CPT & SPT Tests in Assessing Liquefaction Potential

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ABSTRACT: The purpose of this research is to estimate the earthquake induced liquefaction potential of selected reclaimed areas of Dhaka city based on both Cone Penetration Test (CPT) and Standard Penetration Test (SPT). CPT and SPT data have been collected from ten (10) selected reclaimed areas of greater Dhaka city. The filling depth of the reclaimed areas varies from 1.5 to 13.5 m from the existing ground level (EGL). The values of peak ground acceleration (a_{max}) and the magnitude (M) have been taken as 0.15g and7.5 respectively for the liquefaction analyses. The range of SPT-N, Cone tip resistance (MPa), local friction (kPa) and friction ratio varies between 1~42, 0.17~18.58, 0~273.2 and 0~9.34 respectively of the ten (10) selected sites of Dhaka city. Liquefaction potential has been estimated based on both CPT and SPT data. It has been observed that in reclaimed areas of Dhaka city especially for the locations reclaimed by dredged soil up to a filling depth of 1.5 to 4.5m there is high probability of liquefaction occurrence. In most of the cases, liquefaction zone for CPT have been observed in two different depth zones. On the other hand, liquefaction zone for SPT have been observed in only one zone. The highest value of Liquefaction Potential Index (LPI) for CPT and SPT are 21 (Bramangaon) and 28 (Purbachal) respectively. The lowest value of Liquefaction Potential Index for CPT and SPT are 3 (Kawran Bazar) and 1 (Kawran Bazar) respectively. The low liquefaction potential zone value has been found along the center and north south alignment of Dhaka City. The high potential zone has been found in the outer periphery of the study area.

KEYWORDS: Liquefaction potential, Soil profile, CPT, SPT, Cone tip resistance, Sub soil characteristics.

1. INTRODUCTION

Liquefaction problem has become important when it started to affect human and social activities by disturbing the function of facilities and also after rapid urbanization by expanding the cities in reclaimed areas. Ground failures generated by liquefaction has been a major cause of damage during past earthquakes e.g., 1964 Niigata, Japan and 1964 Alaska, USA, 1971 San Fernando, 1989 Loma Prieta, 1995 Kobe, Japan and 2004 Chuetsu, Japan earthquakes. Liquefaction affects buildings, bridges, buried pipelines and lifeline facilities etc. in many ways.

The historical seismicity data and recent seismic activities in Bangladesh and adjoining areas indicate that Bangladesh is at high seismic risk. As Bangladesh is the world’s most densely populated area, any future earthquake shall affect more people per unit area than other seismically active regions of the world. Bangladesh including capital city Dhaka is largely an alluvial plain consisting of fine sand and silt deposits with shallow ground water table in most places. Although the older alluvium is less susceptible to liquefaction, the deposits along the river flood plains may liquefy during a severe earthquake. Human made soil deposits also deserve attention. Loose fills, such as those placed without compaction, are very likely to be susceptible to liquefaction.

Over the past 30~40 years Dhaka city has experienced a rapid growth of urban population and it will continue in the future due to several unavoidable reasons. This high population increase demands rapid expansion of the city. Unfortunately, most parts of Dhaka city has already been occupied. As a result, new areas have been reclaimed by both government and private agencies in and around Dhaka city. In many cases, the practice for developing such new areas is just to fill lowlands of the depth 3~12m with dredged material consisting of silty sand. This causes liquefaction susceptibility for such areas.

Seed and Idriss (1971) have presented test procedures for measuring soil liquefaction characteristics as summarized in Table 4. Their proposed basic simplified method to evaluate liquefaction potential has been modified and improved by Seed et al. (1983); Youd and Idriss (2001); Boulanger and Idriss (2004); Cetin et al. (2004) as described in Table 4.

Seed et al. (1983) has evaluated liquefaction potential using field test data. They used simplified procedure for evaluating the liquefaction potential of sand deposits using data obtained from Standard Penetration Test (SPT). Field data for sites which have been known to be liquefied or not liquefied during earthquakes in the United States, Japan, China, Guatemala, Argentina and other countries have been presented to establish a criterion for evaluating the liquefaction potential of sands in Magnitude 7.5 earthquakes. Then the results of this study have been extended to other magnitude earthquakes using a combination of laboratory and field tests data.

Gratchev et al. (2006) have conducted research to investigate the liquefaction potential of clayey soils under cyclic loading. This research seeks to investigate the liquefaction of clayey soils, a phenomenon that has been the trigger for many natural disasters in the last few decades, including landslides. Research has been conducted on artificial clay-sand mixtures and natural clayey soils collected from the sliding surfaces of earthquake-induced landslides.

Robertson (2009) has developed cone penetration test (CPT) based relationships to evaluate the susceptibility to strength loss and liquefied shear strength for a wide range of soils based on case histories as stated in Table 4. The case histories has indicated that very young, very loose, non-plastic or low-plastic soils tend to be more susceptible to significant and rapid strength loss than older, denser, and/or more plastic soils. The CPT is a useful in situ test that can provide continuous estimates of the potential for flow liquefaction. For low risk projects, the CPT-based method is appropriate when combined with selective samples to confirm the soil type as well as conservative estimates of soil response. For moderate risk projects, the CPT-based method should be combined with appropriate additional in situ testing, as well as selected undisturbed sampling and laboratory testing, to confirm soil response. For high risk projects, the CPT-based method should be used as an initial screening to identify the extent and nature of potential problems has been followed by additional in situ testing and appropriate laboratory testing on high-quality samples. An advanced numerical modeling is appropriate for high risk projects where initial screening indicates a need.

The SPT based liquefaction charts are commonly been used for determining liquefaction potential. Simplified method given by Seed, Tokimatsu and Yoshimi (Y-T) and Idriss and Boulanger (2008) methods of liquefaction assessment have been analyzed by Kumar et al. (2012) as presented in Table 4. Computational methods like artificial neural network (ANN) and neuro-fuzzy technique (NF) has been also discussed as capable for liquefaction assessment using database either from SPT or CPT results. Some pertinent soil properties along with seismic characteristics may help in modeling and analyzing liquefaction potential of prone sites. The major advantage of computational methods is the ability to associate both SPT and CPT indicator properties for better engineering judgment to evaluate site dependent liquefaction.

Sesov et al., (2012) has presented (Table 4) that the investigations and results on the evaluation of the potential of liquefiable soil layers at location where new industrial complex has been planned to be built in southern part of Republic of Macedonia. Investigations combine the results from different in-situ methods, site response analysis and laboratory cyclic triaxial undrained tests. For the purpose of the new industrial complex which has been planned to be built at, first preliminary evaluation of the liquefaction potential has been done with SPT and CPT methods. Results have indicated that for the soil layers where cyclic resistance ratio is lower than the expected cyclic stress ratio might behave as liquefiable. Soil samples have been taken from the boreholes of the site and cyclic undrained triaxial tests have been done.

Guettaya et al. (2013) has presented a case study of liquefaction potential assessment for the foundation of an earth dam in Tunisia. An emphasis has been made on the exploration of geotechnical conditions and the interpretation of field tests (SPT and CPT) and the results have been collected before and after soil densification using the vibro-compaction technique. The SPT resistance values has been increased on average from 12 to 25 blow counts/0.3m, and the CPT resistance has been increased on average from 8MPa to 14MPa. Before vibro-compaction, the factor of safety (FS) against liquefaction fell below 1.0, which means that the soil is susceptible for liquefaction. After vibro-compaction the values of FS exceed the unit which justified the liquefaction mitigation efforts in dam foundation.

Ecemis and Karaman (2014) has performed (Table 4) a set of four high-quality field tests at 20 different locations on the Northern coast of the Izmir Gulf: (1) piezocone penetration test (CPTu), (2) pore pressure dissipation test (PPDT), (3) direct push permeability test (DPPT), and (4) standard penetration test (SPT). The total sounding depth for each test is about 15 m. Uncertainties prevail at the current liquefaction screening method based on the cone penetration test (CPT) as to whether the existence of fines increases liquefaction resistance or decrease cone penetration resistance. Field-based data have been used to evaluate the effects of non-/low plastic fines on liquefaction resistance at the current CPT-based liquefaction assessment method. The liquefaction resistance of sands and silty sands has been reinterpreted from the current CPT-based liquefaction assessment method. The trend, which presents the change of liquefaction resistance with fines content at the same relative density, has been compared with the available laboratory-based data in the literature.

Ndoj et al., (2015) have evaluated the liquefaction, based on the data collected by Piezocone Test (CPTU) and Standard Penetration Test (SPT) as shown in Table 4. These data have been used to evaluate the liquefaction for a case study, in a coastal area of Albania, located in from Lalezi Bay to Hamallaj area, near Durresi city, where several residential buildings and resorts useful during the summer season are foreseen to be built. The site investigation has been carried out with 8 CPTU tests until a maximal depth of 20 m. According to this study, in this area sands, gravelly sands, silty sands and clays are present. The water level is located very close to ground surface, at around 0.5 - 2.0 m under the ground surface. The highest moment magnitude registered in this area is 6.2 and it belongs to Durresi city, for the earthquake happened in December 1926. CPT based method show that all the soils have been classified as "like sands", below the water level where the liquefaction may occur. Also the SPT based method show that the liquefaction may occur in these soils, but the thickness of liquefiable layers of soils is small.

Konni (2015) has been taken a live project having offshore artificial island of 84 km offshore and an attempt has been made to assess compaction levels achieved for offshore artificial islands. Subsequently, liquefaction potential has been evaluated based on SPT, N and CPT data as summarized in Table 4.k). According to the test result it has been found that CPT appears to be better suited to liquefaction assessment than SPT because it is more standardized, reproducible, and cost-effective and yields a continuous penetration record with depth. CPT can be quickly and economically identify the thick and thin liquefiable soil, which is cost-prohibitive in SPT test.

During the recent devastating earthquakes in Christchurch, many residential houses have been damaged due to widespread liquefaction of the ground. In-situ testing has widely been used as a convenient method for evaluating liquefaction potential of soils. Cone penetration test (CPT) and standard penetration test (SPT) are the two popular in situ tests which are widely used in New Zealand for site characterization. Mirjafari et al., (2016) has conducted the Screw Driving Sounding (SDS) test in Christchurch, a correlation has been developed between tip resistance of CPT test and SDS parameters for layers consisting of different fines contents. As SDS method is simpler, faster and more economical test than CPT and SPT, it can be a reliable alternative in-situ test for soil characterization, especially in residential house constructions as shown in Table 4.

Huang and Yu (2017) have evaluated three procedures for liquefaction potential based on in situ. Procedure one is the assessment of "triggering" (initiation) of soil liquefaction. Soil type is very important for assessment of this initiation. Clay content, liquid limit, and water content has been used to evaluate the potential initiation of soil liquefaction. Procedure two is the assessment of liquefaction resistance based on in situ tests. The methods that has been used to evaluate liquefaction are the standard penetration test (SPT), cone penetration test (CPT), dynamic cone penetration test (DPT), Becker penetration test (BPT), and shear wave velocity (VS) test. The liquefaction resistance has been obtained by calculating the penetration resistance in empirical equations. Procedure three is assessment of the site liquefaction index and deformation of liquefiable sites. In this procedure, the depth and thickness of the liquefiable soil layer has been considered. Finally, the site liquefaction potential has been calculated by integrating all test points. Assessment of soil seismic deformation also been introduced.

Hoque et al., (2017) has presented (Table 4.m) 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 have been carried out at the river bank of Jamuna, Bangladesh and each pair of test has been conducted as close as possible.

The goal of this paper is to estimate the earthquake induced liquefaction potential of selected reclaimed areas of Dhaka city and develop liquefaction potential (LPI) map based on CPT and SPT.

2. EVALUATION OF LIQUEFACTION SUSCEPTIBILITY

2.1 Evaluation Based on SPT N-Value

The most common index properties for estimating liquefaction strength is the N-value obtained from the standard penetration test. The standard penetration test (SPT) consists of driving a thick-walled sampler into the granular soil deposit. The measured SPT N-value (blows per foot) is defined as the penetration resistance of the soil, which equals the sum of the number of bows required to drive the SPT sampler over the depth interval of 15 to 45 cm (6 to 18 in).

SPT test is probably the most widely used field test in the Bangladesh as well as in the world. This is because it is relatively easy to use, the test is economical compared to other types of field testing, and the SPT equipment can be quickly adapted and included as part of almost any type of drilling rig.

The most comprehensive liquefaction data catalogs are based on Standard Penetration test (SPT) blow counts (SPT N). Starting in the 1970's, Seed and his colleagues worked to develop a reliable method for assessing liquefaction potential based on SPT data. Their framework for SPT-based assessments of liquefaction potential has been developed in a series of papers that includes Seed and Idriss (1971); Seed and Idriss (1982); Seed et al. (1983)significant contributions have been also made by Tokimatsu and Yoshimi (1983) as summarized in Table 4. This research culminated in the liquefaction criteria published by Seed et al., (1985) as described in Table 4.

The empirical chart published by Seed et al. (1983) is based on a standardized SPT blow count, $(N_1)_{60}$ and the cyclic stress ratio (CSR).To get $(N_1)_{60}$, the measured N_{SPT} corrected for the energy delivered by different hammer systems and normalized with respect to overburden stress. Boundary curves separating nonliquefied from liquefied soils, in terms of CSR and $(N_1)_{60}$have been conservatively drawn to nearly all observed cases of liquefaction in the data catalog. Three separate boundary curves have been presented for clean to silty sands. To consider the effects of earthquake magnitude on the duration of strong shaking, magnitude scaling factors has been specified. Over the last few decades, the empirical method given by Seed et al. (1983), sometimes referred to as the "simplified procedure", has been widely used for evaluating soil liquefaction potential in all around the world.

2.2 Evaluation Based on CPT

For estimating liquefaction potential by in-situ test other than the SPT, the most advanced ones are those using cone penetration resistances. The idea for the cone penetration test is similar to the SPT except that instead of driving a thick-walled sampler into the soil, a steel cone is pushed into the soil. The force required to move the cone into the extended position divided by the horizontally projected area of the cone is defined as the cone resistance, q_c. For liquefaction analysis, the cone penetration test value q_c is corrected for the vertical effective stress. A major advantage of the cone penetration test is that by using the electric cone, a continuous subsurface record of the cone resistance q_c can be obtained. This is in contrast to the SPT, which obtains data at intervals in the soil deposit. Disadvantage of the CPT are that soil samples cannot be recovered and special equipment is required to produce a steady and slow penetration of the cone.

The Cone Penetration test (CPT) yields a continuous profile of penetration resistance and is thus well-equipped for detecting thin, liquefiable layers within a larger, stable soil deposit.

3. SELECTED AREAS FOR THE RESEARCH

Total ten areas of the Dhaka city have been selected for this research. The main targeted areas have been reclaimed lands since some of these lands have been found to be susceptible to liquefaction (Hore, 2013). The reclaimed areas are Bramangaon, Ashian City, Badda, Banasree, Gabtoli, Kawran Bazar, Purbachal, United city, Uttara and Kamrangirchar. Figure 1 shows the selected study areas. The study area is located between the latitude 23°35´N-23°54´N and the longitudes 90°19´ E-90°30´E. the expansion of the city is restricted by the Buriganga River in the south, Turag River in the west and Balu River in the east. The city lies on the lower reaches of the Ganges Delta (Rahman et al., 2011) as described in Table 4.

3.1 Geology of Dhaka

Geological evolution of the Bengal Basin starting from Upper Paleozoic time when Gondwana land break up and collision the Indian plate with the Asian plate and sedimentary cover of the basin with a maximum thickness of 20 km includes three major lithostratigraphic units separated by three major unconformities. Most of the authors have the opinion about the Madhupur tract is the tectonic uplifted surface. Fergussion (1963) believes that the Madhupur tract is the recent uplifted surface due to the 1762 earthquake. Dhaka city is situated in the southern half of the Madhupur Tract and Floodplain area with southern river system. Regional elevation of the area gradually declines towards Buriganga River on the south and the elevation ranges from 10m to 17m but is generally around 14m above mean sea level. Geologically Dhaka city belongs to Bengal Foredeep and is situated in the Pleistocene uplifted block (Madhupur Tract) within the passive margin surrounded by subsiding floodplains bounded on the west by a series of NW-SE trending en-echelon faults including the Dhamrai, Maijail and Kaliakoir ones (WASA, 1991; Morgan and McIntire,1959) as summarized in Table 4.r) and s) . Land surface is covered by gray floodplain and non-Cretaceous floodplain soils. Stratigraphically, Old Dhaka is characterized by hundreds of meters thick unconsolidated sequence of fluvio-deltaic deposits many composed of gravels, sands, silts and clays of Plio-Pleistocene age.

In this paper, subsoil characteristics of two sites (namely Bramangaon and Ashian City have been elaborated.

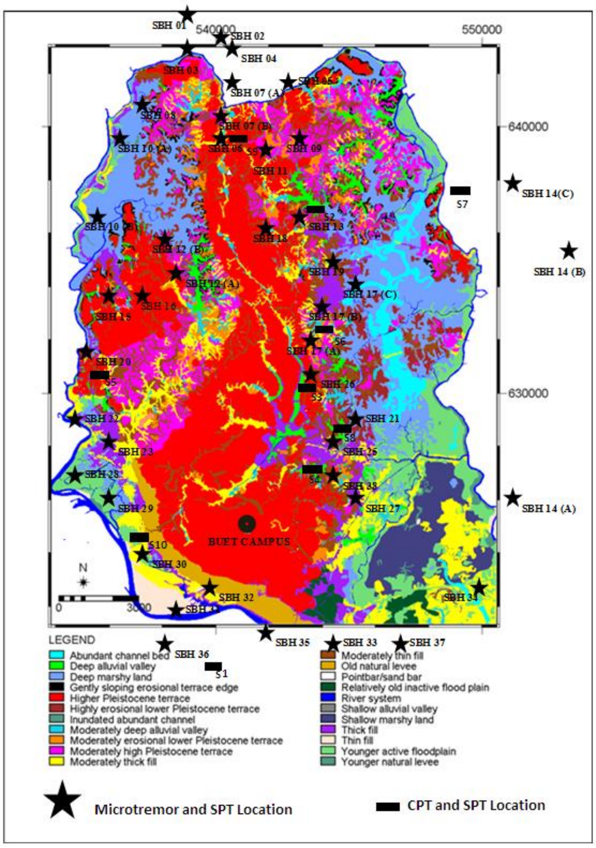

Figure 1 Geological Map showing study areas of Dhaka city.

3.2 Sub - Soil characteristics of Bramangaon

This site has been situated in southeast part of Dhaka city. It is a private land development project where main filing has been done by dredged river sand. The depth of filling of fine sand is 5.0 m from existing ground level. The clayey silt layer exists from 5.0 m to 6.5 m from EGL. After that 1.5 m is sandy silt layer. Then 12.0 m is clayey silt. The uncorrected SPT N value of filling fine sand varies from 4 to 5. The SPT N value of clayey silt layers varies from 5 to 8. The maximum value of SPT N is 8. The minimum value of SPT N is

4. From the CPT test, the cone resistance varies from 0.51 to 16.78 MPa. The average value of cone resistance is 3.88 MPa. Friction varies from 0 to 120.2 kPa. The average value of Friction is 30.79 kPa. Friction ratio varies from 0 to 4.13. The average value of Friction ratio is 1.11.The SPT N values of the boreholes have been shown in the Table 1.

Figure 2 shows Depth (m) vs. Cone Resistance q_t (MPa), Friction (kPa), N_{60} and Depth vs. friction ration (kPa) at Bramangaon. From the CPT test, the cone resistance varies from 0.51 to 16.78 MPa. The maximum value of cone resistance is 16.78 MPa. The minimum value of cone resistance is 0.51 MPa. The average value of cone resistance is 3.88 MPa. Friction varies from 0 to 120.2 kPa. The average value of friction is 30.79 kPa. Friction ratio varies from 0 to 4.13 kPa. The average value of Friction ratio is 1.11 kPa. Results from grain size analysis of the soil samples have been presented in Table 1. The mean grain size (d_{50}), fine content (F_c) of filling sand varies 0.16 to 0.17 mm, 20 to 21% respectively. The mean grain size (d_{50}), fine content (F_c) of silt is 0.046 mm, 71% respectively. Table 2 shows Probable soil classification using CPT data (Robertson, 1990) (as shown in Table 4) at Bramangaon.

Table 1 SPT N value and grain size analysis at Bramangaon

Depth(m)	Description of Soil	SPT N Value	F_c (%)	d_{50} (mm)
1.5	Filling Sand	4	20	0.17
3		5		
4.5		5		
6	Clayey Silt	7	71	0.046
7.5	Sandy silt	8	51	0.076
9	Clayey Silt	5	71	0.046
10.5		5		
12		5		
13.5		4		
15		5		
16.5		6		
18		7		
19.5		8		

Table 2 Probable soil classification using CPT data (Robertson, 1990) at Bramangaon

Depth Range (m)	I_C Range	Probable Soil Classification
0-3	0.82-1.52	Sand
3-6	1.22-1.92	Sand
6-9	1.77-2.82	Sand/Silt
9-12	2.34-3.24	Silty Sand/Silty Clay
12-15	2.48-3.1	
15-18	2.51-3.11	
18-21	1.99-3.15	
21-25	1.66-2.67	Sand

3.3 Sub-Soil Characteristics of Ashian City

This site has been situated in Northern part of Dhaka city. The depth of filling of fine sand is 3.5 m from existing ground level. The silty clay layer exists from 3.5 m to 12.5 m from EGL. After that 4.5 m is fine sand layer. Then 3.0 m is silty clay. The uncorrected SPT N value of filling fine sand varies from 4 to 5. The SPT N value of silty clay layers varies from 3 to 7. The maximum value of SPT N is 42. The minimum value of SPT N is 3. Figure 3 shows Depth (m) vs. Cone Resistance q_t (MPa), Friction (kPa), N_{60} and Depth vs. Friction ration (kPa) at Asian City. From the CPT test, the cone resistance varies from 0.195 to 7.805 MPa. The average value of cone resistance is 1.78 MPa. Friction varies from 0 to 233.9 kPa.The average value of Friction is 31.21 kPa. Friction ratio varies from 0 to 6.35 kPa. The average value of Friction ratio is 1.29 kPa.

SPT has been conducted in the area following procedure described in ASTM D1586. The SPT N values of the boreholes have been shown in the Table 3. The graph between depth vs N value has been shown in Figure 3.

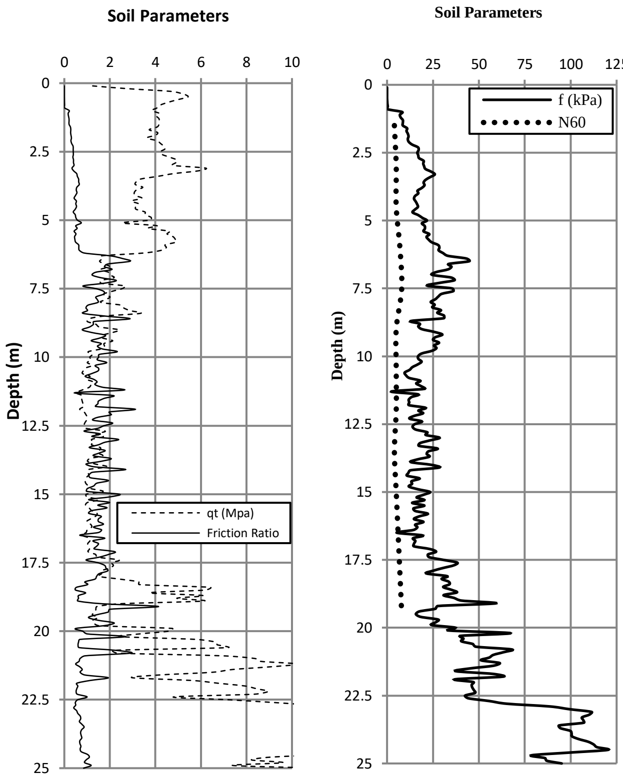

Figure 2 Depth (m) vs. Cone Resistance q_t (MPa), Friction (kPa), N_{60} and Depth vs. friction ration (kPa) at Bramangaon

Table 3 SPT N value and grain size analysis at Ashian City

Depth(m)	Description of Soil	SPT N Value	F_c (%)	d_{50} (mm)
1.5	Filling Sand	4	20	0.16
3		5	21	0.17
4.5	Silty Clay	4	94	0.002
6		3	95	
7.5			96	0.003
9		4		
10.5				
12		7		
13.5	Fine Sand	30	21	0.16
15		36	21	
16.5		42	21	
18	Silty Clay	8	95	0.003
19.5		10	95	

The graph between depth vs friction and cone resistance have been shown in Figure 3. From the CPT test, the cone resistance varies from 0.195 to 7.805 MPa. The maximum value of cone resistance is 7.805 MPa. The minimum value of cone resistance is 0.195 MPa.

Results from grain size analysis of the soil samples have been presented in Table 3. The mean grain size (d_{50}), fine content (Fc) of filling sand varies 0.16 to 0.17 mm, 20 to 21% respectively. The mean grain size (d_{50}), fine content (Fc) of clay varies 0.002 to 0.003 mm, 94 to 96% respectively. The mean grain size (d50), fine content (Fc) of sand is 0.16 mm, 21% respectively. Table 5 shows the probable soil classification using CPT data (Robertson, 1990) at Ashian City.

Table 4 Summary of previous works

No.	Reference	Summary
a.	Seed and Idriss (1971)	a) Significant factors affecting the liquefaction potential of sands during earthquake b) variable field data concerning the liquefaction or non-liquefaction behaviour of sands during earthquakes and compared with evaluations of performance using the simplified procedure.
b.	Seed et al. (1983)	a) Evaluating the liquefaction potential of silty sand deposits (Field data for liquefied or not liquefied during earthquakes in the United States, Japan, China, Guatemala, Argentina, and other countries) using data obtained from standard penetration tests has been reviewed. b) Evaluated the possible magnitude of pore water pressure generation during earthquake shaking. c) evaluating the liquefaction resistance of soils by static cone penetrometer, shear wave velocity, and electrical measurements
c.	Youd and Idriss (2001)	a)In 1996 a workshop sponsored by the National Center for Earthquake Engineering Research (NCEER) was convened by Professors T. L. Youd and I. M. Idriss with 20 experts to review developments over the previous 10 years. b) The following topics have been reviewed and recommendations developed: (1) criteria based on SPT tests; (2) criteria based on CPT tests; (3) criteria based on shear-wave velocity measurements; (4) use of the Becker penetration test for gravelly soil; (4) magnitude scaling factors; (5) correction factors for overburden pressures and sloping ground; and (6) input values for earthquake magnitude and peak acceleration.
d.	Cetin et al., (2004)	a)New correlations for soil liquefaction, b) new correlations are-accumulation of an expanded database (field performance case histories); factors affecting interpretation of SPT data; factors affecting site-specific earthquake ground motions; d) improved methods for in situ cyclic shear stress ratio c)this paper helps to develop magnitude-correlated duration weighting factors, adjustments for fines content, and corrections for overburden stress.
e.	Robertson (2009)	a) Analyzing some case-histories of cone penetration test-based relationships to evaluate the susceptibility to strength loss and liquefied shear strength for a wide range of soils.
f.	Idrissand Boulanger (2008)	a)Fundamentals of liquefaction behaviour for the development and limitations of various engineering analytical procedures; b) methods for liquefaction analysis and use of factors of safety in engineering practice, c) mitigation strategies, and methods for ground improvement; d) Cyclic softening of saturated clays for potential performance of cohesive fine-grained soils.
g	Kumar et al.,(2012)	a) Assessment of liquefaction of soils both in conventional and computational (ANN, NF) methods, using database either from SPT or CPT results.
h.	Sesov et al. (2012)	a)At southern part of Republic of Macedonia the evaluation of the potential of liquefiable soil layers has been done where new industrial complex has been planned to be built, b) assessment of liquefaction hazard at the location with medium to high seismicity and heterogeneous soil condition, c) potential of liquefaction in complex geological condition with high degree of soil heterogeneity.
i.	Ecemis andKaraman (2014)	a)Evaluate the effects of non/low plastic fines on liquefaction resistance at the current CPT liquefaction method. b) Examines the effects of the coefficient of consolidation or drainage characteristics of fine soils (cone penetration resistance)c) coefficient of consolidation depends on fines content and the relative density of the soil d) investigates the contribution of fines content (< 30% by weight) on the liquefaction resistance of soils at different relative densities e) Fines content (>30% by weight) and/or high plasticity of fines can cause additional complications.
j.	Ndoj et al. (2015)	a)CPTU tests (8) at a depth of 20 m, b) soil profiles contain sands, gravelly sands, silty sands and clays b) evaluation of liquefaction in a coastal area of Albania based on the data collected by Piezocone Test (CPTU) and SPT.
k.	Konni (2015)	a)Liquefaction potential has been evaluated based on SPT, N and CPT data in a live project (having 84km offshore artificial island), b) studied the reliability of the data for the liquefaction assessment.
l.	Mirjafari et al. (2016)	a)Correlation developed between tip resistance of CPT test and SDS parameters for soil of different fines contents at Christchurch (New Zealand), b) a chart was proposed which relates the cyclic resistance ratio to the appropriate SDS parameter.
m.	Hoque et al. (2017)	a)Evaluation and comparative analysis of liquefaction potential from SPT and CPT (four pairs) based deterministic relationships which carried out along the river bank of the Jamuna river, Bangladesh (About 85 km from Dhaka city).
n.	Seed and Idriss (1982)	In this paper, the following areas have been covered: a) Liquefaction analysis for the methods for evaluating the potential for under ground motion during earthquake. b) Liquefaction behaviour for a common understanding of the development and limitations of various engineering analytical procedures under ground motion.
o.	Tokimatsu and Yoshimi (1983)	a) Field performance of sandy soil deposits during past earthquakes has been conducted with special emphasis being placed on SPT N-values and fines content, b) field relationship between adjusted dynamic shear stress ratio and normalized SPT N-values together with laboratory tests on undisturbed sands indicate that (1) sands containing more than 10% fines has much greater resistance to liquefaction than clean sands having the same SPT N-values, (2) extensive damage would not occur for clean sands with SPT N_1-values greater than 25, silty sands containing more than 10% fines with SPT N_1-values greater than 20, or sandy silts with more than 20% clay, and (3) sands containing gravel particles seem to have less resistance to liquefaction than clean sands without gravel having the same SPT N-values. c) an improved empirical chart separating liquefiable and non-liquefiable conditions is presented in terms of dynamic shear stress ratio, SPT N-values, fines content, and shear strain amplitude.
p.	Seed et al., (1985)	a)To clarify the meaning of the values of standard penetration resistance used in correlations of field observations of soil liquefaction with values of N_1 measured in SPT tests b) Liquefaction resistance curves for sands with different $(N_1)60$ values and with different fines contents have been proposed.

q.	Rahman et al., (2011)	Dhaka city, the soul of Bangladesh is highly vulnerable to the earthquake disaster (caused liquefaction) due to high density of population, unplanned infrastructure and close proximity with India and Myanmar's active seismic area, poor economic condition, poor emergency preparation and recovery capability.
r.	WASA, (1991)	a) The changing trend of wetlands makes the drainage system of Dhaka City vulnerable and creating water logging problems and b) Land filling and encroachment is the main reasons for shrinking of the wetlands in the city.
s.	Morganand McIntire (1959)	Geological condition of Bengal Basin, East Pakistan and India has been investigated in this research paper. Two areas of Pleistocene terrace border the Bengal basin on the east and west and flank Tertiary and older hills of India. Two large inliers of Pleistocene sediments within the basin are surrounded by Recent flood-plain deposits of the Ganges and Brahmaputra rivers and their combined deltaic plain.
t.	Robertson(1990)	a) A new system has been proposed based on normalized CPT data, b) new charts are based on extensive data (from a 300 m deep borehole with wire-line CPT) available from published and unpublished experience worldwide.
u.	Ansary and Rashid (2000)	a) Susceptibility of liquefaction for Dhaka City Corporation area (150 km^2) has been assessed based on SPT test data from 190 bore holes, b) The liquefaction potential has been evaluated and results have been transformed into a map, which will serve as a general guide to ground-failure susceptibility, effective land use, and efficient town-planning and disaster mitigation and c) first study initiated in Bangladesh as part of the micro zonation investigations.
v.	Iwasaki et al. (1982)	a) Evaluating soil liquefaction potential (based on liquefaction resistance factor, FL and a liquefaction potential factor, PL), b) effectiveness of the method is investigated by calculating the factors FL and PL at both liquefied and non-liquefied sites (Japan earthquakes through shaking table tests).
w.	Ansary and Rahman (2013)	a) Micro-tremor measurements and Subsoil investigations (Standard Penetration Test and Shear Wave Velocity) have been carried out in 45 locations in and around the capital Dhaka city of Bangladesh and b) Soil model (SHAKE) have been developed.

Table 5 Probable soil classification using CPT data (Robertson, 1990) at Ashian City.

Depth Range(m)	I_c Range	Probable Soil Classification
0-3	0.64-1.61	Sand
3-6	1.44-3.25	Sand/Silty clay
6-9	2.84-3.51	Silty Clay
9-12	2.81-3.45	Sandy silt/Silty Clay
12-15	2.28-3.05	Silty sand/Silty Clay
15-18	2.29-3.04	
18-21	0.64-1.61	Sand

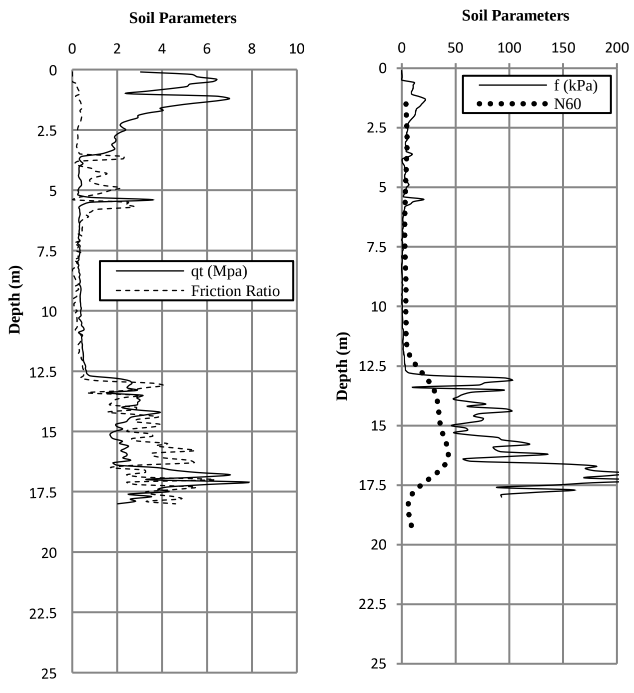

Figure 3 Depth (m) vs. Cone Resistance q_t (MPa), Friction (kPa), N_{60} and Depth vs. friction ration (kPa) at Ashian City

4. LIQUEFACTION POTENTIAL ANALYSIS BASED ON SPT AND CPT

The main objective of this study is to present the liquefaction potential of the selected reclaimed areas. Soil characteristics of the selected reclaimed areas have been determined by field and laboratory tests. Test results have been presented earlier. Liquefaction potential has been estimated using two methods based on CPT (Robertson, 2009) and SPT (Seed et al; 1983) data. The results of these estimations have been presented.

5. GROUND MOTION AND EARTHQUAKE IN AROUND DHAKA CITY

In this research, the value of a_{max} has been taken as 0.15g as Dhaka city exist in the zone 2 of seismic zonation map of Bangladesh (BNBC, 1993). Other researchers (Ansary and Rashid, 2000) also used similar values of a_{max} for the similar purpose as given in Table 4. Though at present the value of a_{max} is being update by various researchers and agencies from 0.15 to 0.2. But it has not been taken to the consideration for this study since it has not been incorporated to BNBC yet. Earthquake ground motion has been influenced by a number of factors. Most important factors are moment magnitude, epicenter distances, local soil conditions, earthquake sources, etc. In Seed-Idriss simplified procedure moment magnitude (M_w) input parameter is also important correction factor. From Table 6, it is seen that ranges of M_w at nearby faults from Dhaka varies 7.5~8.5. However, this value cannot be considered directly for Dhaka since those faults are at quite distant places from Dhaka. Due to non-availability of attenuation law and suitable correlations between distance and ground motion characteristics for Dhaka, the design moment magnitude has been taken 7.5 for this study, which is the lowest value in Table 6.

Bangladesh covers one of the largest deltas and one of the thickest sedimentary basins in the world. According to the report on time predictable fault modeling (CDMP, 2009), earthquake and tsunami preparedness component of CDMP have identified five tectonic fault zones which may produce damaging earthquakes in Bangladesh. These are Madhupur fault zone, Dauki fault zone, plate boundary fault zone -1, plate boundary fault zone -2, and plate boundary fault zone -3. Among these, Madhupur fault zone has been considered as a source of damaging earthquake near Dhaka in this study.

Table 6 Maximum estimated earthquake magnitude in different tectonic faults (CDMP, 2009)

Fault zone	Earthquake events	Estimated magnitude, m_w
Madhupur fault zone	AD 1885	7.5
Dauki fault zone	AD 1897. AD 1500 to 1630 (AD 1548)	8.0
Plate Boundary-1	AD 1762, AD 680 to 980, BC 150 to AD 60, BC 395 to 740	8.5
Plate Boundary-2	Before 16th century	8.0
Plate Boundary-3	Before 16th century	8.3

6. LIQUEFACTION POTENTIAL INDEX (LPI) ANALYSIS

Liquefaction potential based on CPT (Robertson, 2009) and SPT (Seed et al; 1983) data have been estimated. Liquefiable zone is where FS<1, on the other hand non liquefiable zone is where FS>1. The liquefaction analyses results for 10 different locations as described earlier have been presented in Table 7.

Table 7 Liquefaction obtained based on two methods

Sl. No.	Location	CPT Based Liquefied Depth (m)	SPT Based Liquefied Depth (m)
1.	Bramangaon	a)1.5-10	a) 1.5~4.5
2.	Ashian City	a)1.8-3.9 b)12.9-14.4	a) 1.5~3
3.	Badda	a)4.5-5.5 b)8-9.5	a) 1.5~4.5
4.	Banasree	a)0.7-4.8 b)14.4-15.3	a) 1.5~4.5
5.	Gabtoli	a)0.6-5.4	a) 1.5~4.5
6.	Kawran Bazar	a)11.4-12.3	a) 1.5~6
7.	Purbachal	a)1.5-5.0 b)15-15.6	a) 1.5~3
8.	United City	a)3.0-4.5 b)10.5-12.0	a) 1.5~4.5
9.	Uttara	a)2.7-4.8 b)8.7-12.3	a) 1.5~7.5
10	Kamrangirchar	a)1.5-6 b)7.5~12	a) 10.5~11.5

Liquefaction potential index (LPI) has been estimated using Iwasaki et al. (1982) based on CPT data and is shown in Figure 4. The lowest Liquefaction Potential Index (LPI) value for CPT has been found at Kawran Bazar which is 3 and highest value at Bramangaon which is 21. The Liquefaction Potential Index (LPI) ofother sites like Badda, Gabtoli, United City, Ashian city, Uttara, Kamrangirchar, Banasree and Purbachal are 10, 10, 11, 13, 16, 16, 18 and 18 respectively. Based on Liquefaction Potential Index (LPI) for CPT test results, the Dhaka city has been divided in to three zones according to Iwasaki et al. (1982) named low, high and very high as presented in Table 4). The low liquefaction zone has been found at the center position of the study area and spread along the north south direction. The high liquefaction zone has been found in the outer periphery of the study area.

Liquefaction potential index (LPI) has also been estimated using Iwasaki et al. (1982) based on SPT data and is shown in Figure 5. The lowest liquefaction value for SPT has been found at Kawran Bazar which is 1 and highest value at Purbachal which is 28. The Liquefaction Potential Index of other sites like Badda, Gabtoli, United City, Ashian city, Uttara, Kamrangirchar, Banasree and Bramangaon are 10,16, 7, 9, 9, 18,14 and13 respectively. Based on Liquefaction Potential Index for SPT test results, the Dhaka city has been divided in to three zones according to Iwasaki et al. (1982) named low, high and very high. The low liquefaction zone has been found at the center position of the study area and spread along the north south direction. The high liquefaction zone has been found in the outer periphery of the study area.

These results are supported by the Geological Map presented in Figure 1 and past study by Ansary and Rahman (2013) where microtremor survey has also been carried out as described in Table 4.

The similarity of liquefaction potential index map based on CPT (Figure 4) and SPT (Figure 5) data is that for both the cases, low liquefaction zone has been found at the center position of the study area and spread along the north south direction. The very high liquefaction zone has been found in the outer periphery of the study area. CPT based method also show very high liquefaction zone in Northern and North-Western part of Dhaka. High liquefaction zone area is relatively larger for SPT based map.

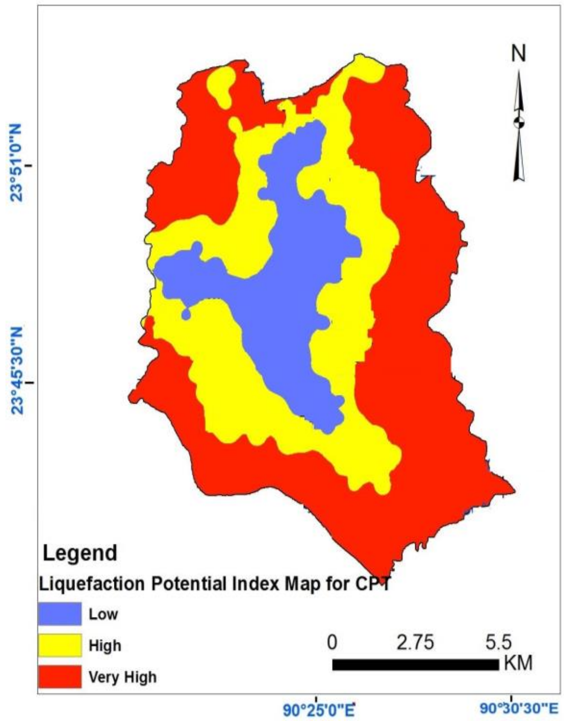

Figure 4 Liquefaction potential index Map based on CPT data

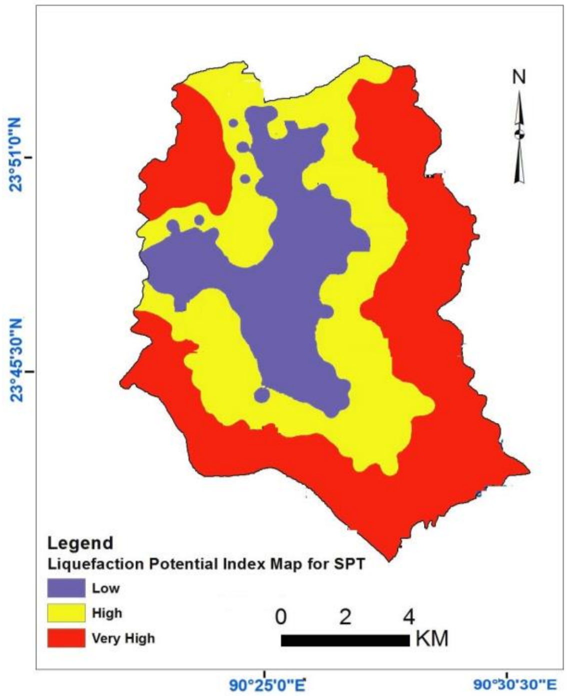

Figure 5 Liquefaction potential index Map based on SPT data

7. CONCLUSIONS

In this research liquefaction potential have been evaluated using procedures based on both SPT and CPT. SPT based evaluation has been carried out by Seed-Idriss Simplified Procedure. Cone Penetration Test (CPT) based evaluation has been carried out by the methods proposed by Robertson. Results of Liquefaction Potential slightly vary in the two methods. One of the reasons of this variation may be due to the process of data collection. SPT N value has been obtained at each 1.5 m interval. On the other hand CPT value has been collected at each 0.01 m interval. This yields a more reliable and continuous CPT data than SPT. Some certain zone of liquefaction which cannot be recognized by SPT clearly has been identified by CPT test results. According to the zonation map of Dhaka city based on Liquefaction Potential Index (LPI),the low potential zone has been found along the center and north south alignment. The high and very high liquefaction zone has been found in the outer periphery of the study area.

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