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ENERGY CALIBRATION FOR ALDOT STANDARD PENETRATION TEST EQUIPMENT AND OPERATORS

Submitted to

The Alabama Department of Transportation

Prepared by

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Abstract

A Standard Penetration Test (SPT) energy testing program was developed for the Alabama Department of Transportation. Six Central Mine Equipment (CME) automatic hammers were calibrated using force and velocity measurements. The energy transfer ratio (ETR) for each hammer system was from 82.2% to 96.1%, with an overall average of approximately 91%. The coefficients of variance (COV) ranged from 2.2% to 5.7%.

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CHAPTER 1: INTRODUCTION

1.1 The Standard Penetration Test

The standard penetration test (SPT) has been widely used for geotechnical explorations for nearly a century. The origin of the SPT dates back to Charles Gow of the Raymond Concrete Pile Company (Figure 1.1). The purpose of the test was to measure the density of soil formations using a standard procedure from which soil correlation combined with experience could be used for foundation design (Davidson et al., 1999). Over the years, its widespread use has led to an abundance of published empirical correlations relating soil penetration resistance to various engineering properties of soil. The most common SPT correlations are concerned with relating soil resistance to bearing capacity, shear strength parameters, soil modulus, and liquefaction potential.

Figure 1.1 Raymond Concrete Pile Company

1.2. ASTM D 1586 Standard

SPT testing equipment and procedures are governed by the ASTM International (ASTM) standard D 1586 (ASTM, 2008). This standard describes the test method for split-barrel sampling of soils for soil classification and determination of penetration resistance. Although the name implies strict standardization, the standard allows some degree of latitude with respect to the type of equipment used for drilling and sampling. In general, the 1586 standard specifies the recommended type and size of drill bits, augers, and drill rods that are suitable for preparing a borehole for sampling purposes. It also describes the standard hammer weight, sampler dimensions, and testing procedures to be used in order to obtain representative soil penetration resistance values.

1.3 SPT Sampling

SPT programs are executed by mobilizing a drill rig to a test site. The most common types of drill rigs include all terrain vehicle's (ATV), track-mounted drill rigs, and truck-mounted drill rigs. However, drill rigs can also be mounted on barges, and other exotic off road vehicles. The type of vehicle selected for the job often depends on the existing site conditions and its transportation capabilities. Other considerations include the type and depth of geology to be sampled.

The soil boring process begins after the drill rig has mobilized to the site and after the boring locations have been determined. Most SPT drill rigs are equipped with a rear engine block which provides the necessary horsepower for the rotary boring operation. Soil borings are performed vertically, to a prescribed depth, and are used to remove the overlying soil using either a hollow-stem auger (dry method) or a mud-rotary (wet method) technique. When the sampling depth has been reached, the boring process stops and the drilling personnel prepare to perform the SPT. In Figure 1.2, an ATV drill rig is shown about to perform a hollow-stem auger soil boring near a bridge abutment in Alabama.

As previously mentioned, the SPT has two objectives. The first objective is to retrieve a physical soil sample for soil classification, and the second objective is to obtain an estimate of the soil strength at the sampling depth. Both of these objectives are achieved simultaneously during the sampling process.

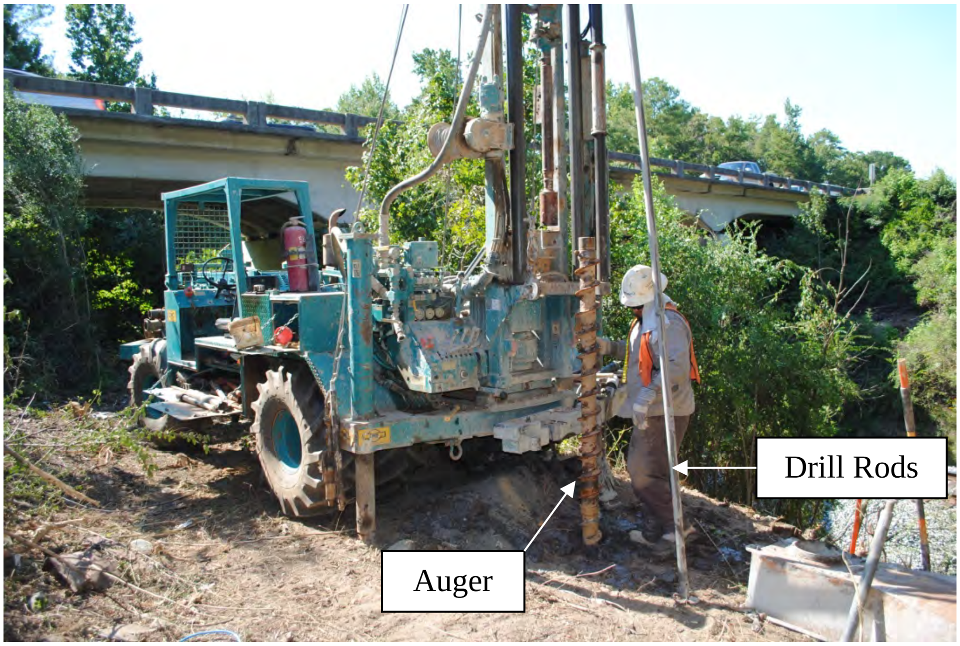

Figure 1.2 Hollow-stem auger drilling

The sampling process begins by attaching a split-spoon sampler of standardized dimensions to the bottom end of a string of drilling rods (Figure 1.3). Once attached, the drill rod string and sampler are lowered to the bottom of the pre-bored hole. It is common for a length of drill rods, greater than the depth of the boring, to be attached to the sampler in order for the drill rods to "stick up" out of the bored hole and above the ground surface approximately three to five feet. Once the drill rods and sampler are in place, the SPT hammer is positioned on top of the drill rod string just prior to performing the test. With the hammer in place, a member of the drilling crew marks three six-inch

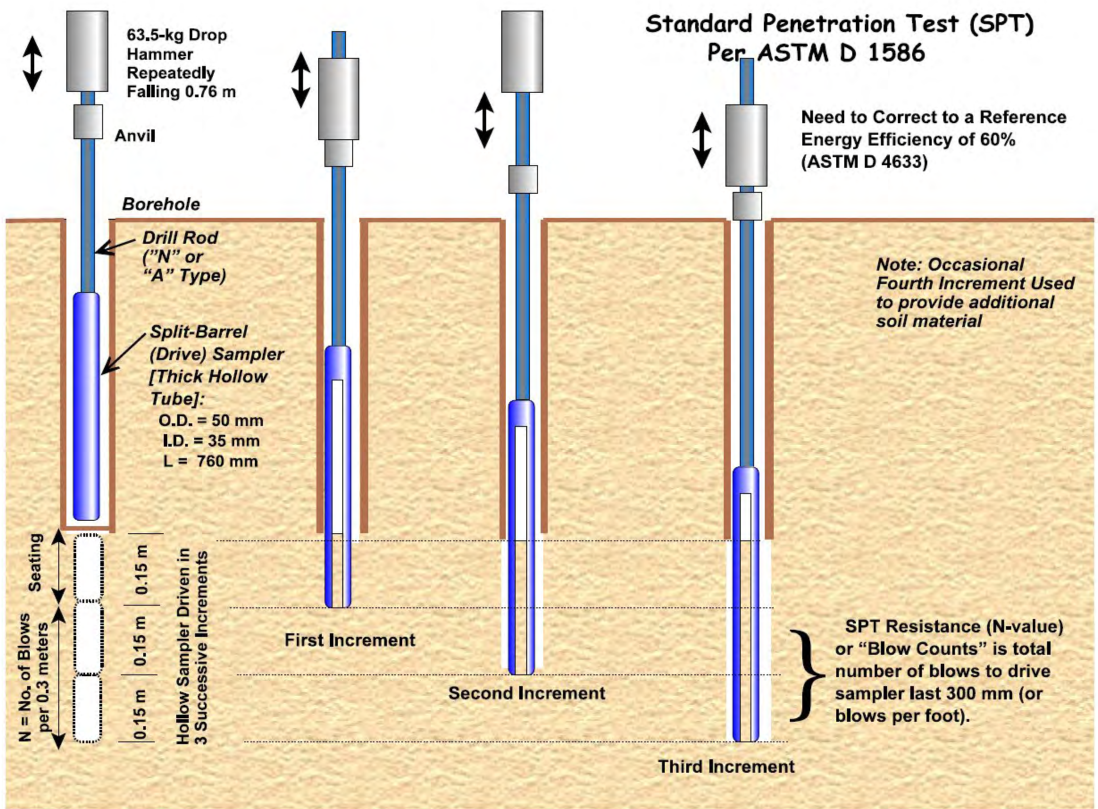

Figure 1.3 SPT sampling process (Mayne et al., 2001)

increments on a section of drill rod exposed above the ground surface. These markings represent the penetration distance that the sampler will experience during the test. After the six-inch increments have been marked, the SPT hammer system is engaged and allowed to repeatedly strike the top of the drill rods until the sampler has penetrated into the borehole a distance of eighteen inches. During the test, the number of hammer blows for each six-inch increment are recorded. The number of blow counts required to drive the sampler the last twelve inches out of the eighteen-inch total is called the N-value. The N-value is the primary engineering parameter obtained from the SPT and is the blow count representation of the penetration resistance of the soil. The N-value has units of blows per foot (BPF).

When the SPT is complete, the sampler and drill rods are removed from the borehole and the soil inside of the sampler is removed and classified before the next SPT. This process is typically repeated at intervals of five or ten feet depth until enough SPTs have been performed to sufficiently characterize subsurface conditions for the foundation or earthwork under consideration. The final end-product of the SPT test is called a boring log. The boring log is a record of site subsurface conditions and is used to stratify soil layers as well as delineate zones of soil type and strength. As an illustration, a representative boring log is provided in Figure 1.4 on the next page. In this figure, the right and left side of the boring log show the respective soil classification and SPT N-values.

1.4 The SPT Hammer

The SPT hammer system is a percussive instrument that provides dynamic impact energy by dropping a 140-pound weight. The drive weight is lifted a distance of 30 inches and then allowed to free-fall and strike the top of the drill rod string. The maximum theoretical potential energy available to drive the sampler is 4200 in-lbs (350 ft-lbs). The apparent soil penetration resistance, or N-value, depends on the energy transferred from the hammer to the drilling rods. Briefly stated, high energy efficient hammers will produce more sampler penetration per blow, and smaller apparent N-

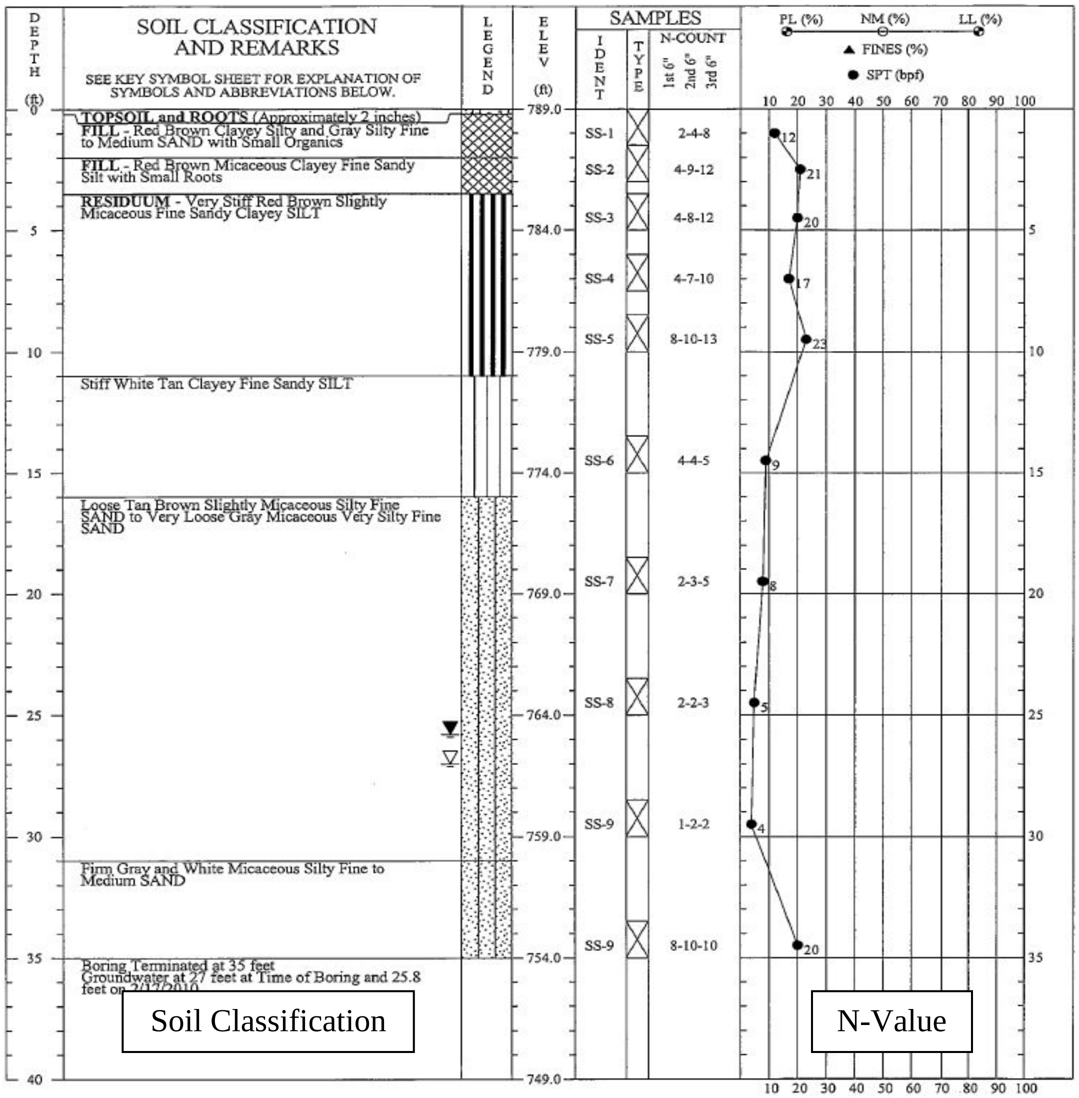

Figure 1.4 SPT boring log

values, compared to a hammer system that is less energy efficient. The N-value is therefore inversely proportional to the magnitude of transferred energy.

There are two types of SPT hammer systems, and can be classified as either manual or automatic. The manual hammer system, which was the only type of hammer available prior to the 1980’s, commonly consisted of a “rope and cathead” lift and release mechanism (Figure 1.5). The cathead is a rotating drum that supplies the motive power for lifting the drive weight during the test. The automatic hammer, which is currently the most widely used hammer system, uses a hydraulic lifting mechanism to repeatedly lift and release the drive weight (Figure 1.6). The automatic hammer is covered extensively in Chapter 2.

There are vast differences in the operational performance between the manual and automatic hammer. The automatic hammer is designed to supply a repeatable sequence of hammer impacts which corresponds to a relatively consistent transfer of impact energy. The manual hammer does not have the precision of the automatic hammer and often provides somewhat of a large variation of transferred energy. This occurs because

Figure 1.5 Manual safety hammer (Kelley and Lens, 2010)

Figure 1.6 Automatic hammer

the efficiency of the manual system is dependent on the ability of the driller to consistently lift and release the drive weight 30 inches between hammer blows. Factors such as operator fatigue and number of turns of rope around the cathead often play a critical role when evaluating the N-values produced by the manual hammer system. The historical average energy transfer efficiency for the manual hammer is estimated to be 60%. This is significantly lower than the 80% average transfer efficiency typically attributed to the automatic hammer.

Despite the variability of the manual hammer, its use was dominant for many decades, and most of the correlations for soil parameters based empirically on N-values were obtained from its energy transfer efficiency. Due to the emergence and popularity of the automatic hammer, which is more efficient, an energy standardization approach has been adopted in the U.S. which is used to normalize the N-value results to a 60% reference energy level.

1.5 N-value Normalization

The N-value is the main engineering parameter obtained from the SPT. Because of its widespread use, variability of N-values has been well documented. Common engineering practice accepts that these values can be highly variable and often are dependent upon the ability of the driller and type of testing equipment used. To quote ASTM D 1586, "Variations in N-values of 100% or more have been observed when using different standard penetration test apparatus and drillers for adjacent borings in the same soil formation." Variation of N-values has also been noticed when comparing N-values from similar hammer systems, i.e. two or more automatic hammers, in the same soil conditions, and sampling at the same time. This variation is the result of individual hammer systems being more or less efficient at transferring energy, even if they are from the same manufacturer.

The engineering community generally agrees that the most effective way to remove some of the N-value variability is by measuring the amount of energy transferred to the drill rods during the SPT. If the amount of transferred energy is known, the N-values can be corrected to a 60% reference energy level using a simple calibration equation

$$N_{60} = N_{Field}\left(\frac{E_{Measured}}{E_{60}}\right) \tag{1.1}$$

where

N_{60} = Penetration resistance adjusted to 60% drill rod energy

N_{Field} = Penetration resistance measured in the field

$E_{Measured}$ = Maximum transferred energy entering the drill rod (from top measurements)

E_{60} = Historical energy transfer efficiency for manual hammers (60%)

1.6 Research Objective

The Alabama Department of Transportation (ALDOT) routinely uses SPT N-values for their geotechnical designs. Currently, ALDOT is transitioning from the traditional Allowable Stress Design (ASD) methodology to the modern Load and Resistance Factor Design (LRFD) standards. With their move to LRFD, the Federal Highway Administration (FHWA) is recommending SPT energy calibration for each SPT drill rig as a method to account for N-value variability in the design process. Therefore, the primary research objective was to determine the average energy transfer efficiency for each of ALDOT's SPT hammers, as well as develop a permanent energy testing program that will meet their future SPT needs.

CHAPTER 2: BACKGROUND

2.1 Introduction

This section is an overview of the general progression of stress wave theory leading up to field energy measurements. The following discussion is presented in a more qualitative format than has traditionally been used and should be helpful to the reader in the understanding of the energy measurement process. A summary of background on the CME automatic hammer has also been provided at the end of the chapter.

2.2 One-Dimensional Wave Equation

Engineering applications related to the dynamic impact of elastic rods are primarily concerned with the transformation of energy into motion via free longitudinal wave oscillations. Assuming that plane cross-sections of the rod remain plane during impact, the one-dimensional wave equation can be obtained by equating the inertia forces to the elastic forces generated in a single rod element. Since materials, such as steel, do not seriously depart from perfectly elastic behavior (for small deformations), the measured stress wave behavior often agrees well with the predictions of elastic theory (Kolsky, 1963). This is likely the primary reason that stress wave measurements using the wave equation have gained such wide-spread acceptance in engineering practice.

As described by Fischer (1959), one-dimensional propagation of a stress wave disturbance in an elastic rod can be described by the linear partial differential equation

$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2} \tag{2.1}$$

where u is the particle displacement of any point x along the rod, and with c and t being the velocity of stress wave propagation and the time associated with passage of the stress wave, respectively. The velocity of stress wave propagation, traditionally called wave speed, is related to the modulus of elasticity E and mass density ρ of the rod by

$$c^2 = E/\rho \tag{2.2}$$

The value of c by itself is considered the fundamental wave speed of the material and is assumed to be constant for steel. Equation 2.1 is the one-dimensional wave equation which has a general solution

$$u(x,t) = f(x+ct) + g(x-ct) \tag{2.3}$$

This general solution implies that the displacement pattern in a rod can consist of two wave functions f and g, which are traveling in opposite directions. The functions f and g must satisfy the boundary conditions for the problem under consideration. Since the boundary conditions of the stress wave are the initial strain and particle velocity, interest is directed toward the derivatives of f and g where, by the chain rule:

$$\frac{\partial u}{\partial x} = f'(x+ct) + g'(x-ct) \tag{2.4}$$

and

$$\frac{\partial u}{\partial t} = cf'(x+ct) - cg'(x-ct) \tag{2.5}$$

Because equations 2.4 and 2.5 represent both the strain and particle velocity in a finite section of the rod, the problem is generally solved as these quantities can physically be measured or approximated. Here it should be noted that the arguments indicate that the

$$(x + ct) \quad \& \quad (x - ct) \tag{2.6}$$

x, t plane is divided into regions of constant strain and particle velocity having stress waves of constant slopes $\pm\, c$. Therefore, the actual stress wave measurements in the field will be concerned with measuring the change in strain and particle velocity due to passage of a constant velocity stress wave (which is propagating at the fundamental wave speed of steel). The implications of this lead to the relationship between force and particle velocity from which wave transmission and reflection theory are built upon.

2.3 Proportionality between Force and Particle Velocity

A thorough discussion on proportionality was provided by Rausche (1981), and is briefly summarized here to illustrate the relationship between force and particle velocity. When the end of an SPT rod is struck by a rigid mass, a zone of compression is generated which creates strain in the rod. The strain causes a compressive force to emerge, and simultaneously produces a motion of rod particles. The rod particles travel with a speed v, which is often referred to as the particle velocity. Since this velocity is associated with a particle of mass m, over time it creates an inertial force $(v/\Delta t)m$ (Newton's second law of motion). This inertia force is in balance with the strain force, and since it takes time for the rod particles to accelerate, the strain in the rod will be transferred at the wave speed of the rod material.

It can be shown that the measured strain and particle velocity in the rod are related to the wave speed by

$$\varepsilon = \frac{v}{c} \tag{2.7}$$

Equation 2.7 can be expanded to represent the stress and force in the rod:

$$\sigma = v\frac{E}{c} \tag{2.8}$$

$$F = v\frac{EA}{c} \tag{2.9}$$

The term EA in Equation 2.9 represents the rigidity, or static stiffness of the rod, whereas the term EA/c represents the dynamic stiffness of the rod (E is the modulus of elasticity and A is the cross-sectional area). EA/c is commonly referred to as the impedance and it is the proportionality constant which relates the stress wave force to its particle velocity. The impedance is the force with which a rod opposes a sudden change of velocity by one unit.

The significance of this relationship is such that when wave propagation exists in only one direction the measured force will always be balanced and proportional with the particle velocity times the impedance, and is commonly illustrated by

$$F = zv \tag{2.10}$$

where

$$z = \frac{EA}{c} \tag{2.11}$$

2.4 Transmission and Reflection of Waves

Boundary conditions in the SPT can be regarded as impedance contrasts existing before and after an interface. These boundary conditions are typically encountered at three locations:

1. the top of the drill rod where the striking end of the hammer meets the struck end of the rod.
2. drill rod joints where the rods are subsequently connected in order to drill to increasing depths.
3. the location of the split-spoon sampler which is in contact with the bottom of the borehole.

One-dimensional wave theory suggests that wave transmission behavior can be characterized by considering force equilibrium and spatial velocity conditions existing at an impedance interface. With these considerations, the pertinent wave transmission and reflection equations can be derived, which form the basis for the stress wave sign convention used in practice (Figure 2.1).

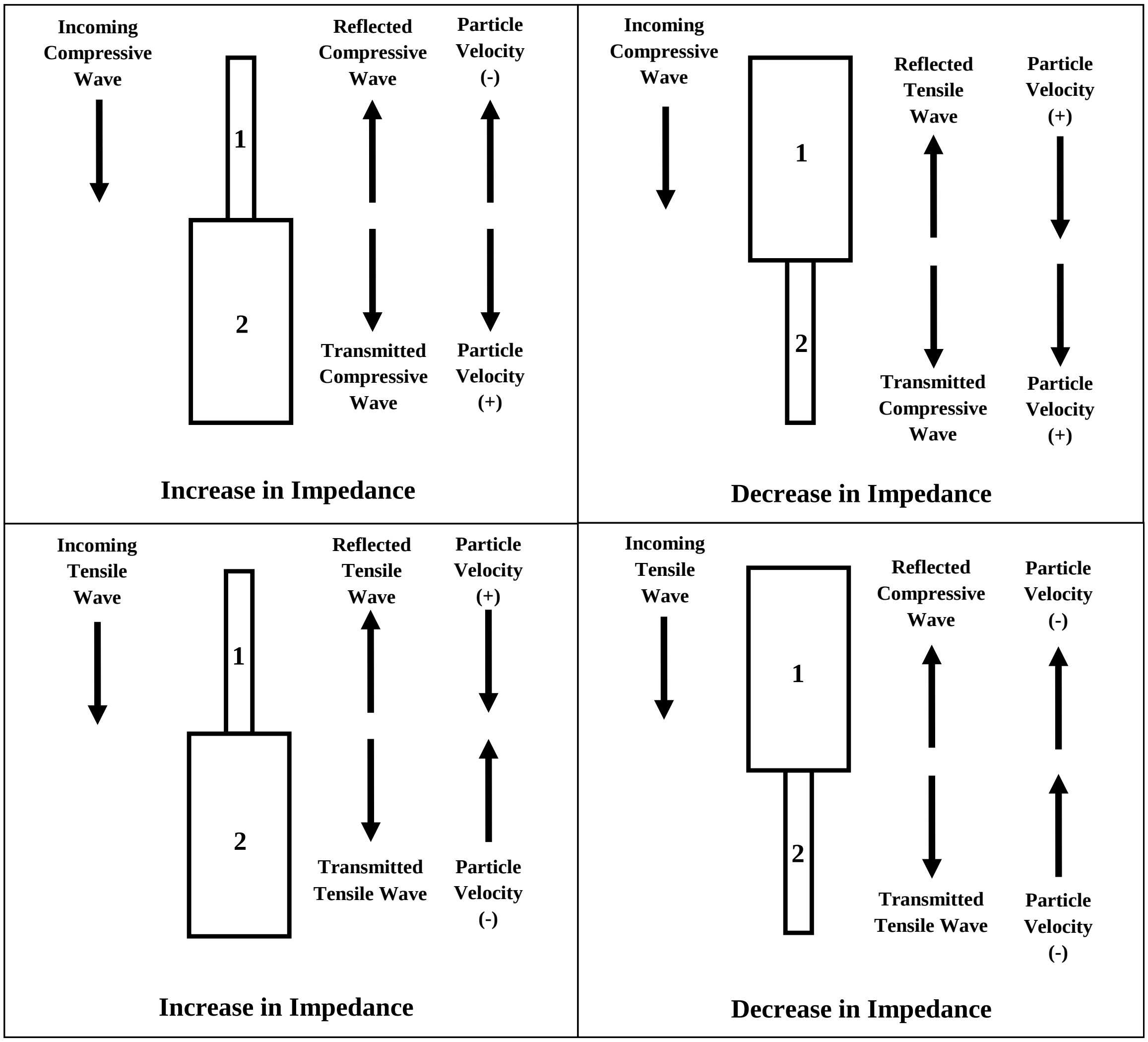

Figure 2.1 Stress wave sign convention (modified from Howie et al., 2003)

The following statements about wave transmission have been paraphrased from Howie (2003) and verbally describe the wave behavior depicted in Figure 2.1:

1. Compressive waves have particle motions that occur in the same direction as wave propagation.
2. Tensile waves have particle motions that occur in the opposite direction of wave propagation.

3. Incident waves will propagate through an impedance interface without changing type, i.e. transmitted compressive waves will remain compressive and tensile waves will remain tensile.
4. An increase in impedance will result in a reflection without change in wave type, i.e. compressive waves will causes compressive reflections.
5. A decrease in impedance will result in a reflection of the opposite wave type, i.e. compressive waves will cause tensile reflections.

2.5 Source of Energy in the SPT

As mentioned in Chapter 1, the SPT is standardized to deliver a theoretical energy of 350 ft-lbs. This theoretical energy is achieved by dropping a 140-lb weight a distance of 2.5 ft. Considering this distance, the theoretical free-fall velocity v_f of the weight can be determined

$$v_f = \sqrt{2gH} \tag{2.12}$$

where

g = Gravitational acceleration

H = Height of free-fall

Because the theoretical free-fall velocity is now known, the theoretical kinetic energy of the hammer can be calculated:

$$E_k = \frac{1}{2} m v_f^2 \tag{2.13}$$

where

m = mass of weight.

During impact, the kinetic energy of the drive weight experiences energy losses that are likely due to friction. The actual kinetic energy available will be less than the theoretical potential energy of 350 ft-lbs. The ratio of these two quantities is called the hammer efficiency E_h, and is one way to classify hammer performance. The hammer efficiency is represented by

$$E_h = \frac{E_k}{PE} \tag{2.14}$$

where

E_h = hammer efficiency

E_k = kinetic energy

PE = theoretical potential energy.

After impact, the kinetic energy of the hammer is progressively transferred to the anvil and drill rod string beneath it. There are additional energy losses during the transfer process, and the actual magnitude of energy transferred to the drill rods will be less than both the theoretical potential energy and the kinetic energy at impact. The ratio of the transferred energy to theoretical potential energy is known as the energy transfer ratio (ETR). The hammer efficiency E_h has the greatest effect on ETR, but the ETR is currently the primary quantity used to assess SPT hammer performance (because it is this energy capable of performing work). The energy transfer ratio is defined as

$$ETR = \frac{EMX}{PE} \tag{2.15}$$

where

ETR = Energy transfer ratio

EMX = Maximum transferred energy to drill rods.

The significance of EMX in equation 2.15 depends on the method used to measure the maximum energy. The first method of energy measurement is called the EFV method, and is currently the only method recommended by ASTM. The second method is called the EF2 method and is typically no longer used due to measurement inaccuracies. A brief explanation of each method follows.

2.6 EFV Method of Energy Measurement

The energy entering the rods can be obtained by considering the amount of work performed on the rods

$$W = \int F dx \tag{2.16}$$

where

W = Work

F = Force

dx = Incremental distance

which can be expressed as a function of time

$$W(t) = E(t) = \int F(t) \frac{dx}{dt} dt = \int F(t) v(t) dt \tag{2.17}$$

where

$E(t)$ = Energy as a function of time

$F(t)$ = Force as a function of time

$v(t)$ = Particle velocity as a function of time

dt = Time increment

These measurements are obtained in the field using an instrumented subassembly containing strain gages and accelerometers (Figure 2.2).

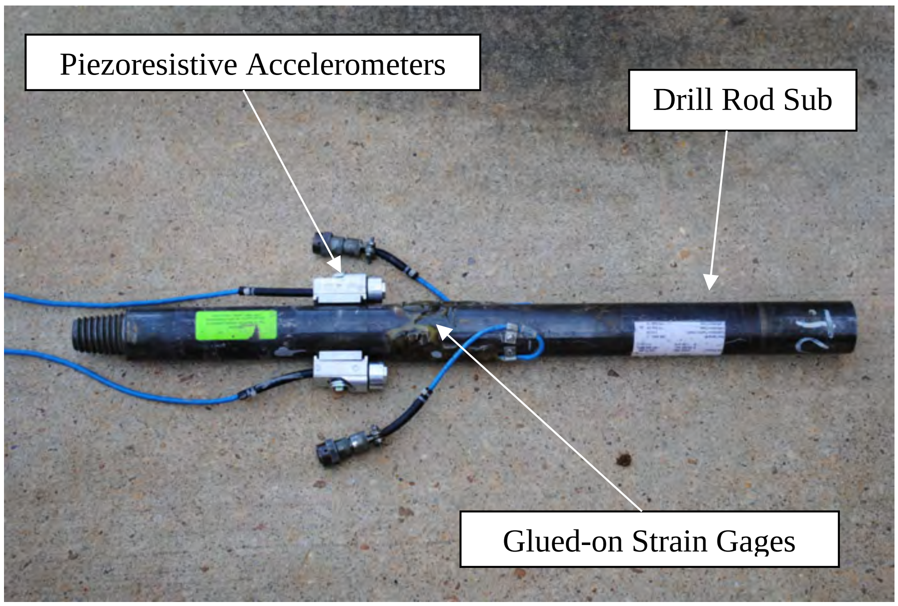

Figure 2.2 Instrumented subassembly

To satisfy the requirements of Equation 2.17, the force and particle velocity can be determined from the measured strain and acceleration from the stress wave by

$$F = \varepsilon EA \tag{2.18}$$

$$v = \int a dt \tag{2.19}$$

where

ε = Measured drill rod strain

a = Measured drill rod acceleration

E = Modulus of elasticity of drill rods

A = Cross-sectional area of drill rods

The total amount of transferred energy from an SPT hammer impact is equal to

$$E(t)_{max} = \int_0^t F(t)v(t)dt \qquad (2.20)$$

which is integrated over the entire time length of the force and velocity record to find the maximum value of transferred energy. This method of energy measurement is called the EFV method since both force and particle velocity measurements are obtained.

2.7 EF2 Method of Energy Measurement

Energy measurements reported prior to the early 90's were likely the result of the force-squared method. The force-squared method, commonly referred to as the EF2 method, exclusively used strain measurements as the basis for energy evaluation in the SPT. During that era, accelerometer technology capable of measuring large acceleration frequencies in the SPT were thought to be unreliable (ASTM, 2010), and by default, only strain measurements were used.

The EF2 method takes advantage of the theoretical proportionality between force and velocity and substitutes the measured force divided by the impedance in place of velocity in Equation 2.17 to obtain

$$E(t)_{EF2} = \frac{c}{EA}\int_0^{t'} F(t)^2 dt \qquad (2.21)$$

where

t' = Time where the incident compression wave goes negative

After substitution, the reciprocal of the impedance is brought to the front of the integral as a constant and the square of the measured force is integrated until the incident wave goes negative.

The energy measured from the EF2 method was often accompanied by a series of correction factors in order to estimate a nominal value of transferred energy. These correction factors, which take into account the position of the load cell, rod length, rod mass, and stress wave velocity dispersion, were later found to be incorrectly applied (ASTM, 2010).

There are additional drawbacks to the EF2 method. Because this method relies on the theoretical proportionality of force and velocity, it can only be accurate provided there are no wave reflections from rod joints or changes in rod cross-sectional area. Furthermore, since force integration is designed to abruptly stop once the initial force signal goes negative, unreliable energy measurements are recorded in certain situations. Large values of energy, higher than the theoretical maximum potential energy, would be measured when testing in high N-value soils. In this situation, the initial compressive wave would fail to go negative (no tensile response) and integration of the reflected compressive wave would continue throughout a longer duration of time and would report artificially high ETR. Similarly, low values of energy would be measured as a result of drill rods having extremely loose rod joints. In this situation, the integrated force signal would prematurely go negative and the integrated force signal would report artificially low ETR.

2.8 Generalized Wave Transmission

This section illustrates the behavior of force and velocity traces measured during an energy test. Consider Figure 2.3 which shows an image of ideal stress wave transmission during the SPT. The x-axis represents the time scale of the wave event and the y-axis represents the force scale. The measured particle velocity is converted to a force by multiplication of the rod impedance, and can be compared to the force signal obtained from the strain measurements. Additionally, the time scale, which is in milliseconds, is often represented as a function of the rod length. Knowing the fundamental wave speed c of the drill rod, as well as the length of the drill rod, the time associated with wave reflections along the length of the rod can be evaluated. The time required for the stress wave to travel down the length of the rod, reflect at the sampler, and then return to the sensors, is known as $2l/c$.

When an SPT hammer strikes the top of the drill rod, it creates a stress wave that propagates down the rod, toward the sampler. Transmission of the stress wave is not instantaneous and is progressively transferred to the drill rods as long as the hammer and rods remain in contact. The incident stress wave created from the impact is compressive, and imparts a positive force (compression) and positive proportional particle velocity (down) to the top of the rod. As the stress wave propagates it eventually passes the location of the sensors, which are often located only a few feet away from the top of the

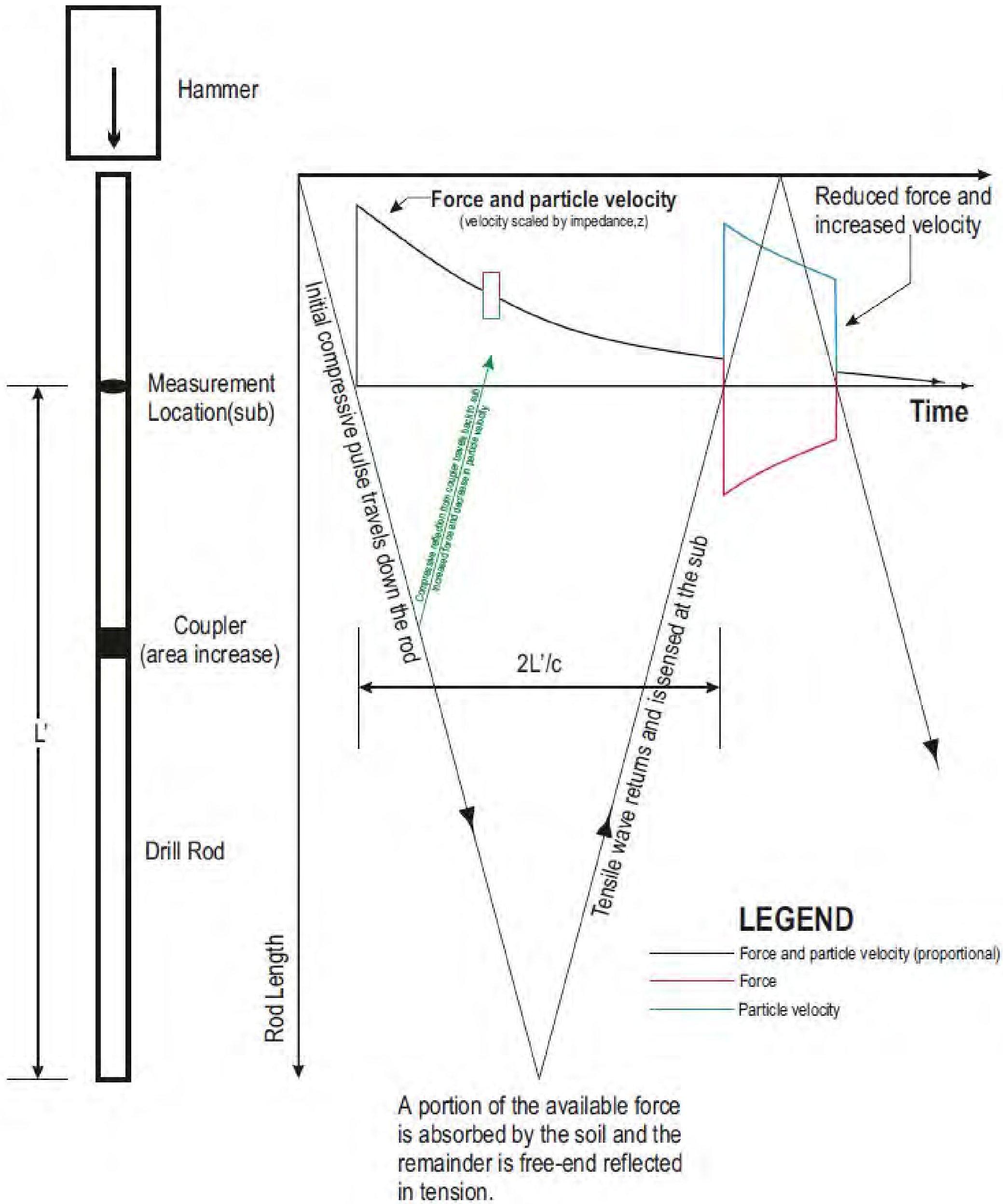

Figure 2.3 Wave transmission (Howie et al., 2003)

rod. After passing the sensors, it continues to travel and will typically encounter impedance contrasts existing at the drill rod joints. These contrasts, which are often due to differences in rod cross-sectional area, generate wave reflections that begin to travel up the rod, and are measured by the sensors at a later time. The type and magnitude of the reflected wave depends on the impedance ratio existing at the joint interface.

At time l/c, the stress wave will reach the sampler and begin to distribute its energy into the ground surface, creating sampler penetration. If the oncoming stress wave force is greater than the resisting force of the soil, a tension wave will be generated, and will reflect from the end of the sampler. This tension wave will travel up the length of the drill rod where its full effect will be measured at the sensors shortly after $2l/c$. Arrival of the tension wave is evident by the decreasing force (negative, tension) and positive particle velocity (down) values of the stress wave. It is the positive, downward particle velocity of the tension wave that begins to pull the rods and sampler down creating penetration. Similarly, if the oncoming stress wave force is less than the resisting force of the soil, a compression wave will be generated, will reflect upward, and will contain a positive force (compression) and negative particle velocity (upward), which will not cause permanent sampler penetration.

2.8.1 Energy Transmission and Sampler Displacement

The magnitude of energy transferred to the rods during an SPT hammer blow depends on the value of the force and velocity signals measured at the sensors. The measured sampler displacement also depends on the value of the measured velocity, which is determined by integration of the velocity signals (double integration of the acceleration signals).

It should be briefly mentioned that energy transmission in the SPT can be divided into two categories. The first category is long drill rod energy transfer, which is the simplest case, and generally only depends on the hammer's efficiency and rod cross-sectional area.   For long drill rods (rod lengths greater than about 50 ft), most of the hammer's energy is transferred to the drill rods prior to the drill rod separating from the hammer during penetration. The second category is short rod energy transfer, and is a more complicated case to consider. Energy transmission for short rods (rod lengths less than 50 ft) depends on the efficiency of the hammer, rod cross-sectional area, secondary hammer impacts, and to some extent, the soil penetration resistance. Three examples are provided below in order to illustrate both types of behavior. The first two examples will discuss the energy transfer behavior for short drill rods, and the third example will discuss the energy transfer for long drill rods.

Figure 2.4 shows a representative force and velocity trace (top) and an energy and displacement trace (bottom) obtained from a CME automatic hammer. The drill rod size was AWJ and the rod length was 19.3 ft (short drill rod classification). The total rod length includes part of the instrumented subassembly, the drill rod combination, and the split-spoon sampler. The SPT blow counts for the three 6-inch increments were 7-13-20. However, this figure shows the wave trace from the fourth blow of the SPT sequence and is representative of low penetration resistance.

After impact, and prior to time $2l/c$, the force and proportional velocity created by the stress wave are overlapped and there is a steep increase in measured energy being transferred from the hammer. There is also an increase in the measured displacement of the drill rod due to the displacement of rod particles at the top.

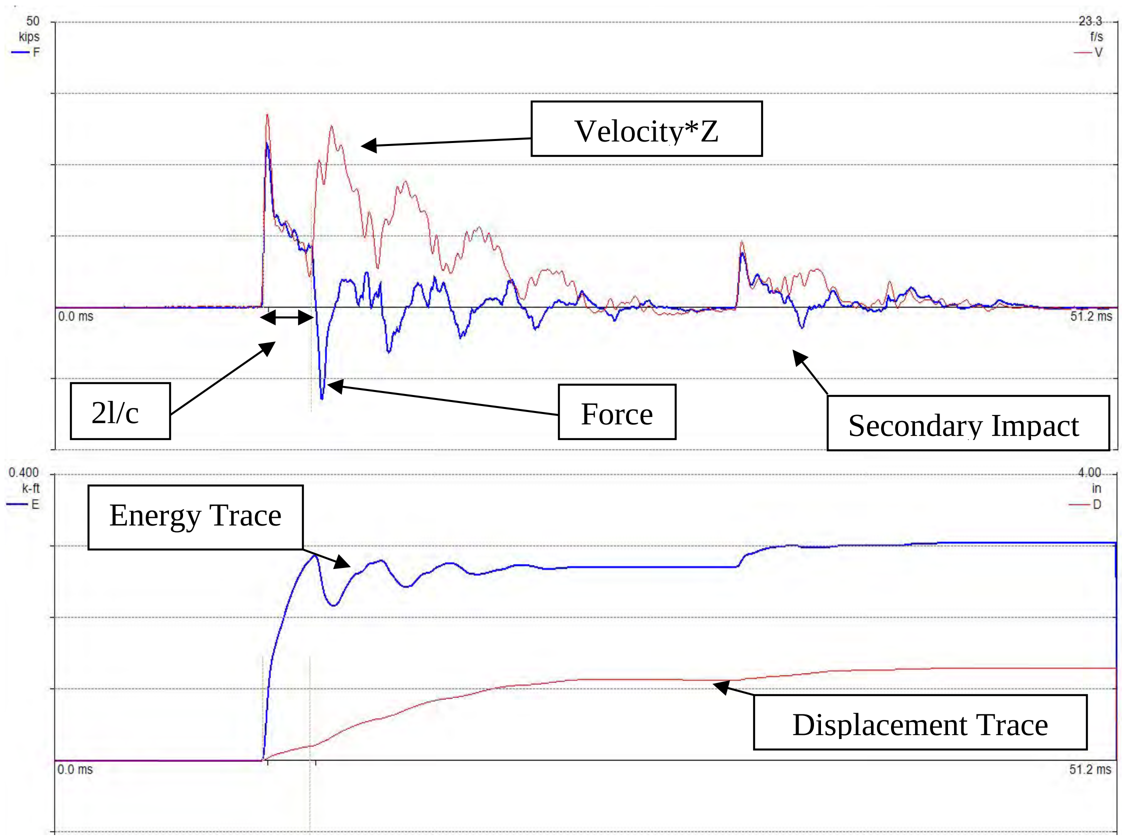

Figure 2.4 EFV & E-D Trace-short rod (19.3 ft)-low penetration resistance

As previously mentioned, when the stress wave reaches the sampler (l/c) it begins to distribute its energy to the soil, and generates a tension wave that reflects up the drill rod. Shortly after time $2l/c$, the full magnitude of the tension wave will arrive at the top of the rod and create separation between the hammer and rods. The initial separation distance between the hammer and drill rods depends on the resisting force of the soil and the magnitude of stress wave energy distributed to the soil from the incident wave. Since the value of force and velocity are greater than zero prior to the arrival of the tension wave, there is still remaining energy in the hammer that has not yet been transferred. Thus, the transfer of energy is prematurely cut off by the arriving reflected tension wave.

During the penetration process, and after the hammer and rods have separated, the energy inside of the drill rod repeatedly cycles through the drill rod, increasing in the downward transmission and decreasing in the upward transmission (but does not yet exceed the energy measured at $2l/c$). Each wave cycle transmits a portion of its energy into the ground surface, and since the particle velocity is always positive (down), a stepwise displacement pattern is created.

At a later time, the hammer strikes the drill rods a second time. This is known as a secondary hammer impact and is evident by the positive force and positive particle velocity near the end of the time scale in Figure 2.4. The additional energy transmitted from this secondary impact produced a slight increase in permanent penetration of the sampler. The maximum measured ETR for this wave trace was 86.4 % with an estimated sampler penetration of 1.3 inches (N-value ~ 9 BPF).

The second example is for the same short rod combination (19.3 ft) and same SPT hammer system (CME Auto). The force and velocity trace (top) and the energy displacement trace (bottom) shown in Figure 2.5 are representative of hammer blow number thirty-eight out of the 7-13-20 SPT sequence. This figure therefore illustrates the energy transmission process during the end of SPT sampling in moderately dense soil.

The energy transmission for this example is approximately the same as the previous example prior to time $2l/c$ and has the same initial increase in energy and displacement. At time l/c, the energy from the stress wave reaches the sampler and begins to distribute its energy to the soil. Since the penetration resistance is now greater during the end of driving, the soil accepts more of the stress wave energy from the incident wave and there is less wave activity after $2l/c$.

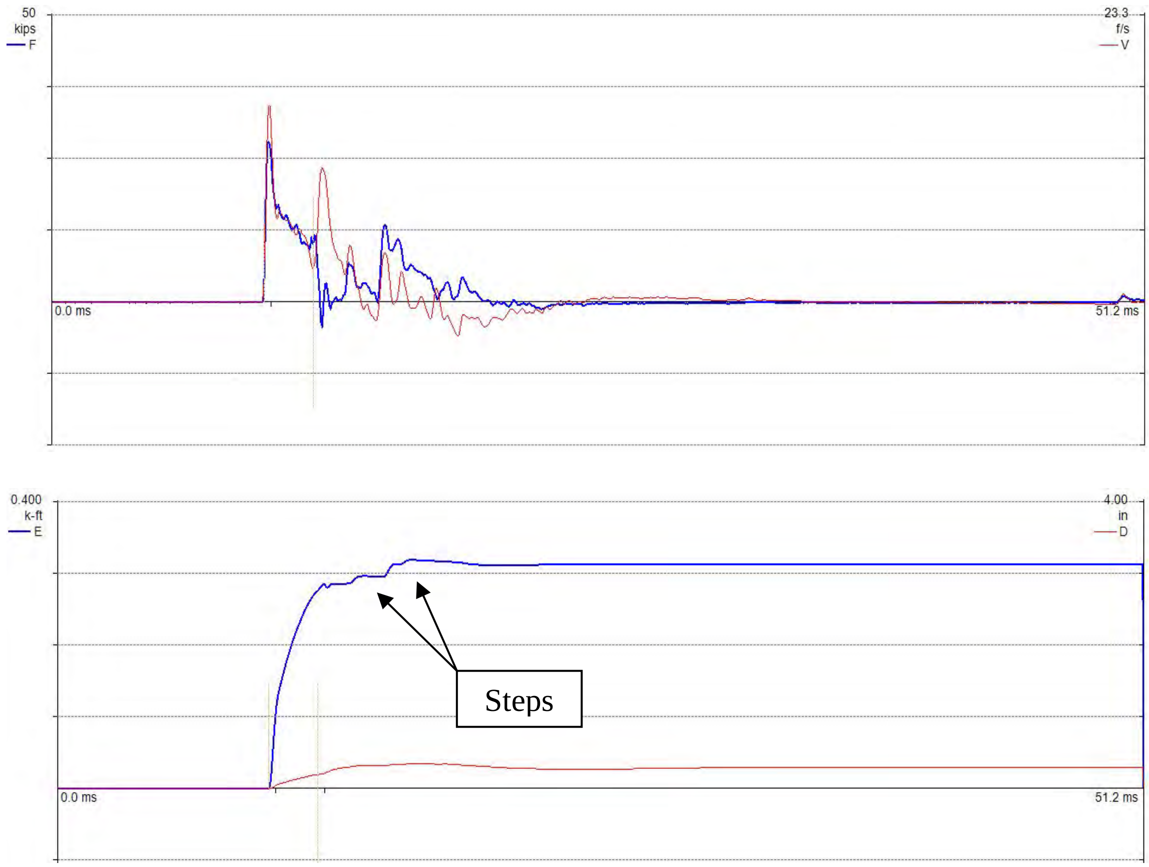

Figure 2.5 EFV & E-D Trace-Short Rod (19.3 ft)-moderate penetration resistance

A small tension wave emerges from the bottom of the sampler, the full magnitude of which is measured shortly after $2l/c$. Because the soil is dense, the sampler penetration is reduced, and the SPT hammer generally follows "better" or has more contact with the drill rods during the penetration process. The increased hammer contact allows more of the hammer's energy to be transferred to the top of the drill rods. The additional hammer energy is measured at a later time and can be seen from the second step in energy between time $2l/c$ and $4l/c$ in Figure 2.5. Just after $4l/c$, there is a secondary hammer impact that transmits the remaining hammer energy, and only slightly contributes to permanent sampler penetration. This secondary impact occurs much sooner than that of the previous example. This is because the separation distance between the rods and hammer is much less when sampling in moderately resistant soil. As the soil resistance increases, the time associated with a secondary hammer impact will decrease, and will occur earlier on the time scale (will move to the left on the scale). The maximum measured ETR for this wave trace was 90.6 % with an estimated sampler penetration of 0.35 inches (N-value ~ 34 BPF).

The final example is for the case of long drill rods. The rod length is 49.3 ft and the SPT blow count sequence is 7-22-34. The wave trace shown in Figure 2.6 is representative of the first hammer blow. Perhaps the most significant characteristic to notice in this wave trace is that the values of force and proportional velocity are approaching zero (x-axis) at $2l/c$. This is an indication that the hammer has transmitted the majority of its energy to the drill rod before arrival of the tension wave. After $2l/c$, the transfer of energy and sampler displacement is similar to that of the first example with low penetration resistance and the stress wave can be seen cycling throughout the drill rod creating a stepwise displacement pattern.

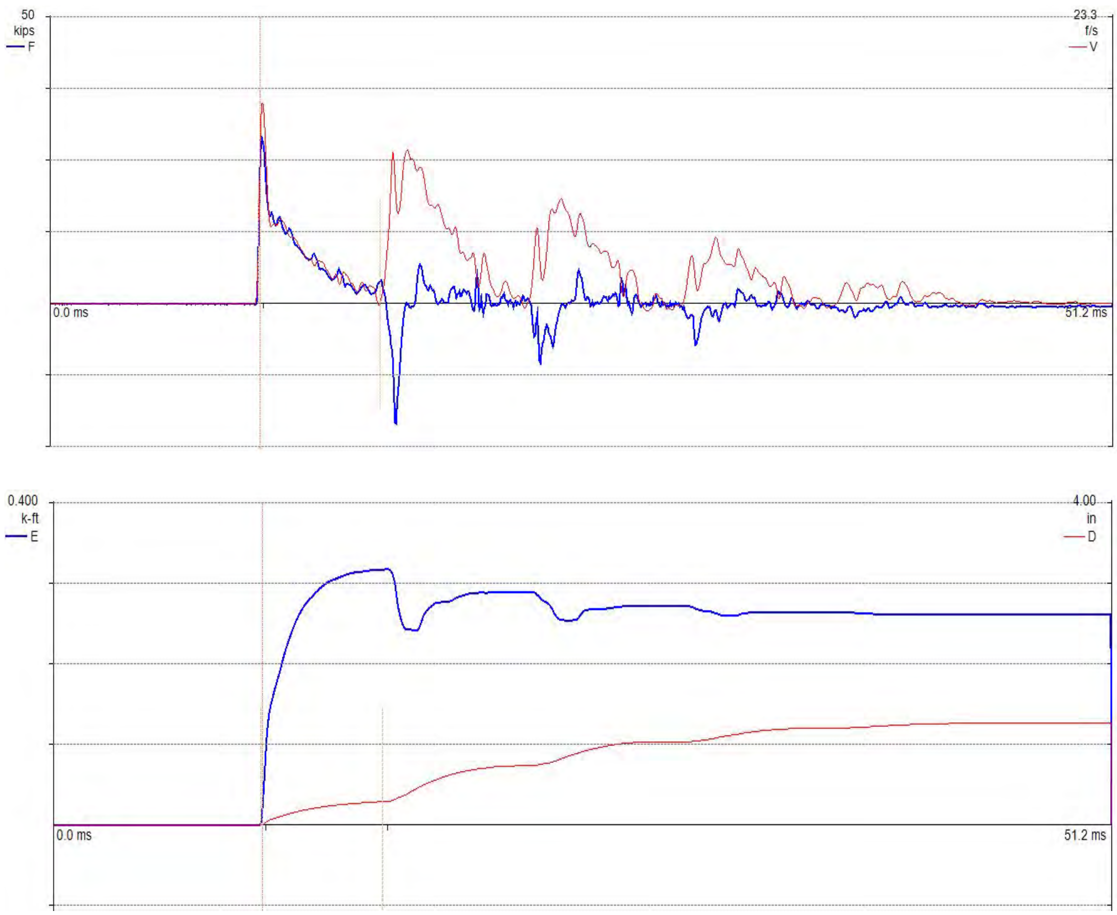

Figure 2.6 EFV & E-D Trace-Long Rod (49.3 ft)-Low Penetration Resistance

For this case, there is no dependency on the interaction between the hammer and rod during the penetration process, and therefore does not depend on soil resistance. Secondary hammer impacts are also not present. Secondary impacts are sometimes noticed for long drill rod combinations. However, the magnitude of the force and velocity is very small which generally does not contribute to measured energy and permanent sampler penetration. The maximum measured ETR for this case was 90.2% with an estimated sampler displacement of 1.26 inches.

One last statement should be made about energy transfer between the short rod and long rod cases previously discussed. Based on the wave behavior of Figures 2.5 and

2.6, the transferred energy for the long rod case can be measured during the short rod case when the soil penetration resistance is large enough. The measured ETR for the short rod case driven into dense soil was 90.6% and the ETR measured for the long drill rod case was 90.2 %. The average measured ETR for all SPT hammer blows for the long rod combination was 90.6%, which is likely to be the baseline transfer efficiency for this CME automatic hammer system.

2.9 CME Automatic Hammer

The Central Mine Equipment Company (CME) patented the automatic hammer in the fall of 1983 (Rassieur, 1983). The automatic hammer provides a relatively consistent hammer impact and subsequently less variation in transferred energy compared to the manual hammer system.

2.9.1 Hammer Automation

The drive weight lifting mechanism is the device that automates the dynamic impact in the SPT. The lifting mechanism is attached to the side of the cylindrical housing tube (Figure 2.7). The lifting mechanism consists of a lower drive sprocket, an upper idler sprocket, sprocket bearings, a drive chain, a chain guide, and a lifting lug. A hydraulic motor is attached to the outside of the housing tube and a portion of this motor extends into the housing where it is bolted to the drive sprocket. The 140-pound drive weight is also located inside the housing tube. The drive weight, which is approximately 19.75 inches in length, is made of lead and is encased in a steel sleeve.

Automation of the drive weight begins when supply pressure from the rear engine block motor is transferred to the hydraulic motor of the hammer. Once this occurs, the sprockets and chain will begin to rotate. The lifting lug, which is attached to the chain, rotates with the chain at the same speed and eventually lifts the drive weight up off of the anvil. During upward travel, and at the end of the chain length, the drive weight is thrown upward a certain distance as the lifting lug releases the weight and begins to travel back down to the location of the motor where it can lift the drive weight once

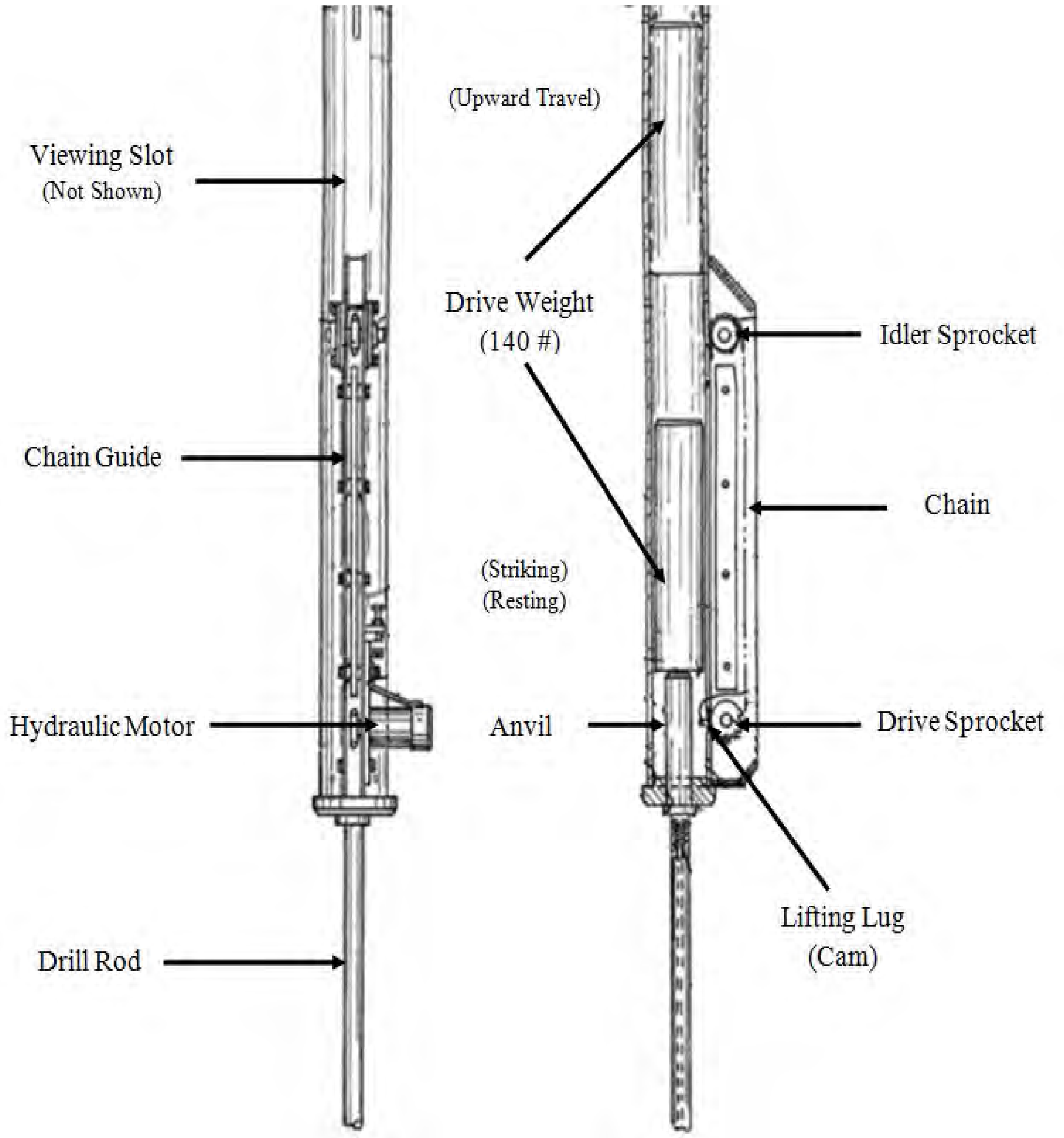

Figure 2.7 CME hammer operational components (modified from Rassieur, 1983)

again. Thus, the lifting lug acts as a cam that turns the rotational motion of the chain and sprocket system into linear, or vertical motion of the drive weight.

It is important to emphasize that at the top of the chain (location of idler sprocket) the lifting lug does not actually drop the drive weight as the commonly used phrase “drop height” suggests. Instead, the lifting lug throws the drive weight a certain distance to achieve the so called drop height. Fall height is a more accurate description that should be used when describing the end result of the releasing mechanism. As will be discussed in Chapter 3, the drive weight throw height is a function of the hammer operation rate.

2.9.2 Drive Weight Viewing Slot

An often overlooked feature of the CME automatic hammer is the viewing slot located on the housing tube just a few inches above the idler sprocket. The viewing slot window allows personnel performing the field investigation to verify whether or not the correct drive weight fall height is being achieved. For most geotechnical applications, the prescribed fall height is 30 inches with an allowable tolerance of ± 1 inch. However, it is not uncommon for organizations to manually reduce this distance in order to achieve a reduced prescribed value of transferred energy (often 60%). Nevertheless, the fall height can be visually monitored by marking the viewing slot using known dimensions from the bottom of the hammer housing. If a reduced fall height is desired, modification of the viewing slot window will be necessary. Figure 2.8 depicts the dimensions recommended by CME in order to meet a 30 inch fall height requirement.

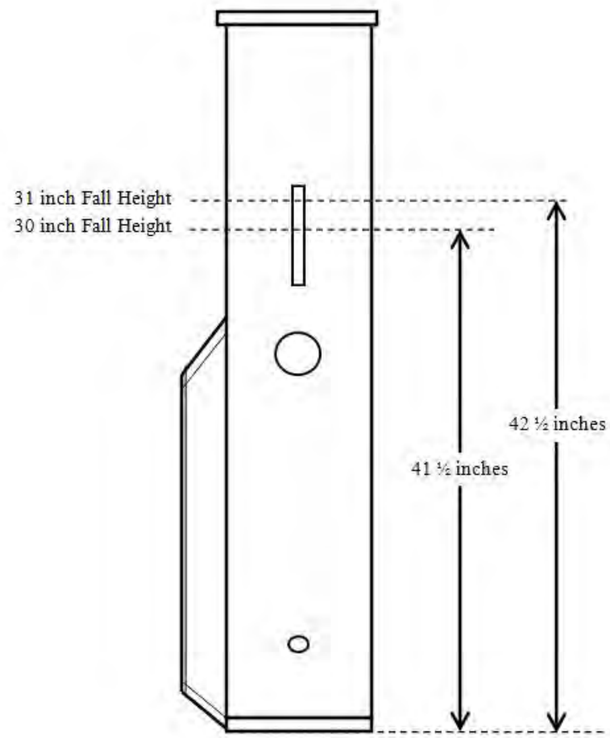

Figure 2.8 Drive weight viewing slot (dimensions from CME operations manual)

CHAPTER 3: LITERATURE REVIEW

3.1 ASTM D 4633-10

ASTM D 4633-10 (ASTM, 2010) describes the test method for performing energy measurements during the standard penetration test. This standard documents the significance and use of the test along with the appropriate testing equipment and procedures that should be followed in order to obtain reliable hammer transfer efficiency. The most prominent details of the standard include:

- The standard recommends force and velocity measurements to characterize the stress wave energy (EFV method).
- Data acquisition technology: The standard allows both digital and analog data acquisition systems that meet the anti-aliasing frequency requirements. For analog systems, the sampling rate should be at least 5 times the low-pass filter frequency. For digital systems, the sampling rate should be at least 10 times the low-pass filter frequency.
- Force measurement: The standard recommends using an instrumented rod section with symmetrically arranged foil strain gages in a full bridge circuit.
- Acceleration measurement: The standard requires a minimum of two accelerometers capable of measuring accelerations to at least 10,000 g, and which have a useable frequency response to at least 4.5 kHz.
- The standard recommends that energy evaluation of hammer systems be limited to moderate N-values within a range of 10 to 50 blows per foot.

The previous recommendation, based on the 2005 standard, recommended an N-value range between 5 and 50 blows per foot.

- The standard reports that energy evaluation of hammer systems is more reliable when the drill rod length is at least 30 ft.
- The energy results should be averaged and reported for impacts associated with the observed N-value. The 2005 standard did not have this limitation and apparently allowed all energy measurements to be averaged, not just those associated with the N-value.
- The standard recommends performing energy measurements for at least 3 SPT sampling depths, with 5 depths preferred. This statement means that enough SPT energy data should be obtained in order to accurately characterize the average energy transmission for a given hammer system.
- The prime method of assessing data is to evaluate individual pairs of force and velocity signals. Due to small wave reflections that are often generated from the bottom of the subassembly, the Force and Velocity Proportionality (FVP) method of assessing data quality is not as accurate in SPT testing as it is in pile driving.

  Individual force and velocity signals should return to zero at the end of the time record. It is common for the velocity signals to "wander off in space" during testing. This is caused by the sensors coming loose during testing or even a malfunction of the sensors.

3.2 EFV Transfer Efficiency in Literature

Table 3.1 contains a summary of energy transfer efficiencies obtained using the force and velocity method of energy measurement. The data in the table was compiled from documented efficiencies from years ranging from 1994 to 2010. While constructing the table, it was found that the level of data defining each ETR was not consistently reported. Some studies reported the number of average records while other studies reported the number of overall averages, which would correspond to the average of each average record for a single testing event. Nevertheless, the significance of the ETR should be based upon the level of data used to determine its value As shown in Table 3.1, the range of reported ETRs for non-CME automatic hammers varied from 49% to 82% with an average of 70.2%. The range of ETRs from the CME automatic hammer group was from 75% to 84.5% with an average of 80.7%. Manual hammer systems in the table experienced ETRs that ranged from 35% to 70.2% with an average of 57.8%.

Although this study is focused on evaluating the variation of energy transfer for the CME automatic hammer, the transfer efficiencies for other automatic hammers, as well as manual hammers, have also been included in the table since they were acquired using the EFV method. The coefficient of variance (COV) for each study was either documented in the literature or calculated from the reported standard deviation. The COVs were provided to show a normalized measure of dispersion for comparative purposes (ratio of standard deviation to the average).

Table 3.1 Historical EFV ETR

Year	Study	Hammer Description	# of Hammers	# Averages	# Overall Averages	ETR	STD	COV
1994	Seattle ASCE Field Testing Program (Batchelor et al., 1994)	Auto - CME	1	8	-	81.4	-	5.8
		Auto - Other	1	5	-	68.5	-	10.8
		Auto -Other (Mud Rotary)	1	4	-	72.8	-	5.8
		R&C - Safety	1	8	-	51.4	-	4.8
		R&C - Safety (300 lb Hamm	1	5	-	74.7	-	3.2
		Safety w/ Spooling Winch	1	8	-	23.1	-	17.8
1997	MnDOT (Lamb, 1997)	Auto - CME	2	-	-	80	2	2.5
		Auto - Rupe	1	-	-	75	3	4.0
		R&C - Safety	1	-	-	67	6.5	9.7
1997	Utah State University (Butler, 1997) (Data from GRL Compiled by Dr. Caliendo for G.Goble)	Auto - CME	-	-	10	75	-	9.0
		Auto - Hydraulic	-	-	5	69	-	15.0
		Auto - Other	-	-	6	49	-	13.0
		R&C - Safety	-	-	15	63	-	12.0
		Donut	-	-	3	43	-	22.0
		Spooling Winch	-	-	3	35	-	8.0
1999	FDOT - University of Florida (Davidson et al., 1999)	Auto - CME	12	101	-	80.1	8	10.0
		Auto - Diedrich	2	12	-	76	5.3	7.0
		R&C - Safety	43	227	-	66	10.7	16.2
2001	MDOT - University of Maryland (Aggour and Radding, 2001)	Auto - CME	1	12	-	81.4	3.9	4.8
		Safety	1	12	-	70.2	8.5	12.1
		Donut - Sprague & Henwood	1	8	-	63.5	4.3	6.8
2005	CALTRANS (Liebich, 2005)	Auto - CME	2	7	-	84.5	5.9	7.0
		Auto - Diedrich	2	8	-	82	5.6	6.8
		Safety Driver	6	43	-	54.6	11.5	21.1
2010	NCDOT (Valiquette et al., 2010)	Auto - (CME & Diedrich)	20	-	20	78.6	5.5	7.0
		Manual - Unknown	8	-	8	62.3	9.8	15.7
2010	VTrans (Kelley and Lens, 2010)	Auto - CME	6	-	6	82.5	-	-
		Safety	2	-	2	63.3	-	-
		Safety Driver (Mobile)	1	-	1	48.1	-	-

3.3 Variation of Transfer Efficiency

The COVs for CME automatic hammers listed in Table 3.1 ranged from 2.5% to 10%. The range of COVs for all other automatic hammers was from 4% to 15%. The manual hammer category experienced COVs that varied from 3.2% to 22 %, which is about twice the variation of the CME group. The details from two prominent SPT energy investigations are summarized below.

3.3.1 FDOT Study

In 1997, an extensive SPT energy investigation was performed by Kimberly Spoor for the Florida Department of Transportation (FDOT) (Davidson et al., 1999). The SPT energy program consisted of performing EFV energy measurements on 43 manual hammer systems as well as 14 automatic hammer systems (12 CME) owned by FDOT and their consultants. During the testing program, numerous drill rig manufacturers had their SPT hammers calibrated and the results from the investigation are depicted in Table 3.2. The overall ETR average for each drill rig type is shown in the second column of the table. The third column shows the standard deviation of ETR test depth averages between different drill rigs of the same model. Apparently, the fourth column represents an overall standard deviation average of the ETR standard deviation measured from individual hammer blows for a given drill rig type.

The data in the third column in Table 3.2 shows that the standard deviation of average energy measured between sample depths for the CME automatic hammer group ranged from 3.9% to 10.1% ETR. Similarly, the energy data in the fourth column shows that the average standard deviation measured between hammer blows were somewhat smaller and ranged from 1.9 % to 2.4 % ETR. The overall ETR for 12 CME automatic hammers in their study was reported to be 80.1% with an overall standard deviation of 8% ETR and a COV of approximately 10% (From Table 3.1).

Table 3.2 Summary of FDOT energy measurements (Davidson et al., 1999)

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

3.3.2 NCDOT Study

Another impressive SPT energy investigation was documented in 2010 on drill rigs owned by the North Carolina Department of Transportation (NCDOT) and their consultants (Valiquette et al., 2010). The testing program, which was conducted approximately five years prior to the release of their report, consisted of one boring of energy measurements per hammer system. During this time period, engineers from Goble, Rausche, and Likins Engineers Inc. (GRL) obtained EFV energy measurements on twenty automatic hammer systems and eight manual safety hammer systems. The total number of hammer blows evaluated for each drill rig ranged from 71 to 489 with an overall drill rig average of 271 hammer blows. Drill rod types used in their study were either AW or AWJ sized drilling rods. Although not listed in their report, the drill rig manufacturers were either CME or Diedrich models . The quantity of each type of drill rig was not reported. Figure 3.1 provides a visual summary of the measured energy variation for each drill rig obtained during the testing program.

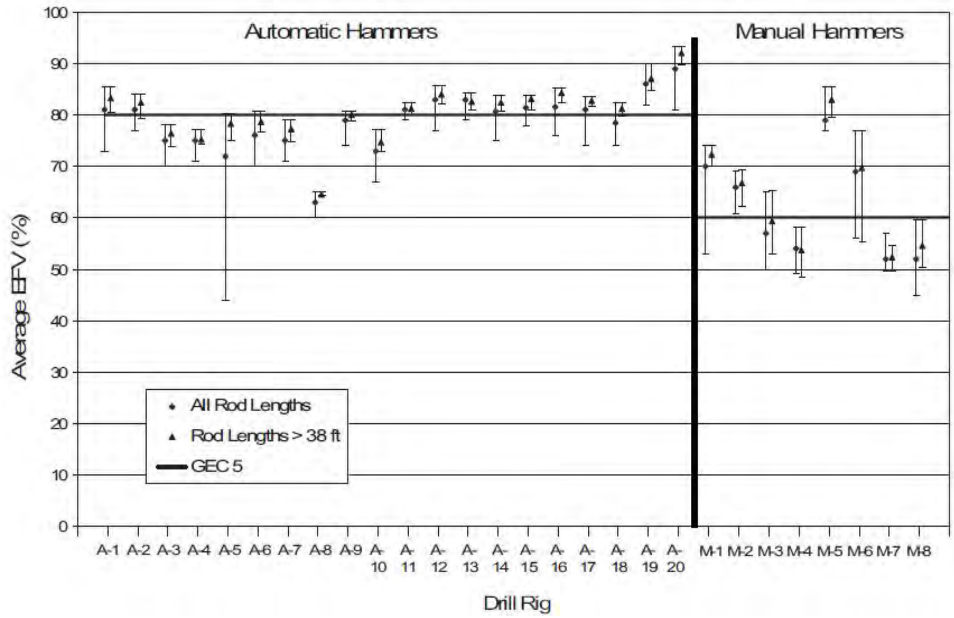

Figure 3.1 NCDOT variation of transfer efficiency (Valiquette et. al, 2010)

In addition to the graphical summary shown in Figure 3.1, the NCDOT report included a summary table documenting the overall ETR average for each drill rig as well as the standard deviation of energy measured between hammer blow counts (Table 3.3).

The data from Table 3.3 show that the standard deviation of EFV energy measured between hammer blows for each drill rig are similar to that determined from the FDOT investigation. The standard deviation values are relatively small, the majority of which have a value less than about 2% ETR. The overall ETR average for the twenty automatic hammers in the NCDOT study was 78.6 % with an overall standard deviation of 5.5 %. The overall COV was calculated as 7 % (Table 3.1).

Table 3.3 Summary of NCDOT energy measurements (Valiquette et al., 2010)

Drill Rig I.D.	Average Uncorrected Efficiency, All Rod Lengths	Average Standard Deviation from Blow to Blow
A-1	81.5	2.12
A-2	80.6	1.71
A-3	74.7	2.29
A-4	74.3	1.83
A-5	71.6	3.41
A-6	75.6	2.04
A-7	75.4	1.68
A-8	63.1	1.75
A-9	78.6	2.01
A-10	73.5	1.42
A-11	81.1	1.78
A-12	82.7	1.53
A-13	82.3	1.77
A-14	80	3
A-15	81.5	1.53
A-16	81.7	1.15
A-17	80.8	1.06
A-18	78.4	1.56
A-19	85.2	5.54
A-20	89.4	1.5

3.4 CME Hammer Operation Rate

In 1999, an SPT energy study was performed for the Bureau of Reclamation on CME automatic hammers (Farrar and Chitwood, 1999). The objective of the study was to determine hammer performance and evaluate the effect of the hammer operation rate on energy transmission. The study found that the CME hammer is a rate-dependent hammer, and that the energy delivered to the drill rods will be a function of the hammer fall height, which depends on the speed of the hammer lifting assembly (and therefore on the engine throttle speed and hydraulic flow control settings). Figures 3.2 and Figure 3.3

below highlight the results of the study and show the variation of fall height and transferred energy when the hammer operation rate is set above or below the CME factory settings of 50 to 55 blows per minute (BPM).

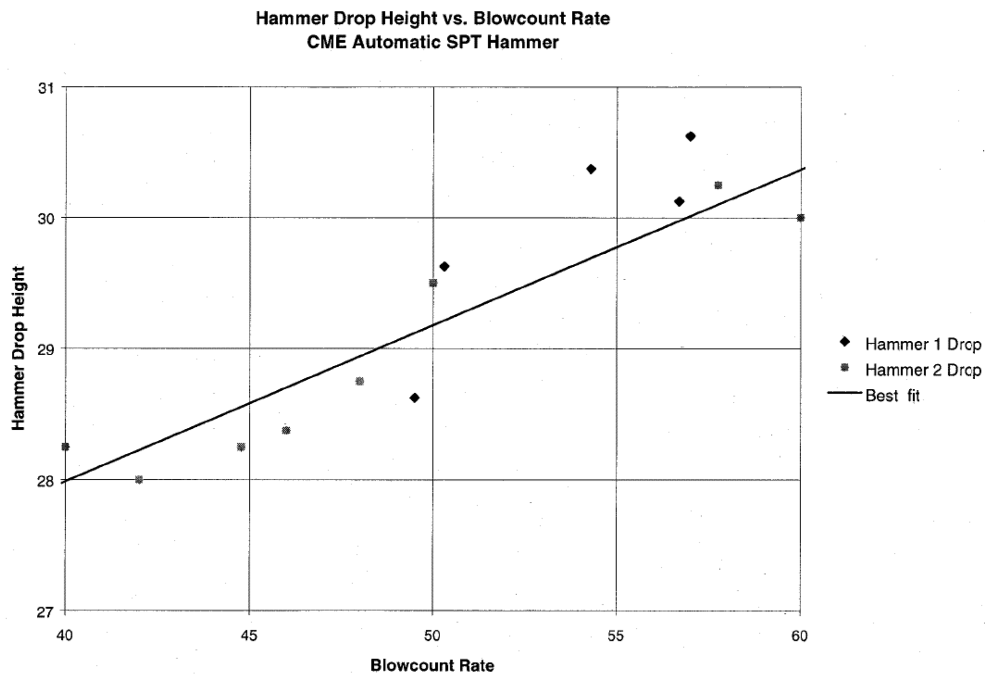

Figure 3.2 Drop height vs. hammer operation rate (Farrar and Chitwood, 1999)

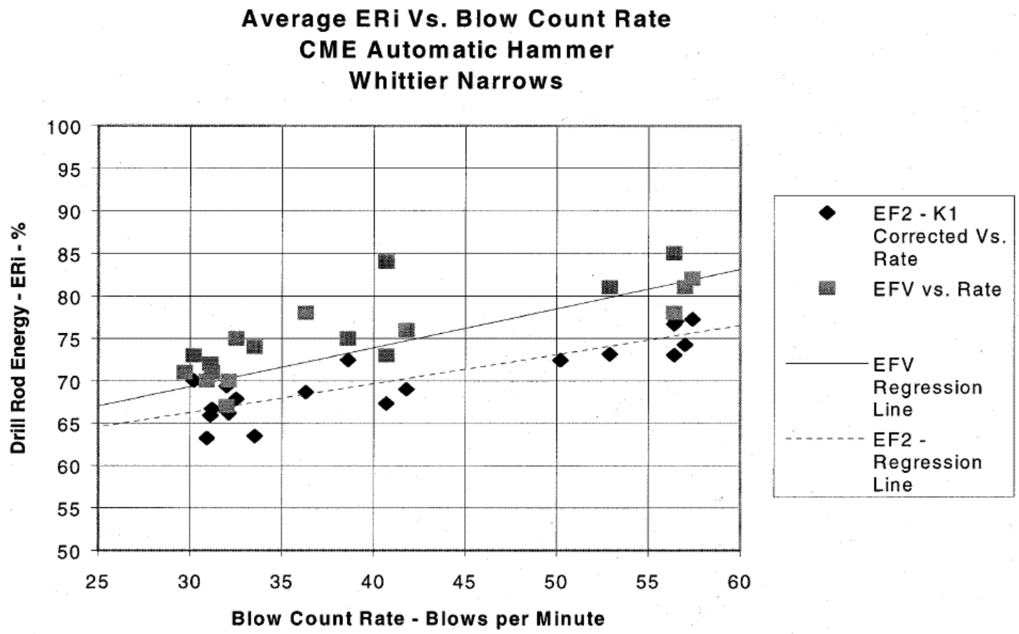

Figure 3.3 Drill rod energy vs. hammer operation rate (Farrar and Chitwood, 1999)

Perhaps the most alarming finding of the study is that when the CME hammer operation speed is set too high, the falling drive weight will strike the lifting lug prior to striking the anvil. If this occurs, a portion of the kinetic energy of the drive weight will be transferred to the mechanical components inside of the housing tube prior to striking the anvil. Farrar notes that this can occur when the rate is set near or above 60 BPM. A picture of the drive chain and lifting lug is provided in Figure 3.4.

Indeed, this type of malfunction happens in practice. Figure 3.5 shows a PDIPLOT summary of energy measurements provided by a private sector consultant. Reportedly, the data was obtained from a drill rig performing a routine SPT investigation. As can be seen from the figure, the hammer was operating slightly above 60 BPM. This high operation rate resulted in the drive weight striking the lifting lug prior to striking the anvil. The measured ETR pattern proves to be erratic and extremely low, producing

ETRs less than 50%, as would be expected if the drive weight free-fall was obstructed in any way.

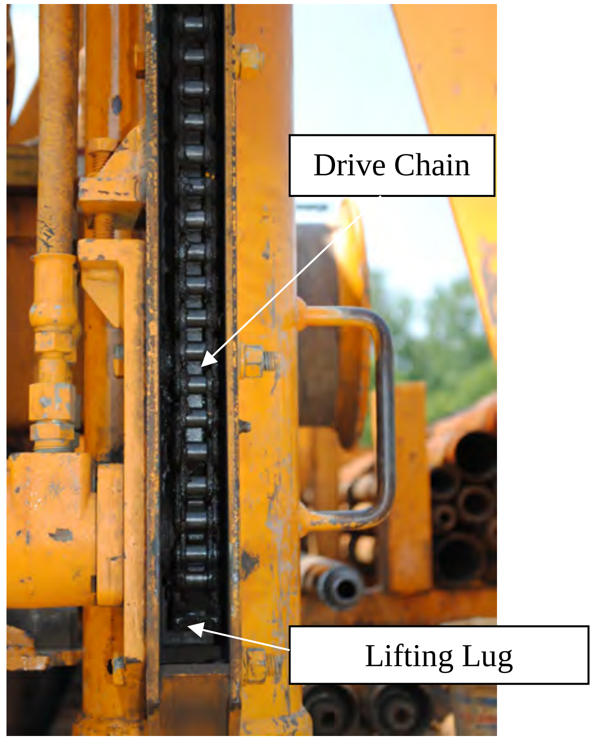

Figure 3.4 Drive chain and lifting lug

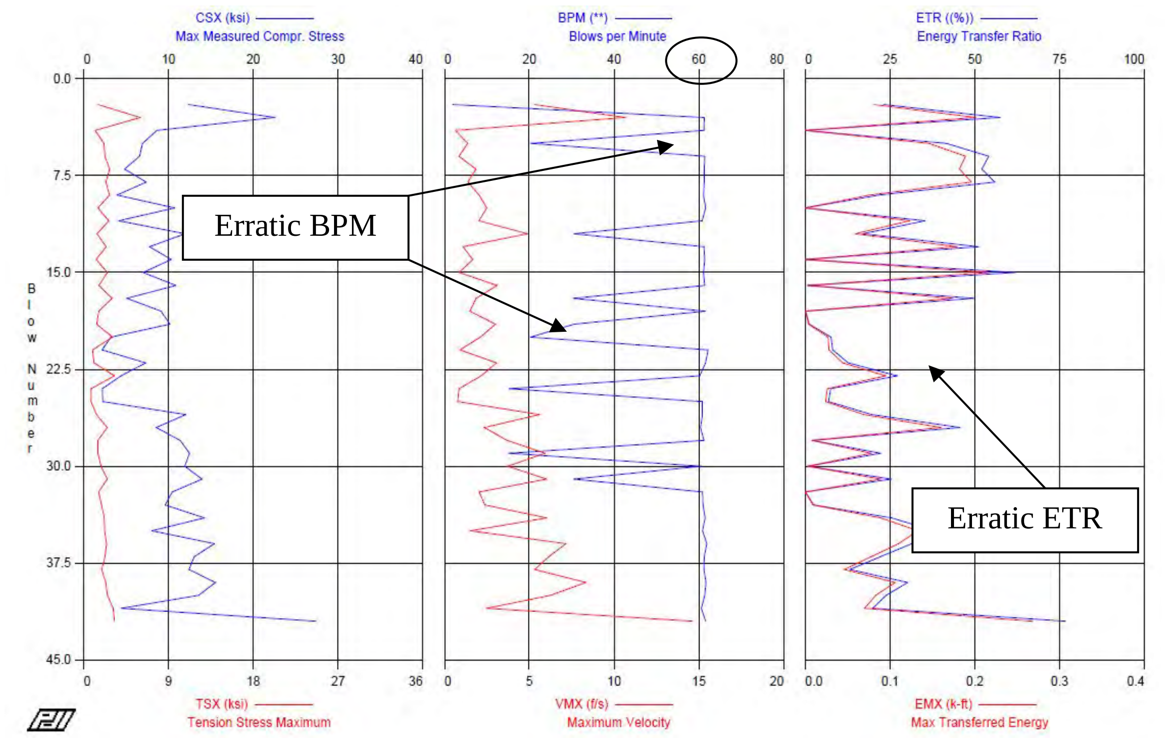

Figure 3.5 CME hammer malfunction

3.5 Rod Length and Energy Transmission

A considerable amount of work has been performed over the last 30 years in order to determine an approximate relationship between drill rod length and energy transfer in the SPT. Both theoretical and experimental investigations conclude that there is a reduction in transferred energy for shorter drill rods compared to the average baseline energy that would be measured for longer rods. The consequences of this reduced energy effect are twofold:

1. Energy measured at shallow depths may not accurately characterize the true hammer baseline energy and would report a reduced value of transfer efficiency. N-values corrected with the reduced transfer efficiency (Equation 1.1) would produce smaller corrected N-values compared to N-

values corrected with the baseline value obtained from longer rods. This result may be conservative in some geotechnical applications.

2. N-values measured at shallow depths would not represent the N-value that would have been obtained if the baseline energy was available to perform work on the soil. The reduced energy from short rod lengths would produce less sampler penetration per blow and may result in a larger N-value than would be obtained if the baseline energy were available.

Attempts at quantifying the relationship between rod length and energy transfer, as well as proposing correction factors to account for the expected energy losses, have been proposed by many researchers. The original correction factors, which were based on the force-squared method, were desired because of the limited force integration time. The EFV method does not have the same integration limitations. However, the general trend of reduced energy transmission is still the same, but to a lesser degree. Details from three prominent rod length investigations are outlined below.

3.5.1 Palacios Study

A theoretical investigation into the behavior of rod length and energy transfer was performed by Schmertmann and Palacios at the University of Florida (Palacios, 1977). Their method of investigation was based on the force-squared method of energy measurement, which was the prevalent method during that era.

The SPT study included energy measurements on four different rod sizes with rod lengths varying from approximately 10 ft to 75 ft. Based on trends in their data, they concluded that for short rod lengths the returning tension wave prematurely terminated the incident compression wave energy due to separation of the drive weight and anvil. Because of the time integration limitations inherent to the force-squared method, the remaining energy content that would have been measured for the case of an infinite rod was, by necessity, estimated using correction factors derived from theoretical wave mechanics. After modifying stress wave theory from Fairhurst (1961), Palacios was able to express the hammer transfer efficiency η_l as a function of rod length (Schmertmann and Palacios, 1979) where

$$\eta_l = (1 - K^n) + \left(\frac{l}{L_h} - n\right)\frac{4\alpha K^n}{(1+\alpha)^2} \qquad (3.1)$$

with

$$K = \left[\frac{1-\alpha}{1+\alpha}\right]^2$$

α = Impedance ratio between hammer and drill rods

L_h = Length of hammer

l = Length of drill rods and sampler

n = Maximum number of completed stress cycles before loss of hammer contact

The numerical result of Equation 3.1 represents the theoretical maximum energy that could be transferred to the drill rods before arrival of the tension wave. This equation forms the basis for the ASTM K_2 correction factors. The dashed line in Figure 3.6 is a graphical representation of Equation 3.1. The non-linear trend of the dashed line suggests that the shortest rod lengths will have the largest reduction in transfer efficiency and that the energy reduction will gradually decrease as the length of the drill rod increases, up to about 50 ft.

3.5.2 Morgano and Liang Study

A study by Morgano and Liang (1992) examined the effects that rod length had on energy transfer in the SPT. They conducted wave equation studies as well as field experiments for various rod lengths using a manual safety hammer system. Unlike the Palacios study, where the force-squared method was used, Morgano and Liang were able to measure the transferred energy using both force and velocity measurements. To the author's knowledge, this was the first study on rod length effects using the EFV method.

In addition to force and velocity measurements, Morgano used a Hammer Performance Analyzer (HPA) to measure the hammer's impact velocity, which was later used to determine the kinetic energy just prior to impact. The HPA measurements were beneficial because they removed potential energy variability associated with drop-height

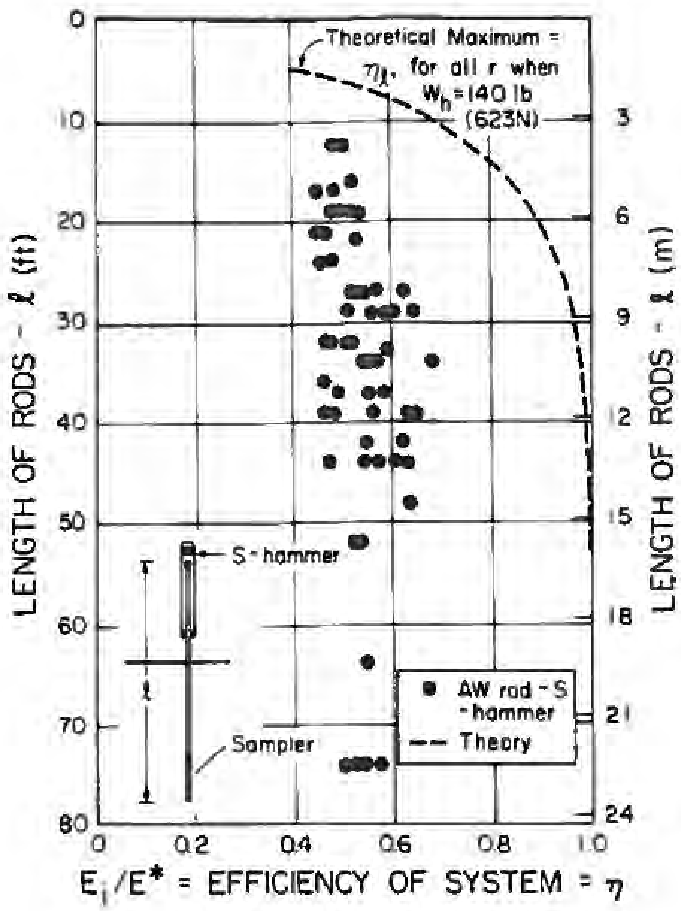

Figure 3.6 Theoretical transfer efficiency (Schmertmann and Palacios, 1979)

inconsistencies of the manual hammer. Because the study included both EFV and kinetic energy measurements, the driving system transfer efficiency was determined in place of the ETR (which is EMX/PE). The driving system transfer efficiency is the ratio of measured EFV energy in the drill rods to the available kinetic energy just prior to impact (EMX/KE).

Figure 3.7 shows the field testing results from their study. Each tick mark in the figure represents the drive system transfer efficiency from one hammer blow. Similarly, Figure 3.8 shows the average of the drive system transfer efficiencies.

Based on the results of Figures 3.7 and 3.8, the energy transfer is independent of rod length for lengths greater than 50 ft. However, for rod lengths less than 50 ft, the energy transferred to the rod is reduced. These findings are similar to those documented by Palacios.

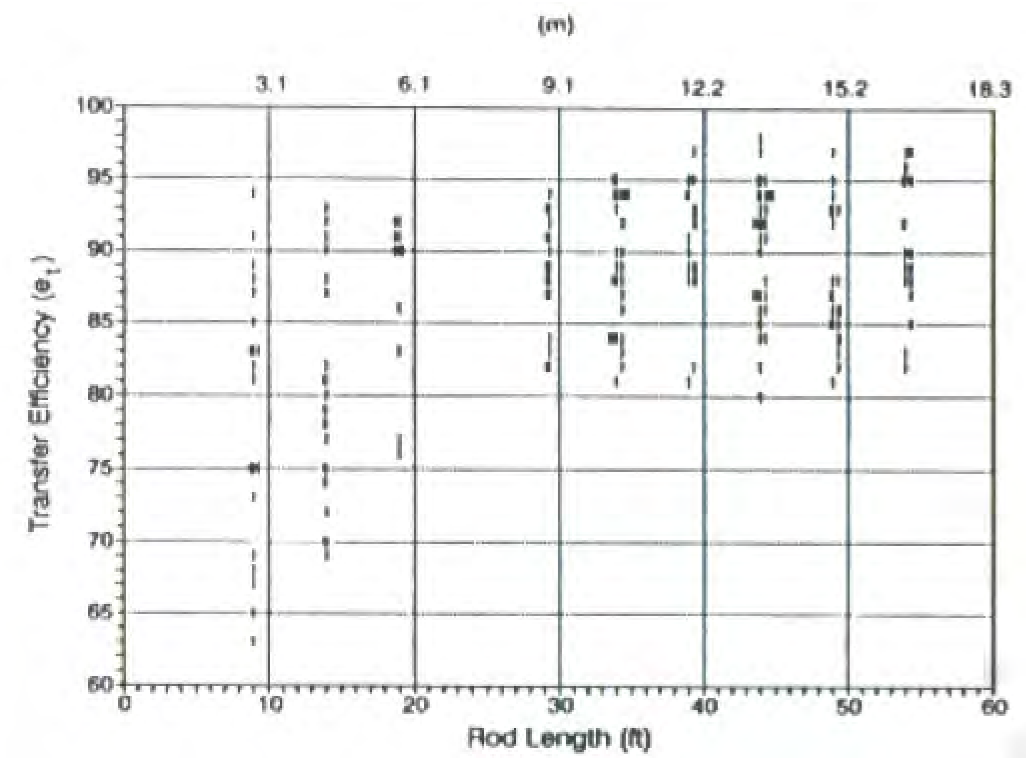

Figure 3.7 Drive system efficiency (Morgano and Liang, 1992)

The results of an SPT wave equation study were also provided in their report. Wave equation simulations were performed on rod lengths varying from 10ft to 100 ft. The energy transfer for each rod length was evaluated using soil resistance forces ranging from 0.5 kips to 13 kips. The results of the wave equation study indicated that the relationship between energy transfer and rod length is more “critical” when lower soil resistances are present.

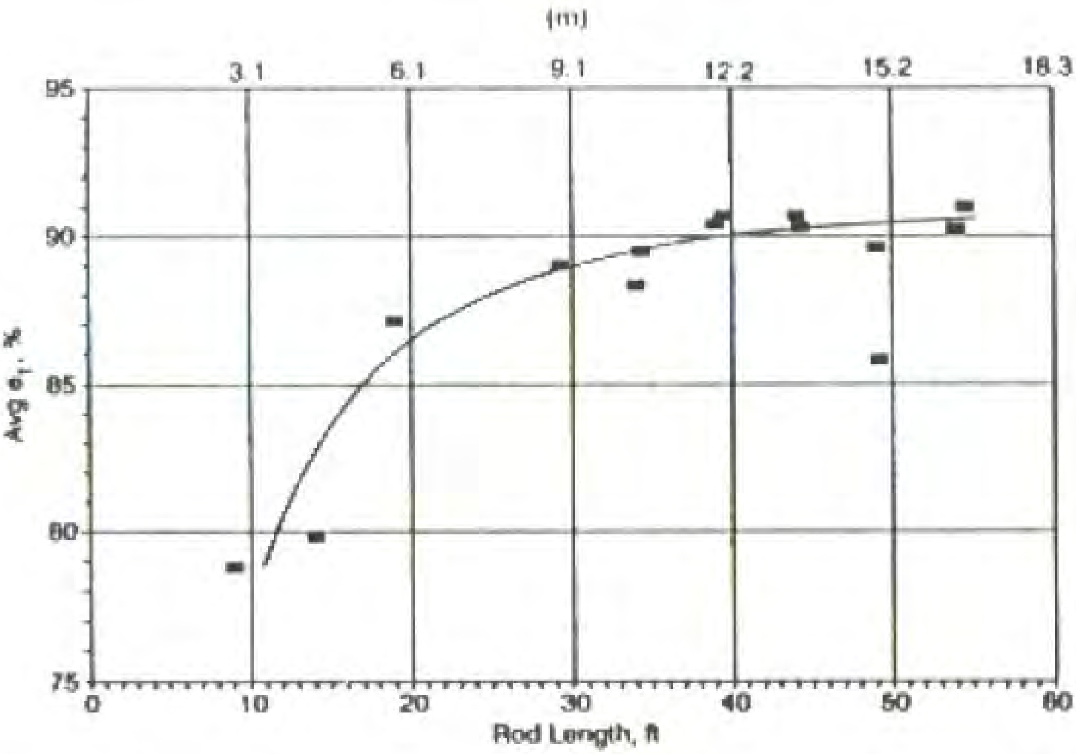

Figure 3.8 Average drive system efficiency (Morgano and Liang, 1992)

As illustrated in Figure 3.9, the shortest rod length driven into the smallest soil resistance produced the lowest transferred energy. The transferred energy apparently increased as the soil resistance and rod length increased with transferred energy stabilizing at a rod length of 50 ft.

Rod Length ft (m)	Ultimate Resistance - kips - (kN)											
	0.5 (2.23)		1.0 (4.45)		2.5 (11.1)		4.0 (17.8)		7.0 (31.2)		13.0 (57.9)	
	EMX kip-ft	e_t %	EMX kip-ft	e_t %	EMX kip-ft	e_t %	EMX kip-ft	e_t %	EMX kip-ft	e_t %	EMX kip-ft	e_t %
10 (3.05)	0.23	82	0.24	86	0.25	89	0.25	89	0.25	89	0.25	89
20 (6.10)	0.24	86	0.24	86	0.25	89	0.25	89	0.25	89	0.25	89
50 (15.24)	0.26	93	0.26	93	0.26	93	0.26	93	0.26	93	0.26	93
100 (30.49)	0.26	93	0.26	93	0.26	93	0.26	93	0.26	93	0.26	93

EMX - Energy transferred to rod
e_t = EMX/E_i, where E_i is the actual kinetic energy ($E_i = \frac{1}{2} mv^2 = 0.8\ W_r h$) of the ram
1 kip-ft = 1.356 kJ

Figure 3.9 Wave equation study (Morgano and Liang, 1992)

3.5.3 NCDOT Study

Close to two decades after the Morgano and Liang rod length study, Valiquette, et al. (2010) performed an investigation into rod length effects for automatic hammer systems. Data from twenty automatic SPT hammers owned by the NCDOT and private consultants were used to investigate the behavior of rod length and energy transfer. To the author’s knowledge, this apparently seems to be the largest rod length study performed on automatic hammers to date.

As previously mentioned in Section 3.3.2, the testing program consisted of one boring of energy measurements per hammer system. Drill rod lengths evaluated in their study ranged from 14 ft to 74 ft, and were either AW or AWJ sized drilling rods.

Based upon their evaluation of the automatic hammer subgroup, they determined that the transferred energy increased up to a rod length of about 38 ft and generally stabilized after that. For each drill rig, they determined baseline transfer efficiencies for rod lengths greater than 38 ft. They then systematically used the individual baseline energy values to normalize the energy measurements obtained from rod lengths less than 38 ft. This approach allowed the general trend of energy reduction to be compared among the various automatic hammer systems in the subgroup, regardless of their baseline transfer efficiency. Finally, the normalized transfer efficiency for each hammer system was averaged and incorporated into a regression analysis from which a best fit line was determined. The results of their investigation are shown in Figure 3.10 and are plotted against the results from the prior studies previously described.

Based on the data in Figure 3.10, the estimated energy reduction for the theoretical method would be larger than that predicted by the NCDOT regression trend, up to a rod length of about 20 ft. The Morgano-predicted energy reduction is slightly less than the NCDOT and theoretical values for all rod lengths. The maximum reduction in transfer efficiency for the NCDOT regression is approximately 10% of the baseline efficiency for the shortest rod lengths.

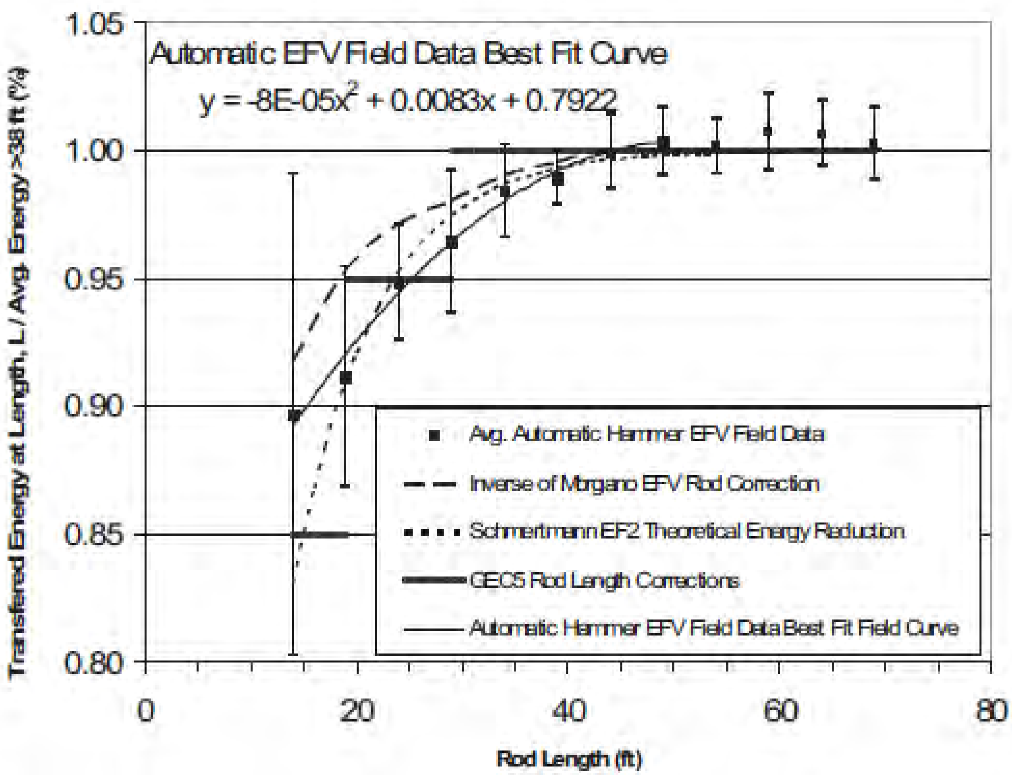

Figure 3.10 Normalized energy transfer (Valiquette et al., 2010)

3.6 Energy Reaching the Sampler

Within the last decade there seems to be a renewed interest in evaluating whether or not the measured energy from the top of the drill stem is the same quantity of energy that reaches the location of the split-spoon sampler. As discussed in Chapter 1, the parameter $E_{Measured}$ in Equation 1.1 is the maximum measured value of energy entering the drill rods obtained from top force and velocity measurements. This energy value is used to characterize the energy transfer efficiency of the hammer system. At the same time, it is also assumed that this is the same quantity of energy that is distributed to the split-spoon sampler, which may not be an accurate assumption for long drill rods.

3.6.1 Palacios Study

As part of his doctoral research, Palacios studied the behavior of energy transmission of SPT drill rods (1977). Among other things, this study explained how internal friction within the steel rods resulted in a decaying energy transmission along the drill rods. Palacios generally explained the mechanism of internal friction and stated that during the energy transmission process, each particle of the rod absorbs energy from the stress wave as rod particles are successively compressed and decompressed during its cycling routine.

Providing an example based upon theory from Kolsky, Palacios showed that internal friction in SPT rods can result in estimated energy losses of 1% for every 10 ft of drill rod, which would ultimately add up to large energy losses in deep borings. Kolsky's theory was based upon strain wave amplitude attenuation, which depends on the specific damping capacity of steel. Specific damping capacity is defined as the measured ratio of the energy dissipated in taking a steel specimen through a stress cycle to the elastic stored energy stored in the specimen when its strain is at a maximum (Kolsky, 1963).

3.6.2 Abou-matar and Goble Study

A report by Abou-matar and Goble (1997) presented the results of a theoretical investigation into the dynamic behavior of the SPT. Their study documented wave equation calculated sampler energies for drill rods having different cross-sectional areas. Specifically, they evaluated the energy transferred to the soil using AW size drill rods and compared it to the energy transferred to the soil using Mayhew size drill rods, which reportedly has more than twice the rod cross-sectional area of the AW size rod. The energy calculated at the top of the rod was apparently identical for both rod types.

From this analysis, they determined that drill rods having a larger cross-sectional area produced an increase in SPT blow counts compared to the blow counts from drill rods having a smaller cross-sectional area. They later explained that this behavior should be expected since the rod's impedance is related to the rod's area. As the rod area increases, the forces in the rod will be larger for a given set of (particle) displacements, and these forces would retain more energy inside of the rod which would result in a reduced quantity of energy available to perform work for penetration. Although their wave equation study was performed using a constant rod length of 54 ft (16.5 meters), they later recommended that rod length correction factors be based on rod length as well as rod cross-sectional area.

In a closure response to the discussion provided by Boulanger and Idriss, which was based upon the original paper, they provided yet another wave equation study that evaluated SPT N-values for AW and NW sized drill rods. Drill rod lengths evaluated in this study ranged from approximately 10 ft to 100 ft and included soil resistances forces of 1.12 kips (5 kN) and 2.24 kips (10 kN). Figure 3.13 shows the wave equation results from their closure report.

Based on these results, they concluded that for rod lengths up to 30 ft, the two rod types did not give significantly different SPT blow counts. However, for rod lengths greater than about 40 ft, the SPT blow counts begin to diverge, with the larger NW rod type producing higher SPT blow counts for the same soil resistance.

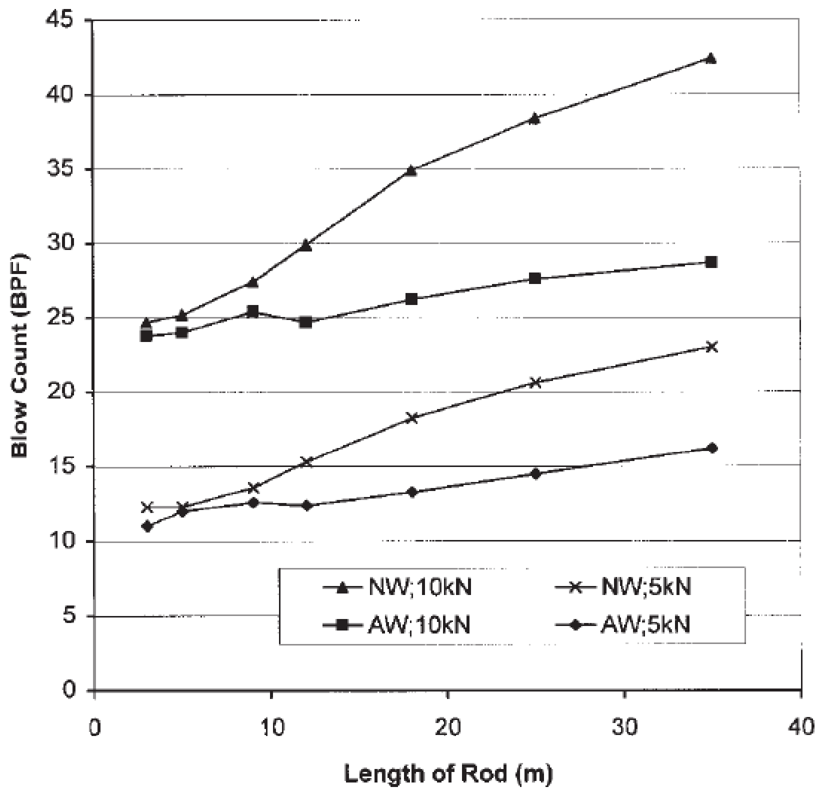

Figure 3.13 Wave equation study (Abou-matar and Goble, 1997)

These conclusions verify the initial claims of the original paper and theoretically indicate that the energy reaching the sampler can be less than that from the top of the drill rod stem when the two different drill rod types are compared, and when they have nearly identical top calculated ETRs.

3.6.3 MnDot Study

The research findings on sampler energy documented by Abou-matar and Goble were strictly based upon theoretical wave equation calculations. In 2005, Goble presented the results of MnDOT's SPT N-value study which evaluated N-values based on rod size and depth. The N-values were obtained from the same site, however, it is not known if they are from the same SPT hammer. Nevertheless, MnDOT's field investigation results support that of the Abou-matar wave equation analysis previously discussed. As shown in Figure 3.14, N-values obtained from the larger N-sized rods produced larger N-values compared to that of the smaller diameter A sized rods. This type of behavior would be expected if there were more energy losses associated with the larger N-size rod group.

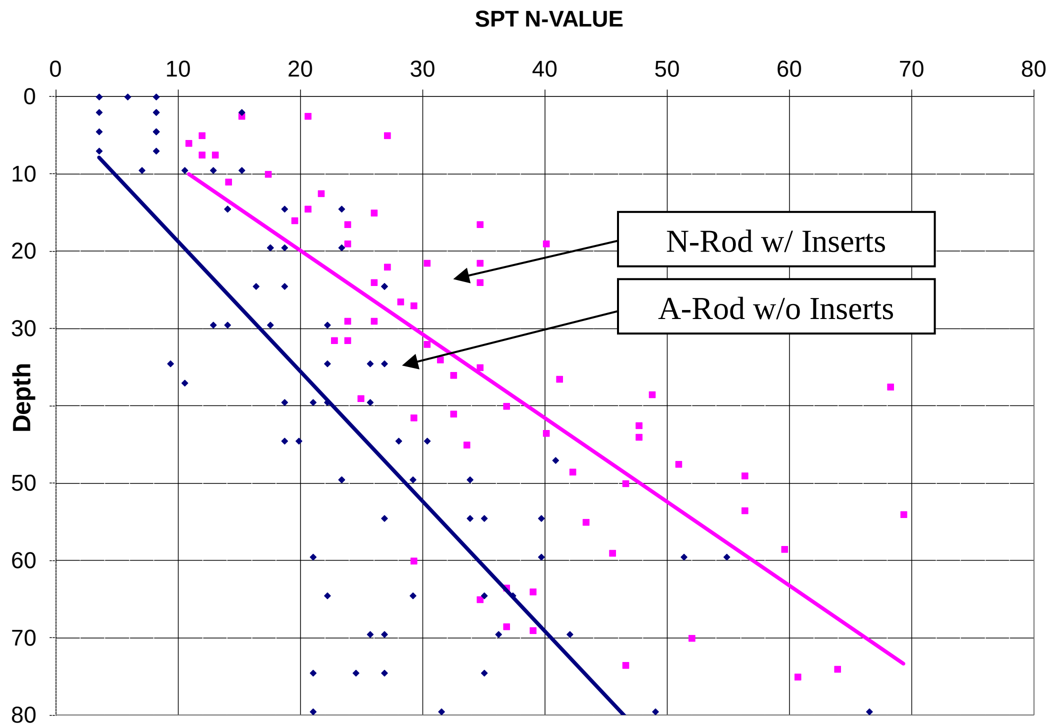

Figure 3.14 MnDot rod type vs. N-value study (modified from Goble, 2005)

3.6.4 Odebrecht Study

As part of an ongoing SPT investigation, Odebrecht et al. (2005) studied the effect that rod length and sampler penetration had on the energy reaching the split-spoon sampler. The SPT testing program consisted of taking force and velocity measurements from below the anvil as well as immediately above the sampler. These top and bottom energy measurements were not taken simultaneously but comparison between the two measurement locations were achieved by using an experimental calibration chamber that could control the penetration of the sampler. The calibration chamber allowed a known granular material to be prepared at a specific density where testing could be performed using controlled boundary conditions. Vertical stress in the chamber was controlled by a pressurization system regulated by air pressure, which used a self-relieving valve for driving an air-water interface system. Figure 3.15 shows the experimental set up and calibration chamber used in their research program.

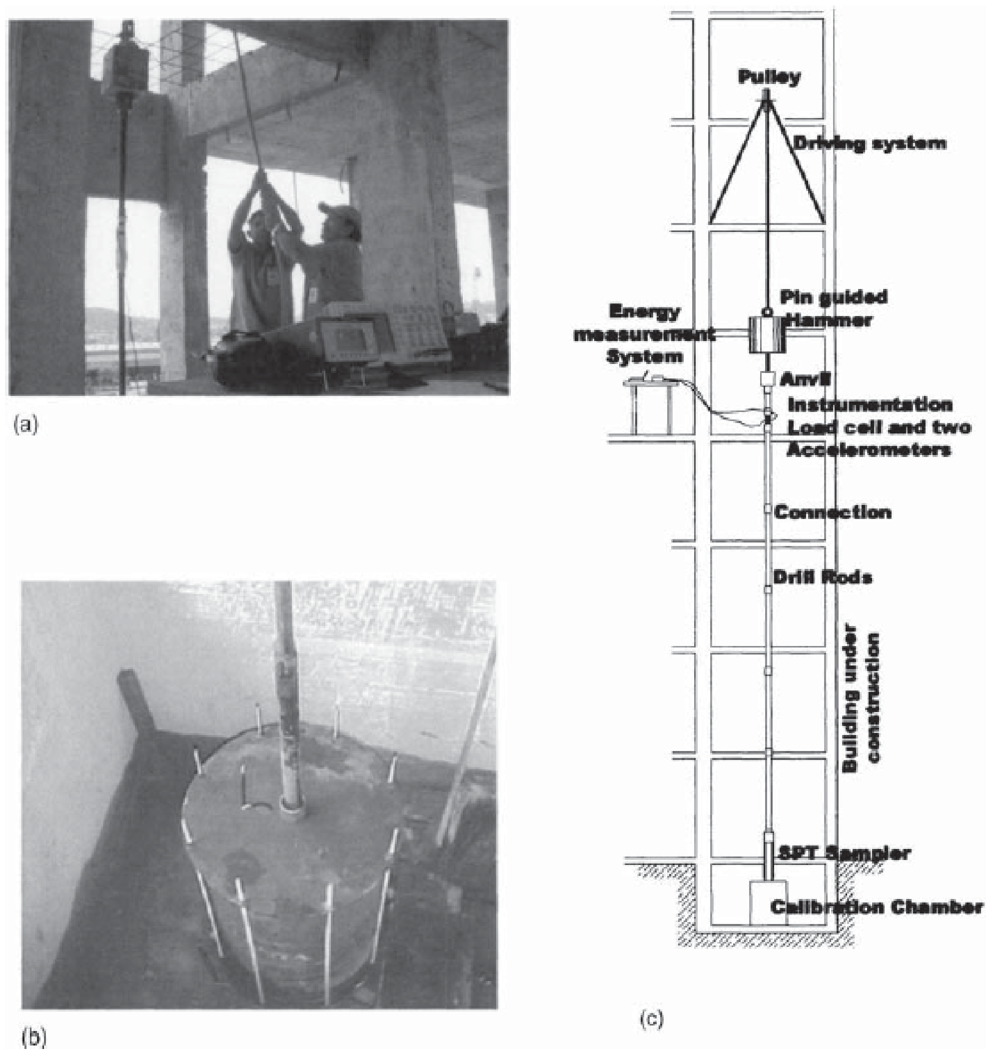

Figure 3.15 Experimental setup (Odebrecht et al., 2005)

The results for the 19 ft rod composition are depicted in Figure 3.16. This figure shows a comparison of EFV energy measurements taken from directly above the sampler and compared to the EFV measurements taken from the top of the rod, just beneath the anvil. As shown, the sampler penetration was indicative of an SPT N-value of 8 blows per foot. The energy measured at the top of the drill rod as well as just above the sampler was 296 ft-lbs of energy (401.5 Joules) (84.5% ETR).

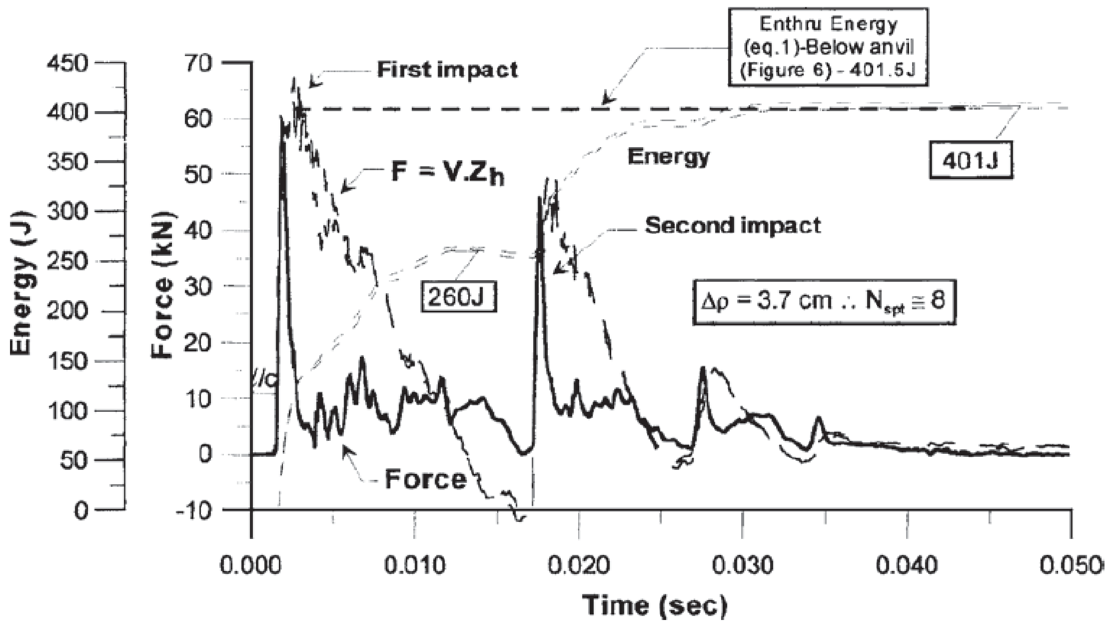

Figure 3.16 Sampler energy-19 ft (5.8 m) rod

Similarly, the experimental results from the 117.5 ft rod composition are depicted in Figure 3.17. This figure provides the same top and bottom energy comparison as the previous example and with the same soil density. The energy measured at the top of the rods was also approximately the same. However, for this case, the energy measured just above the sampler was significantly less than that of the short rod example and was measured at 246 ft-lbs of energy (334 Joules) (70 % ETR), which is approximately a 15% ETR reduction in energy reaching the sampler from the 19 ft rod length to the 117.5 ft rod length. These experimental results are very close to the theoretical 1% ETR loss per 10 ft of drill rod described by the Palacios study in section 3.7.1.

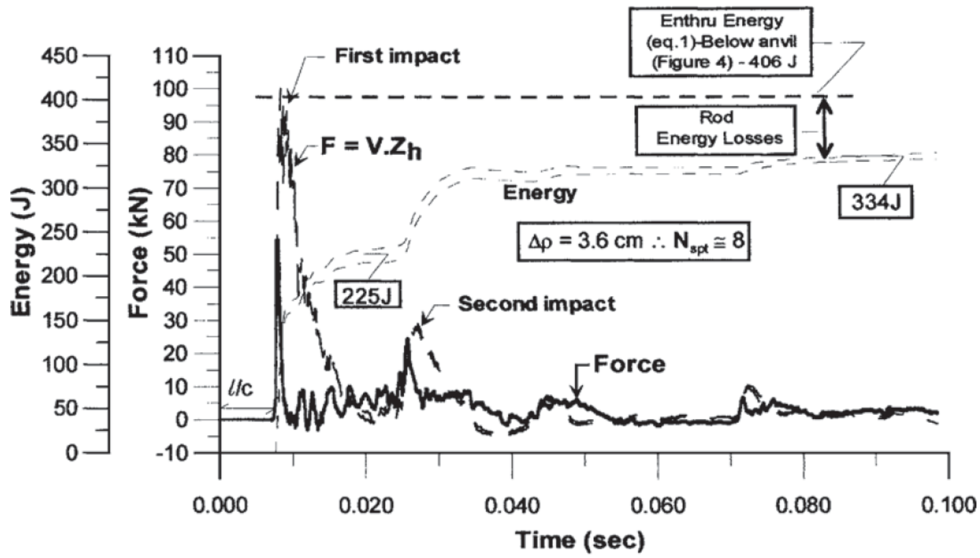

Figure 3.17 Sampler energy-117.5 ft (35.8 m) rod

3.8 Conclusions Based on Previous Work

Overall Average EFV Energy

1. The CME Automatic hammer ETR average in Table 3.1 was 80.7%. The range of ETR averages per study was from 75% to 84.5%.
2. The non-CME automatic hammer ETR average was 70.2% ETR. The range of ETR averages per study was 49% to 82%.
3. The ETR average for the manual hammer category was 57.8%. The range of ETR averages per study was 35% to 70.2%.

Expected Variation of EFV Energy

1. In light of the COVs reported in Table 3.1, the expected range of variation of energy for the CME automatic hammer is from 2.5% to 10%. This 10% maximum estimated value is slightly less than the 15% maximum COV for the

non-CME automatic hammer group, and about one-half of the 22% maximum COV for the manual hammer group.

CME Automatic Hammer

1. The CME hammer is a rate dependent hammer. The energy transferred from the hammer system will generally increase as the velocity of the drive system increases (sprockets, chain, and lifting lug). This speed is controlled by the RPMs of the drill rig engine and the hydraulic flow control settings of the hydraulic motor.
2. CME hammer settings are initially set at the factory to achieve a 30 inch fall height at a hammer operation rate of about 50 to 55 blows per minute. Over time, and after required maintenance is performed, the flow control settings may need readjustment in order to maintain the required fall height. The fall height distance can be verified using the viewing slot window on the drive weight housing tube.
3. CME hammer operation rates exceeding approximately 60 blows per minute may result in reduced energy transfer. This effect is due to an increased drive weight fall height (increased throw height) and a reduced cycle time of the lifting lug (from the increase in chain velocity). When this occurs, the drive weight will strike the lifting lug prior to striking the anvil and will transmit a portion of the energy to the hammer's drive system components rather than to the anvil (Figure 3.5).

Rod Length Effects

1. There is an apparent reduction in transferred energy for short drill rod lengths. This reduction in energy is less than the baseline transfer efficiency that would be measured using longer rod lengths of about 40 ft to 50 ft.
2. The maximum estimated energy reduction for short drill rods is approximately 10% of the baseline ETR value. This value was estimated using the NCDOT regression line from Figure 3.10.
3. The wave equation study performed by Morgano and Liang verifies the theoretical plausibility that short rod length behavior is related to soil penetration resistance. The reduction in energy was more apparent for the shortest rod lengths driven into the weakest soils. The wave equation results also showed that the transferred energy increased as the soil resistance increased (for a given rod length).

Energy Reaching the Split-Spoon Sampler

1. The energy measured at the top of the drill rods may not be the same quantity of energy that performs work on the soil. Energy reduction from stress wave amplitude attenuation can result in large energy losses for deep borings (long rods). Theoretical energy losses were estimated to be 1% ETR per 10 ft of drill rod. Experimental investigations from Odebrecht showed approximately 1.25% ETR loss per 10 ft. (15% total ETR loss with 117.5 ft rod length)
2. Wave equation studies showed that large diameter drill rods may produce larger N-values compared to the N-values produced with smaller diameter rods

(assuming that top measured ETR is the same). This effect was explained by the fact that larger rod sizes tend to retain more of the stress wave energy for a given set of particle displacements. This conclusion was validated by MnDOT's field investigation where measured N-values were compared between two different rod sizes.

CHAPTER 4: ALDOT TESTING PROGRAM

4.1 Introduction

This chapter provides a summary of the ALDOT SPT energy testing program. Described herein are pertinent details related to data acquisition equipment, field testing procedures, office analysis of field energy data, as well as the calibration certificate that was provided for each drill rig. The last few sections of this chapter highlight the results of the testing program, as well as compare these results to the conclusions previously found by others.

4.2 ALDOT Drill Rig Fleet

ALDOT currently maintains six CME drill rigs, each having an automatic hammer. Their drill rig fleet consists of three 550X all terrain vehicles (ATV), two 55 trucks, and one 850 track rig. These drill rigs travel throughout the state of Alabama performing SPTs and are used on a regular basis. ALDOT also uses consultants from the private sector to perform a portion of their work. However, due to the time limitations of the testing program, the consultant SPT hammers were not calibrated. Table 4.1 further classifies each drill rig based on the drill rig identification number.

Table 4.1 ALDOT drill rig inventory

Rig I.D.	CME Rig Model	Rig Type
SE9050	550X	ATV
SE9122	550X	ATV
SE9299	850	Track
SE9445	550X	ATV
ST11151	55	Truck
ST11152	55	Truck

4.3 SPT Analyzer

The SPT Analyzer is a signal conditioning and processing unit that measures and stores raw strain and acceleration signals for each hammer blow during the SPT. The signals are collected through a 12-bit analog-to-digital converter at a sampling frequency of 20 kHz with each record containing a 2048 integer sample size per transducer.

The device processes the measured signals produced from the travelling stress wave, and in real time analog integrates the acceleration signal to obtain particle velocity and calculates force from the measured strain signals using Hooke's Law. Raw voltage signals from each of the transducers are converted to engineering units using calibration factors provided from the manufacturer. The force and velocity signals are then multiplied and integrated over the entire time record to obtain the maximum value of transferred energy to the drill rods.

Digitization of the analog signal uses initial oversampling during the testing process. However, with this model of data acquisition equipment, the final representation of data points is limited to an integer sample size of 1024 (0 to 1023). During the data acquisition process, the SPT Analyzer itself serves as a low-pass filter to the measured signals.

4.4 Instrumented Subassembly

During the testing program, force and velocity measurements were obtained from strain gages and accelerometers mounted to a two-foot long drill rod subassembly having the same approximate diameter (cross-sectional area) as the SPT drill rods (Figure 4.2). The subassembly for this project was an AWJ rod with a tapered "box" connection

Figure 4.1 SPT Analyzer

located at the top of the subassembly and a tapered “pin” connection located at the bottom. The cross-sectional area of the subassembly, which was provided by the manufacturer, was 1.2 square inches.

The instrumented drill rod contained two strain gage bridges which were spaced at approximately 180 degrees from each other. Each strain gage was terminated into a cable having a quick disconnect plug.

Two Model K piezoresistive accelerometers were bolted to the subassembly at diametrically opposed sides of the rod and within 4 inches of the location of each strain gage. During the bolting process, each accelerometer was aligned axially with the rod in the sensitive direction, and with the quick connect plug facing the ground surface during the testing event. Based upon Pile Dynamics, Inc (PDI) specifications, both accelerometers are linear at 10,000 g (20,000 g limit) and with a useable frequency response of 4.5 kHz.

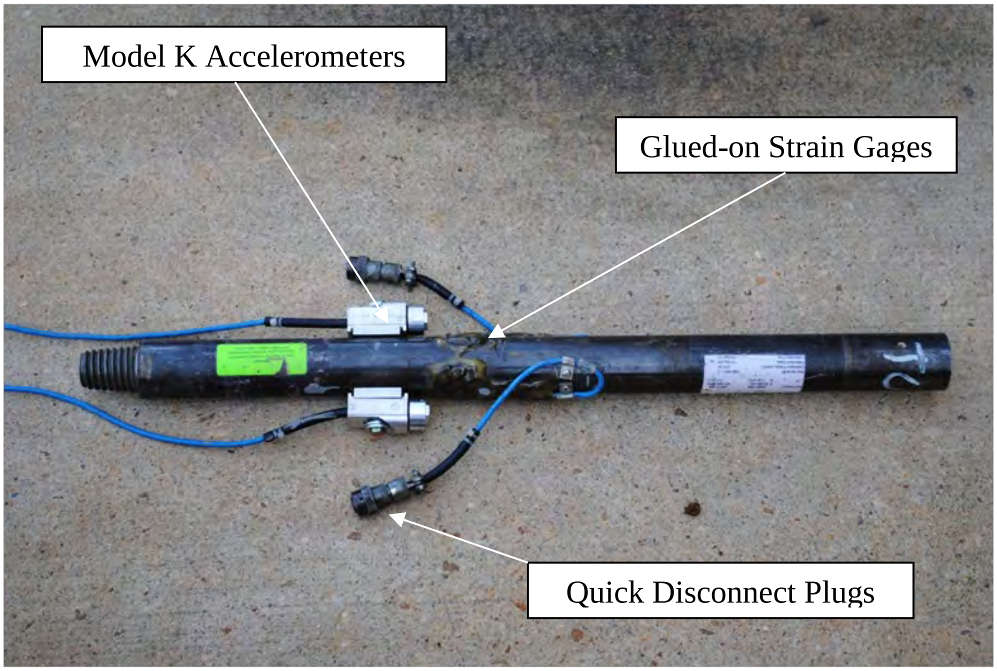

Figure 4.2 Instrumented subassembly

4.5 Field Testing Procedure

The field testing program was designed in such a way as to supplement ALDOT's normal drilling operations as well as to produce a testing method that could be documented and performed using a simple repeatable sequence. Because ALDOT follows ASTM D 1586 guidelines for all of their SPT drilling and sampling procedures, the only additional requirement imposed on their normal operations was mounting of the subassembly to the drill rod stem. ALDOT drillers found that this was a relatively painless addition to their normal procedures as it did not cause large time delays.

4.5.1 Field Documentation

SPT energy measurement field sheets, which were specifically designed for ALDOT, were a critical part of the testing process. The field sheets were formatted in such a way as to include project information and sensor calibrations within the first half of the sheet. The benefits of this formatting design were two-fold; first it allowed the testing engineer to become acquainted with the driller, the drilling equipment, and the scope of the project. Second, it prepared the testing engineer for the SPT energy measurement process. As will be seen later, certain inputs on the field sheet are the same inputs that are required in the SPT analyzer. Therefore, having the field sheets thoroughly filled out prior to energy testing allowed the rest of the testing process to go smoothly.

The second half of the field testing sheet was designed to document the SPT sampling procedure. Documenting rod lengths, measured stick up (if performed), and calculated split-spoon sample depths were considered good practice, and represented what was recorded on the field boring logs that were prepared by the drilling crew. SPT N-values recorded by the drilling crew were later obtained and recorded on the field testing sheet. There is also a section of the field testing sheet that allows for miscellaneous comments to be documented. Due to the space limitations of the form, this was the area that was used to record the drive weight fall height as well as any sensor and data issues experienced during testing. Finally, the field testing sheet included a document control number (DCN) for ALDOT’s organizational purposes. To illustrate formatting of the field sheet, Figures 4.3 and 4.4 show a blank field testing sheet as well as one that is completely filled out.

A field notebook was used as an integral part of the testing program (Figure 4.5 below). The field notebook consisted of a rugged hard-plastic binder with numerous plastic sheet protectors which were used to organize and preserve the binder’s documents. Documentation stored in the binder included extra field testing sheets, manufacturer sensor calibration factors, ASTM procedures, and scratch paper for note taking.

4.5.2 Equipment Set Up

After the borings were drilled to depth, and after the split-spoon and drill rods were placed into the bored hole, the instrumented subassembly containing the strain gages and accelerometers was mounted on top of the drill rod string. The subassembly had a tapered pin connection at its bottom end and was screwed into the tapered box connection located at the top of the drill rod stem.

The quick connect cables for each of the four sensors were attached to the SPT Analyzer by means of a main connection cable which contains a “pig tail” attachment for each of the four sensors. Once all the cables were connected, the SPT Analyzer was turned on and mandatory inputs were then typed into the unit. Figure 4.6 depicts the progression of information screens used by the SPT Analyzer to store information for testing. Explanation of these information screens is documented in the SPT Analyzer User’s Manual and summarized below for convenience:

- Main information screen: Information recorded on the field testing sheet was used to complete the main information screen. The potential energy rating of the hammer was also stored as an input (140 pound drive weight with a free fall height of 2.5 ft).

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RECORD OF SPT ENERGY MEASUREMENTS

Project Name:		**Rig Make / Model:**	
Location:		**Rig I.D.:**	
Date:		**Hammer Serial No.:**	
SPT Inspector:		**Hammer Type:**	
Drilling Company:		**Rod Size:**	

Boring Identification:	
Geologic Region:	
Time Tested:	
Drill Rig Operator:	
SPT Analyzer Serial Number:	*4036T*
Instrumented Rod Type / Area:	
Accelerometer Serial Numbers:	A1: A2:
Accelerometer Calibration Factors:	A1: A2:
Strain Gage Serial Numbers:	F1: F2:
Strain Gage Calibration Factors:	F1: F2:

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
					6 in	
					12 in	
			( )		*18 in*	
					6 in	
					12 in	
			( )		*18 in*	
					6 in	
					12 in	
			( )		*18 in*	
					6 in	
					12 in	
			( )		*18 in*	
					6 in	
					12 in	
			( )		*18 in*	
					6 in	
					12 in	
			( )		*18 in*	

**Rod Length: Total Length From Gages to Tip of Sampler* *Instrumented Subassembly Length: ____2 ft_____*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up* *Length Below Gages:___________0.5 ft__________*

DCN: 01

Figure 4.3 Field sheet-blank

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Page # 1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Test Clinic # 2	**Rig Make / Model:**	CME 55 Truck
Location:	Montgomery, AL	**Rig I.D.:**	ST 11152
Date:	7/8/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNM	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	Boring 1B	
Geologic Region:	Coastal Plain	
Time Tested:	10:00AM - 12:00 PM	
Drill Rig Operator:	J. Mathews	
SPT Analyzer Serial Number:	40367	
Instrumented Rod Type / Area:	1.20 in^2	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 AWJ-1	F2: 206 AWJ-2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1B-1	2.8 + 1 + 0.5 + 5 9.3'	5.3'	4' (4 - 5.5)	2	6 in	Won't use Data Due
				1	12 in	
				2 (3)	18 in	
1B-2	2.8 + 0.5 + 10 13.3'	4.3'	9' (9 - 10.5)	1	6 in	to Very Low Blow Counts
				1	12 in	
				2 (3)	18 in	
1B-3	18.3'	4.3'	14' (14 - 15.5)	3	6 in	
				3	12 in	
				5 (8)	18 in	
1B-4	23.3'	4.3'	19' (19 - 20.5)	3	6 in	Drop Height ≈ 30"
				5	12 in	
				5 (10)	18 in	
1B-5	28.3'	4.3'	24' (24 - 25.5)	13	6 in	
				27	12 in	
				35 (62)	18 in	
1B-6	33.3'	4.3'	29' (29 - 30.5)	13	6 in	Drop Height ≈ 30"
				21	12 in	
				39 (60)	18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*
**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*
**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft
Length Below Gages: 0.5 ft

DCN: 05

Figure 4.4 Field sheet-filled out

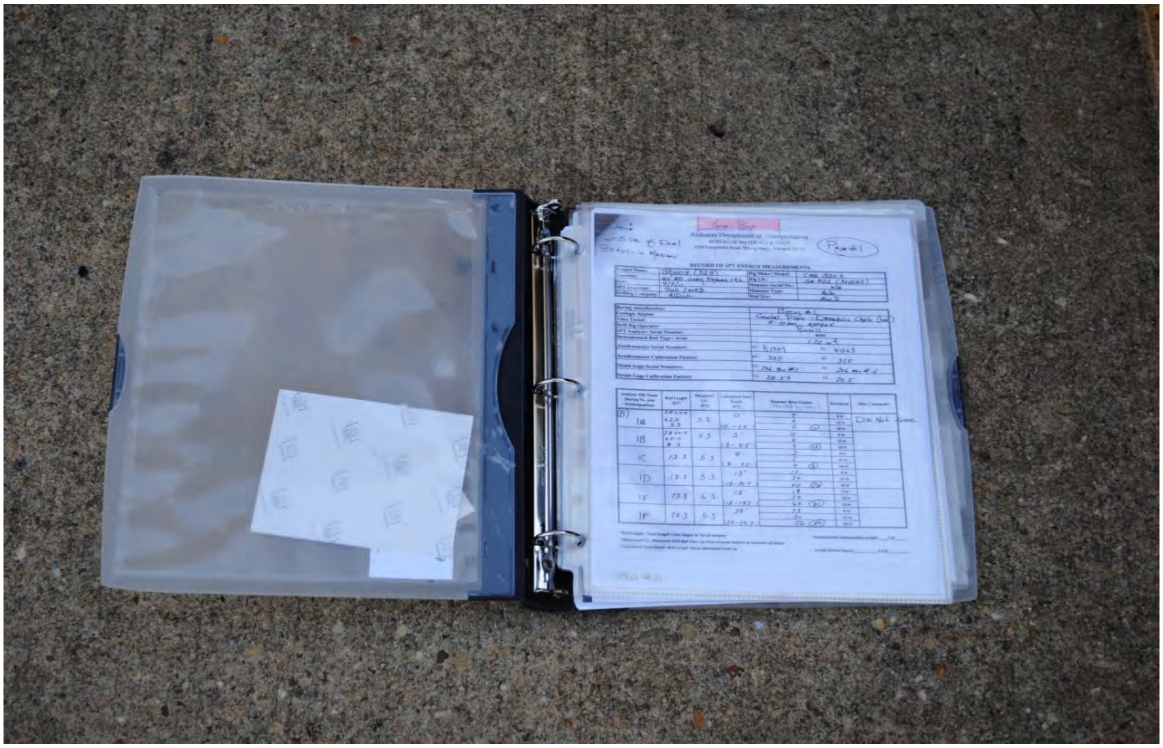

Figure 4.5 Field notebook

- Rod Length: This was the total rod length below the sensors (LE). This value was obtained by measuring the length of the split-spoon sampler, total length of the drill rods, and length of the subassembly below the sensors. This information was updated in the SPT Analyzer and recorded on the field testing sheet for each test depth.
- Test Depth: This value represented the boring penetration depth prior to sampling. It was obtained by subtracting the measured drill rod stick up above the ground surface (up to sensor location) from the Rod Length value previously used as an input. This information was updated in the SPT Analyzer and recorded on the field testing sheet for each test depth.

- Transducers: This describes what sensors were being used. "A" stands for accelerometer and "F" stands for force (strain gage).
- Test: This was used to check the status of all four sensors. If a sensor was not connected or if the sensor was out of the tolerance range, "OK" would change to "Fault". The number beneath "OK" on the accelerometer field displayed the offset voltage for the sensor. Values within ± 4 volts provided acceptable data (PDI Manual, 2011).
- Active: This was used to select each sensor for data collection. If the field displayed "YES" then that sensor was used during the test. Two strain gages and two accelerometers were always used during data acquisition. The average values for each set of sensors were always used for final ETR determination.
- Trigger: Selected which sensor would be the primary device used to detect data. Only one of the sensors can be labeled "YES". PDI suggests that either of the force sensors be used as the trigger sensor.
- Calibration Factor: Pressing this field allowed the user to input the sensor calibration factors provided from the manufacturer.

After the necessary inputs were provided to the SPT Analyzer, the main data collection screen appeared and the SPT Analyzer and sensor were ready to perform the test. Just prior to SPT testing, the anvil was mounted to the top of the instrumented subassembly, and the SPT hammer was removed from its stowed position and placed directly on top of the anvil (Figure 4.7).

Main Information Screen:

PROJECT:	BR - 008 (528)	**INFO 1:**	CME 550x
BORING: **Note: You can update this value every test depth**	1A-1	**INFO 2:**	AUTO
OPERATOR:	RUSSELL	**HAMMER NAME:**	SE 9122
ROD AREA:	1.20 sq.in	**ENERGY RATING:**	350 ft-lbs
EDIT DATE & TIME:		**CONTINUE TO NEXT SCREEN**	

Next:

ROD LENGTH (FT)	*- This is the rod length below the gages - spoon & sub (2.8') +portion of instrumented sub assembly (0.5') + actual drill rod length (?)* ***NOTE: You must update this value for every test depth.***

Next:

TEST DEPTH (FT)	*- This is the initial boring depth just prior to sampling.* ***NOTE: You must update this value for every test depth.***

Next:

TRANSDUCER	TEST	ACTIVE	TRIGGER	CALIBRATION FACTOR
A1	OK	YES	NO	335
A2	OK	YES	NO	325
F1	OK -0.5V	YES	YES	210.54
F2	OK -0.7V	YES	NO	211.5

Main Summary Screen:

PROJECT:	BR - 008 (528)			**REVIEW** (50% FULL)	
BORING:	1A				
INFO 1:	CME 550x			**ROD AREA**	**LENGTH**
INFO 2:	AUTO			1.20 sq.in	18.3'
SPTRIG:	SE 9122			**DEPTH**	**TOTAL BLOW #**
OPERATOR:	RUSSELL			15'	0
A1: OK	335 mV/g *5000	**INCR**	**SAVE**	**CONTINUE NEW DATA**	
A2: OK	325 mV/g *5000	**INCH**	**SX**		
F1: OK	210.54 me/V	6	1		
F2: OK	211.5 me/V				

- Hit continue to go to the main data collection screen: Note that "Pause' is highlighted. You must press "Pause" in order to start collecting data.

- "Pause" will change to "Accept". Once the test is complete and the data has been collected press "Accept".

- After pressing "Accept", it is necessary to press the "Set Up" button. This will bring you back to the Main Summary Screen.

- Press the Box that has the "Boring" information. Now Change the Boring Name (Say 1A-2).

- It is now necessary to change the Rod Length and Depth information. Press the respective buttons and input new values.

- Now "Continue New Data".

- Press "Pause" which will change to "Accept" and begin collecting data.

- Repeat the process until all testing is done.

Figure 4.6 SPT Analyzer information screens

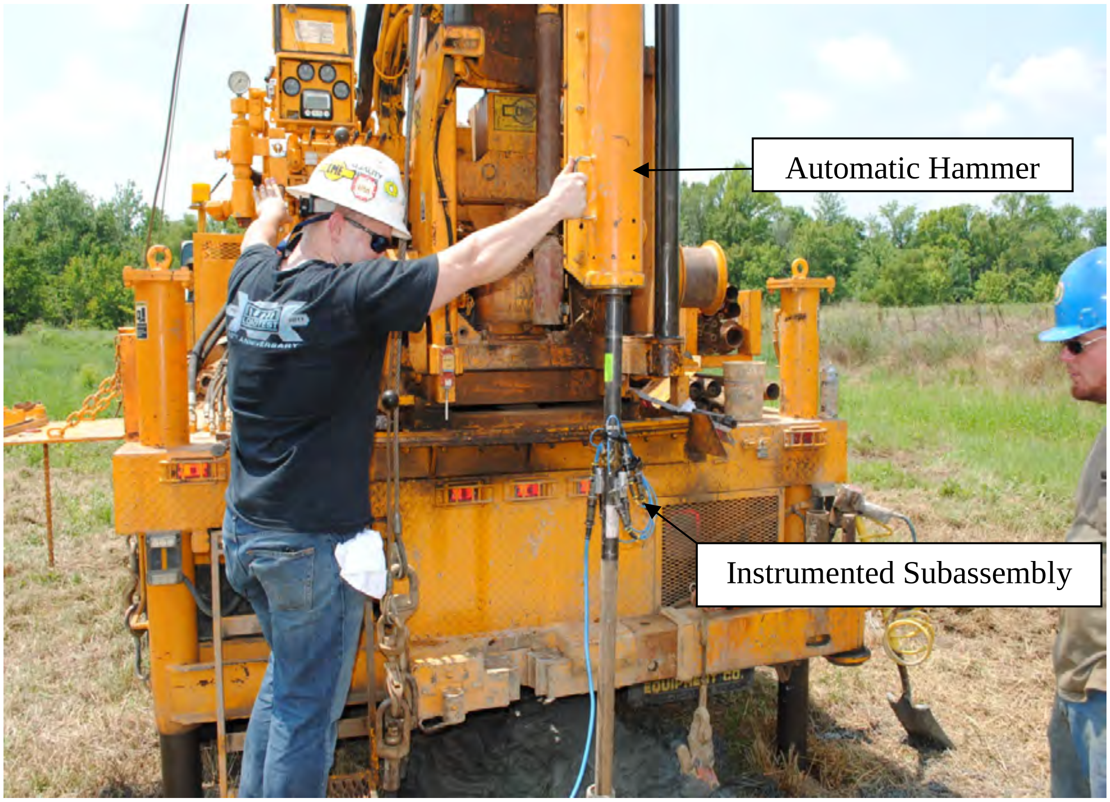

Figure 4.7 Final instrumentation setup prior to testing

4.5.3 Data Acceptance Criteria

During the testing process, the SPT Analyzer collected the data from the sensors and displayed the force and proportional velocity wave forms for visual evaluation (Figure 4.8). The data collection screen allowed for individual force and velocity signals to be evaluated as well as evaluation of the general overlapping trend of the force and velocity signals up to $2l/c$. The criteria used for data acceptance in the field are summarized below:

- Individual pairs of force and velocity must be proportional, and overlapped for each individual record. This provided an indication that sensors were working properly and that the accelerometers were not loose.

- The general trend of the overlapped force and velocity signals must be similar prior to $2l/c$. Serious departures from force and proportional velocity prior to $2l/c$ indicated extremely loose rod connections, and when necessary, the testing was abruptly stopped and the rods tightened. Expecting identical proportionality between the force and velocity signals before $2l/c$ was not practical as some loss of proportionality was expected due to impedance contrasts from rod joints.
- Both force and velocity signals must reach zero at the end of the time record.
- The initial rise time of the force and velocity signals must be similar for the first few data points. However, they were never exactly proportional at the peak magnitude where FVP is measured. The FVP value ranged from 0.7 to 1.0 during the testing program. FVP less than 1.0 was attributed to tensile wave reflections emerging a few inches below the end of the instrumented subassembly. The reflected tension wave slightly increased the measured particle velocity and slightly decreased the measured force signal.
- ETRs must be within an acceptable range (Less than 100 %). The hammer fall height was inspected for ETRs ranging outside the 75% to 85% range. The hammer fall height was inspected at least once during each borehole.

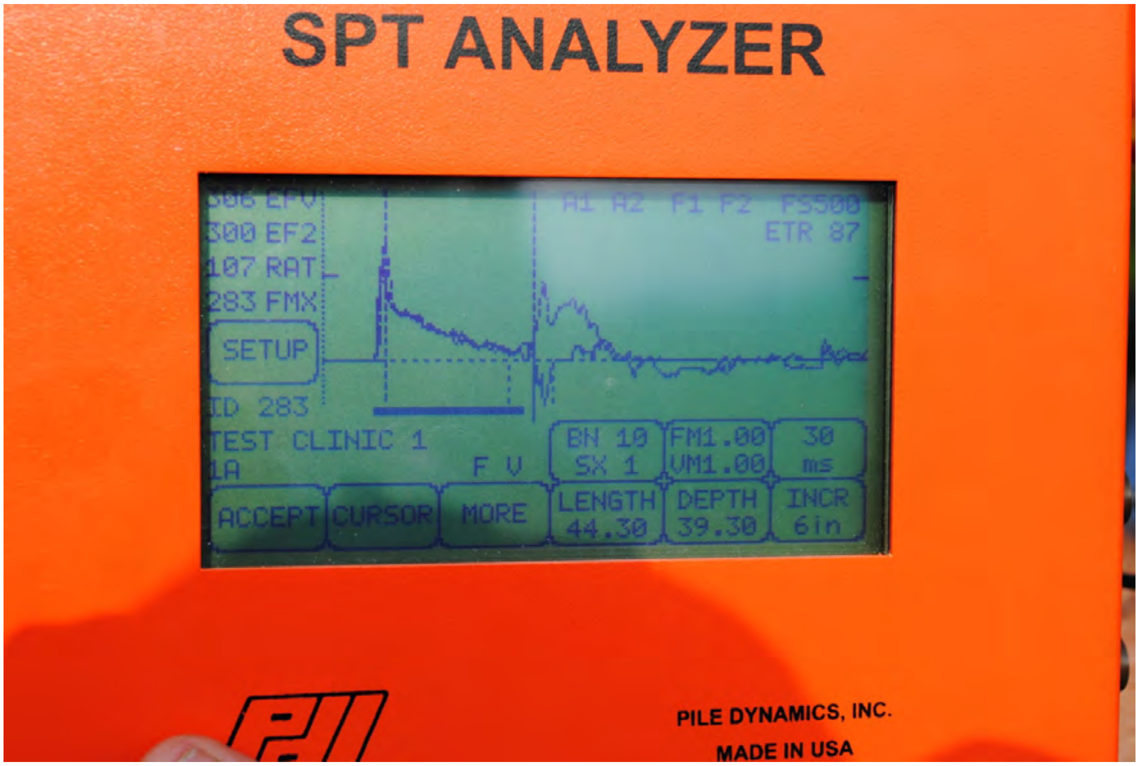

Figure 4.8 Representative force and velocity wave trace

4.6 Office Analysis of Field Data

Once the necessary field energy measurements were performed, further evaluation of the records was required in order to determine the overall ETR for each drill rig. The following subsections highlight the necessary steps used to acquire the ETR for each test depth and subsequently for the entire testing event for each drill rig.

4.6.1 Retrieving Data from the SPT Analyzer

The SPT Analyzer used an external memory card to transfer field data records to a personal computer. There are two options available for transferring data with this model. Specifically, the SPT Analyzer gives you the option to

1. “Halve the Sampling Rate” or,
2. “Save the First Half”

As previously mentioned in section 4.3, the SPT Analyzer initially over samples during the testing process and collects a total of 2048 samples per sensor. However, when the SPT Analyzer attempts to write the raw data files to the memory card it only allows a sample size of 1024 samples per sensor to be transferred. Therefore, when Option 1 is chosen, 1024 data records per sensor will be transferred using a sample frequency of 10 kHz corresponding to a time duration of 102.4 milliseconds. This corresponds to one-half the digitization sampling rate. Similarly, when Option 2 is chosen, 1024 data records per sensor will be transferred using a sample collection frequency of 20 kHz and with a time duration of 51.2 milliseconds. This corresponds to one-half of the maximum time duration that was used during data acquisition.

The signal conditioning system of the SPT Analyzer is such that the unit itself acts as a low-pass filter for force and velocity signals. The cut-off frequency of the SPT Analyzer is reportedly 3 kHz. Based upon ASTM 4633-10 analog sampling requirements for dynamic testing, in order to faithfully represent the true wave form and prevent aliasing, the data acquisition sampling rate should be at least 5 times the low pass filter frequency. Therefore, the data records in the ALDOT testing program were transferred from the SPT Analyzer to the data card using Option 2 from above, which corresponded to a 20 kHz digitization frequency and a time scale of 51.2 ms. Using Option 2 was sufficient for ALDOT's SPT needs and produced quality force and velocity records throughout the testing program. Comparison was made with ETR averages between options 1 and 2, and the difference between the calculated ETRs was about 1%.

4.6.2 PDAW Software Program

PDAW is the software that was used during the testing program to evaluate the energy measurements on a blow-by-blow basis. Conveniently, this software program can be downloaded to any personal computer or laptop. The primary advantage of this program is that the testing engineer can perform a second evaluation of force and velocity records in a comfortable setting, without being rushed. An example of the PDAW information screen is provided in Figure 4.9 and shows a force and velocity wave trace as well as the calculated EFV energy trace in the upper and lower sections of the screen, respectively. Calculated ETRs as well as other additional quantities were provided by PDAW on a blow-by-blow basis as shown on the left side of the screen.

Figure 4.9 PDAW information screen

The objective of this stage of the data evaluation process was to verify the quality of the individual force and velocity records and “adjust” the data set before uploading it to the final software program PDIPLOT. During the testing program the following data adjustments were found to be necessary and were generally performed for each data set and in this order:

1. Defined the beginning velocity time increment using command VA. This time increment was around data point 190 out of 1024 and corresponded to the data point that defines the initial rise time of the velocity signal.
2. Defined the end velocity time increment using command VE. This time increment data point 1023. The VE command was required because PDAW uses a signal rotation technique to make the velocity zero at time VE.
3. Used the velocity time shift command VT to shift and align the velocity signals such that the initial slope of the rise times of the force and velocity are approximately the same. The velocity scale was shifted 0.5 to 1.5 data points during the testing program due to the separation of the strain gages and accelerometers on the instrumented subassembly. The reason for doing so was to define the true wave up and wave down behavior of the stress wave as if the sensors were each at the same location. While performing the VT function, it was noticed that the ETR increased approximately 1%.
4. Verified that the force and velocity signals reached zero at the end of the time record.

5. Deleted any records where individual pairs of force and velocity do not overlap or when the velocity does not follow a trend toward zero. This an indication of loose sensors or simply sensor malfunction which might not have been noticed during field testing.

4.6.3 PDIPLOT Software

PDIPLOT was another software package used during the testing program. The function of PDIPLOT was to organize and present the energy records in such a way as to visually and numerically describe the characteristics of the testing event. The first page of the PDIPLOT summary (Figure 4.10) includes a graphical display of 6 calculated quantities from the PDAW program. These quantities could be chosen from a number of available quantities, however, for reporting purposes the six that were chosen include:

1. CSX – Maximum compression stress at the sensor location. This quantity indicated that the impact force (stress) delivered from the hammer was generally consistent from blow to blow. Erratic CSX values for automatic hammers likely indicate that hammer maintenance and / or evaluation should be performed. Erratic CSX values could also be the result of malfunctioning strain gages.
2. VMX – Maximum downward velocity at the sensor location. This quantity provided an indication of the maximum velocity measured during testing and therefore a brief visual assessment that the accelerometers were working properly and were tightly bolted to the subassembly.

3. EMX – Maximum energy transmitted to the transducers over the entire stress wave event. (Max EFV)
4. E2E – E2E is the EFV energy at time $2l/c$. This quantity of transferred energy increased with depth and eventually converged to the value of EMX once the rod's length was long enough.
5. BPM – Hammer operation rate in blows per minute. Since CME hammers are rate dependent, this quantity was always reported. BPM provides an indication of drill rig operator consistency (engine throttle control) and hammer performance.
6. ETR – Energy transfer ratio (EMX/PE). This is the value that characterized the transfer efficiency of the hammer system.

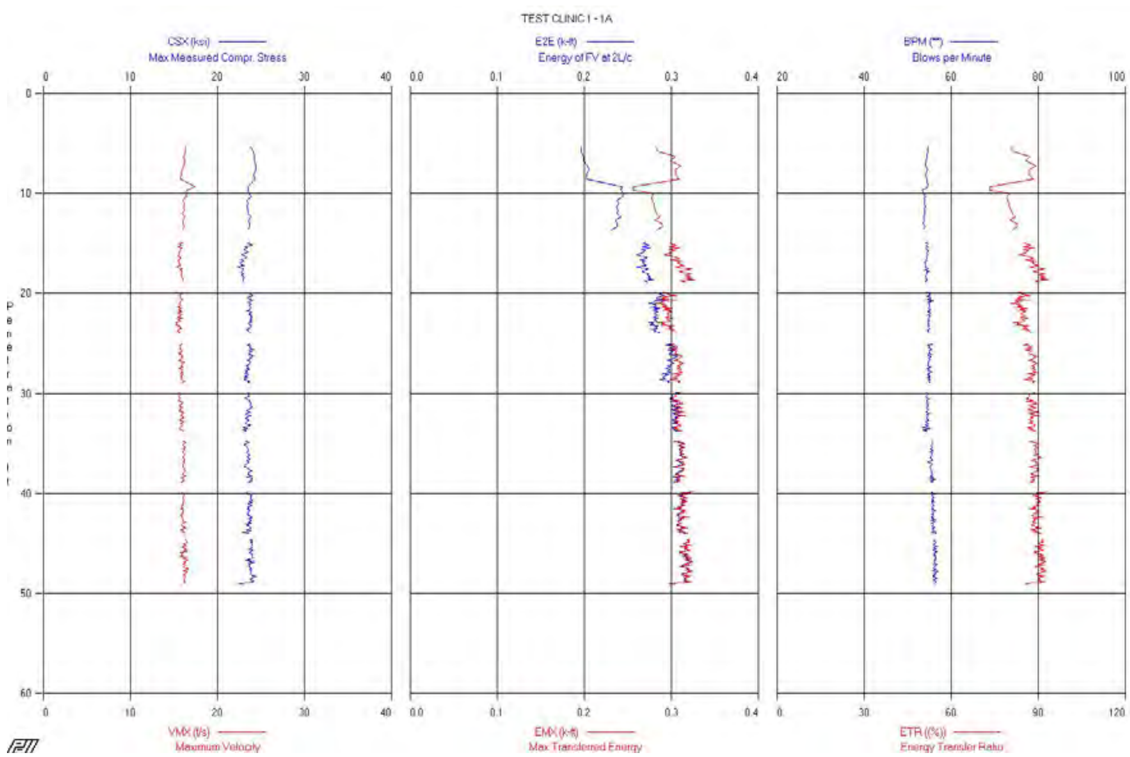

Figure 4.10 PDIPLOT summary-ALDOT drill rig SE 9299

4.7 Calibration Certificate

The final end product of the testing program was the energy calibration certificate. The calibration certificate was designed to provide a transparent snapshot of the testing event as well as the overall consistency of the hammer system. The calibration certificate documentation included drill rig, driller, boring identification, and type of drill rods used for sampling. Also, for each sample depth, the calibration certificate recorded the average hammer operation rate, drill rod lengths, SPT blow counts and average ETR per test depth. The standard deviation for the measured ETR for each test depth was recorded in the last column of the certificate. This is an important statistic that was used to evaluate the consistency of transferred energy to the drill rods between hammer blows. These values should generally be small for CME Automatic hammers and should certainly be less than about 10 for a CME hammer performing under optimum conditions and when sampling in a relatively consistent soil density. The ETR and BPM values recorded on the calibration certificate were obtained from PDIPLOT.

The calibration certificate format used in the testing program is shown in Figure 4.11. As can be seen from the figure, testing was performed under as many depths, or rod lengths as possible. This approach provided ALDOT with enough test data where they could determine an ETR average for short rod lengths, if desired. An overall ETR was provided near the bottom of the certificate. This value was determined as the overall average of the average ETRs per test depth, and was weighted by the number of individual records analyzed for each test depth. Finally, an overall coefficient of variation was provided and is located at the bottom of the certificate. This COV represents the variation of the ETR averages within the rod lengths used during testing.

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

SPT Testing Clinic # 1
Montgomery County, Alabama
Trotman Road

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
SE 9299 CME - 850 (Track)	ALDOT	J. Mathews	1A	6/17/2011	AW-J	54.4	9.3	4 - 5.5	3 - 3 - 5	8	300	85.7%	2.9
						53.8	14.3	9 - 10.5	4 - 7 - 13	15	277	79.1%	3.1
						54.3	19.3	14 - 15.5	7 - 13 - 20	31	308	88.0%	2.5
						54.9	24.3	19 - 20.5	9 - 18 - 20	38	295	84.3%	1.8
						54.9	29.3	24 - 25.5	11 - 20 - 26	46	307	87.7%	1.1
						54.5	34.3	29 - 30.5	6 - 15 - 19	33	307	87.7%	1.2
						54.7	39.3	34 - 35.5	8 - 15 - 22	37	311	88.9%	1.1
						55.8	44.3	39 - 40.5	8 - 16 - 35	51	312	89.1%	1.3
						56.2	49.3	44 - 45.5	7 - 22 - 34	56	317	90.6%	1.3
										[d]Average Measured Energy:	**307.1**	**87.7%** Overall Average ETR %	

Calibration Prepared By: JNH Date: 6/17/2011		[e]Energy Transfer Ratio (ETR) COV: **3.89** %

Figure 4.11 Energy calibration certificate-ALDOT SE9299

4.8 Summary of ALDOT Results

This section of Chapter 4 provides a concise outline of the testing results and compares them to some of the findings of the literature review section.

4.8.1 Measured Transfer Efficiency

The overall average ETR for each drill rig in the ALDOT testing program ranged from 82.2% to 96.1% (Table 4.2). Two of their drill rigs were determined to have ETRs less than 90% while the remaining four drill rigs had measured ETRs higher than 90%. Most of the ETRs are considerably higher than the CME ETR averages from Table 3.1, which varied from about 75% to 84.5%. The overall average for the ALDOT CME fleet was 91%, which is about 10% higher than the 80.7 % CME average calculated from Table 3.1.

After a rigorous inspection of the force and velocity records, it was determined that some of these CME hammers were simply operating at a high transfer efficiency. The drive weight fall height was evaluated for each rig, and each fall height was within the 30-inch tolerance. These drill rigs are properly maintained and receive maintenance based upon the recommend usage schedule of the manufacturer (which is based on the number of usage hours). Furthermore, evaluation of SPT N-values at each Testing Clinic revealed that hammer systems with higher ETRs produced smaller N-values compared to hammers with lower ETRs while performing SPTs in the same geology and at the same approximate sampling depth.

Table 4.2 ALDOT summary statistics

Rig I.D.	# Single Records	# Averages	Overall Average BPM	STD (BPM)	COV (BPM)	Overall Average ETR	STD (ETR)	COV (ETR)
SE9050	220	8	52.65	0.74	1.40	93.1	5.34	5.74
SE9122	396	8	52.05	0.58	1.10	82.2	1.81	2.21
SE9299	355	9	54.83	0.75	1.36	87.7	3.41	3.89
SE9445	281	9	54.14	0.57	1.06	95.2	3.94	4.14
ST11151	214	6	52.13	0.24	0.46	92.2	3.21	3.48
ST11152	228	6	52.95	0.33	0.62	96.1	2.60	2.71

4.8.2 Variation of Transfer Efficiency

The statistical computer program SAS was used to create box and whisker plots that visually show the distribution of transferred energy between hammer blows for each drill rig. A legend, or key, for the box and whisker format is provided in Figure 4.12. The length of the box represents the interquartile range (IQR) for the data set, which is the range of data within the 25^{th} to 75^{th} percentile of the distribution and which contains

50% of the data around the median (or mean if normal). The whiskers highlight the maximum measured energy below the upper fence (1.5IQR). If the distribution of data is close to normal, the empirical rule can be used to evaluate where the approximate standard deviation boundaries are on the box plot figures. Generally speaking, and for all practical purposes, approximately two-thirds of the data in the distribution will lie within one standard deviation from the mean (± 34%), which will be located slightly outside of the 25th and 75th percentile markers of the IQR box. Similarly, the whiskers will be located somewhere between two and three standard deviations from the mean, depending on the location of outliers.

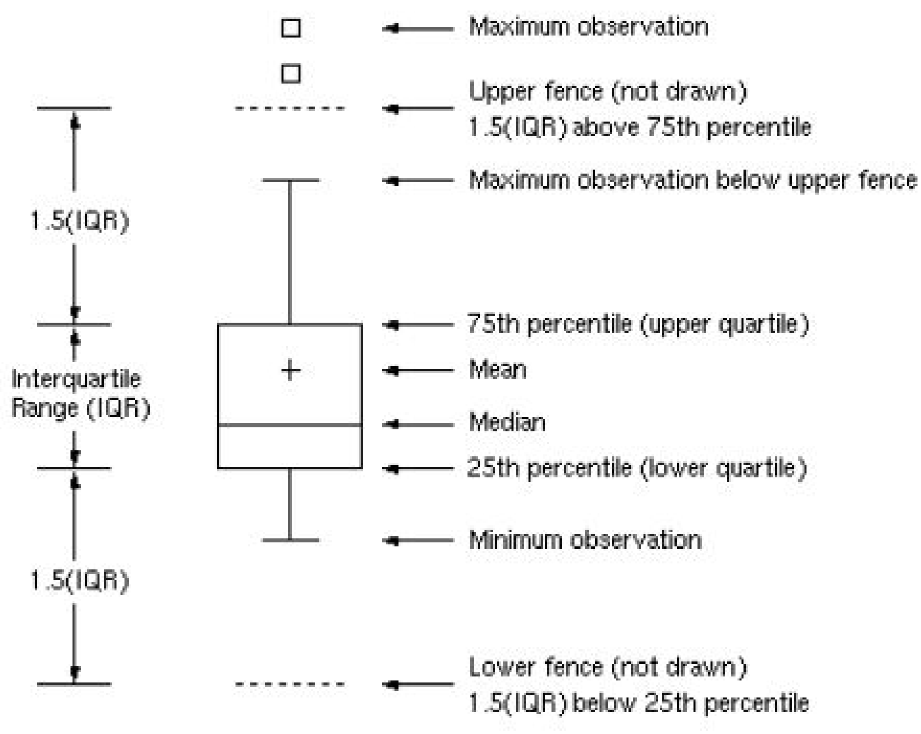

Figure 4.12 Box and whisker legend (SAS 9.2)

The ALDOT box plots in Figure 4.13 suggest that that the distribution of energy records between hammer blows is practically normal. Some of the box plots do exhibit long tails in the direction of lower energy but the average calculated energy is very close to the median value and seems to be relatively unaffected by the slight skewness of the distribution. Four out of six box plots show energy measurements below the 1.5IQR distribution of the 25th percentile. However, this is not a concern, and can likely be attributed to SPT measurements performed in soils having slightly erratic soil density located at shallow depths.

The overall standard deviation between energy averages for each drill rig ranged from 1.81% to 5.34% ETR for the entire drilling fleet. These results compare relatively well to the automatic hammer standard deviations reported by FDOT and NCDOT whose maximum standard deviations ranged from 10.1% ETR (FDOT) to 5.5% ETR (NCDOT). Similarly, the ETR COVs for ALDOT ranged from 2.21% to 5.74%. The ALDOT COV values are within the expected 10% COV range for CME automatic hammers documented in Table 3.1

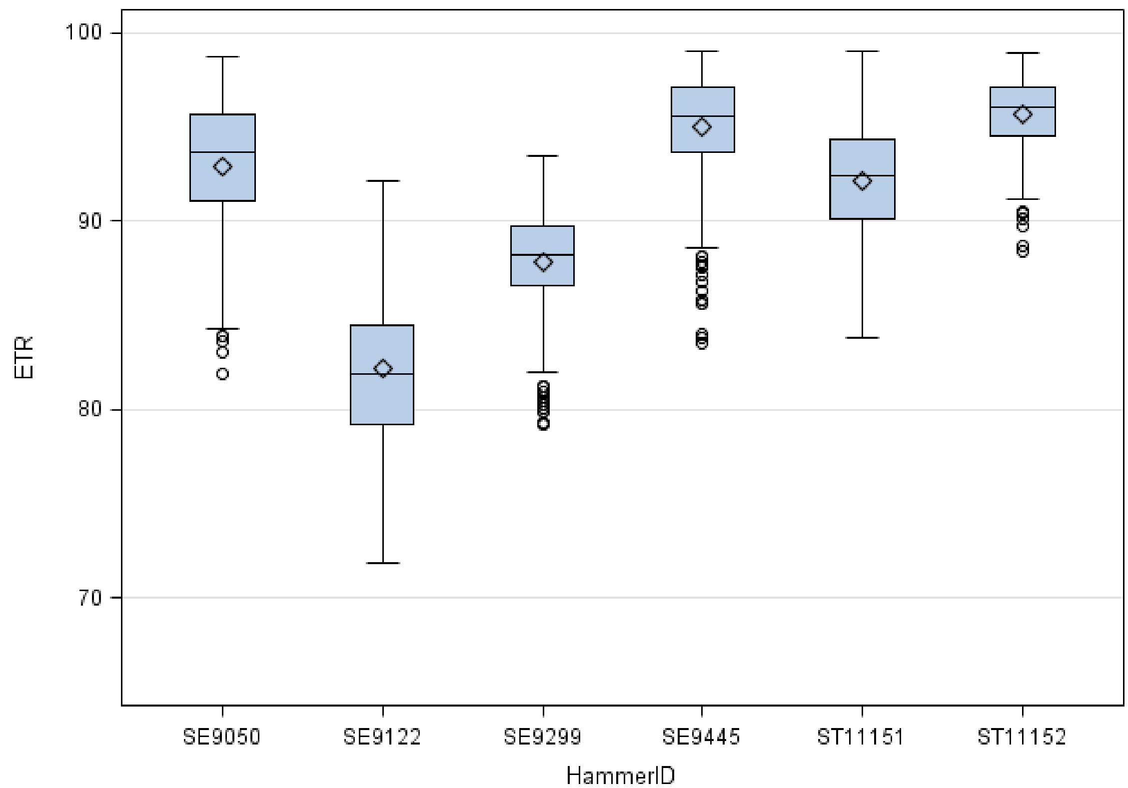

Figure 4.13 Energy box plots-ALDOT (Blow to Blow)

4.8.3 Variation of Hammer Operation Rate

The average hammer operation rate for each drill rig, along with its standard deviation and coefficient of variation, were previously provided in Table 4.2. The shape of the hammer operation rate box plots in Figure 4.14 show that the distribution of data is practically normal. The range of average hammer operation rates experienced during the testing program was from approximately 52 blows per minute to 55 blows per minute. These measurements correspond well to the CME manufacturer hammer settings of 50 to 55 blows per minute. The standard deviation of hammer operation rate for each hammer system in the fleet was found to be less than 1BPM. The calculated COV for each group was either slightly higher or lower than 1 %, which basically shows that the CME automatic hammer is relatively consistent from blow to blow.

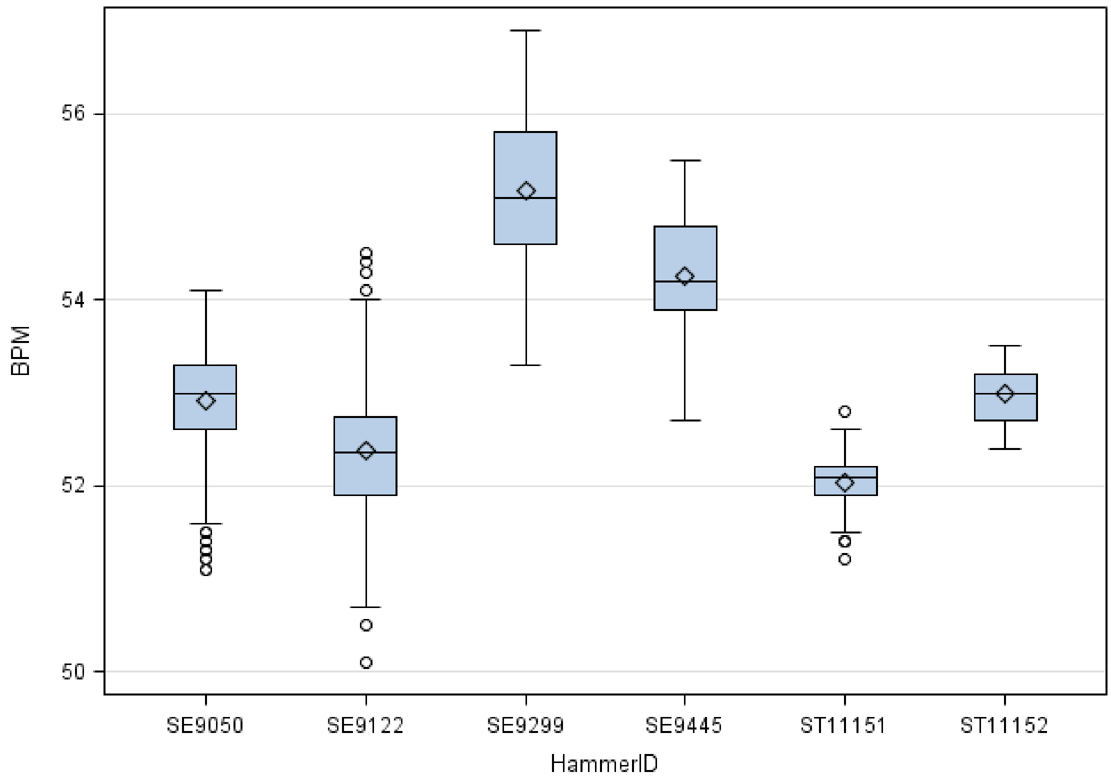

Figure 4.14 Hammer operation rate box plots-ALDOT (blow to blow)

4.8.4 Rod Length Effects

SPT energy measurements were performed at as many depths as possible in order to establish a relationship between short rod lengths and energy transfer for the type of geology tested. This was primarily performed in order to allow ALDOT to establish short rod length correction factors, if desired. The field data from the testing program has been plotted in Figure 4.15, which shows the average ETR per rod length measured for each drill rig. The general trend of the data suggests that the average ETR for each hammer begins to stabilize to the approximate hammer baseline energy at a rod length of 33 ft. This behavior supports the ASTM 4633 recommendation that energy transfer is "more reliable" when the rods length is at least 30 ft.

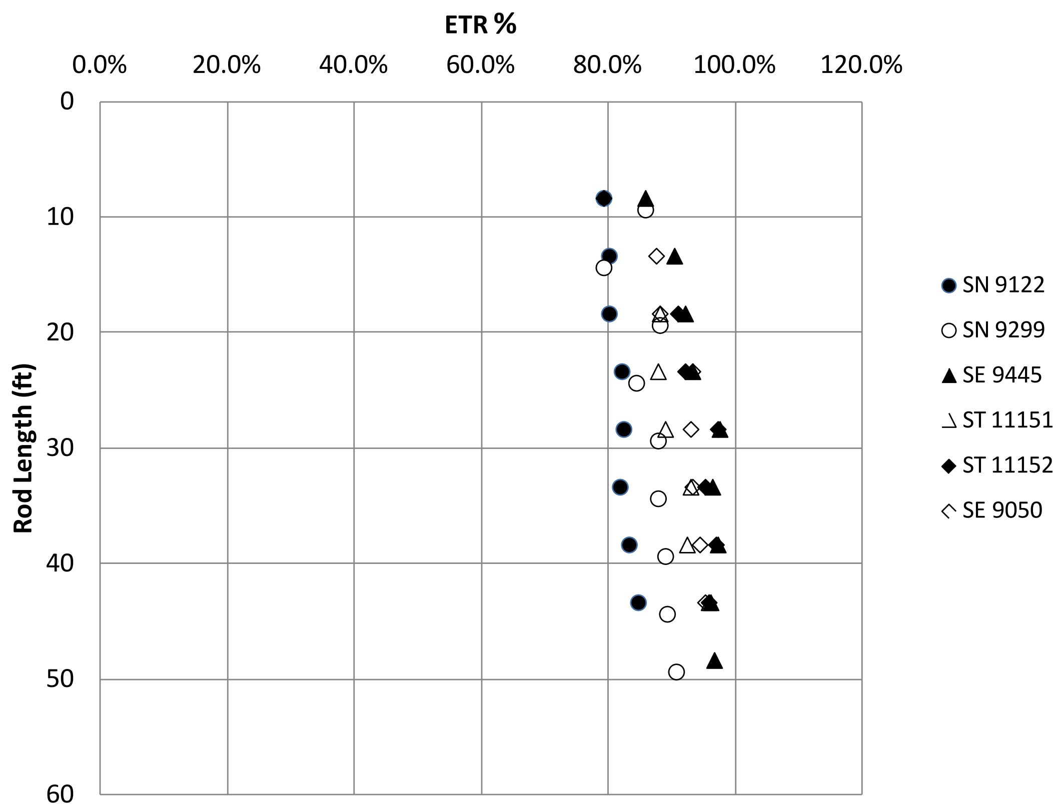

Figure 4.15 ETR vs. rod length-ALDOT

Utilizing the normalization approach used by the NCDOT, the ALDOT data was plotted against the NCDOT's data using baseline transfer efficiencies observed at 33 ft as well as 38 ft. The average ETR at 38 ft was used in order for a comparison to be made with the NCDOT data. These results are plotted in Figure 4.16. Additional comparisons with the ALDOT and NCDOT data were made by plotting the results of the Morgano and

Liang study, as well as the theoretical transfer efficiency η_l from Equation 3.1, and are shown in Figure 4.17.

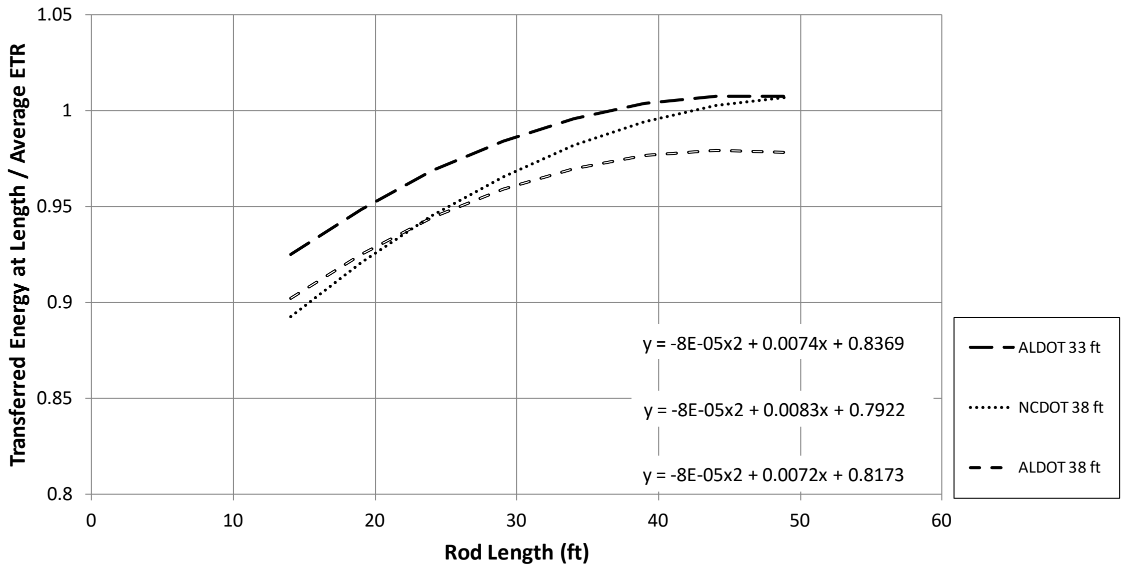

Figure 4.16 Rod length study comparison-ALDOT & NCDOT

Inspection of the transfer efficiency trends in Figure 4.16 reveals that ALDOT's short rod behavior generally agrees with that of the NCDOT study. The trends produced using baseline hammer efficiencies of 33 ft and 38 ft bound the upper and lower limits of the NCDOT regression trend, with an approximate difference between the upper and lower regression lines of 2.5% efficiency.

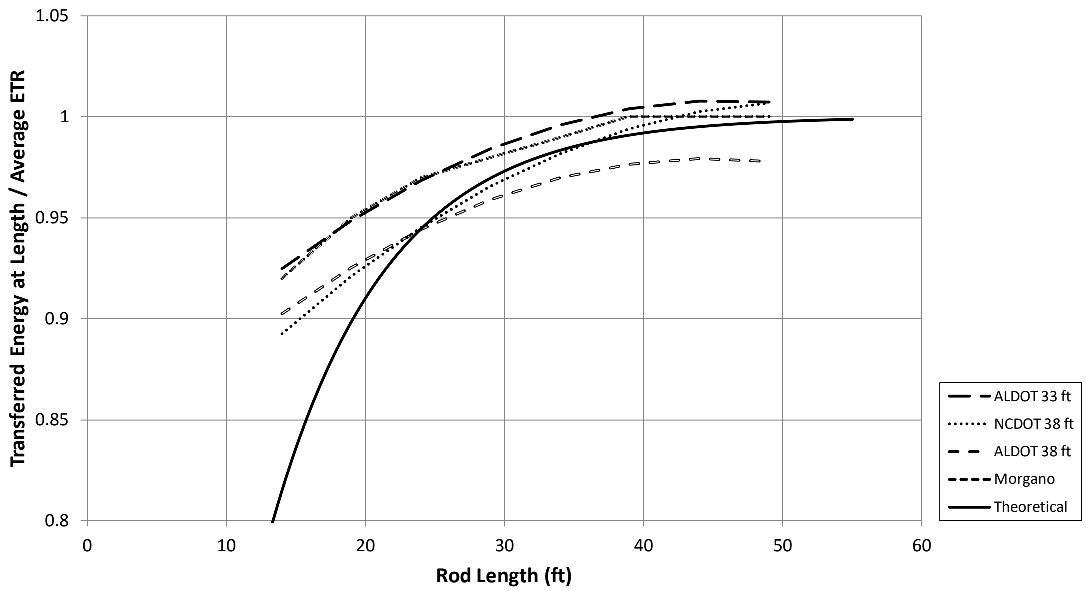

Figure 4.17 Rod length study comparison-all studies

Figure 4.17 above shows the hammer efficiency regressions for all of the short rod studies, and the apparent trend was still the same. The shortest rods produce a larger reduction in transfer efficiency compared to longer rods. The theoretical regression line seems to slightly overpredict the energy losses for rod lengths less than about 25 ft when compared to the other regression lines. The regression line from the Morgano study approximately follows that of the ALDOT trend normalized from energy measurements above 33 ft.

CHAPTER 5: CONCLUSIONS

An SPT energy testing program was developed for the Alabama Department of Transportation. The testing was performed in a simple, repeatable sequence, which supplemented ALDOT's normal SPT operations. A calibration certificate documenting hammer performance was provided for each drill rig. A copy of each calibration certificate can be found in Appendix A of this report. Concluding remarks summarizing the testing program are provided below.

1. A total of six CME hammers were tested. The number of energy averages obtained for each hammer was from 6 to 9 (sample to sample), and were obtained from rod lengths less than about 50 ft. The overall ETRs for each hammer were from 82.2% to 96.1%, with an overall average of approximately 91%. The associated COVs ranged from 2.2% to 5.7%.
2. The average hammer operation rate for each drill rig were within the CME recommendations and varied from about 52 to 55 BPM. The calculated COVs were from 0.46% to 1.4%.

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APPENDIX A: ALDOT Drill Rig Calibration Certificates

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Record of Standard Penetration Test Energy Calibration

For

SE 9122 – Central Mine Equipment 550X ATV

Date of Calibration: April 5th, 2011

Documentation:

Alabama Department of Transportation

BUREAU OF MATERIALS & TESTS

3700 Fairground Road Montgomery, Alabama 36110

U.S. 80 Over French Creek
Marengo County, Alabama
BR0008 (528)

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
SE 9122 CME - 550x (ATV)	ALDOT	Russell	B-1	4/5/2011	AW-J	51.6	8.3	3 - 4.5	4 - 8 - 9	14	277	79.1%	3.3
						53.2	13.3	8 - 9.5	3 - 2 - 4	4	280	80.0%	4.5
						51.5	18.3	13 - 14.5	14 - 34 - 40	74	280	80.0%	4.5
						51.7	23.3	18 - 19.5	19 - 34 - 47	87	287	82.0%	2.8
						51.8	28.3	23 - 24.5	23 - 30 - 50	84	288	82.3%	3.6
						52	33.3	28 - 29.5	21 - 32 - 40	70	286	81.7%	3.3
						52.6	38.3	33 - 34.5	18 - 31 - 50	78	291	83.1%	3.9
						52	43.3	38 - 39.5	18 - 30 - 45	74	296	84.6%	5.4
									[d]**Average Measured Energy:**		**287.6**	**82.2%**	

Overall Average ETR %

[a]Energy results for SPT sampling are averaged and reported for hammer impacts during the final 1 ft of driving, which relates to the observed N-value. In some cases, certain blows produce poor quality data and were not used to calculate the Average Measured Energy. This may result in less blows evalutated for ETR than what is shown on the boring logs.

[b]Measured Energy is based on the EFV method, as outlined in ASTM D4633-10, for each blow recorded by the SPT Analyzer.

[c]Energy Transfer Ratio is the Measured Energy divided by the theoretical SPT energy of 350 foot-pounds (140 pound hammer falling 2.5 feet).

The average EFV and ETR values may differ slightly and insignificantly from those in the PDIPLOT tables due to roundoff.

[d]The overall Average Measured Energy is calculated by taking the weighted average of the number of hammer blows analyzed (last 1 ft) and the Average Measured Energy for each sample depth tested.

[e]ETR COV determined by calculating the overall standard deviation for the average ETR per sample depth (c) and then dividing by the overall average ETR.

The STDEV function from Excel was utilized to determine the standard deviation.

Statistical Analysis - Overall Coefficient of Variation

Calibration Prepared By: JNH Date: 4/5/2011		[e]Energy Transfer Ratio (ETR) COV: **2.21** %

DCN: 01

Location:
East Side of Dual
Bridges - in Median

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Page #1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	BR0008 (528)	**Rig Make / Model:**	CME 550 X
Location:	US 80 over French Crk.	**Rig I.D.:**	SE 9122 (360083)
Date:	4/5/11	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH / WRB	**Hammer Type:**	Auto
Drilling Company:	ALDOT	**Rod Size:**	AW J

Boring Identification:	Boring #1	
Geologic Region:	Coastal Plain - Demopolis Chalk (Kd)	
Time Tested:	8-10 AM Approx.	
Drill Rig Operator:	Russell	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in²	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 AW #1	F2: 206 AW #2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts	Increment	Misc. Comments
(B) 1A	2.8+0.5 +2.0 5.3	5.3	0' (0 - 1.5)	3	6 in	Did Not Save
				4	12 in	
				7 (11)	18 in	
1B	2.8+0.5 +5.0 8.3	5.3	3' (3 - 4.5)	4	6 in	
				8	12 in	
				9 (17)	18 in	
1C	13.3	5.3	8' (8 - 9.5)	3	6 in	
				2	12 in	
				4 (6)	18 in	
1D	18.3	5.3	13' (13 - 14.5)	14	6 in	
				34	12 in	
				40 (74)	18 in	
1E	23.3	5.3	18' (18 - 19.5)	19	6 in	
				34	12 in	
				47 (81)	18 in	
1F	28.3	5.3	23' (23 - 24.5)	23	6 in	
				30	12 in	
				50 (80)	18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft

Length Below Gages: 0.5 ft

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

PAGE #2

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	BR0008 (528)	**Rig Make / Model:**	CME 550 X
Location:	MS 80 OVER FRENCH CRK.	**Rig I.D.:**	SE 9122 (360083)
Date:	4/5/11	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH / WRB	**Hammer Type:**	Auto
Drilling Company:	ALDOT	**Rod Size:**	AW J

Boring Identification:	Boring #1	
Geologic Region:	Coastal Plain - Demopolis Chalk (kd)	
Time Tested:	8-10 AM APPROX	
Drill Rig Operator:	RUSSELL	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in 2	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 AW #1	F2: 206 AW #2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts	Increment	Misc. Comments
1G	33.3	5.3	28'	21	6 in	
				32	12 in	
			(28-29.5)	40 (72)	18 in	
1H	38.3	5.3	33'	18	6 in	
				31	12 in	
			(33-34.5)	50 (81)	18 in	
1i	43.3	5.3	38'	18	6 in	
				30	12 in	
			(38-39.5)	45 (75)	18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: ____2 ft_____

Length Below Gages:___________0.5 ft_________

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Record of Standard Penetration Test Energy Calibration

For

SE 9299 – Central Mine Equipment 850 Track

Date of Calibration: June 17th, 2011

DCN: 02

Documentation:

Page 1 – Calibration Certificate
Pages 2 to 3 – Field Sheets
Pages 4 to 6 – PDIPLOT
Page 7 – PDI Curves F&V Trace

Alabama Department of Transportation

BUREAU OF MATERIALS & TESTS

3700 Fairground Road Montgomery, Alabama 36110

SPT Testing Clinic # 1

Montgomery County, Alabama

Trotman Road

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
SE 9299 CME - 850 (Track)	ALDOT	J. Mathews	1A	6/17/2011	AW-J	54.4	9.3	4 - 5.5	3 - 3 - 5	8	300	85.7%	2.9
						53.8	14.3	9 - 10.5	4 - 7 - 13	15	277	79.1%	3.1
						54.3	19.3	14 - 15.5	7 - 13 - 20	31	308	88.0%	2.5
						54.9	24.3	19 - 20.5	9 - 18 - 20	38	295	84.3%	1.8
						54.9	29.3	24 - 25.5	11 - 20 - 26	46	307	87.7%	1.1
						54.5	34.3	29 - 30.5	6 - 15 - 19	33	307	87.7%	1.2
						54.7	39.3	34 - 35.5	8 - 15 - 22	37	311	88.9%	1.1
						55.8	44.3	39 - 40.5	8 - 16 - 35	51	312	89.1%	1.3
						56.2	49.3	44 - 45.5	7 - 22 - 34	56	317	90.6%	1.3
									[d]Average Measured Energy:		**307.1**	**87.7%**	

Overall Average ETR %

[a]Energy results for SPT sampling are averaged and reported for hammer impacts during the final 1 ft of driving, which relates to the observed N-value. In some cases, certain blows produce poor quality data and were not used to calculate the Average Measured Energy. This may result in less blows evalutated for ETR than what is shown on the boring logs.

[b]Measured Energy is based on the EFV method, as outlined in ASTM D4633-10, for each blow recorded by the SPT Analyzer.

[c]Energy Transfer Ratio is the Measured Energy divided by the theoretical SPT energy of 350 foot-pounds (140 pound hammer falling 2.5 feet).

The average EFV and ETR values may differ slightly and insignificantly from those in the PDIPLOT tables due to roundoff.

[d]The overall Average Measured Energy is calculated by taking the weighted average of the number of hammer blows analyzed (last 1 ft) and the Average Measured Energy for each sample depth tested.

[e]ETR COV determined by calculating the overall standard deviation for the average ETR per sample depth (c) and then dividing by the overall average ETR.

Statistical Analysis - Overall Coefficient of Variation

Calibration Prepared By: JNH Date: 6/17/2011		[e]Energy Transfer Ratio (ETR) COV: **3.89** %

DCN: 02

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Page #1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Testing Clinic #1	**Rig Make / Model:**	CME 850 Track
Location:	Trotman Road	**Rig I.D.:**	SE 9299
Date:	6/17/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH / WRB	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	1A			
Geologic Region:	Coastal Plain			
Time Tested:	approx. 7:00 AM to 8:30 AM			
Drill Rig Operator:	J. Mathews			
SPT Analyzer Serial Number:	4036T			
Instrumented Rod Type / Area:	AWJ - 1.20 in 2			
Accelerometer Serial Numbers:	A1:	K1569	A2:	K1563
Accelerometer Calibration Factors:	A1:	335	A2:	325
Strain Gage Serial Numbers:	F1:	206 AWJ - 1	F2:	206 AWJ - 2
Strain Gage Calibration Factors:	F1:	210.54	F2:	211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1A	2.8+0.5 +1.0+5.0 9.3	5.3'	4' (4-5.5)	3	6 in	
				3	12 in	
				5 (8)	18 in	
↓	14.3'	5.3'	9' (9-10.5)	4	6 in	
				7	12 in	
				13 (20)	18 in	
↓	19.3'	5.3'	14' (14-15.5)	7	6 in	
				13	12 in	
				20 (33)	18 in	
↓	24.3'	5.3	19' (19-20.5)	9	6 in	
				18	12 in	
				20 (38)	18 in	
↓	29.3'	5.3'	24' (24-25.5)	11	6 in	
				20	12 in	
				26 (46)	18 in	
↓	34.3'	5.3'	29' (29-30.5)	6	6 in	
				15	12 in	
				19 (34)	18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

Instrumented Subassembly Length: 2 ft

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Length Below Gages: 0.5 ft

DCN: 02

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Page #2

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Testing Clinic #1	**Rig Make / Model:**	CME 850 Track
Location:	Troutman Rd	**Rig I.D.:**	SE 9299
Date:	6/17/2021	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH / WRB	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	1A			
Geologic Region:	Coastal Plain			
Time Tested:	Approx. 7:00 AM - 830 AM			
Drill Rig Operator:	J. Mathews.			
SPT Analyzer Serial Number:	4036T			
Instrumented Rod Type / Area:	AWJ - 1.20 IN^2			
Accelerometer Serial Numbers:	A1:	K1569	A2:	K1563
Accelerometer Calibration Factors:	A1:	335	A2:	325
Strain Gage Serial Numbers:	F1:	206 AWJ-1	F2:	206 AWJ-2
Strain Gage Calibration Factors:	F1:	210.54	F2:	211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1A	39.3'	5.3'	34	8	6 in	
				15	12 in	
			(34-35.5)	22 (37)	18 in	
↓	44.3'	5.3'	39	8	6 in	
				16	12 in	
			(39-40.5)	35 (51)	18 in	
↓	49.3'	5.3'	44	7	6 in	
				22	12 in	
			(44-45.5)	34 (56)	18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft

Length Below Gages: 0.5 ft

DCN: 02

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Record of Standard Penetration Test Energy Calibration

For

SE 9445 – Central Mine Equipment 550x ATV

Date of Calibration: June 17th, 2011

DCN: 03

Documentation:

Alabama Department of Transportation

BUREAU OF MATERIALS & TESTS

3700 Fairground Road Montgomery, Alabama 36110

SPT Testing Clinic # 1

Montgomery County, Alabama

Trotman Road

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
SE 9445 CME - 550x (ATV)	ALDOT	Dingler	2A	6/17/2011	AW-J	54.1	8.3	4 - 5.5	3 - 3 - 5	8	300	85.7%	1.9
						53.6	13.3	9 - 10.5	3 - 6 - 10	16	316	90.3%	2.3
						53.2	18.3	14 - 15.5	5 - 10 - 16	26	322	92.0%	2.9
						54.2	23.3	19 - 20.5	8 - 13 - 20	32	326	93.1%	1.7
						54.7	28.3	24 - 25.5	11 - 20 - 20	40	341	97.4%	2.1
						54.9	33.3	29 - 30.5	11 - 19 - 28	46	337	96.3%	1.1
						54.8	38.3	34 - 35.5	8 - 13 - 34	47	340	97.1%	1
						54	43.3	39 - 40.5	12 - 18 - 44	62	336	96.0%	1.7
						53.8	48.3	44 - 45.5	12 - 21 - 47	21	338	96.6%	1.3
									[d]Average Measured Energy:		**333.3**	**95.2%** Overall Average ETR %	

[a]Energy results for SPT sampling are averaged and reported for hammer impacts during the final 1 ft of driving, which relates to the observed N-value. In some cases, certain blows produce poor quality data and were not used to calculate the Average Measured Energy. This may result in less blows evalutated for ETR than what is shown on the boring logs.

[b]Measured Energy is based on the EFV method, as outlined in ASTM D4633-10, for each blow recorded by the SPT Analyzer.

[c]Energy Transfer Ratio is the Measured Energy divided by the theoretical SPT energy of 350 foot-pounds (140 pound hammer falling 2.5 feet).

The average EFV and ETR values may differ slightly and insignificantly from those in the PDIPLOT tables due to roundoff.

[d]The overall Average Measured Energy is calculated by taking the weighted average of the number of hammer blows analyzed (last 1 ft) and the Average Measured Energy for each sample depth tested.

[e]ETR COV determined by calculating the overall standard deviation for the average ETR per sample depth (c) and then dividing by the overall average ETR.

Statistical Analysis - Overall Coefficient of Variation

Calibration Prepared By: JNH Date: 6/17/2011		[e]Energy Transfer Ratio (ETR) COV: **4.14** %

DCN: 03

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Page #1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Testing Clinic #1	**Rig Make / Model:**	CME 550 X ATV
Location:	Trotman Road	**Rig I.D.:**	SE 9445
Date:	6/17/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNM / WRB	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	2A			
Geologic Region:	Coastal Plain			
Time Tested:	App. 830 - 930 AM			
Drill Rig Operator:	Dusty			
SPT Analyzer Serial Number:	4036T			
Instrumented Rod Type / Area:	AWJ - 1.20 in²			
Accelerometer Serial Numbers:	A1:	K1569	A2:	K1563
Accelerometer Calibration Factors:	A1:	335	A2:	325
Strain Gage Serial Numbers:	F1:	206 AWJ-1	F2:	206 AWJ-2
Strain Gage Calibration Factors:	F1:	210.54	F2:	211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
2A.	2.8 +0.5 +5 8.3'	4.3'	4'	3	6 in	
				3	12 in	
			(4-5.5)	5 (8)	18 in	
↓	13.3'	4.3'	9'	3	6 in	
				6	12 in	
			(9-10.5)	10 (16)	18 in	
	18.3'	4.3'	14'	5	6 in	
				10	12 in	
			(14-15.5)	16 (26)	18 in	
	23.3'	4.3'	19'	8	6 in	
				13	12 in	
			(19-20.5)	20 (33)	18 in	
	28.3'	4.3'	24'	11	6 in	
				20	12 in	
			(24-25.5)	20 (40)	18 in	
↓	33.3'	4.3'	29'	11	6 in	
				19	12 in	
			(29-30.5)	28 (47)	18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft

Length Below Gages: 0.5 ft

DCN: 03

Page #2

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Testing Clinic #1	**Rig Make / Model:**	CME 550 x ATV
Location:	Trotman Road	**Rig I.D.:**	SE 9445
Date:	6/17/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNM / WRB	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	2A	
Geologic Region:	Coastal Plain	
Time Tested:	Approx. 830 - 930 AM	
Drill Rig Operator:	Dinsler	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	AWJ - 1.20 in²	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 385	A2: 325
Strain Gage Serial Numbers:	F1: 206 AWJ-1	F2: 206 AWJ-2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
2A	38.3'	4.3'	34'	8	6 in	
				13	12 in	
			(34-35.5)	34 (47)	18 in	
↓	43.3'	4.3'	39'	12	6 in	
				18	12 in	
			(39-40.5)	44 (62)	18 in	
	48.3'	4.3'	44'	12	6 in	
				21	12 in	
			(44-45.5)	47 (68)	18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*
**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*
**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: ____2 ft_____

Length Below Gages:__________0.5 ft_________

DCN: 03

Alabama Department of Transportation
BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

Record of Standard Penetration Test Energy Calibration

For

ST 11151 – Central Mine Equipment 55 Truck Mount

Date of Calibration: July 8th, 2011

DCN: 04

Documentation:

Page 1 – Calibration Certificate
Pages 2 to 3 – Field Sheets
Pages 4 to 11 – PDIPLOT
Page 12 – Force & Velocity Trace

Alabama Department of Transportation

BUREAU OF MATERIALS & TESTS
3700 Fairground Road Montgomery, Alabama 36110

SPT Testing Clinic # 2
Montgomery County, Alabama
Near Trotman Road

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
ST 11151 CME - 55 (Truck)	ALDOT	J. Mathews	1A	7/8/2011	AWJ	52.5	18.3	14 - 15.5	2 - 4 - 7	10	308	88.0%	3
						52.2	23.3	19 - 20.5	5 - 8 - 4	10	307	87.7%	4.3
						52.3	28.3	24 - 25.5	15 - 21 - 27	46	311	88.9%	1.2
						52	33.3	29 - 30.4	24 - 32 - 50/0.4'	79	325	92.9%	1.9
						51.9	38.3	34 - 35.5	15 - 24 - 40	61	323	92.3%	1
						51.9	43.3	39 - 39.9	39 - 50/0.4'	51	335	95.7%	1.7
									[d]Average Measured Energy:		**322.6**	**92.2%**	

Overall Average ETR %

[a]Energy results for SPT sampling are averaged and reported for hammer impacts during the final 1 ft of driving, which relates to the observed N-value. In some cases, certain blows produce poor quality data and were not used to calculate the Average Measured Energy. This may result in less blows evalutated for ETR than what is shown on the boring logs.

[b]Measured Energy is based on the EFV method, as outlined in ASTM D4633-10, for each blow recorded by the SPT Analyzer.

[c]Energy Transfer Ratio is the Measured Energy divided by the theoretical SPT energy of 350 foot-pounds (140 pound hammer falling 2.5 feet).

The average EFV and ETR values may differ slightly and insignificantly from those in the PDIPLOT tables due to roundoff.

[d]The overall Average Measured Energy is calculated by taking the weighted average of the number of hammer blows analyzed (last 1 ft) and the Average Measured Energy for each sample depth tested.

[e]ETR COV determined by calculating the overall standard deviation for the average ETR per sample depth (c) and then dividing by the overall average ETR.

Statistical Analysis - Overall Coefficient of Variation

Calibration Prepared By: JNH Date: 7/8/2011		[e]Energy Transfer Ratio (ETR) COV: **3.49** %

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Page #1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Test Clinic #2	**Rig Make / Model:**	CME 55 Truck
Location:	Montgomery, AL.	**Rig I.D.:**	ST-11151
Date:	7/8/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	Boring 1-A	
Geologic Region:	Coastal Plain	
Time Tested:	7:30 AM - 7:30 AM	
Drill Rig Operator:	J. Mathews	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in²	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 AWJ-1	F2: 206 AWJ-2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1A-1	2.8+0.5 +5.0' 8.3'	4.3'	4' (4-5.5)	5	6 in	Questionable DATA
				2	12 in	
				2 (4)	18 in	
Skip Sample (WOH)	13.3'	4.3'	9' (9-10.5)		6 in	
				W.O.H.	12 in	
					18 in	
1A-2	18.3'	4.3'	14' (14-15.5')	2	6 in	Drop Height ≈ 30"
				4	12 in	
				7 (11)	18 in	
1A-3	23.3'	4.3'	19' (19-20.5)	5	6 in	
				8	12 in	
				4 (12)	18 in	
1A-4	28.3'	4.3'	24' (24-25.5)	15	6 in	
				21	12 in	
				27 (48)	18 in	
1A-5	33.3'	4.3'	29' (29-30.4')	24	6 in	Drop Height ≈ 30"
				32	12 in	
				50/0.4' (100)	18 in	

Rod Length: Total Length From Gages to Tip of Sampler
Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages
Calculated Start Depth: Rod Length Minus Measured Stick Up

Instrumented Subassembly Length: 2 ft
Length Below Gages: 0.5 ft

DCN: 04

Alabama Department of Transportation
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Page #2

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Test Clinic #2	**Rig Make / Model:**	CME 55 Truck
Location:	Montgomery, AL	**Rig I.D.:**	ST-11151
Date:	7/8/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH	**Hammer Type:**	Automatic
Drilling Company:	ALDot	**Rod Size:**	AWJ

Boring Identification:	Boring 1-A	
Geologic Region:	Coastal Plain	
Time Tested:	7:30 Am - 12:00 pm	
Drill Rig Operator:	J. Mathews	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in²	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 Awj-1	F2: 206 Awj-2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1A-6	38.3	4.3'	34'	15	6 in	
				24	12 in	
			(34-35.5)	40 (64)	18 in	
1A-7	43.3	4.3'	39'	39	6 in	Drop Height ≈ 30"
				50/0.4' (100)	12 in	
			(39-39.9)		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft

Length Below Gages: 0.5 ft

DCN: 04

Alabama Department of Transportation
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Record of Standard Penetration Test Energy Calibration

For

ST 11152 – Central Mine Equipment 55 Truck Mount

Date of Calibration: July 8th, 2011

DCN: 05

Documentation:

Alabama Department of Transportation

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SPT Testing Clinic # 2
Montgomery County, Alabama
Near Trotman Road

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
ST 11152 CME - 55 (Truck)	ALDOT	J. Mathews	1B	7/8/2011	AWJ	52.5	18.3	14 - 15.5	3 - 3 - 5	7	318	90.9%	2
						53.3	23.3	19 - 20.5	3 - 5 - 5	10	322	92.0%	2
						53.1	28.3	24 - 25.5	13 - 27 - 35	83	340	97.1%	1.5
						52.6	33.3	29 - 30.5	13 - 21 - 39	59	333	95.1%	1.4
						53	38.3	34 - 35.5	24 - 38 - 50	92	339	96.9%	1.2
						53.2	43.3	39 - 39.9	24 - 50/0.4'	49	335	95.7%	1.6
									[d]**Average Measured Energy:**		**336.4**	**96.1%** Overall Average ETR %	

[a]Energy results for SPT sampling are averaged and reported for hammer impacts during the final 1 ft of driving, which relates to the observed N-value. In some cases, certain blows produce poor quality data and were not used to calculate the Average Measured Energy. This may result in less blows evalutated for ETR than what is shown on the boring logs.

[b]Measured Energy is based on the EFV method, as outlined in ASTM D4633-10, for each blow recorded by the SPT Analyzer.

[c]Energy Transfer Ratio is the Measured Energy divided by the theoretical SPT energy of 350 foot-pounds (140 pound hammer falling 2.5 feet).

The average EFV and ETR values may differ slightly and insignificantly from those in the PDIPLOT tables due to roundoff.
[d]The overall Average Measured Energy is calculated by taking the weighted average of the number of hammer blows analyzed (last 1 ft) and the Average Measured Energy for each sample depth tested.

[e]ETR COV determined by calculating the overall standard deviation for the average ETR per sample depth (c) and then dividing by the overall average ETR.

Calibration Prepared By: JNH Date: 7/9/2011		Statistical Analysis - Overall Coefficient of Variation [e]Energy Transfer Ratio (ETR) COV: **2.71** %

DCN: 05

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Page # 1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Test Clinic # 2	**Rig Make / Model:**	CME 55 Truck
Location:	Montgomery, AL	**Rig I.D.:**	ST 11152
Date:	7/8/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNM	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	Boring 1B	
Geologic Region:	Coastal Plain	
Time Tested:	10:00AM - 12:00 PM	
Drill Rig Operator:	J. Mathews	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in²	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 AWJ-1	F2: 206 AWJ - 2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1B-1	2.8 + 1 + 0.5 + 5 9.3'	5.3'	4' (4 - 5.5)	2	6 in	Won't use Data Due
				1	12 in	
				2 (3)	18 in	
1B-2	2.8 + 0.5 + 10 13.3'	4.3'	9' (9 - 10.5)	1	6 in	to Very Low Blow Counts
				1	12 in	
				2 (3)	18 in	
1B-3	18.3'	4.3'	14' (14 - 15.5)	3	6 in	
				3	12 in	
				5 (8)	18 in	
1B-4	23.3'	4.3'	19' (19 - 20.5)	3	6 in	Drop Height ≈ 30"
				5	12 in	
				5 (10)	18 in	
1B-5	28.3'	4.3'	24' (24 - 25.5)	13	6 in	
				27	12 in	
				35 (62)	18 in	
1B-6	33.3'	4.3'	29' (29 - 30.5)	13	6 in	Drop Height ≈ 30"
				21	12 in	
				39 (60)	18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*
**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*
**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft
Length Below Gages: 0.5 ft

DCN: 05

Alabama Department of Transportation
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RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	Test Clinic #2	**Rig Make / Model:**	CME 55 Truck
Location:	Montgomery, AL	**Rig I.D.:**	ST 11152
Date:	7/8/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	Awj

Boring Identification:	Boring 1B	
Geologic Region:	Coastal Plain	
Time Tested:	10:00 AM - 12:00 PM	
Drill Rig Operator:	J. Mathews.	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in²	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 Awj-1	F2: 206 Awj-2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
1B-7	38.3'	4.3'	34'	24	6 in	
				38	12 in	
			(34-35.5)	50	18 in	
1B-8	43.3'	4.3'	39'	24	6 in	Drop Height ≈ 30"
				50/0.4'	12 in	
			(39-39.9)		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	

Rod Length: Total Length From Gages to Tip of Sampler

Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages

Calculated Start Depth: Rod Length Minus Measured Stick Up

***Instrumented Subassembly Length:** ____2 ft____*

***Length Below Gages:** __________0.5 ft_________*

DCN: 05

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Record of Standard Penetration Test Energy Calibration

For

SE 9050 – Central Mine Equipment 550X ATV

Date of Calibration: July 12th, 2011

DCN: 06

Documentation:

Page 1 – Calibration Certificate
Pages 2 to 3 – Field Sheets
Pages 4 to 13 – PDIPLOT
Page 14 – Force & Velocity Trace

Alabama Department of Transportation

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231 Bypass HPP-0035 (10)
Montgomery County, Alabama
Near Trotman Road

Automatic Hammer Serial Number and Rig Model	Rig Owner	Rig Operator	Boring No. Tested	Date Tested	Drill Rod Size	Average Hammer Operation Rate (BPM)	Drill Rod Length (ft) (LE)	Sample Depth (feet)	SPT Blow Count (blows per six inches) (From Boring Log)	[a]No. of Blows Analyzed (From PDIPLOT)	[b]Average Measured Energy (Average EFV) (ft-lbs)	[c]Energy Transfer Ratio (%) (Average ETR)	ETR Standard Deviation (From PDIPLOT)
SE 9050 CME - 550X (ATV)	ALDOT	K Drake	B22	7/12/2011	AW-J	51.3	8.3	4 - 5.5	1 - 3 - 4	7	277	79.1%	8.1
						52.5	13.3	8 - 9.5	2 - 3 - 5	9	306	87.4%	2.8
						53.3	18.3	14 - 15.5	2 - 3 - 3	6	308	88.0%	4.1
						51.9	23.3	19 - 20.5	5 - 5 - 10	19	326	93.1%	2.7
						52.6	28.3	24 - 25.5	3 - 9 - 21	30	325	92.9%	3
						53	33.3	29 - 30.5	5 - 17 - 32	49	326	93.1%	2.5
						53.3	38.3	34 - 35.5	5 - 13 - 24	38	330	94.3%	2.5
						53.3	43.3	39 - 40.4	6 - 30 - 50/0.4'	71	333	95.1%	2.9
									[d]Average Measured Energy:		**325.9**	**93.1%**	

Overall Average ETR %

[a]Energy results for SPT sampling are averaged and reported for hammer impacts during the final 1 ft of driving, which relates to the observed N-value. In some cases, certain blows produce poor quality data and were not used to calculate the Average Measured Energy. This may result in less blows evalutated for ETR than what is shown on the boring logs.

[b]Measured Energy is based on the EFV method, as outlined in ASTM D4633-10, for each blow recorded by the SPT Analyzer.

[c]Energy Transfer Ratio is the Measured Energy divided by the theoretical SPT energy of 350 foot-pounds (140 pound hammer falling 2.5 feet).

The average EFV and ETR values may differ slightly and insignificantly from those in the PDIPLOT tables due to roundoff.
[d]The overall Average Measured Energy is calculated by taking the weighted average of the number of hammer blows analyzed (last 1 ft) and the Average Measured Energy for each sample depth tested.

[e]ETR COV determined by calculating the overall standard deviation for the average ETR per sample depth (c) and then dividing by the overall average ETR.

Statistical Analysis - Overall Coefficient of Variation

Calibration Prepared By: JNH Date: 7/12/2011		[e]Energy Transfer Ratio (ETR) COV: **5.74** %

DCN: 06

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Page #1

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	231 Bypass 4PP-0035(10)	**Rig Make / Model:**	CME 550X
Location:	Montgomery, AL	**Rig I.D.:**	SF 9050
Date:	7/12/2011	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	Awj

Boring Identification:	B-22		
Geologic Region:	Coastal Plain		
Time Tested:	7/11 to 7/12 - to 9:30 AM		
Drill Rig Operator:	Kieth Drake		
SPT Analyzer Serial Number:	4036T		
Instrumented Rod Type / Area:	1.20 in^2		
Accelerometer Serial Numbers:	A1: K1569	A2: K1563	
Accelerometer Calibration Factors:	A1: 335	A2: 325	
Strain Gage Serial Numbers:	F1: 206 Awj-1	F2: 206 Awj-2	
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5	

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
B22-1	2.8+0.5 +5 8.3'	4.3'	4' (4-5.5)	1	6 in	After Shelby
				3	12 in	
				4 (7)	18 in	
B22-2	13.3'	5.3'	8' (8-9.5)	2	6 in	After Shelby
				3	12 in	
				5 (8)	18 in	
B22-3	18.3'	4.3'	14' (14-15.5)	2	6 in	~~After Shelby~~ * No Data Recorded *
				3	12 in	
				3 (6)	18 in	
B22-4	23.3'	4.3'	19' (19-20.5)	5	6 in	
				5	12 in	
				10 (15)	18 in	
B22-5	28.3'	4.3'	24' (24-25.5)	3	6 in	Drop Height ≈ 30"
				9	12 in	
				21 (30)	18 in	
B22-6	33.3'	4.3'	29' (29-30.5)	5	6 in	
				17	12 in	
				32 (49)	18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*
**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*
**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft

Length Below Gages: 0.5 ft

DCN: 06

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PAGE # 2

RECORD OF SPT ENERGY MEASUREMENTS

Project Name:	231 Bypass HPP-0035(10)	**Rig Make / Model:**	CME 550X
Location:	Montgomery, AL	**Rig I.D.:**	SE 9850
Date:	7/12/11	**Hammer Serial No.:**	N/A
SPT Inspector:	JNH	**Hammer Type:**	Automatic
Drilling Company:	ALDOT	**Rod Size:**	AWJ

Boring Identification:	B-22	
Geologic Region:	Coastal Plain	
Time Tested:	7/11 to 7/12 to 9:30 Am	
Drill Rig Operator:	Keith Drake	
SPT Analyzer Serial Number:	4036T	
Instrumented Rod Type / Area:	1.20 in 2	
Accelerometer Serial Numbers:	A1: K1569	A2: K1563
Accelerometer Calibration Factors:	A1: 335	A2: 325
Strain Gage Serial Numbers:	F1: 206 AWJ-1	F2: 206 AWJ-2
Strain Gage Calibration Factors:	F1: 210.54	F2: 211.5

Analyzer File Name (Boring No. plus Subdesignation)	Rod Length (FT)	Measured S.U. (FT)	Calculated Start Depth (FT)	Hammer Blow Counts (Provided By Others)	Increment	Misc. Comments
B22-7	38.3'	4.3'	34'	5	6 in	
				13	12 in	
			(34-35.5)	24 (37)	18 in	
B22-8	43.3'	4.3'	39'	6	6 in	
				30	12 in	
			(39-40.4)	50/0.4' (92)	18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	
					6 in	
					12 in	
			( )		18 in	

**Rod Length: Total Length From Gages to Tip of Sampler*

**Measured S.U.: Measured Drill Rod Stick Up From Ground Surface to Location of Gages*

**Calculated Start Depth: Rod Length Minus Measured Stick Up*

Instrumented Subassembly Length: 2 ft

Length Below Gages: 0.5 ft