to the analyzer; and the SPT PC and PDA Plot software for use in evaluating the data.

The following equipment component descriptions were adapted from the SPT Analyzer™ Users Manual (Pile Dynamics, Inc., 1995):

SPT Rods. Because nonuniformity of cross-section causes force/velocity disproportionality, it is imperative to conduct the test using an instrumented rod of the same size as the drill string. Therefore, two instrumented rods were purchased from Pile Dynamics, Inc. – an AW rod and an NW rod. The rod sizes were selected after surveying the FDOT districts for the most frequently used sizes. AW being used predominately. Figure 4-2 shows the two instrumented rods.

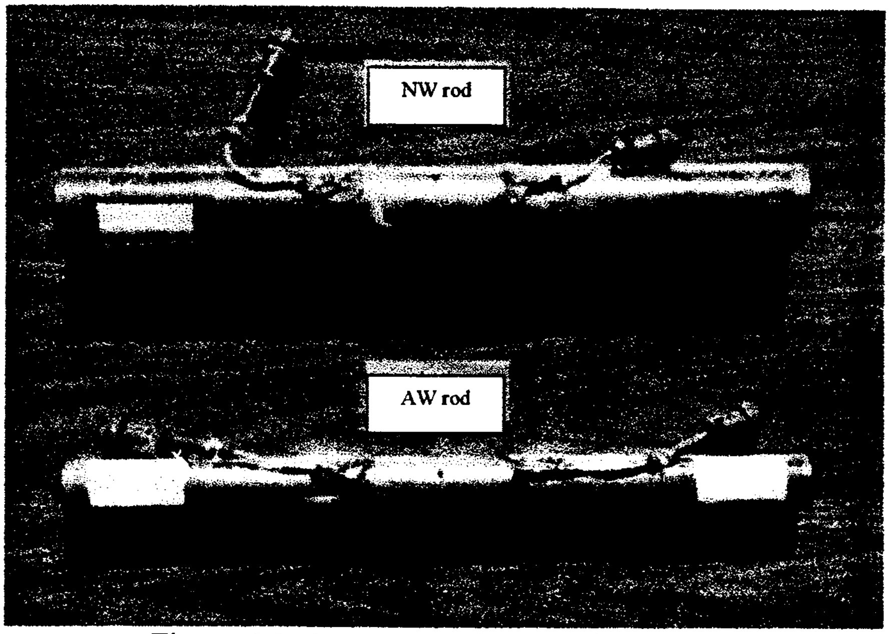


Figure 4-2. Instrumented NW and AW Rods

Sensors. Foil strain gages (350 ohm) glued directly onto the rod in a full Wheatstone bridge configuration measure strain, which is converted to force using the cross-sectional area and modulus of elasticity of the rod. For the testing program documented in this report, the strain gages were attached to measure axial response, though other applications might warrant torsional measurements. A short cable with quick disconnect plug is attached to each bridge, as shown in Figure 4-2.

Figure 4-3 shows the piezoresistive accelerometers, which are bolted to the instrumented rod. The acceleration measured by these sensors is instantly integrated to obtain velocity, which is used in the Fv computations. Three accelerometers were included in the purchase price. The accelerometers are mounted on rigid aluminum blocks and are terminated in a short cable with a quick disconnect plug. The block is bolted to the instrumented rod, with the block oriented axially and the cable in the down position.

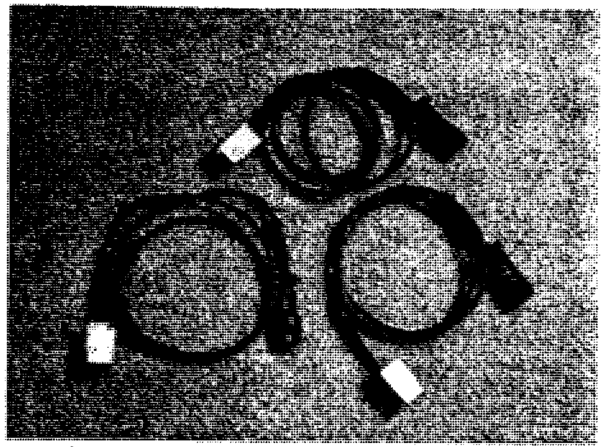


Figure 4-3. Accelerometers (3 shown)

SPT Analyzer Data Control Unit. The SPT Analyzer data control unit (the Analyzer), shown in Figure 4-1, has an LCD touch-screen for entering rod area and length, descriptions and names, and user comments. The programmed screens allow for easy data control and review. When the test is in progress, the beginning of the hammer blow triggers the analyzer to begin recording data. The analog data from the gauges are digitized at 20 kHz for a period of 100 milliseconds. These data are continuously displayed on the analyzer screen as the force wave (from the strain gauges) and the velocity wave (from the integral of the data from the accelerometers). The trace of the velocity wave is scaled such that it is proportional to the force wave; it is scaled at the force scale divided by the impedance, Z. Four channels of data are recorded for each of the blows: 2 force and 2 velocity. The data are saved for a user-selected blow frequency in the memory of the unit. The memory holds the data from approximately 179 blows. The raw data and energy-related quantities are stored in the memory until downloaded into a computer using the SPTPC software. After analyzing the data using SPTPC, data plots can be made using PDAPLOT, or transferred to a spreadsheet or database for further evaluation.

Cables. A number of cables were included with the unit. Each of the four individual sensors is connected to a single connection cable, often called the "pigtail" cable, which in turn is connected to the main cable for the data control unit (Figures 4-4 and 4-5).

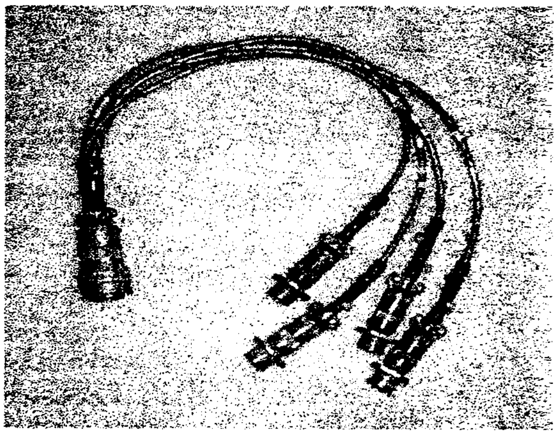


Figure 4-4. "Pigtail" Connection Cable

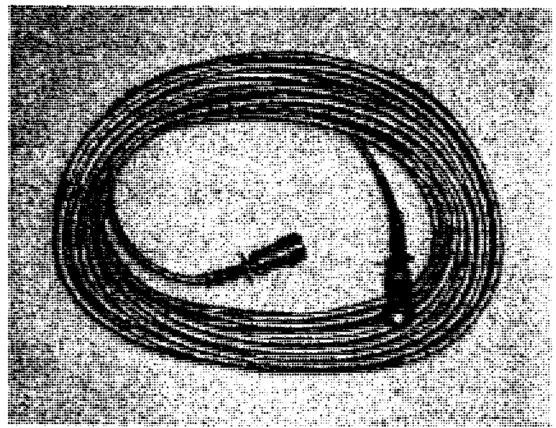


Figure 4-5. Main Cable

The SPT Analyzer™ is powered by either a 12 volt DC vehicle battery or from a 120/240-volt AC power supply. The respective cables are shown in Figures 4-6 and 4-7.

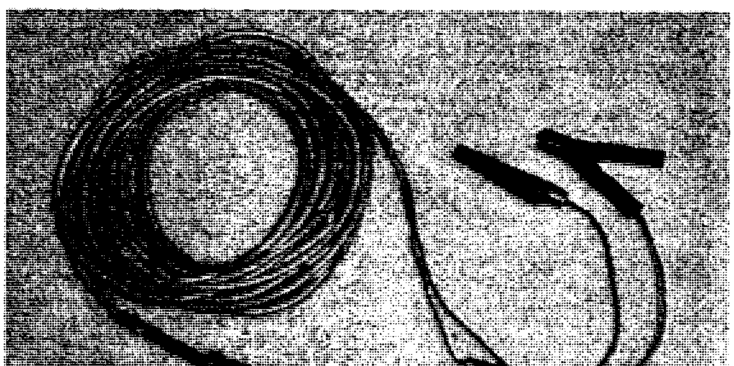


Figure 4-6. Cable for 12-Volt Vehicle Battery

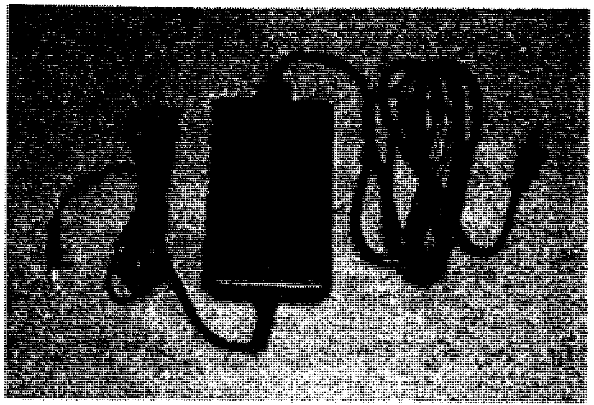


Figure 4-7. Cable for 120/240-Volt AC Power Supply

Figure 4-8 shows an instrumented AW rod section to which two accelerometers are bolted. The cables hanging from the gages are ready to be connected to the "pigtail" cable. The rod will then be ready to mount on top of the drill string.

Figure 4-8. Instrumented AW Rod with Accelerometers Attached.

# CHAPTER 5
# FIELD TESTING PROGRAM

## 5.1 Scope of Testing and Equipment Capabilities and Limitations

The development of the scope of testing for this research considered the capabilities and limitations of the analyzer and equipment as well as the availability and time constraints of FDOT and consultant drill rigs and crews.

Factors that were considered in developing and refining the methodology and scope included the following:

1. The large number of drill rigs to be tested imposed a constraint on the scope of testing with each individual rig. Originally, 126 rigs were identified for testing. However, this was a high count. The actual number of rigs routinely working in support of FDOT was much lower. Ultimately, 58 SPT hammer systems were tested. Even with this reduced number, it was not possible to perform extensive testing with each rig.
2. Conducting the SPT energy measurements using the SPT Analyzer does not take much more time than is needed to conduct an SPT boring without energy measurements. One of the main limitations on taking energy measurements is that the analyzer can only hold data from 179 hammer blows. After the memory is full, the data must be downloaded to the SPT-PC program on a laptop computer. This downloading process may take up to 1.5 hours.

3. Consultants making their drill rigs available to the authors did so at a cost to themselves in lost productivity. Therefore, the authors' efforts attempted to maximize the use of time with the consultants, ensuring no time was wasted. When several drill rigs could be brought to one location to perform borings in "like" conditions, this was done. However, many times it was required to travel to a job site to test with a consultant. As such, many borings were performed in unique soil conditions not similar to any other borings in the study.
4. Many of the FDOT projects using SPT testing are for deep foundations. As previously discussed, past research has shown that transferred energy increases with increasing length of the drill string (Morgano and Liang, 1992). The transferred energy ratio levels off with a drill string length of about 50 feet. Therefore, testing should attempt to include at least some sampling with drill string lengths of around 50 feet or longer.
5. Many variables (hammer type, drill rig type, rod type, etc.) affect the transfer of energy to the drill string. While all of these variables cannot be eliminated or normalized, the variable of soil density and type should be eliminated where possible by testing groups of drill rigs at the same location.

Considering these factors, a standard scope of testing for all SPT systems was selected. This scope consisted of having the subject drill crew first drive at least two, and typically three, split spoons within the top 10 feet of the ground surface. These were not instrumented, but rather served as an opportunity for the drill crew and equipment to "warm up." Then, the borehole was advanced to a depth of approximately 10 feet where the first instrumented SPT was performed. Subsequent SPTs were performed at approximate depths of 20, 30, and 40 feet, often with additional tests at 15, 25, and 35 feet when time allowed. At a depth of 40 feet, the drill string length is typically 46 to 48 feet long, which is close to the 50 feet discussed above.

At least one boring was performed with each SPT rig. When time allowed, the borehole was advanced deeper. Additional boreholes were performed with the same SPT rig if possible.

This scope generally allowed for the completion of two 40-foot SPT borings as described in between 3.5 and 4.5 hours. Then approximately 1 to 1.5 hours was required to download data from the analyzer. Downloading was occasionally required sooner when 179 blows were recorded before completion of the two borings.

In general, testing has shown that for a good day of testing when all drill rigs are made available at the same or nearby test locations, four 40-foot SPT borings can be completed as described. However, it is often difficult to coordinate for several rigs to be standing by at one location. If traveling to different sites to test the drill rigs is required, and when the drill rigs are working on production jobs where the analyzer operators are required to fit their measurements into their production borings, the authors found that completing two to three borings in a day was often the limit.

## 5.2 Test Procedure

The conduct of testing generally adhered to the following procedure, although exceptions were often made as circumstances allowed or dictated.

Upon arriving at a test location, SPT system information was recorded on the field log forms, hammer measurements were made and marks were made on the safety hammer stems at points where the bottom of the hammer barrel would be located for drops of 28, 30 and 32 inches. The drill crews were directed to perform two or three "warm-up" SPTs before testing commenced at a depth of 10 feet.

Then an SPT boring was advanced to a specified depth with sampling at a specified interval (often 5-foot) based on the time available. The borehole was advanced using the rotary wash technique in all but one case, which was advanced using hollow-stemmed augers. Most of the rotary wash borings used a bentonitic drilling mud slurry, although a few used a polymer slurry or just water. No sampling used liners in the split spoon samplers. Before sampling at each depth, the drill string with the split spoon sampler attached was lowered into the borehole. Then the instrumented 2-foot drill rod section was attached to the top of the drill string. For automatic hammers, the anvil was attached to the top of the instrumented rod. For safety hammers, the safety hammer's stem was attached to the top of the instrumented rod. Once all parties (the drillers, analyzer operator, and observer) were ready, the drillers proceeded to perform the SPT, driving the split spoon a penetration of 18 inches as called for by the ASTM. During testing, the data recovered by the analyzer were observed and evaluated using the force and velocity traces on the analyzer's screen to determine, among other things, if all gauges were recording data and if that data looked reasonable. If not, then testing was temporarily stopped while the problem-causing factor was identified and corrected. Frequently, problems arose with a faulty accelerometer which required replacing.

The analyzer recorded data for all blows during the 18-inch spoon drive. Also, the analyzer operator and assistant attempted to assess the average drop height for the series of hammer blows by visually observing the hammer's height relative to the markings on the hammer stem. After driving the sampler, the recovered soil sample was observed and classified visually according to USCS procedures. The borehole was advanced deeper for the next test where the above procedures were repeated.

During testing, the analyzer operators made efforts to not unduly influence the normal operations of the drillers. Drillers were directed/encouraged to perform their work as they normally would. As an exception to this, in a few instances certain conditions were "controlled" during testing. One test boring with each of Systems 13 and 57 was controlled by wrench tightening all rod sections, ensuring the rods were vertical, and ensuring a 30 inch hammer drop (System 57 only). System 58 varied the rate of the automatic hammer blows, and System 59 varied the safety hammer drop height.

As often as required, the data recorded on the analyzer were downloaded onto a laptop computer into the SPT-PC program. The downloaded data were in the .x01 file type typical of PDA. The SPT-PC program allows evaluation of the data as described in Chapter 4.

## 5.3 Data Recorded

Each system was assigned a system number, 1 through 59. System number 22 was numbered but not tested due to the researchers not having the needed drill rod connectors on hand. Therefore a total of 58 systems were tested. A system was defined as the hammer, drill rig, and the operator (for the safety hammer only). If any of these main components were to change, a new system number was assigned. For instance, in two cases the same drill rig was used to test with both its automatic and safety hammers. These were numbered separately as Systems 13 and 57 and as Systems 58 and 59. In many cases the driller's procedures included one person pulling the rope for SPT sampling up to a depth of 10 feet and the other pulling after that. In these cases, no new system number was assigned.

Data recorded for Systems numbered 57, 58, and 59, and for portions of System 13 were recorded during an early phase of this research and were numbered and included in the index last. For System 58 the rate of automatic hammer blows was controlled, and for System 59, the drop height for a safety hammer was controlled. A portion of System 58 and all of System 59 were controlled to a degree that they are not considered representative of normal operations.

For each test series, general system information was recorded for the SPT system being tested. The field logs with the system information recorded are included in Appendix B. SPT Analyzer data were recorded as previously described.

A total of 77 test borings were performed. Of these, 42 systems were tested on only 1 SPT boring, 14 systems were tested on 2 borings, and 2 systems were tested on more than two borings. Approximately 7,700 hammer blows were performed, but not all were recorded, particularly in cases when high blow count material caused the Analyzer memory to fill.

# CHAPTER 6
# EVALUATION OF DATA

## 6.1 General

Data downloaded into the SPT-PC program were evaluated for quality and adjusted or excluded as appropriate. The data were then written to a PDA Plot/ASCII file that was exported to an MS-Excel spreadsheet. With the spreadsheet, the data for individual blows within a single SPT sample were used to create a single record for the sample. These records were then included in an indexed file that has one record for each sample. This indexed file was used as a source for basic presentation of data and comparison of variables. A total of 358 records are in the index; 340 of these contain reasonable and useable data originating from normal operation conditions. A total of 4639 hammer blows contribute to the 340 records.

## 6.2 Data Quality Evaluation

Data were reviewed using the SPT-PC program. Each blow from each SPT sample was reviewed and evaluated. The data were evaluated to ensure that all gauges were recording in phase and that all appeared to be returning reasonable readings.

Occasionally, accelerometer gauge data were unusable and had to be excluded. These cases were often the result of one of the two mounted accelerometer gauges malfunctioning and providing erratic readings, often where the velocity trace did not return to zero at the end of record. Several times, accelerometers required replacing. In some cases the gauges worked loose during testing which simply required tightening the mounting bolts.

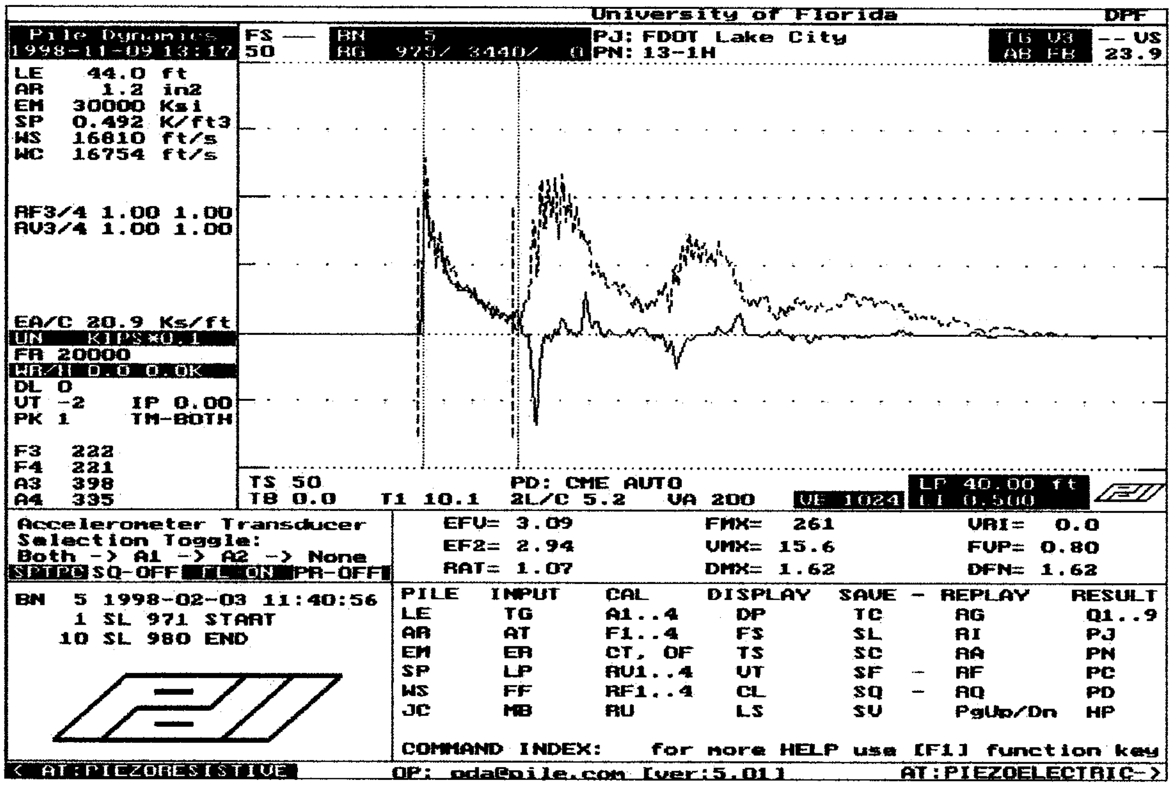



Figure 6-1. SPT-PC Display for One Hammer Blow with CME Automatic Hammer (System 13).

Figure 6-1 presents a typical hammer blow as presented by the SPT-PC program. This figure shows a single blow by a CME automatic hammer (System 13) with a 44-foot long AW-rod drill string at a sample depth of 40 feet. Both the force (solid line) and velocity (dashed line) wave traces are shown. The data from this blow show "good" proportionality with both the force and velocity traces roughly coinciding from the initial impact to the time 2L/c, which is the theoretical time required for the wave to travel to the tip of the sampler and back. The figure indicates time 2L/c by the vertical dashed lines. Beyond time 2L/c the velocity increases greatly while the force fluctuates between negative (tension) and slightly positive (compression) as tension and compression waves continue to travel up and down the drill string. As is shown on the figure, the transferred energy EFV value for this hammer blow is 309 ft-lbs and the EF2 value is 294 ft-lbs. Dividing these values by 350 ft-lbs, the theoretical potential energy for a 30-inch hammer drop, gives energy transfer ratios of $ER_{FV}$ = 88% and $ER_{F2}$ = 84%. These are reasonable and within the range expected for an automatic trip hammer.

The calculated final displacement of the rods from this hammer blow, DFN, is 1.62 inches. This is reasonable since the recorded SPT N-value (blow count) was 7 for this sample which is the equivalent of 1.71 inches/blow (12 inches/7 blows).

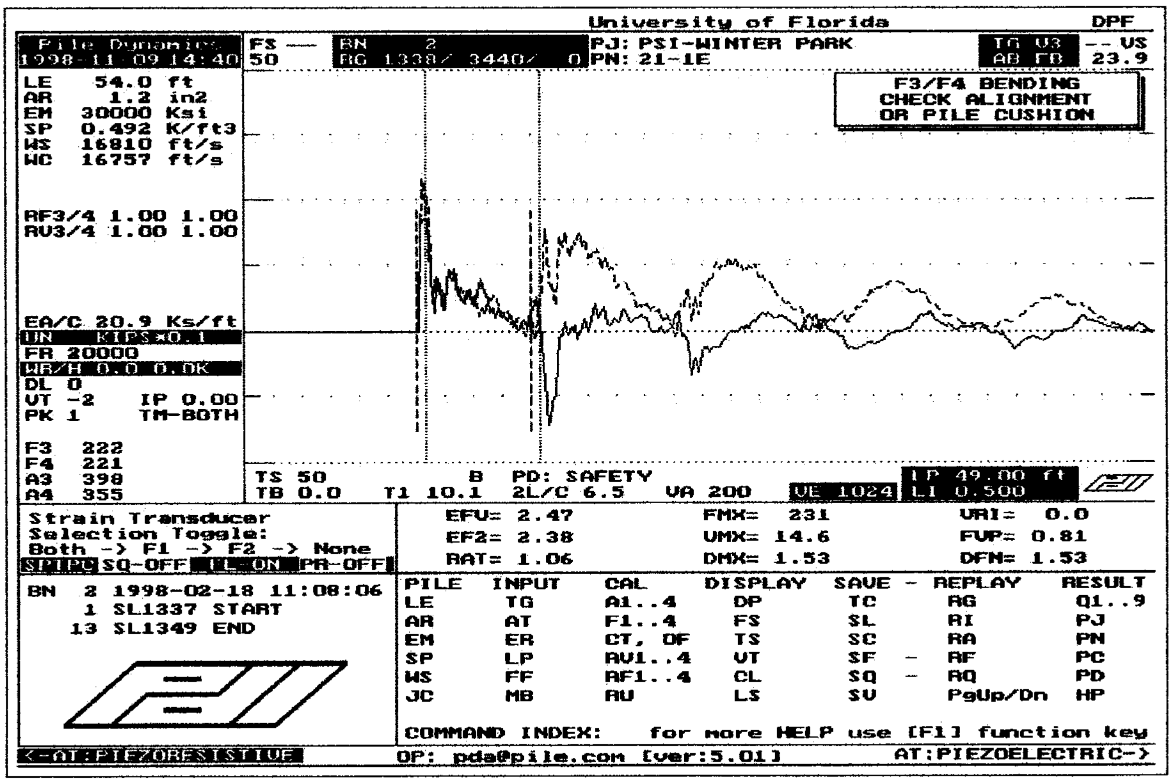



Figure 6-2. SPT-PC Display for One Hammer Blow with Safety Hammer (System 21).

Figure 6-2 presents another typical hammer blow as presented by the SPT-PC program. This figure shows a single blow by a safety hammer with rope and cathead (System 21) with a 54-foot long AW-rod drill string at a sample depth of 49 feet. As with the automatic hammer in Figure 6-1, the data from this blow also show "good" proportionality. The program raised a flag for this blow indicating variation in strain gauge data (F3 and F4) due to possible bending. As is shown on the figure, the transferred energy EFV value for this hammer blow is 247 ft-lbs and the EF2 value is 238 ft-lbs which corresponds to energy transfer ratios of $ER_{FV}$ = 71% and $ER_{F2}$ = 68%.

These values are reasonable and within the range expected for a safety hammer. As compared to the automatic hammer blow, the decline of the force and velocity waves is not nearly as smooth and uniform. This is likely due to the wave transmission from the safety hammer.

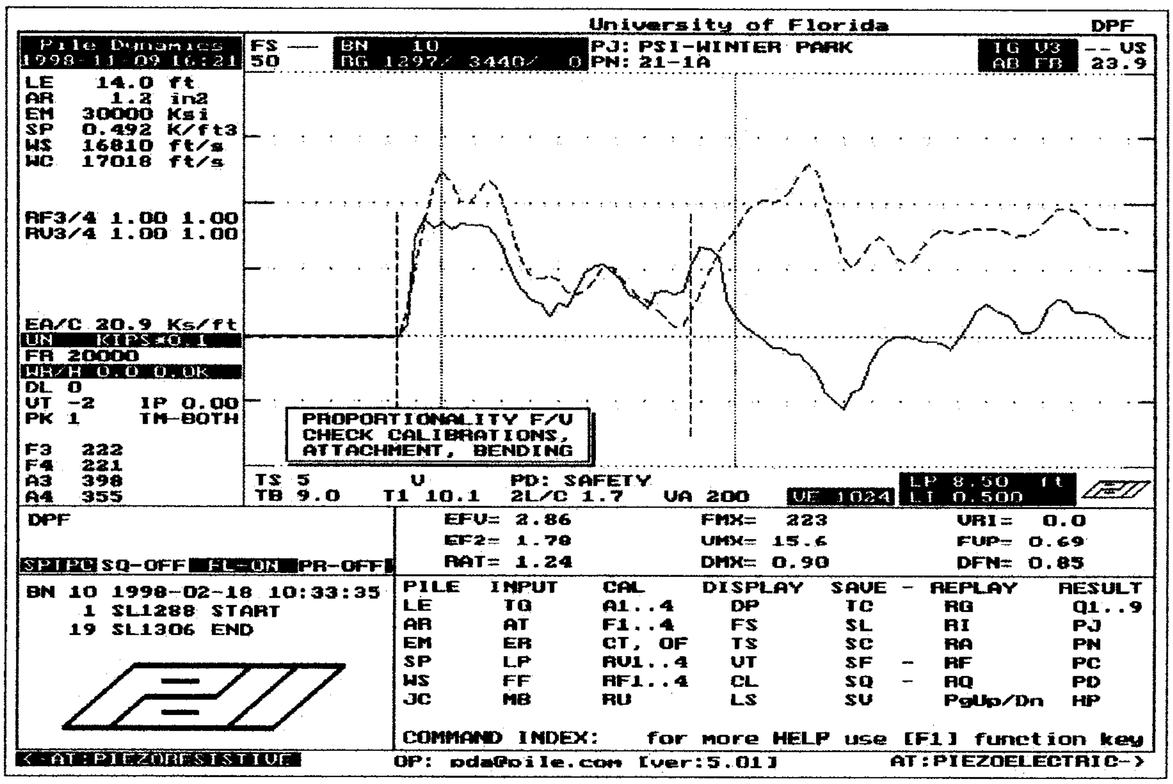


Figure 6-3. SPT-PC Display for One Hammer Blow with Safety Hammer (System 21).

In general, the data from samples taken at greater depths (i.e. with longer drill strings) appeared much better in quality for both the safety and automatic hammers than data from shallow samples. Figure 6-3 presents data from a shallow sample with the same safety hammer as in Figure 6-2. In this figure, the time scale has been expanded from 50 to 5 milliseconds to better view the interval from time zero to 2L/c. The proportionality of force and velocity data is not as good for this blow. Because of this, the EFV and EF2 transferred energy calculations vary notably with EFV = 286 ft-lbs and EF2 = 178 ft-lbs which corresponds to energy transfer ratios of $ER_{FV}$ = 77% and $ER_{F2}$ = 51%. Applying the appropriate ASTM correction factors $K_1$=1.12 and $K_2$=1.13 to this $ER_{F2}$ calculation increases the $ER_{F2}$ from 51% to 65%, which is still less than, but much closer to, the $ER_{FV}$ amount of 77%.

Also, the ratio (RAT) of measured time for the force to go to zero versus the theoretical time as defined in equation (10) is 1.24 which is outside the 0.9 to 1.2 range allowed by the ASTM for calculating energy using the EF2 method. The EFV method is still valid.

In the majority of cases the trace of the initial impact showed that as the force trace peaked and then began to fall, the velocity trace continued upward for a brief period. The velocity then returned to close proportionality to the force trace. This is evidenced on the SPT-PC display as the force-velocity proportionality, FVP, which is the ratio of the value of the force to the velocity at the time of maximum velocity. This can be seen in Figures 6-1, 6-2, and 6-3 as 0.80, 0.81, and 0.69, respectively. It is possible that this higher peak of the velocity trace may be attributed to the multiple joints in the drill string in the vicinity of the instrumented rod causing a "slack" which effectively reduces the cross-sectional rod area and its impedance. Also, this may be in part caused by the measurement rod section being smaller in cross-sectional area than the anvil, and at times larger than the drill rod below to which it is attached. In any event, these common data characteristics were not considered abnormal and were not cause to exclude that data from the evaluation.

After each hammer blow within a sample was reviewed, bad data from specific gauges were identified and removed, and the phase of the force and velocity traces were adjusted to be synchronized (using the VT command), the SPT-PC data from all blows for that sample were written to a PDA Plot ".q00" file using the save quantities (SQ) command. These PDA Plot files include for each blow: the time, blow number, EFV, EF2, RAT, maximum force in the drill rod (FMX), maximum velocity of the rod (VMX), maximum displacement of the rod (DMX), calculated ram velocity at impact (VRI), force-velocity proportionality (FVP), and final displacement of the rod (DFN).

The set of data for the sample was given a subjective quality rating from 1 to 3. Generally, when data showed either a good proportionality or reasonable proportionality but with consistent readings from all gauges, a rating of 1 was assigned. For data where either proportionality was marginal or one of the gauges was malfunctioning or inoperable, but the data still appeared reasonable, a rating of 2 was assigned. The few times that data were bad, generally due to malfunctioning gauges, a rating of 3 was assigned. Data with a quality rating of 3 were not used in evaluations presented herein.

An SPT-PC screen plot is included in Appendix C for one blow from each tested system. In general, the selected plot was taken from the SPT sample recovered from the greatest depth, since the wave forms from longer rod lengths were generally better than those from shorter rod lengths.

## 6.3 Data Reduction

Portions of the data written to the PDA Plot ".q00" files were imported to MS-Excel spreadsheets. One worksheet was used for each SPT hammer system. Using the spreadsheet, data for each SPT sample were reduced.

Data reduction included calculating the energy transfer ratios, both $ER_{FV}$ and $ER_{F2}$, by dividing the measured energies, EFV and EF2, by 350 ft-lbs which is the potential hammer energy based on the ASTM specified 30-inch drop (as per equations 8 and 9). As previously discussed the EF2 measurements do not have the ASTM corrections applied and have not been corrected since these have not been the source for energy comparisons contained in this report. Nonetheless, these have been included for comparison of the two methods. EF2 data for which the time to force=0 did not fall within the ASTM specified 0.9 to 1.2 x (2L/c) were excluded.

Where the testers observed estimated hammer drop heights, $ER_{FV}$ was additionally calculated by dividing the measured energy by the potential hammer energy based on the observed hammer drop height.

The energy ratios for blows from the sample were averaged and standard deviations were calculated. Only the hammer blows contributing to the SPT N-value (the last 12 inches of the 18-inch drive of the spoon) were used in calculations. Also, the ratio of energy ratios calculated by the two different methods was calculated using $ER_{FV}$ / $ER_{F2}$.

The data from each SPT system were summarized with a tabular and graphical presentation of the results near the top of the worksheet. Where more than one test boring was performed, additional tabulations and graphs were used, as required. A presentation of one complete worksheet is in Appendix D. Further, a presentation of the summary data for each system is included in Appendix E.

Figure 6-4 shows a portion of one such summary for SPT System 39. The figure shows the reduced data for the six SPT samples taken from test boring 1. On the graph, the energy transfer ratio, $ER_{FV}$, is plotted versus L', the rod length distance from the gauges to the tip of the sampler. The data in this figure, and many others in this report, have been plotted versus rod length both as a convenient way of presenting the data recovered and since previous studies have found that energy transfer increases with increasing rod length.

Two curves are plotted: one for the standard $ER_{FV}$, and one for the $ER_{FV}$ based on the observed drop height. It should be understood that ER values are calculated from the measured transferred energy. To calculate an energy transfer ratio, the transferred energy is divided by the potential energy of the hammer before its fall. It is customary, and per the ASTM, to divide by 350 ft-lbs (based on a 140 lb hammer falling the prescribed 30 inches) which gives the energy transfer relative to a "correct" hammer fall. However, in an effort to view and assess the energy transfer relative to the actual potential energy, the transferred energy ratios were also calculated by dividing the measured energies by the observed potential energy (140 lb times the observed drop height). This calculation attempts to remove from the ratio the effects of drop height. This may be useful in trying to assess an SPT system's performance characteristics excluding or limiting the effect of one major component/variable -- the operator. However, when the purpose of the evaluation is to determine the entire system's performance, which includes the operator, so that $N_{60}$ can be calculated, then the energy transfer ratio should be used as calculated with the theoretical potential energy as shown in equation (8) or (9).

| Record/ Sample Number | Drill String Length | for 30" drop; PE=350 ft-lbs | | | | | | | | $ER_{FV}$ / $ER_{F2}$ ratio | for observed drop | | sam-ple size | SPT blow count N |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $ER_{FV}$ (%) | | | | $ER_{F2}$ (%) | | | | | drop (in) (est.) | $ER_{FV}$ (%) | | |
| | | max | min | avg | σ | max | min | avg | σ | | | | | |
| 1 | 13.9 | ### | ### | **64.3** | 3.0 | 57.7 | 54.3 | 56.0 | 1.1 | 1.15 | 32.3 | 59.8 | 36 | 40 |
| 2 | 23.9 | ### | ### | **65.3** | 9.1 | 57.1 | 47.1 | 52.9 | 3.3 | 1.23 | 32.3 | 60.8 | 10 | 10 |
| 3 | 33.9 | ### | ### | **63.9** | 6.1 | 66.6 | 48.3 | 55.5 | 4.9 | 1.15 | 32.3 | 59.4 | 18 | 18 |
| 4 | 43.9 | ### | ### | **66.4** | 3.4 | 68.6 | 50.3 | 62.5 | 3.3 | 1.06 | 32.3 | 61.8 | 34 | 34 |
| 5 | 45.9 | ### | ### | **72.1** | 2.7 | 75.7 | 63.4 | 68.3 | 3.0 | 1.05 | 32.0 | 67.6 | 30 | 43 |
| 6 | 45.9 | ### | ### | **71.8** | 3.4 | 72.6 | 60.9 | 66.2 | 3.1 | 1.09 | 31.5 | 68.4 | 12 | 41 |
| 7 | | | | | | | | | | | | | | |
| 8 | avg | max | min | avg | avg | max | min | avg | avg | avg | avg | avg | total | avg |
| ALL | 34.6 | ### | ### | **67.3** | 4.6 | 75.7 | 47.1 | 60.2 | 3.1 | 1.12 | 32.1 | 63.0 | 140 | 31.0 |

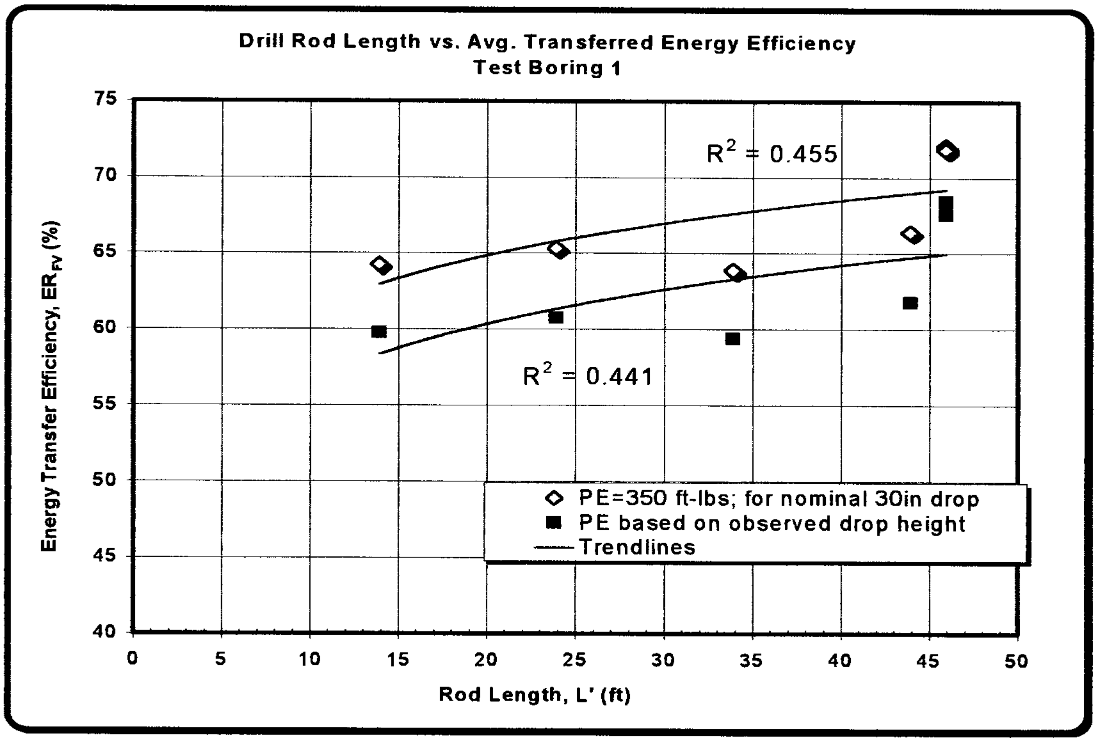



Figure 6-4. Summary of SPT Testing Information for System 39.

The set of data resulting for each SPT sample formed one record in the overall project index. Therefore, if testing for one SPT system consisted of 2 test borings with 6 SPT samples taken from each boring, then 12 individual records would be included in the index. A record summary for each system was written at the top of each worksheet for exporting to the project index. Such a summary can be seen at the top of the SPT system worksheet (Appendix D) where all data for that system have been summarized for exporting to the project index.

## 6.4 Project Data Index

The project data index was created as an MS-Excel spreadsheet. Each record was imported into the project index. A printout of this index is included as Appendix F. The index includes 358 records from 58 SPT systems. Of these, 340 records from 4639 hammer blows from 57 systems originate from "normal" operations and are considered to be from reasonable data. There are 9 records (from System 58 boring 10, and System 59) that were "controlled" tests which are not indicative of "normal" operations. Another 9 records are bad data resulting from gauge malfunctions from systems numbered 12, 42, and 56. The index was used to analyze and compare the results of testing. The bad data are presented in the index but were not considered in further evaluations.

# CHAPTER 7
# PRESENTATION AND DISCUSSION OF RESULTS

## 7.1 General

Data in the project index file were compiled, sorted, graphed and evaluated to assess what effect common variables have on the energy transfer ratios. Several of these variables are presented and discussed in the following sections.

Except where stated, the $ER_{FV}$ ratio has been used instead of the $ER_{F2}$ ratio since as previously discussed, unlike the F2 method, the FV method is theoretically exact, requires no corrections, and is not based on the incorrect assumption that the drill string has a uniform cross-section. The energy transfer ratios are often plotted versus L', the rod length from the instrument gauges to the tip of the sampler. This is done both as a convenient way to present data from testing and also because previous research has shown that energy transfer tends to increase with increasing rod length (Morgano and Liang, 1992).

## 7.2 Profile of SPT Systems Tested

A total of 58 SPT systems were tested to gather data for this research. Table 7-1 provides the types of drill rigs and hammers tested. A listing of each of the systems by their system identification number is included at the beginning of Appendix E. Further details on system compositions are presented in the following sections.

Table 7-1. Types and Numbers of SPT Drill Rigs and Hammers Tested.

| Drill Rig Type | hammers/systems tested | |
|---|---|---|
| | safety | automatic |
| Acker | 1 | - |
| BK 51 | 1 | - |
| BK 81 | 1 | - |
| CME 45 | 17 | 2 |
| CME 55 | 14 | 6 |
| CME 75 | 1 | 3 |
| CME 85 | - | 1 |
| Diedrich D25 | 1 | - |
| Diedrich D50 | 3 | 2 |
| Diedrich D120 | 1 | - |
| Failing 250 | 1 | - |
| Failing 1500 | 2 | - |
| Mobile drill | 1 | - |
| Total | 44 | 14 |

## 7.3 Safety versus Automatic Hammers

As reported by other researchers, the testing found that the energy transfer from automatic hammers was notably higher than for safety hammer systems. Figure 7-1 presents the 340 good data records from this project's testing. The data are plotted as energy transfer ratios, $ER_{FV}$, versus drill rod length. The data from automatic and safety hammer systems are presented separately. The data in the figure are also summarized in Table 7-2.

While the data in Figure 7-1 are dispersed for both hammer types, the average energy transfers for automatic hammer systems are notably higher than for safety hammers. This is also shown in Table 7-2. Also, as is shown by the standard deviations, the automatic hammers deliver a more consistent energy when considering the variation from sample to sample, and also when considering the variation of the energy transfer of individual blows which make up a single sample.

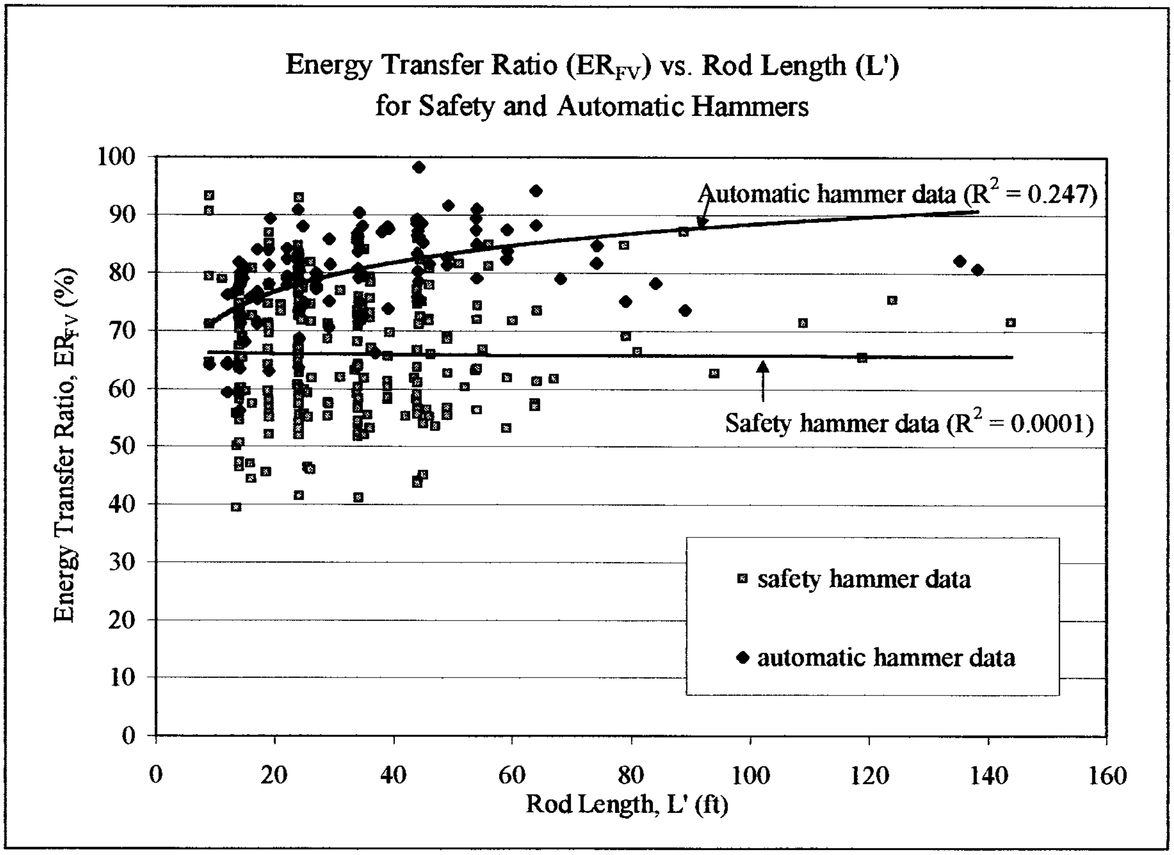



Figure 7-1. Safety and Automatic Hammers; Energy Transfer Ratios, $ER_{FV}$, versus Rod Length, L'.

Table 7-2. Summary of Energy Transfer Data by Hammer Type.

| Hammer Type | Average $ER_{FV}$ | Standard Deviation, σ, of $ER_{FV}$ | Average σ for each Record | Number of | |
|---|---|---|---|---|---|
| | | | | Records | SPT systems |
| Safety (w/rope and cathead) | 66.0 | 10.7 | 4.1 | 227 | 43 [(a)] |
| Automatic (all types) | 79.6 | 7.9 | 2.3 | 113 | 14 |
| Automatic (CME) | 80.1 | 8.0 | 2.2 | 101 | 12 |
| Automatic (Diedrich) | 76.0 | 5.3 | 3.4 | 12 | 2 |

(a) Not 44 systems; System #59 was a controlled test and is excluded from calculations.

## 7.4 Effect of Drill Rig Type

The type of drill rig used in conducting the SPT may affect the energy transfer to the drill rods as a result of various factors. For drill rigs with safety hammers, factors may include, among other things, the diameter of the cathead, the height of the mast and subsequent length of rope required, and the configuration, design, and maintenance of the pulleys which may affect the resistance of the falling rope and hammer. For drill rigs with safety hammers, the researchers observed that the hammer manufacturer was often unknown by the drill crew and was not necessarily the same manufacturer as the drill rig. It is possible that drill rig design and operational condition have a significant effect on energy transfer. Figure 7-2 presents energy transfer ratios for various drill rig types using safety hammers. The data in Figure 7-2 are summarized in Table 7-3.

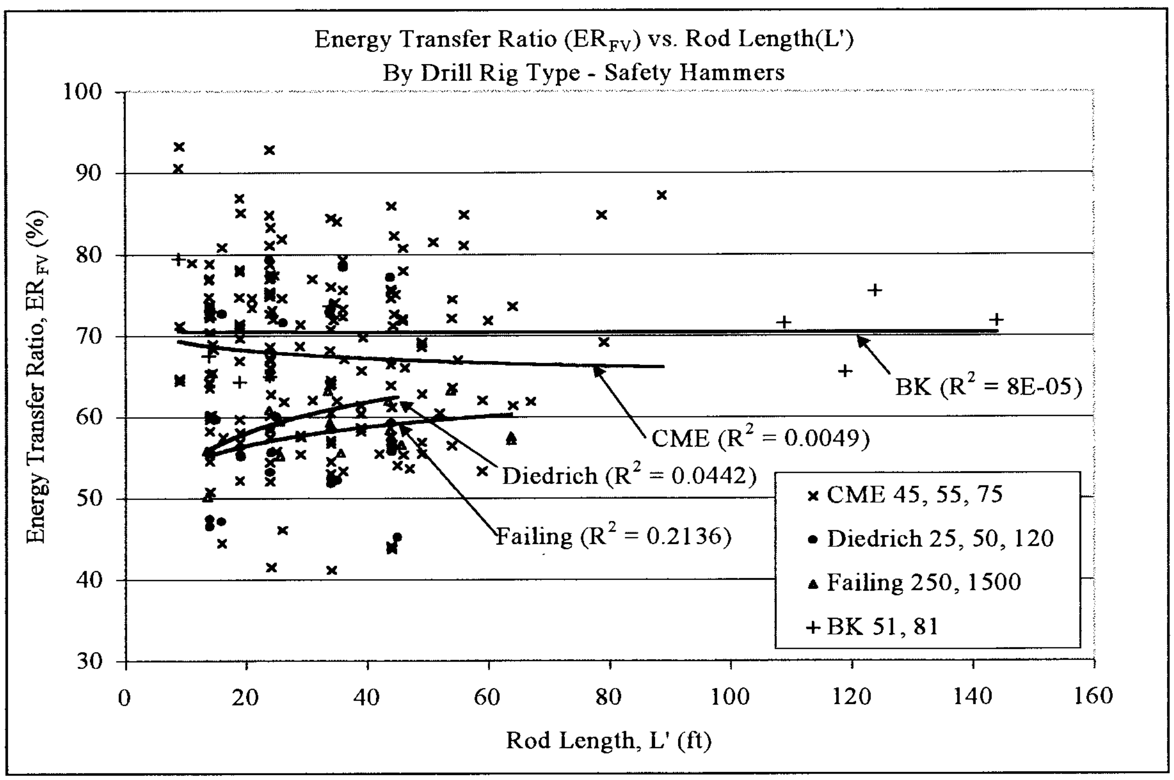



Figure 7-2. Energy Transfer Ratios, $ER_{FV}$, by Drill Rig Type (Safety Hammers).

The data for the Acker and Mobile drill rigs are not presented on the figure since there were so few samples/data points with these rigs. They are nonetheless summarized in the table.

Table 7-3. Summary of Energy Transfer Data by Drill Rig Type.

| Drill Rig Type | Average $ER_{FV}$ (%) | Std. Deviation, σ, of $ER_{FV}$ | Average σ for each Record | Data source—number of: Records | SPT systems |
|---|---|---|---|---|---|
| Safety Hammers | | | | | |
| CME 45 | 67.4 | 9.6 | 4.4 | 80 | 16 |
| CME 55 | 68.2 | 11.2 | 4.3 | 91 | 14 |
| CME 75 | 63.1 | 3.8 | 2.9 | 4 | 1 |
| Diedrich D25,50,120 | 59.7 | 10.3 | 4.3 | 24 | 5 |
| Failing 250 & 1500 | 58.1 | 3.4 | 3.1 | 14 | 3 |
| BK 51 and 81 | 70.4 | 5.0 | 3.1 | 9 | 2 |
| Acker | 64.6 | 1.9 | 3.3 | 2 | 1 |
| Mobile Drill | 43.8 | 3.1 | 2.8 | 3 | 1 |
| | | | Totals | 227 | 43 |
| Automatic Hammers | | | | | |
| CME 45 | 80.7 | 10.1 | 2.1 | 19 | 2 |
| CME 55 | 78.4 | 8.2 | 2.3 | 53 | 6 |
| CME 75 | 83.1 | 5.1 | 1.9 | 22 | 3 |
| CME 85 | 81.2 | 3.9 | 2.4 | 7 | 1 |
| Diedrich D50 | 76.0 | 5.3 | 3.4 | 12 | 2 |
| | | | Totals | 113 | 14 |

Based on these data, the order of safety hammer drill rigs from highest to lowest average energy transfer ratio is: BK, CME, Acker, Diedrich, Failing, Mobile. The 3 records contributing to the Mobile drill rig data show a low energy transfer ratio. These are the only data in this project recovered using a hollow-stemmed auger. Additionally, these 3 samples were recovered with rod lengths of 13.5, 18.5, and 23.5 feet, much shallower than the typical sample, which may have been a factor in the low energy ratios.

For drill rigs with automatic hammers, factors affecting energy transfer may include the manner in which the automatic hammer is mounted to the drill rig. For drill rigs with automatic hammers, it is likely that the hammer design is much more influential in energy transfer than is the drill rig. Nonetheless, these data are presented in Figure 7-3, which shows energy transfer ratios for various drill rig types using automatic hammers. The data in Figure 7-3 are also summarized in Table 7-3.

Based on these data, the order of automatic hammer drill rigs from highest to lowest average energy transfer ratio is: CME 75, CME 85, CME 45, CME 55, and Diedrich D50. The energy transfer ratio for the CME 45 varied greatly with change in rod length.

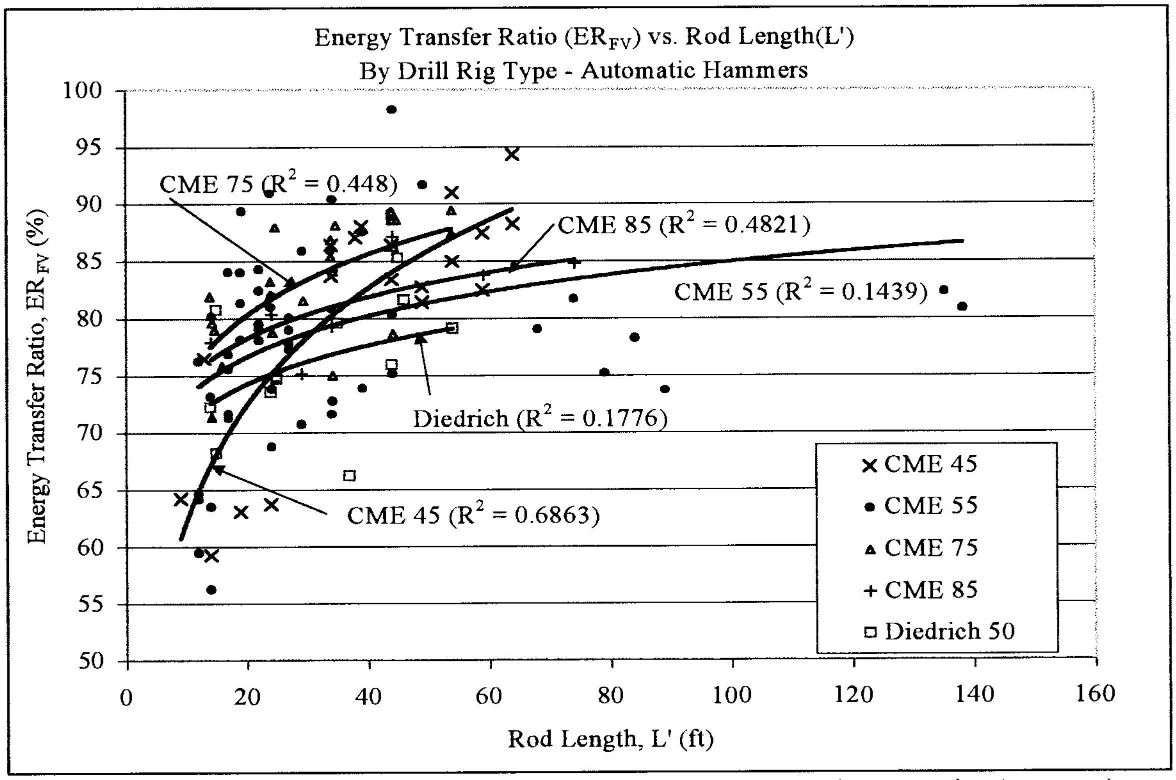



Figure 7-3. Energy Transfer Ratios, $ER_{FV}$, by Drill Rig Type (Automatic Hammers).

## 7.5 Effect of Drill Rod Length

As shown on Figure 7-1, when considering test data from all tested SPT systems together, a moderate relationship between rod length and energy transfer is apparent for automatic hammers. Energy transfer increases with increased rod length. The best-fit logarithmic curve has a coefficient of determination, $R^2$, of 0.247, which corresponds to a coefficient of correlation of 0.497. For the safety hammers, there is almost no correlation.

However, when looking at the data for SPT systems by themselves instead of grouping them all together, in the majority of cases a moderate relationship between rod length and energy transfer is apparent. This can be seen in the graphical summary data for individual systems included in Appendix E. Figure 7-4 presents data from System 13, the automatic hammer for which the most test data were recovered. This shows a good fit. Figure 7-5 shows data from System 23, a safety hammer. This also shows a good fit.

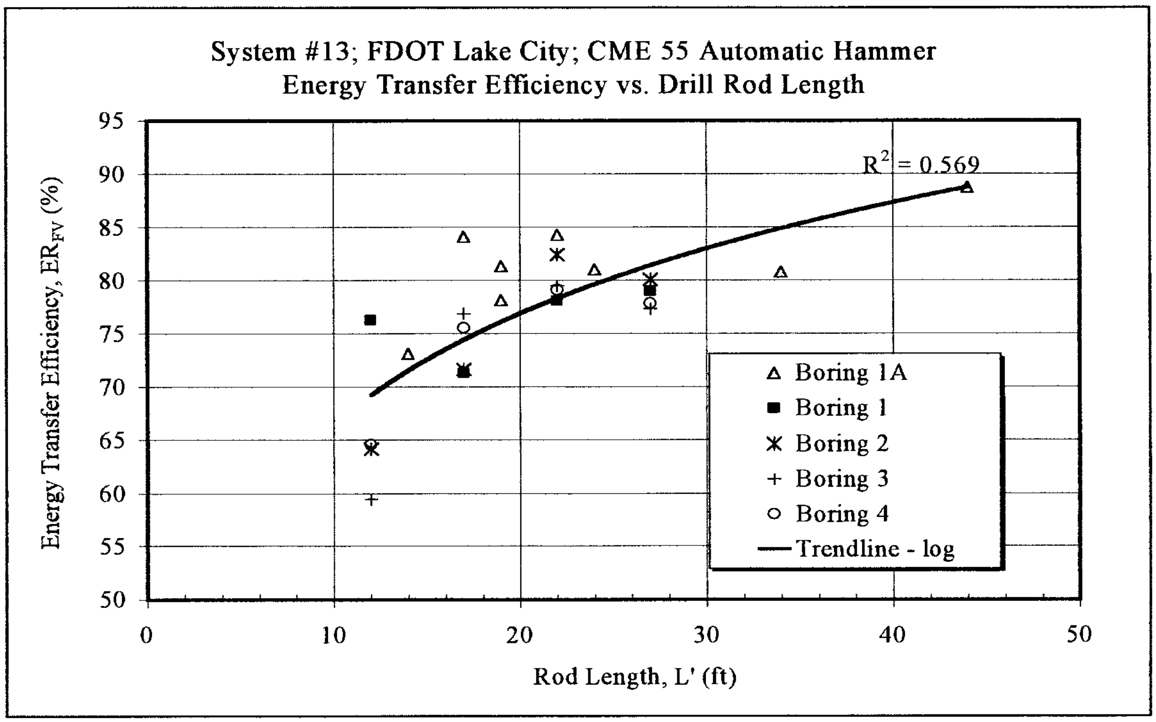



Figure 7-4. Energy Transfer Efficiency versus Rod Length (System 13, Automatic Hammer).

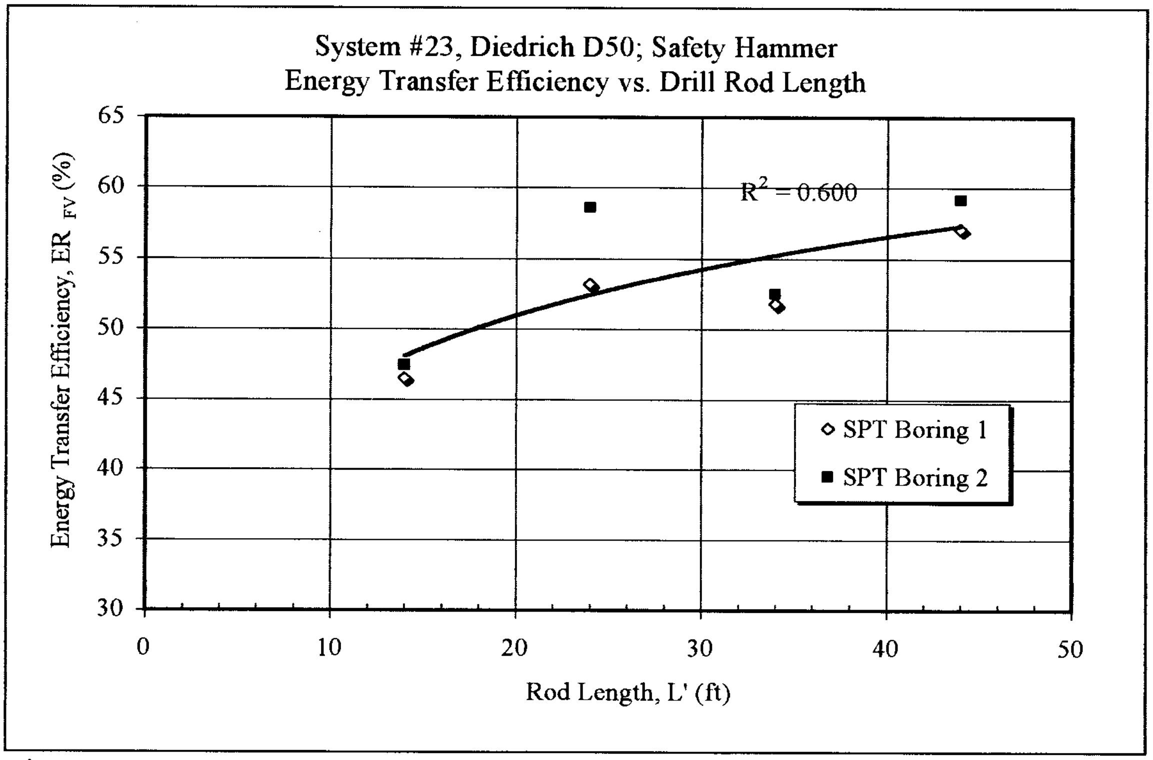



Figure 7-5. Energy Transfer Efficiency versus Rod Length (System 23, Safety Hammer).

These data support the Morgano and Liang (1992) findings that energy transfer efficiency increases with increasing rod length. They found that efficiencies leveled off at rod lengths of approximately 50 feet. Additional data for longer rod lengths are needed for this study to assess and confirm those findings.

## 7.6 Effect of Drill Rod Type

Several types of drilling rods were used in conduct of the testing. These included AW, AWJ, N3, NW, and NWJ. Figures 7-6 and 7-7 present data from safety and automatic hammers, respectively, according to drill rod type.

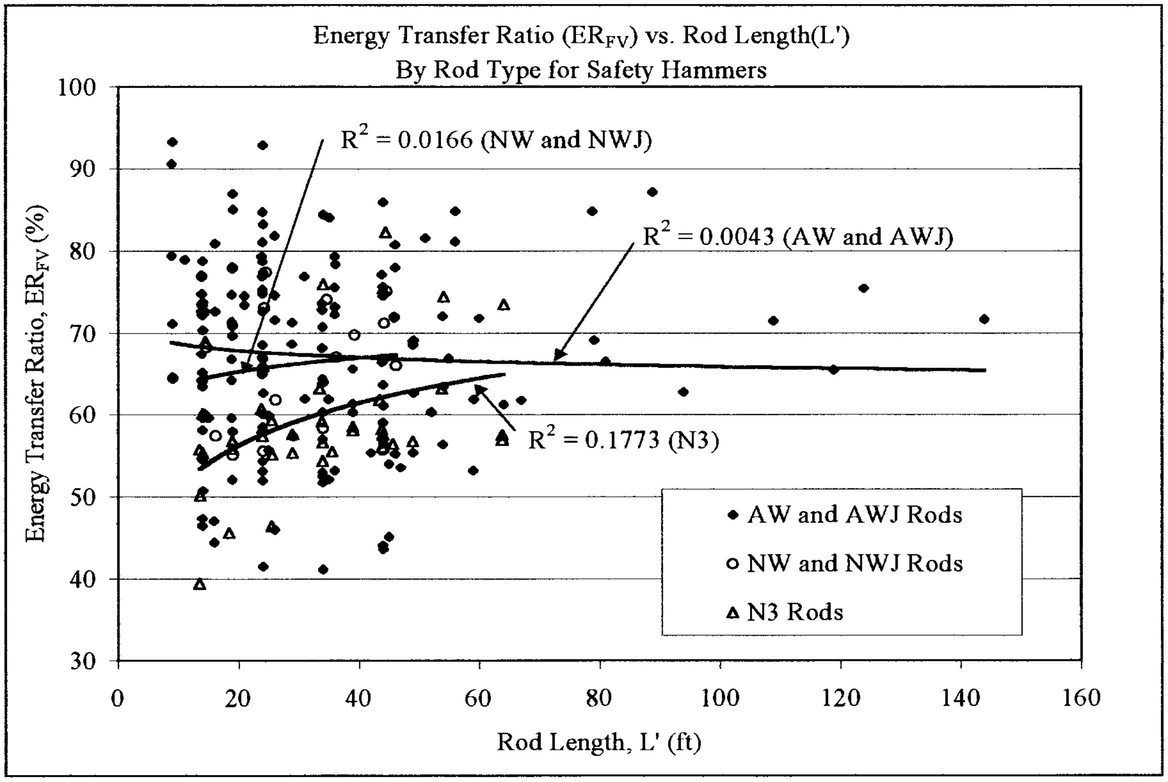



Figure 7-6. Energy Transfer for Safety Hammers by Drill Rod Types.

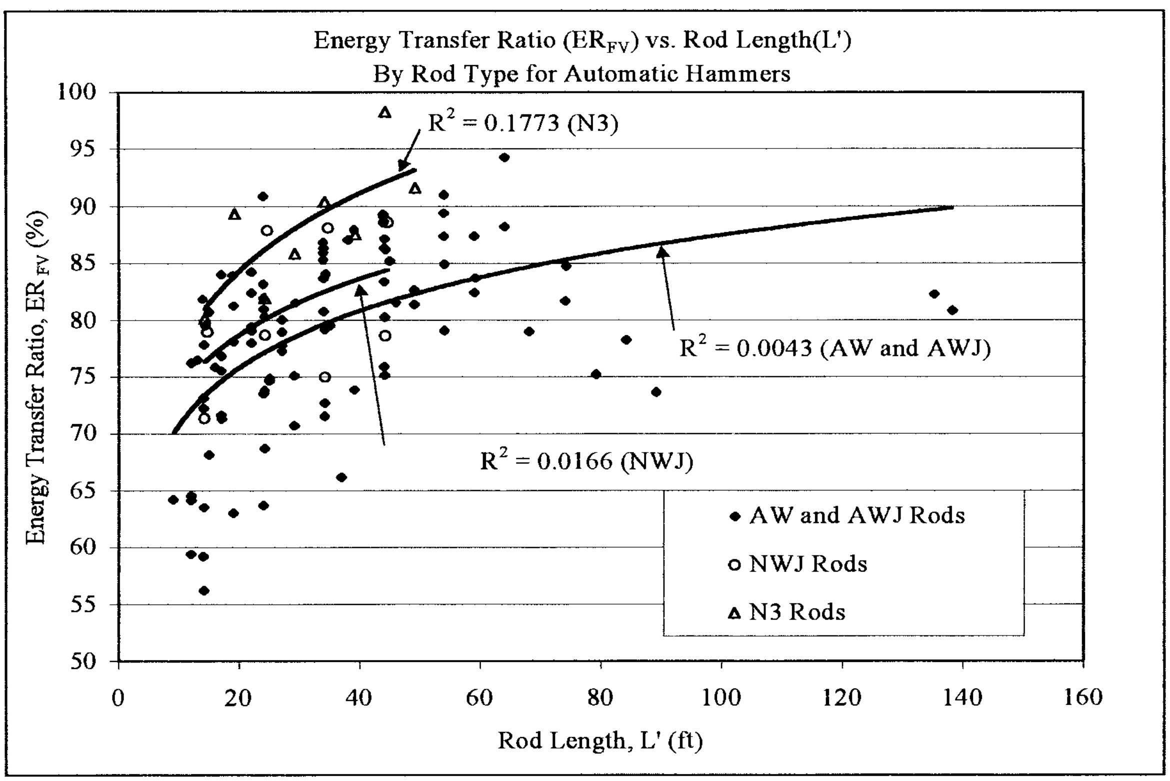



Figure 7-7. Energy Transfer for Automatic Hammers by Drill Rod Types.

Table 7-4 presents a summary of test results broken down by drill rod type for both safety and automatic hammers. As shown in the table, the majority of data were recorded on SPT systems using either AW or AWJ sized drill rods. Forty-three (43) systems used either AW or AWJ rods while only 15 used the N-series drill rods. The N3 rod appears to have returned energy ratios notably lower for the safety hammer and higher for the automatic hammer. However, for two reasons this may not be meaningful. First, the number of SPT systems from which these data originated is limited, particularly for the automatic hammer where all data came from one system. Secondly, energy measurement with N3 rods used the least "uniform" drill string of all testing.

Table 7-4. Summary of Energy Transfer Data by Drill Rod Type.

| Rod Type | Average $ER_{FV}$ (%) | Std. Deviation, σ, of $ER_{FV}$ | Average σ for each Record | Data source--number of: Records | Data source--number of: SPT systems |
|---|---|---|---|---|---|
| Safety Hammers | | | | | |
| AW | 66.3 | 12.6 | 4.6 | 60 | 11 |
| AWJ | 68.1 | 9.8 | 4.5 | 108 | 20 |
| N3 | 59.4 | 8.3 | 3.0 | 39 | 8 |
| NW | 70.5 | 2.9 | 3.3 | 4 | 1 |
| NWJ | 66.1 | 7.5 | 3.2 | 16 | 3 |
| | | | Totals | 227 | 43 |
| Automatic Hammers | | | | | |
| AW | 76.6 | 7.2 | 2.6 | 64 | 8 |
| AWJ | 83.2 | 6.8 | 1.7 | 33 | 4 |
| N3 | 88.1 | 5.3 | 3.2 | 8 | 1 |
| NWJ | 80.9 | 6.1 | 2.0 | 8 | 2 |
| | | | Totals | 113 | 15[(a)] |

(a) More than the total number of Automatic SPT systems since one system (#7) was tested with both AWJ and NWJ rods.

The poor rod uniformity for N3 rod drill strings was a result of the following. In the testing, two different instrumented 2-foot drill rod sections were available for use. One was AW rod (area = 1.17in$^2$) and the other NW (area = 2.30in$^2$). As a result, the use of connectors was frequently required for use with J threaded rods and for N3 rods. The use of connectors creates a change in impedance along the drill string, which is in addition to the change caused by the normal connection of drill string sections. This was particularly significant for systems using N3 rods. In those instances, measurements were taken using the larger NW instrument with connectors on each end to "sub" the instrument to the smaller N3 rod system. This caused a notable change in impedance. As would be expected for a non-uniform drill string, the proportionality of the force and velocity waves was generally poor in these cases and the $F^2$ method is not valid. While the Fv method is valid and should be able to accurately measure the energy transfer, the presence of the larger NW instrumented rod and the additional connectors may have unduly affected the energy transfer relative to that which would have occurred if the instrumented rod were N3.

In one case the same SPT system was used to perform two borings with different rod type on each boring. Figure 7-8 presents the results of this test. The System 7 CME 55 automatic hammer advanced two SPT borings, one with AWJ and one with NWJ rods. For this test, more energy was transferred to the rods with the NWJ rods (average of 85.9%) than the AWJ rods (average of 82.8%).

In many cases, drillers in the field reported use of a combination of standard and "lightweight" drill rods. Drill crews sometimes interchanged these within the same test boring. The researchers did not measure and record each component of the drill string during testing.

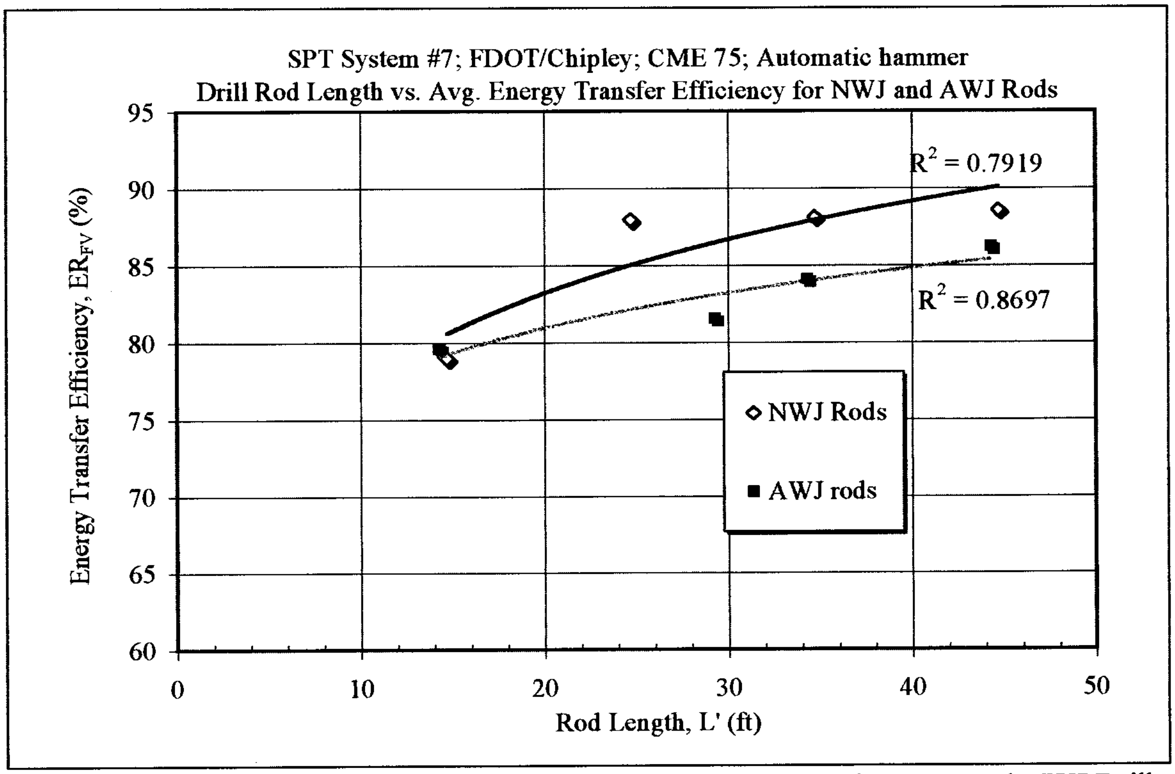



Figure 7-8. Energy Transfer Efficiency versus Drill Rod Length for AWJ and NWJ Drill Rod Types (System 7).

## 7.7 Effect of Hammer Drop Height

Although the ASTM specifies that the hammer fall from a height of 30 inches, with an allowance of +/- 1-inch, it is difficult to consistently drop the hammer from that height. There is generally some variation from that height due to assorted factors: driller experience, driller fatigue, sampler penetration, etc. Observed safety hammer drop heights ranged from 26 to 36 inches with an average of 31.9 inches. The automatic hammers are much better suited at repeating an appropriate drop height than the safety hammers. The observed automatic hammer drop heights ranged from 29 to 31.5 inches with an average of 30.1 inches.

Figure 7-9 shows energy ratio data for the 206 safety hammer records for which observed drop height data are available. From the 206 records, there were 10 with hammer drops less than 29 inches, 67 for 29 to 31 inches, and 129 above 31 inches. The SPT Analyzer operator and assistant estimated the drop heights by visually observing the height of the hammer barrel rise relative to markings made on the hammer stem. These estimates must therefore be considered approximate.

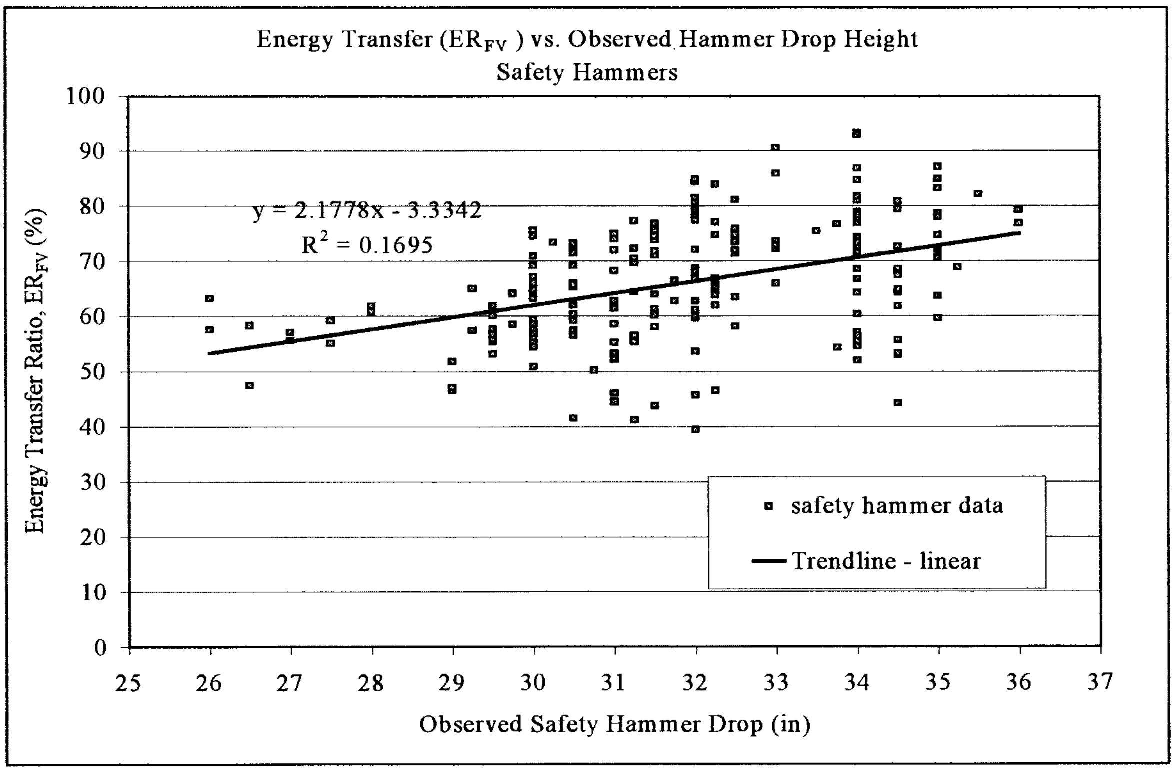



Figure 7-9. Energy Transfer Ratio versus Observed Hammer Drop for Safety Hammers.

Figure 7-10 presents the data from the 82 of the 101 CME automatic hammer records for which the drop heights were observed and estimated. The SPT Analyzer operator and assistant estimated the drop heights by visually observing the height of the hammer's rise in the slot on the side of the hammer assembly. These estimates must therefore be considered approximate. Another indication (in addition to visual observation) of drop height for the

CME automatic hammers may be the blow rate since faster operation generally results in higher hammer "throws." This is discussed later in Section 7.8.

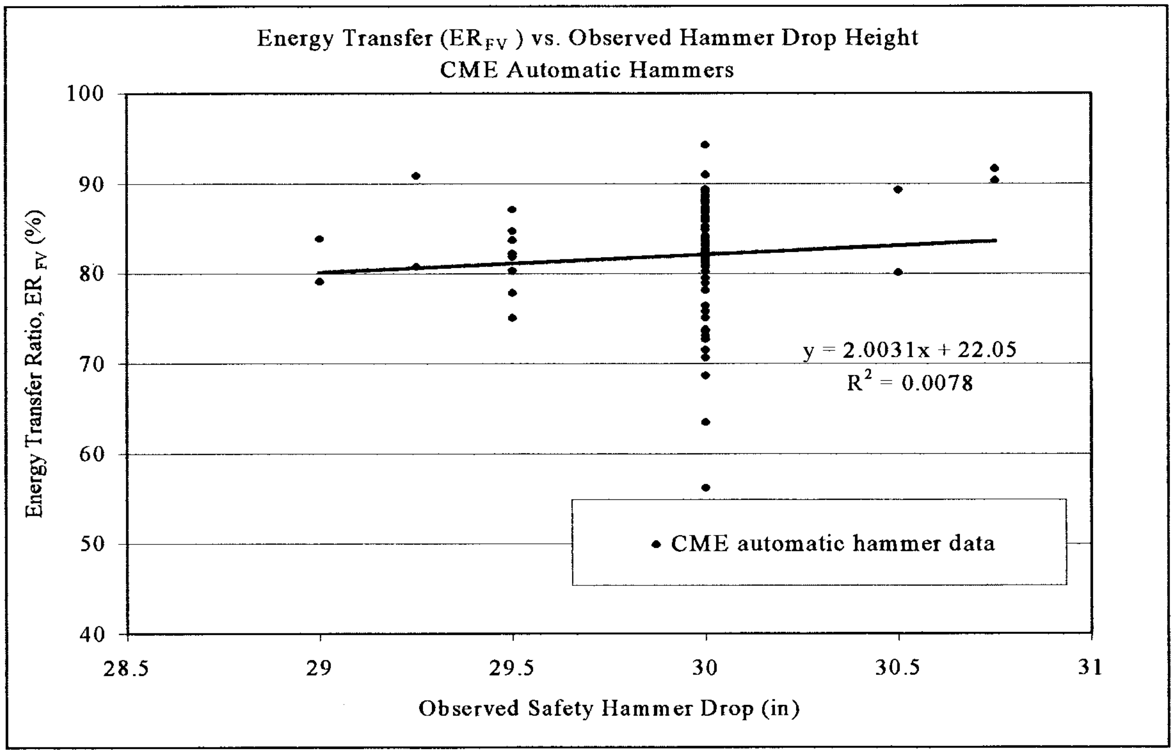



Figure 7-10. Energy Transfer Ratio versus Observed Hammer Drop for CME Automatic Hammers.

As expected, the data for both safety and automatic hammers show an increase in energy transfer with an increase in drop height. Although there is significant scatter, there is a moderate correlation for the safety hammers and a weak correlation for the automatic hammers.

Figure 7-11 shows the energy transfer ratios for safety hammers which have been calculated using both the potential energy based on observed hammer drop heights and for the nominal potential energy for the specified 30-inch drop height (as presented on Figure 7-1). This attempts to show a normalization of the SPT system performance to drop height. Adjusting the data to normalize drop height eliminates one of the most obvious sources of test variation - the operator's ability to consistently drop the hammer from a 30-inch height. These normalized data present an indication of safety hammer system performance, exclusive of the operator's hammer drop height.

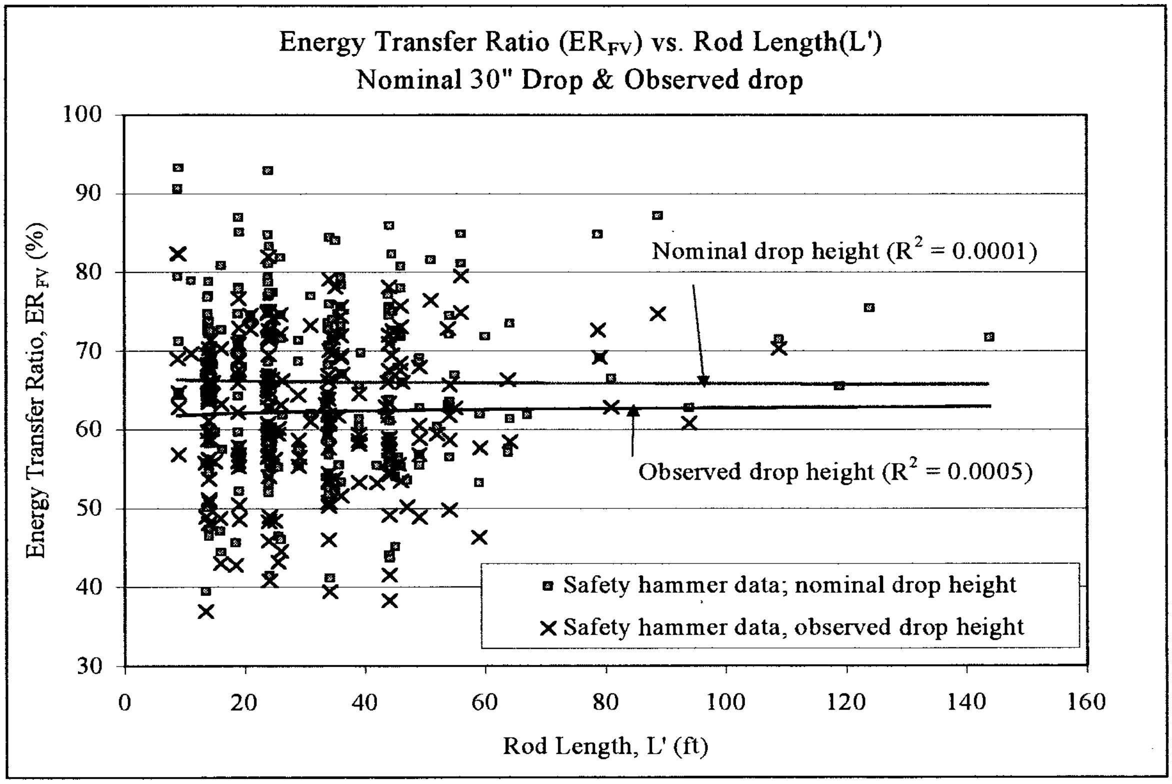



Figure 7-11. Energy Transfer Ratio versus Rod Length for Nominal and Observed Hammer Drop for Safety Hammers.

This graph shows the energy transfer ratios that would be expected had all tests been performed with a 30-inch hammer drop. This assumes that an increase in the hammer's drop height results in a proportional increase in transferred energy; for instance, a 33-inch hammer drop would have 1.1 times (or 33/30) the energy transfer of a 30-inch drop. This assumption is not exact since the safety hammers do not have a pure free-fall and their velocities (and kinetic energies) at impact are not purely a function of drop height; rather, the rope resistance can be major factor in reducing the impact velocity.

Nonetheless, the comparison of data for nominal and observed drop heights shown in the figure is informative. In many cases, the data points adjusted for the observed drop heights are as much as 5 to 10 percent below the nominal data points. Adjusting the data for drop height reduces the average energy transfer, $ER_{FV}$, for safety hammers from 66.0% to 62.2%.

Tests for controlled drop height were performed with one SPT system, System 59. For this test, five hammer blows were performed with each of the following stroke lengths: 26, 28, 30, 32, and 34 inches. Each series of blows was conducted with the same rod length and section combination. The test was not conducted at a normal sampling rate and was not a cut-string drop test. Rather, the driller raised the hammer carefully to the specified height with the rope and cathead, stopped for confirmation of the pull height, and then threw the rope forward to allow the hammer to fall. The results of these tests are shown in Figure 7-12. As expected, the transferred energy increased with increasing hammer drop height.

The increase in energy transfer was proportionally larger than the increase in drop height. For instance, the height increase from 30 to 34 inches, a 13.3% increase, resulted in a measured energy transfer ratio increase, $ER_{FV}$, from 43% to 54% ($E_{FV}$ increase from 151 to 188 ft-lbs), a 25% increase. Figure 7-12 also shows the energy transfer that would be expected if change in energy transfer were only a function of drop height. This disproportionate increase in energy transfer may likely be a result of a diminishing relative influence of the rope and cathead resistance as the hammer is dropped from greater heights. Certainly these results indicate that the hammer has a higher velocity, and hence kinetic energy, at impact for the higher drop heights. The use of a hammer velocity-measuring device would be useful in better assessing these effects.

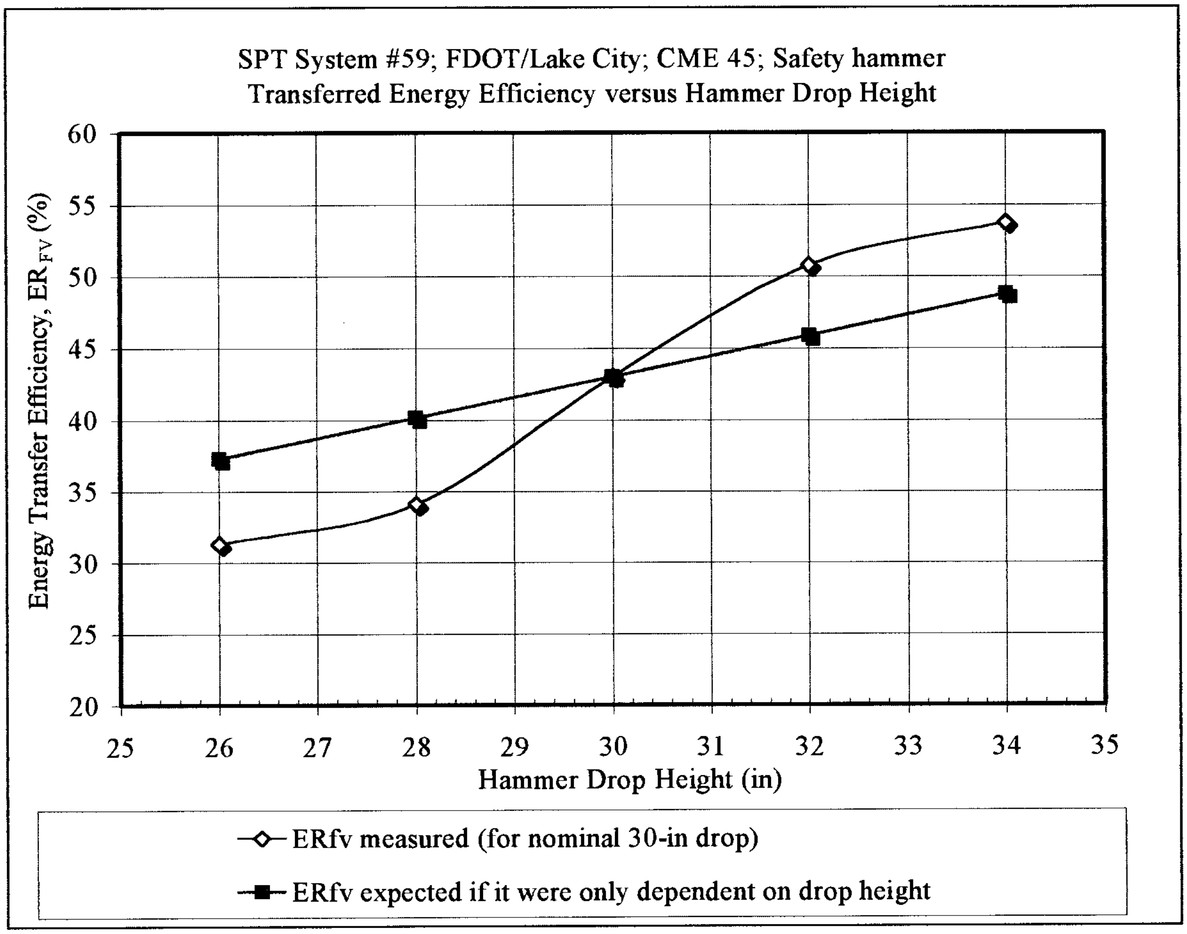



Figure 7-12. Energy Transfer versus Controlled Drop Height for System 59.

## 7.8 Effect of Hammer Blow Rate

Figure 7-13 presents energy transfer ratio versus blow rate for safety hammers. These data do not show a clear trend. For safety hammers, the factors that may link blow rate to energy transfer may be a result of either operator technique or soil effects. For instance, for an operator to hammer very quickly, he may have to begin pulling on the rope, removing its slack and hindering the hammer's "free fall," before the hammer impact is complete. This would result in a reduced transferred energy.

Alternately, in some cases a faster blow rate might be achievable by the operator who has a better rope throw, and hence more hammer impact velocity, than by an operator who has a poor rope throw that unduly slows the fall of the hammer.

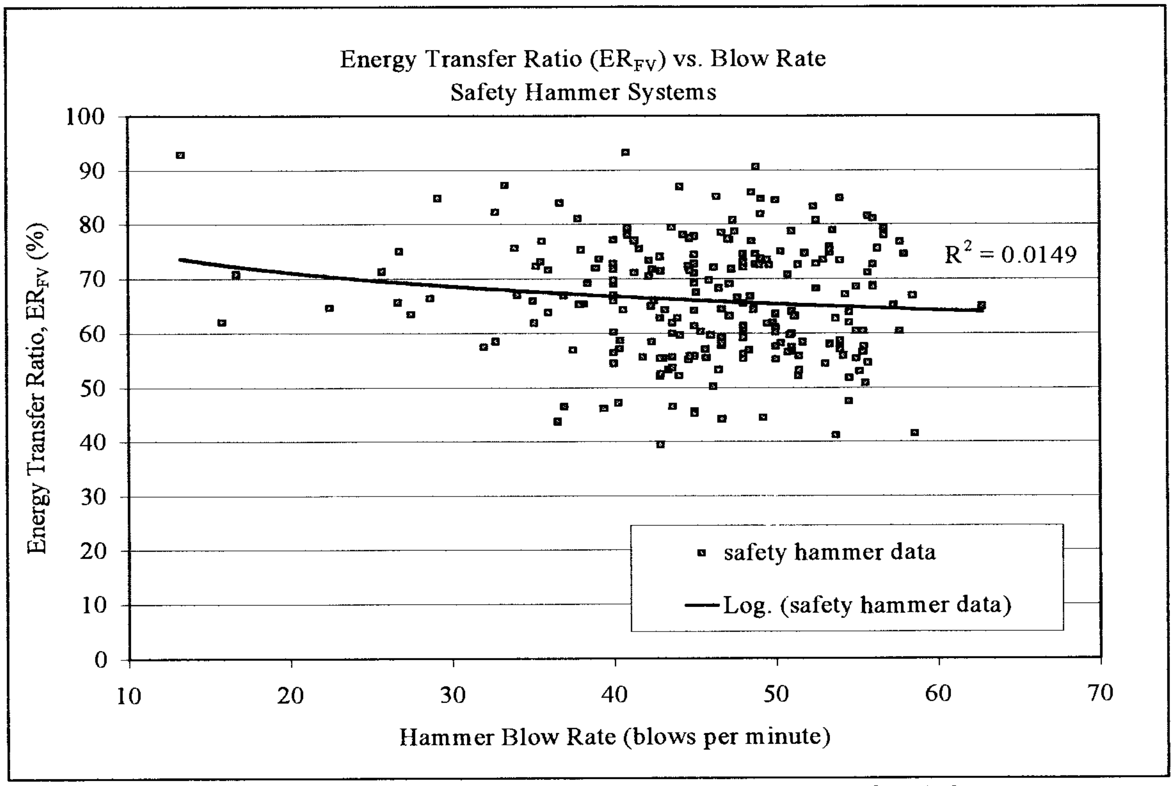



Figure 7-13. Energy Transfer Ratio versus Hammer Blow Rate for Safety Hammers.

The N-value may be influenced by blow rate as a result of possible liquefaction of the soil. It is possible that in some cases a slow rate would not cause this while a faster rate would. Possible liquefaction would reduce the sampler's resistance to penetration, reducing the resistance to penetration, increasing the sampler's set for each blow, inversely reducing the N-value.

Neither the operator technique or soil effects are discernable from the data presented here. While this can not be determined from the data in the figure, further evaluation may reveal a relationship.

For an automatic hammer system, a more direct relationship exists between the blow rate and energy transfer. This is because the CME and Diedrich automatic hammers' stroke lengths vary with the rate of operation. Both hammers have been designed to operate in a manner resulting in a nominal 30-inch hammer drop. To accomplish a 30-inch drop, each relies on the chain and cam assembly to lift the hammer at a speed such that when the cam releases the hammer, the hammer will continue upward due to its inertia for a small distance to provide a 30-inch drop. The faster the chain travels the higher the hammer is thrown. Also, the faster the chain travels the faster the blow rate. If the rate is set much above 60 blows per minute, the chain and cam will catch and begin raising the hammer before it has completed its blow.

As expected, the data presented in Figure 7-14 show that for automatic hammers transferred energy increases with an increased blow rate.

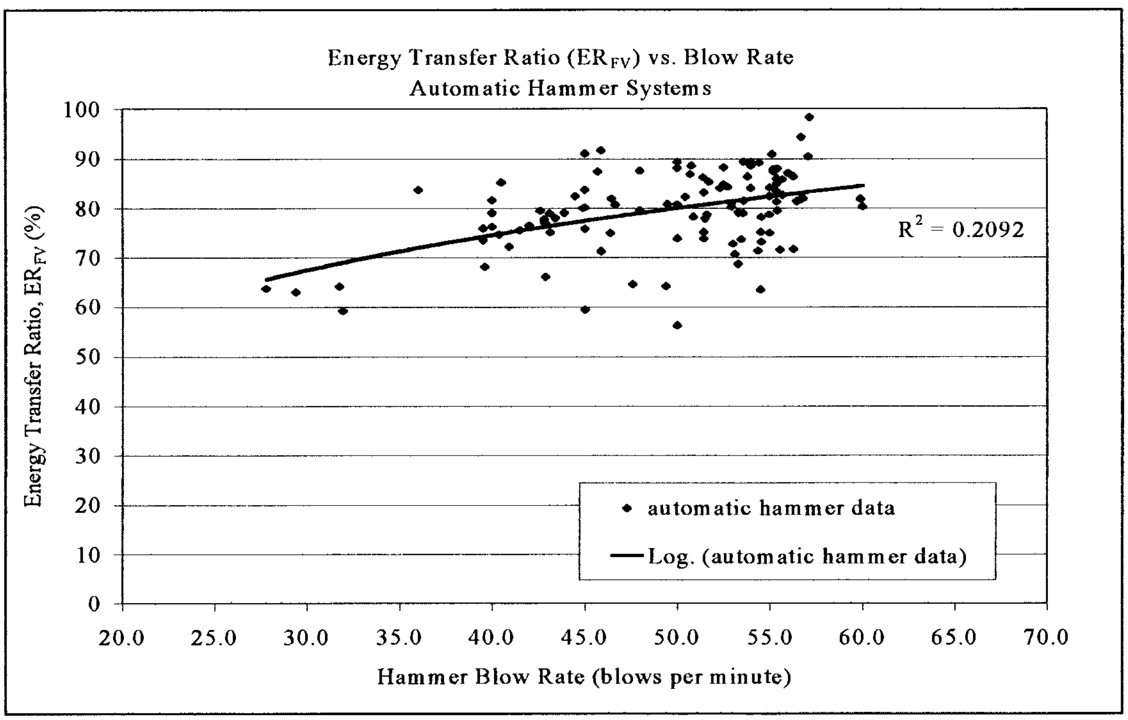



Figure 7-14. Energy Transfer Ratio versus Hammer Blow Rate for Automatic Hammers.

## 7.9 Effect of Number of Rope Turns around Cathead

The number of rope turns, or wraps, around the cathead for safety hammer systems can effect the transfer of energy as a result of increasing or decreasing resistance to the fall of the hammer. All else being the same, an increased number of turns would reasonably result in more resistance to the hammer's fall, a reduction in the velocity of the hammer at impact, and a transfer of less energy. Conversely, fewer turns would result in more energy transfer.

ASTM 1586 directs that no more than 2.25 rope turns be used during the SPT test. According to the ASTM, "It is generally known and accepted that 2 3/4 or more rope turns considerably impedes the fall of the hammer and should not be used to perform the tests." Nonetheless, several drill crews performed the test with in excess of 2.25 rope turns.

Table 7-5 shows the results of testing. The results are also shown on Figure 7-15. As expected, the energy transfer decreased with an increase in the number of rope turns. Although few data records are available for more than 2.25 turns, the data do indicate that the use of 2.75 turns resulted in reduced energy transfer. Records for 1.25 turns suggest that using this reduced number of turns does not affect energy transfer.

Table 7-5. Summary of Energy Transfer Ratios by Rope Turns on Cathead.

| Number of Rope Turns | Energy Transfer Ratio, $ER_{FV}$ (%) | Standard Deviation | Data source – number of: | |
|---|---|---|---|---|
| | | | Records | SPT systems |
| 1.25 | 66.4 | 12.4 | 24 | 6 |
| 1.75 | 66.8 | 12.3 | 59 | 11 |
| 2.25 | 66.0 | 9.6 | 138 | 25 |
| 2.75 | 57.8 | 5.4 | 6 | 2 |
| | | Total | 227 | 44[(a)] |

(a) Actually 43 different systems; data from System 12 used both 1.25 and 2.25 turns.

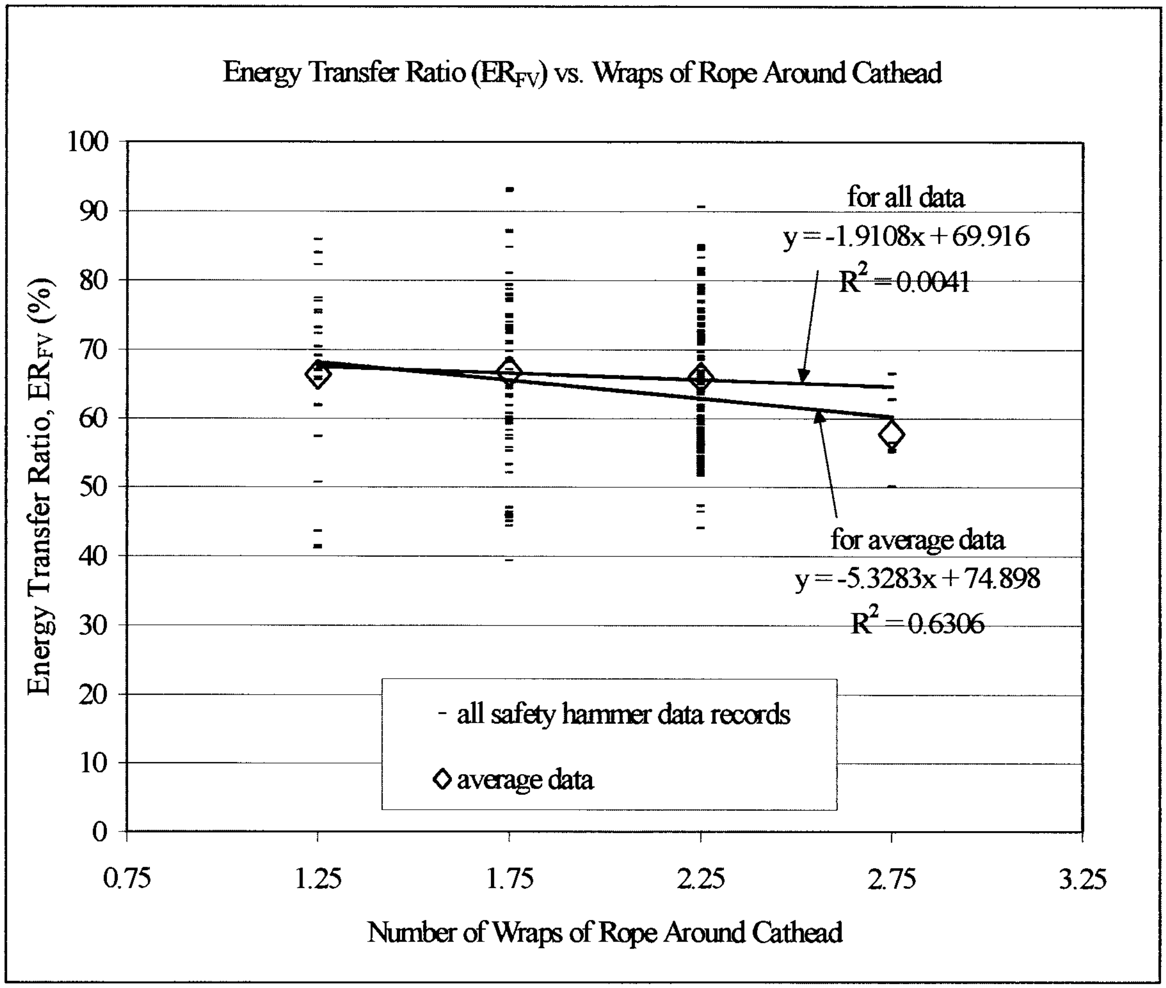



Figure 7-15. Energy Transfer Ratio versus Number of Rope Turns.

## 7.10 Effect of N-Value

The energy transfer ratios have been graphed versus the SPT N-value in Figure 7-16. Although there may be a relation between the two, it is not evidenced in this figure. Additional evaluation of these data considering the soil types or other factors may reveal meaningful information.

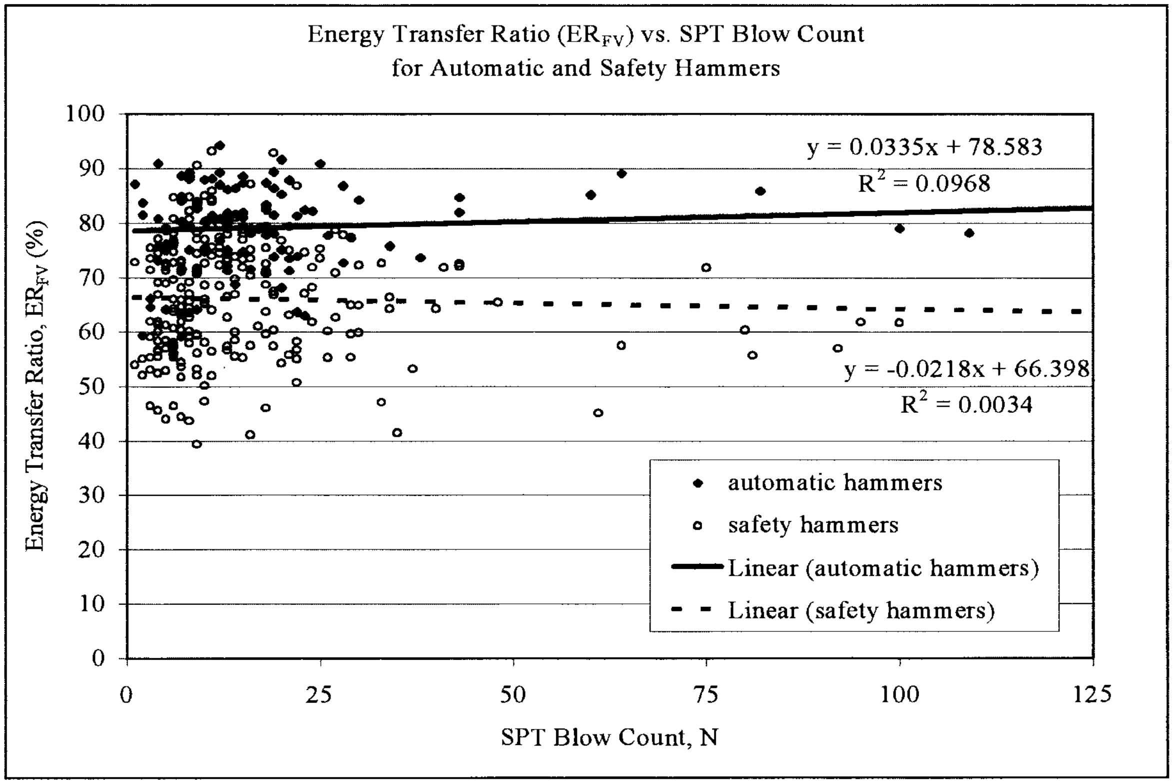



Figure 7-16. Energy Transfer Ratio versus SPT Blow Count

## 7.11 Comparison of $ER_{FV}$ and $ER_{F2}$ Calculations

As previously discussed, the energy transfer calculations from the Fv methodology have been used almost exclusively within this report. Even so, the F2 calculations are also included in the data index for comparison. The $ER_{F2}$ values have been corrected with the ASTM D 4633 specified $K_1$ and $K_2$ corrections. The $K_1$ correction accounts for the wave energy not sensed by the load cells because of their distance below the anvil, and the $K_2$ correction accounts for energy that is cut off early because of short rod lengths (less than 45 feet). The $K_c$ correction, which corrects for the actual wave speed versus the assumed or theoretical wave speed used in the measurement equipment, was not used (was assumed to be 1.0) since this was not evaluated during data reduction. Based on a review of several hammer blow records with the SPT-PC software, the authors believes that neglecting the $K_c$ correction will not result in a large error. The $K_1$ and $K_2$ corrections will typically be more significant than the $K_c$ correction for rod lengths shorter than about 35 to 45 feet. Nonetheless, one may wish to consider the $K_c$ correction in the future.

In some instances the F2 calculations were not valid because the measured force trace did not show that force went to 0 between the ASTM specified 0.9 to 1.2 times 2L/c (as discussed in Section 6.2). For these cases the EF2 calculations were not included in the data index or on these figures.

Some researchers have discussed the use of the Fv and F2 calculations and have debated which is most appropriate. Recently Butler (1997) looked at this issue and made observations and assessments of the two methods. Butler found that both methods had limitations. The F2 method gave higher energy values than the Fv method for high blow counts ($N>50$). The Fv method predicted higher energy transfer for low blow counts ($N<10$), due to the additional energy from the additional hammer displacement.

Figure 7-17 presents the ratio of $ER_{FV}$ to $ER_{F2}$ for the records for which both calculations are available. These data are plotted versus N-value (blow count) with the blow counts from SPT samples with refusal driving conditions being estimated. Three data points are off of the figure with N-values greater than 100.

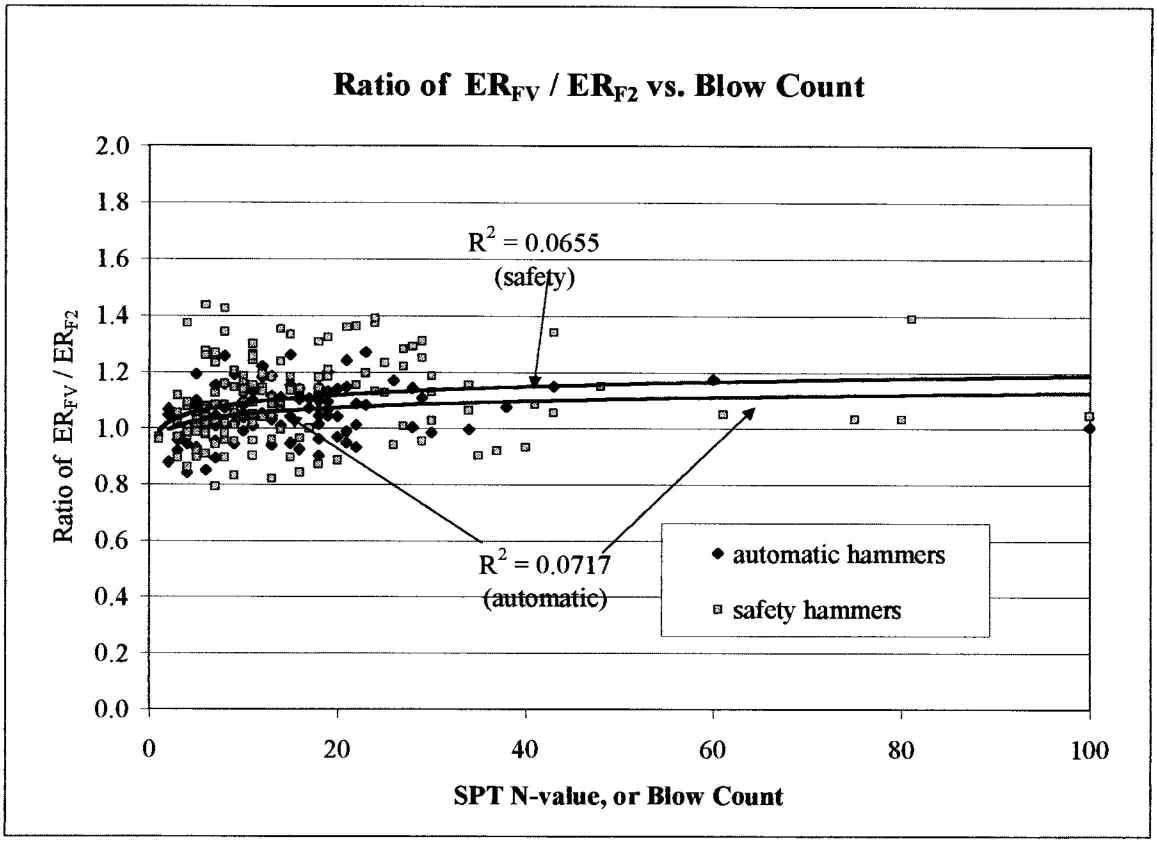



Figure 7-17. $ER_{FV}$ /$ER_{F2}$ versus SPT N-value, or Blow Count.

Based on this figure, $ER_{FV}$ is generally greater than $ER_{F2}$ as shown by most data points plotting above 1.0. However, it appears that $ER_{FV}$ tends to be not as large relative to $ER_{F2}$ for shorter rod lengths. This is not in agreement with Butler's findings that low blow counts ($N<10$) resulted in higher $ER_{FV}$ values. Sufficient data with high blow counts are not available to assess their affect.

Figure 7-18 shows the ratio of $ER_{FV}$ to $ER_{F2}$ versus rod length. Again, this shows that $ER_{FV}$ values are generally greater than $ER_{F2}$. Also, this ratio does not appear to have a notable relationship to rod length.

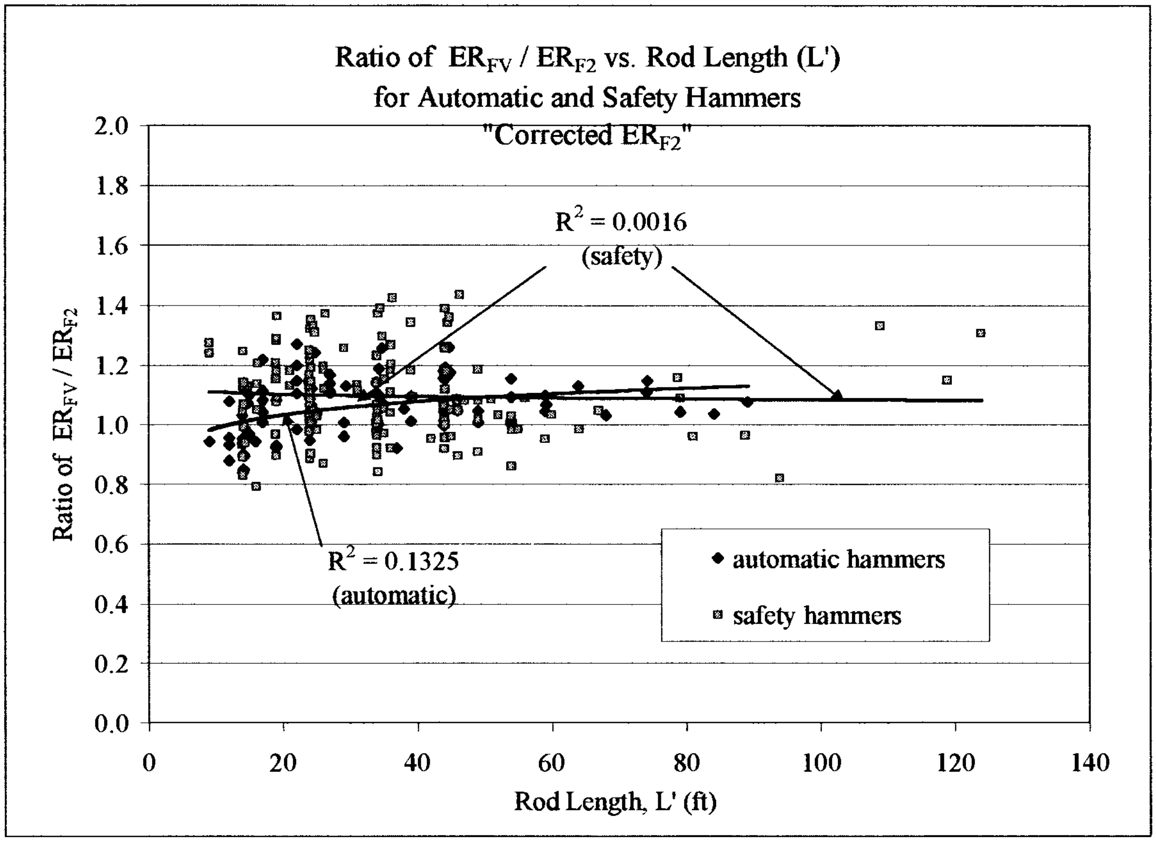



Figure 7-18. $ER_{FV}$ /$ER_{F2}$ versus Drill Rod Length for Automatic and Safety Hammers.

Figure 7-19 shows ratio of $ER_{FV}$ to $ER_{F2}$ versus rod length as with Figure 7-18, but with uncorrected $ER_{F2}$ values. These $ER_{F2}$ calculations include no $K_1$, $K_2$, or $K_c$ corrections as specified in the ASTM. The primary correction effect is to increase the EF2 values for rod lengths shorter than 45 feet. This generally agrees with the data presented, from which it can be seen that increasing the $ER_{F2}$ values for shorter rod lengths would bring both the Fv and F2 calculations into closer agreement.

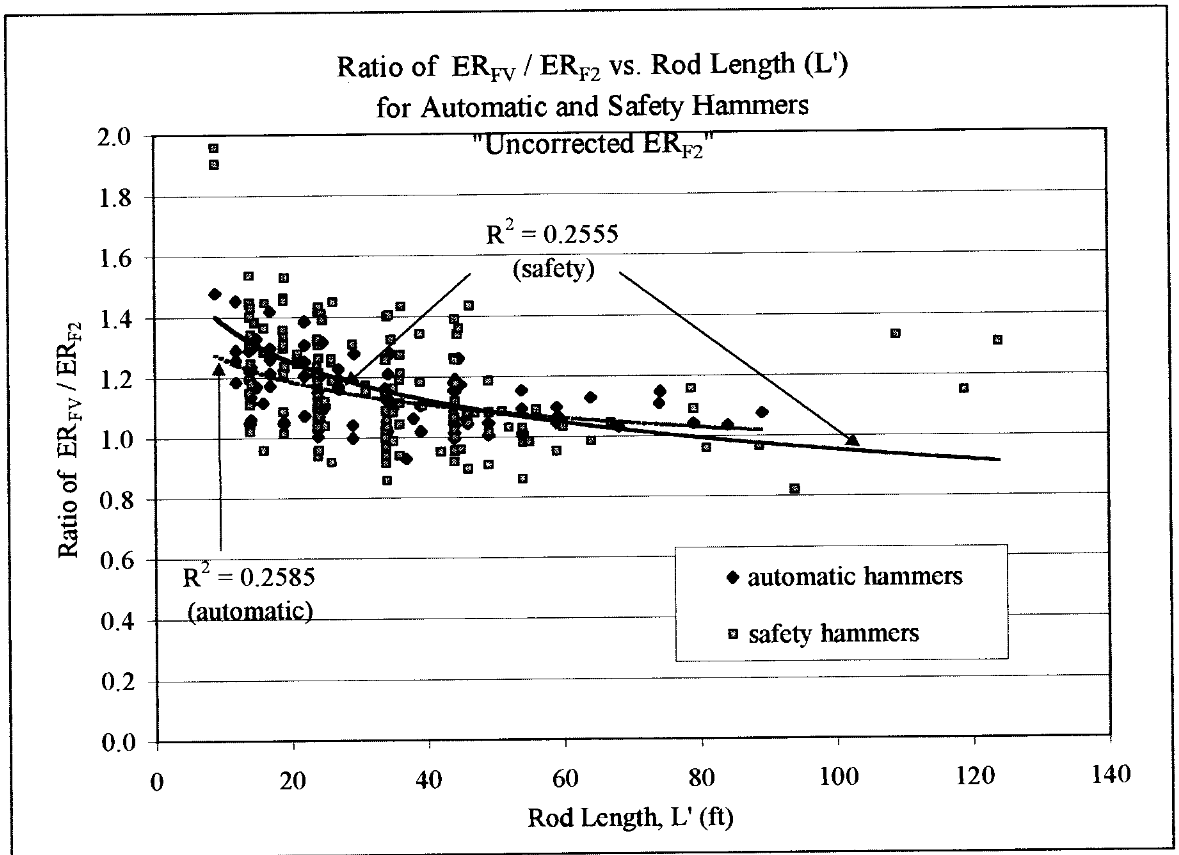



Figure 7-19. $ER_{FV}$ /$ER_{F2}$ versus Drill Rod Length for Automatic and Safety Hammers.

## 7.12 Equipment Performance

The following observations regarding the performance of the equipment and software are made based on the field testing experience.

Most of the testing and data gathering took place over a six-month period. There were approximately 32 days during this period in which the equipment was used for 55 drill rigs/SPT systems (the other 3 systems were tested during preliminary testing about 5 months earlier). At the beginning of the 6-month testing period, equipment on hand consisted of: the analyzer unit (the small processing box with LCD display); two 2-foot long drill rod sections (one AW and one NW) on which strain gauges were permanently affixed; three piezoresistive accelerometers (manufactured by ENTRAN); the necessary cables; and the SPT-PC software loaded on a Pentium 133mHz laptop computer.

In general, the equipment proved to be easy-to-use and suited to hot, dusty, and occasionally damp field conditions. No problems were experienced with the analyzer unit. The analyzer's LCD screen was easy to see in bright light. It was easy to monitor force and velocity traces of the data being recovered for data quality. The analyzer unit was small enough to carry around during conduct of the test to allow observation of other aspects of the testing while still being able to readily view the data.

One limitation to the analyzer is that it can only store data for 179 hammer blows, after which the data must be downloaded to the SPT-PC program on a computer. This downloading process requires about 20 seconds per hammer blow. Therefore a minimum of one hour is required to download a "full" analyzer. During this research, up to 1.5 hours was at times required depending on how the data were stored on the analyzer, with more individual files requiring more time that a single large file. It was often possible to work around this limitation with minimal effect, but obviously more data could have been recovered were this limitation not present.

The strain gauges mounted onto the 2-foot rod sections functioned reliably. The gauges provided a good check against each other. Data from each gauge almost always closely agreed with the other gauge, as would be expected except in cases of bending. On two different occasions the AW rod required returning to PDI to fix cables. The cables had sustained damage in the area where they entered the "goop," a glue which affixes and protects the strain gauges. It is not unreasonable to expect that some wear and tear on the cables will occur, particularly where it is attached to the drill rod and transitions from a dynamic area with strong impacts felt by the rod to the free hanging cable.

The proper and reliable functioning of the piezoresistive accelerometers offered the greatest hindrance to smooth operations. Accurately measuring the acceleration is a must for use of the FV methodology. While the two accelerometers bolted onto the drill rod generally did perform as expected and returned reliable, consistent, and reasonable results, there were many times when one or both of the accelerometers performed erratically. The "bad" accelerometers were replaced with the "spare." During the testing phase of this research, work often had to cease due to malfunctioning accelerometers. Accelerometers were sent back to PDI to service or recalibrate as required. Of eight accelerometers used during testing, six were rendered inoperable or unrepairable and another was in questionable condition at the end of testing. Considering that the total number of hammer blows the gauges were subjected to during this research was approximately 7,700, this does not represent a good life for the accelerometers, particularly when considering a cost of close to $1000 each.

The SPT-PC software, which is used to view, evaluate and adjust the data as required, was useful and suitable for purposes of this research.

CHAPTER 8

# SUMMARY, CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

## 8.1 Summary and Conclusions

As discussed herein, in order to reduce the significant variability in and uncertainty associated with the SPT N-value, it is has been recommended that N-values be standardized to $N_{60}$. Many have suggested that this standardization be achieved by correcting the measured field N-values by the ratio of that SPT system's energy transfer to the standard 60% energy of 210 ft-lbs. This requires knowing the performance characteristics of SPT systems.

In this research SPT energy measurements were made using the Pile Dynamics, Inc. manufactured SPT Analyzer® for a total of 58 SPT hammer systems commonly performing work for the Florida Department of Transportation. SPT systems included safety and automatic hammers, a variety of drill rig manufacturers, various drill rod types, and various soil conditions. Almost all tests were performed under field conditions with normal operating procedures to provide a measure of "real world" performance of complete SPT hammer systems.

From the 58 SPT systems, 77 SPT borings were performed which allowed for a total of 340 SPT samples of good data to be taken. These samples provided the data forming the records in the project index. This index has been used to evaluate overall system performance, in terms of energy transferred to the drill rods, and the effect that selected variables have on system performance.

Based on the data recovered during this research and limited evaluation of that data, there are several findings that stand clear:

1. Energy transfer ratios ($ER_{FV}$) for automatic hammer systems are on average notably higher than for safety hammer systems. CME automatic hammers averaged 80.1% and Diedrich automatic hammers averaged 76.0%, while safety hammers averaged 66.0%. These values are within the expected ranges as identified by other researchers and presented in Table 2-3.

2. For the safety hammer systems tested, as shown in Table 7-3, the highest energy transfer ratios came from BK drill rigs, then CME, Acker, Diedrich, Failing, and finally Mobile Drill with the lowest. For automatic hammer systems, higher energy transfer ratios came from the CME drill rigs than from the Diedrich drill rigs.

3. An increase in drill rod length results in an increase in energy transfer. This supports the findings of Morgano and Liang(1992). This effect was most apparent from the results of the automatic hammer systems.

4. The type of drill rod used during testing appears to have a possible minor effect on energy transfer when considering use of the AW or AWJ versus NW or NWJ. The test data show close agreement for the two rod groups with safety hammers. For the automatic hammers, the NWJ tended to have a higher energy transfer than the AW, but lower than the AWJ. The N3 rod had the lowest energy transfer of all rod type for the safety hammer systems, and the highest for the automatic hammer systems.

The results for the N3 rod may have been unduly affected by the use of the larger NW instrumented rod in the N3 drill string.

5. For safety hammer systems, the majority of drillers over-pulled the hammer resulting in hammer strokes in excess of the ASTM D1586 specified 30 inches with the average height being 31.9 inches. While the researchers made concerted efforts not to influence or disrupt normal drilling operations, the drillers may not have performed as they normally would. Had the drillers always hammered the specified 30-inch drop, the average energy transfer ratio for safety hammers would likely have been on the order of 62.2% instead of 66.0%.

6. The safety hammer's blow rate has an undetermined effect on energy transfer. However, an increase in the automatic hammer's blow rate causes an increased energy transfer as shown on Figure 7-14. This is most likely a result of the faster rate throwing the hammer slightly higher. If the automatic hammer is operated at too fast a rate (>55 to 60 bpm), the cam will "catch" and begin raising the hammer before it has fully struck the anvil, thus reducing the transferred energy.

7. Increasing from 2 nominal turns of the rope around the cathead to 2.75 turns results in a notable reduction in energy transfer, whereas decreasing from 2 nominal turns to 1.25 turns has little effect. This concurs with ASTM D1586.

8. The uncorrected energy transfer efficiencies based on the F2 method were generally lower than the Fv efficiencies, particularly for the shorter rod lengths. This is as expected. Use of the ASTM specified correction factors for the F2 method brings the two methods into closer agreement.

Regarding the use of energy measurements taken during SPT sampling, the following conclusions and assessments are offered:

9. The data recovered are not sufficient to provide a "calibration" for each individually tested SPT system, particularly the safety hammer systems. A good calibration effort would likely require numerous test borings, possibly in varying soil conditions, and at different times of the workday so the driller has experienced varying levels of fatigue.

10. While limited SPT energy data from a drill rig are not suited for calibrating that rig, the data should nonetheless prove informative to the engineer using SPT data from the drill rig. Also, it may be useful in spotting performance problems of a system.

11. The SPT Analyzer, or other energy testing device, may be useful in assessing individual sites where previously recovered subsurface data appear suspect and the engineer wishes to perform additional investigation. Also, on large and/or critical projects, a selected plan of energy transfer testing may be warranted to verify SPT system performance as well as to allow for increased design confidence and economy.

12. The SPT Analyzer™, or other energy-testing device, may be useful in performing specific research directed toward specific hammer system components or toward assessing soil properties.

13. Further evaluation and reduction of the data may reveal significant relationships between system and operation variables. These may be useful in development of SPT N-value correction factors.

Regarding the use of the Pile Dynamics, Inc. manufactured SPT Analyzer for the purpose of SPT sampling, the following conclusions and assessments are offered:

14. The reliability of the Entran piezoresistive accelerometers is of primary concern. In its present design/configuration and considering its cost, these accelerometers have not proved to be well suited to SPT testing.

15. For use in large projects where many data are to be gathered, the SPT Analyzer's download time requirements are a constraint.

16. With the exception of the two above comments, the SPT Analyzer proved well suited to SPT testing, rugged, and easy to use; the SPT-PC program was also well suited to evaluating data.

## 8.2 Recommendations for Future Research

Through the course of this research, the authors have identified several areas in which future evaluation and research would be useful. These are discussed below.

1. Is the correction to $N_{60}$ valid? As discussed herein, correction of field N-values to $N_{60}$ values is achieved by multiplying $N_{field}$ by the ratio of $ER_{measured}$ to $ER_{60}$. While an increase in ER will certainly cause a reduction in N, is this relationship truly linear? Might not this effect be dependent on the soil's physical and dynamic properties?

2. Is 60% truly a good standardization value? If most safety hammers, from which the correlations were developed, are transferring more energy than 60%, then perhaps the true "standard" energy is higher.

3. How does energy transfer as measured at the top of the rod relate to energy transferred to the sampler? While measurement of energy transfer at the top instead of the bottom of the rod is performed as a means of convenience and necessity, it is ultimately the energy that reaches the sampler that causes its penetration. What do variables such as rod type and length have to do with this?

4. What soil parameters such as quake and damping can be determined from this testing? Determination of such data could lead to improved design of pile supported foundations.

5. Specific hammer system variables could be evaluated using controlled testing to better identify the effect the variables have on blow count.

6. Results from additional testing with the SPT Analyzer should be added to the data index begun with this research. A larger index will provide a better base from which to assess SPT system performance.

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