Liquefaction potential mapping of Newtown, Kolkata, India using Deterministic and Reliability analysis

Srijani Sett (srijanisett.18@gmail.com)
Indian Institute of Engineering Science and Technology https://orcid.org/0000-0002-3857-6879
Kalyan Kumar Chattopadhyay
Indian Institute of Engineering Science and Technology

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Srijani Sett[1] and Kalyan Kumar Chattopadhyay[2]

[1] Research Scholar, Department of Civil Engineering, Indian Institute of Engineering Science and Technology (IIEST) Shibpur, Howrah, West Bengal 711103, India. (**srijanisett.18@gmail.com**)

[2] Professor, Department of Civil Engineering, Indian Institute of Engineering Science and Technology (IIEST) Shibpur, Howrah, West Bengal 711103, India. (**kkc@civil.iiests.ac.in)**

Abstract

Liquefaction is a phenomenon where the effective stress of the soil gets reduced to zero and the soil losses its shear strength completely. Such occurrence is common during an earthquake and hence the need for evaluating the liquefaction potential of soil arises. The region of Newtown-Rajarhat is undergoing a massive industrial and residential growth and as the area has layers of sand and silt mixed with clay and organic matter, it is essential to determine its liquefaction potential. In this study, the deterministic methods proposed by Youd et al. (2001) and Boulanger and Idriss (2014) were utilized to evaluate the liquefaction potential of the region using 102 borehole data for earthquake magnitudes of 6 and 7. However it was observed that both methods gave different results for the same input parameters. The parameter uncertainties were identified and a reliability analysis was performed to represent the liquefaction potential in terms of reliability index and probability of liquefaction. The First-Order-Second-Moment (FOSM) method was utilized here and contour maps were prepared for depths of 7m and 13m for both the earthquake magnitudes. It was concluded that the study area is vulnerable to liquefaction at a depth of 13m in the regions of Newtown, Rajarhat and Sector V.

Keywords

Liquefaction potential, Contour maps, First Order Second Moment (FOSM) method, Probability of Liquefaction, Reliability Index.

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1. Introduction

During earthquakes, one of the major causes for massive building damage and destruction is the occurrence of liquefaction. Vigorous shaking, which occurs during an earthquake, can lead to build up of pore water pressure in undrained fine sands and silty soils. This can reduce the effective stress of the soil to zero, thereby resulting in complete loss of shear strength in soil. This phenomenon is known as liquefaction and it can result in sand boils, lateral spreading of soil, etc. An effective way to prevent this is by determining the liquefaction potential of soil. There are several ways to calculate the liquefaction potential eg. deterministic methods, probabilistic methods, etc. The deterministic method expresses the liquefaction potential of soil by a factor of safety which is calculated using SPT value, CPT value, shear wave velocity of a soil. Initially this method was only applicable for sands but recent advances have made it possible to apply it on all types of soil.

However, this method has its disadvantages, the most common being that it lacks precision and is conservative in nature. It has been found that certain assumptions made in the method have proven to give uneconomical results thereby making it uncertain in nature. To address the uncertainties, reliability analysis along with deterministic methods can be used to determine the liquefaction potential of soils. Reliability methods express the liquefaction potential of a soil by a reliability index and probability of liquefaction. Not only does it determine the safety of a soil against liquefaction, but it also helps us understand how much safe or unsafe a soil is by using probability percentages.

2. Previous Studies

The deterministic approach was first developed by Seed and Idriss (1970) and has been since known as 'The Simplified Procedure'. It evaluates the liquefaction potential of soil using basic soil parameters like SPT value, fines content, overburden pressure, etc via a factor of safety. Since then a number of researchers have incorporated several factors and corrections to make this procedure more accurate. Youd et al. (2001) incorporated the corrections and proposed a new set of equations. Andrews and Martin (2000) considered soil parameters clay content and liquid limit together to assess the liquefaction susceptibility of silty soils. Cetin et al. (2004) developed deterministic and probabilistic correlations for assessment of likelihood of initiation of liquefaction. They also proposed a stochastic model, developed within a Bayessian framework, for assessment of seismic liquefaction risk initiation which addressed the relevant uncertainties. Boulanger and Idriss (2004) proposed the evaluation procedure of liquefaction potential or cyclic failure of clay-like fine grained soil in line with the Seed-Idriss (1970) procedure. Bray and Sanchio (2006) reported the criteria for determination of liquefaction susceptibility of fine grained soil based on their experiments of cyclic laboratory tests on silty and clayey soil. Boulanger and Idriss (2006) proposed liquefaction susceptibility criteria for saturated silts and clays on the basis of their stress strain behavior. Idriss and Boulanger (2010) updated the SPT based liquefaction case histories and gave a probabilistic solution for the liquefaction triggering correlation [Idriss and Boulanger (2004), (2008)]. Boulanger and Idriss (2014) presented CPT-based liquefaction procedure and studied the effect of change of MSF in the SPT based liquefaction co-relations.

U.S Army Corps (1997) introduced the basic probability and reliability methods that can be used in Geotechnical engineering and gave values of target reliability indices for different expected performance level. Duncan (2000) has shown that simple reliability analysis can be incorporated in routine geotechnical practices by solving examples to understand the Taylor series expansion, uncertainty and probability of failure concepts. Juang (2000) calculated reliability indices by Bayes' Theorem and formed a mapping function between factor of safety and actual probability. Hwang (2004) developed a reliability method based on the Seed (1985) liquefaction analysis method and formed probabilistic CRR curves from probability density distribution function and regression of liquefied case history data of notable earthquakes. Juang (2006) used Neural Network to determine a limit state model for liquefaction resistance from field CPT data. Using First Order Reliability Method (FORM), the reliability analysis was performed and model uncertainty was estimated by Bayessian mapping functions. From the $P_L - \beta$ mapping functions, the probability of failure was determined. A comparative study was conducted on SPT data by different reliability methods (FOSM, Advanced FOSM, Monte Carlo Simulation (MCS) and Point Estimation Method (PEM)) by Jha et al. (2008) against soil liquefaction and presented a combined method of FOSM and PEM to find out a minimum safety factor to be adopted in soil liquefaction analysis. Singnar and Sil (2018) evaluated the liquefaction potential of Guwahati city using both Deterministic and FOSM method conducted on 82 boreholes considering the Great Shillong 1897 earthquake of magnitude 8.1. The uncertainties in deterministic method were corrected in the reliability analysis and subsequent contour maps were plotted which shows that the city is vulnerable to liquefaction even at a depth of 15m. Umar et al. (2018) performed deterministic and reliability analysis (FOSM) on 234 field data cases in Bihar. They mapped out the reliability index and probability of failure due to liquefaction for depths of 1.5m, 3m and 5m from which they concluded that reliability analysis can be used in geotechnical projects.

Chakraborty et al. (2004) have microzonised Kolkata city by developing contour maps at depths of 2.5m, 5m, 7.5m and 10m in terms of liquefaction assessment by deterministic methods. They concluded that the most susceptible area is South Kolkata whereas Central Kolkata happens to be most stable against liquefaction. Shinley and Narajan (2011) evaluated seismic microzonation of Kolkata city and deemed the Nagerbazar and Nimtala areas to be safest in seismic concern. Nath et al. (2017) examined 654 sites covering an area of 435 km^2 of Kolkata city and performed in depth liquefaction potential analysis. They concluded that the artificially filled areas of Salt Lake, Newtown and Rajarhat were found to be at high soil liquefaction risk.

Previous literature review shows that different deterministic methods were developed to evaluate the liquefaction potential of soil among which some methods continue to be used in construction projects. The uncertainties related to parameters and analytical models remain unaddressed in deterministic approaches which can make them conservative in nature. Reliability analysis methods have been studied and implemented on field cases where the liquefaction potential of soil is measured by a probability of liquefaction. Results of reliability analysis are not only economical but they represent the soil susceptibility to liquefaction in a way which is better suited to the engineer.

The objective of this paper is to evaluate the liquefaction susceptibility of Newtown-Rajarhat study area for two earthquake magnitudes of 6 and 7. Comparative study is conducted by two deterministic methods of Youd et al. (2001) and Boulanger and Idriss (2014) and contour maps are constructed at 7m and 13m depths. Reliability analysis is performed on both the deterministic methods and subsequent contour maps are constructed for Boulanger and Idriss (2014) method at depths 7m and 13m to assess the regions in the study area that are most vulnerable to liquefaction.

3. Topography

West Bengal is situated in the Bengal fan basin which has been considered as an active seismic zone. The Bureau of India Standard (BIS2002) places West Bengal in the seismic zones of II to V and its corresponding peak Ground acceleration (PGA) is of the order of 0.1g to 0.36g. Though West Bengal experiences sparse seismicity, some devastating earthquakes like 1857 Great Shillong Earthquake (M = 8.1), 1934 Bihar-Nepal Earthquake (M = 8.1), 1950 Assam earthquake (M = 8.7), 1964 Sagar Island Earthquake (M = 5.4) and in recent times, 2011 Sikkim Earthquake (M = 6.9) have made the region hazardous.

Kolkata is the capital of West Bengal and is the major commercial and industrial hub of the state. It is well connected to the rest of the country through roadways, railways, waterways and airways. In 2009, the North eastern part of Kolkata city was established as Newtown by West Bengal Housing Infrastructure Development Corporation (WBHIDCO). Since then Newtown and its surrounding Rajarhat region has developed immensely in terms of industries, hospitalities, residential and commercial aspect and has been named as Solar city. Further projects are being planned and constructed here, an important one being the Kolkata metro for Line 6 which will cover a distance of 30km connecting the Netaji Subhas Chandra Bose International airport with New Garia. The entire region falls in both the seismic zones of III and IV and is underlain by major faults of Eocene Hinge Zone, Dhubri fault, Dauki fault, Garhmoyna-Khandaghosh fault, Jangipur-Gaibandha fault, Pingla fault, Debagram-Bogra fault, Rajmahal fault, Sylhet fault and Sainthia-Bahmani fault [Nath et al. (2014)] A seismic map has been prepared for the last 100 years and is presented in Fig. 1. It can be observed that earthquake magnitude in the range of 4.0 to 4.9 and 5.0 to 5.9 has occurred mostly and spread throughout Bangladesh, Nepal, Myanmar and North East region of India.

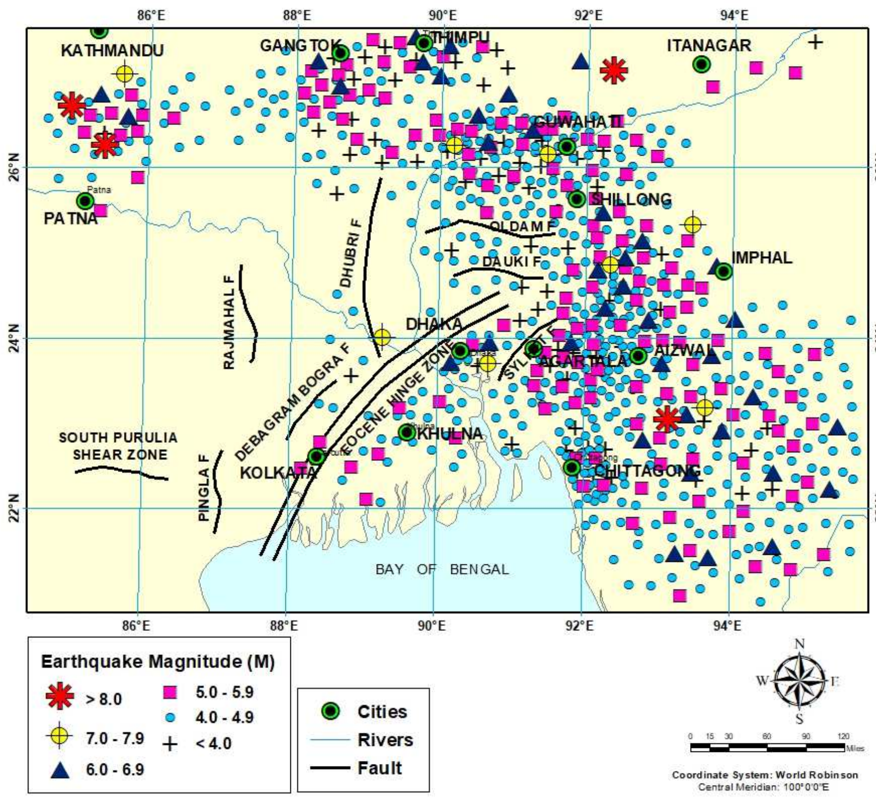

Fig. 1 Seismic map of Eastern India, North-East India, Nepal, Bhutam and Myanmar for the last 100 years

The area chosen for this study lies between latitudes and longitudes of 22º 33' 32" N to 22º 39' 04" N and 88º 22' 24" E to 88º 30' 17" E. A total of 14 sites were carefully selected and considered for this study which are marked and shown in Fig. 2. Three to four sites are grouped together based on their proximity to each other and formed into four such regions of Rajarhat, Newtown, Sector V and South Dum Dum. The average soil properties along the depth of these regions are summarized and presented in Table 1. Detailed borelog showing the different soil strata situated in the locations of Newtown, Rajarhat, Sector V and South Dum Dum are shown in Fig. 3.

Table 1 Average soil properties of Newtown-Rajarhat area

Region	Stratum	Depth	Characteristics of soil	Range of N value
Rajarhat	I	0.0 – 14.0	Soft to medium, blackish grey clayey silt with decomposed wood and organic matter	3 to 5
	II	14.0 – 18.5	Stiff to very stiff, brownish grey silty clay with sand mixture	12 to 20
	III	18.5 – 24.4	Medium dense, yellowish grey fine silty sand with kankars	16 to 26
	IV	24.4 – 32.0	Dense to very dense, brownish grey silty sand	19 to 25
Newtown	I	0.0 – 9.2	Soft to medium, deep grey clayey silt with	1 to 10

			traces of sand and decomposed wood.	
	II	9.2 – 16.5	Soft to medium, yellowish grey silty clay with mica and sand mixture	13 to 18
	III	16.5 – 34.7	Dense to very dense, brownish grey silty sand with mica	25 to 30
Sector V	I	0.0 – 5.8	Soft to medium, brownish grey clayey silt with fine sand mixture	4 to 6
	II	5.8 – 26.0	Medium dense, yellowish grey silty fine sand with mica and clay binder	16 to 19
	III	26.0 – 37.1	Very dense, grayish silty sand with mica	23 to 30
South Dum Dum	I	0.5 – 10.4	Medium to stiff, deep blackish grey sikty clay with decomposed wood	4 to 10
	II	10.4 – 15.5	Very stiff, light grey clayey silt with organic matter	16 to 18
	III	15.5 – 35.1	Very stiff to hard, yellowish grey clayey silt with laminated fine sand	16 to 22

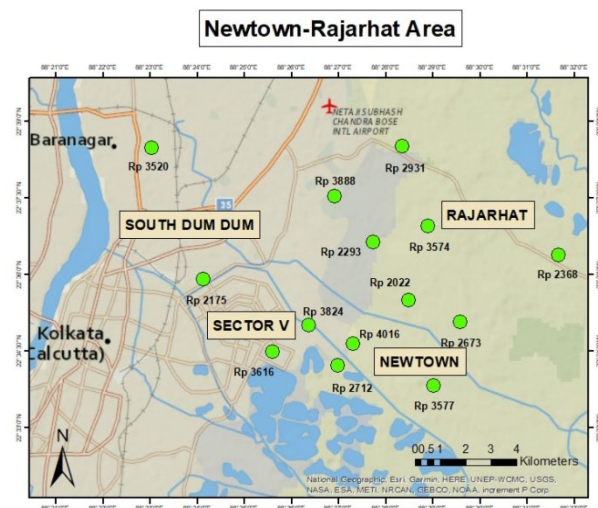

Fig. 2 Map showing the borehole sites (marked by green dots) in Newtown-Rajarhat area

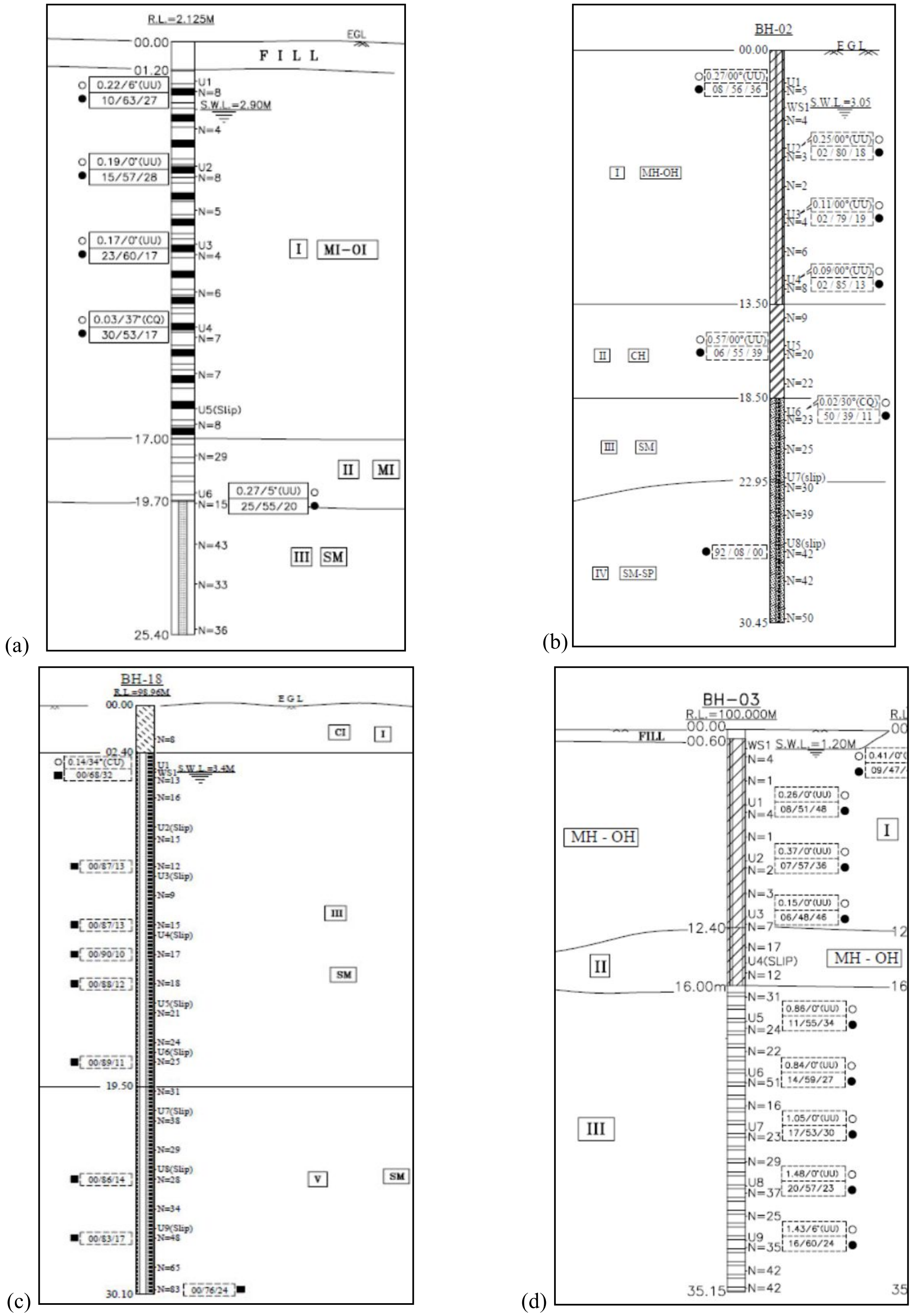

Fig. 3 Typical borehole showing the lithological variation in (a) Newtown, (b) Rajarhat, (c) Sector V and (d) South Dum Dum

4. Methodology

The evaluation of liquefaction potential for the Newtown-Rajarhat study area is determined by both deterministic and probabilistic methods. Deterministic methods proposed by Youd et al. (2001) and Boulanger and Idriss (2014) are used on 102 boreholes distributed in 14 sites throughout the study area to assess the susceptibility of liquefaction in this region. Reliability analysis was conducted on both the deterministic procedures and contour maps are developed for the study area at depths of 7m and 13m for earthquake magnitude of 6 and 7.

4.1 Deterministic Approach

The Deterministic approach uses a factor of safety against liquefaction for earthquakes of different magnitudes by calculating the cyclic stress ratio (CSR) and the cyclic resistance ratio (CRR) of soil. CSR is the dynamic load imposed on soil during activities like earthquake, tsunamis, pile driving etc and CRR is the capacity of the soil to resist this load. The liquefaction potential of the soil is thus determined by a Factor of Safety which is the ratio of CRR to CSR. The soil is considered unsafe against liquefaction when FS < 1, it is considered safe against liquefaction when FS > 1, and for FS = 1, it becomes a marginal case.

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

Youd et al. (2001): The CSR in this method is determined from the simplified procedure previously proposed by Seed and Idriss (1970) which is given as:

$$CSR = 0.65 \times \frac{\tau_{max}}{\sigma'_v} = 0.65 \times \frac{a_{max}}{g} \times \frac{\sigma_v}{\sigma'_v} \times r_d \tag{2}$$

where a_{max} = maximum horizontal acceleration at ground surface, g = acceleration due to gravity, σ_v = total vertical stress at depth z, σ'_v = effective vertical stress at depth z, r_d = shear stress reduction factor.

As the soil is not a rigid column, a factor to consider the flexibility of soil is used which is known as shear stress reduction factor. Its maximum value is 1 which is at the ground surface and its value decreases with increase in depth (z). It is evaluated using the following equations:

For $z \leq 9.15$, $r_d = 1.0 - 0.00765\, z$, (3a)

and for $9.15 \leq z \leq 23$, $r_d = 1.174 - 0.0267\, z$. (3b)

The Cyclic Resistance Ratio (CRR) of soil is related to various in situ soil parameters like CPT penetration resistance, SPT blow count or Shear wave velocity V_s. In general, the CRR is calculated for an effective overburden pressure σ'_v = 1 atm and earthquake magnitude M_w = 7.5. To evaluate CRR for different earthquake magnitudes and overburden pressure, the parameters MSF and K_σ are included. The adjusted equation is given as:

$$CRR_{M,K_\sigma} = CRR_{7.5,1} \times MSF \times K_\sigma \tag{4}$$

$$\text{MSF} = \frac{10^{2.24}}{{M_w}^{2.56}} \tag{5}$$

$$K_\sigma = (\sigma'_v/P_a)^{(f-1)} \quad (6)$$

where MSF is the Magnitude scaling factor which accounts for the earthquake magnitude M under consideration, K_σ is the Overburden correction factor to account for overburden stresses at depth of interest and P_a is atmospheric pressure. The CRR is calculated here using the SPT (N) value of the soil. The N value collected from field data is corrected for a number of factors such as hammer efficiency (C_E), borehole diameter (C_B), rod length (C_R), sampler with or without liner (C_S) and overburden stress (C_N).

$$(N_1)_{60} = C_E\, C_B\, C_R\, C_S\, C_N\, N \quad (7)$$

where, $C_N = \sqrt{\frac{P_a}{\sigma'_v}} \leq 1.7$. The expression for CRR is given as

$$CRR_{7.5,1} = \frac{1}{34-(N_1)_{60CS}} + \frac{(N_1)_{60CS}}{135} + \frac{50}{(10 \times (N_1)_{60CS})^2} - \frac{1}{200} \quad (8)$$

The term $(N_1)_{60CS}$ is calculated using the equation

$$(N_1)_{60CS} = \alpha + \beta (N_1)_{60} \quad (9)$$

where α and β are two constants which are functions of fines content (FC) of soil. When FC ≤ 5%, the value of α = 0 and β = 1.0, for FC ≥ 35%, α = 5 and β = 1.2 and for 5% < FC < 35%, the value of α and β are calculated using equation (9a) and (9b) respectively.

$$\alpha = exp\left[1.76 - \left(\frac{190}{FC^2}\right)\right] \quad (9a)$$

$$\beta = \left[0.99 + \left(\frac{FC^{1.5}}{1000}\right)\right] \quad (9b)$$

Boulanger and Idriss (2014): This is the most recent and updated procedure to evaluate the liquefaction potential of soil and is used commonly in construction projects. In this method, due to certain modifications in the parameters [r_d, MSF, C_N, K_σ and $(N_1)_{60CS}$], the value of CSR and CRR is modified. The equation to evaluate CSR is the one proposed by Seed and Idriss (1970) which is mentioned in equation (2).

In Youd et al. (2001) method, stress reduction factor (r_d) was a function of depth only, whereas in Boulanger and Idriss (2014) method, it is a function of depth as well as earthquake magnitude (M).

$$r_d = \exp\left[\alpha(z) + \beta(z)\right] \quad (10)$$

$$\text{where, } \alpha(z) = 1.0121 - 1.125\, sin\left(\frac{z}{11.23} + 5.133\right) M \quad (10a)$$

$$\beta(z) = 0.106 + 0.118\, sin\left(\frac{z}{11.28} + 5.142\right) \quad (10b)$$

The expression of CRR is given as

$$CRR_{7.5,1} = \exp\left\{\frac{(N_1)_{60CS}}{14.1} + \left(\frac{(N_1)_{60CS}}{126}\right)^2 - \left(\frac{(N_1)_{60CS}}{25.4}\right)^2 - 2.8\right\} \quad (11)$$

where the SPT N value for equivalent clean sand is $(N_1)_{60CS} = (N_1)_{60} + \Delta(N_1)_{60}$. The corrected N value $(N_1)_{60}$ is evaluated using equation (7) but the overburden correction factor C_N is calculated according to equation (12).

$$C_N = \left(\frac{P_a}{\sigma_v'}\right)^a \leq 1.7 \qquad (12)$$

$$a = 0.784 - 0.0768\sqrt{(N_1)_{60CS}} \qquad (12a)$$

The term $\Delta(N_1)_{60}$ is a function of fines content (FC) and is expressed as

$$\Delta(N_1)_{60} = \exp\left\{1..63 + \frac{9.7}{FC+0.01} - \left(\frac{15.7}{FC+0.01}\right)^2\right\} \qquad (13)$$

The $CRR_{7.5,1}$ expressions is corrected by using the factors MSF and K_σ which are given as

$$MSF = 1 + (MSF_{max} - 1)\ \{8.64 \exp\left(\frac{-M}{4}\right) - 1.325)\} \qquad (14)$$

$$K_\sigma = 1 - C_\sigma ln\left(\frac{\sigma'_{vo}}{P_a}\right) \leq 1.1 \qquad (15)$$

$$C_\sigma = \frac{1}{18.9 - 2.55\sqrt{(N_1)_{60CS}}} \leq 0.3 \qquad (15a)$$

where the value of MSF_{max} = 1.8 for sand and MSF_{max} = 1.09 for clay & plastic silt.

The two procedures of Youd et al. (2001) and Boulanger and Idriss (2014) are utilized on all 102 boreholes in the study area for two earthquake magnitudes of 6 and 7. A typical borelog (borehole no. 2 of site Rp 3888), situated in Rajarhat region, is presented in Table 2 and Table 3 showing the soil properties along depth and calculated values of $CRR_{7.5,1}$, CSR, FS for both methods of Youd et al. (2001) and Boulanger and Idriss (2014).

Table 2 Calculation of Factor of safety by Youd et al. (2001) procedure for a typical borehole for M = 7

Depth (m)	Characteristics of soil	Bulk Density (kN/m^3)	Fines content %	N value	$CRR_{7.5,1}$	CSR	FS
2.18	Brownish grey, clayey silt with sand mixture.	18.74	93	4	0.1100	0.1089	1.1207
5.23	Deep grey, clayey silt with traces of organic matter.	18.74	97	4	0.1080	0.1446	0.6980
8.18		14.91	88	3	0.1027	0.1874	0.5229
11.18	Deep grey, silty clay with traces of sand mixture.	17.95	96	12	0.1880	0.1672	0.9103
14.18	Brownish grey, clayey silt	19.72	94	20	0.2485	0.1467	1.2329
17.18	Brownish grey, clayey silt with traces of steel grey patches.	19.03	94	17	0.2028	0.1357	1.0550
20.23		19.03	94	23	0.2461	0.1230	1.3529
23.23	Brownish grey, clayey silt	19.03	95	22	0.2186	0.1146	1.2433
26.23		19.03	95	21	0.1978	0.1092	1.1424

29.18	Brownish grey, silty sand with calcareous nodules	20.21	97	31	0.2453	0.1004	1.4489
33.73	Brownish grey, clayey silt with sand mixture	20.50	56	53	0.5734	0.0953	3.4006

Table 3 Calculation of Factor of safety by Boulanger and Idriss (2014) procedure for a typical borehole for M = 7

Depth	Characteristics of soil	Bulk Density	Fines content	N value	$CRR_{7.5,1}$	CSR	FS
2.18	Brownish grey, clayey silt with sand mixture.	18.74	93	4	0.1177	0.1088	1.2010
5.23	Deep grey, clayey silt with traces of organic matter.	18.74	97	4	0.1131	0.1414	0.8486
8.18		14.91	88	3	0.1099	0.1794	0.6530
11.18	Deep grey, silty clay with traces of sand mixture.	17.95	96	12	0.1648	0.1601	1.0733
14.18	Brownish grey, clayey silt	19.72	94	20	0.2071	0.1463	1.4413
17.18	Brownish grey, clayey silt with traces of steel grey patches.	19.03	94	17	0.1772	0.1440	1.2193
20.23		19.03	94	23	0.2111	0.1371	1.5076
23.23	Brownish grey, clayey silt	19.03	95	22	0.1935	0.1306	1.4201
26.23		19.03	95	21	0.1800	0.1250	1.3579
29.18	Brownish grey, silty sand with calcareous nodules	20.21	97	31	0.2277	0.1148	1.8125
33.73	Brownish grey, clayey silt with sand mixture	20.50	56	53	0.5628	0.1099	4.3281

4.2 Reliability Analysis

Deterministic approach uses a factor of safety to determine whether a soil will liquefy or not but fails to give a probability of failure due to liquefaction based on this safety factor. A probability of failure merely does not predict the chances of occurrence or non-occurrence of liquefaction, rather predicts how safe or unsafe a soil is against liquefaction. The statistical, model and parameter uncertainties remain unaddressed in deterministic methods thereby making it less accurate in nature. By using reliability analysis, the uncertainties can be incorporated and probability of failure due to liquefaction can be obtained. This becomes useful during various construction projects as the engineer is given the freedom to choose the type and amount of mitigation measure to be adopted in seismic regions, thereby making the approach economical.

To conduct a reliability analysis, first a deterministic model with a performance function is required. A set of random variables on which the performance function varies are identified and their mean and standard deviation values are determined. Lastly, a limit state for the performance function is to be assigned and a method is chosen which defines the mean and standard deviation values of this limit state function. The reliability index is evaluated with the help of this method and their subsequent probability of liquefaction is determined. In the present study, the deterministic models selected are the procedures proposed by Youd et al. (2001) and Boulanger and Idriss (2014). The factor of safety (FS) determined by the deterministic models is being used as the performance function. The limit state function (FS = 0) is designated by Z, which takes the form Z = R – S, where R is the resisting load (CRR) and S is the load imposed on the soil (CSR). When Z > 0, liquefaction doesn't occur, Z < 0, liquefaction occurs and Z = 0 is considered as a limit state condition. The method used in this study to define the mean and standard deviations of the limit state is First Order Second Moment (FOSM) Method.

First Order Second Moment Method (FOSM): This method requires the first order terms of the Taylor series expansion and its first two moments (mean and standard deviation) to determine the reliability index. The mean and standard deviation of the random variables R and S are denoted as μ_R, μ_S and, σ_R, σ_S. The mean (μ_Z), standard deviation (σ_Z) and coefficient of variation (δ_Z) of performance function Z is calculated as

$$\mu_z = \mu_R - \mu_S \tag{16}$$

$$\sigma_Z = \sqrt{\sigma_R^2 + \sigma_S^2} \tag{17}$$

$$\delta_z = \frac{\sigma_z}{\mu_z} \tag{18}$$

The mean and coefficient of variation of CSR is determined by

$$\mu_{CSR} = 0.65(\frac{\mu_{a_{max}}}{g})(\frac{\mu_{\sigma_v}}{\mu_{\sigma_v'}})(\frac{\mu_{r_d}}{\mu_{MSF}})(\frac{1}{\mu_{K_\sigma}}) \tag{19}$$

$$\delta_{CSR}^2 = \delta_{a_{max}}^2 + \delta_{\sigma_v}^2 + \delta_{\sigma_v'}^2 + \delta_{r_d}^2 + \delta_{MSF}^2 + \delta_{K_\sigma}^2 - 2\rho_{\sigma_v \sigma'_v} \sigma_v {\sigma'}_v \tag{20}$$

where $\rho_{\sigma_v \sigma'_v}$ = correlation co-efficient between σ_v and σ'_v. The coefficient of variation of CRR is determined as:

$$\delta_{CRR} = \frac{\Delta CRR}{2\mu_{CRR}} \tag{21}$$

where $\Delta CRR = CRR\left(\mu_{(N_1)_{60}} + \sigma_{(N_1)_{60}}\right) - CRR\left(\mu_{(N_1)_{60}} - \sigma_{(N_1)_{60}}\right)$

Therefore Reliability Index (β) is a ratio of mean to standard deviation and is represented by

$$\beta = \frac{\mu_Z}{\sigma_Z} = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \tag{22}$$

After obtaining the value of β, the probability of liquefaction can be expressed as

$$P_L = 1 - \varphi(\beta) \tag{23}$$

where φ(β) = normal cumulative probability distribution of random variables.

5. Results And Discussion

A deterministic study based on the methods proposed by Youd et al. (2001) and Boulanger and Idriss (2014) has been conducted on the Newtown-Rajarhat area and the results are compared. Reliability analysis is performed on both the deterministic methods and subsequent contour maps are prepared for deterministic and reliability analysis. The soil properties used are the bulk density, SPT value, depth of groundwater table and fines content varying along the depth of soil. Two earthquake magnitudes (M = 6 and 7) have been used and their corresponding peak ground acceleration are taken as 0.119g and 0.17g respectively [Chakraborty et al. (2004)].

Factor of safety and reliability index values are obtained for all 102 boreholes which are plotted along depth (Fig. 4 and Fig. 5 respectively) following the procedures of Youd et al. (2001) and Boulanger and Idriss (2014) for earthquake magnitudes of 6 and 7. The Factor of safety values are divided into three zones which are 0 to 0.5, 0.5 to 1.0 and > 1.0 and are labeled as critical, moderately critical and safe. Similarly, the reliability index values are categorized into three zones of < -2.0, -2.0 to 1.0 and > 1.0 which are marked as critical, moderately critical and safe. The zones in both cases are demarcated with dot and dash lines.

Fig. 4 depicts that the Youd et al. (2001) method tends to give lower factor of safety values compared to those given by Boulanger and Idriss (2014) method. This may be due to the factors like Magnitude Scaling Factor (MSF), stress reduction factor (r_d), correction for overburden stress (C_N), corrected SPT value [$(N_1)_{60CS}$], overburden correction pressure (K_σ) which are calculated more accurately in the Boulanger and Idriss (2014) method.

In Fig. 4 and Fig. 5, it is observed that most of the factor of safety and reliability index points fall in the safe and moderately critical zone and a very few of them fall in the critical zone. Also, comparing the plots it can be observed that the factor of safety points in the moderately critical and critical zone are more in number than the reliability index points in those zones. This may be attributed to the fact that there are certain uncertainties involved in deterministic methods that are addressed by the reliability analysis which gives more accurate results.

The soil shows susceptibility to liquefaction up to 30m of depth for factor of safety and reliability index graphs. To understand the susceptibility of the soil at different depths, the soil profile is divided into two layers based on the SPT borelogs whose average depths are 7m and 13m. Factor of safety, reliability index and their corresponding probability of liquefaction values are calculated at these average depths for both earthquake magnitudes and the most vulnerable borehole of each site are presented in Table 4 and Table 5 respectively.

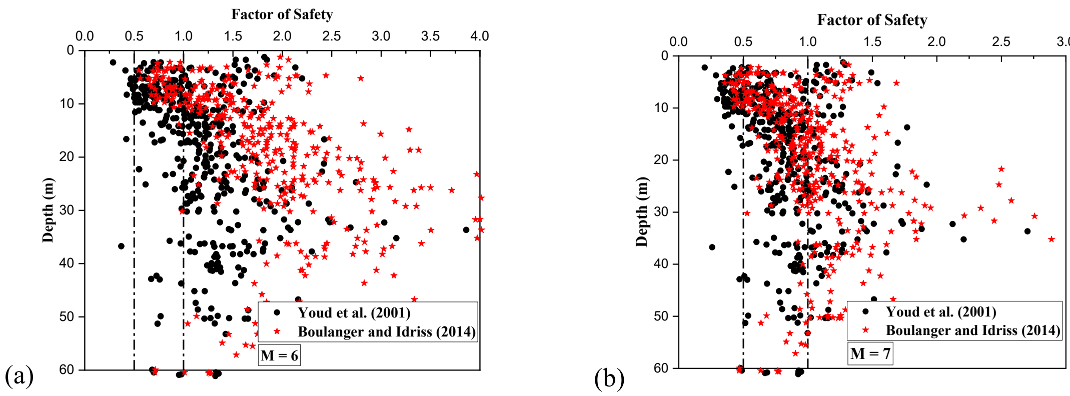

Fig. 4 Factor of Safety vs Depth [Youd et al. (2001) and Boulanger and Idriss (2014)] for (a) M = 6 and (b) M = 7

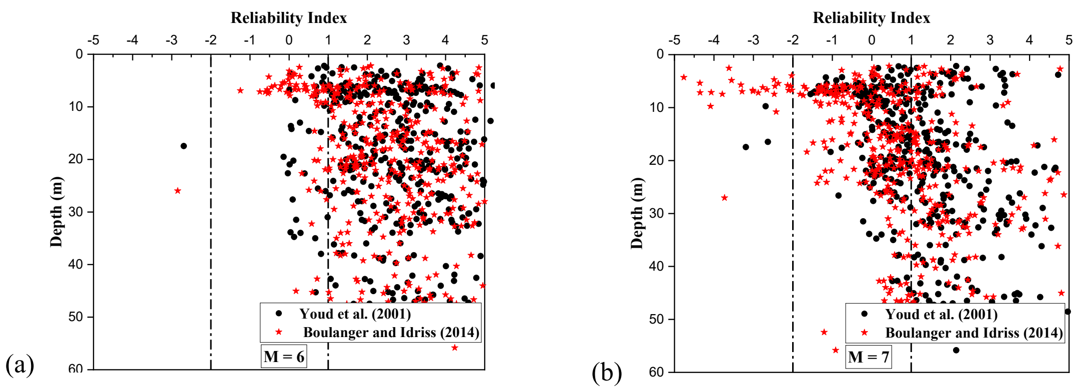

Fig. 5 Reliability Index vs Depth [Youd et al. (2001) and Boulanger and Idriss (2014)] for (a) M = 6 and (b) M = 7

Table 4 Factor of Safety (FS), Reliability Index (β) and Probability of liquefaction (P_L) values [Youd et al. (2001) and Boulanger and Idriss (2014)] for M = 7 at a depth 7m

Location No.	Youd et al. (2001)			Boulanger and Idriss (2014)		
	FS	β	P_L %	FS	β	P_L %
2022	0.355	-0.309	62.14	0.538	-0.900	81.60
2175	0.402	-1.090	86.21	0.584	-1.275	89.89
2293	0.381	-2.037	74.52	0.400	-1.178	88.06
2673	0.338	-0.214	58.46	0.473	-1.631	94.85
2712	0.540	-1.121	86.89	0.781	-1.256	89.54
2931	0.522	-0.134	55.32	0.673	-0.899	81.57
3520	0.791	-0.987	83.82	0.809	-2.876	99.80
3574	0.353	-1.513	93.49	0.356	-3.604	99.10
3577	0.664	-0.960	83.15	0.729	-3.337	99.96
3616	0.321	-1.431	78.62	0.369	-1.452	92.68

3824	0.345	0.170	43.24	0.458	0.054	47.84
3888	0.523	-0.337	63.19	0.653	-0.956	83.05
4016	0.847	1.307	09.56	1.144	1.305	09.59

Table 5 Factor of Safety (FS), Reliability Index (β) and Probability of liquefaction (P_L) values [Youd et al. (2001) and Boulanger and Idriss (2014)] for M = 7 at a depth 13m

Location	Youd et al. (2001)			Boulanger and Idriss (2014)		
No.	FS	β	P_L %	FS	β	P_L %
2022	0.411	0.161	43.60	0.617	0.014	49.44
2175	0.856	0.982	16.31	0.904	0.595	27.59
2293	0.838	1.531	06.18	1.009	0.942	17.31
2673	0.809	0.372	35.49	0.959	0.890	20.89
2712	0.508	-2.537	99.44	0.748	-3.043	99.88
2931	0.743	1.245	10.66	0.876	0.832	20.27
3520	1.029	1.393	08.18	1.132	0.679	24.85
3574	0.690	0.955	16.98	0.862	0.583	27.91
3577	0.541	1.194	11.62	0.689	0.477	31.67
3616	0.628	0.978	16.41	0.758	0.076	46.98
3824	0.788	0.781	21.74	1.010	-0.084	53.35
3888	0.511	0.751	22.64	0.703	0.561	28.74
4016	0.798	-0.162	56.43	2.034	2.026	02.14

Contour maps are constructed for both the deterministic methods of Youd et al. (2001) and Boulanger and Idriss (2014) for earthquake magnitudes of 6 and 7 at depth 7m and 13m which are presented in Fig. 6 to Fig. 9. Comparing the contour maps it can be seen that Boulanger and Idriss (2014) [Fig. 6(b), Fig. 7(b), Fig. 8(b) and Fig. 9(b)] illustrates most of the region to be much safer than the Youd et al. (2001) ones [Fig. 6(a), Fig. 7(a), Fig. 8(a) and Fig. 9(a)]. The regions of Newtown, Rajarhat, Sector V and South Dum Dum appear to be most vulnerable to liquefaction at both depths of 7m and 13m. Therefore it can be concluded that Youd et al. (2001) procedure appears to be more conservative than Boulanger and Idriss (2014) procedure, hence reliability index contour maps are constructed for Boulanger and Idriss (2014) method at 7m and 13m depth for M = 6 (Fig. 10) and M = 7 (Fig. 11).

The relation between factor of safety and probability of liquefaction for both the deterministic procedures of Youd et al. (2001) and Boulanger and Idriss (2014) is depicted graphically in Fig. 12. It can be observed that there is a difference of almost 0.2 between both the methods which can be explained by the fact that some factors, like MSF, $(N_1)_{60CS}$, r_d, C_N, K_σ, are calculated more accurately in the Boulanger and Idriss (2014) method for which the curve (red) tends to be on the higher side of the factor of safety (x-axis) as well as the probability of liquefaction (y-axis) of the graph.

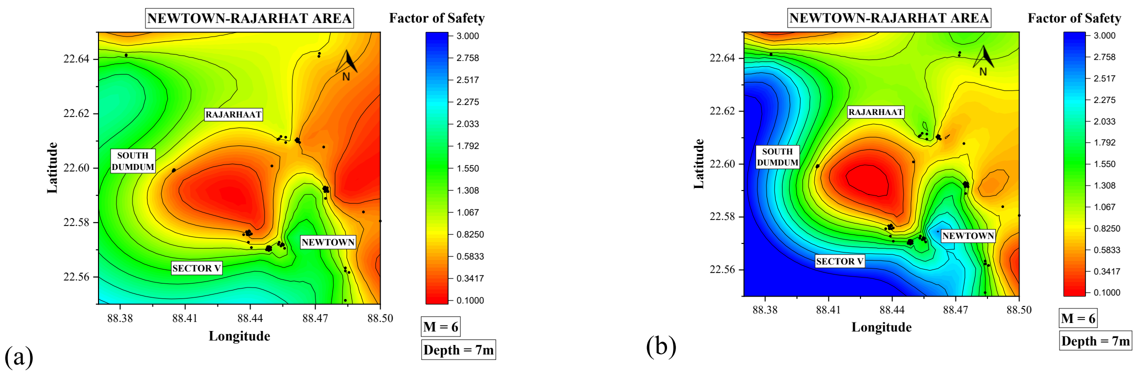

Fig. 6 Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 6 and Depth = 7m

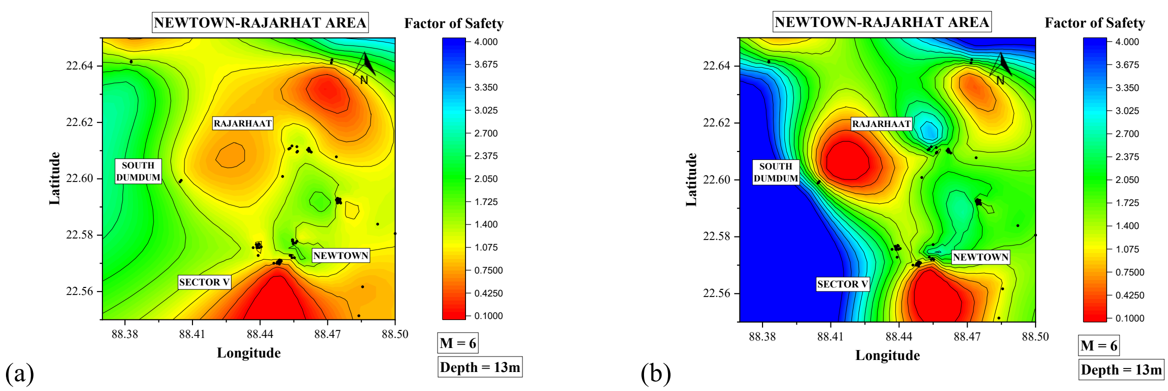

Fig. 7 Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 6 and Depth = 13m

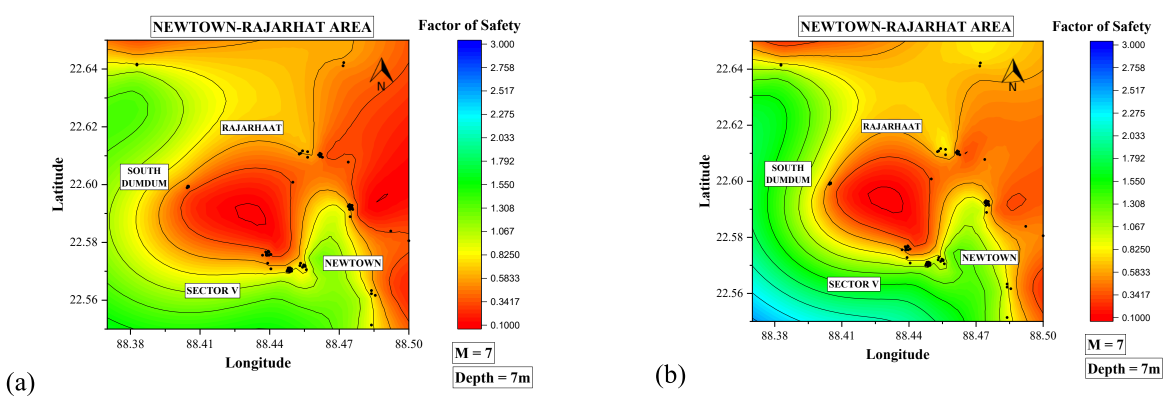

Fig. 8 Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 7 and Depth = 7m

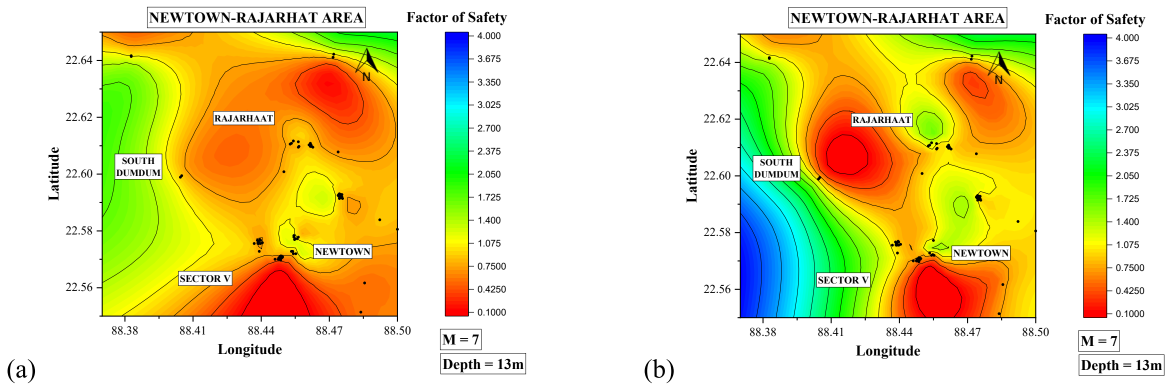

Fig. 9 Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 7 and Depth = 13m

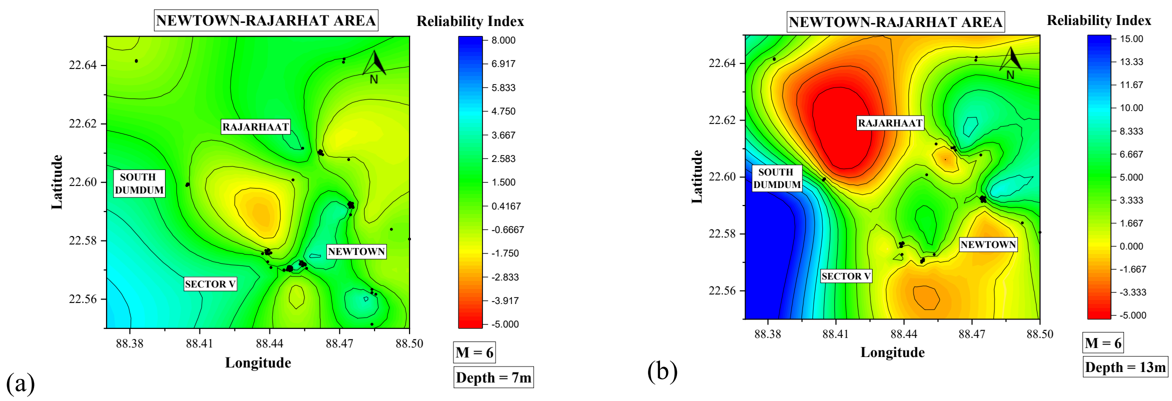

Fig. 10 Reliability Index Contour map by Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 6 at (a) Depth = 7m and (b) Depth = 13m

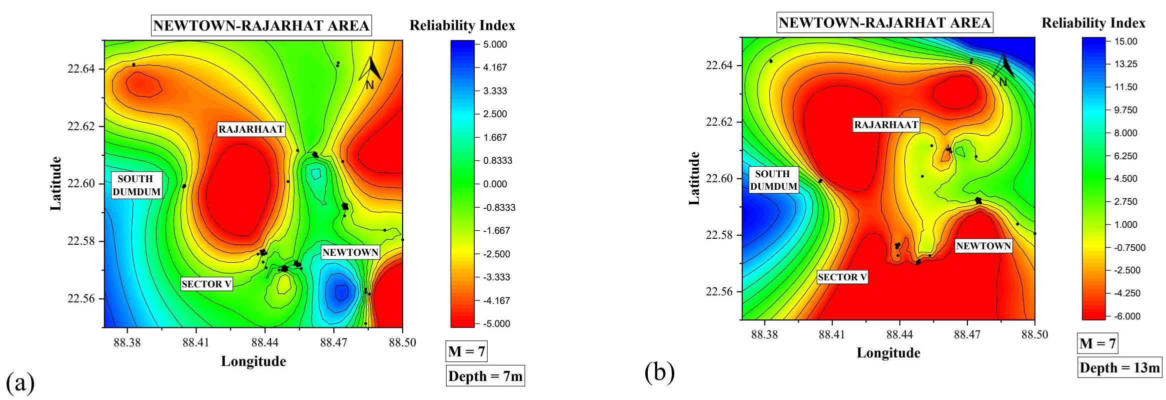

Fig. 11 Reliability Index Contour map by Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 7 at (a) Depth = 7m and (b) Depth = 13m

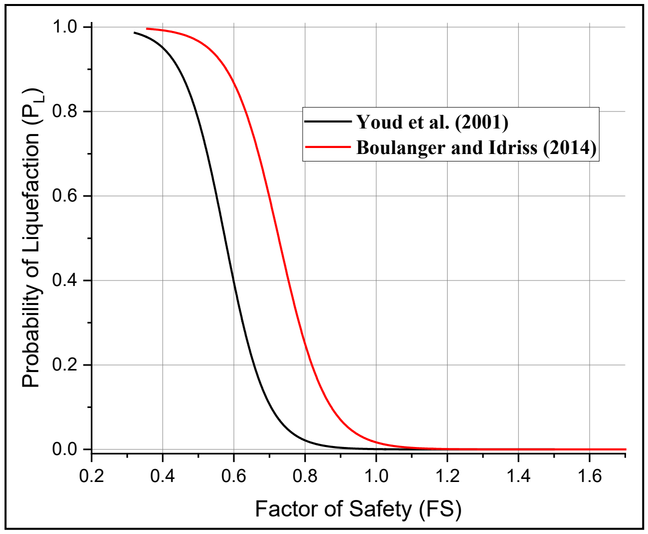

Fig. 12 Liquefaction Probability curve using First Order Second Moment (FOSM) method

The deterministic contour map study shows the regions of Newtown, Rajarhat, Sector V and South Dum Dum to be most susceptible to liquefaction at 7m and 13m depths, whereas the reliability contour maps depict the regions of Newtown, Rajarhat and Sector V to be most vulnerable at 13m depth. The area of Newtown-Rajarhat is mostly filled with layers of clayey silt and sand with presence of organic matter. High ground water table and low N value of soil in such soil profile can attribute to the high susceptibility to liquefaction in these regions.

6. Conclusion

The Rajarhat-Newtown area is evaluated for liquefaction potential for two earthquake magnitudes of 6 and 7. Deterministic methods of Youd et al. (2001) and Boulanger and Idriss (2014) were used to calculate the factor of safety of the study area and their contour maps were constructed at 7m and 13m depths. Reliability analysis was conducted on both the deterministic procedures using FOSM method for the two earthquake magnitudes of 6 and 7. Contour map study was done for the method of Boulanger and Idriss (2014) at 7m and 13m depth as this method was observed to give lesser conservative values. The contour maps were studied to assess the depth and the regions in the study area which are most susceptible to liquefaction.

Measuring the liquefaction susceptibility of a region in terms of factor of safety gives much lower results than their corresponding reliability index values. This is clearly seen in Fig. 4 where the moderately critical and safe zone contains considerably more factor of safety points than the reliability index points in the same zones in Fig. 5. Deterministic methods do not account for the various uncertainties in the parameters and factors used in calculation of factor of safety. Using reliability analysis along with deterministic methods account for these uncertainties, thereby giving more accurate and economic results. Thus it can be concluded that the deterministic methods are conservative in nature.

The deterministic contour maps (Fig. 6 to Fig. 9) show the regions of Newtown, Rajarhat, Sector V and South Dum Dum to be most vulnerable to liquefaction at both 7m and 13m depths. However, the reliability contour maps show the study area to be susceptible most at 13m depth in the regions of Newtown, Rajarhat and Sector V. The soil in these regions, in the first 15m, greatly comprises of alternating layers of soft, clayey silt and fine silty sand along with decomposed wood and organic matter with the ground water table at an average depth of 3m to 5m from the surface. Therefore it can be concluded that the Newtown-Rajarhat area is highly susceptible to liquefaction at most of the regions and proper mitigation measures should be adopted during any constructions.

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Figures

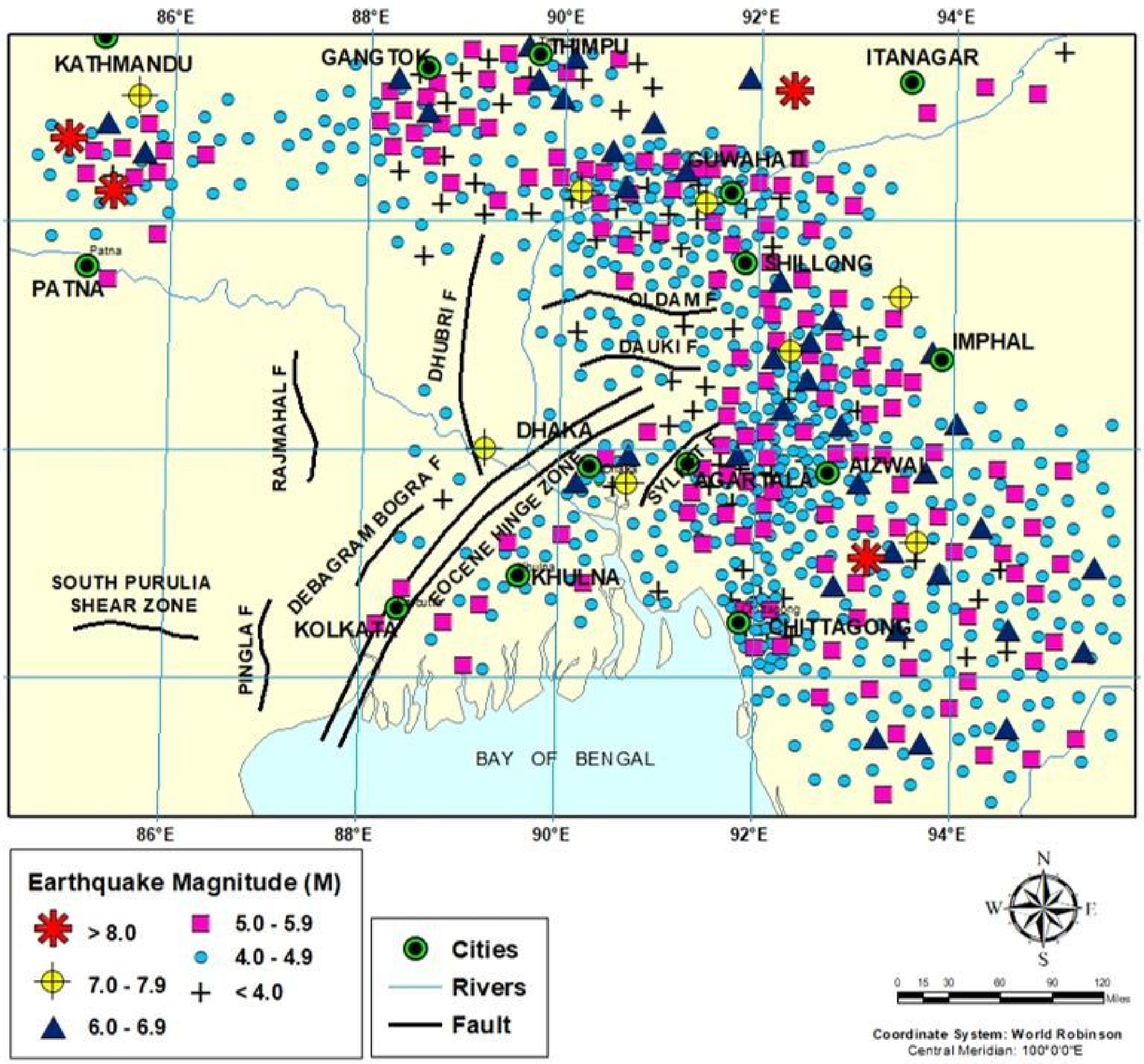

Figure 1

Seismic map of Eastern India, North-East India, Nepal, Bhutam and Myanmar for the last 100 years

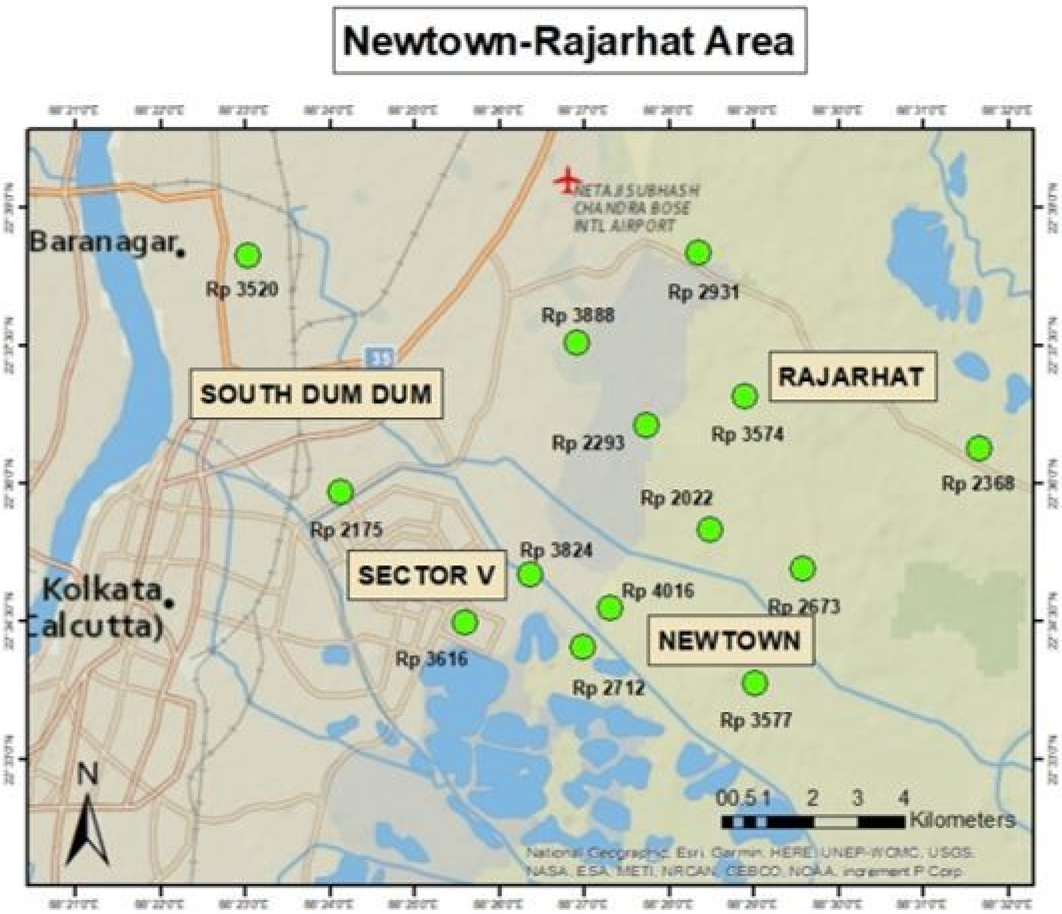

Figure 2

Map showing the borehole sites (marked by green dots) in Newtown-Rajarhat area

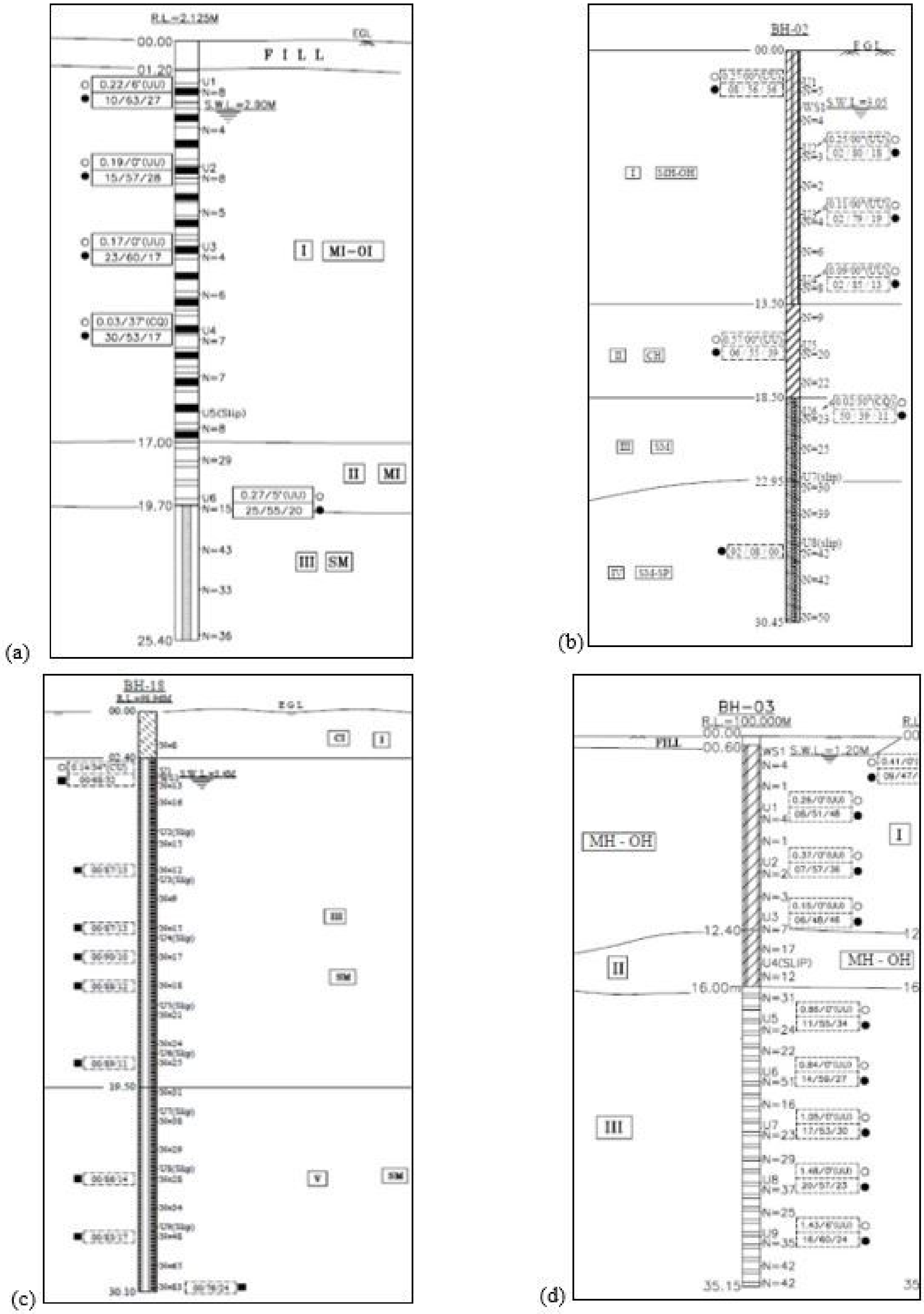

Figure 3

Typical borehole showing the lithological variation in (a) Newtown, (b) Rajarhat, (c) Sector V and (d) South Dum Dum

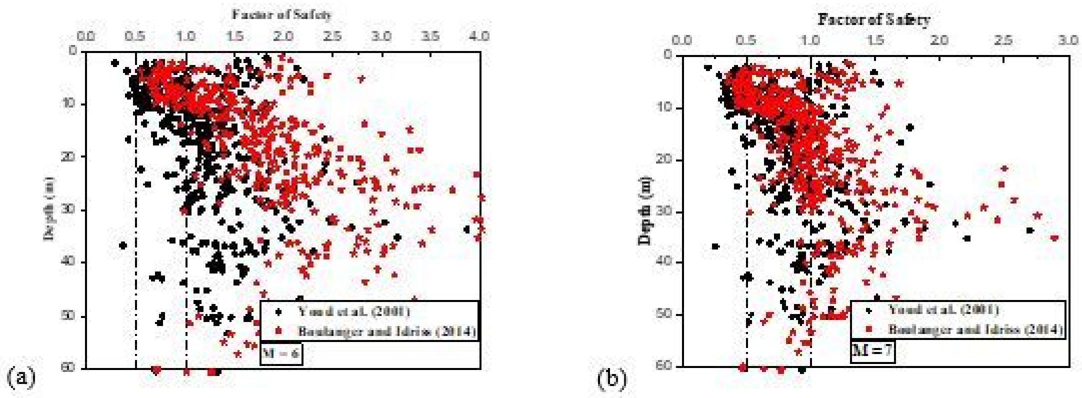

Figure 4

Factor of Safety vs Depth [Youd et al. (2001) and Boulanger and Idriss (2014)] for (a) M = 6 and (b) M = 7

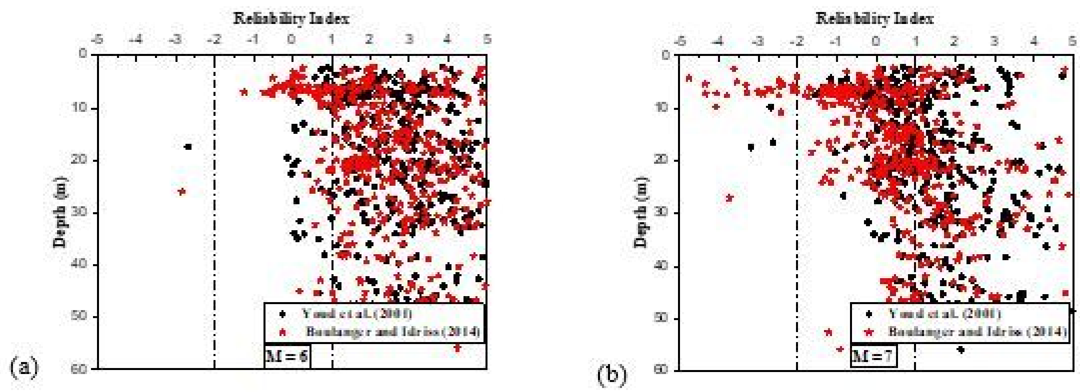

Figure 5

Reliability Index vs Depth [Youd et al. (2001) and Boulanger and Idriss (2014)] for (a) M = 6 and (b) M = 7

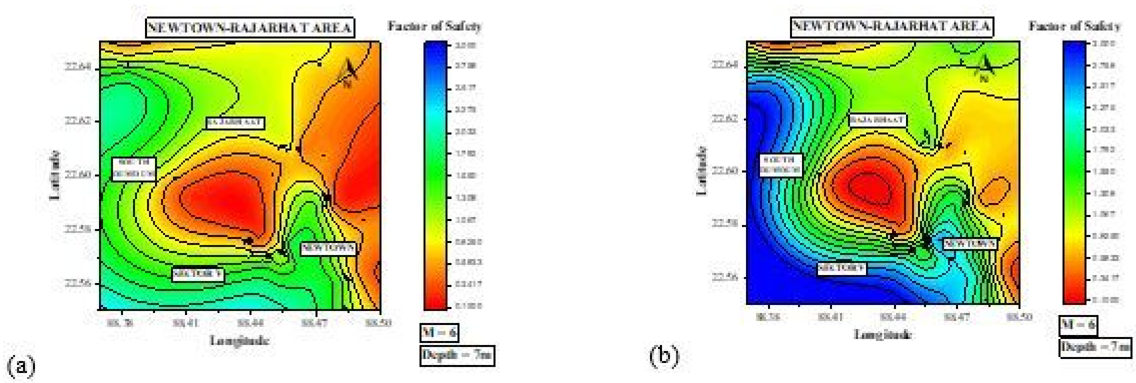

Figure 6

Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 6 and Depth = 7m

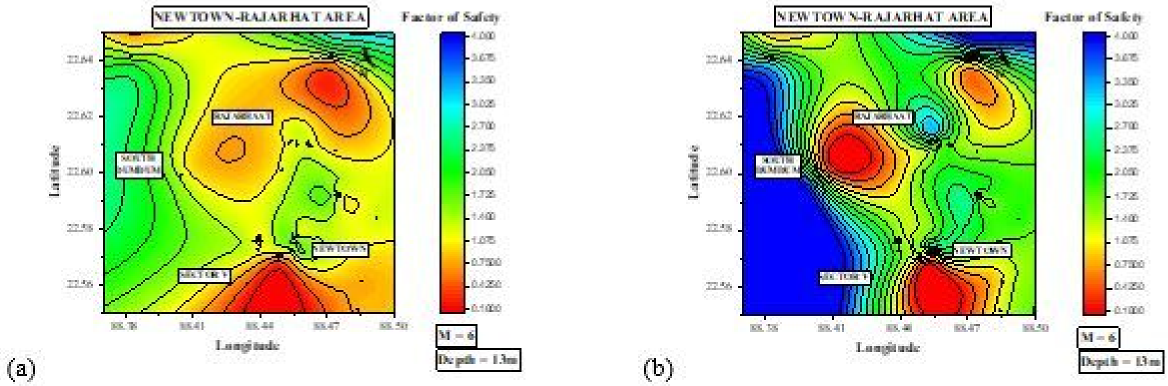

Figure 7

Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 6 and Depth = 13m

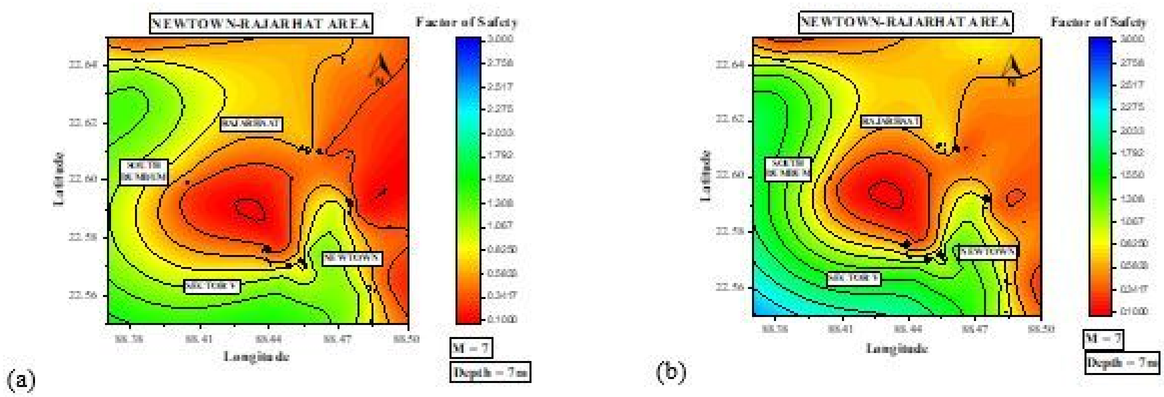

Figure 8

Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 7 and Depth = 7m

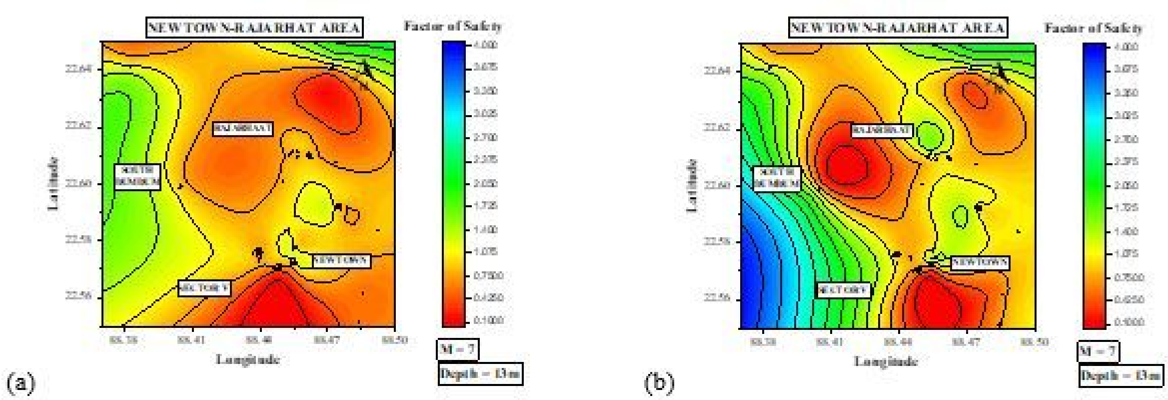

Figure 9

Factor of Safety Contour map by (a) Youd et al. (2001) and (b) Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 7 and Depth = 13m

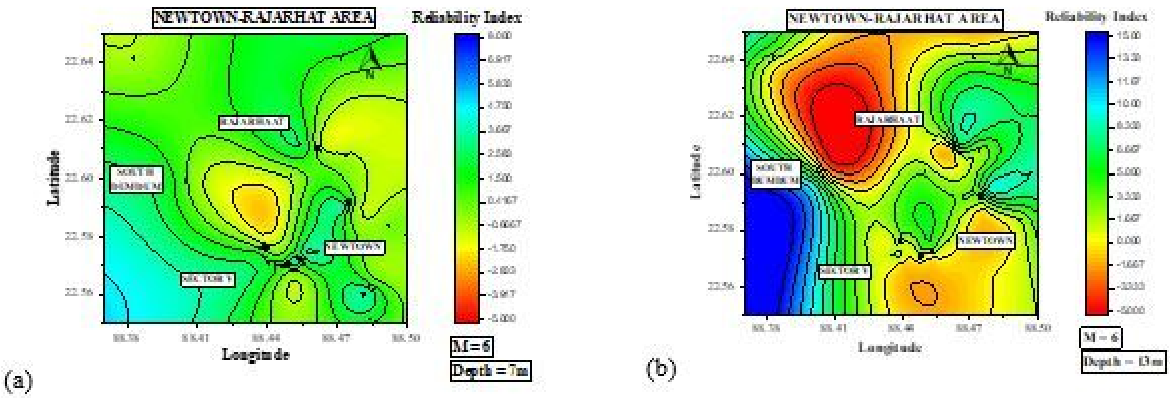

Figure 10

Reliability Index Contour map by Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 6 at (a) Depth = 7m and (b) Depth = 13m

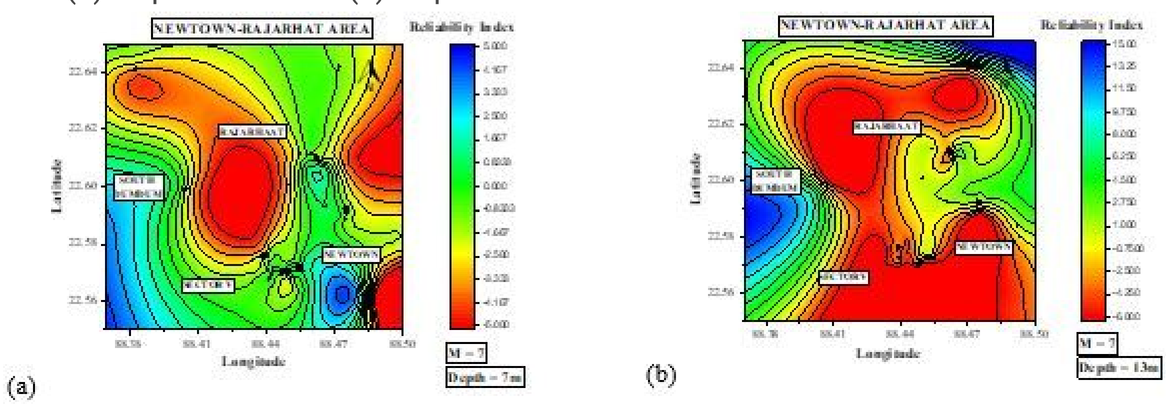

Figure 11

Reliability Index Contour map by Boulanger and Idriss (2014) method for Newtown-Rajarhat area for M = 7 at (a) Depth = 7m and (b) Depth = 13m

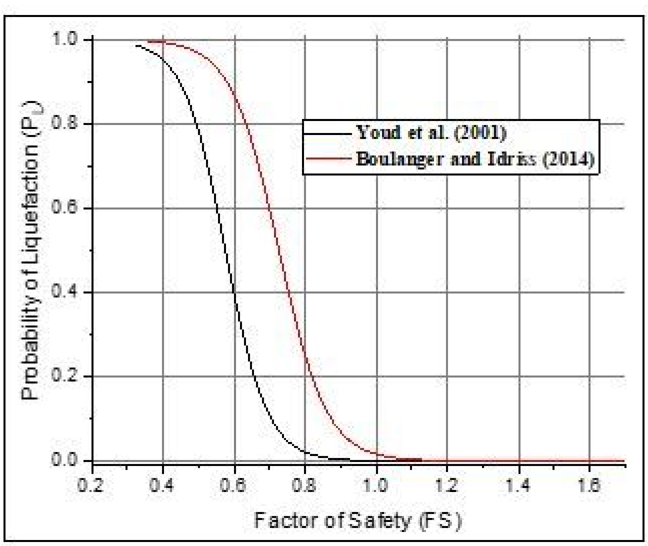

Figure 12

Liquefaction Probability curve using First Order Second Moment (FOSM) method