Efficiency Measurement of Indian Standard SPT Hammer Context for Liquefaction

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Abstract—The standard penetration test (SPT) is the most widely used in in-situ test. This test involves hammer impact on penetration rods, and resulting penetration resistance or blow counts is strongly influenced by the amount of hammer energy actually transferred into the rods. Research has shown that the energy transfer to the rod is lesser than the actual energy generated by the blows of hammer, so the direct approach of determining the transferred energy, based on force and acceleration measurements near the top of the drill rods, should be adopted. The proposed approach provides a unified method of measuring transferred energy in the SPT. The measured energy data can be used in a consistent manner to correct the recorded blow counts to a reference energy level for each test and allow reliable correlation of the same in assessment of liquefaction potential evaluation.

Keywords: SPT, N-value, Energy measurement, liquefaction potential evaluation

I. INTRODUCTION

Standard Penetration Test (SPT) is the most commonly used in situ test in estimating soil properties, especially in cohesion less soils. This is due to the simplicity and low cost of the test, in addition to the availability of wide range of correlations between SPT blow counts and material properties. However, measured SPT blow counts are affected by several factors such as the diameter of the borehole, rod length, split spoon sampler configuration, and energy applied. Thus, several corrections are applied to SPT blow counts in order to achieve a normalized value prior to use. Among the most important factors is the energy efficiency factor for the hammer, which varies depending on equipment and operator skill. For example, the transmitted energy is affected by careless measure of drop, hammer weight inaccuracy, eccentric strike of hammer on drill rod collar, variation in size of anvil system, use of bent drill rods, lack of hammer free fall due to ungreased sleeves, stiff rope on weight, excess turns on cathead, and incomplete release of rope. Thus, the energy correction factor is highly dependent on local practice and should not be generalized.

A. Spt System

SPT system is comprised of the standard hammer (weight 63.5 kg), the mechanism that lifts and drops the hammer, (the anvil, stem and anvil or drive-head) as shown in Fig. 1. Two shapes of hammers are widely used; the Safety and the Donut hammer (Fig.2). The safety hammer, which is relatively long and therefore has a corresponding small diameter. The safety hammer, has an internal striking ram that greatly reduces the risk of injuries. The donut hammer is short in length and therefore larger in diameter than the safety hammer. The longer safety hammers are more efficient in transferring energy into the rods than the squat donut hammers (SPT correction research report by M.Sheriff Aggour and W.Rose Radding). In an energy calibration study by Kovacs et al. (1983), the mean energy ratio delivered by a safety hammer was found to be about 60%, whereas the mean energy ratio for a donut hammer was about 45%.

![Fig. 1: SPT Setup](image1)

![Fig. 2: Donut and Safety Hammers](image2)

The common practice in performing the SPT is to raise the hammer 30 inch by means of a rope wrapped around a rotating pulley and then throw the rope smartly to dissociate it from the pulley, in this way letting the hammer fall onto the anvil fastened to the top of the drill stem. Since the rope is rarely completely dissociated from the pulley, the actual energy delivered using this technique depends on the skill of the operator, smoothness of cathead (amount of rust) and very much on the number of times the rope is originally wrapped around the pulley. Kovacs et al. (1982) recommended that two turns of the rope around the pulley should be used to minimize the importance of the number of turns and operators characteristics as variables of the delivered energy.
To eliminate the variability of the energy delivered to the hammer that rises using the rope and pulley technique, an automatic trip hammer has been introduced. A mechanical system raises the hammer and a tripping device releases it from a 76 cm height. It has been found that these systems also do not deliver the theoretical free-fall energy to the drilling rods, probably because of the energy losses associated with the anvil system at the top of the drill stem. In the United States, the two most common SPT hammer systems are the safety hammer with cathead and rope mechanism and the automatic trip hammer system. The test uses a thick-walled sample tube, with an outside diameter of 50 mm and an inside diameter of 35 mm, and a length of around 650 mm (ASTM D1586).

In India, the SPT drive weight assembly shall consist of a driving head and a 63.5 kg weight with 75 cm free fall. It shall be ensured that the energy of the falling weight is not reduced by friction between the drive weight and the guides or between rope and winch drum (IS: 2131-2002). The rods to which the sampler is attached for driving should be straight, tightly coupled and straight in alignment. The test uses a thick-walled sample tube, with an outside diameter of 50 mm and an inside diameter of 38 mm, and a length of around 508 mm (IS: 9640-1980).

Also an energy ratio (ER) of 60% is accepted as the approximate average for U.S. testing practice and as a reference value for energy correction. ER depends on the type and weight of SPT hammer, anvil, lifting, mechanism and method of hammer release. If N-value is measured in any other country using different weight, fall and lifting mechanism etc. they should be made to SPT N-value for differences in efficiency using the falling equation (JGS, 1998):

\[
(N_1)_{\text{ref}} = \frac{\text{ER}_{\text{ref}}}{\text{ER}_{\text{}}}(N_1)_{\text{m}}
\]

Where \((N_1)_{\text{m}}\) and \(\text{ER}_{\text{}}\) are the measured N-value and corresponding energy efficiency. \((N_1)_{\text{ref}}\) and \(\text{ER}_{\text{ref}}\) are the N-value at an energy ratio of 60% and energy efficiency equal to 60%. Since hammer efficiency and hammer used in India is different from one used in USA, hence it is necessary to normalize the measured N-value to get \((N_1)_{\text{ref}}\).

B. Liquefaction Potential Evaluation

The “simplified procedure” developed by Seed and Idriss (1971) is most commonly used method to evaluate the liquefaction potential of a site. The simplified is given below: The factor of safety against liquefaction is defined as

\[
\text{F.S.} = \left(\frac{\text{CSR}}{\text{CRR}}\right) MSF
\]

Where CSR = cyclic stress ratio, CRR = cyclic resistance ratio of in situ soil for magnitude 7.5 and MSF = magnitude scaling factors.

Youd and Idriss (2001) recommended the following equation for obtaining MSF

\[
\text{MSF} = 10^{2.24 - \frac{2.56}{W_e}}
\]

Where \(W_e\) = Earthquake magnitude

Cyclic stress ratio may be calculated from relationship

\[
\text{CSR} = \frac{\text{av}_0}{\sigma_0} = 0.65 \text{av}_0 \frac{\sigma_{v0}}{\sigma_0} \left(\frac{\alpha_{vmax}}{g}\right)
\]

where

- \(\alpha_{vmax}\) = Peak horizontal ground acceleration
- \(g\) = Acceleration due to gravity
- \(\sigma_0\) = Total effective overburden pressure
- \(\sigma_{v0}\) = Effective vertical overburden pressure
- \(r_d\) = stress reduction coefficient

Lio and Whiteman (1986) proposed the following equation for determining stress reduction coefficient \(r_d\)

\[
r_d = \frac{1.0 - 0.000765 z}{\text{for } z \leq 9.15 \text{ m}}
\]

\[
r_d = \frac{1.174 - 0.0267 z}{\text{for } 9.15 < z \leq 23.0 \text{ m}}
\]

Where \(z\) is the depth below ground surface in meters.

C. CRR from SPT

Based on the SPT and field performance data, Seed et al. (1985) had developed a chart (Fig. 3) that can be used to determine CRR of in situ soil.

Fig. 3: SPT clean sand base curve for magnitude 7.5 earthquake (courtesy Seed et. al. 1985)

Rauch (1998) proposed the following equation for determining CRR based on SPT N-value \((N_1)_{\text{ref}}\) for an earthquake of magnitude 7.5.

\[
\text{CRR} = \frac{1}{34 - (N_1)_{\text{ref}}} \left[ \frac{(N_1)_{\text{ref}}}{135} + \frac{50}{[10(N_1)_{\text{ref}} + 45]^2} \right] - \frac{1}{200}
\]

Where \((N_1)_{\text{ref}}\) refers to the SPT blow count normalized to an overburden pressure of approximately 100 kPa and a hammer efficiency of 60%. Other correction factors such as overburden pressure, borehole diameter, rod length and samples with or without liners have also to be applied (Youd and Idriss, 2001). Thus, it is necessary to measure the average energy transferred to the SPT rods with an aim to convert measured N-values in terms of \((N_1)_{\text{ref}}\) using Eq. 1.

II. ENERGY MEASURING SYSTEM

To measure the energy transmitted from the hammer to the drill string, some form of instrumented equipment is required. The equipment should have strain gauges for obtaining force measurements and accelerometers for obtaining velocity data. The equipment should be capable of
recording and displaying the velocity and force waveforms as well as calculating energy values using both the F2 and FV methods. The instrument used in this research is SPT analyzer manufactured by Pile Dynamics Inc., USA.

A. SPT Analyzer

The SPT analyzer used in this research is manufactured by Pile Dynamics Inc. (PDI) is one of the instrument that may be used for energy measurement. The analyzer consisted of an instrumented 60 cm long AWJ drill rod section (Fig 4), a hand-held unit (Fig. 5) to read and store data and the necessary wiring to connect the gauges on the instrumented rod to the hand-held unit and the software for use in evaluating the data. The equipment/test set up is shown in Fig. 6.

![Calibrated SPT rod with sensors](image1)

![Hand held unit](image2)

Fig. 4: Calibrated SPT rod with sensors

Fig. 5: Hand held unit

The force squared method is described in ASTM D4633 and requires the use of three correction constants. These constants correct for the distance between the anvil and the measurement device, the rod length and the ratio of the actual to the theoretical time at which the force at the rod top becomes equal to zero. There is uncertainty associated with the use of these correction constants. Furthermore, the third correction is only valid for actual times of occurrence of zero force greater than 90% and less than 120% of the theoretical time calculated by 2L/c, where L equals the rod length and c is the wave speed in the steel rod. If this is not the case, the EF2 method can not be used to evaluate energy. In reality, due to changes in impedance with different rod cross-section changes, presence of collars and adaptors in the drill string connector conditions, etc; reflections will occur before the first compression wave reaches the end of the sampler. The result of this is that the time of zero force may fall outside the limit and thus the method is frequently invalid for SPT testing. The first method, the force velocity method is unaffected by changes in cross-sectional area and is based on measured values. This method is believed to be exact and is the method used in this project.

B. Methods of Energy Measurement

Two methods can be used to calculate maximum transferred energy to the drill rods. The first method, uses the integration of the product of the force and velocity record over time (Force-Velocity Method) and is referred to as EFV. For this method the transferred energy is determined by:

\[ EFV = \int F(t) V(t) dt \]  

(8)

Where

\[ F = \text{the force at time } t \]

\[ V = \text{the velocity at time } t \]

The integration begins at impact (time the energy transfer begins) and ends at the time at which energy transferred to the rod reaches a maximum value (i.e., integration over the entire force and velocity record). This method is theoretically sound and requires no correction factors (Abounatar and Goble, 1997).

The second method calculates transferred energy to the drill rod using the square of the force record (F2 Method) referred to as EF2 and is as follows:

\[ EF2 = \left( \frac{c}{EA} \right) \int [F(t)]^2 dt \]  

(9)

Where

\[ c = \text{stress wave propagation speed in the drill rod} \]

\[ E = \text{modulus of elasticity of the drill rod} \]

\[ A = \text{cross sectional area of the drill rod} \]

\[ F = \text{the force at time } t \]

The integration started at the time of impact and ends at the time of the first occurrence of a zero force after impact. The force squared method is described in ASTM D4633-86 and requires the use of three correction constants. These constants correct for the distance between the anvil and the measurement device, the rod length and the ratio of the actual to the theoretical time at which the force at the rod top becomes equal to zero. There is uncertainty associated with the use of these correction constants. Furthermore, the third correction is only valid for actual times of occurrence of zero force greater than 90% and less than 120% of the theoretical time calculated by 2L/c, where L equals the rod length and c is the wave speed in the steel rods. If this is not the case, the EF2 method can not be used to evaluate energy. In reality, due to changes in impedance with different rod cross-section changes, presence of collars and adaptors in the drill string connector conditions, etc; reflections will occur before the first compression wave reaches the end of the sampler. The result of this is that the time of zero force may fall outside the limit and thus the method is frequently invalid for SPT testing. The first method, the force velocity method is unaffected by changes in cross-sectional area and is based on measured values. This method is believed to be exact and is the method used in this project.

III. DATA INTERPRETATION

Since the research is in preliminary stage, only limited data has been acquired till date and the same is shown in Table 1.

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Depth of sampling</th>
<th>Maximum Energy Transferred (Measured) kN-m</th>
<th>Energy Transfer (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>1</td>
<td>0.90</td>
<td>0.3241</td>
<td>68.09</td>
</tr>
<tr>
<td>2</td>
<td>1.10</td>
<td>0.2963</td>
<td>62.25</td>
</tr>
<tr>
<td>3</td>
<td>1.25</td>
<td>0.2700</td>
<td>56.72</td>
</tr>
<tr>
<td>4</td>
<td>1.65</td>
<td>0.2906</td>
<td>61.06</td>
</tr>
<tr>
<td>5</td>
<td>1.95</td>
<td>0.2522</td>
<td>52.98</td>
</tr>
</tbody>
</table>

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### Table 1: Energy Measurement data

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.15</td>
<td>0.2470</td>
<td>51.89</td>
</tr>
<tr>
<td>7</td>
<td>2.30</td>
<td>0.2752</td>
<td>57.82</td>
</tr>
<tr>
<td>8</td>
<td>2.45</td>
<td>0.2762</td>
<td>58.04</td>
</tr>
<tr>
<td>9</td>
<td>2.60</td>
<td>0.2882</td>
<td>60.55</td>
</tr>
<tr>
<td>10</td>
<td>2.90</td>
<td>0.2596</td>
<td>54.55</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>58.29 %</td>
</tr>
</tbody>
</table>

Since all design chart for the liquefaction potential evaluation is based on $N_{60}$, it is necessary to convert the field $N$-value in terms of $N_{60}$ using appropriate correlation. The work is under progress and will develop correlation for energy conversion.

### IV. CONCLUSION

The Standard Penetration Test (SPT) is currently the most popular and economical means of obtaining subsurface information. Although, the consistency of the SPT $N$ values is questioned, i.e., the ability of the test to reproduce blow counts using different hammer systems under the same site/soil conditions. In order to reduce the significant variability associated with the SPT N value, it was recommended that $N$ values be standardized to $N_{60}$. This standardization is to be achieved by correcting the measured field $N$ values by the ratio of that energy transfer to the standard 60% energy of a free fall hammer. Based on the measurement of energy transfer by SPT analyzer, it is found preliminary that average energy is 58.29% as compared to standard energy of 60%. Since all design chart for the liquefaction potential evaluation is based on $N_{60}$, it is necessary to convert the Indian SPT $N$-value in terms of $N_{60}$ using appropriate correlation. The work is under progress and will hopefully develop a correlation for energy conversion.

### REFERENCE


