EFFECT OF ENERGY EFFICIENCY OF HAMMER ON LIQUEFACTION POTENTIAL OF SOIL

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ABSTRACT: Standard Penetration Test (SPT) N values and the energy correction factor play a crucial role in the soil liquefaction assessment. In the Liquefaction potential assessment, the cyclic resistance ratio is estimated considering soil strength measured through SPT N values. Due to various mechanical energy losses, energy measured just below anvil and above the sampler doesn't equal the theoretical energy, hence corrected SPT N values are used in the most of the codes. However Indian Standard Code does not specify any correction for hammer energy, various studies have shown that there is a need to upgrade the present version of IS 1893. In this study, an attempt has been made to measure, hammer energy first time in India uses indigenously developed SPT -Hammer Energy Measuring Apparatus (HEMA) by the Department of Civil Engineering, IISc, Bangalore at below the anvil and above the sampler tube. Then variations of energy values are used to understand the effect on the estimation of liquefaction potential in Indian cities.

Keywords: Liquefaction, SPT-N-Value, Hammer Energy, Correction Factor

1 Introduction

In spite of all of its uncertainties and drawbacks, SPT is still a widely used test for accessing the dynamic, seismic and liquefaction properties of the site. With time, a lot of researchers have contributed to standardize and make SPT a more efficient ground exploration test. Various corrections have been proposed for getting corrected SPT- N value of any site. Among all the corrections, energy correction is the most important. Measurement of hammer energy during SPT test is part of SPT testing in the most of western countries (ASTM D4633, 1986; IRTP/ISSMFE, 1988; Euro code 7, 1996) and there is a separate ASTM code (ASTM D6066, 2011) to arrive normalized N values for estimation of liquefaction potential. However, there is no such standard in the Indian code of practice for SPT testing and liquefaction assessment. Again, different code prescribes different energy correction to be applied even for same hammer and lift- release mechanism. This leads to non-uniform results.

2 Energy Measurement in SPT

Energy correction is a very important for getting true SPT-N value of any site. The maximum theoretical energy transferred is 473.4 J. As the safety hammer widely used in the US has approximate 60% energy transfer, to keep the earlier data and correlations useful and valid, 60% energy transfer was assumed as standard. But multiple codes for practice and authors have reported different energy values even for the same hammer and drop mechanism. This is mostly due different types of rods, anvil, etc. used, local site conditions, efficiency and skill of operator, etc. Hence, it becomes impractical to rely on a single value provided by an author or code to get the true value of energy correction (Howie, et al. 2003).

The Department of Civil Engineering, IISc, Bangalore has fabricated two instrument rods, each with one strain gauge transducer and one accelerometer. The transducer records the stress variation while the accelerometer gives acceleration. These signals are received by a microcontroller which filters, amplifies the signals and processes them via Analog to Digital Convertor. A program on Lab view platform has been written to get velocity profile using acceleration data. The software uses Force-Velocity Method (EFV) method to integrate the product of force and velocity with respect to time as prescribed in ASTM D4633 to give final energy output (Selvam, et al. 2013). The current practice is to measure the energy just below the anvil. But few present studies by Aoki, et al. (2007) have shown that actual energy transferred for penetration is better represented by measuring the energy transferred just above the sampler. Hence, initial experiments were conducted by IISc to study the difference in energy measured just below the anvil and above the sampler.

Even in the same borehole, the energy correction required is varying with depth by a great extent. The energy efficiency recorded in a single borehole has varied from 39.4% (185.28 J) to 59.8% (283.09 J) i.e. nearly 20% difference measured just below the anvil. In another borehole the difference of 15% in energy transferred has been recorded with maximum value as 65.9% (312.01 J) and minimum value as 49.3% (233.41 J) below the anvil. For the same boreholes the energy measured just above the sampler varied from 35.23% (166.77 J) to 43.06% (203.84 J) and 43.75% (207.11 J) to 62.06% (293.79 J) with depth i.e. difference of approximately 8% and 18% respectively. Nearly 3% to 25% energy difference has been found between the energy measured just below the anvil and above the sampler. Thus, considering the whole data set the min C_E was found to vary from 0.65 to 1.15 below the anvil and from 0.58 to 1.03 above sampler.

This paper evaluates the extent up to which liquefaction potential of a site will be affected by differences in energy correction applied as per different codes as well as measured energy below the anvil and above the sampler or across the borehole depth in India.

3 Methodology adopted for Estimating Liquefaction Potential

Liquefaction potential can be determined by estimating factor of safety (FOS) i.e. ratio of CRR and CSR. CSR represents the induced shear stress in soil during the earthquake. CRR represents the resistance of soil against liquefaction. CRR is the function of $(N_1)_{60cs}$ (Idriss and Boulanger 2010) i.e. corrected SPT-N value. As per (Idriss and Boulanger 2010), Corrected $\boldsymbol{N_m}$ value i.e. $(\boldsymbol{N_1})_{\boldsymbol{60}}$ is obtained as

$$(\boldsymbol{N_1})_{\boldsymbol{60}} = \boldsymbol{N_m} \times \boldsymbol{C_N} \times \boldsymbol{C_E} \times \boldsymbol{C_B} \times \boldsymbol{C_S} \times \boldsymbol{C_R}$$

Where C_N = overburden correction factor, C_E = energy correction factor, C_B = correction factor for borehole diameter, C_S = correction factor for the presence or absence of liner, C_R = rod length correction factor, N_m= measured SPT blow count, $(N_1)_{60}$ = corrected penetration resistance at an overburden stress of 1 atm. Correction for rod length, bore-hole diameter and liner have applied as per Seed et. al. (1985), Youd et al. (2001), Cetin et. al. (2004). Adjustment for fine content and C_N has been taken from Idriss and Boulanger (2004, 2008) recommendation.

Seed et al. (1985) suggested correcting various SPT energy ratios to energy ratio of 60% for use in liquefaction analyses as follows:

$$C_E = \frac{ER_m}{60\%}$$

Where ER_m is the measured value of the delivered energy as a percentage of the theoretical free-fall hammer energy.

The equation for estimation of CRR based on corrected SPT value is as follows:

$$CRR_{M=7.5,\sigma_V'=1atm} = exp\left(\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right)$$

CSR value can be estimated using the equation, developed as part of Seed & Idriss, (1971) Simplified Liquefaction Procedure. CSR value is adjusted to reference M = 7.5 and σ_v' = 1 atm given as follows;

$$CSR_{M=7.5,\sigma_V'=1atm} = \frac{CSR_{M,\sigma_V'}}{MSF\,.\,K_\sigma} = .65\,\frac{a_{max}}{g}\frac{\sigma_v}{\sigma_v'}r_d\,\frac{1}{MSF.K_\sigma}$$

Idriss and Boulanger (2008) recommended K_σ relationship in term of $(N_1)_{60cs}$. Formulas for r_d and MSF have been taken from Idriss and Boulanger (2010).

Factor of safety can be given as follows,

$$FOS = \frac{CRR_{M=7.5,\sigma_V'=1atm}}{CSR_{M=7.5,\sigma_V'=1atm}}$$

For FOS less than 1, soil is considered as liquefiable and for FOS more than 1, considered as non-liquefiable.

4 Liquefaction according to Various Codes

Skempton (1986) documented hammer energy efficiencies for multiple countries. The Liquefaction assessment has been tabulated for different countries assuming following typical values: N=15, FC=0%, depth = 10 m, borehole dia. = 150 mm with clay liner, Υ_b =17 kN/m^2, a_{max}/g=0.24 (Zone 4 according to IS1893: 2002), M=6.5 and water table depth = 0m from ground level.

Table 1 shows that the minimum energy transfer ratio was reported in Venezuela and maximum in Japan. The CRR and FOS value for assumed data for Japan is 71.7% higher than Venezuela for Donut hammer with Cathead release mechanism. Also from the table, it is clear that for the same hammer and release mechanism (i.e. Donut with Cathead) the site is non- liquefiable according to Japan while liquefiable according to the rest of the country. The Factor of Safety varies from 0.69 to 1.18 for a Donut hammer with cathead release mechanism. If all types of hammer and release mechanisms are involved the FOS starts varying from 0.69 to 1.89. This clearly indicates that giving suggestion of hammer energy in the code based on the widely used hammer type in the country may lead to huge uncertainty in the assessment of Liquefaction potential.

Table.1: Energy transfer ratio for different countries as reported by Skempton, (1986) and their effect on liquefaction FOS

Country	Hammer Type and Release Mechanism	EMR %	CRR M= 7.5& σ'v= 1atm	FOS
Argentina	Donut, Cathead	45	0.16	0.73
Brazil	Pin Weight, Hand drop	60	0.32	1.39
China	Automatic Donut, Hand Trip	72	0.23	1.03
	Donut, Dropped	55	0.21	0.91
	Donut, Cathead	50	0.18	0.81
Columbia	Donut, Cathead	50	0.18	0.81
Japan	Donut, Tombi	78-85	0.43	1.89
	Donut, Cathead 2 turns & special release	65-67	0.27	1.18
UK	Automatic, Trip	73	0.32	1.39
US	Safety, Cathead, 2 turn	55-60	0.22	0.96
	Donut, Cathead, 2 turns	45	0.16	0.73
Venezuela	Donut, Cathead	43	0.16	0.69

5 Variation of Factor of Safety with Energy Efficiency of SPT test setup

As aforesaid, that the energy transferred reported across the world ranges from 40% to 90%. Fig. 1 & 2 show how the factor of safety calculated with respect to depth changes with variation in energy correction factor. The data have been taken from two boreholes from Gorakhpur, Haryana. The Figure shows that the factor of safety increases with increase in energy transfer ratio. In Borehole 79, the liquefiable soil layer thickness is approximately 7.5 m (from 3 m to 10.5 m) for a 24-45 % energy transfer. While the liquefiable soil layer thickness reduces to approximately 6 m (from 4.5m to 10.5 m) for a 60-90 %, energy transfers.

Similarly, for the BH-10, the liquefiable soil layers are from 3m to 10.5 m and 18m to 20m, for a 24-40% energy transfer and from 4.5m to 10.5 m for a 45 % energy transfer. While for a 66-90 % energy transfer, soil layer is non- liquefiable.

Thus, as reported by Selvam et. al. (2013), the soil in both boreholes are liquefiable across higher thickness if the actual measured energy transferred (40% - above sampler) is accounted in the calculation. Whereas these

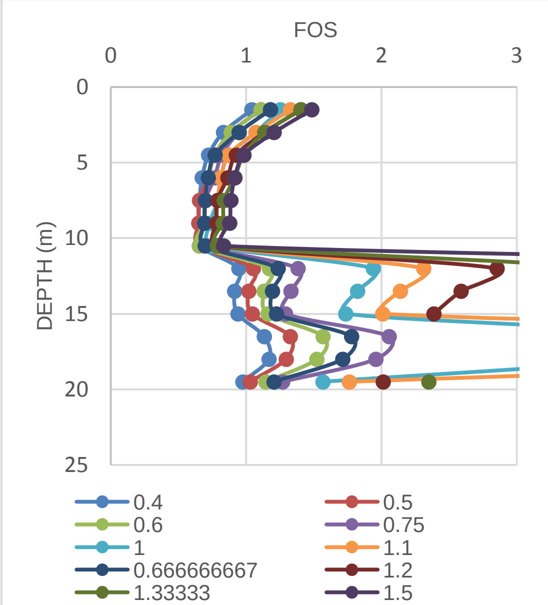

Fig. 1: Factor of Safety (FOS) v/s depth for different Energy Correction Factor for BH 79, Gorakhpur, Haryana

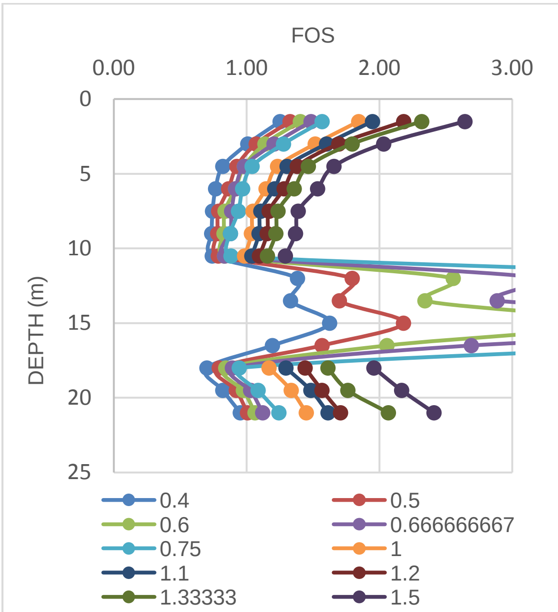

Fig. 2: Factor of Safety (FOS) v/s depth for different Energy Correction Factor for BH 10, Gorakhpur, Haryana

sites are non-liquefiable if the energy measurement at below the anvil (60%) is considered. Also, the liquefaction severity (thickness of liquefiable layer) of these sites significantly reduces if widely taken energy correction of 0.7 was adopted for calculation, which may or may not be true.

6 Conclusions

The pilot test set-up showed 3% to 25% energy difference between energy measurement at sampler and the anvil. Energy measurement below anvil found that about 20% difference in energy transfer at different depths for the same site. Hence, the energy transfer percentage should be measured for each blow and at all depths for actual assessment of any engineering property of soil. Such differences need to be properly taken care, otherwise lead to highly conservative results or unsafe results. The actual energy transferred plays a very crucial role in assessment of liquefaction and any uncertainty in energy transfer percentage leads to great uncertainties in the liquefaction potential of soil. This study shows that variations of hammer energy in liquefaction calculation may change soil layer category from liquefiable to non-liquefiable in the same borehole. Hence it is recommended to use actual energy measurement set-up at the site, than using some arbitrary energy correction factor for finding liquefaction at any site.

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