Energy transfer in SPT – Rod length effect

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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 detailed and profound studies are often used as soil 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 rod resistance. Presented in this paper is the result of a study performed to investigate the influence of rod length on the transfer energy via SPT. Both numerical studies and field tests were employed to study the subject matter. Numerical studies included the use of a wave equation based GROUNDWORK computer program. Field tests utilized the File Driving Analyzer (FDA) 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 metal 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 "driving"), gives an indication of the soil strength (relative density, stiffness). Often, a field study will be based only on the results of the test.

This study will focus only be investigating the effect of rod length on the blow count and energy of SPT. It has been shown that variables such as:

1. hammer type (sledgehammer or automatic)
2. number of blow (standard or modified)
3. actual drop height
4. rod length

may significantly effect the results (blow count) of the SPT test unless 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 transfer energy. The research included a numerical study using a version of the Wave Equation Analyzer Program (GROUNdWORK) and field measurement 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 can be computed from the wave theory equation. 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 force $F(t)$ acts on a displacement $x(t)$ (Figure 1):

$W = \int F(x(t))\, dx(t)$

or

$W = \int P(x(t))\, dx(t)$

where $v(x)$ is the corresponding velocity.

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

$W = \int_{x_{0}}^{x(t)}\, P(x)\, dx$

Therefore, if we obtain measurement of force and velocity at the top of the rod, the transferred energy resulting from a hammer impact can be computed 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, 1979), the authors used load cells to measure the impact force over time. They concluded that the hammer is efficient when transferring energy at time $t = 2L/L$, where L is the length of rod and sampler.
Fig. 1 Energy transmission in a uniform rod

\[
W = \rho L \sqrt{E I} \nu \Delta \frac{d}{2}
\]

(4)

where \( E \) is Young's modulus of elasticity of the rod material, \( I \) is the rod's cross-sectional area, \( \rho \) is the density of the rod, \( v \) is the particle velocity and \( \Delta \) is the stress wave speed.

Since equation (5) is only valid until the tensile reflection wave reaches the point on the far end, it will no longer hold after time \( 2L/v \). The computation was therefore terminated at time \( 2L/v \). However, the hammer may eventually (after time \( 2L/v \)) impact the rod one or more subsequent times depending on the soil resistance, thereby generating additional energy. Schenketman and Palacios concluded that this additional energy transferred by subsequent impacts would not increase the hammer penetration significantly.

Schenketman and Palacios' field experiments concluded that the transmitted energy during the first hammer impact is independent of the rod length and therefore would affect the measured hammer penetration. However, this conclusion was based on the assumption that the additional energy transferred during subsequent impacts would not cause significant hammer 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 5) and the potential energy, \( W_0 \), where \( W_0 \) is the hammer weight and \( h \) is the drop height (equation 8 under \( 7.2 \times 10^5 \)).

An extensive experimental study was performed by the U.S. National Bureau of Standards (Kramer, Schenketman, and Yekel [33]). In this study, the authors modeled targeted penetration of 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:

\[
\text{ETR} = \frac{E_T}{E_k}
\]

(6)

where \( E_T \) is energy transferred to rod from the first compression wave pulse (first impact) and \( E_k \) is kinetic energy just before impact.

The transferred energy, \( E_T \), was computed from:

\[
E_T = \frac{1}{\rho} \int_{v_1}^{v_2} E_{1,2} \sqrt{\rho \Delta} \nu \Delta \frac{d}{2}
\]

(7)

The above equation was developed from the study performed by Schenketman and Palacios, where:

- \( K_1 \) is the correction factor for load cell location
- \( K_2 \) is the correction factor for rod length
- \( E_1 \) is Young's Modulus of Elasticity
- \( \rho \) is Mass density of steel
- \( A \) is Cross sectional area of rod
- \( F(t) \) is 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 inherent in the Schenketman, Palacios study. The results of this study again indicated transferred energy that was independent of rod length. However, like the Schenketman, Palacios study, the measured transferred energy included only the energy up to time \( 2L/v \) (first impact only) although a correction factor (\( K_2 \)) 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 a numerical study using a wave equation analysis program to simulate the driving action in the hammer-end rod system. Second, field experiments included measurement of time dependent force and piston movement on rods in various positions during SPT testing. The hammer velocity during its fall was also measured 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 models were used to determine the velocity of the hammer mass and spring system model for pile driving analysis. The versatility of SPT wave analysis program allowed the use of this numerical method of analysis to effectively model SPT testing. Further, many refinements have been made to the program. The version used for this study was developed by Gobele, Buehler, and Associates, Inc. in...
wave only, the computation of energy is carried out past time 2πc and therefore excludes the transferred energy from all subsequent impacts. The main use of the 50% was to measure the SPT hammer velocity just before impact. This measurement made it possible to compute the impact kinetic energy prior to impact. Knowledge of the kinetic energy transferred to the rock allowed for a determination of transfer efficiency versus road length.

5.5 Wave attenuation analysis

Based on information given in Table 1, the results of the wave equation study are summarized in Table 2. Table 2 lists the maximum transmitted energy, EMS, and transfer efficiency, e, for ultimate and subcrack values ranging from 0.2 to 1.10 ksi (7.7 kN/m). These values have been selected for road lengths of 10, 20, 50, and 100 ft. (3.05, 6.09, 15.2, and 30.5 m).

For this study, a transfer efficiency of 0.9 was assumed in which case the available energy prior to impact is 90% of the potential energy. When E is the weight of the (0.54 kip or 2.42 kN) and is the strip length (2.5 ft or 0.76 m) of the rock. Therefore, the impact energy, E, is 0.58 kip (2.64 kN). Note that is used in this paper only includes driving tension and transfer losses and not hammer losses occurring prior to impact. The results of the study also include graphs output time-dependent force and velocity (at top left) and transmitted energy (right). As examples for a 1 ksi (4.45 kN) and 2 ksi (8.84 kN) materials, the rock length analyzed is shown in Figures 3 and 4. For each set of cases, the top graph shows a plot of force and velocity, the bottom graph...
Table 2. Summary of wave equation analysis results

<table>
<thead>
<tr>
<th>Length (ft)</th>
<th>0.5 (2.23)</th>
<th>1.0 (4.45)</th>
<th>2.5 (11.1)</th>
<th>4.0 (17.8)</th>
<th>7.0 (31.2)</th>
<th>13.0 (35.5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 (3.05)</td>
<td>0.23 % EMX</td>
<td>0.28 % EMX</td>
<td>0.25 % EMX</td>
<td>0.25 % EMX</td>
<td>0.25 % EMX</td>
<td>0.25 % EMX</td>
</tr>
<tr>
<td>20 (6.10)</td>
<td>0.24 % EMX</td>
<td>0.28 % EMX</td>
<td>0.25 % EMX</td>
<td>0.25 % EMX</td>
<td>0.25 % EMX</td>
<td>0.25 % EMX</td>
</tr>
<tr>
<td>50 (15.24)</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
</tr>
<tr>
<td>100 (30.49)</td>
<td>0.16 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
<td>0.26 % EMX</td>
</tr>
</tbody>
</table>

EMX - Energy transferred to rod

$e_{EMX} = \frac{EMX}{\text{mass}} \cdot \frac{\text{velocity}}{2}$

where $E_i$ is the actual kinetic energy ($E_i = \frac{1}{2} m v^2 = 0.8 \text{ W s}$) of the rod

$k = \frac{0.336}{kJ}$

is transferred energy. The maximum value of the ENTHBU 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 (2.22 kN), $e_i$ was lowest at 62% when modeling a 10 ft (3.05 m) rod. The driving pump transfer efficiency increased to 80% and 93% for rod lengths of 20 ft (6.10 m) and 50 ft (15.24 m), respectively. The transfer efficiency remained at 93% for the 100 ft (30.49 m) rod, indicating that transferred energy is independent of soil length for lengths greater than approximately 50 ft (15.24 m).

![Fig. 3 Records of compressed force and velocity and transferred energy for rod lengths 10 ft (3.05 m) and 20 ft (6.10 m).](image1)

![Fig. 4 Records of compressed force and velocity and transferred energy for rod lengths 50 ft (15.24 m) and 100 ft (30.49 m).](image2)

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5.2 Field experiments

As indicated earlier, field testing included the measurement of time dependent force and velocity to obtain the transferred energy, EN, 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, $\eta$, for different real lengths based on measurements.

Some sample data from the field tests are shown in Figures 3 and 5. Each data set shows records of force and proportional velocity using two different time scales. The top curve is a complete record of 100 mm, the bottom curve shows an expanded record of 50 mm long. The red length is given as part of the title. The additional alphanumeric records which occurred after the 20 mm time as predicted by the wave analysis theory.

More data on hammer velocity measurements is shown in Figure 7. The horizontal scale is time in seconds; the vertical scale is velocity in ft/s. 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 hammer blow, i.e., the absolute value of the hammer velocity is measured. Reviewing Figure 7, the section of the safety hammer can be determined as follows: impact occurs at point A at which time the velocity is zero. Just after impact, a sudden, sharp decrease in velocity occurs. At point B, the radar picks up entrance motions instead of decreasing to zero which is typical of radar technology. At point C, the hammer is in the upstroke stage. At point D, the hammer is nearing the maximum stroke and again due to entrance motions, the velocity does not go to zero. At point E, the hammer has started its downstroke. The increasing section of the composite curves from point E to F represents the hammer downstroke. As indicated in Figure 5, the slope of the linear portion in the acceleration $(a = \frac{dv}{dt})$ which for this little data is estimated to be 0.02 g. This contribution is less than the gravitational acceleration constant $g = 32.2 ft/s^2$ or $g \approx 15 m/s^2$ which indicates that the hammer is not "free falling" as would be expected with a safety hammer.

The results of these tests have been summarized in Figures 8 and 9. Figure 8 shows a graph of transfer efficiency versus rod length. Each $\eta$ represents the driving system transfer efficiency from one hammer blow. This $\eta$ value was computed from the ratio of EN to $\eta$ where, in this case, $\eta$ is the available kinetic energy just prior to the impact and is computed as $E = \frac{1}{2}mv^2$ with $\frac{1}{2}$ being the measured impact velocity. The new 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 29.8 (8.94 m) or greater were computed with a nominal drop height of 30 inches (76 cm). However, due to high frequency vibrations, the drop height was reduced to 24 inches (60.96 cm) for rod lengths of 4 (1.27) and 8 (2.44) in order to obtain stable acceleration measurements (no accelerometers work perfectly at every frequency). However, since hammer velocity measurements were made using the HPA, this was still possible to obtain representative driving system transfer efficiencies. It was observed that even when a consistent 30 inch (76 cm) stroke was called for, the actual stroke varied by approximately 27 (6.85) to 35 inches (89 cm).
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 sample 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 6). The curve in Figure 30 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 30 ft (9.1 m), where the transfer efficiency remains constant. The field 'N' value (N0) could then be modified by the appropriate correction factor N1/N0, where N0 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 7% 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 coring. This relationship resulted in a modification factor which could be used to correct field measured blow counts for rod length.

4 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 phenomenon is anticipated and is more pronounced with rod lengths ranging from 30 ft (9.1 m) to 20 ft (6.1 m).
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