Evaluation of Liquefaction Potential from SPT and CPT: a Comparative Analysis

Évaluation du potentiel de liquéfaction du SPT et du CPT: une analyse comparative

Mohammad Mominul Hoque
Dept. of Civil Engineering, Assistant Professor, Daffodil International University, Dhaka-1207, Bangladesh, mominul.ce@diu.edu.bd

Mehedi Ahmed Ansary
Dept. of Civil Engineering, Professor, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

Abu Siddique
Dept. of Civil Engineering, Professor, Bangladesh University of Engineering and Technology, Dhaka-1000, Bangladesh

ABSTRACT: This paper presents evaluation and comparative analysis of liquefaction potential from Standard Penetration Test (SPT) and Cone Penetration Test (CPT) based deterministic relationships. Both methods have significant relative advantages, and can often be optimal when used in combinations. In this research, four pairs of SPT and CPT tests were carried out at the river bank of Jamuna, Bangladesh and each pair of test was conducted as close as possible. Particle size analysis on collected samples indicated that, fines content varied in the range of 3.5 to 39.2 percent. The recorded SPT N-values in different boreholes varied from 1 to 42 and maximum CPT resistance (q_c) was approximately 20 MPa. It was observed that the recorded SPT N-value and CPT resistance considerably varied at some depths in certain locations. These result in some inconsistency in the safety factors against liquefaction calculated on the basis of SPT and CPT data. So, it is emphasized that quality test data is required to obtain consistent and reliable results when both methods are used in combinations for liquefaction analysis.

RÉSUMÉ: Cet article présente l'évaluation et l'analyse comparative du potentiel de liquéfaction à partir des relations déterministes basées sur le test de pénétration standard (SPT) et le test de pénétration du cône (CPT). Les deux méthodes présentent des avantages relatifs importants et peuvent souvent être optimales lorsqu'elles sont utilisées en combinaison. Dans cette recherche, quatre paires de tests SPT et CPT ont été effectués à la rive de Jamuna, au Bangladesh, et chaque paire de tests a été menée aussi près que possible. L'analyse granulométrique des échantillons recueillis indique que la teneur en fines varie de 3,5 à 39,2%. Les valeurs N du SPT enregistrées dans différents trous de forage variaient de 1 à 42 et la résistance maximale au CPT (q_c) était d'environ 20 MPa. Il a été observé que la valeur N du SPT et la résistance au CPT enregistrées variaient considérablement à certaines profondeurs dans certains endroits. Il en résulte une certaine incohérence dans les facteurs de sécurité contre la liquéfaction calculés sur la base des données SPT et CPT. Il est donc souligné que des données d'essai de qualité sont nécessaires pour obtenir des résultats cohérents et fiables lorsque les deux méthodes sont utilisées dans des combinaisons pour l'analyse de liquéfaction.

KEYWORDS: liquefaction potential, standard penetration test, cone penetration test and deterministic correlations.

1 INTRODUCTION

The Standard Penetration Test (SPT) and Cone Penetration Test (CPT) are the two most widely used in-situ tests for evaluating the liquefaction characteristics of soils.Thebasic framework for liquefaction evaluation methods (Seed and Idriss, 1971) based on SPTfirst began to evolve afterthe wake of a pair of devastating earthquakes that occurred in Alaska and Niigata in 1964.Countless effort of numerous researchers(Seed et al. 1985, 2003, Youd et al. 2001, Boulanger and Idriss, 2014) have made subsequent progresses of liquefaction evaluating methods and continue to evolve today. The SPT based deterministic relationship (Seed et al. 1985) is one of the most widely accepted correlation for evaluation of seismically induced soil liquefaction and which has set standard for practicing engineers. On the other hand, CPT based correlations is increasingly used for liquefaction studies because of its consistency and efficiency, and is now represent nearly co-equal status with regard to accuracy and reliability relative to SPTbased correlations. The fundamental of both methods, as adopted by numerous researchers, compares the earthquakeinducedcyclic stress ratios (CSR) with the cyclic resistance ratios (CRR) of the soil, usually determined from in-situ parameter such as SPT N-value or CPT cone tip resistance.Both SPT and CPT methods have significant relative advantages, and both tests are far batter when used in combinations. This research intended to evaluate and compare liquefaction potential using both SPT and CPT based deterministic correlations.

2 FIELD INVESTIGATIONS

In this research, field investigations were carried out along the riverbank of the Jamuna River, Bangladesh. The geologic formations of the research site are mainly consisting of alluvial sand and silt deposits of Holocene age. The alluvial sands are light to brown-grey coloured, coarse to fine silty sand of subrounded in shape. The sand contains mostly quartz, feldspar, mica and significant amount of heavy minerals. The alluvial silts have the same color as the sands, but are fine sandy to clayey silt and are poorly stratified (Alam et al. 1990).

A total of four pairs of SPT and CPTtests were performed in different locations within the study area and each pair was carried out as close as possible, maximum horizontal distance not greater than 10m. Boreholes for the SPT were advanced by percussion method with bentonite slurry and an automatic type SPT hammer-release was used for the measurement of N-values from SPT. Potential source of uncertainty that may affect N-values have been carefully taken into account. The split spoon sampling method was used to obtain representative disturbed soil samples from boreholes and used for laboratory investigations. The SPT N-value and samples were collected every 1.52 m intervals.

CPT soundings were advanced using a Hogentoglar type piezocone penetrometer with a cross sectional area of 10 cm^2 and which can measures the pore water pressure (u_2), as well as the cone tip resistance (q_c) and sleeve friction (f_s). To perform CPT sounding, the cone was pushed vertically into the ground at a constant rate of approximately 20 mm/sec. During the advancement, measurements of dynamic pore water pressure, cone tip resistance and sleeve friction were recorded continuously at increments of 10 mm. The modified cone tip resistance ($q_{c,1,mod}$) in MPa (top scale) andnormalized SPT $N_{1,60}$ values (bottom scale) are presented in Figure 1.

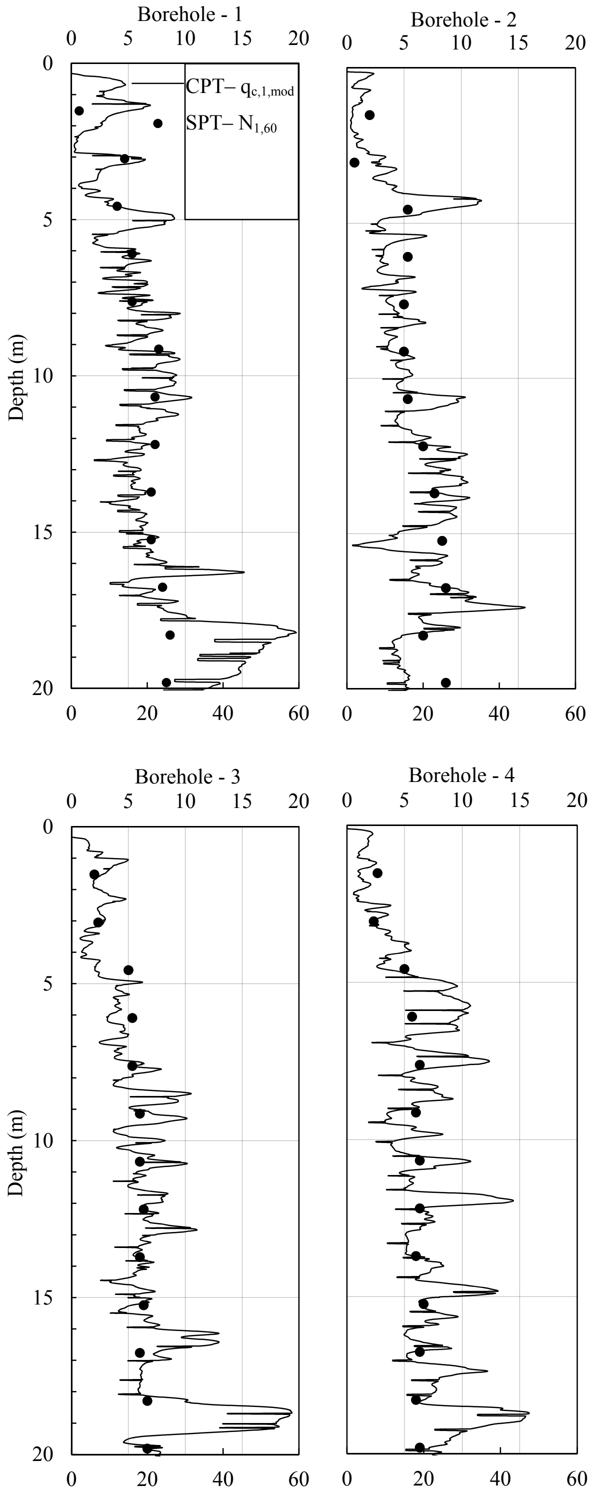

Figure 1. Penetration depth vs.modified cone tip resistance $q_{c,1,mod}$ and normalized$N_{1,60}$ values for all boreholes.

It has been found that, the soils within the test area primarily comprised of silt, fine and medium sands, and clay. As such, the combination of silt and sand are generally non-plastic and the combination of silt, clay and sand are low-plastic. Soils are moist from ground surface and ground water table is located approximately at 3 m below from ground surface. Density state of soil at different depths varies from loose to medium dense.

3 LABORATORY INVESTIGATIONS

Laboratory investigations included mainly visual observations and mechanical sieve analysis. Soil samples recovered from various depths were individually assessed and classified based on sieve analysis. Samples are light brown to grey in colour and grains are mostly subrounded in shape. Out of 52 recovered samples, 44 samples were used for sieve analysis. Soil samples obtained from 1.52 m and those contained considerable amount clay were excluded from sieve analysis. From sieve analysis it was observed that soils are containing appreciable amount of fines (material finer than 0.075 mm) ranging from 3.5 to 39.2 percent, fineness modulus (F.M.)varied from 0.18 to 1.11 and mean grain size (D_{50}) in the range of 0.09 to 0.23 mm. Based on the sieve analysis results, the soils were generally classified into two groups; either well graded sands with little silt or poorly graded sands with silt. According to unified soil classification system, the soils can be symbolized as SW and SP-SM respectively. As fines content is one of the important parameter in liquefaction analysis fromdeterministic relationships, only fines content for each borehole are presented in Table 1.

Table 1. Fines content of sand at different boreholes.

Depth (m)	*BH-1*	*BH-2*	*BH-3*	*BH-4*
3.05	26.8	ND*	17.96	ND*
4.57	32.5	32.44	16.89	ND*
6.10	32.5	26.39	19.8	ND*
7.62	38.4	36.35	20.7	5.85
9.14	11.3	39.2	16.95	6.25
10.67	12.4	38.1	17.8	5.5
12.19	8	38	7.44	5.5
13.72	17.3	22	5.5	5.39
15.24	12.5	24.4	4.15	5.4
16.76	7.68	5.85	5.05	5.15
18.29	32.03	7.5	4.95	6.75
19.81	22.7	6.85	3.5	6

BH = Borehole and ND* = not determined

4 DATA ANALYSIS

The SPT and CPT based deterministic relationships compares the earthquake-induced cyclic stress ratios (CSR_{eq}) with the in-situ equivalent uniform cyclic stress ratios ($CSR_{eq,M=7.5,1atm}$) of the soil. The soil's $CSR_{eq,M=7.5,1atm}$ is correlated to in-situ parameters obtained from SPT blow count (N-values) and CPT penetration resistance (cone tip resistance, q_c). The measured SPT N-values, normalized for both effective overburden stress and energy, equipment and procedural factors affecting SPT testing to $N_{1,60}$ values and CPT cone tip resistance, q_c is normalized and modified to $q_{c,1,mod}$ for effective overburden stress and the frictional effects of apparent fines content and character. Normalized $N_{1,60}$ and modified $q_{c,1,mod}$ is then used to calculate $CSR_{eq,M=7.5,1atm}$ from deterministic relationships.In the deterministic correlations both $N_{1,60}$ and $q_{c,1,mod}$ represented as a function of fines content. It should be noted that, $CSR_{eq,M=7.5,1atm}$ is obtained after adjusting both for magnitude-correlated duration weighting factor and effective initial overburden stress (expressed through a K_σ factor). Factor of safety (often known as liquefaction potential or liquefaction resistance) against liquefaction can now be obtained from the ratio of $CSR_{eq,M=7.5,1atm}$ to CSR_{eq}. In general, it is assumed that, if the value of safety factor greater than unity, the deposit is safe against liquefaction for a given earthquake.

4 .1 *Earthquake-induced Cyclic Stress Ratio*

The earthquake-induced cyclic stress ratio, at a given depth, within the critical soil stratum, is usually expressed as a representative value (or equivalent uniform value) equal to 65% of the maximum cyclic shear stress ratio as –

$$\mathrm{CSR_{eq}} = 0.65 \times (\mathrm{a_{max}/g}) \times (\sigma_v/\sigma'_v) \times (\mathrm{r_d}) \quad (1)$$

Where, σ_v and σ'_v are the vertical total stress and effective stress at a given depth, a_{max}/g is the maximum horizontal acceleration (as a function of gravity) at the ground surface, and r_d is the shear stress reduction factor that accounts for the dynamic response of the soil profile. In this research maximum horizontal acceleration at the ground surface was taken 0.25g and values of r_d were estimated from the depth vs. r_d correlation (after Cetin and Seed, 2000).

4 .2 *In-situ Uniform Cyclic Stress Ratio*

The measured SPT N-values were first corrected for effective overburden stress, energy, equipment, and procedural effect to obtained fully standardized $N_{1,60}$ values as –

$$\mathrm{N_{1,60}} = (1/\sigma'_v)^{0.5} \times \mathrm{C_R} \times \mathrm{C_s} \times \mathrm{C_B} \times \mathrm{C_E} \quad (2)$$

Where, C_R is the correction for rod length, C_s is the correction for non-standardized sampler configuration, C_B is the correction for borehole diameter, and C_E is the correction for hammer energy efficiency.

Similarly, measured cone tip resistances, q_c were normalized and modified for effective overburden stress and the frictional effects of apparent fines content and character to obtained to $q_{c,1,mod}$ values as –

$$\mathrm{q_{c,1,mod}} = (\mathrm{q_c} \times (\mathrm{P_a}/\sigma'_v)^{c}) + (\mathrm{\ddot{A}q_c}) \quad (3)$$

Where, P_a is the atmospheric pressure, normalization exponent (c) is a function of both normalized tip resistance ($q_{c,1}$) and friction ratio (R_f), $\ddot{A}q_c$ is the function of $q_{c,1}$, R_f and c.

Then, normalized $N_{1,60}$ and modified $q_{c,1,mod}$ were used to calculate $CSR_{eq,M=7.5,1atm}$ from deterministic relationships (Seed et al, 2003). An earthquake magnitude of M_w = 7.5 was assumed for the adjustment of magnitude-correlated duration weighting factor. Soil's unit weights were back calculated from SPT N-value vs. unit weight correlation (Bowles, 1982) to estimate total and effective overburden stresses.

5 RESULTS AND DISCUSSIONS

Factor of safety obtained from SPT and CPT based deterministic relationships are presented in Figure 2 for different boreholes. As SPT N-values were recorded every 1.52 m intervals, factor of safety for both SPT and CPT were also evaluated at same depth intervals. In case of CPT, an average value of cone tip resistances over 0.30 m were taken as penetration resistance, at same depths where SPT blows were counted. For all boreholes it can be observed from Figure 2 that, majority of the cases safety factors obtained from CPT based relationship gives lower values as compared to SPT based relationship. Although safety factors obtained both SPT and CPT are found to be mostly identical throughout the boreholes depth, for some depths, factor of safety obtained from CPT are higher than that from SPT. Safety factors obtained from CPT analysis indicate that, liquefaction can occur throughout the entire depth of 20m in all the boreholes, except some thin layers in borehole-2 and borehole-3. On the other hand, safety factors obtained from SPT analysis indicate that liquefaction can be expected in all borehole locations at depths less than 10 m and 12.5 m in borehole-1 and borehole-2 respectively.

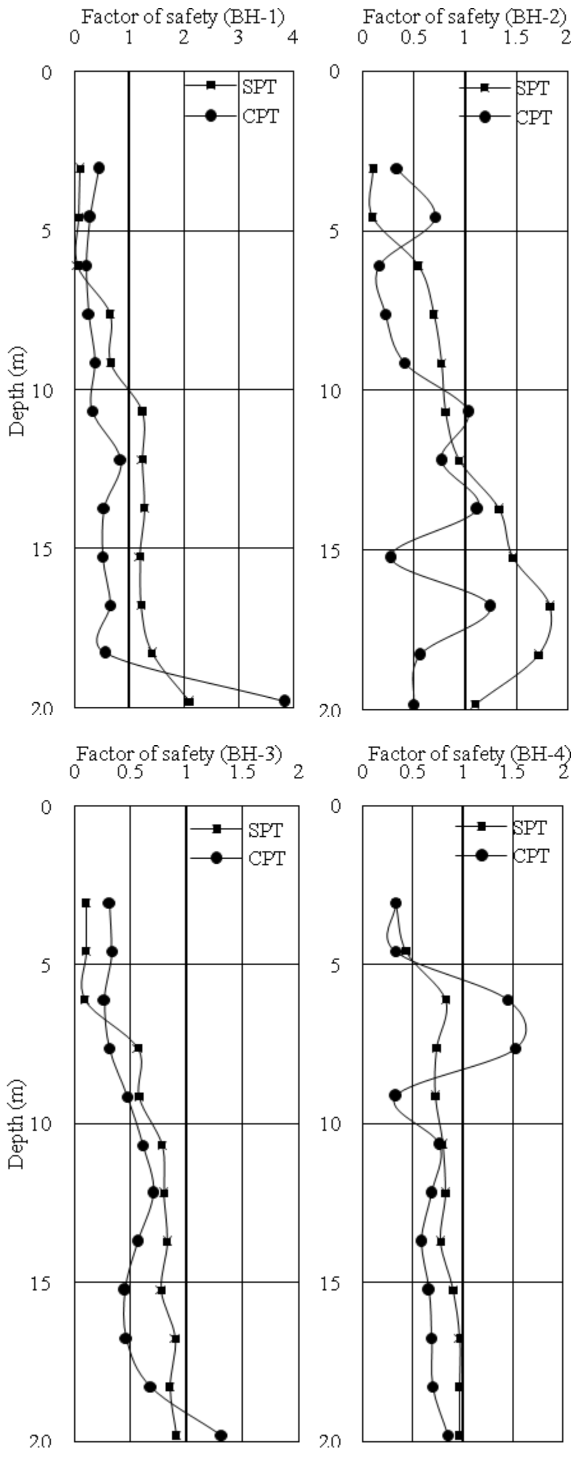

Figure 2. Factor of safety against liquefaction from SPT and CPT.

Inconsistency in safety factors evaluated from SPT and CPT may be resulted due to the variations in recorded SPT N-values and CPT cone tip resistances at same depth. Probably these variations were due to boreholes distance between each pair of SPT and CPT. In addition to that, energy efficiency of SPT hammer was not directly estimated in the field and efficiency ratio was assumed as 60% of the applied energy. Due to this reason, factor of safety against liquefaction from SPT may have resulted in over estimation compared to CPT.

6 CONCLUSION

Four pairs of SPT and CPT tests were carried out to evaluate and compare liquefaction potential from SPTand CPT based deterministic relationships. It was observed that, the recorded SPT N-valueand CPT resistance considerably vary at same depth. Due to this inconsistency, safety factors against liquefactionresults an over and/or under estimation compare to each other. So, it is highly recommended to ensure high quality tests data to confirm accurate and reliable results when both methods are used in combinations.

7 REFERENCES

Alam M.K., Hasan S.A.K.M., Khan M.R. and Whitney J.W. 1990.Geological Map of Bangladesh.Geological Survey of Bangladesh, Dhaka.

Bolton Seed H., Tokimatsu K., Harder L.F. and Chung R.M. 1985. Influence of SPT procedures in soil liquefaction resistance evaluations. Journal of Geotechnical Engineering 111(12), 1425-1445.

BoulangerR.W.and IdrissI.M. 2014. CPT and SPT based liquefaction triggering procedures. Rep. No. UCD/CGM-14, 1.

Bowles, J.E. 1982. Foundation Analysis and Design. McGraw-Hill, New York.

Cetin K.O. and Seed, R.B. 2000. Earthquake-Induced Nonlinear Shear Mass Participation Factor (r_d). Geotechnical Engineering Research Report No. UCB/GT2000/08. University of California, Berkeley.

Seed H.B. and Idriss I.M. 1971. Simplified Procedure for Evaluating Soil Liquefaction Potential. Journal of the Soil Mechanics and Foundations Division 97 (9), 1249-1273.

Seed, H. B., Tokimatsu, K., Harder, L. F., Chung, R. M. 1985. Influence of SPT procedures in soil liquefaction resistance evaluations. Journal of Geotechnical Engineering, 111(12), 1425-1445.

Seed R.B., Cetin K.O., Moss R.E. Kammerer A.M., Wu J., Pestana J.M., Riemer M.F., Sancio R.B., Bray J.D., Kayen R.E. andFaris A. 2003. Recent advances in soil liquefaction engineering: a unified and consistent framework. In Proceedings of the 26th Annual ASCE Los Angeles Geotechnical Spring Seminar.Long Beach, California.

Youd T.L., Idriss I.M., Andrus R.D., Arango I., Castro G., Christian J.T., Dobr, R., Finn W.L., Harder Jr L.F., Hynes M.E. and Ishihara K. 2001. Liquefaction resistance of soils: summary report from the 1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. Journal of geotechnical and geoenvironmental engineering127(10), 817-833.