# Rational Way of Estimating Liquefaction Severity: An Implication for Chattogram, the Port City of Bangladesh

**Md. Aftabur Rahman** [ID] · **Shoukat Ahmed** · **Mahmood Omar Imam**

**Abstract** Earthquake-induced liquefaction is responsible for the extensive damage to the infrastructures in both developed and developing cities. Chattogram, the second largest city of Bangladesh and one of the vital port city in the south Asian region is situated in the active seismic region, and the frequency of recent small magnitude earthquakes around the city reveals that a significant earthquake of probable magnitude 7.0 or higher is due. Therefore, liquefaction severity at different locations of Chattogram Metropolitan Area is estimated based on the in situ parameters. Two widely used liquefaction assessment procedures has been applied to estimate the liquefaction susceptibility at the selected locations. Later, geospatial techniques are applied to prepare a hazard map based on liquefaction potential of discrete locations. The flat tidal part of the city is identified as extremely liquefy prone areas, while the small hillocks and nearby areas at the central part of city are safe against liquefaction hazard. Geological variation of parameter in all directions are also taken into account to prepare the hazard map. Predicted liquefaction potential is then compared with a second data set and the linear regression between the observed and predicted liquefaction potential portray consistent approximation in all cases. Case studies and practical experience also justify the developed hazard map. Therefore, the developed hazard map can be a useful tool for the disaster mitigation policy of Bangladesh Government.

**Keywords** Chattogram · Liquefaction · Idris and Boulinger · T-Y method · Geospatial analysis

## 1 Introduction

Earthquake-induced long-lasting geotechnical hazard is responsible for the destruction and damage of infrastructures all over the world. Among different hazards, liquefaction is one of the devastating consequence of an earthquake and cause severe damage to infrastructures and human lives. Earthquake records of different times revealed the destructive damage by liquefaction and reported in many technical writings (Kuribayashi and Tatsuoka 1975; Tohno and Yasuda 1981; Tokimatsu et al. 1994; Kasai and Maison 1997; Cubrinovski et al. 2011). Since the term coined after the 1964 Niigata earthquake, researchers in the field of geotechnical engineering devoted their effort to analyze liquefaction severity. The regional geological formation plays an essential role during earthquake ground motion and responsible for the onset of liquefaction. Typically, the upper formation having

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loose fine sand or sandy deposit can liquefy by the violent shake as the effective stress becomes zero owing to the cyclic seismic loads acting within the very short time duration.

Moreover, the dynamic nature of liquefaction makes it complicated and yet an exact procedure for the determination of liquefaction severity is a scratching issue (Towhata 2014). To analyze the hazard and possible future damage, several simplified procedures have been developed and updated progressively to account for different parameters and uncertainties (Huang and Miao 2017). Liquefaction hazard estimation after the massive earthquakes and assessment of probable liquefaction severity for different cities have been determined and can be an eloquent option to mitigate future hazard, especially for the urban areas. Hence, assessment of liquefaction potentiality based on simplified procedures have been estimated for different cities vulnerable to earthquake hazard (Dawson and Baise 2005; Dixit et al. 2012; Kajihara et al. 2013; Pokhrel et al. 2013; Sharma and Hazarika 2013; Neelima Satyam and Rao 2014; Choudhury et al. 2015; Rahman et al. 2015; Rahman and Siddiqua 2016; Gautam et al. 2017). Liquefaction hazard map based on liquefaction potentiality is also prepared to prevent damages by the probable mega quake. The assessment procedure is most important for the developing and under-developed countries those are at risk of a future gigantic earthquake (Madabhushi and Haigh 2012). Not only the liquefaction assessment at discrete points of a city is enough for hazard mitigation, but also the whole scenario needs to be assessed. Precise estimation of liquefaction severity based on sophisticated in situ test and/or laboratory investigation is not applicable in all cases, especially for the developing and under-developed countries. Yet, some tools are available which can be used to estimate liquefaction at the concerned points. To make up the whole scenario for disaster mitigation and city planning, severity of any geotechnical hazard like liquefaction for the entire area needs to be quantified. To the date, no straight forward procedure is available for such hazard zonation. Recently, geospatial distribution by suitable techniques provide the distribution of any quantity over the problem domain (Mendes and Lorandi 2010; Nandi and Shakoor 2010; Kidmose et al. 2011; Mhaske and Choudhury 2011; Pradhan et al. 2011). Geospatial distribution of liquefaction has also applied for different case studies and proven to be

a useful tool for liquefaction hazard mapping (Dawson and Baise 2005; Kajihara et al. 2013; Pokhrel and Kiyota 2016). Therefore, considering the facts, the current research firstly examined the available liquefaction assessment tools and afterward, a liquefaction hazard assessment procedure is formulated. Geospatial techniques was then introduced and used to prepare severity map for the selected region. Finally, the procedure was applied to estimate liquefaction severity of Chattogram city, which is the port city of a geographically important country, Bangladesh. A hazard map was prepared to identify the critical zones and validated with the available datasets. The following sections describe in detail the development of a hazard map for liquefaction severity.

## 2 Determination of Liquefaction Severity

The destruction of liquefaction was first seen after the Niigata earthquake in 1964, where several buildings were tilted. Following the disaster, geotechnical experts were working to develop a methodology to evaluate liquefaction severity. Seed and Idriss (Seed and Idriss 1970) was the first who developed a simplified procedure for liquefaction assessment. A factor of safety (FS) value for liquefaction was defined, where FS is the ratio of the cyclic resistance of soils over the cyclic stress induced during earthquakes. The cyclic stress induced during seismic excitation is empirically estimated using the seismic magnitude and peak ground acceleration. Besides, the cyclic resistance is estimated empirically using simplified in situ test data. The commonly used in situ test for geotechnical investigation is standard penetration test (SPT) and hence, SPT, N value was used to evaluate the cyclic resistance and adopted by Seed and Idriss (Seed and Idriss 1970). For a soil layer, the FS value less than one depict the chances of liquefaction. Following Seed and Idris method, liquefaction assessment procedures have been extensively studied and different methods are formulated to determine FS against liquefaction occurrence (Youd and Perkins 1978; Tokimatsu and Yoshimi 1983; Youd et al. 2001; Cetin et al. 2004; Idriss and Boulanger 2006; Bolton Seed et al. 2008; Maurer et al. 2015). Also, the cyclic resistance can be determined experimentally by the cyclic shear test or torsional shear test. Nowadays, remote sensing can be a promising option to evaluate

the liquefaction though it requires enormous expenses and cannot be applied in all case histories (Konagai et al. 2013). Comparing the rationality of different approaches, simplified evaluation based on empirical relationships is found to be appropriate to estimate liquefaction severity of Chattogram city.

Among various simplified procedures, Seed and Idriss method has provided a good match for most of the cases and can be a plausible approach for liquefaction evaluation (Chang et al. 2011). Also, the T-Y method provided satisfactory outcomes in many cases. Recently, an update of the original Seed and Idriss procedure have been made by Idriss and Boulanger (Idriss and Boulanger 2006) and proven to be useful for practical utilization. Therefore, based on the literature study and rationality, both the modified Seed and Idris method and T-Y methods were used to estimate liquefaction potentiality for Chattogram city.

Factor of safety (FS) for liquefaction is written mathematically by the following equation:

$$FS = \frac{CRR}{CSR} \tag{1}$$

where $CRR$ is cyclic resistance ratio and $CSR$ is cyclic stress ratio.

### 2.1 Idriss and Boulinger Method

The cyclic stress ratio can be estimated as

$$CSR = 0.65 \frac{a_{max}}{g} \frac{\sigma_0}{\sigma_0'} r_d \tag{2}$$

where $a_{max}$ is the maximum surface acceleration, $\sigma_0$ is the total overburden pressure, $\sigma_0'$ is the effective overburden pressure, and $r_d$ is the stress reduction factor. The previous equation is slightly modified to adjust CSR with a standard earthquake magnitude of 7.5 and can be written as,

$$CSR_{7.5} = \frac{CSR}{MSF} \tag{3}$$

The magnitude of an earthquake can vary and account for an absolute magnitude, a magnitude scaling factor (MSF) is introduced and cyclic stress is modified according to the designed earthquake (M) by using MSF.

$$MSF = 6.9 \exp\left(-\frac{M}{4}\right) - 0.058 \leq 1.8 \tag{4}$$

At the same time, cyclic resistance ratio can be estimated using the SPT, N value. Before using the approach, uncorrected N values must be corrected for overburden, hammer efficiency, rod length, and other necessary corrections. Afterward, the corrected SPT, N values are adjusted to equivalent clean sand $((N_1)_{60cs})$ as

$$(N_1)_{60cs} = (N_1)_{60} + \Delta(N_1)_{60} \tag{5}$$

where

$$\Delta(N_1)_{60} = \exp\left(1.63 + \frac{9.7}{FC + 0.1} - \left(\frac{15.7}{FC + 0.1}\right)^2\right) \tag{6}$$

Here FC is fines content of the soils at concerned depth.

The value of CRR is calculated according to the given equation:

$$CRR = \exp\left[\frac{(N_1)_{60cs}}{14.1} + \left(\frac{(N_1)_{60cs}}{126}\right)^2 - \left(\frac{(N_1)_{60cs}}{23.6}\right)^3 \right.$$
$$\left. + \left(\frac{(N_1)_{60cs}}{25.4}\right)^4 - 2.8\right] \tag{7}$$

### 2.2 T-Y Method

Tokimatsu and Yoshimi (Tokimatsu and Yoshimi 1983) found that fines content greater than 10% can resist liquefaction considerably and the soils having SPT, N value greater than 25 provides better resistance to liquefaction. Based on the findings, they proposed an update of the liquefaction evaluation procedure and effectively applied in different cases. The cyclic stress ratio can be estimated as

$$CSR = 0.1(M - 1) \frac{a_{max}}{g} \frac{\sigma_0}{\sigma_0'} (1 - 0.015z) \tag{8}$$

Here, z is the depth of interest to evaluate liquefaction.

Besides, cyclic resistance ration is calculated as

$$CRR = 0.45 \times 0.57 \left[\frac{16\sqrt{N_a}}{100} + \left(\frac{16\sqrt{N_a}}{C_s}\right)^{14}\right] \tag{9}$$

where

$$N_a = N_1 + \Delta N_f \tag{10}$$

$$\Delta N_f = \begin{cases} 0 & FC < 5 \\ FC - 5.0 & 5 < FC < 10 \\ 0.1FC + 4 & other \end{cases} \tag{11}$$

## 2.3 Liquefaction Potential Index (LPI)

The previous calculation determines the possibility of liquefaction at a particular depth. However, the onset of liquefaction is not dependent on a particular depth; instead the entire stratum needs to be evaluated. Iwasaki and co-researchers developed an index called Liquefaction Potential Index (LPI), which is proportional to the thickness of the liquefiable layer and the value of the FS against liquefaction of each layer (Iwasaki et al. 1981). A weighting function is used in LPI calculation, and the weighted values decrease as the depth increase, eventually close to zero after 20 m from the ground level. The following equation gives an estimation of LPI:

$$LPI = \int_0^{20} F(z)W(z)dz \tag{12}$$

where $W(z)$ is the smoothing function.

$$F(z) = \begin{array}{ll} 1 - FS & FS < 1.0 \\ 0.0 & FS \geq 1.0 \end{array} \tag{13}$$

$$W(z) = \begin{array}{ll} 10 - 0.5z & z \leq 20.0m \\ 0 & z > 20.0m \end{array} \tag{14}$$

LPI value is, therefore, used to quantify the hazard associated with liquefaction. The site said to be severely liquefied where LPI value exceeds 15.0. LPI value less than 5.0 indicates very little to minor severity, while LPI in between 5 and 15.0 depict the moderately liquefied zone.

## 3 Geostatistical Analysis to Prepare Severity Map

The simplified methods discussed above estimate chances of liquefaction only at the discrete points. It is practically impossible to drill a borehole at all locations of a city. Discussion based on the results from discrete points do not portray the whole scenario. For this, a procedure to evaluate the severity of un-

sampled locations is mandatory in the disaster mitigation policy. Spatial distribution of discrete data's using statistical analysis is a plausible approach to prepare a quantitative hazard map. Among several statistical methods, geospatial analysis is the rational one and applied in many types of research. The kriging interpolation is one of the powerful geostatistical tools that can effectively predict the values at unsampled locations. This method is used extensively to estimate different topographical and geological quantities such as rainfall, elevation, water table, soil properties, soil contaminations and many others (Mendes and Lorandi 2010). Kriging is an interpolation method which is based on the weighted average of properties over a certain range. The conventional interpolation scheme estimates a weighted average of points over a certain range, while in Kriging, a semivariogram is plotted to weight nearby points. In Kriging interpolation, the variance between sampling points is determined in the first step. The low variance shows the closeness of the sampling points, while the variance outside the range indicates that there is no longer any spatial relationship between the sampling points. The variance at the range, where variance level off is called sill, and the first variance is termed as a nugget of the variance. The computed variance is plotted against geographical distance known as semivariogram, and, the best fit distribution is taken. However, the accuracy of the interpolation scheme largely depends on how well the model variogram fits the data sets. Fundamentals of the semivariogram in Kriging is schematically shown in Fig. 1. Besides, the weighted average
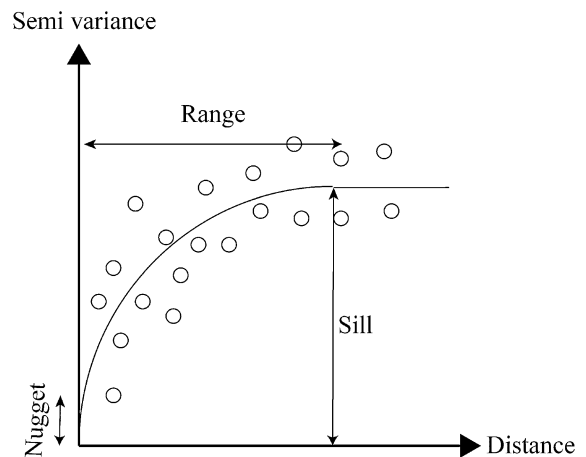


Fig. 1 Fundamentals of kriging interpolation

in Kriging interpolation is independent of the fixed domain and can capable of capturing the uneven distribution of data sets. The inherent nature of capturing the dynamics of the weighted average makes the Kriging interpolation a rational approach for geospatial analysis. Moreover, the directional variability, known to as anisotropy, is also taken into consideration in Kriging interpolation. Kriging also provides an estimation of error at each interpolated points, providing a measure of confidence in the modeled surface. However, the sampled data sets must not portray any trend over the domain and need to be checked before application of kriging interpolation.

Besides, for the evenly distributed data sets, the conventional interpolation also performs well. Inverse distance weighting (IDW) is a simplified interpolation scheme and have many applications in the spatial distribution of possible parameters. The fundamentals of IDW is based on the weighted average of sampled points within the influence zone. IDW assumes that each measured point has a local influence that diminishes with distance. The current research employed both the sophisticated kriging interpolation and simple IDW to prepare a hazard map of liquefaction vulnerability.

## 4 Problem Statement

Bangladesh is one of the South Asian countries, and the major seaport of the country is located in Chattogram, which is geologically and strategically important in the south Asian region. The country is located at the boundary of two plates: The Indian plate and the Eurasian plate. The north-east moving Indian plate collides with the Eurasian plate, which is responsible for the occurrence of many historical earthquakes in northeast India, Nepal, Bangladesh, and Myanmar (Ministry of Disaster Management and Relief 2015). Though the paleoseismic history within or near Bangladesh is not available, the history of major earthquakes for the last 200 years makes the country a seismically active one (Khan 2010). To be specific, the country has been affected by a few significant earthquakes in the last century, and recent frequent earthquakes of small to medium magnitude indicate the probability of a major earthquake (2015).

Besides, the return period of those historical earthquakes reveals the high possibility of a mega-strike within or around Bangladesh. A major earthquake of probable magnitude 7.0 or higher is on the queue, according to many researchers in seismology (Steckler et al. 2016). Earthquake records of magnitude higher than 3.5 in and around the country reveal that the cluster of earthquakes is quite dense in Chattogram and surrounding areas. Chattogram is the second largest city of Bangladesh, and the country's major seaport is situated in this city (Fig. 2). The city is located within $22°14'$ and $22°24'30''$ north latitude and between $91°46'$ and $91°53'$ east longitude and on the bank of river Karnafuly. The city is bounded to the west by the Bay of Bengal and Halda River to the north-east. Chattogram is one of the divisional cities of the country. The urbanization is growing quite rapidly in the city as the country's first tunnel is being constructed under the Karnafuly River (BridgeAuthority 2013). The major economic zone is under construction, and many other development works are going on around Chattogram city. The heart of the city is bounded as Chattogram Metropolitan Area (CMA) of approximately 775 km$^2$ and is currently accommodating about 5 million of its inhabitant and continually growing. Being vulnerable to a moderate to a massive earthquake, the city needs quantitative analysis of earthquake associated hazards. Moreover, the country's economy depends on the seaport of this city and the destruction of the city by the earthquake hazard leads to complete collapse of the country.

CMA was formed mostly by the sedimentation of loose fine sands, silty sands, and soft clay layers except for some small hillocks of quaternary geology. With this formation, liquefaction associated during an earthquake can cause extensive damage to the infrastructures. Hence, a quantitative analysis of liquefaction susceptibility of the city is critically important to reduce the possible destruction. Analysis of liquefaction severity of Chattogram city is seldom found in technical papers, reports or by any means. Keeping the real scenario in mind and feeling the necessity of a hazard map for liquefaction possibility, Chattogram city is selected in current research, and subsequent sections describe the detailed procedure of liquefaction assessment and hazard map.
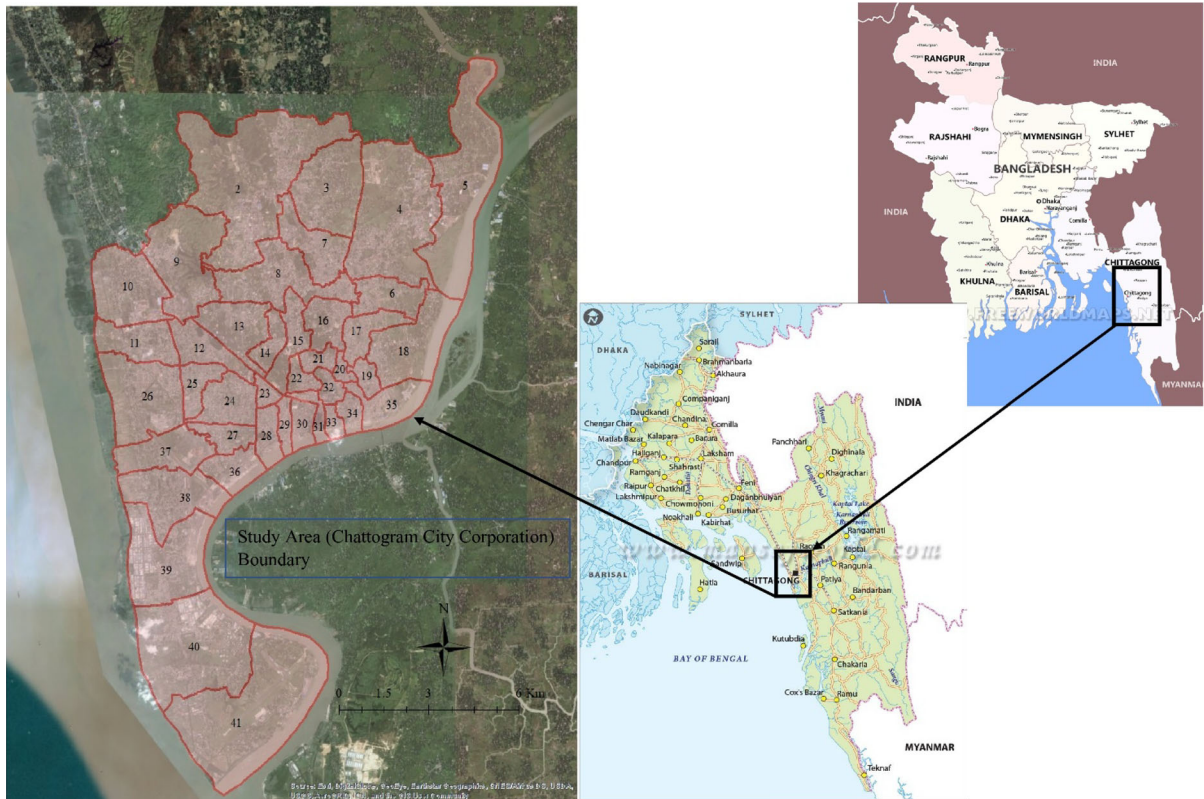
**Fig. 2** Location of study area (Chattogram city)

## 5 Geology of the City

Chattogram district is a part of the hilly eastern region of Bangladesh, characterized by an N-S trending folded mountain range. The two distinct patterns are seen for the surface geology of the Chattogram city. Quaternary sediments are exposed in the southern part of the city in between Karnafuly River to the east and south and Bay of Bengal to the west. Tertiary sediments are exposed in the northern part of the study area. The city has an exception over the other part of the country as it contains both tidal flat land and hilly terrain that branch off from the Himalayas. The tidal deposits are represented by the alteration of sand, grayish silty sand and sticky clay. Most of the tidal sediments are underlain by the fine, medium-grained yellowish brown silty sand and sands of Dupitila formation. That tidal deposit eventually makes a soft upper layer of current formation except the central location, which has small hillocks. Therefore, a sudden seismic activity of greater magnitude may cause severe geotechnical hazard over the entire city.

The risk is more concerned as the city is expanding rapidly. Presence of soft soil at shallow depth in most part of the city area enhance the chance of liquefaction. In addition, the tidal waves submerged some parts of the city every day and the co-occurrence of tidal waves and seismicity may trigger liquefaction. The detailed geological formation of Chattogram city is available in previous references (Khan 1991, 2010; BridgeAuthority 2013).

## 6 Liquefaction Analysis of Chattogram City

Chattogram is the second largest city, which is expanding rapidly due to the industrialization and urbanization. To meet with the increasing demand, many infrastructures are built, especially in the metropolitan areas (within CMA). Therefore, sub-soil investigation has been performed quite many locations all over the city areas. Chattogram city consists of 41 wards and all the wards except no. 01 is considered for current research. The discarded ward is considerably
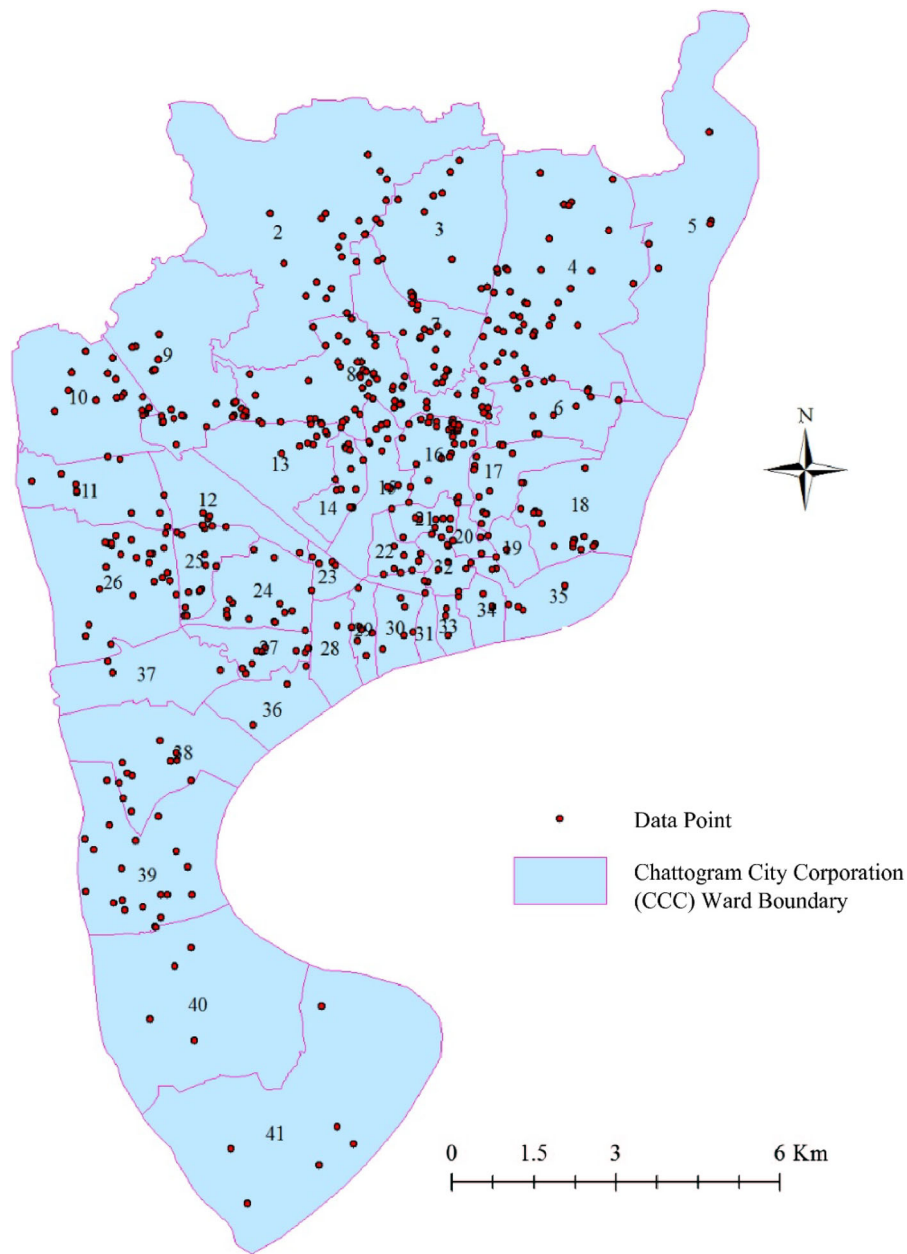
**Fig. 3** Location of borehole points in CMA

distant from the city and yet developed. Geotechnical investigation over the ward no-01 is seldom available and therefore, discarded in the analysis. The current study aimed to collect geotechnical investigation reports from different private organizations. A total of 492 soil investigation reports were collected from different organizations, and necessary information's were extracted from the collected soil investigation reports. The collected data sets can cover most of the city area, though quite dense distribution is seen at the center core of the city. Location of datasets are shown in Fig. 3. Ward no-40 and 41 lacks sufficient data sets as the city's only airport, naval base, and air base are situated in those regions along the west bank of Karnafuly River, and restricts a considerable area owing to the security issue. However, the overall
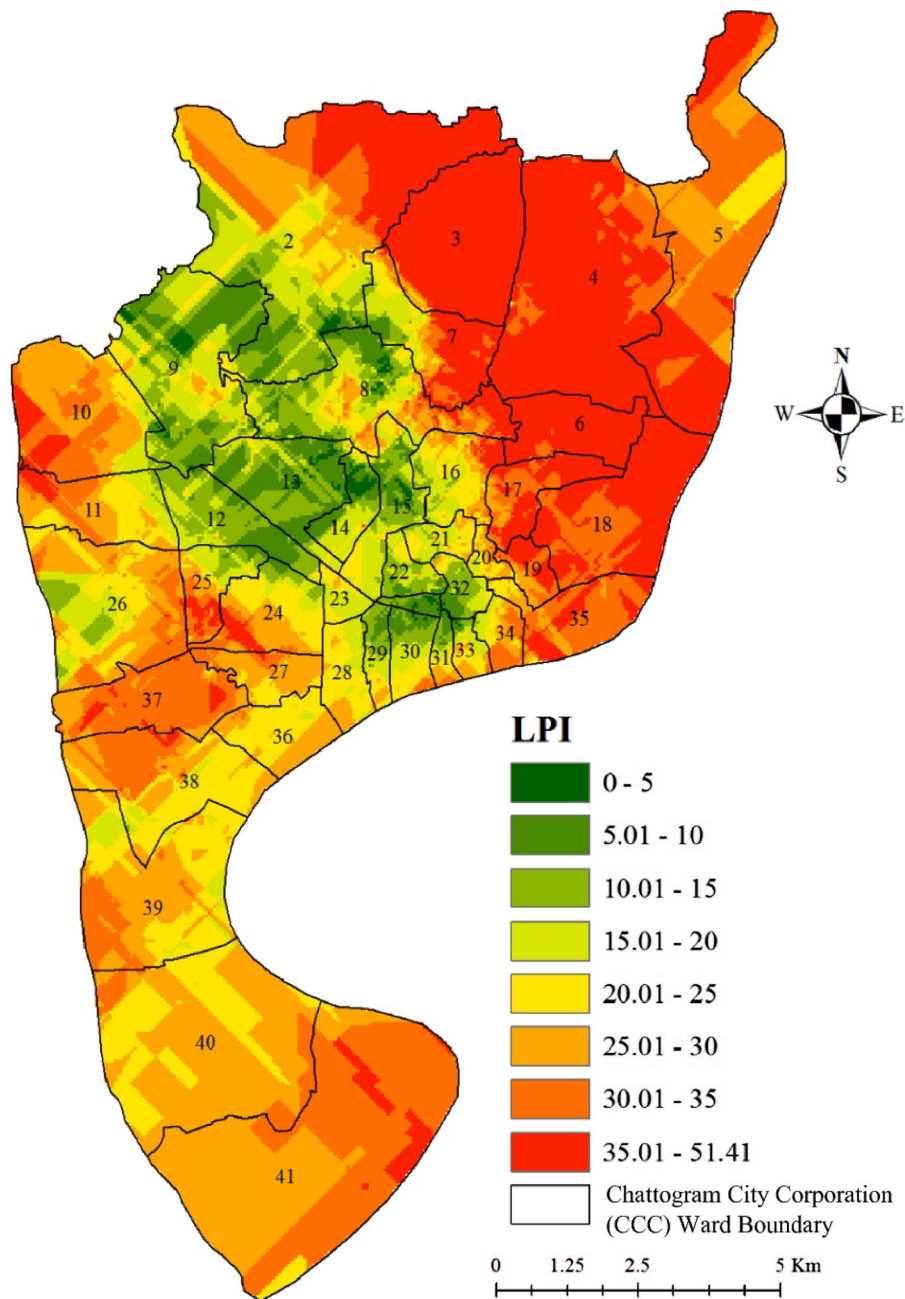
**Fig. 4** Liquefaction potential map of Chattogram City (Idriss and Boulinger method) by Kriging interpolation without anisotropy

distribution of data sets is satisfactory for the spatial distribution. Using the borehole information, total and effective overburden pressure was calculated to determine the cyclic stress ratio. Besides, SPT, N at different layers were used to estimate the cyclic resistance ratio. In most of the investigation reports, SPT, N values were found at every 1.5 m interval, and

borehole profile shows the N values generally up to 30 m or until hard strata encountered. FS of liquefaction at a 1.5 m interval of the stratum was calculated using both Idriss and Boulinger and T-Y method. Afterward, FS values were summed up by smoothing function to determine LPI for the entire stratum. The response of the entire stratum is necessary to evaluate
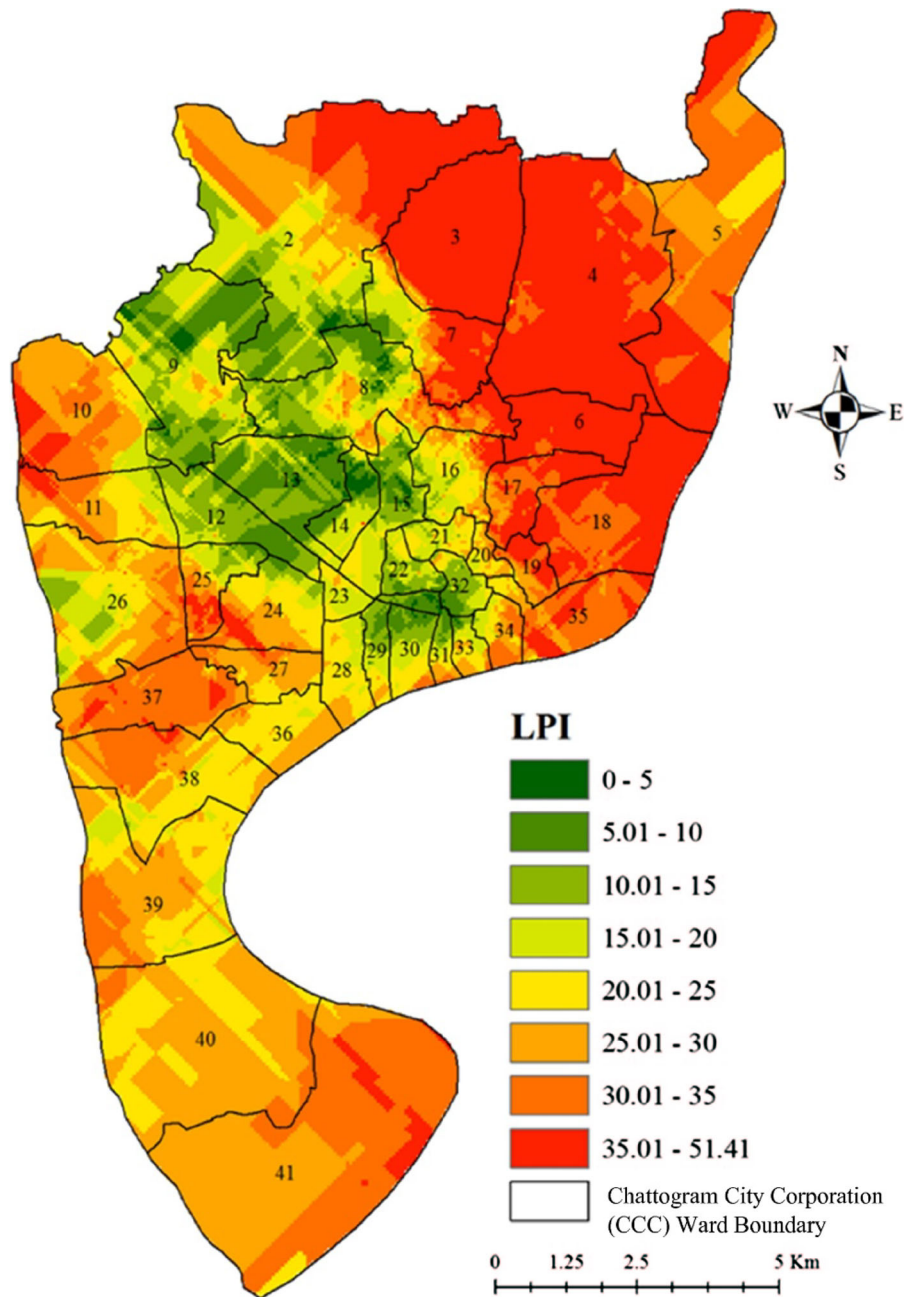
**Fig. 5** Liquefaction potential map of Chattogram City (Idriss and Boulinger method) by Kriging interpolation with anisotropy

the liquefaction susceptibility rather FS at different layers. Therefore, LPI values are used to discuss the severity of liquefaction over the concerned region. In the estimation of the cyclic stress ratio, which is the induced stress during liquefaction, a probable magnitude of earthquake and peak ground acceleration is necessary. Historical evidence of significant

earthquakes and recent frequent distribution of earthquakes justify the chance of a magnitude 7.0 or greater earthquake in or around Bangladesh, to be specific, close to the Chattogram city. The proposed Bangladesh National Code (BNBC-2015) also state the possibility of a magnitude 7.0 or greater earthquake. An approximation of peak ground acceleration also
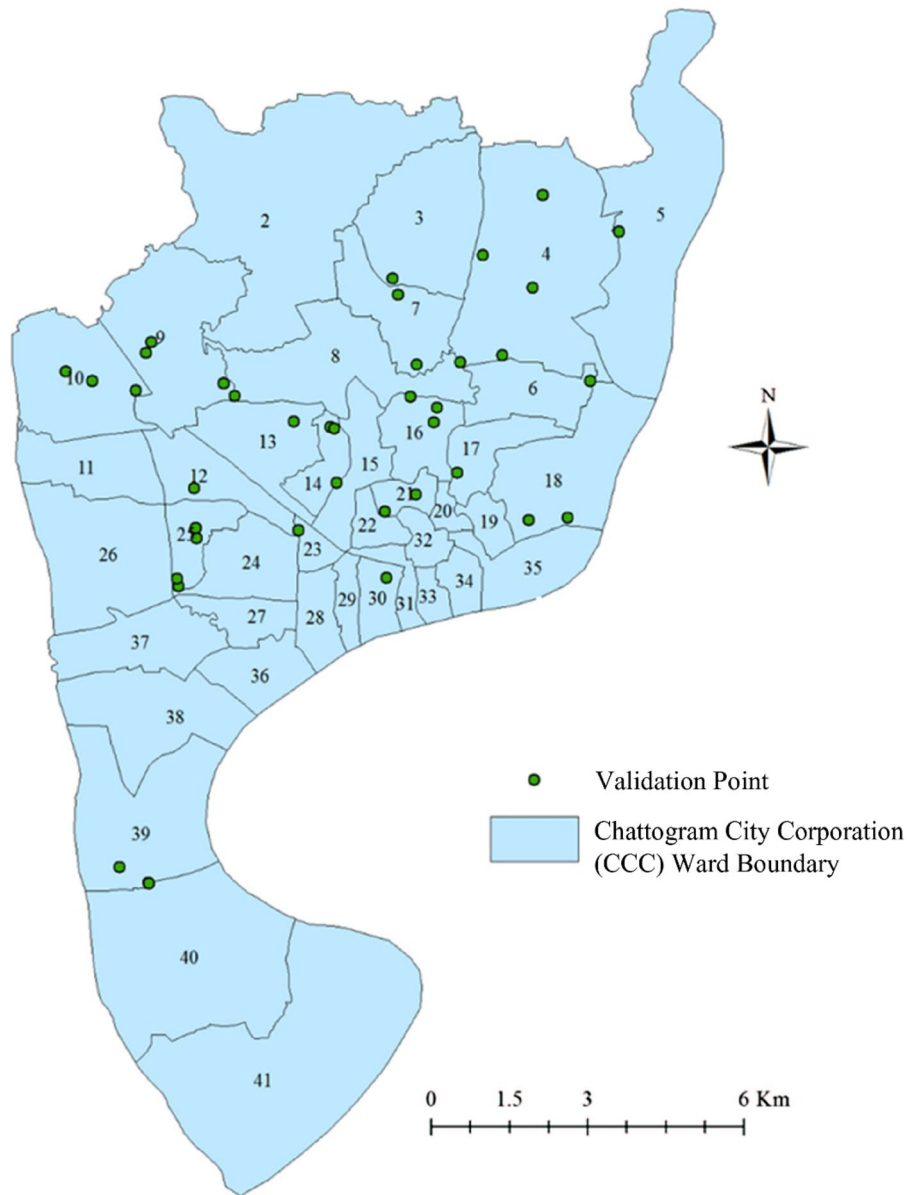
**Fig. 6** Second set of data used for validation of developed procedure

needs technical justification. The current BNBC-2006 provides a seismic zonation map of Bangladesh and Chattogram falls in seismic zone-II with a zone coefficient 0.20, give a tentative peak ground acceleration as 0.2 g. However, accounting for maximum considered earthquake (MCE) motion at different parts of the country, the current seismic zonation map is modified in proposed BNBC-2015. The MCE motion correspond to having a 2% probability of exceedance within a period of 50 years. Chattogram

city area lies into the severe intense zone with zone coefficient 0.28 g. Therefore, the above discussion on earthquake magnitude and peak ground acceleration suggested to use the value as 7.0 and 0.28 g, respectively following the proposed BNBC guideline (2015).

After LPI values were calculated at each borehole locations, the geospatial analysis was performed to determine the liquefaction severity at the un-sampled locations. Both ordinary kriging and IDW interpolation were used to quantify the LPI to determine the
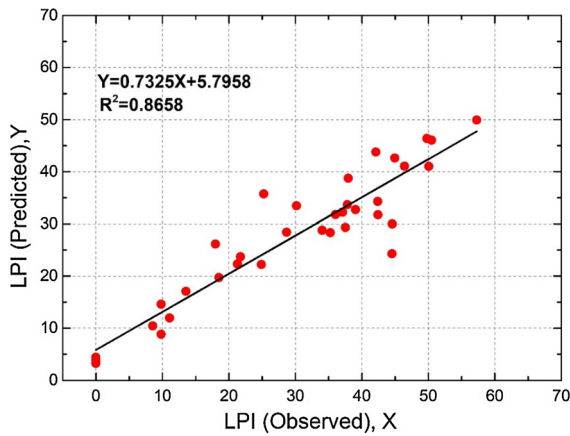
**Fig. 7** Observed and predicted LPI values at validation points (Idriss and Boulinger method) by Kriging interpolation without anisotropy
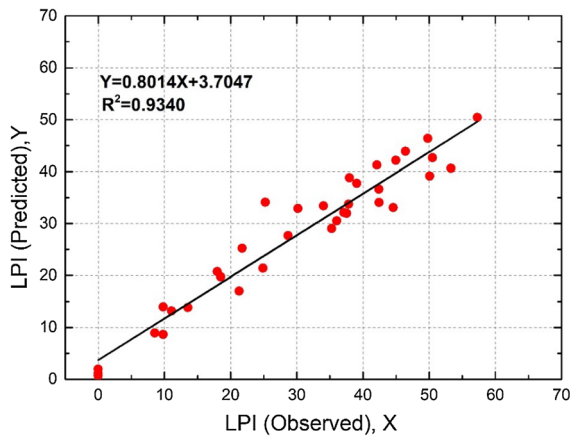


**Fig. 8** Observed and predicted LPI values at validation points (Idriss and Boulinger method) by Kriging interpolation with anisotropy

liquefaction hazard zone. Validation of the derived hazard map was done to justify the developed procedure. A simple numerical code was developed to estimate the liquefaction potential index for the selected locations.

# 7 Results and Discussions

The extracted parameters from boreholes were used to estimate factor of safety against liquefaction. Both the methods describe in preceding section were used calculate the liquefaction severity. The estimated factor of safety was then integrated and weighted to

determine the susceptibility of entire layer. The term used to define the liquefactions of entire layer is known as Liquefaction Potential Index (LPI). However, these discrete values do not portray the scenario of the whole city. Hence, an update of the existing procedure is necessary and to meet the demand, geospatial analysis, more specifically, the kriging interpolation was applied to plot the distribution of liquefaction susceptibility over the CMA. Figure 4 depicts the LPI distribution of the CMA based on Idris and Boulinger method without anisotropy. Though the severity of liquefaction is very high when LPI is greater than 15.0, the legends show more color bar to understand the insight of liquefaction phenomena. It is found that the central part of the CMA has better resistance to liquefaction, while the northern part of the city is extremely vulnerable to liquefaction. The ward no 3, 4, 6, 7, 17, 18, 19, and 35 on the north of the CMA are incredibly vulnerable having huge LPI values. The preceding statement is justified based on the practical consideration of that locality. As a rule of thumb, the authority in those areas generally adopts a deep pile foundation as the soils are incredibly soft at shallow depth. Suppose, Chandgaon, which is the ward no 4 and proliferating with so many high-rise structures, mostly on soft deposit. The Chandgaon ward lies in severe liquefaction zone and explicitly justify the developed procedure. Also, the distribution of the input profile is quite dense in the said regions, reveal the accuracy of the outcomes. The severity of liquefaction is also very high on the southern part of the city where major seaport and the second largest airport of the country is situated. The air-force base and the naval academy, two important defense infrastructures are also in this region. The southern part is also subject to flooding during high tides, which enhance the chances of liquefaction at the concurrent occurrence. Meanwhile, the central part of the city exhibits higher safety against liquefaction. That can be attributed by the small hillocks in those areas and elevation of the surface is also high compared to other parts. The busy street of the city, named GEC circle and its surroundings lies in the green zone showing less possibility to liquefaction hazard. To be conclusive, most part of the city areas are susceptible to liquefaction based on the geospatial analysis. According to the geological map prepared by Geological Survey of Bangladesh, the formation is mainly dune sand and alluvium formation. Soft silty fine sands,
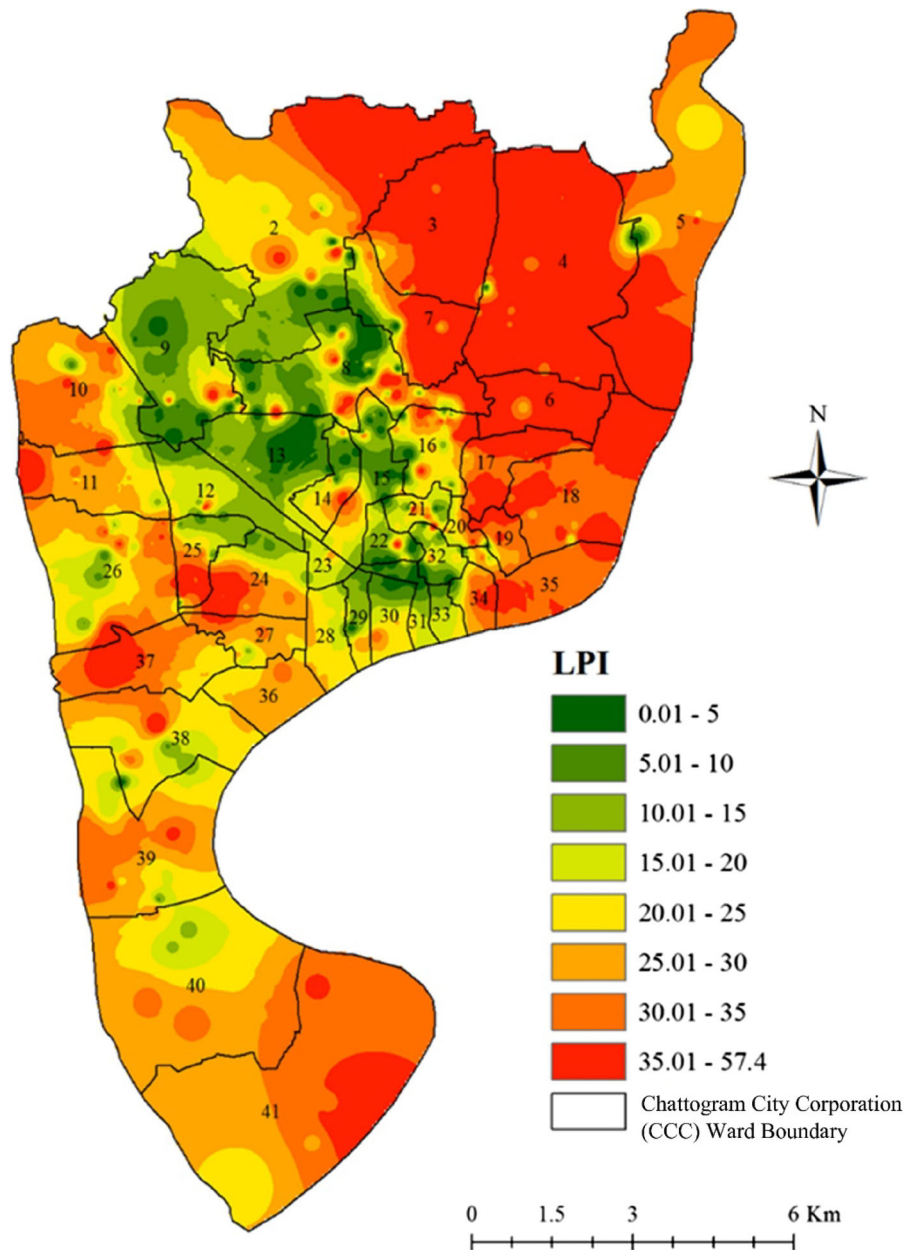
**Fig. 9** Liquefaction potential map of Chattogram City (Idriss and Boulinger method) by IDW interpolation

silty clay and clayey soils make the upper formation at almost all part of the city except the hills and its surroundings. The liquefaction severity from the observed data sets and geological formation are quite compatible. All the discussion made here exclude the anisotropic criteria of the spatial distribution. At the same time, considering the anisotropic distribution i.e. directional variability which is typical in geospatial distribution, a LPI distribution of the entire city area was also prepared and shown in Fig. 5. The directional variability seemingly shows alike distribution of isotropic condition. Both the map provides severe liquefaction susceptibility over the growing city area.

However, further verification is necessary to state the severity of liquefaction implicitly. Therefore, a second data set was collected, which sparsely cover
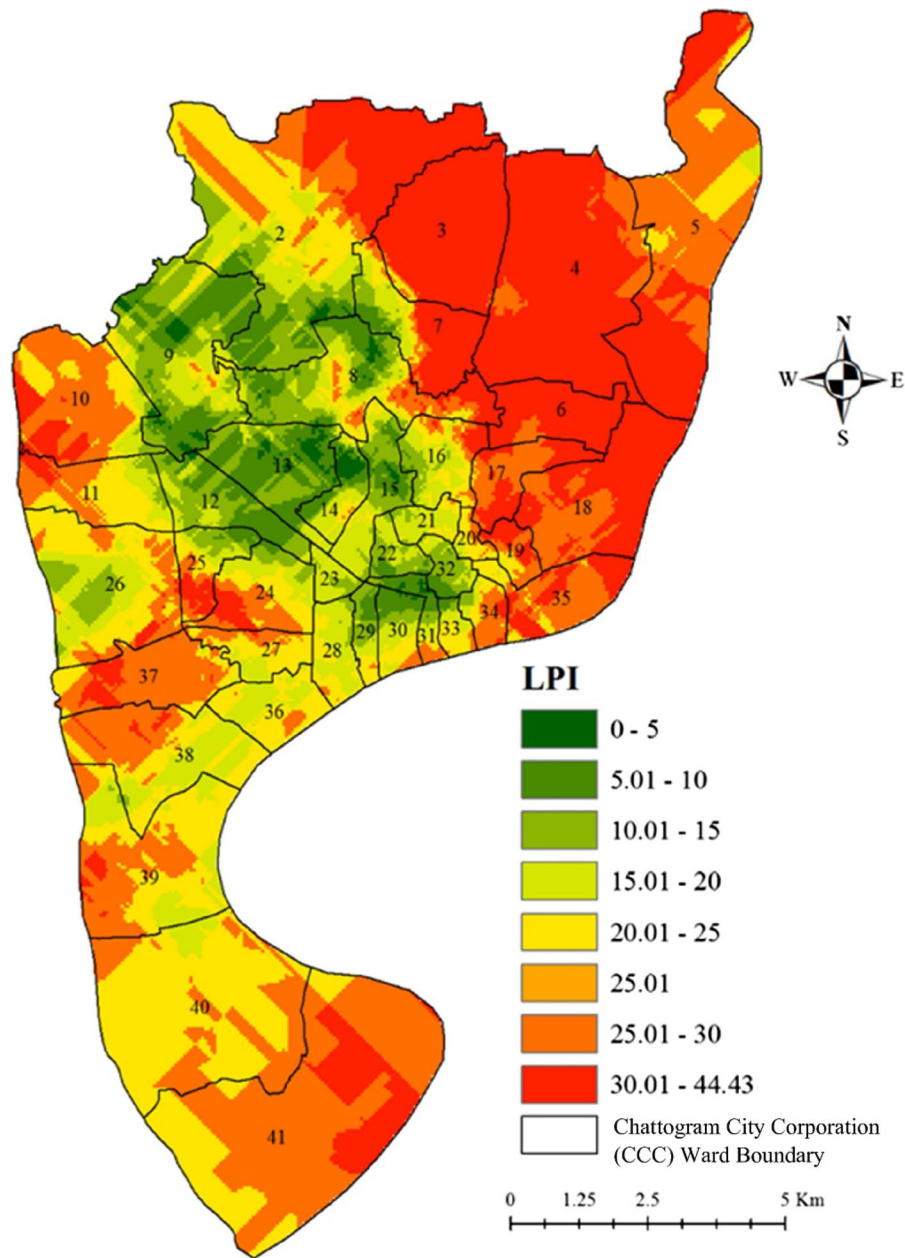
**Fig. 10** Liquefaction potential map of Chattogram City (T-Y method) by Kriging interpolation without anisotropy

the CMA boundary. A total of 37 borehole profiles were collected in the second phase (Fig. 6), and LPI values were determined. Besides, LPI values of the validation points were extracted from the hazard map. Observed and predicted values are plotted in Figs. 7 and 8 for isotropic and anisotropic consideration, respectively. In both figures, observed LPI is plotted in the horizontal axis, while the vertical axis plot LPI

from the prepared map of the isotropic and anisotropic condition. The linear relationship between observed and predicted values having an R-squared value higher than 0.86 in both cases portray a excellent match. The best fit line in case of anisotropic condition shows more closeness having a much higher regression coefficient than the isotropic condition. The directional variability is real in case of geological and
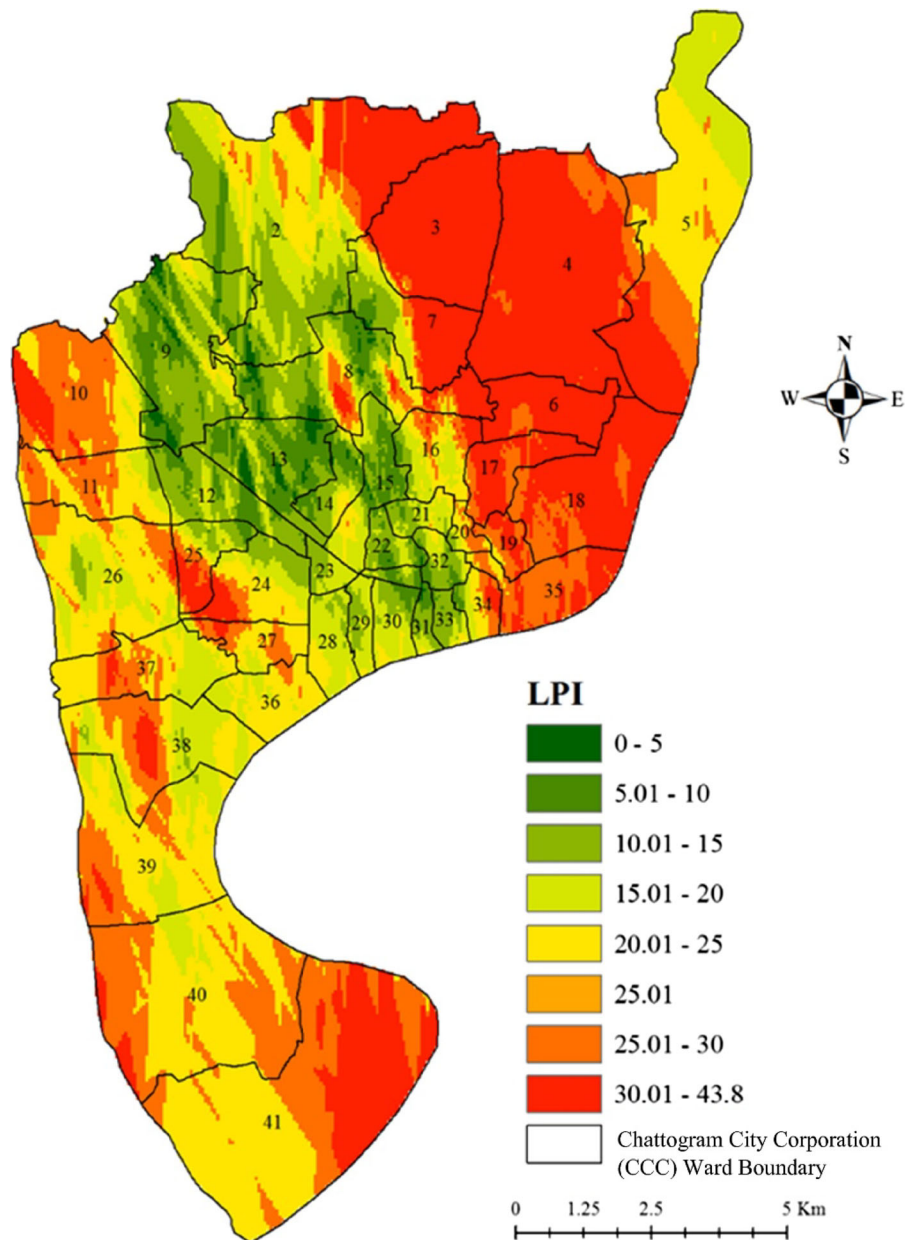
**Fig. 11** Liquefaction potential map of Chattogram City (T-Y method) by Kriging interpolation with anisotropy

geomorphological datasets and having a better match of the anisotropic distribution attribute to the accuracy of the developed susceptibility map.

The random distribution of data sets and suspicious input parameters at some locations may arise doubts for such quantitative hazard map. A second evaluation procedure is necessary, and therefore, simplified IDW interpolation was done for the selected region. The borehole points are scattered somewhat over the entire

region, which also supports IDW interpolation. Figure 9 depict the liquefaction hazard map based on IDW interpolation. The green zone in Fig. 9, which cover the center part of the city has minimum danger and said to be safe against liquefaction. The north side and south of the city was found severely susceptible for liquefaction. The alike distribution among the hazard maps based on different interpolation
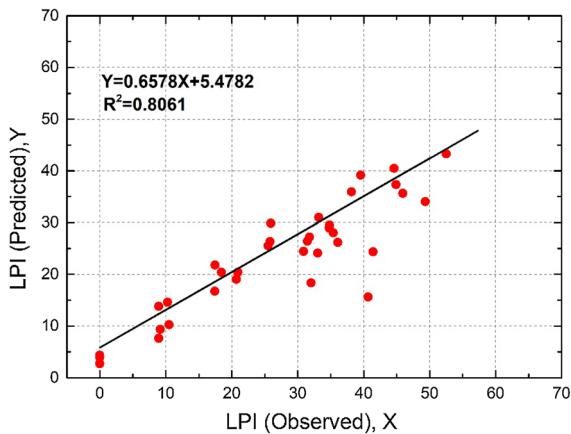
**Fig. 12** Observed and predicted LPI values at validation points (Idriss and Boulinger method) by Kriging interpolation with anisotropy
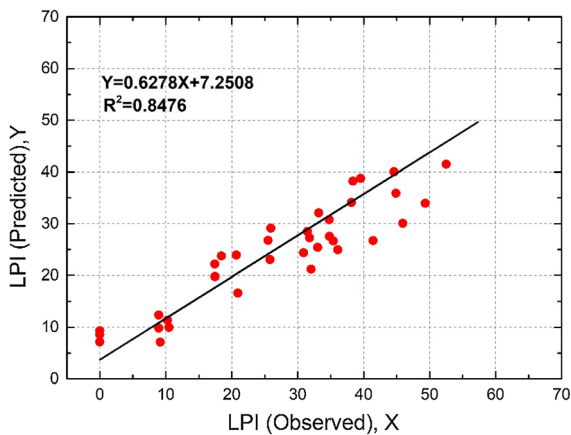


**Fig. 13** Observed and predicted LPI values at validation points (Idriss and Boulinger method) by Kriging interpolation with anisotropy

technique with directional variability implicitly proves the accuracy of the hazard map.

The discussion made above is based on the simplified procedure developed initially by Seed et al. and later updated by Idris and Boulinger. Determination of LPI involves uncertainties in extracting dataset, fixing parameters, etc. A cross-check of the developed hazard map with the different method is somewhat useful where actual parameters are hard to determine. Liquefaction assessment can be possible by experimentally, though the sampling and testing facility is seldom available. Considering the limitation of the proposed research, other simplified model based on in situ parameters was chosen.

Regarding simplified analysis, different code of practices and methods are found in technical writings. It is not worthy to compare all rather the widely used Idris and Boulinger method's verification is a plausible way to quantitatively describe the hazard scenario of the city due to earthquake-induced liquefaction. Toki-matsu and Yoshimi developed a scheme to estimate FS against liquefaction. Though the development of this method is dated back, it provides overall outcomes in real case studies (Chang et al. 2011). Therefore, LPI values were estimated based on the T-Y method and subsequently, kriging interpolation was applied to prepare a hazard map considering both isotropic and anisotropic condition. Figures 10 and 11 shows the hazard map of CMA for the isotropic and anisotropic condition, respectively. The trend of both isotropic and anisotropic condition portray alike distribution of Idris and Boulinger method. The green zone showing small LPI values are also compatible with the previous maps though safe zone extends to a slightly larger area than the former. Using the second data sets, a regression model for both isotropic and anisotropic conditions were developed and shown in Figs. 12 and 13, respectively. The computed R-squared values are greater than 0.80 in both cases. However, the larger regression coefficient was seen in anisotropic distribution, which justifies the directional variability of geological parameters. The approximation of LPI values not greater than 15.0 shows much consistency for the former method, i.e. Idris and Bulinger method. Regression coefficient also portrays a good approximation, though the nature of severity is same for all cases.

## 8 Conclusion

Having uncertainty in the step of liquefaction assessment, this research aimed to prepare a hazard map of a geographically and strategically important port city of the South Asian region, named Chattogram in Bangladesh. Two practically developed schemes were used to estimate FS after every 1.5 m of the selected locations. Summing up FS for a particular location, liquefaction severity was measured at all the discrete positions. Geospatial analysis using kriging interpolation was done to prepare a liquefaction hazard map over the Chattogram Metropolitan Area (CMA). The major portion of the city was found to extremely

susceptible to liquefaction hazard except for the central part, where small hillocks and quaternary formation were seen. Especially, the northern and southern part of CMA were identified as an extremely liquefied zone. The developed hazard map based on two approaches were further validated through a second dataset, and the regression coefficient was greater than 0.80 in all cases. Especially, the anisotropic consideration provides better consistency in both procedures. The alike distribution and validation, therefore, justify the prepared hazard scenario for liquefaction and can be an important indicator of the disaster mitigation plan. However, the investigation needs further sophisticated analysis to verify the existing procedure before incorporating into the code of practice and disaster guideline.

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