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Volume 04, Issue (1), Page: 49-58, 2022

Ministry of Science and Technology

Government of The People's of Bangladesh
Bangladesh Secretariat, Dhaka.

Evaluation of Liquefaction Potential Index and Severity Mapping for Rangpur City Corporation

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Abstract

This paper aims to investigate the Liquefaction Potential Index (LPI) of different Wards and prepare a liquefaction severity map of Rangpur City Corporation. A Liquefaction severity map of a city helps the legislators and policymakers with informed land use planning as well as the development of the town. Disturbed soils from 10 Wards among 33 Wards of Rangpur were collected for different depths in a single borehole. The locations for the borehole were selected based on the seismic soil profile and engineering geology reports available for Rangpur City Corporation in CDMP-II. Standard Penetration Test (SPT) and Microtremor test were done on the field. Then, the Grain Size Distribution test and Liquefaction Potential Index (LPI) were determined for the collected samples in the laboratory. Based on the results of the tests done in the field and laboratory, the severity was classified as moderate, moderate to severe, and severe. Based on the Liquefaction Potential Index (LPI) value, four Wards of Rangpur City Corporation fall within the moderate risk class, three Wards show moderate to severe risk of liquefaction, and the remaining 3 Wards belong to the severe risk class.

Received: 23.07.2022

Revised: 31.03.2023

Accepted: 10.05.2023

DOI: https://doi.org/10.3329/jscitr.v4i1.67368

Keywords: Liquefaction potential index; Standard penetration test; Microtremor test; Severity mapping.

Introduction

Earthquakes are a primary geological hazard that reasons destruction to life and infrastructures. One major discipline of studies, which has caught the attention of researchers, is soil liquefaction capability and the damage from it during an earthquake. When liquefaction occurs, the solid-state of granular soil transforms into the flowable liquefied stage as it is exposed to excess pore water pressure and reduced effective stress during an earthquake. Historically, Bangladesh has experienced some earthquakes, which have caused destruction in the past (Bilham and England 2001). Liquefaction probability becomes higher when the soil is cohesionless, e.g., sandy and loose in density (Noor *et al.,* 2013). GIS mapping is an effective tool for depicting the distribution of liquefaction threats over an area (Ahmed and Shayea 2017). Testing undisturbed soil samples to identify the liquefiable soil is costly, and laboratory conditions cannot reproduce actual field conditions (Abdullah and Abdelaal 2021). Hence, in-situ tests like Standard Penetration Tests (SPT) can be a viable option for determining liquefaction potential. The previous SPT reports of the soil of Rangpur City Corporation and Rapid Visual Surveys (RVS) showed that the land is

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composed of loose sand. Moreover, it was found from previous literature that several earthquakes have hit Rangpur in the past. Though earthquakes cannot be averted, the consequences of the damage can be decreased with proper planning and management. Having previous knowledge of the possible damage and identifying the regions of substantial risk due to earthquakes can reduce the potential damage from catastrophic to moderate. It is essential to point out the possible liquefaction-prone zones of the country and raise awareness against constructing high-rise buildings in those zones. This country's population has increased significantly since last century, and the loss can be catastrophic if attention against the red zones still needs to be raised appropriately. It is necessary to research to enhance the knowledge about the possible hazard and the corresponding damages that can occur due to liquefaction. Transforming potential red zones into a map will serve as a general guide to ground-failure susceptibility, effective land use and town planning, and disaster mitigation. This paper focuses on determining liquefaction and depicting its severity for Rangpur City Corporation using in-situ field tests and laboratory tests. With the help of this research, the preliminary locations of liquefiable soil distribution of Rangpur City can be identified, which will help the legislators and policymakers towards informed land use planning as well as the development of this fast-expanding city.

Study Area Profile

Rangpur is in the northern region of Bangladesh (Longitude: 25.56° North; Latitude: 89.25° East). The Paurashava turned into City Corporation on 28 June 2021 with an area of 205.7 km^2. It is divided into 33 Wards and is expanding rapidly. However, unplanned urbanization has occurred due to poor legislative management and awareness (Islam and Sarker 2016). Along with this, the threat of liquefaction because of earthquakes is present in the area. Previously, earthquakes have been experienced in Rangpur, and the city faced damages, especially during the Great Indian Earthquake in 1897. Old structures and historical buildings had collapsed. The Dhubri Earthquake (1930), with a magnitude of 7.1 and the epicenter at Dhubri, Assam, caused significant damage in the eastern parts of the Rangpur district. Some rail tracks at Rangpur got damaged due to the 1997 earthquake. Fig. 1 shows that Rangpur lies close to the Dauki fault and depicts the location of earthquakes with epicenters near Rangpur.

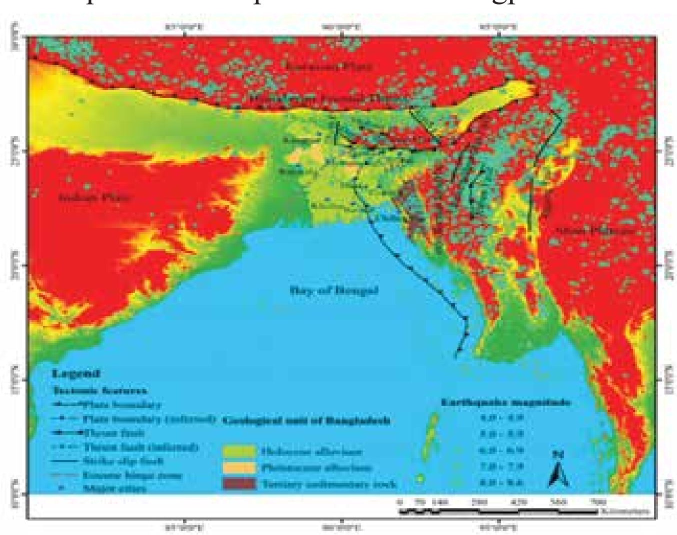


Fig. 1. Seismotectonic map of Bangladesh and surrounding regions showing epicenters of earthquakes (Rahman *et al.,* 2020; Steckler *et al.,* 2016; Kayal *et al.,* 2012 and Alam *et al.,* 1990).

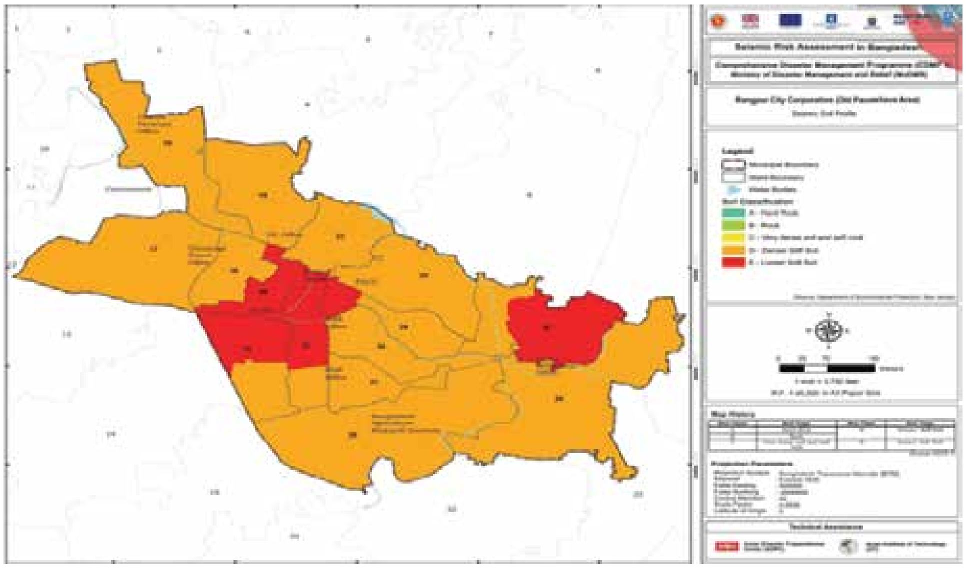


Fig. 2. Soil type of Rangpur City Corporation (Source: CDMP-II).

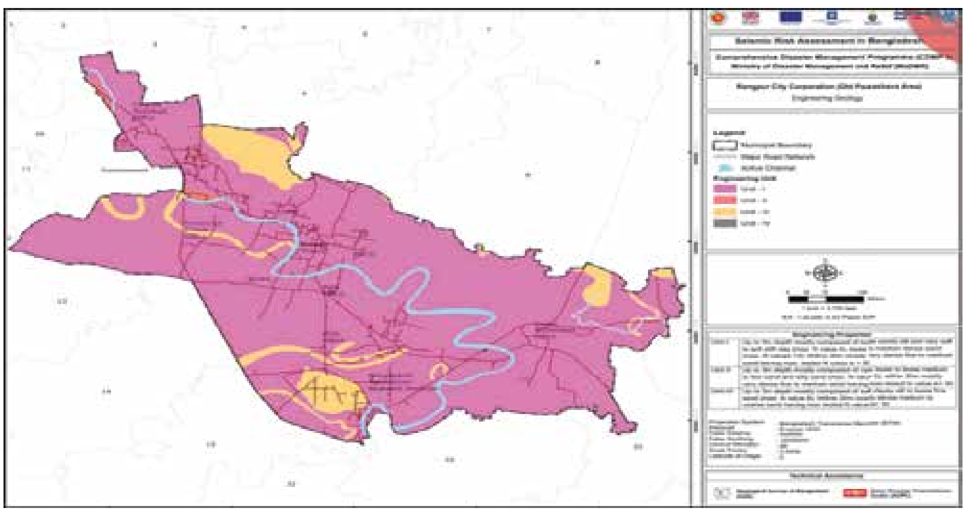


Fig. 3. Engineering geology of Rangpur City Corporation (Source: CDMP-II).

Materials and Methods

Selection of test locations

Initially, the maps prepared by the second phase of the Comprehensive Disaster Management Programme (CDMP-II) were studied to determine the location of boreholes. According to Fig. 2, though five soil classes have been identified, most Wards are either class C or E. As the seismic soil profile was confined within two categories, engineering geology was also considered for the three Wards where two SPTs were performed. In Fig. 3, Rangpur City Corporation shows four different engineering geological formations. Both Ward 18 and 19 are composed of Unit I and Unit III. For these two Wards, points for boreholes have been selected so that 1-point falls in Unit I and the other falls in Unit III. Whereas Ward 16 and Ward 29 mainly consist of Unit I, with a few locations having Unit II. For Ward 16 and 29, all three borehole points were in Unit I. The sites of the remaining six Wards were selected so that the maximum area of the wards and surrounding areas could be covered. After the initial selection of points, field surveys were conducted. Due to the space requirement of the Standard Penetration Test and considering the ease of equipment mobilization, the points were reconfirmed before starting the tests.

In-situ soil tests

Standard Penetration Tests (SPT) have been used as a conventional test to determine the soil profile in ten selected Wards of Rangpur City Corporation. Two standard penetration tests have been conducted in Ward no. 18 and 19. In Ward no. 16 and 29, three standard penetration tests were performed. For the rest of the locations, one test was performed per Ward.

Boreholes were dug, each having a diameter of 100 mm. Disturbed samples have been collected from an interval of 1.5m to 30m for 14 boreholes. Undisturbed samples have also been collected where cohesive soil has been obtained. Two boreholes were supposed to be made of 45m depth. However, as the soil was very dense and the SPT value was 50, the maximum depth explored was 40.5m.

Microtremor test

Site characteristics play a significant part in changing the frequency and amplitude of the motion generated in bedrock. Hence, the natural frequency of soil should be determined along with obtaining the peak ground acceleration value. Three microtremor tests have been conducted in 3 Wards of Rangpur City Corporation, Wards no. 16, 18, and 19. Data has been recorded for 1 hour with a sampling frequency of 100 Hz. Five sensors located 25m apart recorded the ambient ground vibrations in North-South, East-West, and Up-Down directions. Nakamura (1989) developed the Horizontal to Vertical Spectral Ratio (HVSR) approach. It is applied to ambient noise and generates a Fourier spectral ratio of amplitude versus frequency (Ansary et al., 2003). The H/V method is applied to obtain the natural frequency and amplification factor in the locations mentioned. Fast Fourier Transformation (FFT) has been used to transfer the time domain data of each window to frequency domain data. The obtained results have been superimposed with the Chi Chi earthquake (1999), Cyoto earthquake (1979), and Imperial Valley earthquake (1979).

Laboratory tests

Disturbed soil collected from different depths of boreholes has been tested in the laboratory. Ten sieve analyses for soil from different depths were performed for each borehole.

Determination of liquefaction potential index (LPI)

Evaluation of the liquefaction resistance of soils is important for any earthquake-prone region. This simplified procedure was originally developed by Seed and Idriss (1971) using blow counts from the Standard Penetration Test (SPT) is widely used throughout the world where SPT is correlated with a parameter representing the seismic loading on the soil called the Cyclic Stress Ratio (CSR). This parameter is compared to the Cyclic Resistance Ratio (CRR) of the soil, and if it exceeds CRR, the soil is likely to be liquefied. A safety factor against liquefaction is defined as the ratio of CRR to CSR:

$$FL = CRR/CSR * K\sigma * Ka$$

$$CRR = CRR_{7.5(ave)} * MSF$$

Where $CRR_{7.5(ave)}$: calculated cyclic resistance ratio (average of all selected methods at a desired depth) for an earthquake with M = 7.5

For this study, CRR was calculated using the equation proposed by Thomas F. Blake (NCEER workshop, 1997), where CRR is correlated to $N1_{(60)}$. The following curve in Figure 4 is used for calculating the $CRR_{7.5}$. Here $N1_{(60)}$ is the corrected SPT blow count.

MSF: Magnitude Scaling Factor;

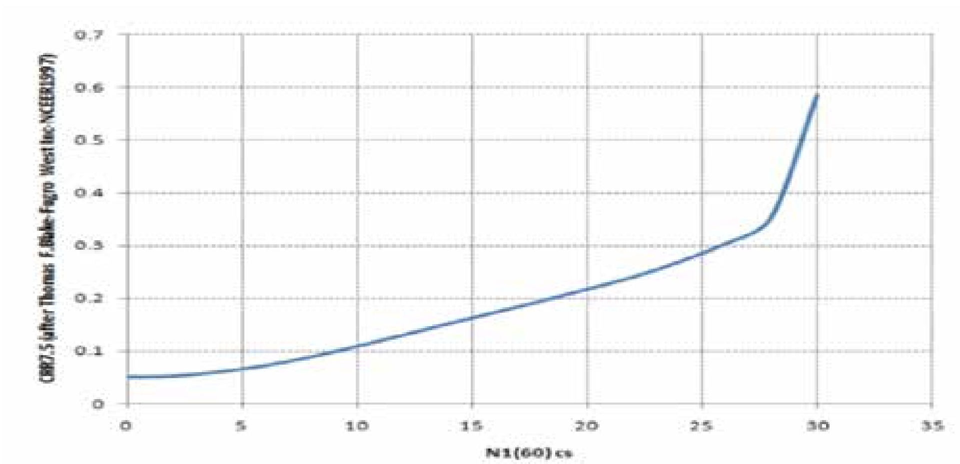


Fig. 4. Proposed CRR 7.5 curve for clean sand

Since the CSR and $CRR_{7.5}$ are provided for earthquake magnitude of 7.5, a Magnitude Scaling Factor should be multiplied at $CRR_{7.5}$ to adjust its value for the target earthquake magnitudes. For this experiment, as the target earthquake magnitude was assumed as 7.5, no MSF value was used.

K_σ: Overburden stress correction factor

K_a:Ground slope correction (was considered 1.0)

CSR: The Cyclic Stress Ratio (CSR), is given by Seed and Idriss' (1982) formula (also known as the 'Simplified' approach):

$$CSR_{7.5} = 0.65\ \left(\frac{\sigma_v}{\sigma_v'}\right)\left(\frac{a_{max}}{g}\right)(r_d)$$

Where:

$CSR_{7.5}$: the cyclic stress ratio with reference to earthquake magnitude of 7.5

σv: Total overburden pressure at the depth considered

σv: Effective overburden at the same depth

amax: Maximum horizontal acceleration at the ground surface

amax= 0.35g was considered for this study. According to the Seismic Risk Atlas (CDPM-II) most of the Wards of this study falls within a PGA value of 0.30g-0.34g. Whereas, a value greater than 0.38g was obtained for Ward 20 and 30.

g: Acceleration due to earth's gravity

r_d: Stress reduction factor

As for this study, the r_d value was calculated using the empirical relation given by (Kayen *et al.,* 1992)

r_d = 1-0.012z; (z represents depth from surface)

If F_L >1 is obtained, this indicates no soil liquefaction will occur. Liquefaction is expected to be experienced if F_L equal to or less than 1 is obtained. Commercially available software has been used to determine the F_L.

The proposed LPI value (Iwasaki *et al.,* 1982) has assumed 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 1.0 (Ansary *et al.,* 2018). From the value of LPI, different risk classes have been obtained, as shown in Table 1. The following are used to estimate the LPI:

$$LPI = \int_0^{20} F(z) W(z)\, dz$$

$LPI = W(z)\, dz$

$F(z) = 1 - F_L \quad for\ F_L < 1.0$

$F(z) = 0 \quad for\ F_L \geq 1.0$

$W(z) = 10 - 0.5z \quad for\ z < 20m$

$W(z) = 0 \quad for\ z > 20m$

z is the depth from the ground surface in meters.

Table 1. Class of risk based on liquefaction potential index

LPI	Risk Class
LPI = 0	Very Low
0 < LPI ≤5	Low
5 < LPI ≤15	Moderate
15 < LPI	Severe

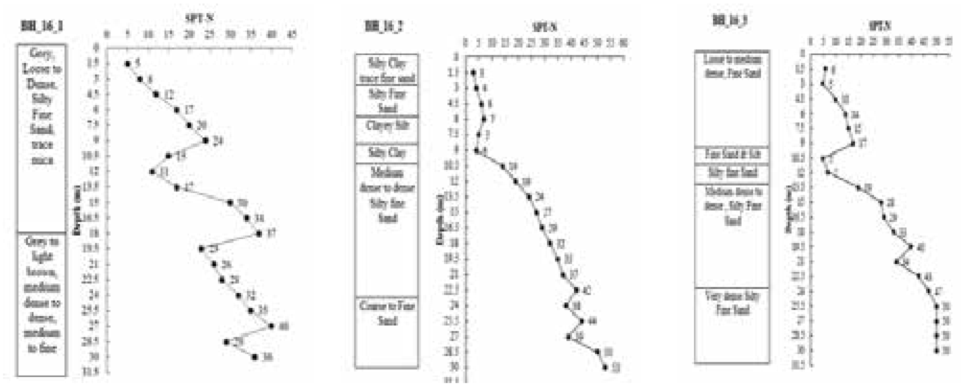
Results and Discussion

Soil profile

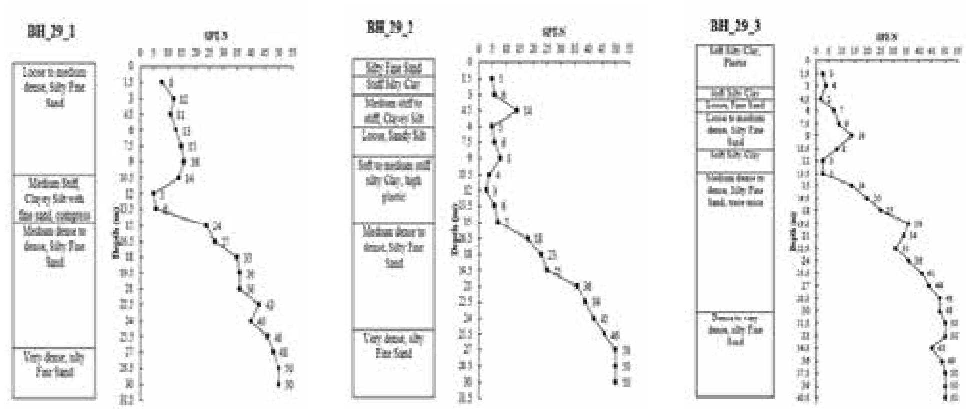
Soil profiles were studied based on the SPT-N profile for each borehole. It was observed that for almost all the Wards up to a depth of nearly 5 to 10 m, the soil profile is mainly consisting of loose to medium sand, then a 1.5 to 5 m depth of stiff silty clay layer, and then a medium dense to a dense silty sand layer of varying depth, and finally very dense silty fine sand layer. Figure 5 represents the sample SPT-N profile of Ward 16 and Ward 29.

Grain size distribution of Soil

Grain Size Distribution of soils at different depths have been calculated to determine the D10 and D60 value, which are required to calculate the Liquefaction Potential Index (LPI) value of the corresponding depth. Figure 6 shows a sample gradation curve of two boreholes at a depth of 9m. Similar graphs have been generated for all 16 boreholes.

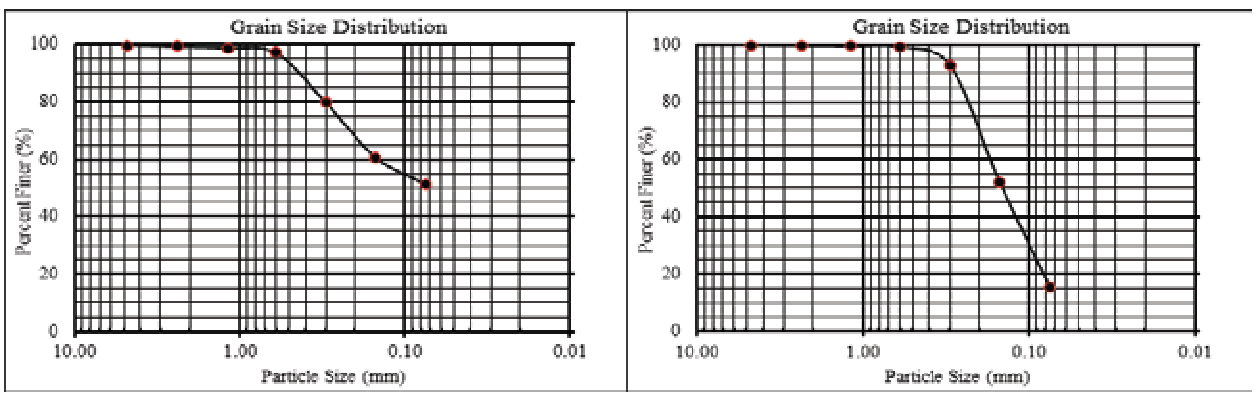


(a)



(b)

Fig. 5. Bore log of (a) Ward 16 & (b) Ward 29



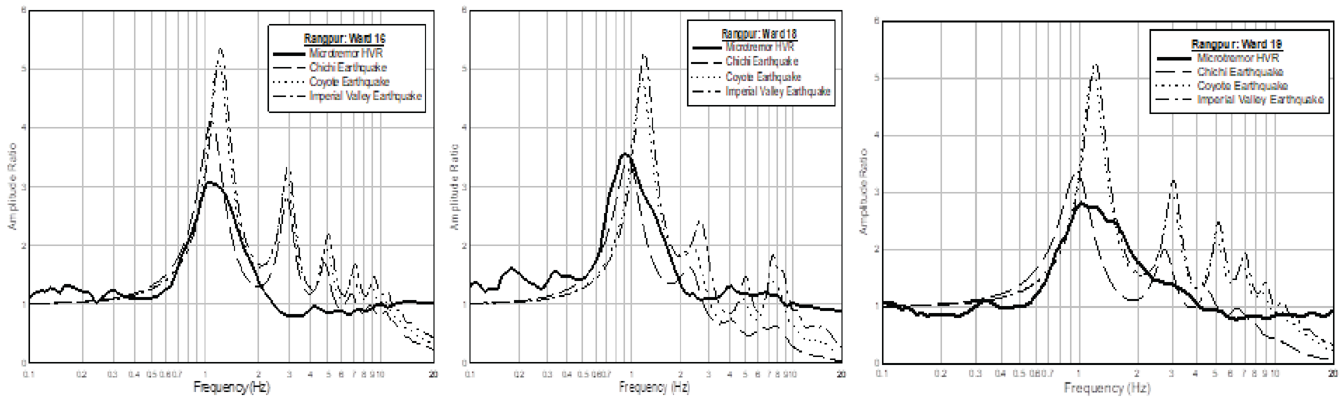
(a) (b)

Fig. 6. Gradation Curve at 9 m depth; (a)BH 16_1, (b) BH 16_2

Natural frequency and peak ground acceleration (PGA) of soil

Figure 7 shows the Amplitude Ratio vs. Frequency graphs, which were obtained from the microtremor results of Ward 16, 18 & 19. The frequency at which the amplitude ratio is the maximum is known as the natural or predominant frequency of the soil. The period corresponding to this is known as the predominant period.

The figure shows that the predominant frequency for Ward 16, 18, and 19 are 1.0 Hz, 0.9 Hz, and 1.0 Hz, respectively. And their predominant period is 1 sec, 1.2 sec, and 1 sec. Thus, if the earthquake motion has a predominant period equal to that of the soil, resonance will occur that will amplify the earthquake motions amplitude and cause massive damage during earthquakes. From the microtremor analysis, the peak ground acceleration (PGA) values have been obtained for three Wards of Rangpur, which are also required to calculate the Liquefaction Potential Index (LPI) value. The values are 0.35g, 0.33g, and 0.36g, respectively, for Ward 16, 18, and 19.



(a) Ward 16 (b) Ward 18 (c) Ward 19

Fig. 7. Amplitude ratio vs Frequency plot; (a) Ward no. 16; (b) Ward no.18; (c) Ward no. 19

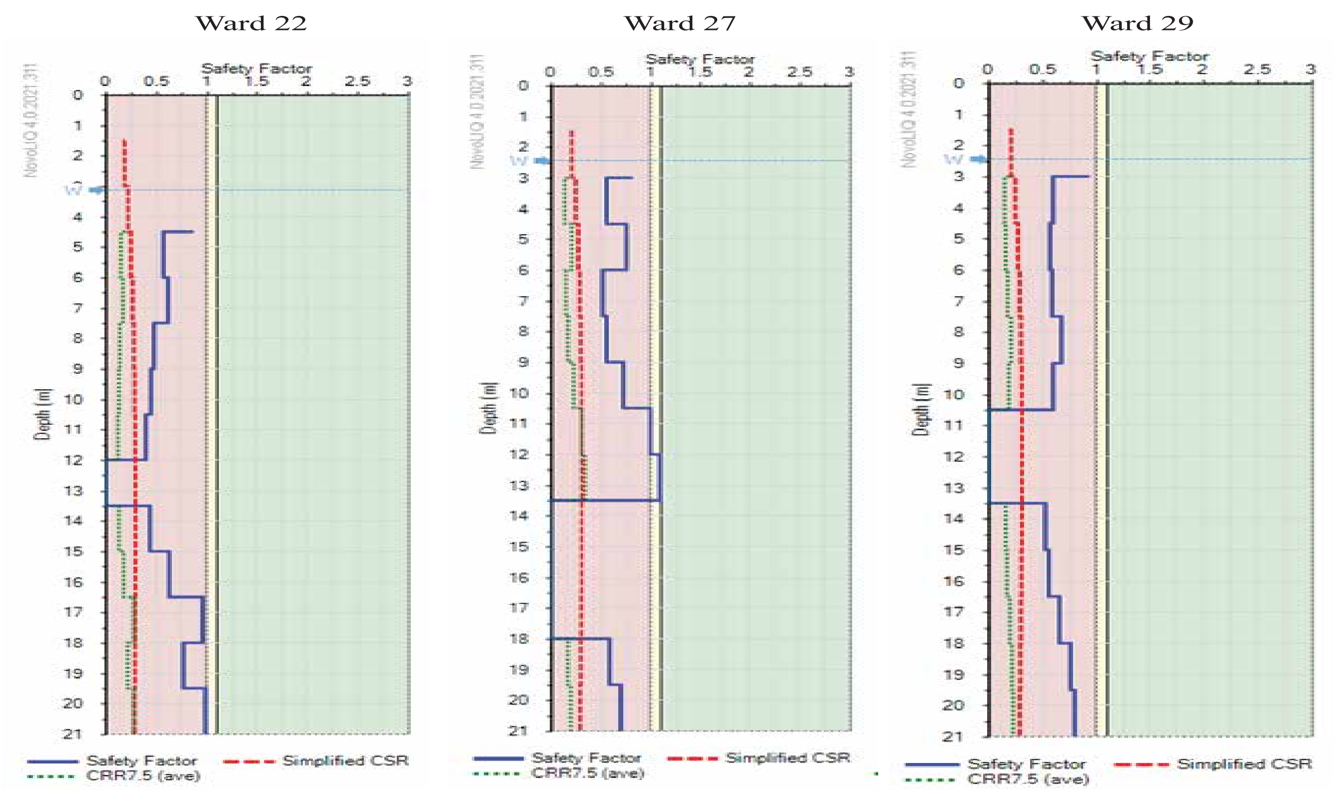


Fig. 8. FL of bore hole for Ward 22, Ward 27 and Ward 29

Liquefaction potential index (LPI)

The safety factor against liquefaction was calculated for each borehole at different depths. Almost all soils from different Wards are susceptible to liquefaction at different depths. Fig. 8 represents three samples of the safety factor derived for Ward 22, Ward 24, and Ward 27.

Severity mapping

Fig. 9 shows the map of all ten Wards' liquefaction risk classes. Thus, among all the ten Wards, based on the Liquefaction Potential Index (LPI) value, four Wards fall within the moderate risk class, three

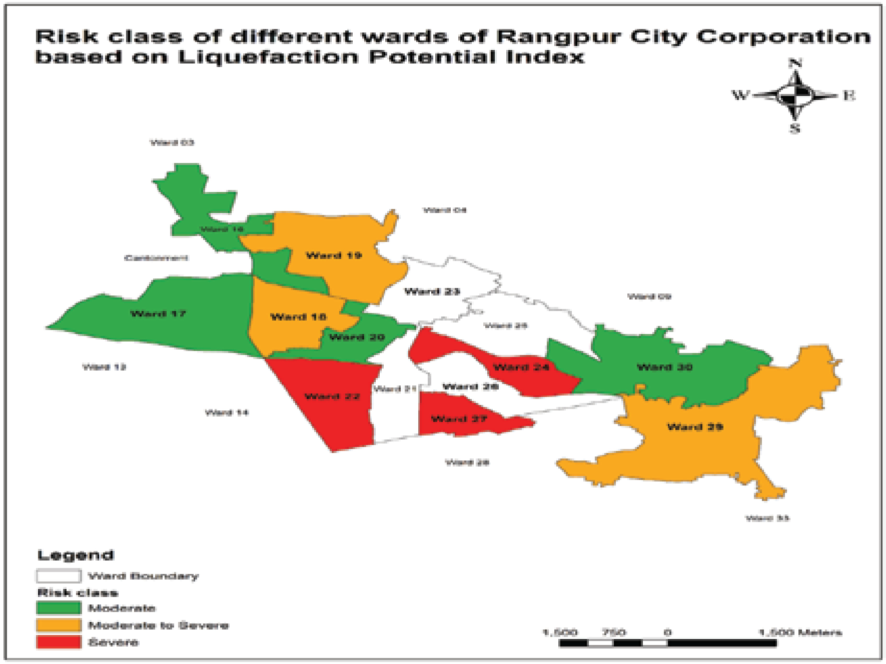


Fig. 9. Risk class of ten studied Wards based on LPI values

Wards show moderate to severe risk of liquefaction, and the remaining three Wards belong to the severe risk class.

Conclusions

This paper shows the liquefaction potential against ground shaking during an earthquake for Rangpur City Corporation based on in-situ soil testing and analysis from 10 different wards. The observation of this study has been shown by a map that depicts the classes of severity based on liquefaction potential. According to this study, it is a matter of concern that most of the places under this study of Rangpur City Corporation are very likely to liquefy during an earthquake. Further study needs to be conducted on the remaining wards of Rangpur City Corporation to get a comprehensive picture of the liquefaction susceptibility, which may also help generate micro-zonation maps.

Acknowledgement

The authors are grateful to the Special Research Grant 2020-2021 of the Ministry of Science and Technology (MoST), Bangladesh (SI. No. 427, Engineering and Applied Science) for their financial support to continue this research.

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