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ORIGINAL PAPER

Soil Liquefaction Potential of Kalyani Region, India

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Abstract High-magnitude earthquakes can result in severe destruction in regions susceptible to liquefaction. To avoid such casualty, one needs to specify the liquefaction susceptibility of the area and suggest proper measures for construction designs. In the present work, the liquefaction potential of the Kalyani region is evaluated. Three moderate- to high-magnitude earthquake scenarios (M_w = 6.5, 7.0, and 7.5 and PGA = 0.143g, 0.170g, and 0.202g, respectively) are considered for the present analysis at the six selected borehole sites in the study region. Liquefaction potential in terms of the factor of safety (*FoS*) against liquefaction is evaluated using a field approach based on *N* values with the help of a simplified method commonly known as Seed and Idriss method. Further, an attempt is made to define the severity against liquefaction by drawing the liquefaction hazard map of the study area based on the liquefaction potential index (*LPI*) values. It is found from the results that, for the shallow depths, susceptibility towards liquefaction decreases as the magnitude of earthquake decreases. We also observed that the minimum difference in the *FoS* obtained for a 7.0 magnitude earthquake was found to be 40% greater than that for the 7.5 magnitude earthquake. The same result is valid for the *LPI* analysis; for 7.5 M_w, the *LPI* is very high and the susceptibility towards liquefaction is about 93%. For the 7.0 M_w, the *LPI* is high and the severity against liquefaction is between 58 and 93% probability, whereas for 6.5 M_w, the *LPI* is moderately high with less than 53% susceptibility towards liquefaction.

Keywords Liquefaction · Liquefaction potential index · Cyclic stress ratio · Cyclic resistance ratio · Factor of safety

Introduction

Whenever a major earthquake occurs, it is observed that it causes serious damage to the foundation, structure, and underground structure constructed on the extensive areas of reclaimed land due to soil liquefaction and displacement of ground in the horizontal direction [1]. It has been shown that the determination of liquefaction potential of any region must be taken into account for ground improvement before the construction of any structure [2]. When a high-intensity earthquake hits a sandy soil deposit which is in loose, saturated, and undrained cohesionless condition, then the rapid decrease in the shear strength of the soil takes place such that the shear strength of the soil eventually becomes zero. This phenomenon is termed as liquefaction. As the pore water pressure increases, soil particles lose their contact with each other and move in unidentified directions resulting in sinking of heavyweight structures and floating of low-weight structures. The occurrence of soil liquefaction depends on various factors like the type of soil, thickness of the soil strata, soil grain size, relative density, water table depth, fines content, etc. [2]. Correspondingly, severity of liquefaction is influenced by the reduction of effective stress, shear modulus degradation, and intensity and magnitude of the earthquake, duration of the ground motion, distance from the source of the earthquake, ground acceleration, etc. [2–4]. Ground

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failure is influenced by the liquefied and non-liquefied thickness of the soil layers induced by liquefaction.

After the Alaska and the Niigata earthquakes, the liquefaction analysis became a major issue in the geotechnical earthquake engineering. Seed and Idriss [5] presented the evaluation of liquefaction potential work for the first time and it was further carried gradually by [4, 6–15]. Some of these cited works are based on field methods such as the standard penetration test (*SPT*) and the cone penetration test (*CPT*). The *SPT* is extensively used by the researchers worldwide to evaluate the liquefaction potential of the soil. Many researchers in India too have determined liquefaction susceptibility for different sites using the *SPT* test data. Some examples are [16] for Bangalore City; [17] for Guwahati City; [18] and [19] for Mumbai; [20] for Lucknow City; [21–24] for Kanpur City; [25] for Kolkata region and [26–28] for Roorkee region.

The *FoS* indicates the liquefaction potential of a soil layer at a specific depth but it does not indicate the level of severity against liquefaction potential of a site on the whole. To overcome this drawback of the *FoS*, [29] suggested the liquefaction potential index (*LPI*) to evaluate the liquefaction susceptibility. The value of *LPI* includes depth, thickness, and factor of safety for liquefaction of soil layers and predicts the capability of liquefaction to cause damage at the ground level at selected sites. The *LPI* is repetitively used by experts to evaluate the level of liquefaction severity for different locations of soils. The *LPI* is a single value factor evaluated for the liquefaction hazard map of the selected location as an alternative for many factors at different layers of the soil [18, 30–32]. The *LPI* has been calibrated using the *SPT* test data to characterize the liquefaction potential of sites [18, 28, 30, 33].

In the present study, the liquefaction potential of the sites within the All India Institute of Medical Sciences (AIIMS) Kalyani, Kolkata Campus, is assessed based on the *SPT* data. The present analysis is done for the six borehole locations in the *AIIMS* Kolkata Campus. Liquefaction susceptibility of the six sites is evaluated in terms of the *FoS* against liquefaction for three different magnitudes of earthquakes (M_w) covering moderate to high-magnitude earthquake scenarios with M_w = 6.5, 7.0, and 7.5, corresponding to peak ground acceleration (*PGA*) values of 0.143*g*, 0.170*g*, and 0.202*g*, respectively [21]. The water table is considered at the ground surface for all the scenarios. Further, the level of liquefaction severity is also evaluated in terms of the *LPI* for the selected sites and a liquefaction hazard map for the *AIIMS* Kolkata Campus is prepared. This liquefaction hazard map could be of use to design engineers in the preliminary and detailed design of any construction/infrastructure development within and outside of the Kalyani Campus region.

Study Area

Kolkata, the capital city of West Bengal state in India, is located on the east bank of the Hooghly River, approximately 75 km west of the border with Bangladesh. Kolkata is one of the most populous cities in India [34]. The *AIIMS* Kalyani region comes under the Nadia District of West Bengal and it is located around 50 km from Kolkata. The Indian Seismic Code (IS 1893:2016) divides the country into four seismic zones (zone II to V). The scale used to measure the susceptibility to earthquakes ranges from II to V in an increasing order. Kolkata lies in seismic zone III.

Damages to the Civil Engineering structures have been reported in Kolkata due to both the far and the near source earthquakes in the past [35]. Based on the available past records of the last 350 years, it can be said that Kolkata and its surrounding region underwent some thirty strongly felt earthquakes. The epicentres of majority of these earthquakes were from ‘far sources’ and only a few of them were from the ‘near sources’. Epicentres for all the moderate to large earthquakes were located south of Kolkata near the Ganges delta mouth.

Details of the study area, site locations are mentioned in Table 1. The table gives the depth of the borehole, latitude, and longitude of the borehole, water table—actual, and water table—assumed along with the number of *SPT* samples. Due to small variation in the water table, water is assumed at the ground surface for all the sites. The location map is presented in Fig. 1 to visualize the precise area of the *AIIMS* Kalyani Campus. The 6 boreholes data considered for the liquefaction analysis is widely distributed throughout the considered area of the study as shown in Fig. 1c.

Methodology

Liquefaction potential is entirely dependent on the earthquake intensity and the resistance of the soil against liquefaction. The susceptibility towards liquefaction in this research work is evaluated using the simplified method based on [5] and [4]. The evaluation procedure of liquefaction potential consists of the following three steps.

1. Evaluation of the cyclic stress ratio (*CSR*)
2. Evaluation of the cyclic resistance ratio (*CRR*)
3. Evaluation of the factor of safety (*FoS*)

Evaluation of the Cyclic Stress Ratio

The cyclic stress ratio/shear stress due to earthquake is calculated using a simplified procedure given by [5].

Table 1 Detail location of boreholes in AIIMS Kalyani, Campus, Kolkata

S. no.	Site identification	Borelog depth (m)	Latitude	Longitude	Water table (m)		Number of the *SPT* samples
					Actual	Assumed	
1	BH-01	15.00	N22°58′12.62″	E88°31′38.44″	2.8	Ground	08
2	BH-02	15.50	N22°58′16.20″	E88°31′34.27″	3.1	Ground	08
3	BH-03	15.00	N22°58′22.27″	E88°31′42.24″	1.6	Ground	09
4	BH-04	15.00	N22°58′34.55″	E88°31′47.16″	3.3	Ground	10
5	BH-05	15.00	N22°58′30.55″	E88°31′52.90″	1.4	Ground	09
6	BH-06	15.00	N22°58′43.74″	E88°31′53.97″	1.8	Ground	09

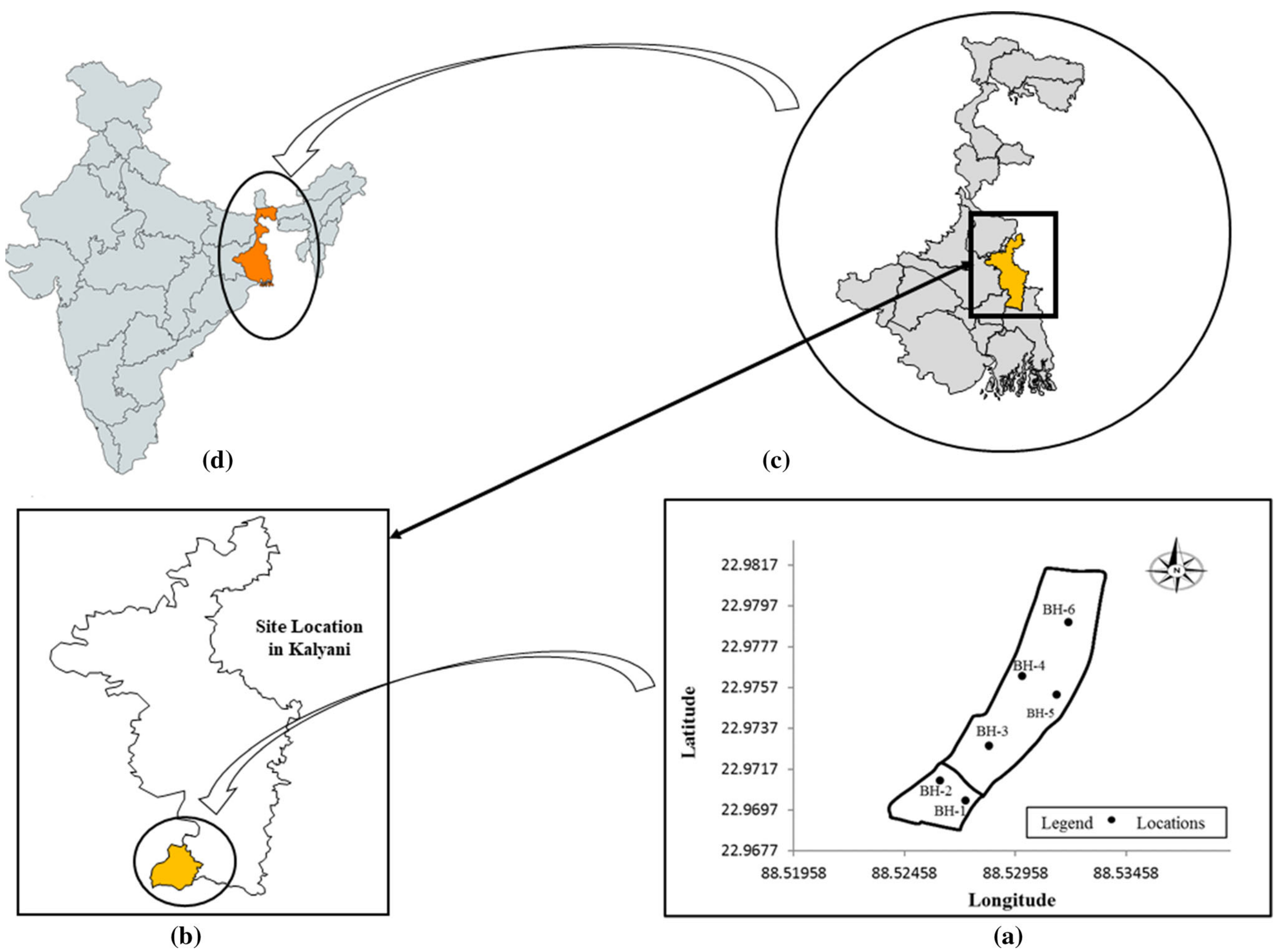


Fig. 1 Location of sites: **a** map of India, **b** map of West Bengal (W. B.), **c** map of Kalyani District (W.B.), and **d** location of the site in Kalyani

Fraction of this evaluated shear stress with effective stress gives the value of the Cyclic Stress Ratio (*CSR*).

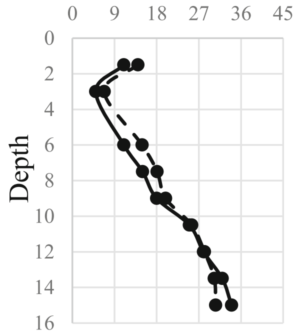
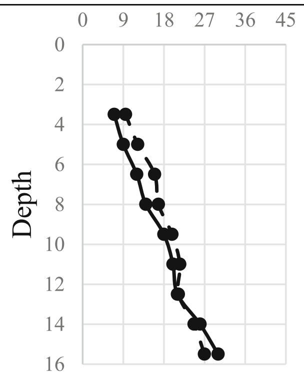
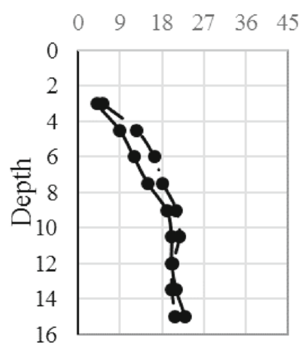
$$CSR = 0.65 \times \left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_{vo}}{\sigma'_{vo}}\right) \times r_d \quad (1)$$

where σ'_{vo} is the effective stress; a_{max} is peak horizontal acceleration at the ground surface; σ_{vo} is the total stress; g is the acceleration due to gravity and r_d is the stress reduction coefficient evaluated using [4].

Evaluation of the Cyclic Resistance Ratio

The cyclic resistance ratio (CRR) gives the resistance of soil against liquefaction. The simplified method developed

Table 2 Characteristics of the soil of AIIMS Kalyani Campus [BH-01 to BH-06]

Site Identification	Depth (m)	γ (κN/m³)	Description: Fill	Description: Symbol	N-Value	$(N_1)_{60}$	SPT Profile (N Value; $(N1)60$)
BH-01	1.0	18.4		A	-	-	
	1.5			B	11	14.0	
	3.0				5	6.8	
	6.0			C	11	14.9	
	7.5				15	18.1	
	9.0				18	19.9	
	10.5				25	25.5	
	12.0				28	28.2	
	13.5			D	32	30.3	
	15.0				34	30.6	
BH-02	1.0	18.0		A	-	-	
	3.5			B	7	9.52	
	5.0				9	12.21	
	6.5			C	12	15.96	
	8.0				14	16.79	
	9.5				18	19.80	
	11.0				20	21.53	
	12.5				21	21.20	
	14.0	18.7			26	24.69	
	15.5				30	26.97	
BH-03	1.0	18.3		A	-	-	
	3.0			B	4	5.44	
	4.5				9	12.64	
	6.0			C	12	16.31	
	7.5				15	18.24	
	9.0				19	21.09	
	10.5				20	21.63	
	12.0				20	20.23	
	13.5				21	20.03	
	15.0				23	20.81	

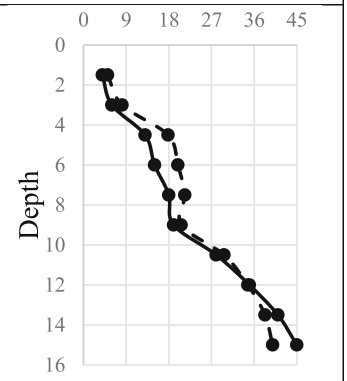
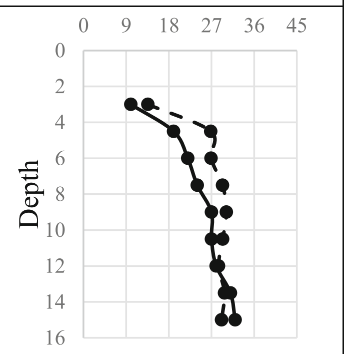
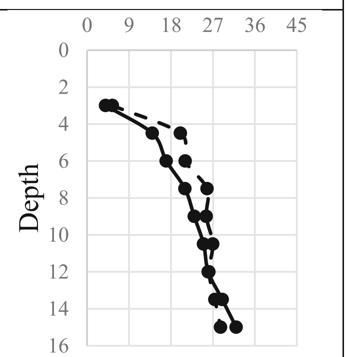
A = Fill with clay, grassroots, etc.
B = Medium brownish-grey clayey silt with traces of sand and kankar.
C = Medium light grey silty fine sand with traces of mica.
D = Dense to very dense light grey fine to medium sand with traces of silt.

by [5] and later elaborated by [4] is used to calculate the values of the *CRR* (Eq. 2).

$$CRR_{7.5} = \left(\frac{1}{34-(N_1)_{60cs}} + \frac{(N_1)_{60cs}}{135} + \frac{50}{[10(N_1)_{60cs}+45]^2} - \frac{1}{200}\right) \quad (2)$$

$$(N_1)_{60cs} = \alpha + \beta (N_1)_{60} \quad (3)$$

Table 2 continued

Site Identification	Depth (m)	γ (κN/m³)	Description		N-Value	$(N_1)_{60}$	SPT Profile (N Value, (N1)60)
			Fill	Symbol			
BH-04	1.0	18.8		A	-	-	
	1.5	18.6		B	4	5.10	
	3.0	18.7			6	8.16	
	4.5				13	17.83	
	6.0			C	15	19.91	
	7.5				18	21.37	
	9.0	18.6			19	20.61	
	10.5				28	29.63	
	12.0			D	35	34.66	
	13.5				41	38.29	
	15.0	18.8			45	39.89	
BH-05	1.0	18.2		A	-	-	
	3.0			B	10	13.6	
	4.5				19	26.84	
	6.0			C	22	26.92	
	7.5				24	29.35	
	9.0				27	30.15	
	10.5				27	29.38	
	12.0				28	28.50	
	13.5				31	29.75	
	15.0			D	32	29.13	
BH-06	1.0	18.0		A	-	-	
	3.0			B	4	5.44	
	4.5				14	20.02	
	6.0	18.8		C	17	21.06	
	7.5				21	25.75	
	9.0				23	25.58	
	10.5				25	26.97	
	12.0				26	26.15	
	13.5				29	27.42	
	15.0			D	32	28.65	

A = Fill with clay, grassroots, etc. **B** = Medium brownish-grey clayey silt with traces of sand and kankar.

C = Medium light grey silty fine sand with traces of mica. **D** = Dense to very dense light grey fine to medium sand with traces of silt.

where $(N_1)_{60CS}$ = Corrected N values with fines evaluated using Eq. 3, α and β = coefficients factors.

Recorded $SPT\ N$ values are corrected for fines contents using Eq. 3, denoted as $(N_1)_{60CS}$, for the evaluation of $CRR_{7.5}$. $(N_1)_{60CS}$ in Eq. 3 consists of constants α and β whose values depend on the fine content of soil and in the present study, they are evaluated based on [4].

For evaluation of the CRR from the SPT data, first the measured $SPT\ N$ value is corrected by applying the following corrections (Eq. 4) leading *to* $(N_1)_{60}$ value.

$$(N_1)_{60} = N \times C_N C_E C_B C_R C_S \tag{4}$$

where $(N_1)_{60}$ = the normalized corrected SPT blow count with hammer efficiency of 60%; N = the measured SPT blow count in situ. In Eq. 4, C_N = Overburden pressure

Correction; C_E = energy ratio correction; C_B = borehole diameter correction; C_R = Rod correction and C_S = sampling method corrections. The values of these corrections are given in Table 2 [4]. Accordingly, values of C_N correction are determined using Eq. 5. The value of C_N should not exceed 1.7 and it decreases with depth [4].

$$C_N = \left(\frac{P_a}{\sigma'_{VO}}\right)^{0.5}. \tag{5}$$

Equation 2 is used to evaluate the *CRR* for the earthquake magnitude of 7.5. For different magnitudes of earthquakes, the *CRR* is calculated by applying the magnitude scaling factor (*MSF*) as given in Eq. 6 [4].

$$CRR = CRR_{7.5} \times MSF \tag{6}$$

The *MSF* is evaluated from Eq. 7 as suggested by [4].

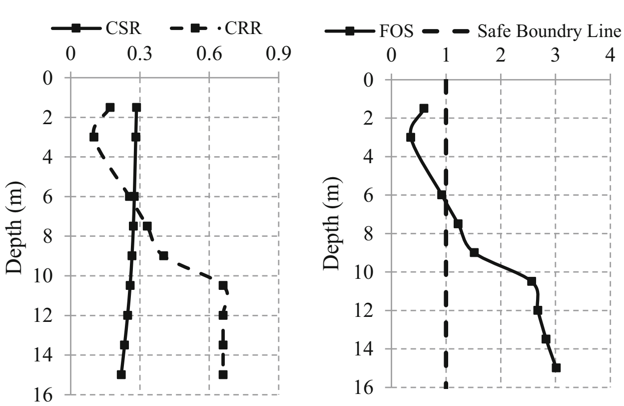
$$MSF = \frac{10^{2.24}}{M_w^{2.56}}. \tag{7}$$

Evaluation of the Factor of Safety

The liquefaction potential of sites is assessed in the terms of the Factor of Safety (*FoS*) against liquefaction. The *FoS*, calculated using Eq. 8, is defined as the ratio of shear stress causing liquefaction (*CRR*) to shear stress due to earthquake loading (*CSR*).

$$FoS = \frac{CRR}{CSR}. \tag{8}$$

For a given site, if the *FoS* is found to be less than 1.0, then it is susceptible to liquefaction whereas if the *FoS* is found to be 1.0 or greater than 1.0, it is not susceptible to liquefaction.



(a) *CSR, CRR* with the depth **(b)** *FoS* with the depth

Fig. 2 *CSR*, *CRR* and *FoS* with the depth for *BH-01* (M_w = 7.5, *PGA* = 0.202*g*)

Determination of Liquefaction Potential Index

The liquefaction potential index (*LPI*) is a single-valued factor for the evaluation of the level of the liquefaction severity at a particular site. In this study, the *LPI* was evaluated by the expression (Eq. 9) given by [36],

$$LPI = \int_0^{20} F(z).w(z)dz \tag{9}$$

where z is the midpoint depth of the soil layer and dz is a differential increment of depth.

$$F(z) = 1 - FoS \text{ for } FoS < 1.0;$$
$$F(z) = 0 \text{ for } FoS \geq 1.0;$$
$$w(z) = 10 - 0.5z \text{ for } z < 20 \text{ m};$$
$$w(z) = 0 \text{ for } z > 20 \text{ m}.$$

$F(z)$ and $w(z)$ are the severity factor and the weighting factor, respectively.

The *LPI* is evaluated using Eq. 10 given by [37] which is valid for the soil depths less than or equal to 20.0 m.

$$LPI = \sum_{i=1}^{n} w_i F_i H_i \tag{10}$$

where

$$F_i = 1 - FoS_i \text{ when } FoS_i < 1.0$$
$$F_i = 0 \text{ when } FoS_i \geq 1.0$$

H_i is the thickness of the soil layers; n is layer number; F_i is severity for liquefaction of the ith layer;

$$w_i = 10 - 5z_i \tag{11}$$

where w_i is the weighting factor and z_i is the depth of ith layer (m).

Geotechnical Characteristics of Study Area

Soil profile and soil parameters are essential to evaluate the liquefaction potential of any region/site. Parameters such as water table depth, *SPT N* values, dry density, specific gravity, and fine contents were collected from the in situ test. Geotechnical investigation, using one of the most traditional and reliable tests, i.e. *SPT,* was conducted by the [38].

Deposited soil consists of two layers. Soft to medium clay was found to exist up to a depth of 4.0 m to 5.0 m and after that, a layer of silty fine sand be found [21]. The soil of Kolkata region generally consists of normal deposits, river channel deposits, and reclaimed land. Normal deposits contain silty clay/clayey silt layers with traces of silt and fine sand. The top layer of river channel deposits

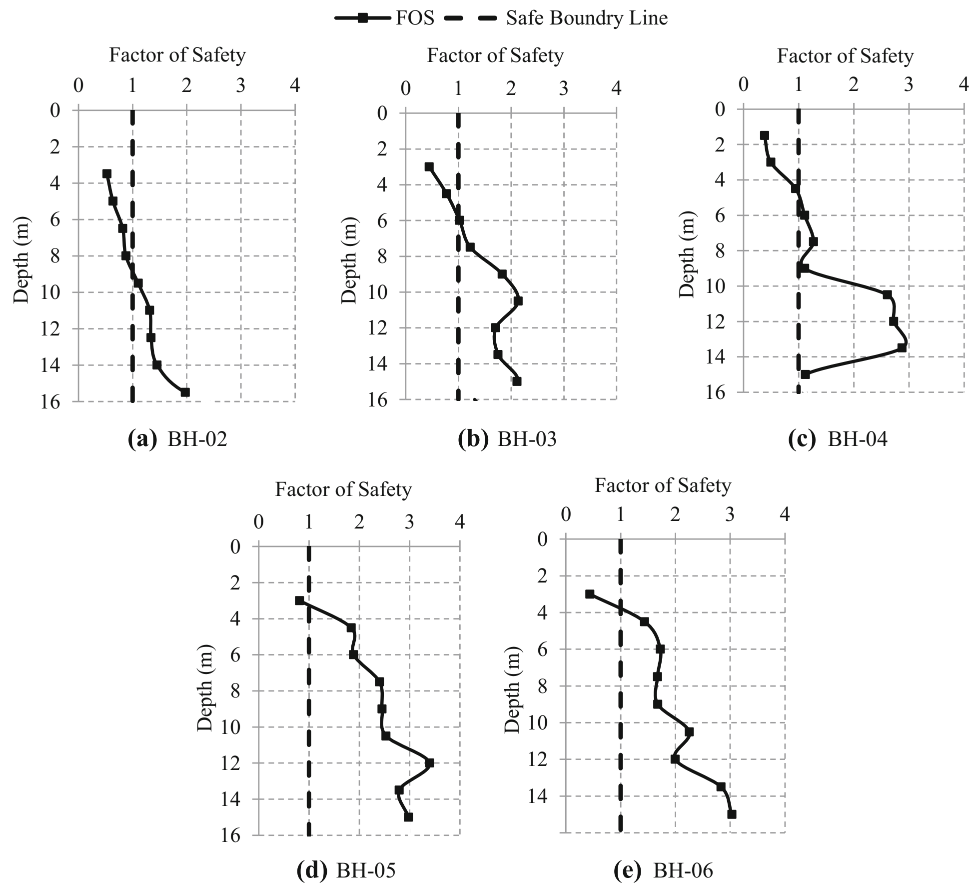


Fig. 3 *FoS* against liquefaction with the depth of *BH-02* to *BH-06* for $M_w = 7.5$, $PGA = 0.202g$

Table 3 Detailed calculation of *FoS* against liquefaction required for liquefaction for BH-02 ($M_w = 7.5$ and $PGA = 0.202g$)

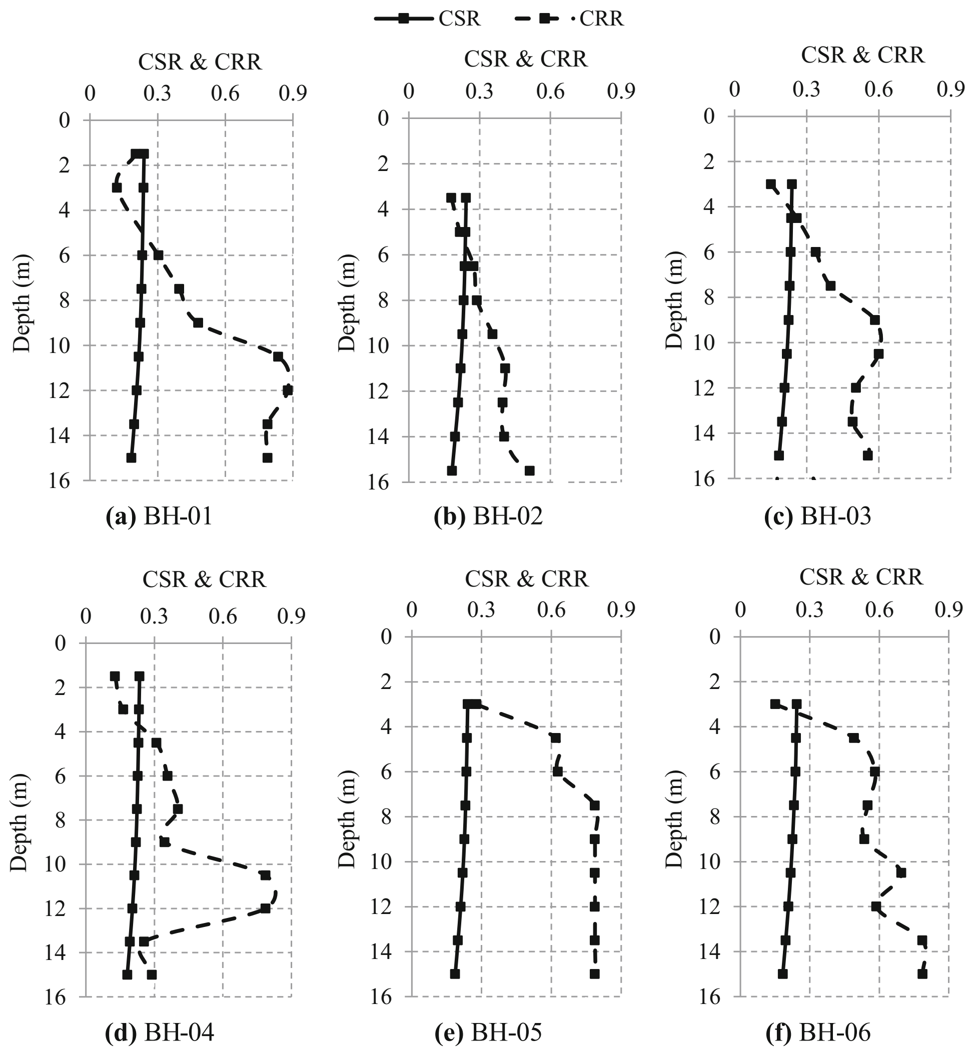
Depth (m)	γ (κN/m^3)	Fines (%)	σ_{vo} (kPa)	σ_{vo}' (kPa)	r_d	CSR	N_{SPT}	C_N	C_R	$(N_1)_{60}$	$(N_1)_{60Fines}$	$CRR_{7.5}$	FoS
3.5	18.0	21	61.80	27.47	0.98	0.29	7	1.70	0.80	9.52	14.12	0.15	0.52
5	18.0	21	88.29	39.24	0.97	0.29	9	1.60	0.85	12.21	17.04	0.18	0.62
6.5	18.0	21	114.78	51.01	0.95	0.28	12	1.40	0.95	15.96	21.12	0.23	0.82
8	18.0	21	141.26	62.78	0.94	0.28	14	1.26	0.95	16.79	22.01	0.24	0.86
9.5	18.0	21	167.75	74.56	0.91	0.27	18	1.16	0.95	19.80	25.29	0.30	1.11
11	18.0	21	194.24	86.33	0.88	0.26	20	1.08	1.00	21.53	27.16	0.34	1.31
12.5	18.0	21	220.73	98.10	0.84	0.25	21	1.01	1.00	21.20	26.81	0.33	1.32
14	18.7	12	248.24	110.90	0.79	0.23	26	0.95	1.00	24.69	27.02	0.34	1.48
15.5	18.7	12	275.76	123.70	0.74	0.22	30	0.90	1.00	26.97	29.38	0.43	1.95

and reclaimed land consists of fine sand with silty soil up to few metres [21]. Mondal et al. [23] observed that the soil of Kalyani District is classified as Gangetic alluvium. Kalyani region soil is a mixture of silt and sand so its moisture-retaining capacity is very low. For shallow depth, the soil consists of soft compressible silty clay/clayey silt and after that clay deposits which are very stiff with intermediate sand were found for a large depth of 40 to 50 m [23].

In Table 2(a, b), the soil profile for all the 6 site locations in the study region is given. The soil profile consists of the characteristics of soil samples, i.e. unit weight (γ), description about soil type, *SPT N* values, and corrected *SPT N* values, $(N_1)_{60}$, from the overburden correction and hammer efficiency correction of 60%, which is required for the evaluation of the liquefaction resistance.

From Table 2(a, b), it can be concluded that the top surface of the *AIIMS* Kalyani Campus is filled with clay,

Fig. 4 *CSR* and *CRR* with the depth (M_w = 7.0, $a_{\max}$ = 0.170g)



grassroots, and other wastes. From the depth of 1.5 m to 5.0 m, a layer of medium brownish-grey clayey silt with traces of sand and kankar was found followed by medium light grey silty fine sand with traces of mica for the depth up to 12.0 m. The last layer consisted of dense to very dense light grey sand having a size of fine to medium with traces of silt. From the above study, it can be concluded that the soil profile of the *AIIMS* Kalyani Campus generally consists of clay and sand with traces of mica and silt.

From Table 2(a, b), it can be observed that the minimum corrected value of $(N_1)_{60}$ is 5, obtained at 3.0 m of depth at *BH-06*. The value of $(N_1)_{60}$ is greater than the corresponding N value up to the depth of 10.0 m. Beyond the depth of 10.0 m, $(N_1)_{60}$ values are less than the corresponding *SPT* N values, which can be attributed to the overburden (C_N) and rods correction (C_R). In Table 2(a, b), different symbols (*A B C & D*) are used to classify different types of soil investigated at various depths of borehole locations. There is a marginal difference in bulk density values (varying from 18.0 kN/m^3 to 18.8 kN/m^3) for all the sites in the study region.

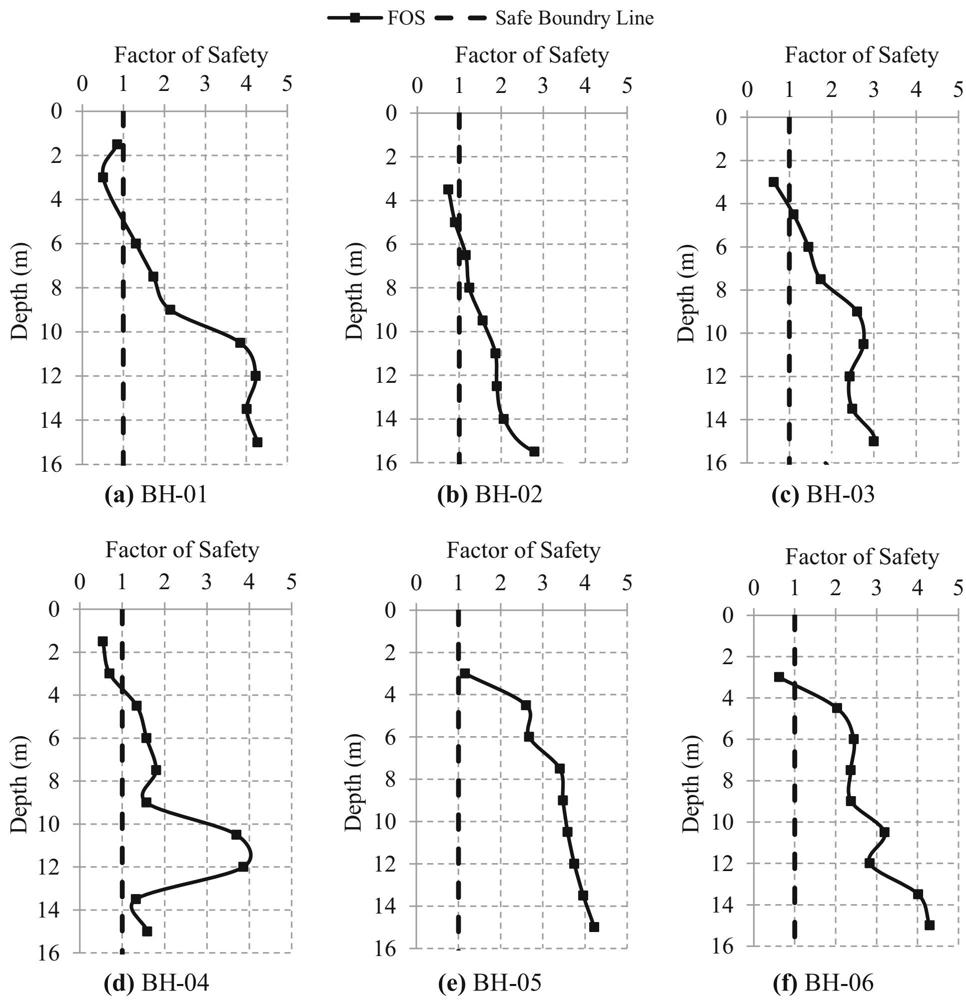
Liquefaction Potential of Sites

In this study, the liquefaction potential of all the five sites in the *AIIMS* Kalyani, Kolkata Campus, is evaluated using the *SPT* data for different earthquake scenarios, i.e. M_w = 6.5, 7.0, and 7.5, corresponding to *PGA* = 0.143g, 0.170g, and 0.202g, respectively, and considering water table at the ground level.

Liquefaction potential for M_w = 7.5, PGA = 0.202g

In Fig. 2, the variation of the *CSR*, the *CRR*, and the *FoS* against liquefaction with depth is given for *BH-01*. It can be observed from Fig. 2a that up to 6.0 m depth, the *CRR* is less than the *CSR*; therefore, the *FoS* against liquefaction is less than one. This means that the site is susceptible to

Fig. 5 *FoS* with the depth (M_w = 7.0, a_{max} = 0.170g)



liquefaction up to the shallow depth of 6.0 m (Fig. 2b). The higher values of the *CRR* as compared to the *CSR* can be attributed to the presence of fines and higher *N* values.

The variation of the *FoS* against liquefaction with depth is given for *BH-02* to *BH-06* in Fig. 3. The *FoS* values increase with the depth for all the sites in *AIIMS* Kalyani Campus. It can be observed from Fig. 3, that the values of the *FoS* against liquefaction are less than unity at shallow depths for all the sites. Figure 3 indicates the zone of liquefaction up to 6.0 m depth for *BH-02* to *BH-04* and up to 3.0 m for *BH-05 & 06*.

Table 3 gives the detailed calculations of the *FoS* against the liquefaction for *BH-02*. From Table 3, it can be noted that the sample of the location (*BH-02*) is taken up to the depth of 15.5 m and fines content varies from 12 to 21%. The values of total and the effective stress of the soil increase with depth. For *BH-02*, the *SPT N* values lie from 7 to 30. The corrected *N* values after overburden correction $(N_1)_{60}$ and correction for fine content $(N_1)_{60cs}$ with depth are given in Table 3. It can be observed from Table 3 that the $(N_1)_{60}$ and $(N_1)_{60cs}$ values increase with the depth. This trend can be attributed to the overburden correction (C_N) and presence of fines contents. The values of the *CRR* increase with the depth and vary from 0.15 to 0.43 up to the 15.5 m depth. From the values of the *FoS* reported in Table 3, it is clear that there is a chance for liquefaction up to the shallow depth (up to 9.0 m) in this region, in case of strong earthquake, i.e. M_w = 7.5 and *PGA* = 0.202g.

Liquefaction potential for M_w = 7.0, PGA = 0.170g

The decrease in the magnitude of the earthquake decreases the severity towards liquefaction. Figures 4 and 5 depict in detail, the variation of the *CSR*, the *CRR*, and the *FoS* against liquefaction for all the 6 sites (*BH*-01 to *BH-06*) of AIIMS Kalyani Kolkata Campus. It can be observed from Fig. 4a and b that in the case of *BH-01* and *BH-02*, the values of the *CRR* are less than the *CSR* values up to the depth of 5.0 m and after that the *CRR* values are greater than the *CSR* values. This means that the *FoS* is less than one (Fig. 5a, b) and the sites will liquefy up to the depth of 5.0 m. Further, for *BH-03* and *BH-04*, similar trends were

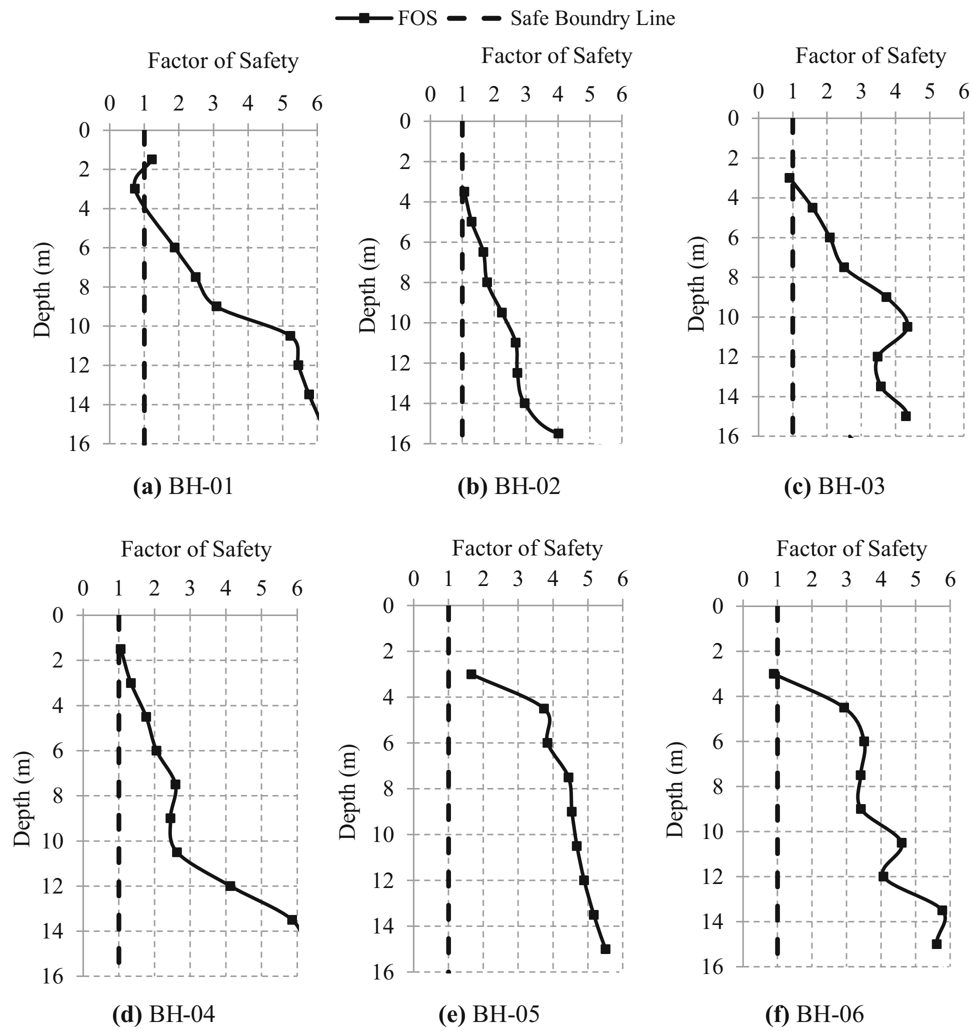


Fig. 6 *FoS* against liquefaction with the depth (M_w = 6.5, a_{max} = 0.143g)

Table 4 Computation of liquefaction potential index for BH-02 with M_w = 7.5 & *PGA* = 0.202g

Depth (m)	*CSR*	$CRR_{7.5}$	*FoS*	*Z* (m)	*w* (*z*)	*H* (m)	F_i	*w* (*z*).F.H
3.5	0.29	0.15	0.52	1.75	9.13	3.5	0.48	15.18
5.0	0.29	0.18	0.64	4.25	7.88	1.5	0.36	4.31
6.5	0.28	0.23	0.82	5.75	7.13	1.5	0.18	1.97
8.0	0.28	0.24	0.87	7.25	6.38	1.5	0.13	1.20
9.5	0.27	0.30	1.10	8.75	5.63	1.5	0.00	0.00
11.0	0.26	0.34	1.31	10.25	4.88	1.5	0.00	0.00
12.5	0.25	0.33	1.34	11.75	4.13	1.5	0.00	0.00
14.0	0.23	0.34	1.45	13.25	3.38	1.5	0.00	0.00
15.5	0.22	0.43	1.97	14.75	2.63	1.5	0.00	0.00
LPI = $\sum$w(z).F.H								22.662

observed but the depth of liquefaction is reduced (i.e. 4.0 m depth). Also, the remaining sites performed well and remained safe from liquefaction in the considered earthquake scenario.

Liquefaction potential for M_w = 6.5, PGA = 0.143g

For this particular case, the severity of liquefaction decreases and a very minor effect is found. The *FoS* against

Table 5 Computation of liquefaction potential index for BH-02 with M_w = 7.0 & *PGA* = 0.170

Depth (m)	*CSR*	$CRR_{7.0}$	*FoS*	*Z* (m)	*w*(*z*)	*H* (m)	F_i	*w*(*z*).F.H
3.5	0.29	0.18	0.74	1.75	9.13	3.50	0.26	8.18
5.0	0.29	0.22	0.90	4.25	7.88	1.50	0.10	1.17
6.5	0.28	0.27	1.16	5.75	7.13	1.50	0.00	0.00
8.0	0.28	0.29	1.24	7.25	6.38	1.50	0.00	0.00
9.5	0.27	0.36	1.56	8.75	5.63	1.50	0.00	0.00
11.0	0.26	0.41	1.86	10.25	4.88	1.50	0.00	0.00
12.5	0.25	0.40	1.90	11.75	4.13	1.50	0.00	0.00
14.0	0.23	0.40	2.06	13.25	3.38	1.50	0.00	0.00
15.5	0.22	0.51	2.79	14.75	2.63	1.50	0.00	0.00
		$LPI = \sum w(z).F.H$						9.35

Table 6 Computation of liquefaction potential index for BH-02 with M_w = 6.5 & *PGA* = 0.143

Depth (m)	*CSR*	$CRR_{6.5}$	*FoS*	*Z* (m)	*w*(z)	*H* (m)	F_i	*w*(z).F.H
3.5	0.29	0.22	1.07	1.75	9.13	3.50	0.00	0.00
5.0	0.29	0.26	1.29	4.25	7.88	1.50	0.00	0.00
6.5	0.28	0.33	1.66	5.75	7.13	1.50	0.00	0.00
8.0	0.28	0.35	1.78	7.25	6.38	1.50	0.00	0.00
9.5	0.27	0.43	2.24	8.75	5.63	1.50	0.00	0.00
11.0	0.26	0.49	2.68	10.25	4.88	1.50	0.00	0.00
12.5	0.25	0.48	2.73	11.75	4.13	1.50	0.00	0.00
14.0	0.23	0.49	2.96	13.25	3.38	1.50	0.00	0.00
15.5	0.22	0.62	4.02	14.75	2.63	1.50	0.00	0.00
$LPI = \sum w(z).F.H$								0.00

Table 7 Summarized *LPI* values of all the six sites for the different earthquake magnitudes

S. no.	Site identification	Liquefaction Potential Index (*LPI*)		
		M_w = 7.5 & *PGA* = 0.202*g*	M_w = 7.0 & *PGA* = 0.170*g*	M_w = 6.5 & *PGA* = 0.143*g*
1	BH-01	16.14	11.04	0.00
2	BH-02	22.66	9.35	0.00
3	BH-03	18.08	10.16	2.47
4	BH-04	16.25	10.54	0.00
5	BH-05	5.15	0.00	0.00
6	BH-06	15.59	10.51	2.97

liquefaction with respect to depth is presented in Fig. 6. It is observed from Fig. 6a that only for *BH-01*, the *FoS* is less than one for depths less than 4.0 m. Thus, it can be said that except for some pockets in *BH-01*, all the sites are safe from liquefaction susceptibility.

Liquefaction Potential Index: Kalyani Region

Liquefaction potential index (*LPI*) has also been evaluated in this study to illustrate the liquefaction susceptibility at the *AIIMS* Kalyani, Kolkata Campus. The *LPI* values are determined by Iwasaki et al. (1982) method in the present

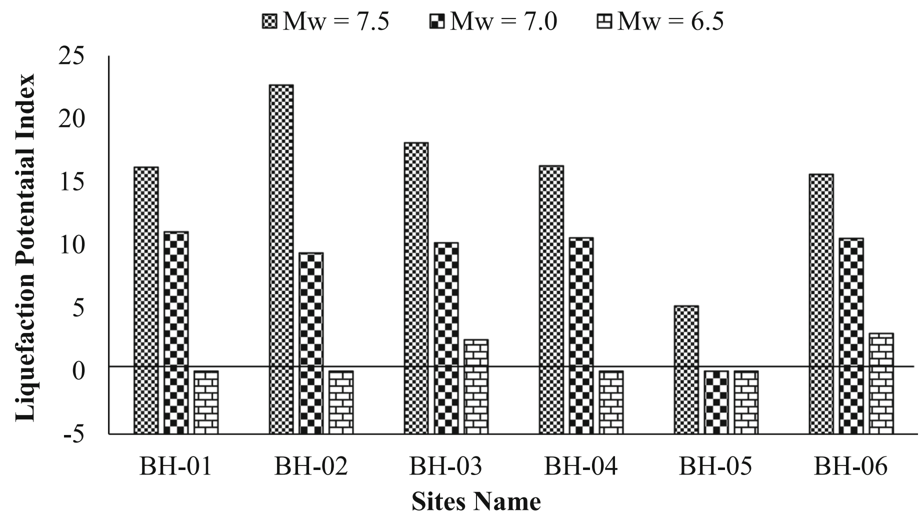


Fig. 7 Graph between *LPI* values and the site name

study. Different parameters are set by various researchers to classify the level of severity against liquefaction based on the *LPI* values. The classification suggested by [36] has been considered in this study. Different levels of severity in decreasing order are very high (*LPI* value greater than 15), high (*LPI* value between 5 and 15), low (*LPI* value between 0 and 5), and very low (*LPI* value zero) (Iwasaki et al., 1982). During their post-earthquake investigation for Monterey bay region, California, [33] suggested that the probability of liquefaction exposure on the surface is 93% for the *LPI* value greater than 15, it is 58% to 93% for the *LPI* value between 5 and 15 and it is below 58% for the *LPI* value less than 5.

The computed value of the *LPI* for *BH-02* is presented in Tables 4, 5, and 6 for the earthquake magnitudes M_w = 7.5, 7.0, and 6.5, for the corresponding *PGA* = 0.202*g*, 0.170*g*, and 0.143*g*, respectively. Further, Table 7 summarizes the *LPI* values of all the 6 sites for all the earthquake scenarios considered in the present study. It is evident from Tables 4, 5, and 6 that when the earthquake magnitude increases, the values of the *LPI* will also increase. For M_w = 7.5 and *PGA* = 0.202*g*, the *LPI* values for *BH-02* is 22.66 which means that the probability of liquefaction exposure on the surface is 93%. Further for other earthquake scenarios, the *LPI* value reduced from 9.35 for M_w = 7.0 to 0.0 for M_{w} = 6.5. Based on the *LPI* values, it can be said that the level of severity against liquefaction lies in high and low level for earthquake magnitude of 7.0 and 6.5, respectively.

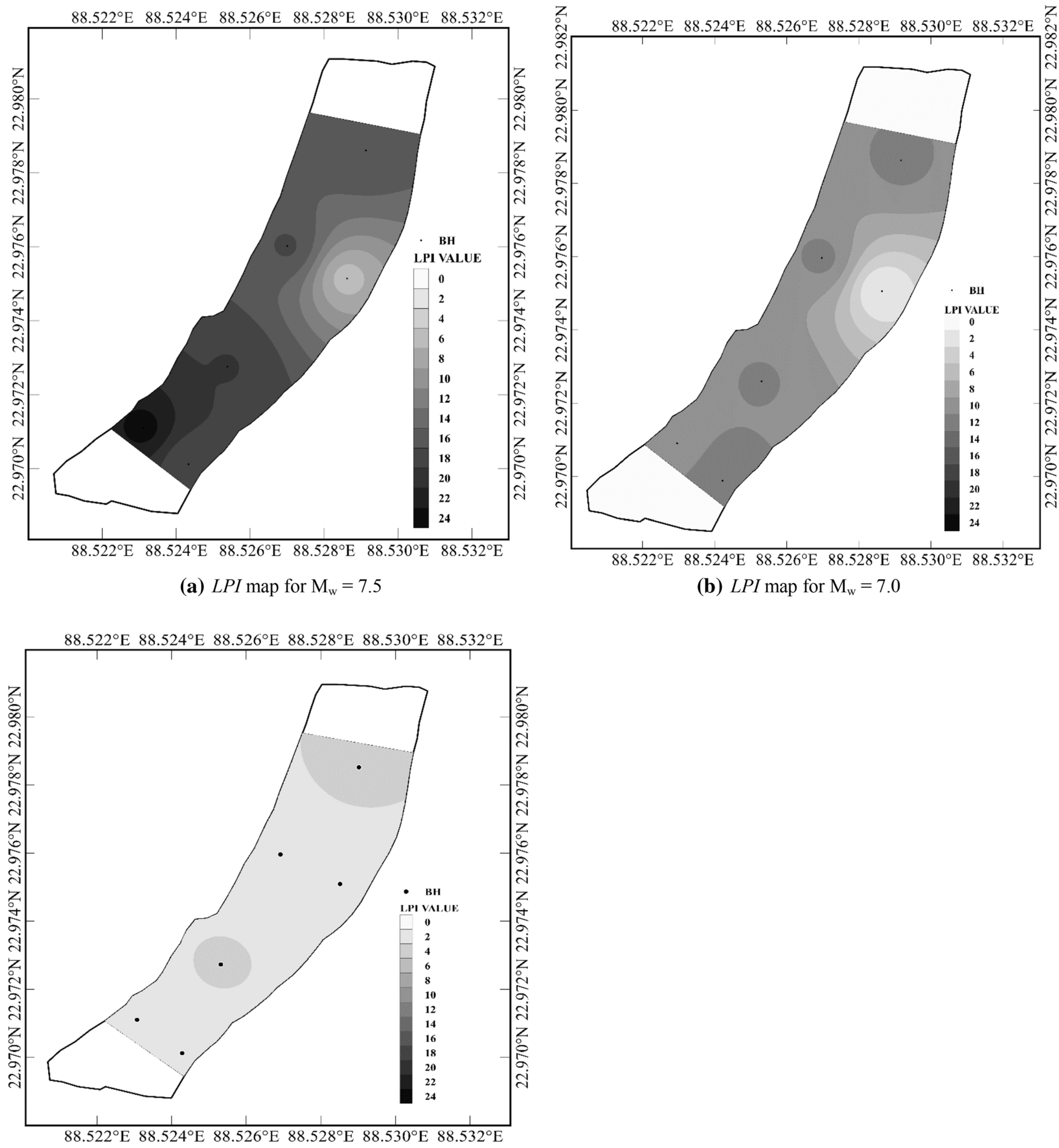
The *LPI* values of all the 6 boreholes for all the earthquake scenarios considered in the present study are represented in the graphical form in Fig. 7. From Table 7 and Fig. 7, it can be observed that for M_w = 7.5, all the five locations are having *LPI* values greater than 15 (except *BH-05*), which means that the probability of liquefaction is very high for all the sites and the chances for liquefaction exposure on the surface is 93% probability [33].

Similarly, for other earthquake scenarios, the level of liquefaction severity lies from high severity (M_w = 7.0) to low severity (*Mw* = 6.5). In case of M_w = 7.0 and *PGA* = 0.170*g*, the *LPI* values vary from 05 to 15 at all the locations except *BH-05* (*LPI* = 0). Therefore, the *LPI* values indicate that the chance of liquefaction is high (liquefaction exposure on the surface is 58% to 93%) except for *BH-05*. From Table 7, it is observed that liquefaction severity was found to be low for M_w = of 6.5 and *PGA* = 0.143*g*. When M_w exceeds from 7.0 to 7.5, the liquefaction severity jumps from high to very high. Further, Fig. 7 shows that the *LPI* values at all the sites show different levels of liquefaction severity depending on the different earthquake scenarios considered in this study.

The *LPI* interpolation maps against liquefaction severity for *AIIMS* Kalyani Kolkata Campus are shown in Fig. 8 for different magnitudes of earthquakes. From Fig. 8, it is clear that the major part of the campus is at low to high risk of susceptibility for liquefaction. For an earthquake of low magnitude, all the sites in study region may not liquefy. However, there is chance for liquefaction in this region, in case of strong earthquake.

Summary and Conclusions

In the present study, liquefaction potential of sites has been evaluated using the 'Simplified method' given by Seed and Idriss's method for the *AIIMS* Kalyani, Kolkata Campus. The liquefaction potential was evaluated for moderate to high-magnitude earthquake scenarios (M_w values of 6.5, 7.0, and 7.5, corresponding to *PGA* values of 0.143*g*, 0.170*g*, and 0.202*g*, respectively). The water table is considered at the ground level for all the 6 sites. Further, the liquefaction hazards map has been prepared on the based



(a) *LPI* map for $M_w = 7.5$

(b) *LPI* map for $M_w = 7.0$

(c) *LPI* map for $M_w = 6.5$

Fig. 8 *LPI* map of *AIIMS* Kalyani Campus, Kolkata, for the different earthquake magnitude

on the liquefaction potential index (*LPI*) values. The following conclusions can be drawn from the present study:

1. For the earthquake magnitude (M_w) of 7.5 and *PGA* of 0.202*g*, all the 6 sites were observed to be susceptible to liquefaction, with the average depth of susceptibility being 7.0 m for *BH-01* to *BH-04* whereas for the rest of the sites (i.e. *BH-05* & *06*) the susceptibility to liquefaction is up to the shallow depth of 3 m only.
2. The *FoS* against liquefaction for *PGA* = 0.170*g* and M_w = 7.0 is relatively greater. However, it is still less than one for shallow depths at most of the sites except

BH-05 & *BH-06*; thus indicating that most of the sites are susceptible to liquefaction. The depth of liquefaction though reduces for M_w = 7.0 as compared to that for M_w = 7.5. The minimum difference in the *FoS* obtained for a 7.0 magnitude earthquake is found to be 40% greater than that for M_w = 7.5 due to the difference in *MSF* and *PGA*.

3. For M_w = 6.5 and *PGA* = 0.143*g*, all the 6 sites in *AIIMS* Kalyani region may not liquefy. The values of the *FoS* against liquefaction for this particular case are observed to be two times of the *FoS* values for M_w = 7.5 and *PGA* = 0.202*g*.
4. From the *LPI* values, it is observed that the liquefaction severity is found to be very high ($LPI > 15$; expose to liquefaction about 93%) for all the sites except *BH-05* ($LPI < 5$) for the magnitude of earthquake M_w = 7.5 and *PGA* = 0.202*g*. When M_w = 7.0 and *PGA* = 0.170*g*, liquefaction severity was found to be high (i.e. $LPI < 5$; chance of liquefaction is in between 58 and 93%) except for BH-05. Further, for M_w = 6.5 and *PGA* = 0.143*g* liquefaction severity was found to be low vulnerable/exposure to liquefaction is below 58% based on the *LPI* values (*LPI* = 0 to 5).

The findings of the present study are helpful to identify liquefaction-prone zones in the study region. The conclusions drawn are of very much practical significance and liquefaction hazard maps may be employed by design engineers in the preliminary and detailed design of any construction/infrastructure, i.e. design of structures, underground structures, and foundations design. The conclusions of this study are limited to the *AIIMS* Kalyani, Kolkata Campus area.

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Declarations

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

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