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Energy transfer in SPT – Rod length effect

C.M.Morgano
Goble Rausche Likins and Associates, Inc., Cleveland, Ohio, USA
(Formerly: The University of Akron, Ohio, USA)

R.Liang
The University of Akron, Ohio, USA

ABSTRACT: The blow count (N-value) from the Standard Penetration Test (SPT) has been correlated with various engineering soil properties such as strength, stiffness, compressibility, etc. These deduced soil properties are often used as sole information for foundation analysis and design. The SPT N values however, depend greatly on the energy transferred during each hammer impact. Previous studies, although not necessarily complete, indicate that energy transfer in SPT was dependent upon, among other factors, rod length and soil resistance. Presented in this paper is the result of a study performed to investigate the influence of rod length on the transfer energy on SPT. Both numerical studies and field tests were employed to study the subject matter. Numerical studies included the use of a wave equation based GRLWEAP computer program. Field tests utilized the Pile Driving Analyzer^{TM} (PDA) and Hammer Performance Analyzer (HPA) to measure both energy transferred and kinetic energy from the hammer impact. Based on the results from the study, the effect of rod length on energy transfer was quantified.

1 INTRODUCTION

The Standard Penetration Test (SPT) has been the most widely used in-situ soil testing method in North America. The test is performed by dropping a hammer on a slender steel rod which is then driven into the ground. A split-spoon sampler is connected to the bottom of the rod to obtain a soil sample. The number of hammer blows required to drive the sampler three 6-inch intervals, referred to as the "blow count", gives an indication of the soil strength (relative density, stiffness). Often, a foundation design will be based only on the results of this test.

The name given to the test may be misleading since in some ways the test is not at all "standard". It has been shown that variables such as:

1. hammer type (safety/donut or automatic)
2. number of rope turns around cathead
3. actual drop height
4. rod length

may significantly effect the results (blow counts) of the SPT test since they may effect the energy transfer from the hammer to the rod.

This paper presents the results of a study performed to study the effect of the rod length on the transferred energy. The research included a numerical study using a version of the Wave Equation Analysis Program (GRLWEAP) and field measurements of transferred energy with varying rod length. It is conceivable that the accuracy of SPT testing can be improved if the effect of rod length is considered when interpreting the results.

2 ENERGY TRANSFER THEORY

Energy transmission to a thin rod may be computed from the work-energy theorems. With the assumptions of linear elastic material, uniform cross section and one dimensional wave propagation, by definition, an increment of work is done when a time (t) variable force F(t) acts on a displacement $\Delta\delta$ (Figure 1):

$$\Delta W = F(t)\Delta\delta \tag{1}$$

or

$$\Delta W = F(t)v(t)\Delta t \tag{2}$$

where v(t) is the corresponding velocity.

The energy transferred from the beginning ($t_1 = 0$) up to some time t_2 can be computed as:

$$W = \int_{t_1=0}^{t_2} F(t)v(t)dt \tag{3}$$

Therefore, if we obtain measurements of force and velocity at the top of the SPT rod, the transferred energy resulting from a hammer impact can be computed by taking the integral of the product of force and velocity with respect to time.

3 PAST STUDIES

The energy transfer theory in SPT testing has been studied both theoretically and experimentally by many authors. In one such study titled the "Energy Dynamics of SPT" (Schmertmann, Palacios 1979), the authors used load cells to measure the impact force over time. They concluded that the hammer effectively stops transferring energy at time t = 2L/c, where L is the length of rod and sampler

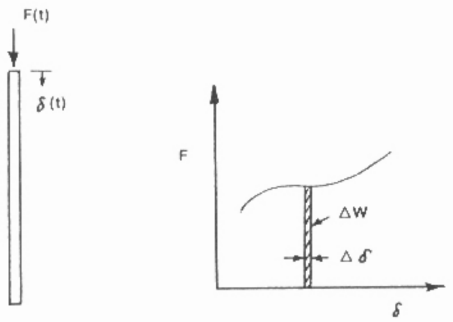


Fig. 1 Energy transmission in a uniform rod

and c is velocity of stress wave propagation in steel (5,120 m/s or 16,800 ft/sec). This is based on the assumption that a tensile stress wave will be reflected at the sampler causing the anvil to separate from the hammer once the tensile wave reaches the top of the rod.

Because only force wave forms were measured in this study, Schmertmann and Palacios computed the energy transferred to the rod by:

$$W = c/EA\int F^2(t)dt \tag{4}$$

where E is Young's modulus of elasticity of the rod material, A is the rod's cross sectional area, and c is the stress wave speed. They were able to write this relationship by using the proportionality relationship which was found to exist in one dimensional wave propagation (Timoshenko, Gere 1961):

$$\sigma = \frac{E}{c}V \tag{5}$$

where σ is the stress, V is the particle velocity and c is the stress wave speed.

Since equation (5) is only valid until upwards traveling reflection waves reach the pile top, proportionality will no longer hold after time 2L/c. The computation was therefore terminated at time 2L/c. However, the hammer may eventually (after time 2L/c) impact the rod one or more subsequent times depending on the soil resistance therefore transferring additional energy. Schmertmann and Palacios concluded that this additional energy transferred by subsequent impacts would not increase the sampler penetration significantly.

Schmertmann and Palacios' field experiments concluded that the transferred energy during the first hammer impact is indeed dependent on rod length and therefore would effect the measured blow count. However, this conclusion was based on the assumption that the additional energy transferred during subsequent impacts would not cause significant sampler penetration. A graph of rod length versus system efficiency was developed where the system efficiency was defined as the ratio of measured transferred energy (from equation 4) and the potential energy, Wh, where W is the hammer weight and h is the drop height (usually 30 inches or 76.2 cm).

An extensive experimental study was performed by for the National Bureau of Standards (Kovacs, Salomone, Yokel 1981). In this study, the authors marked targets on the SPT hammer and used light beam scanners to determine the velocity of the hammer during the hammer fall. Measurement of hammer velocity made it possible to compute the kinetic energy of the hammer prior to impact.

They defined a energy transfer ratio as:

$$ETR = E_r/E_v \tag{6}$$

where

E_r = Energy transferred to rod from the first compression wave pulse (first impact)
E_v = Kinetic energy just before impact
The transferred energy, E_r was computed from:

$$E_r = \frac{1}{A\sqrt{E\rho}}\frac{K}{K_l}\int_0^{\Delta t}[F(t)]^2 dt \tag{7}$$

The above equation was developed from the study performed by Schmertmann and Palacios, where:
K = Correction factor for load cell location
K_l = Correction factor for rod length
E = Young's Modulus of Elasticity
ρ = Mass density of steel
A = Cross sectional area of rod
F(t) = Force-time function during the first compression wave pulse (first impact).

The measurement of hammer impact velocity effectively eliminated the variable of drop height which was inherited in the Schmertmann, Palacios study.

The results of this study again indicated transferred energy that was indeed dependent on rod length. However, like the Schmertmann, Palacios study, the measured transferred energy included only the energy up to time 2L/c (first impact only) although a correction factor (K_l) was incorporated to account for the fact that there may not be sufficient time for the kinetic energy of the hammer to be transferred to the rod before the returning tensile wave causes the hammer to separate from the rod.

4 PROJECT DESCRIPTION

The research in this project included first a numerical study using a wave equation analysis program to simulate the driving action in the hammer-rod-soil system. Second, field experiments included measurement of time dependent force and acceleration on rods at various sites during SPT testing. The hammer velocity during its fall was also monitored to compute the kinetic energy at impact.

4.1 Wave equation analysis study

The wave equation analysis program was originally developed for modeling of the pile driving process. Subsequent computer studies and correlation of field measurements have established the validity of the lumped mass and spring model for pile driving analysis. The similarity of SPT testing to pile driving has led to the use of this numerical method of analysis to effectively model SPT testing.

In recent years, many refinements have been made to the program. The version used for this study was developed by Goble Rausche Likins and Associates, Inc. in

Table 1. Summary of input parameters for wave equation analyses.

Hammer data		
Weight	140 lbs	623 N
Length	50 inches	1270 mm
Stroke	30 inches	762 mm
Efficiency	0.8	0.8
Cap Weight	10 lbs.	44.5 N
Rod/sampler data		
Length	10, 20, 50, 100 ft	3.1, 6.1, 15.2, 30.5 m
Cross-section area	1.18 inch^2	7.61 cm^2
Steel modulus	30,000 ksi	207 GPa
Specific weight	492 pcf	77.5 kN/m^3
Soil data		
Skin quake	0.10 inch	2.5 mm
Toe quake	0.02 inch	0.5 mm
Smith skin damping	0.1 s/ft	0.328 s/m
Smith toe damping	0.1 s/ft	0.328 s/m
Resistance distrib.		
Skin friction	25%	25%
End bearing	75%	75%

Cleveland, Ohio and is called GRLWEAP (GRL and Associates 1990). Some program modifications were made to facilitate the need of having transferred energy versus time as output. The graphics program (GRLGRF) was also modified to allow graphic output of transferred energy versus time.

To effectively model the driving process of an SPT, the program requires data input for properties of 1) hammer, 2) rod and sampler and 3) soil. The input data used in the analyses for all three of the above parameters have been summarized in Table 1. These values are based on recommendations given in the GRLWEAP manual and on results of past field experiments. Since a more detailed discussion on the method and input parameters is beyond the scope of this paper, the reader is referred to the abundant literature on the subject.

4.2 Field experiments

The field experiments included measurement of time dependent force and acceleration as well as hammer velocity. The acceleration record was numerically integrated to obtain velocity. These tasks were accomplished with the use of a Pile Driving Analyzer^{TM} (PDA), Model GCPC, and a Hammer Performance Analyzer (HPA). A schematic of the equipment set-up in the field is shown in Figure 2. Both of these units are manufactured by Pile Dynamics, Inc. in Cleveland, Ohio. Detailed description of this equipment can be found in a paper titled "Field measurements and the pile driving analyzer" (Likins, G. E. 1985).

The PDA system uses reusable transducers to measure time dependent force and piezoelectric accelerometers to measure acceleration which is then integrated to obtain velocity. The HPA uses radar technology to monitor the motion (time dependent velocity) of rams in pile driving hammers. This information is used to evaluate the performance of the hammer.

For this study, the PDA was used mainly to measure the energy transferred to the SPT rods according to equation (3). Unlike the research performed by Schmertmann et al., and subsequently Kovacs et al., where the measured transferred energy included that from the first compression wave only, the computation of energy is carried out past time 2L/c and therefore includes the transferred energy from all subsequent impacts.

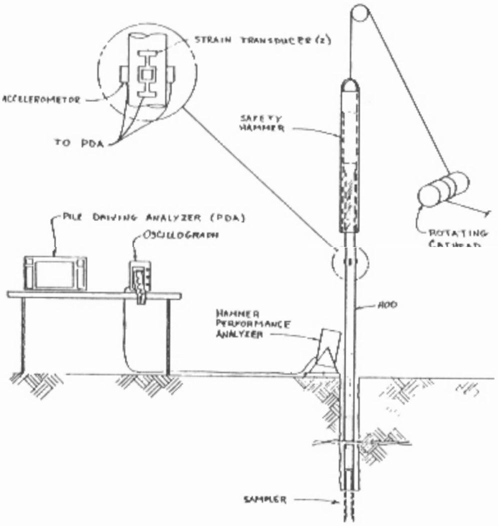


Fig. 2 Schematic of equipment set-up

The main use of the HPA was to measure the SPT hammer velocity just before impact. This measurement made it possible to compute the hammer kinetic energy prior to impact. Knowledge of the kinetic energy transferred to the rods allowed for a determination of transfer efficiency versus rod length.

5 RESULTS

5.1 Wave equation analysis

Based on input parameters given in Table 1, the results of the wave equation study are summarized in Table 2. Table 2 lists values of maximum transferred energy, EMX, and transfer efficiency, e_t, for ultimate soil resistance values ranging from 0.5 (2.2) to 13.0 kips (57.9 kN). These values have been tabulated for rod lengths of 10 (3.05), 20 (6.10), 50 (15.24) and 100 ft (30.5 m). Values of EMX are direct output from the wave equation analysis. The driving system transfer efficiency, e_t, was obtained by computing the ratio of EMX/E_i where E_i is the impact energy (kinetic energy), that is, the energy available just prior to impact. For this study, a hammer efficiency of 0.8 was assumed in which case the available energy prior to impact is 80% of the potential energy, or $E_i = 0.8\ (W h_r)$ where W_r is the weight of the (0.14 kips or 0.62 kN) and h is the drop height (2.5 ft or 76.2 cm) of the ram. Therefore, the impact energy, E_i, is 0.28 kip-ft (0.38 kJ). Note that e_t as used in this paper only includes driving system and transfer loses and not hammer loses occurring prior to impact.

The results of the study also include graphical output time dependent force and velocity (at top of rod) and transferred energy, labeled ENTHRU. An example for a 1 kip (4.45 kN) soil resistance for each rod length analyzed is shown in Figures 3 and 4. For each set of curves, the top graph shows a plot of force and velocity, the bottom graph

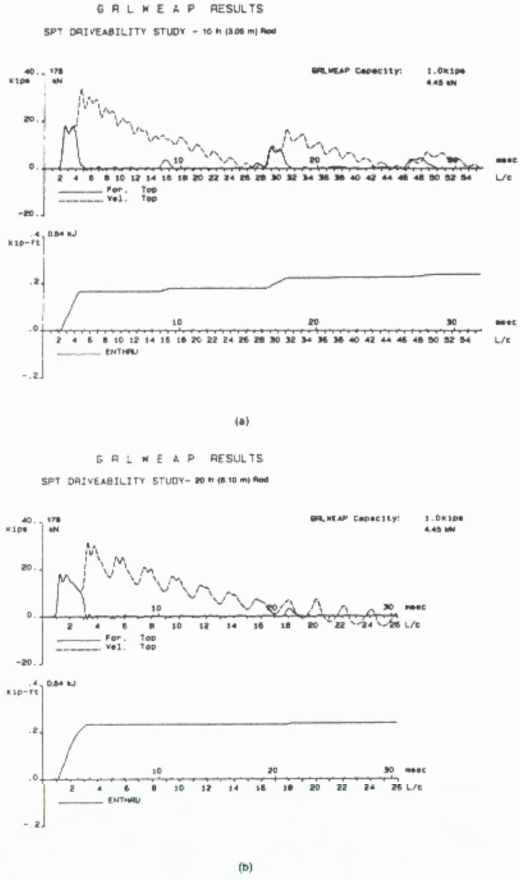
Table 2. Summary of wave equation analysis results

Rod Length ft (m)	Ultimate Resistance - kips - (kN) 0.5 (2.23) EMX kip-ft	e_t %	1.0 (4.45) EMX kip-ft	e_t %	2.5 (11.1) EMX kip-ft	e_t %	4.0 (17.8) EMX kip-ft	e_t %	7.0 (31.2) EMX kip-ft	e_t %	13.0 (57.9) 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 = ½ mv^2 = 0.8 $W_r h$) of the ram
1 kip-ft = 1.356 kJ

is transferred energy. The maximum value of the ENTHRU curve is the maximum transferred energy, EMX.

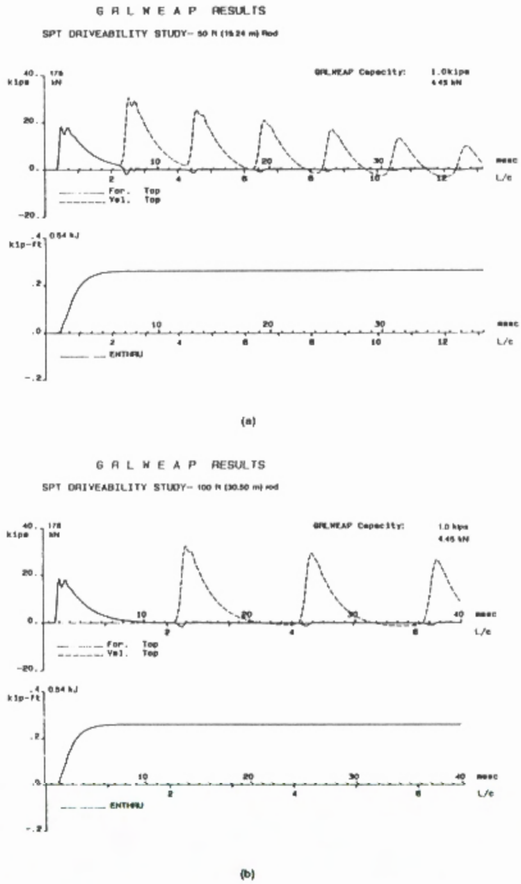
The results of the wave equation study indicated that the transferred energy, or the transfer efficiency is dependent on the rod length. This relationship is more critical when lower soil resistances are present. With a soil resistance of 0.5 kips (2.2 kN), e_t was lowest at 82% when modeling a 10 ft (3.05 m) rod. The driving system transfer efficiency increased to 86% and 93% for rod lengths of 20 (6.10) and 50 ft (15.2 m), respectively. The transfer efficiency remained at 93% for the 100 ft (30.50 m) rod, indicating that transferred energies are independent of rod length for lengths greater than approximately 50 ft (15.24 m).



(a)

(b)

Fig. 3 Records of computed force and velocity and transferred energy for rod lengths a) 10 ft (3.05 m) and b) 20 ft (6.10 m).



(a)

(b)

Fig. 4 Records of computed force and velocity and transferred energy for a) 50 ft (15.24 m) and b) 100 ft (30.50 m).

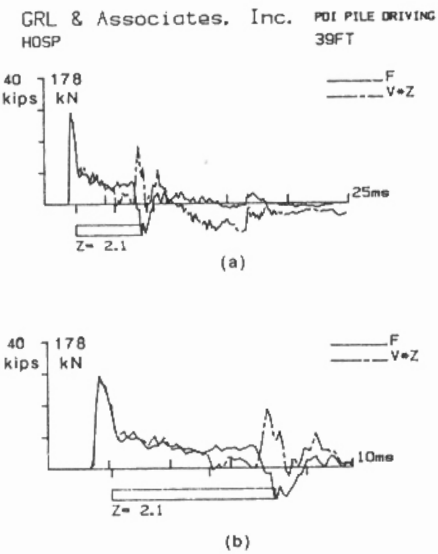


Fig. 5 Measured force and velocity records for a 39 ft (11.90 m) rod a) condensed scale and b) expanded scale.

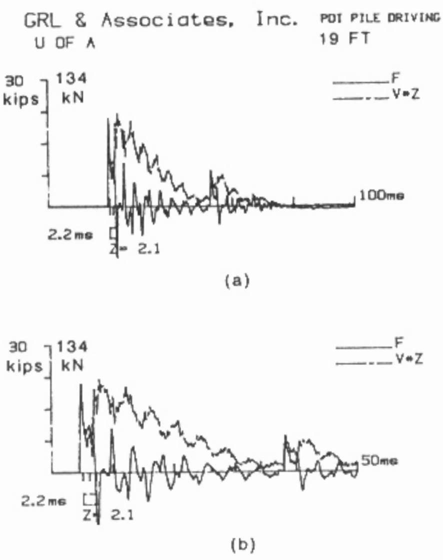


Fig. 6 Measured force and velocity records for a 19 ft (5.80 m) rod a) condensed scale and b) expanded scale.

Figures 3 and 4 also show the characteristics of the hammer impact and the effects of impacts at times greater than 2L/c after initial impact. As can be seen from the calculated records, the energy transferred to the rod from these subsequent impacts can be significant reaching a 40% increase for a 10 ft (3.05 m) rod with 1 kip (4.45 kN) resistance. Also note that for rod lengths of 50 (15.24) and 100 ft (30.50 m), all the energy is transferred during the first and only impact.

5.2 Field experiments

As indicated earlier, field testing included the measurement of time dependent force and velocity to obtain the transferred energy, EMX, and the measurement of the hammer velocity to obtain kinetic energy just before impact. These two separate measurements made it possible to also compute driving system transfer efficiencies, e_t, for different rod lengths based on measurements.

Some sample data from the field tests are shown in Figures 5 and 6. Each data set shows records of force and proportional velocity using two different time scales. The top curve is a complete record of 100 ms; the bottom curve shows an expanded record of 50 ms long. The rod length is given as part of the title. Note the additional subsequent impact(s) which occurred after the 2L/c time as predicted by the wave equation analysis study.

Sample data of hammer velocity measurements is shown in Figure 7. The horizontal scale is time in seconds; the vertical scale is velocity in ft/sec. Each maximum velocity peak represents one hammer blow and is the velocity just prior to impact. Note that the radar does not recognize the direction of the ram movement, i.e., the absolute value of the ram velocity is displayed. Referring to Figure 7, the motion of the safety hammer can be described as follows: Impact occurs at point A at which time the velocity is maximum. Just after impact, a sudden, sharp decrease in velocity occurs. At point B, the radar picks up extraneous motions instead of decreasing to zero which is typical of radar technology. At point C, the hammer is in its up stroke stage. At point D, the hammer is nearing the maximum stroke and again due to extraneous motions, the velocity does not go to zero. At point E, the hammer has started its down stroke. The increasing linear section of the repetitive curves (from point E to F) represent the hammer downfall. As indicated in Figure 7, the slope of this linear portion is the acceleration (a = dv/dt) which for this sample data is computed to be 0.62 g. This acceleration is less than the gravitational acceleration constant "g" ($g = 32.2$ ft/s^2 or 9.81 m/s^2) which indicated that the hammer is not "free falling" as would be expected with a safety hammer.

The results of these field tests have been summarized in Figures 8 and 9. Figure 8 shows a graph of transfer efficiency versus rod length. Each "|" represents the driving system transfer efficiency from one hammer blow. This e_t value was computed from the ratio of EMX/E_i where, in this case, E_i is the available kinetic energy just prior to the impact and is computed as $E = ½ mv^2$ (with v being the measured impact velocity). The curve in Figure 9 represents the "average" transfer efficiency for each respective rod length.

In Figures 8 and 9, the transfer efficiencies for rod lengths of 29 ft (8.84 m) or greater were computed with a nominal drop height of 30 inches (762 mm). However, due to high frequency vibrations, the drop height was reduced to 24 inches (58.8 cm) for rod lengths of 9 (2.74), 14 (4.27) and 19 ft (5.80 m) in order to obtain reliable acceleration measurements (no accelerometers work perfectly at every frequency). However, since hammer velocity measurements were made using the HPA, it was still possible to obtain representative driving system transfer efficiencies. It was observed that even when a nominal 30 inch (762 mm) stroke was called for, the actual stroke varied from a approximately 27 (68.5) to 33 inches (83.8 cm).

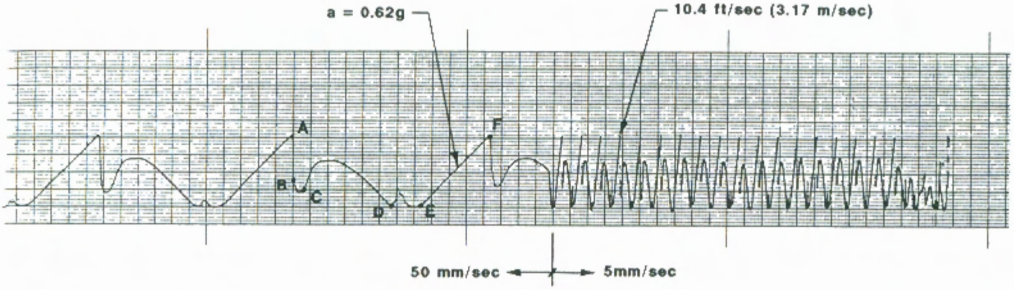


Fig. 7 Sample data of hammer velocity measurement from the HPA.

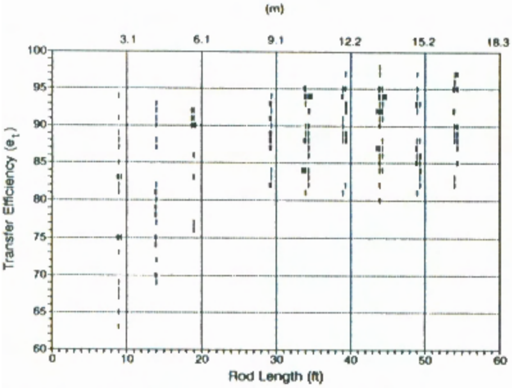


Fig. 8 Transfer efficiency, e_t, versus rod length (ft)

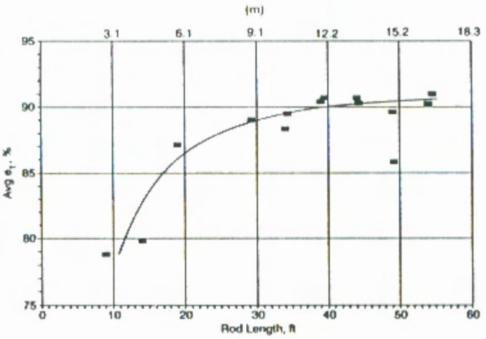


Fig. 9 Average transfer efficiency, e_t, versus rod length

6 CONCLUSIONS AND RECOMMENDATIONS

The curve shown in Figure 9 suggests that the transferred energy is independent of rod length for lengths greater than approximately 50 ft (15.2 m). However, for rod lengths shorter than 50 ft (15.2 m), the energy transferred to the rod is reduced. This reduction is non-linear and is more prevalent with rod lengths ranging from 10 (3.05) to 30 ft (9.15 m).

Based on the results of the wave equation analysis study and field testing results, it is concluded that rod length does affect the energy transferred to the rod even after all subsequent impacts are considered, and that the energy is reduced for shorter rod lengths. Because the energy needed to drive the sampler into the ground is reduced, an increased blow count results, compared to longer rods. The field blow count should therefore be modified to account for the lower transfer efficiencies for varying rod lengths.

Using the curve in Figure 9, a relationship was developed by plotting the percent difference in transfer efficiency (relative to the transfer efficiency of a rod length of 50 ft (15.2 m)) versus rod length as shown in Figure 10. The curve in Figure 10 indicates the required modification factor to be applied to account for the reduction of transfer efficiency. The correction factor is 1.0 for rod lengths greater than 50 ft (15.2 m) where the transfer efficiency remains constant. The field "N" value (N_f) could then be modified by the appropriate correction factor N_c/N_f where N_c is the modified or corrected "N" value for rod length. For example, the field N value for a rod length of 20 ft (6.1 m) would be increased by 5% to account for the reduced transfer efficiency. Although N for short rods could also be considered a base value with correction factor 1.0, the proposed method would be more conservative for design applications.

In conclusion, currently available strain transducers and accelerometers allow for accurate and reliable dynamic measurements which can be used for SPT hammer performance evaluations. In this study, these dynamic measurements were used to develop a relationship between transfer efficiencies and rod length in SPT testing. This relationship resulted in modification factors which could be used to correct field measured blow counts for rod length.

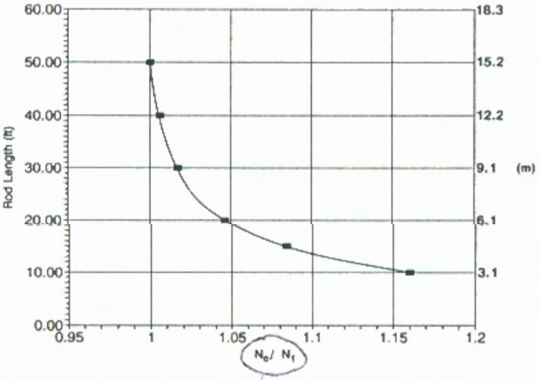


Fig. 10 Correction factors to account for rod length

should be N_f/N_c

7 ACKNOWLEDGEMENTS

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