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TECHNICAL NOTE

Liquefaction Assessment of Rajshahi City Corporation, Bangladesh

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Abstract Rajshahi City Corporation (RCC) has been marked as a geologically vulnerable in terms of earthquake. However, no scientific method has been determined to figure out the influencing factors. This is the first approach to detect the vulnerability of RCC area. In this point of view, the liquefaction hazard map has the innate power to evaluate the potentiality of earthquake-prone areas. The liquefaction map was prepared using sixty borehole profiles data among 30 wards of RCC. The most widely popular Seed's method (1971) is employed to calculate liquefaction potential index (LPI) using an earthquake scenario of magnitude M7.0 with peak ground acceleration of 0.12 g (BNBC 2010 draft version). Based on LPI value, Rajshahi city area has been divided into four different liquefaction severity categories (i.e., very low, low, high, and very high) and finally mapped through ArcGIS for the complete visualization. This initial study might be helpful for engineers and planners to plan and execute different structural scheme in this region. This paper also summarizes the calculation procedure of determining LPI from available literature to build up a single framework.

Keywords SPT-N · RCC · Seed's Method · Factor of Safety · Liquefaction Potential Index · Arc GIS

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Introduction

Earthquake is one of those natural catastrophic disasters that can cause immense damage to structures and people within a short period of time. The world's most massive earthquake which has been recorded on 22 May 1960 in Southern Chile named "Great Chile Earthquake" with a magnitude of 9.5, snatched away many lives from Hawaii, Japan, and Philippines [1]. Liquefaction is an important parameter associated with earthquake event, and it is an important tool to assess earthquake hazard. Assessment of liquefaction is based on different parameters such as SPT-N value, CPT value, Shear Wave Velocity (SWV) value and Becker Penetration Test [2]. Several Methods were introduced already to evaluate liquefaction by analytically: (1) Seed's method- modified [2] (2) Tokimatsu and Yoshimi (T–Y) method [3] (3) Japan Road Association (JRA) method [4] –new version (4) Chinese Code for Seismic Design of Buildings (CSDB) method [5] (5) Semi-empirical procedure [6] (6) Probabilistic and deterministic assessment [7] (7) Shear Wave Velocity (SWV) method [8] (8) Multi-channel analysis of surface wave method (MASV) [9] (9) Arias Intensity Approach [10]. Another way was proposed to evaluate liquefaction as liquefaction severity index (Ls) [11] and also introduced a threshold value of factor of safety of 1.2 rather than having 1

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[12, 13]. Measurement of shear wave velocity is not economically feasible at all so that the correlation of uncorrected SPT-N value and shear wave velocity were listed in many journals [14, 15]. Based on the SPT-N value, the most efficient method to assess liquefaction potentiality is Seed's method [16] which has been modified and refined in step by step by many researchers [2, 17–24].

However, Liquefaction is such a determinant by which it is known how much damages can be done for the earthquake to a state or an area. This study has followed the idea of using uncorrected SPT-N value to determine liquefaction potential index (LPI) value [25]. The event liquefaction has some specific mechanism by which it can occur during or just after earthquake. Due to cyclic shear deformations, granular materials continue to be stressed, and as a result, pore water pressure increases within the granular materials. As a result of the subsequent increase in pore water pressure due to earthquake shaking and loading, granular materials get converted from solid state to liquid state and with that increase in pore water pressure, the effective stress of the granular materials is reduced to zero which is termed as liquefaction [26]. Dissipation of excess pore water pressure may also be responsible for occurring sand boils. The process of sand boils can be a mechanism contributing to liquefaction during an earthquake.

Historical earthquakes which have occurred in Bangladesh and North-East (NE) India are enlisted in Table 1 [27]. Bangladesh is being suffered the colossal loss of lives, infrastructures for these destructive earthquakes enlisted in the table. For the Great Indian earthquake of 1897, most of the private and public houses were severely destroyed.

A significant number of research works have been already performed on different region of Bangladesh considering earthquake, especially for liquefaction hazard map using GIS [25, 28–30], while a very limited (we can say there are almost no) published articles are available on the liquefaction assessment of Rajshahi City Corporation, Bangladesh. In this study, the authors have tried to focus on the liquefaction assessment of RCC using Seed's relation which is mostly utilized for site characterization regarding soil liquefaction. As a first approach to introduce liquefaction evaluation and susceptibility for RCC, Bangladesh will get a novel idea to modify the building code to construct infrastructure in this specific region. This paper also highlights the comprehensive review of the calculation procedure available on the literature and summarizes them in a single framework.

Table 1 Record of historical earthquakes in Bangladesh and NE India

Date	Name of the earthquake	Magnitude (Richter Scale)
10-01-1869	Cachar Earthquake	7.5
14-07-1885	Bengal Earthquake	7.0
12-06-1897	Great Indian Earthquake	8.7
08-07-1918	Srimangal Earthquake	7.6
02-07-1930	Dhubri Earthquake	7.1
15-01-1934	Bihar–Nepal Earthquake	8.3
15-08-1950	Assam Earthquake	8.5

Geology and Geomorphology

Rajshahi city is a major urban, commercial and educational center in the north region of Bangladesh and lies at 24°22′26″N 88°36′04″E geographically. The metro city of Rajshahi covers an area of 900 square kilometers with a population density of 1070 per square kilometers. Out of this 900 square kilometers area, Rajshahi City Corporation (RCC) has an area of 96.68 square kilometers with population of approximately 2.5 million and annual population growth rate of roughly 1.25%. The selected 60 borehole data are enough to evaluate the potential liquefaction hazard of RCC area which has been discussed in detailed in the next section. Geographically, Rajshahi city is located in Barind tract and Bengal basin region. It has been identified as a segment of old alluvium which has no resemblance with the surrounding floodplains. The subsurface strata consist of sandy soil and fine sand with a variation in water content of about 30–35%. The soil deposit in the Barind tract is gray to light brownish gray which is composed of silty loam, sand, fine sand, and silty clay [31]. The study area of this research is shown in Fig. 1.

Seismotectonics

In consideration of geological site and tectonics of Bangladesh, five fault zones have emerged which are active enough in causing earthquake damages [32]. Bangladesh is covered by active fault zone such as Indian Plate, Furasian Plate and Bogra fault [30]. Despite having these zones, there are several thrust lines which may result in earthquake. In consideration of characteristics of fault, length of fault and record of earthquakes, etc., Bogra fault zone which has maximum earthquake magnitude of about 7.0 in Richter scale [33] and this district lies within Rajshahi Division. To calculate the factor of safety and further liquefaction potential index, peak ground acceleration (PGA) plays a pivotal role. The seismic zoning map along with peak ground acceleration of different zones is shown in Fig. 2.

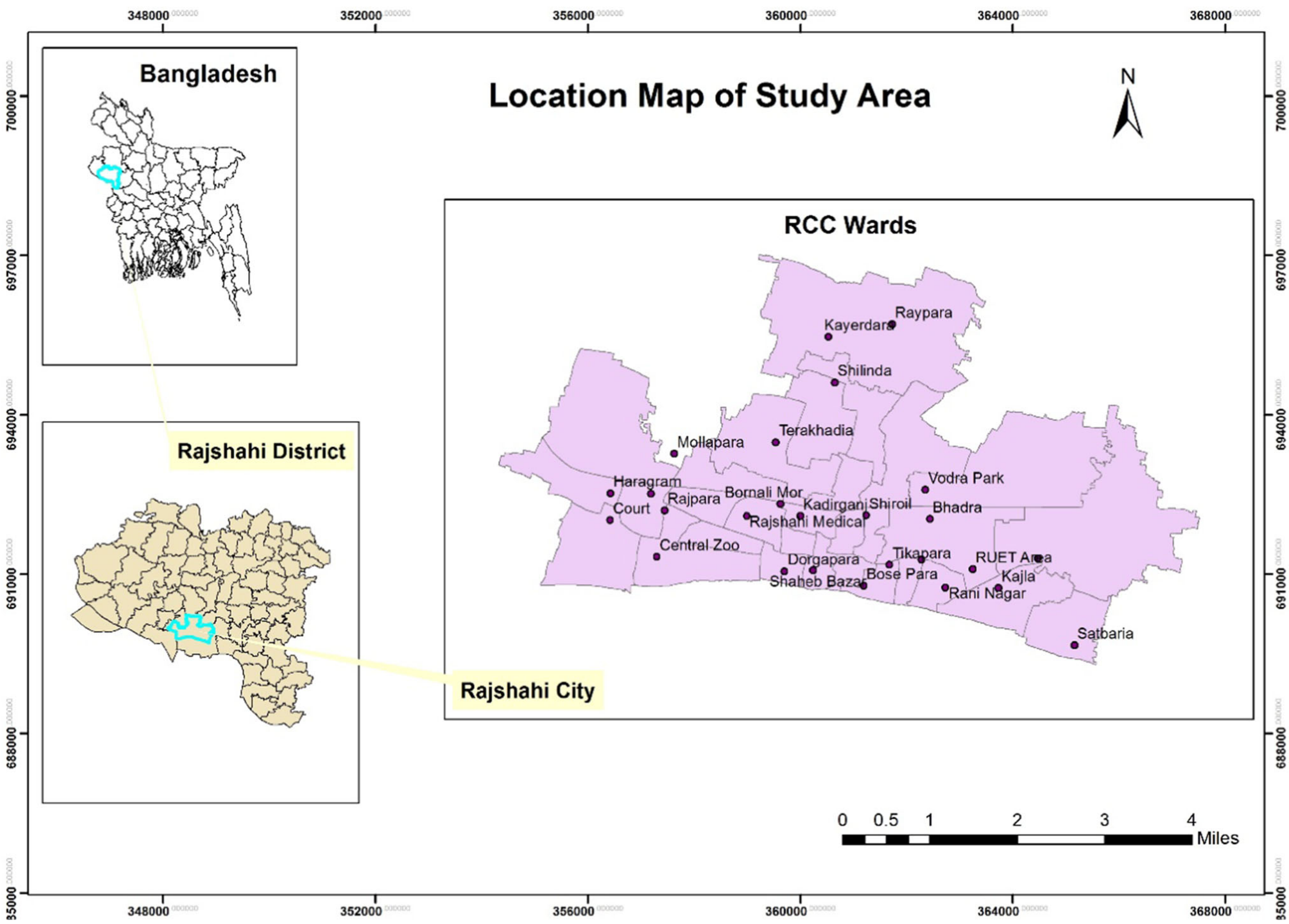

Fig. 1 Map of the study area

The first Bangladesh National Building Code (BNBC) was developed in 1993, and it has updated to its latest version in 2017 after going through several amendments. In this study, BNBC-2010 (draft version) [34] is adopted for the zone coefficient which is called peak ground acceleration (a_{max}). According to BNBC-2010 (draft version) [34], Bangladesh is divided into four regions i.e., Zone-1, Zone-2, Zone-3 and Zone-4 with zoning coefficient of 0.12, 0.20, 0.28 and 0.36, respectively. Among these four zones, Rajshahi is located in Zone-1 which has zoning coefficient of about 0.12.

Evaluation of Liquefaction Assessment

There are numerous research articles in which standard penetration test (SPT) results have been successfully utilized for the assessment of liquefaction potential [2, 6, 13, 14, 16, 20, 21, 24, 35]. These literatures have motivated the authors of this research paper to apply same idea in this study. Rajshahi City Corporation has a total number of 30 wards. Two boreholes (BH) from each ward with total 60 BH are taken into account to conduct investigation of liquefaction potential assessment. SPT value is easily and readily available, and from SPT, it is very flexible to determine liquefaction potential from SPT value by going through some simple mathematical calculations by Microsoft Excel software. In the study, 60 BH along with other geotechnical properties (water content, density, specific gravity) of RCC was used to compute the factor of safety against liquefaction using Seed's Method (1971). Then, the factor of safety is employed to calculate LPI for every BH location to produce liquefaction hazard map. The BH locations and coordinates are shown in Fig. 3 and Table 4, respectively. For this study, Ground Water Table (GWT) level is considered at approximately 3 m from the ground level (GL) as the ground water fluctuates near Rajshahi City Corporation area from 2 m $\sim$ 6 m [36, 37].

Cyclic Stress Ratio, CSR

Cyclic stress ratio, CSR is generally expressed for the seismic demand of the soil layer. CSR is a functional term

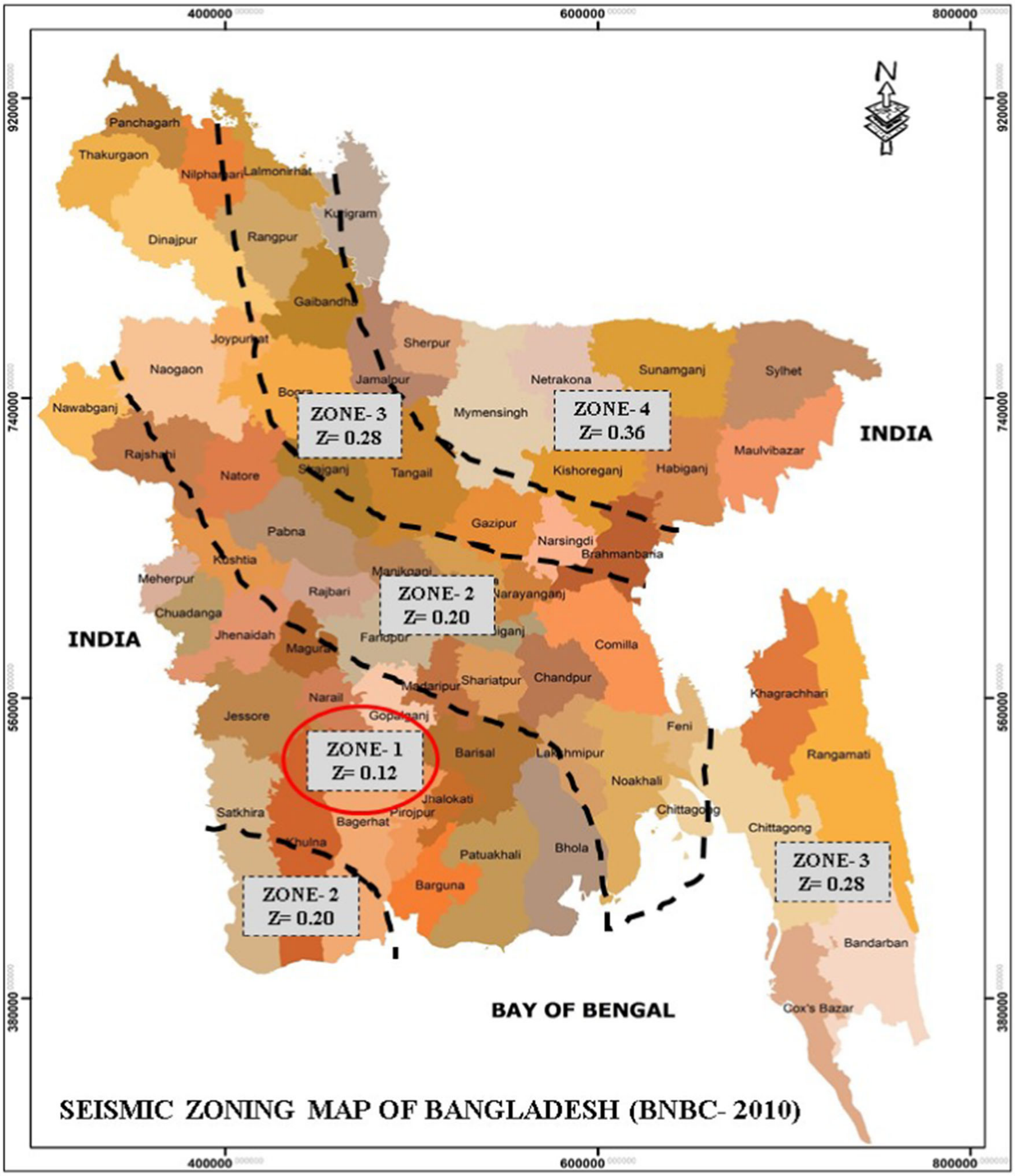

Fig. 2 Seismic zoning map of Bangladesh

of peak ground acceleration, the acceleration due to gravity, total and effective overburden stress and stress reduction factor. The following expressions can determine the cyclic stress ratio at different depths of soil depositions:

$$CSR = 0.65 \frac{a_{\max}}{g} \frac{\sigma_v}{\sigma_v'} r_d \tag{1}$$

where 0.65 is a weighting factor which is used to convert peak cyclic stress ratio to cyclic stress ratio, a_{max} is the peak ground acceleration (PGA) which is generally expressed as a function of acceleration due to gravity, g is the acceleration due to gravity, σ_v and $\sigma_v^{'}$ are the total overburden stress and effective overburden stress, respectively, which deal with depth of the soil layer and unit weight of the soil layer, r_d is the stress reduction factor and M is the earthquake magnitude. Equation 1 [16] is used for the method of Seeds.

The expression for the determination of the stress reduction factor, r_d is given by the following equation:

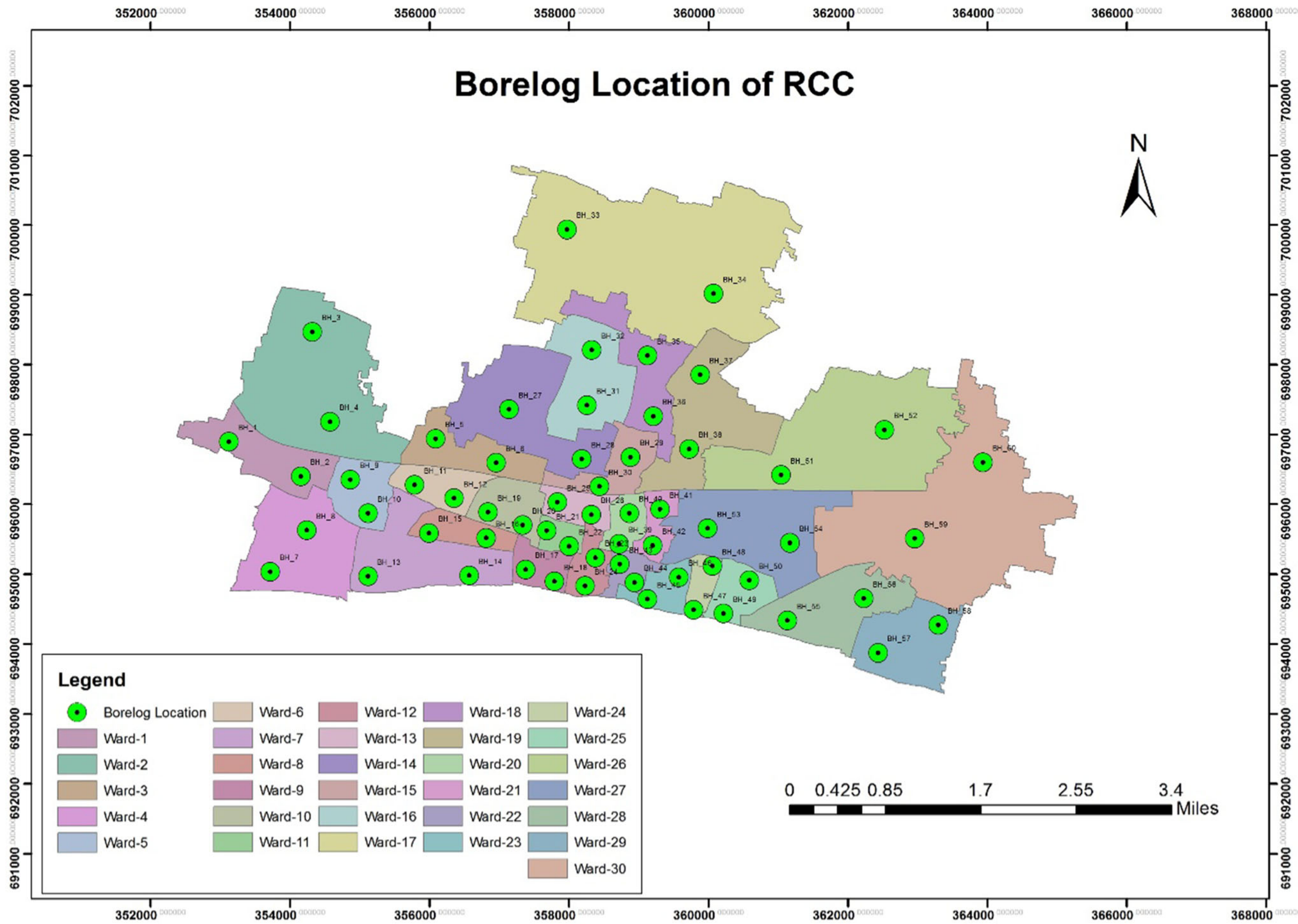

Fig. 3 Showing borehole locations in this study area

$$r_d = 1 - 0.00765z\,(z \leq 9.15m) \quad (2)$$

$$r_d = 1.174 - 0.0267z\,(9.15 < z \leq 23m) \quad (3)$$

$$r_d = 0.744 - 0.008z\,(23 < z \leq 30m) \quad (4)$$

$$r_d = 0.5\,(z > 30m) \quad (5)$$

where z is the depth of the soil layer in meter, m. The first, second and fourth formula of Eqs. 2, 3 and 5 were developed and recommended by Youd, and Idriss [23], and the third formula is given by Robertson and Wride [22].

Cyclic Resistance Ratio, CRR

Cyclic resistance ratio, CRR represents the ability to resist liquefaction. Equation 6 [38] is taken in this study for Seed's Method (1971).

$$CRR_{7.5} = \frac{a + cx + ex^2 + gx^3}{1 + bx + dx^2 + fx^3 + hx^4} \quad (6)$$

where $x = N_{1,60,FC}$, $a = 0.048$, $b = -0.1248$, $c = -4.721E - 3 \neq$, $d = 9.57E - 3$, $e = 6.136E - 4$, $f = -3.285E - 4$, $g = -1.673E - 5$, $h = 3.714E - 6$.

Here, the term $N_{1,60,FC}$ is a combination of corrected SPT-N number with two coefficient of αandβ which are dependent on the fines content. This is to keep the diagnosis short and to make calculation easier, we assume the fines content less than 5% for our research.

Magnitude Scaling Factor, MSF

Earthquake magnitude of about 7.5 is only applied for the analysis of the clean sand or CRR curves. Since there was minimal field data for the liquefaction in the 1970s, Seed and Idriss [17] introduced a scaling factor which is applicable for any magnitude less than or greater than 7.5. For the analysis of the Seed's Method (1971) MSF is taken from the equation of revised MSF which given by the following equation:

$$MSF = \frac{10^{2.24}}{M_w^{2.56}} \quad (7)$$

Here, Mw is the earthquake magnitude.

More recently, Idriss [39] revised two more equations (Eqs.) for the MSF. The equations are defined by:

Table 2 Liquefaction severity level

LPI	Iwasaki et al. (1982)	Luna and Frost (1998)	MERM (2003)
LPI = 0	Very low	Little to None	None
$0 < LPI \leq 5$	Low	Minor	Low
$5 < LPI \leq 15$	High	Moderate	Medium
LPI > 15	Very high	Major	High

$$MSF = 6.9\exp\left(\frac{-M_w}{4}\right) - 0.06\ \text{for}\ M_w \geq 5.2 \quad (8)$$

$$MSF = 1.82\ \text{for}\ Mw \leq 5.2 \quad (9)$$

Here, Mw is the magnitude of the earthquake.

Factor of Safety (FS)

The factor of safety is generally used for the assessment of liquefaction susceptibility of any area. It is given as like the following relation:

$$FS = \frac{CRR}{CSR} \quad (10)$$

FS is the easiest way to quantify liquefaction susceptibility, and it depends upon the *CSR* and *CRR* which are varied with soil depth, ground water table depth, unit weight of soil profile, earthquake magnitude and peak ground acceleration. *FS* greater than or equal to unit indicates non-liquefiable soil layer, whereas *FS* less than unit implies liquefiable soil strata.

Liquefaction Potential Index (LPI)

Generally, *FS* is used for the assessment of liquefaction, but it is not the final parameter for the assessment. In this regard, another parameter is introduced which is liquefaction potential index (LPI) [18, 19]. The determining equation is developed in two forms [18, 19, 40] which are applied everywhere for the liquefaction assessment. The liquefaction potential index (LPI) is developed by [18, 19] is given by the following equations:

$$LPI = \int_0^{20} F(z).w(z)dz \quad (11)$$

This equation is valid up to 20 m soil layer. Here, z is the midpoint of the soil profile and $w(z)$, and $F(z)$ are the weighting factor and the severity factor, respectively, which are calculated as per following expressions:

$$F(z) = 1 - FS \quad \text{for}\ FS < 1.0 \quad (12)$$

$$F(z) = 0 \quad \text{for}\ FS \geq 1.0 \quad (13)$$

$$w(z) = 10 = 0.5z \quad \text{for}\ z < 20\ m \quad (14)$$

$$w(z) = 0 \quad \text{for}\ z > 20\ m \quad (15)$$

The calculation equation is explained in the following terms [40]:

$$LPI = \sum_{i=1}^{n} w_i F_i H_i \quad (16)$$

where

$$F_i = 1 - FS_i \quad \text{for}\ FS_i < 1.0 \quad (17)$$

$$F_i = 0 \quad \text{for}\ FS_i \geq 1.0 \quad (18)$$

where *H*i is the thickness of the discretized soil layers; *n* is number of layers; *Fi* is liquefaction severity for ith layer; *FSi* is the factor of safety for ith layer; wi is the weighting factor (= 10–0.5 zi); and *zi* is the depth of i-th layer (m).

Based on the quality of LPI value, severity of liquefaction levels is given by Table 2 from the literature [19, 40, 41]. Equations 16, 17 and 18 are adapted to perform this research, and liquefaction severity classification is done by the methodology given by Iwasaki et al. [19].

Table 3 LPI computation for BH 8 in Seed's Method (1971)

Depth (m)	Unit weight, kN/m^3	r_d	MSF	(N_1, 60)	CSR	CRR	FS	Z (m)	H	W(z)	F(z)	LPI	Total LPI	Comment
0.91	14.02	0.99	1.19	17	0.07	0.21	2.82	0.46	0.91	9.77	0	0	12.69	High
1.82	13.73	0.98	1.19	6	0.07	0.08	1.11	1.37	0.91	9.31	0	0		
3.04	15.00	0.97	1.19	9	0.07	0.11	1.53	2.44	1.21	8.78	0	0		
4.57	14.02	0.96	1.19	13	0.09	0.16	1.71	3.81	1.52	8.09	0	0		
6.09	14.32	0.95	1.19	12	0.11	0.15	1.36	5.34	1.52	7.33	0	0		
9.14	12.85	0.93	1.19	5	0.13	0.07	0.56	7.62	3.04	6.18	0.43	8.22		
12.19	14.81	0.84	1.19	7	0.13	0.09	0.68	10.7	3.04	4.66	0.31	4.47		

Table 4 Coordinates of each borehole (BH) location and calculated liquefaction potential index (LPI)

Word no.	Bore hole no.	Coordinates		Liquefaction Potential Index (LPI) for Mw = 7 and = a_{max}0.12 g	
		Latitude (N)	Longitude (E)	Seed's method (1971)	
				LPI Value	Comment
1	BH 1	24°22′52.25"N	88°32′56.14"E	0	Very low
	BH 2	24°22′36.46"N	88°33′32.87"E	0	Very low
2	BH 3	24°23′43.79"N	88°33′38.03"E	0	Very low
	BH 4	24°23′2.06"N	88°33′47.44"E	0	Very low
3	BH 5	24°22′54.59"N	88°34′41.33"E	7.92	High
	BH 6	24°22′43.64"N	88°35′12.20"E	12.95	High
4	BH 7	24°21′51.88"N	88°33′17.82"E	12.37	High
	BH 8	24°22′11.23"N	88°33′36.31"E	12.69	High
5	BH 9	24°22′35.15"N	88°33′58.11"E	2.97	Low
	BH 10	24°22′19.42"N	88°34′7.39"E	1.32	Low
6	BH 11	24°22′32.93"N	88°34′30.92"E	10.29	High
	BH 12	24°22′26.90"N	88°34′51.00"E	11.95	High
7	BH 13	24°21′50.19"N	88°34′7.59"E	14.36	High
	BH 14	24°21′50.99"N	88°34′59.07"E	7.55	High
8	BH 15	24°22′10.55"N	88°34′38.37"E	18.51	Very high
	BH 16	24°22′8.51"N	88°35′7.54"E	7.84	High
9	BH 17	24°21′54.12"N	88°35′27.81"E	21.76	Very high
	BH 18	24°21′48.68"N	88°35′42.49"E	19.77	Very high
10	BH 19	24°22′20.53"N	88°35′8.33"E	4.54	Low
	BH 20	24°22′14.69"N	88°35′26.16"E	7.6	High
11	BH 21	24°22′12.18"N	88°35′38.40"E	6.12	High
	BH 22	24°22′5.13"N	88°35′49.91"E	6.29	High
12	BH 23	24°21′59.99"N	88°36′3.33"E	7.32	High
	BH 24	24°21′46.72"N	88°35′58.12"E	5.96	High
13	BH 25	24°22′25.50"N	88°35′43.59"E	0	Very low
	BH 26	24°22′19.94"N	88°36′0.97"E	0	Very low
14	BH 27	24°23′8.68"N	88°35′18.57"E	0	Very low
	BH 28	24°22′45.79"N	88°35′55.88"E	1.08	Low
15	BH 29	24°22′46.94"N	88°36′20.68"E	0	Very low
	BH 30	24°22′33.12"N	88°36′4.89"E	0	Very low
16	BH 31	24°23′10.90"N	88°35′58.14"E	0	Very low
	BH 32	24°23′36.54"N	88°36′0.34"E	0	Very low
17	BH 33	24°24′32.62"N	88°35′47.08"E	14.79	High
	BH 34	24°24′3.49"N	88°37′2.14"E	12.35	High
18	BH 35	24°23′34.27"N	88°36′28.71"E	5.32	High
	BH 36	24°23′6.12"N	88°36′31.98"E	5.29	High
19	BH 37	24°23′25.59"N	88°36′55.63"E	0	Very low
	BH 38	24°22′51.04"N	88°36′50.50"E	0	Very low
20	BH 39	24°22′6.37"N	88°36′15.32"E	0.73	Low
	BH 40	24°22′20.77"N	88°36′20.31"E	2.38	Low
21	BH 41	24°22′22.73"N	88°36′35.91"E	0	Very low
	BH 42	24°22′5.85"N	88°36′32.36"E	0	Very low
22	BH 43	24°21′57.06"N	88°36′15.74"E	17.74	Very high
	BH 44	24°21′48.63"N	88°36′23.38"E	13.06	High

Table 4 continued

Word no.	Bore hole no.	Coordinates		Liquefaction Potential Index (LPI) for Mw = 7 and = a_{max}0.12 g	
		Latitude (N)	Longitude (E)	Seed's method (1971)	
				LPI Value	Comment
23	BH 45	24°21′40.88“N	88°36′30.03”E	7.26	High
	BH 46	24°21′51.23“N	88°36′45.82”E	1.4	Low
24	BH 47	24°21′36.07“N	88°36′53.49”E	0	Very low
	BH 48	24°21′56.67“N	88°37′2.87”E	0	Very low
25	BH 49	24°21′34.51“N	88°37′8.69”E	0	Very low
	BH 50	24°21′50.10“N	88°37′21.73”E	0	Very low
26	BH 51	24°22′39.33“N	88°37′37.44”E	8.67	High
	BH 52	24°23′0.84“N	88°38′29.78”E	4.73	Low
27	BH 53	24°22′13.97“N	88°37′0.19”E	10.3	High
	BH 54	24°22′7.65“N	88°37′42.22”E	13.49	High
28	BH 55	24°21′31.50“N	88°37′41.26”E	0	Very low
	BH 56	24°21′42.16“N	88°38′19.96”E	0	Very low
29	BH 57	24°21′16.88“N	88°38′27.58”E	0	Very low
	BH 58	24°21′30.11“N	88°38′58.07”E	0	Very low
30	BH 59	24°22′10.31“N	88°38′45.62”E	0.35	Low
	BH 60	24°22′46.12“N	88°39′20.13”E	0.73	Low

Results and Discussion

The factor of safety is a crucial parameter for the evaluation of the liquefaction potential index where weighting factor, discretized soil layer and liquefaction severity are also associated. With the help of these parameters, LPI value is calculated, and liquefaction severity level of each BH profile is identified by Table 2. In this research, the methodology given by Iwasaki et al. [19] is adopted. Table 3 illustrates the procedure for computation of factor of safety as well as LPI value for Seed's Method (1971) for BH 8 as a representative borehole profile among the 60 borehole profiles.

LPI values are calculated for all 60 BH locations and presented in Table 4. From Table 4, it is evident that Rajshahi is very low to very high susceptibility of liquefaction hazards. From Table 4, which is prepared by considering Seed's Method (1971), represents 60 BH profiles among which 23, 10, 23 and 4 BH profiles have categorized as very low, moderate, high, and very high possibility of earthquake in the scale of LPI.

Statistical analysis has been performed for 60 BH profiles and the probability of the percentage of liquefaction severity for Seed's Method (1971) are 38.33% for very low, 16.67% for moderate, 38.33% for high and 6.67% for very high potential. Considering the aforementioned method, most substantial value of LPI is found 21.76 which is in ward no. 9 and the lowest value is seen 0 for several BH locations (see Table 4). In order to visualize the susceptibility of liquefaction easily, liquefaction severity map has been prepared considering Seed's Method (1971) using Arc GIS software (Fig. 4).

A new approach is introduced for the site characterization of Rajshahi City Corporation for liquefaction susceptibility has been drawn taking average value of the LPI of the particular ward. On the other hand, contour line diagram and the average shear wave velocity at a depth of 30 m are very important tool to identify the dynamic behavior of the subsoil strata and plot the liquefaction hazard map [25, 28]. Figure 4 depicts that the average LPI greater than 15 is seen at ward no. 9 and 22. These wards cover Shaheb Bazar followed by Bose Para which are mostly densely areas in RCC. The southwest part of RCC is marked as high susceptibility based on the aforementioned method [19]. The biggest central zoo of Rajshahi Districts, the biggest Rajshahi Medical College in Rajshahi division and other administrative buildings are located in southwest part of RCC (See Figs. 1 and 4). The ward nos. 16, 17, 26 and 27 are the growing areas in RCC, especially 26 and 27 have already been introduced as a residential area where developers build high rise buildings day by day.

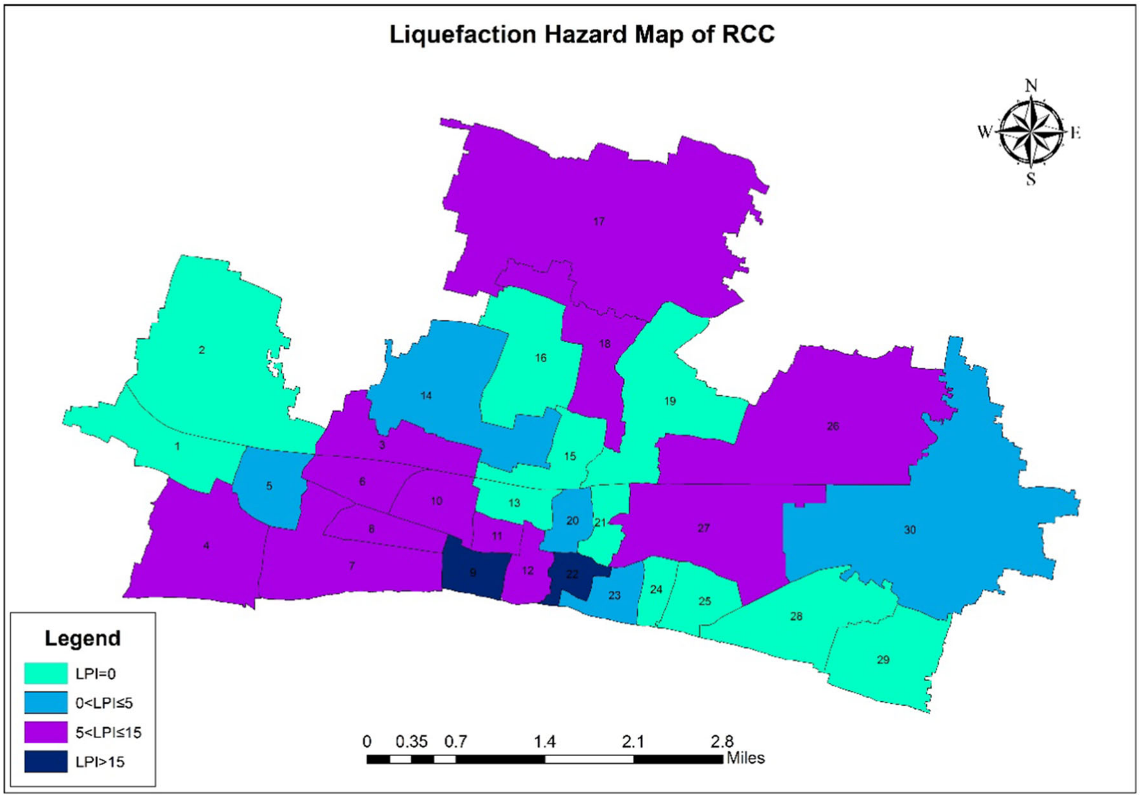

Fig. 4 Liquefaction hazard map based on LPI value in Seed's Method (1971)

Conclusions

In this study, liquefaction hazard map with GIS was prepared with an assumed earthquake magnitude 7. Some specific limitations were found while going through detailed investigation of LPI value. First of all, SPT-N value along with other geotechnical characteristics of soil such as water content, density, specific gravity has been collected from soil report. Although, soil reports are well documented with proper authentication details, but these values should be measured directly on the field to get more accurate results. Secondly, ground water table (GWT) has been considered as constant parameter in this study rather this parameter depends on seasonal variation. For obtaining more accurate results, fines content should be measured directly on the field prior to the knowledge of geological conditions and features of the study area with proper monitoring.

Despite having all the limitations, this study can be considered as a first attempt to calculate susceptibility of earthquake by calculating LPI value and may be used as a preliminary guideline for the geotechnical engineers as well as city planners of RCC. This paper prepares the liquefaction hazard map using the Seed's Method (1971) as well as summarizes the calculated formulas available in the literature to make a single framework. To facilitate extended opportunities to the Geotechnical Engineer, a forecast model should be prepared based on statistical forecasting methodology in future study. As a result, this kind of prepared map may be used as a critical parameter for the development of the city.

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Declarations

Conflict of Interests On behalf of all authors, the corresponding author states that there is no conflict of interest.

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