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PROVISION OF BUILDING CODES IN THE CONTEXT OF SEISMIC SITE CHARACTERIZATION AND LIQUEFACTION SUSCEPTIBILITY ASSESSMENT

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ABSTRACT: Integration of regional code-based provisions considering local site effects and updated analytical techniques is a must in the field of seismic site characterization and liquefaction susceptibility assessment. Aiming to do so, we have introduced provisions of BNBC 2020 to characterize seismic site class and liquefaction susceptibility with the largest database to date and generated vulnerability maps of Dhaka City and classified the areas into different zones considering the potential risk factors. The results show that the geologic age of soil plays a significant role in triggering liquefaction in different areas of Dhaka City and the majority portion of the recent artificial fill areas are subjected to high liquefaction potential for a 7.5 magnitude earthquake. The study also supplements the newly published Bangladesh National Building Code (2020) and provides guidelines according to the code to conduct engineering studies as per recommended seismic site class and liquefaction susceptibility for design considerations following the newly published mandates.

Keywords: Earthquake, Liquefaction, Shear Wave Velocity, Dhaka City, BNBC 2020

1. INTRODUCTION

Dhaka city, the capital of Bangladesh and the most densely populated mega-city of the world, is largely an alluvial plain consisting of fine sand and silt deposits with a shallow groundwater table which triggers factors of soil liquefaction due to earthquakes. The past historical records, coupled with recent low to moderate-magnitude earthquakes near Dhaka, are indications of its earthquake source and vulnerability [1].

Seismic soil liquefaction is a phenomenon of special concern for cities going through a rapid urbanization process where low-lying lands are being filled up with sand as a part of the expansion process. Such phenomena have been recorded and developed in many parts of the world [2,3,4].The process by which a granular material undergoes a transition from a solid state to a liquefied state as a result of an increase in the pore water pressure is referred to as liquefaction [5]. Ground deformation takes place as an aftermath of cyclic mobility due to static and dynamic pressure.

Damages that can be ascribed to the phenomena of earthquake-induced liquefaction have resulted in hundreds of millions of dollars worth of costs for society [6]. Furthermore, most soil improvement techniques are not always feasible for large areas associated with the probability of liquefaction. Hence, accurate soil liquefaction prediction is necessary for safe foundation engineering practices and post-earthquake emergency evacuation design in liquefaction-prone areas.

Liquefaction has been investigated with different methods, including experimental [7,8] and numerical methods [9,10]. However, for our study, we adopted *SPT* [11,12] based evaluation techniques to determine liquefaction susceptibility for different investigation points distributed in different locations of Dhaka City.

For the depiction of seismic site class and liquefaction susceptibility of a specific area, it is not always possible to carry out an investigation at all foundation support locations due to time as well as budget constraints. Therefore, for sustainable land use management using optimal utilization of resources development of digital soil maps have grown in interest amongst the mass in the recent few decades. Many advances were made in soil mapping and cartography in both Europe and the United States, and the soil profile concept was developed [13].

The ability to collect environmental covariates with proximal and remote sensing coupled with spatial statistics and other numerical techniques allowed greater detail in the mapping of soil properties as well as better quantification of those properties [14]. Accordingly, an attempt has been made to interpret liquefaction susceptibility and seismic site characteristics of soils within the boundary of Dhaka City using the latest *SPT*-based empirical equations developed by Cetin [11] coupled with provisions of the newly published Bangladesh National Building Code 2020 [15].

2. RESEARCH SIGNIFICANCE

The current study is the first approach after the publication of the new BNBC 2020 [15] to integrate code-based provisions for seismic site characterization and liquefaction hazard assessment. This research will open new dimensions for the application of site-specific stress reduction factors in the field of liquefaction susceptibility assessment using the latest *SPT*-based deterministic liquefaction evaluation methods. The outcome of the study will also help investors and policymakers of the country to plan for infrastructural developmental works according to classified zones in terms of seismic characteristics and liquefaction vulnerability, which is also expected to contribute to the plan and design sustainable and economically feasible infrastructures in Dhaka City.

3. GEOLOGY AND SEISMICITY OF THE PROJECT AREA

The expansion of Dhaka city has taken space haphazardly in the past few decades, yielding an increased population day by day, with more than 30,000 people residing per square kilometer [16]. About 10% of Bangladesh's population, which contributes 36% of the country's gross domestic product (GDP), lives in Dhaka metropolitan area.

Dhaka City is located close to the seismically active convergent plate boundary between the Eurasian and the Indian plates, where lots of seismically active faults exist. The Himalayan System (product of the Eurasian plate) and Arakan – Indo subduction collision system (product of Indo – The Burma plate) are the two major tectonic systems that have the potential to produce large earthquakes in the Bengal Basin and are expected to cause damage to Dhaka city as well. [17]. Major severe earthquakes that caused severe damage in Bangladesh as per CDMP [18] report is shown in Table 1.

Table 1 Major Seismic events near Bangladesh

Earthquake	Year	Magnitude	Distance
Cachar	1869	7.5	250km
Bengal	1885	7.0	170km
Great Indian	1897	8.7	230km
Srimangal	1918	7.6	150km
Dubri	1930	7.1	250km
Bihar-Nepal	1934	8.3	510km

Apart from the Bengal and Sri-mangal earthquakes, most events had epicenters beyond the 200km buffer zone from the study area. The latest earthquake catalog (from 1762 to 2022) of more than 5 magnitude earthquakes conforms to the claims of seismic activities near the northeast and southeast parts of Bangladesh, which is likely to have a major effect on Dhaka as well. (Figure – 1) Studies carried out under Comprehensive Disaster Management Program [18] also confirm that Dhaka is amongst the highest-risk cities in terms of the severity of the damage. A recent study predicted that in Dhaka City, about 270,604 buildings (83% of the total buildings) would be moderately damaged and out of them, about 238,164 buildings (which was 73% of the total buildings) will be damaged beyond repair for a scenario earthquake of 7.5 magnitudes occurred at a distance of about 50 km far from city center [18].

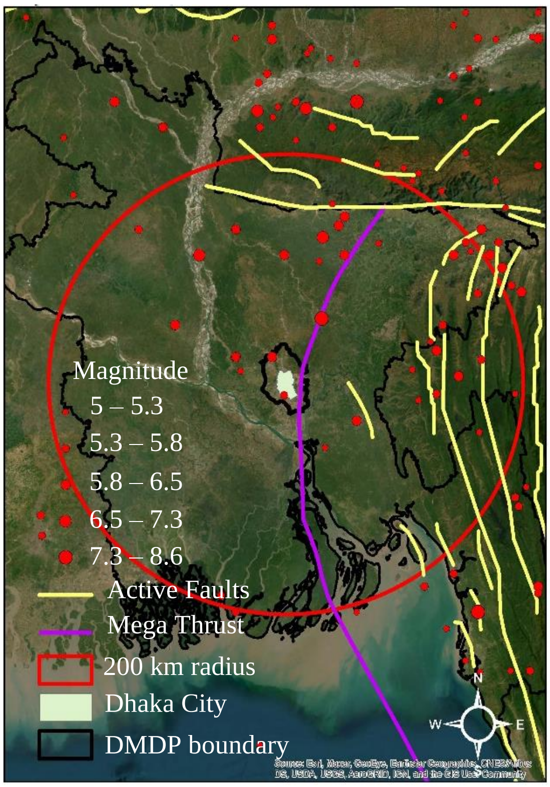

Fig.1 Major Seismic Events and Active Faults near Dhaka City from 1762 to 2022

The majority of Dhaka city is partly on the elevated Pleistocene terrace (Madhupur Terrace), having a maximum elevation of 14 m and partly on the Holocene floodplains having a minimum elevation of 2 m.

Considering geological, geotechnical as well as geomorphological properties, Dhaka can be categorized into six surface geological units, which are as follows: Pleistocene Terrace Deposition (PTD), Holocene Terrace Deposition (HTD), Holocene Alluvium Deposition (HAD), Holocene Alluvial Valley Fill Deposit (HAVFD), Holocene

Alluvial Channel Deposit (HACD) and Artificial Fill (AF) [19] (Figure - 2).

The Pleistocene deposit is the oldest deposit within the city boundary, and it mainly covers the central part of the region. It is mainly composed of yellowish brown to reddish brown, stiff to very stiff clayey silt, silty clay and medium dense to dense silty sand. The Holocene deposit consists of dark grey to grey, very soft to soft silty clay, clayey silt, and grey to yellowish brown, very loose to medium dense silty sand. On the other hand, some low-lying marshy areas near the eastern fringes and outskirts of the city area have been filled with dredged river sand from the nearby river using a hydraulic deposition system. The artificial fill is composed of grey, very soft to soft clayey silt, and very loose to lose silty sand and sand. Considering potential risks due to earthquakes, the artificially filled areas are lying in a danger zone in terms of liquefaction vulnerability.

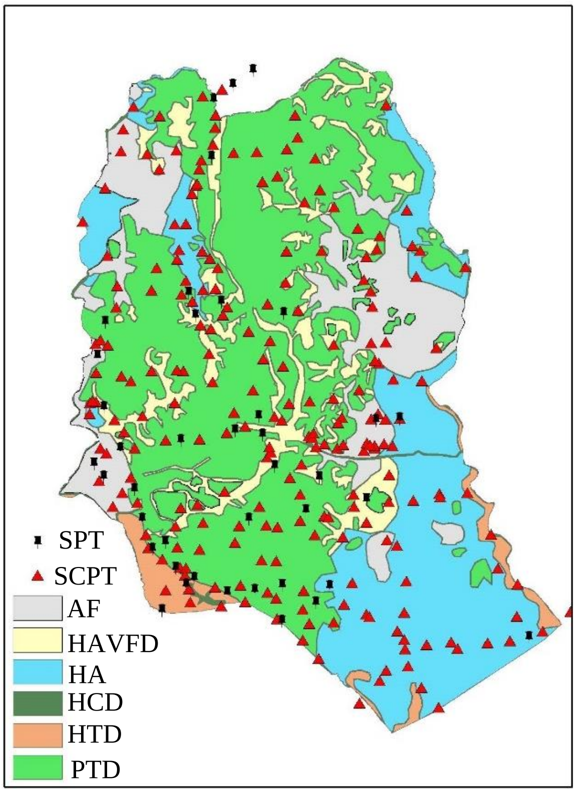

Fig.2 Surface Geology of Dhaka City along with distribution of geotechnical investigation points

4. DATABASE DEVELOPMENT

The dataset used in the current study supersedes previous datasets used in the past [19 - 20] for seismic site characterization and liquefaction hazard assessments. 224 nos. of high-quality *SPT* drilling data where the author's themselves were directly involved were used for the research within the period of 2015 – 2022, which included major ongoing projects such as the Dhaka Metro Rail Project, Dhaka Sub-Way Project, Amulia – Demra Expressway Project, etc. where usage of hydraulic rotary was ensured during the drilling operations. The dataset used by Zillur [20] was also merged with the dataset of recent investigations as a part of the overall upgradation process of the database. The distribution of *SPT* value along depth for the 3063 nos. of data collected from different boreholes is shown in (Figure - 3).

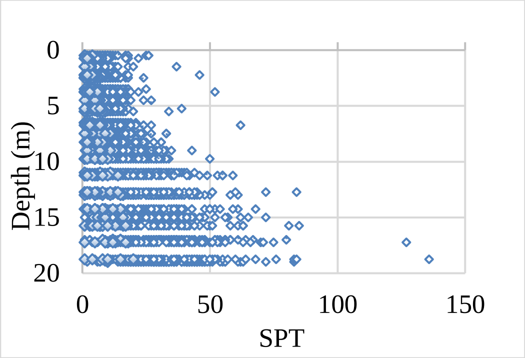

Fig.3 Distribution of SPT along depth (up to 20m)

The statistics of the geotechnical input parameters for the 3063 nos. of *SPT*-based dataset used for the study are presented in Table 2.

Table 2 Statistical description of the dataset

Notation	Min	Max	Mean	SD
SPT	1	136	15.67	14.31
FC	2	100	64.52	33.28
σ'_{vo}	1.12	366.42	107.10	63.67
r_d	0.99	0.72	0.87	0.08

In addition, 40 nos. of Seismic Cone Penetration Test data were included for seismic site characterization based on Vs_{30} evaluation. A scatter plot of shear wave velocity along a depth up to 30m is presented in (Figure – 4).

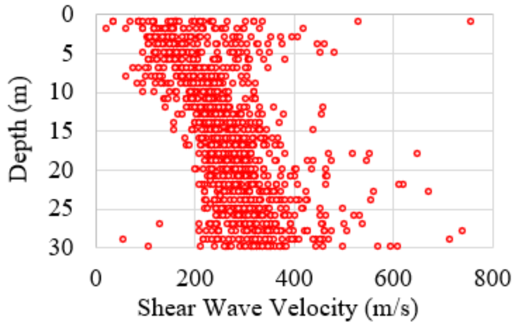

Fig.4 Distribution of shear wave velocity (*Vs*) along depth (up to 20m)

The Seismic Cone Penetration Test is one of the newest multi-measurement tools for field investigation consisting of a seismic sensor for the registration of the shear wave propagation velocity (*Vs*) along with cone resistance, sleeve friction as well as pore pressure. A sample shear wave velocity profile of one of the 40 data record points is shown in Figure – 5.

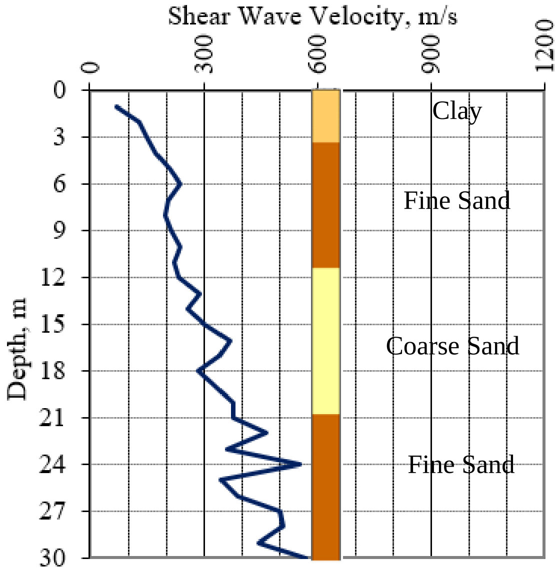

Fig.5 Sample Shear Wave Velocity (V_s) Profile

5. ANALYTICAL APPROACH & METHODOLOGY

5.1 Seismic Site Classification

The current study is an attempt to prepare a seismically induced liquefaction hazard map as well as a seismic site classification map of the Dhaka City Corporation area based on the most updated SPT-based method for liquefaction susceptibility evaluation developed by Cetin [11], integrating it with provisions of BNBC 2020 [15] for assessing liquefaction potential and site classification using shear wave velocity data.

For the evaluation of shear wave velocity, we used Wair's [21] SPT-based co-relationship for specific soil layers up to 30m depth. Accordingly, provisions of BNBC 2020 [15] were utilized for seismic site classification. The correlation suggested by Wair [21] is as follows.

$$\mathrm{Vs} = 30\,\mathrm{N}_{60}{}^{0.215}\sigma_{\mathrm{v}}{}^{0.275} \tag{1}$$

The age scaling factor for Pleistocene and Holocene deposition suggested for the equation is 1.13 and 0.87, respectively.

In addition to the *SPT*-based evaluation of shear wave velocity, additional shear wave data from Seismic Cone Penetration Test conducted for the Dhaka Sub-way project was also included for the estimation of Vs_{30}. Average soil property has been determined by using the following Eq 2

$$\overline{\mathrm{Vs}} = \frac{\sum_{i=1}^{n} \mathrm{di}}{\sum_{i=1}^{n} \mathrm{di/Vsi}} \tag{2}$$

Where, di = soil layer thickness of layer i, n= number of the soil layer in upper 30m and Vsi = Shear wave velocity of i layer

The seismic site class property as per provision of BNBC 2020 using shear wave velocity data of the upper 30m soil layer is as follows: SA for shear wave velocity > 800 m/s, SB for shear wave velocity within the range of 360 - 800 m/s, SC for shear wave velocity within the range of 180 – 360 m/s and SD for shear wave velocity < 180 m/s.

5.2 Evaluation of Liquefaction Susceptibility

For *SPT*-based liquefaction triggering relationships, the load induced by an earthquake (CSR) and resistance against liquefaction (CRR) are variables which compared while evaluating the factor of safety against liquefaction.

$$\mathrm{F_L} = \frac{\mathrm{CRR_{7.5}}}{\mathrm{CSR}} \cdot \mathrm{MSF} \tag{3}$$

For the calculation of the cyclic stress ratio, the following Eq 4 is used.

$$\mathrm{CSR} = \left(\frac{\tau_{av}}{\sigma'_{v_0}}\right) = 0 \cdot 65 \left(\frac{a_{max}}{g}\right)\left(\frac{\sigma_{v_0}}{\sigma'_{v_0}}\right) \cdot r_d \tag{4}$$

Since the inception stages, the stress reduction factor, r_d used for evaluating cyclic stress ratio, went through a lot of upgradations as different researchers used an updated database from time to time and introduced new equations. The stress reduction factor is a site-specific parameter that depends on different factors such as depth, dynamic characteristics of soil as well as ground motion characteristics [22]. For our study, we used BNBC 2020 [15] recommended stress reduction factor considering local perspectives, which is shown in Eq 5

$$r_d = 1 - 0.015\,z \tag{5}$$

Where, z is the depth of the soil column in meters.

Peak ground acceleration value and *PGA* for respective boreholes have been calculated according to the provisions of BNBC 2020. BNBC 2020 characterizes seismic site class based on the estimation of average shear wave velocity, Vs_{30}, for the top 30m of the soil layer. The seismic zone co-efficient (Z) for Dhaka city, according to BNBC 2020 is 0.2, which is the value for a maximum credible earthquake having a return period of 2475 and 2% probability of exceedance in 50 years. The surface *PGA* value considering site amplification scenarios and design basis earthquake considerations have been calculated using the following Eq 5

$$\mathrm{PGA} = \frac{2}{3} . \mathrm{S} . \mathrm{Z} . \frac{\mathrm{I}}{\mathrm{R}} \tag{6}$$

where $\frac{\mathrm{I}}{\mathrm{R}} = 1$ has been considered for free field liquefaction assessment. S has been considered 1.15 for seismic site class SC and 1.35 for seismic site class SD, according to BNBC 2020. Hence, the PGA value used in liquefaction evaluation is 0.15 for locations falling under site class SC and 0.18 for locations falling under site class SD.

Even though past studies considered a moment magnitude of 7 for evaluation of liquefaction susceptibility however, a recent probabilistic seismic hazard assessment carried out suggested that a magnitude of 8.02 [23] may be generated by the Dauki fault on the other faults near the Chittagong Tripura fold belt may generate an earthquake of 8.5[24]. However, for our assessment, we used a magnitude of 7.5 for the estimation of the cyclic resistance ratio, which is also a function of clean sand equivalent (N_{160}) as well as fines content (FC). The following Eq 7 developed by Cetin [11] has been adopted for CRR evaluation.

$$\mathrm{CRR}\left(N_{1,60}, M_W, \sigma'_v, FC, P_L\right) = \exp\left[\frac{\left(\begin{array}{c} N_{1,60}\cdot(1+0.00167\cdot FC) - 27.352\cdot\ln(M_W) \\ -3.968\cdot\ln\left(\frac{\sigma'_v}{P_a}\right) + 0.089\cdot FC \\ +16.084 + 2.96\cdot\Phi^{-1}(P_L) \end{array}\right)}{11.771}\right] \tag{7}$$

where P_L = 50% has been considered for deterministic evaluation.

To assess the damage potential of each site liquefaction potential index (*LPI*) originally proposed by Iwasaki [25,26] was utilized for risk assessment. The *LPI* assumes that the severity of liquefaction is proportional to the thickness of the liquefied layer, the proximity of the liquefied layer from the ground surface, and the amount by which the factor of safety (F_L) is less than 1.

$$\mathrm{LPI} = \int_0^z \mathrm{F(z)} . \mathrm{W(z)} . \mathrm{dz} \tag{8}$$

Where, F (z) = 1 – FS, for FS < 1.0

F (z) = 0, for FS $\geq$ 1.0

W (z) = 10 – 0.5z, for z < 20 m

W (z) = 0, for z > 20

Based on the calculated index values for each borehole, geostatistical analysis was conducted to prepare a continuous map [27,28] to get an understanding of the ground conditions in unsampled locations. Even though different geostatistical [29] methods are used for the preparation of geospatial maps however, for our case, we used the Inverse distance weighting (IDW) method to prepare site Vs_{30}, site classification and liquefaction hazard map of Dhaka City.

6. VALIDATION & PERFORMANCE EVALUATION

For our study, we used a logistic regression model [30] according to the transformed binary results of liquefaction susceptibility into liquefiable and non-liquefiable cases and used the K-fold cross-validation technique consisting of 70% and 30% of the dataset, respectively, for validating the results produced by the latest empirical equation developed by Cetin. Performance evaluation was carried out based on receiver operating characteristics (ROC) analyses which have also been used in the field of geotechnical engineering [31].

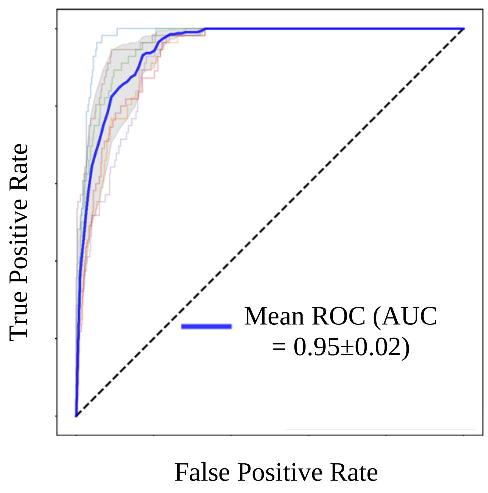

Fig.6 ROC analysis results with K-fold cross-validation

The area under the curve (AUC) value of more than 0.7 is a very good fit for the data. In our case, the mean AUC value for K-fold cross-validation was found to be more than 0.9. Hence, the equation may be considered reliable for evaluating liquefaction susceptibility in the context of Dhaka City.

7. RESULTS AND DISCUSSION

Vs_{30} distribution map (Figure - 7) yielding in a seismic site characterization map of Dhaka City using Vs_{30} following provisions of BNBC 2020 [15] was prepared based on the most updated database containing pertinent geotechnical information to date. The boundaries were delineated considering the Vs_{30} range specified in BNBC2020. The current map (Figure - 7) supersedes the study carried out by

Zillur [19], which was developed according to NEHRP (National Earthquake Hazards Reduction Program, the USA) guidelines and provisions of Eurocode 8 in the absence of local mandates.

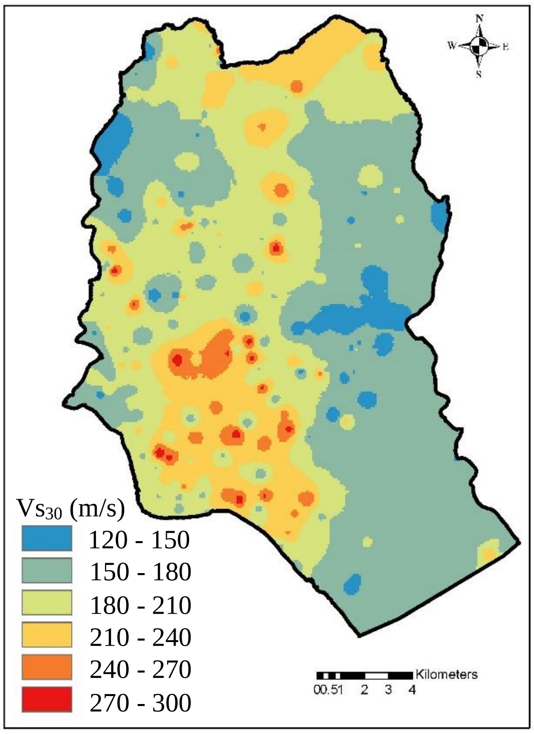

Fig.7 Vs_{30} Distribution map of Dhaka City

In addition, a cumulative frequency distribution curve was plotted considering geotechnical investigation points lying with zones classified as Artificial Fill, Holocene Deposition and Pleistocene Deposition. (Figure - 8)

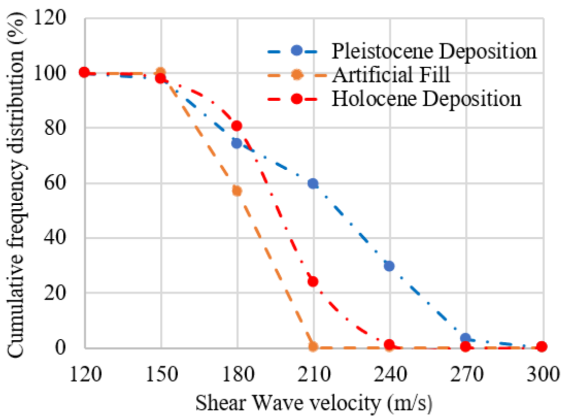

Fig.8 Cumulative distribution plots for Vs30

From the study, it has been observed that the entire study area either falls under seismic site class "SC" or "SD". According to BNBC 2020 [15], seismic site class "SD" should be considered in the design of infrastructures in the absence of adequate site-specific information yielding in surface PGA value of 0.18 according to free field assessment conditions. The seismic site class map (Figure - 9) generated based on Vs_{30} distribution showed that a significant amount of area falls under seismic site class "SD" in the south-eastern parts of the city, which was previously classified as seismic site class "D" as per NEHRP guidelines which is equivalent to site class "SC" according to BNBC 2020.

Considering a threshold value of 180 m/s for shear wave velocity, it was observed that 43% of the sites lying within Artificially filled land fall under seismic site class "SD," whereas the percentage for Holocene and Pleistocene depositions are respectively 19% and 25%.

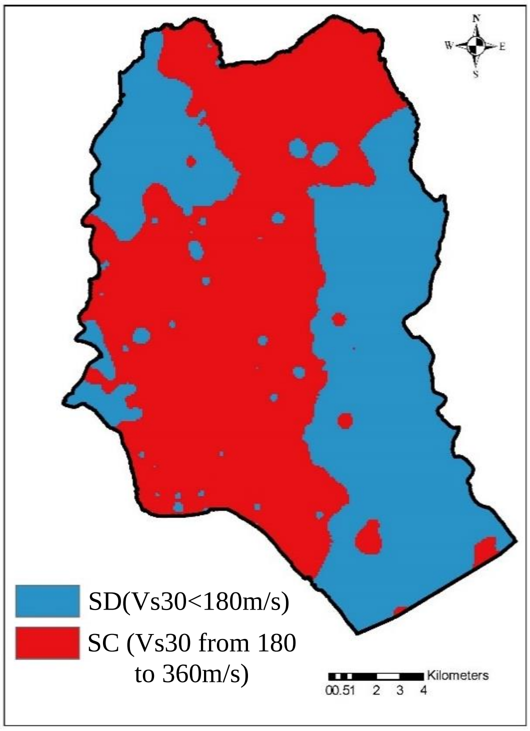

Fig.9 Seismic Site Class of Dhaka City (BNBC 2020)

Based on the liquefaction potential index (LPI) evaluated at each drill-hole location, a map (Figure 10) for delineating LPI in unsampled locations within the domain of Dhaka City boundary was generated. Subsequently, based on Iwasaki's [26] proposed range for very low, low, high and very high susceptibility, boundaries were outlined for each respective zone within the city area. The results showed around 9% of the areas within the city boundary lie in a highly susceptible zone. On the other hand, high, low and very low susceptible zones cover around 32%, 50% and 9% of the city area. Most of the areas underlain by Pleistocene deposition lie within low to very low susceptible areas. At the same time, the areas composed of Artificial fill and Holocene alluvium lie with high to very highly susceptible liquefaction-prone regions.

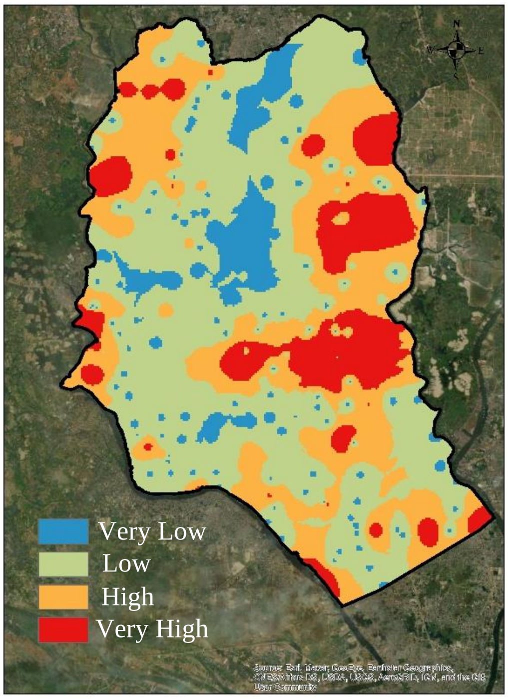

Fig.10 Liquefaction susceptibility map of Dhaka City

Cumulative distribution plots for Liquefaction Potential Index were also plotted for different geological conditions. (Figure - 11)

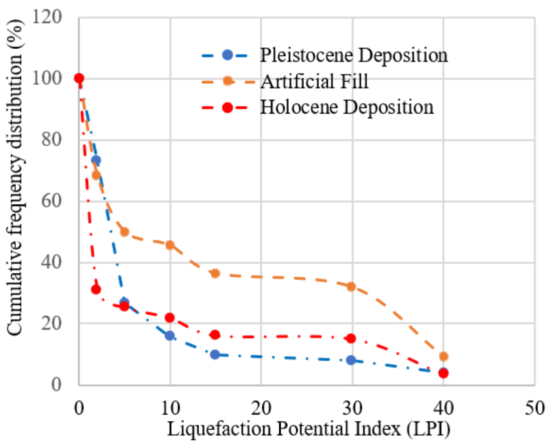

Fig.11 Cumulative distribution plots for LPI

According to Holzer [32 - 33] threshold value for the surface manifestation of liquefaction based on the liquefaction potential index (LPI) is considered 5. The cumulative distribution curve illustrates that 50% of the sites located within the Artificially filled area have LPI values higher than 5. On the other, the percentage is 27% and 22%, respectively, for Pleistocene and Holocene depositions. The investigation points for Artificial Fill, Holocene Deposition and Pleistocene Deposition were 30, 92 and 102 numbers. Even though the liquefaction triggering value for boreholes lying within Pleistocene deposition was slightly higher than the boreholes within the domain of Holocene deposition, it is to be mentioned here that according to Iwasaki [26], zones susceptible to very high liquefaction is considered to have an LPI value of 15 or more. Considering that as a threshold limit for high susceptibility, the percentage of Artificial Fill, Holocene Deposition and Pleistocene Deposition were respectively 36%, 16% and 10%.

8. CONCLUSIONS

The results of the current study show that areas near the eastern fringes of the city area which is also the cross-passage of some major ongoing projects such as Dhaka Metro Rail (Line 1 and Line – 5), Dhaka Amula Demra Expressway, as well as residential development projects in Bashundhara and Aftabnagar, have a liquefaction potential index of more than 15 coupled with a shear wave velocity of less than 180 m/s which may trigger amplification of surface *PGA* value. On the other compared to past studies, the coverage area of seismic site class "SD" is substantially higher within the city boundary, which requires special moment resistance frames for infrastructural development as per BNBC 2020 [15].

Even though the current study paves the way for the utilization of regional stress reduction factors and code-based provisions for seismic site characterization as well as evaluation of liquefaction potential, there are limitations in consideration of the groundwater table, which usually fluctuates due to seasonal variation. On the other hand, areas lying under seismic site class "SD" require special consideration with much more detailed site-specific studies integrating layer-wise dynamic soil properties, which are prospects for future research. Also, continuous upgradation of the maps related to shear wave velocity distribution and liquefaction potential index is envisaged using an updated database with more closely spaced data points for macro-scale analysis.

9. ACKNOWLEDGMENTS

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