Liquefaction Potential of Sites in Kalyani Region based on Shear Wave Velocity Data

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Abstract
Liquefaction hazard is one of the most catastrophic effects of an earthquake. When dynamic loading occurs, saturated sandy soil in undrained conditions loses its shear strength due to the development of excess pore water pressure. Therefore, it is imperative to evaluate a site for its susceptibility to liquefaction. The main objective of the present study is to calculate the liquefaction potential of 6 sites in Kalyani region which are located at around 50 km from the City of Kolkata in the State of West Bengal, India. For this purpose, six bore locations are selected in the All India Institute of Medical Sciences, Kalyani, Kolkata Campus.

The liquefaction potential of the site is calculated at all the six locations for an earthquake of magnitude 7.5 and peak ground acceleration (PGA) of 0.16 g. The water table is considered at the ground level. Liquefaction potential in terms of Factor of Safety against liquefaction is calculated with the depth based on the shear wave velocity data. Further, liquefaction potential index is also evaluated for all the considered sites. It is observed that the possibility of liquefaction is very high at shallow depths. Moreover, a parametric study is carried out for various values of the magnitudes of earthquakes and PGA values to show its effects on liquefaction susceptibility.

Keywords: Peak Ground Acceleration, Shear Wave Velocity, Liquefaction Potential, Liquefaction Potential Index, SPT N Value, Seismic Hazard.

Introduction

Geotechnical investigation is carried out to identify the properties of the soil, where any major civil engineering structure is to be constructed. If the investigation is done for the site which comes under the earthquake prone areas then it is necessary to establish whether the given site is liquefiable or not. Standard Penetration Test (SPT), Cone Penetration Test (CPT), Becker Hammer Test (BHT) and Multichannel Analysis Surface Wave (MASW) Test are some of the field methods used to measure the liquefaction potential of soil. Earlier, the liquefaction potential of a site was calculated by the simplified procedure developed by Seed and Idriss[35] using the Cyclic Resistance Ratio (CRR) value obtained by N values of SPT. Since then, the method has been continuously reformed and simplified by various authors.[36-38,47]

Another popular method for the evaluation of the liquefaction potential using the CPT was given by Robertson and Campanella[32]. This method of evaluation has also been reformed and updated several times.[30,34,41]

The shear wave velocity (Vs) method for determination of the liquefaction potential is preferable over other methods such as SPT, CPT etc. because it is not affected by large particles and is less sensitive toward soil compression and reduced penetration resistance due to the presence of fines, thus requiring minor corrections.[31] It is also a non-destructive test and can be used both in the field and in the laboratory.[14,44]

In this method, shear wave velocity is considered as an index property of soil to determine liquefaction potential resistance. Both liquefaction potential resistance and shear wave velocity are similarly influenced by stress history, age of soil geology, void ratio and different states of stress.

In the last two decades, many researchers have given relationships between liquefaction potential resistance and shear wave velocity. They have used different methods like field test, penetration –Vs correlation, numerical investigation, laboratory experiments etc.[3,6,10,12,20,24,33,37,43,44] All these evaluations were based on the simplified procedure of Seed and Idriss[35] method. Several corrections have been applied to Vs for overburden stress and an analytical expression is established with Cyclic Stress Ratio (CSR). Several seismic tests have been used to measure shear wave velocity in the field like CPT, MASW, suspension logger, down-hole and cross-hole.[22,47] Sensitiveness of the calculation and condition of soil are highly affected by the precision of the tests. Stokoe et al[42] and Belloti et al[5] have shown that the velocity achieved by the shear wave is equally dependent on the motion of the particle and principal stresses.

The evaluation of liquefaction potential index (LPI) is required to mitigate the damages caused by liquefaction. Iwasaki et al[18] proposed LPI to overcome the limitations associated with Factor of Safety (FoS). LPI is frequently used by researchers to evaluate the liquefaction potential of soils. LPI offers an advantage by providing a single value for the entire location for liquefaction hazard maps instead of several factors at different layers.[11,40,46] LPI has been calibrated using SPT test data to characterize the liquefaction potential of sites.[11,29,40,45] Iwasaki et al[19] categorized levels of liquefaction severity as very low, low, high and very high depending on LPI values (LPI=0, 0<LPI<5, 5<LPI<15, LPI>15 respectively).

This study includes the summary of the procedure used to calculate the liquefaction potential for Kalyani region based on shear wave velocity data by the method given by Andrus and Stokoe[4]. For this purpose, six bore holes in the All India Institute of Medical Sciences (AIIMS) Kolkata campus were considered for geotechnical investigation. Due to the industrialization, the city is growing at a very fast rate and it is necessary to identify the seismic hazardous areas. Also, the city lies in the seismic zone III as per IS 1893:2016 Part-I[16] and thus as high seismic risk.

Area of Study

The present study is done for the assessment of the liquefaction potential of 6 sites in All India Institute of Medical Sciences (AIIMS) Kalyani Campus, Kolkata. Kalyani is a city located around 50 kilometers from Kolkata-the capital of the State of West Bengal, India. Kalyani lies along the east bank of Hooghly River within the upper Ganges delta. As with most of the Indo-Gangetic plain, the soil is predominantly alluvial in origin. The *in situ* tests data were collected at six different sites in the AIIMS Kalyani, Kolkata campus. The details of locations of all the six sites are shown in the fig. 1. Table 1 gives various details of all the sites such as bore log depth, latitude, longitude and ground water table.[23]

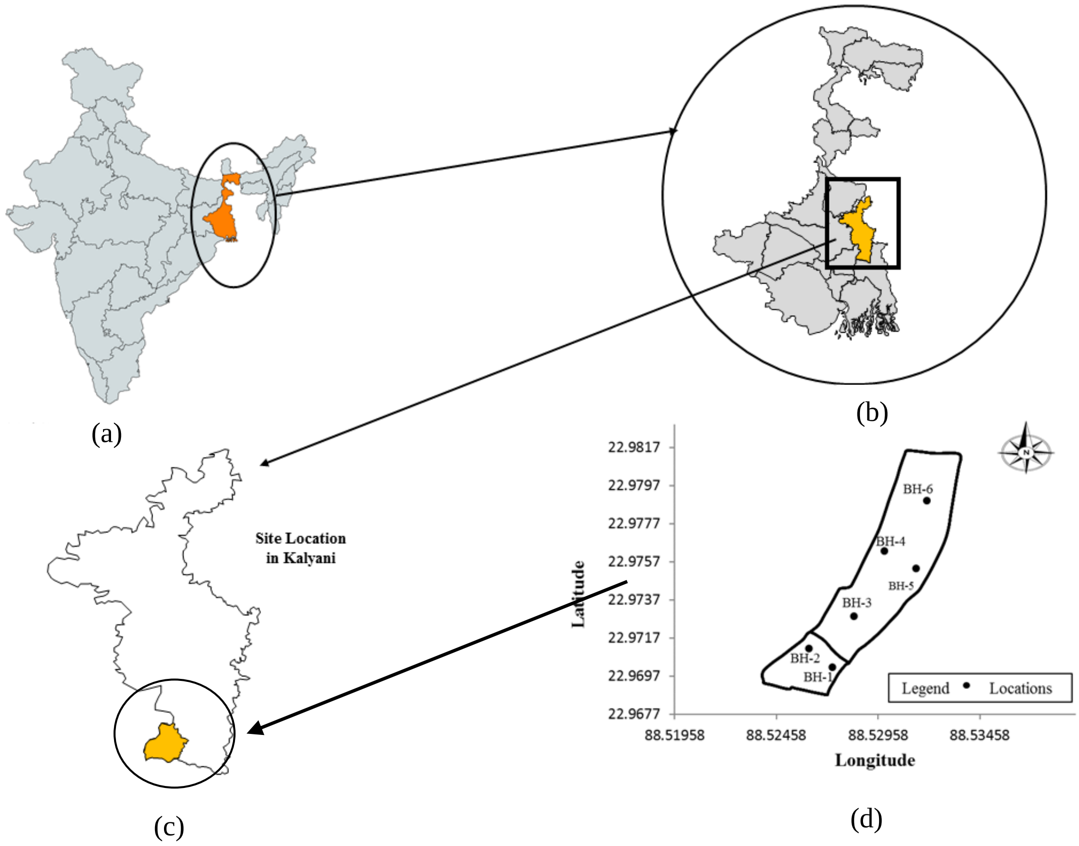


Fig. 1: Location of site (a) Map of India (b) Map of West Bengal (c) Map of Kalyani district (W.B.) (d) Location of site in Kalyani

Table 1
Borelog Details

S.N.	Site	Borelog Depth (m)	Latitude	Longitude	Water Table (m)	
					Actual	Assumed
1	BH-01	15.00	N22°58´12.62´´	E88°31´38.44´´	2.8	Ground
2	BH-02	15.50	N22°58´16.20´´	E88°31´34.27´´	3.1	Ground
3	BH-03	16.00	N22°58´22.27´´	E88°31´42.24´´	1.6	Ground
4	BH-04	15.00	N22°58´34.55´´	E88°31´47.16´´	3.3	Ground
5	BH-05	15.00	N22°58´30.55´´	E88°31´52.90´´	1.4	Ground
6	BH-06	15.00	N22°58´43.74´´	E88°31´53.97´´	1.8	Ground

Methodology

In the present study, liquefaction potential is evaluated based on the shear wave velocity data. The methodology of analysis includes the following three steps:

(i) Evaluating the CSR by simplified procedure given by Seed and Idriss[35]
(ii) Evaluating the CRR of the sites based on the field tests data[4]
(iii) Calculating the Factor of Safety (FoS) with depth based on the information from the above two steps.

Cyclic Stress Ratio (CSR): The average shear stress due to earthquake loading or CSR is computed based on the simplified method proposed by Seed and Idriss[35]. The CSR is defined by eq. 1:

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

where a_{max} is the peak horizontal acceleration for seismic zone III (for the present study, a_{max} = 0.16g is considered as per IS:1893, 2016); σ_{vo} and σ'_{vo} are the total and effective stresses; g is the acceleration due to gravity and rd is the stress reduction coefficient, calculated by Youd et al.[48]

Cyclic Resistance Ratio (CRR): Cyclic Resistance Ratio (CRR) is a value of CSR which is used to separate the condition of liquefaction and non-liquefaction in terms of Vs1 or corrected SPT resistance. Andrus and Stokoe[3] proposed an empirical relationship to determine CRR. Further, the CRR value is updated for correction factor (Kc) which is a factor of aging and cementation. This correction leads to increase in the value of shear wave velocity. In this study, CRR is evaluated from eq. (2):[4]

$$CRR = \left\{ a\left(\frac{K_c V_{s1}}{100}\right)^2 + b\left(\frac{1}{V^*_{s1} - K_c V_{s1}} - \frac{1}{V^*_{s1}}\right)\right\} MSF \tag{2}$$

where V^*_{s1} is upper limiting value of V_{s1}, evaluated from eq. 3 for different fines content range; a and b are curve fitting parameters and MSF is magnitude scaling factor [MSF = 1, for the Mw = 7.5].[48]

V^*_{s1}=215 {FC ≤ 5%} (3a)
V*s1=215-0.5(FC-0.5) {5 %< FC ≤ 35%} (3b)
V^*_{s1}=200 {FC ≥35%} (3c)

where FC = average of fines content in the sandy soil.

Eq. 3(a) and eq. 3(c) illustrate a constant value of 215 m/s for fines contents less than equal to 5 percent and a constant value of 200 m/s for fines contents more than equal to 35%. The fines contents between 5% and 35% are evaluated from the eq. 3(b). Several studies have been done for the fines correction in past years. Muley et al[27] studied the effect of the fines on the sand of Roorkee region.

Factor of Safety against Liquefaction: The final step in the analysis is to compute the FoS against liquefaction which is the ratio of CRR to CSR as mentioned in eq. 4:

$$FoS = \frac{CRR}{CSR} \tag{4}$$

Existence of liquefaction is expected when the values of FoS ≤ 1 and there is no liquefaction for the values of FoS > 1.

Evaluation of Liquefaction Potential Index: Liquefaction potential index (LPI) is a single-valued parameter for the evaluation of liquefaction potential at a specific site. Iwasaki et al[19] proposed an expression for calculating the LPI as in eq. 5:

$$LPI = \int_0^{20} F(z).w(z)dz \tag{5}$$

where z = Depth of the midpoint of the soil layer (0 to 20 m), dz = Differential increment of depth, F (z) = Severity factor and w (z) = Weighting factor calculated using eq. 6:

F(z) = 1-FoS for FoS<1 6(a)
F(z) = 0 for FoS<1 6(b)
w(z)=10-0.5z for z < 20 m 6(c)
w(z)=0 for z > 20 m 6(d)

For the soil profiles with depth less than or equal to 20 m, LPI is calculated by using the following eq. 7:

$$LPI = \sum_{i=1}^{n} w_i F_i H_i \tag{7}$$

where

F_i = 1-Fos_i when Fos_i <1.0 8(a)
F_i = 0 when Fos_i ≥ 1.0 8(b)

where H_i = Thickness of the discretized soil layers; n = Number of the layers, F_i = Liquefaction severity for i_{th} layer, FoS_i = Factor of safety for i_{th} layer and w_i = Weighting factor calculated by eq. 9:

w_i = 10-0.5z_i (9)

where z_i = Depth of i_{th} layer (m).

The different level of liquefaction severity is described on the basis of LPI values. Levels of severity are very low, low, high and very high, their respective LPI values are 0, 0 to 5, 5 to 15 and greater than 15 respectively.[19]

Geotechnical Investigation: Geotechnical investigation of any location is done to explore the soil properties and to consider the measures to be taken during the construction in that area. In this research work, an investigation is executed in the campus of AIIMS Kalyani, Kolkata by Geotechnical Consultant Centre for Advanced Engineering, Kolkata for the project of AIIMS by performing an *in situ* test for geotechnical investigation purpose. Majority of soil of Kalyani district, Kolkata is classified as Gangetic alluvium. Due to the mixture of sand and silt, the capacity of soil to retain moisture is very low. Soft, compressible silty clay/clayey silt is found up to depth of 14.0 m and for the depth between 40m and 50 m, soil is stiff with intermediate sand.[26]

The samples were reported from all the six sites for evaluation of liquefaction potential. Details of SPT N values and other index properties with depth are given in table 2 for all the six sites in AIIMS, Kalyani, Kolkata Campus. Table 2(a) shows the properties of clay type soil which include N value, fines contents, water content, bulk density, plasticity characteristics and evaluated values of corrected SPT N value and shear wave velocity with the depth. Shukla et al[39] and Dagar et al[9] mentioned the shear wave velocity with the depth for study region.

Fig. 2 represents the shear wave velocity curve for all the sites i.e. BH-01 to BH-06 with depth. It can be observed from fig. 2 that the shear wave velocity increases with the depth for all the six sites. This behavior is consistent with the SPT values across the depths (Table 2).

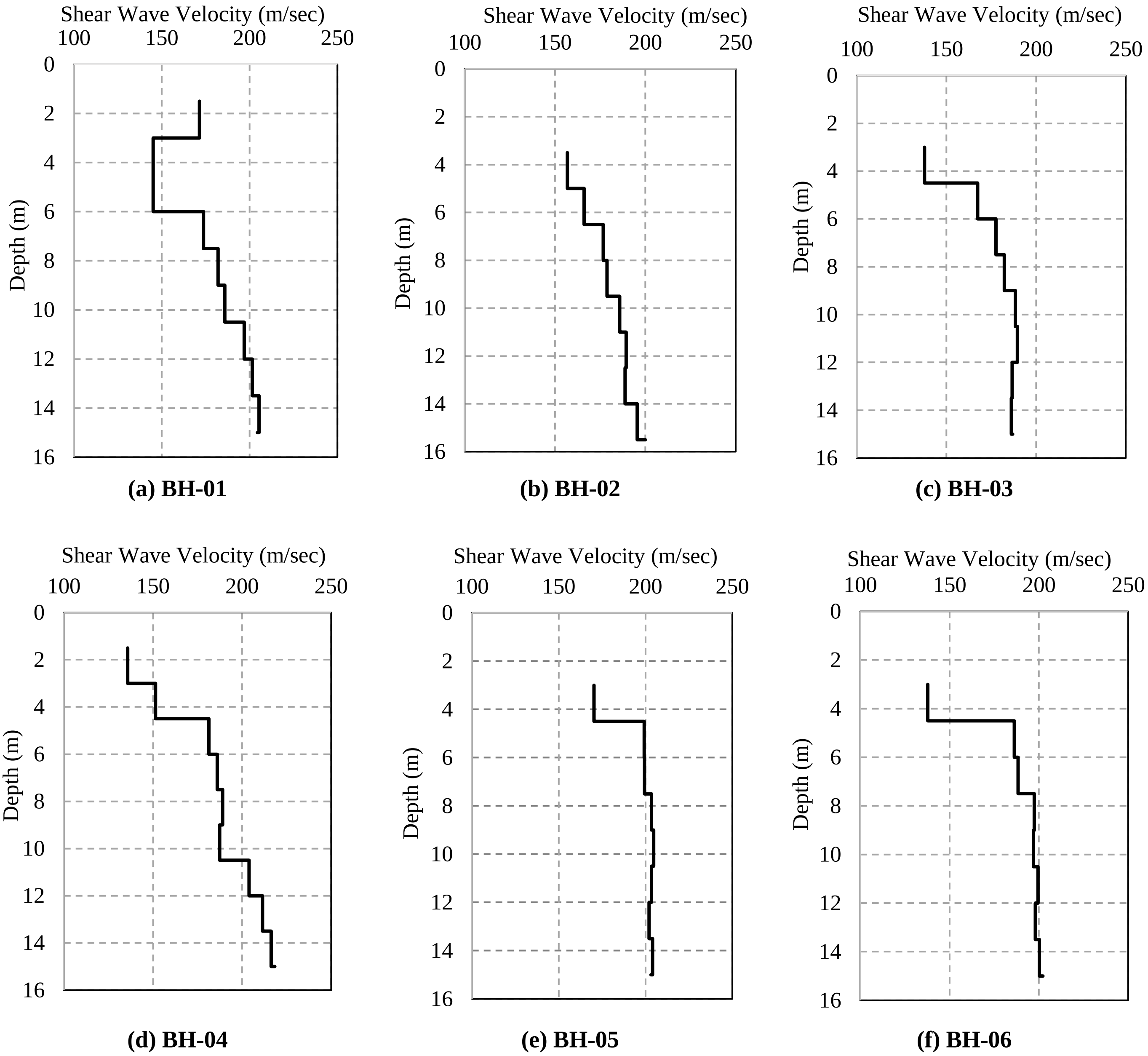


Fig. 2: Shear Wave velocity with the depth for all six sites in AIIMS Kalyani Campus

Table 2(a)
Properties of the clay type soil samples for BH-01 to BH-06

Site Identification	Depth (m)	Bulk Density (g/cc)	Specific Gravity (G)	Water Contents	Fines	LL	PL	PI	N-Value	$(N_1)_{60}$	V_{s1}
BH-01	6.00	1.84	2.66	27.29	72	42	22	20	11	14.9	174
	7.50	1.84	2.66	27.29	72	42	22	20	15	18.1	182
	9.00	1.84	2.66	27.29	72	42	22	20	18	19.9	186
	10.50	1.84	2.66	27.29	72	42	22	20	25	25.5	197
BH-03	3.0	1.83	2.67	26.43	68	46	21	25	4	14.9	157
	4.5	1.83	2.67	26.43	68	46	21	25	9	5.44	138
	6.0	1.83	2.67	26.43	68	46	21	25	12	12.64	167
	7.5	1.83	2.67	26.43	68	46	21	25	15	16.31	178
	9.0	1.83	2.67	26.43	68	46	21	25	19	18.24	182
	10.5	1.83	2.67	26.43	68	46	21	25	20	21.09	188
	12.0	1.83	2.67	26.43	68	46	21	25	20	21.63	190
	13.5	1.83	2.67	26.43	68	46	21	25	21	20.23	187
	15.0	1.83	2.67	26.43	68	46	21	25	23	20.03	186
BH-05	3.00	1.82	2.66	26.06	76	45	23	22	10	13.6	170
BH-06	3.00	1.8	2.66	26.81	71	47	22	25	4	5.44	138
	4.50	1.8	2.66	26.81	71	47	22	25	14	20.02	186
	6.00	1.8	2.66	26.81	71	47	22	25	17	21.06	188

Table 2 (b)
Properties of the sand type soil samples for BH-01 to BH-06

Site Identification	Depth (m)	Bulk Density (g/cc)	Specific Gravity (G)	Sand	Silt	Clay	N-Value	$(N_1)_{60}$	V_{s1}
BH-01	1.5	1.84	2.67	88	12	0	11	14.0	172
	3.0	1.84	2.67	88	12	0	5	6.8	145
	12.00	1.84	2.64	85	15	-	28	28.2	201
	13.50	1.84	2.64	85	15	0	32	30.3	205
	15.00	1.84	2.64	85	15	0	34	30.6	205
BH-02	3.50	1.80	2.63	76	21	3	7	9.52	157
	5.00	1.80	2.63	76	21	3	9	12.21	166
	6.50	1.80	2.63	76	21	3	12	15.96	177
	8.00	1.80	2.63	76	21	3	14	16.79	179
	9.50	1.80	2.63	76	21	3	18	19.80	186
	11.00	1.80	2.63	76	21	3	20	21.53	189
	12.50	1.80	2.63	76	21	3	21	21.20	189
	14.00	1.87	2.65	88	12	0	26	24.69	195
	15.50	1.87	2.65	88	12	0	30	26.97	200
BH-04	1.50	1.88	2.65	77	23	0	4	5.10	136
	3.00	1.86	2.65	77	23	0	6	8.16	151
	4.50	1.87	2.65	79	21	0	13	17.83	181
	6.00	1.87	2.65	79	21	0	15	19.91	181
	7.50	1.87	2.65	79	21	0	18	21.37	186
	9.00	1.87	2.65	83	17	0	19	20.61	189
	10.50	1.86	2.65	83	17	0	28	29.63	187
	12.00	1.86	2.65	83	17	0	35	34.66	204
	13.50	1.86	2.65	83	17	0	41	38.29	211

	15.00	1.86	2.65	83	17	0	45	39.89	216
BH-05	4.50	1.82	2.63	85	15	0	19	26.84	199
	6.00	1.82	2.63	85	15	0	22	26.92	199
	7.50	1.82	2.63	85	15	0	24	29.35	203
	9.00	1.82	2.63	85	15	0	27	30.15	205
	10.50	1.82	2.63	85	15	0	27	29.38	203
	12.00	1.82	2.63	85	15	0	28	28.50	202
	13.50	1.82	2.63	85	15	0	31	29.75	204
	15.00	1.82	2.63	85	15	0	32	29.13	203
BH-06	7.50	1.88	2.64	84	16	0	21	25.75	203
	9.00	1.88	2.64	84	16	0	23	25.58	205
	10.50	1.88	2.64	84	16	0	25	26.97	203
	12.00	1.88	2.64	84	16	0	26	26.15	202
	13.50	1.88	2.64	84	16	0	29	27.42	204
	15.00	1.88	2.64	84	16	0	32	28.65	203

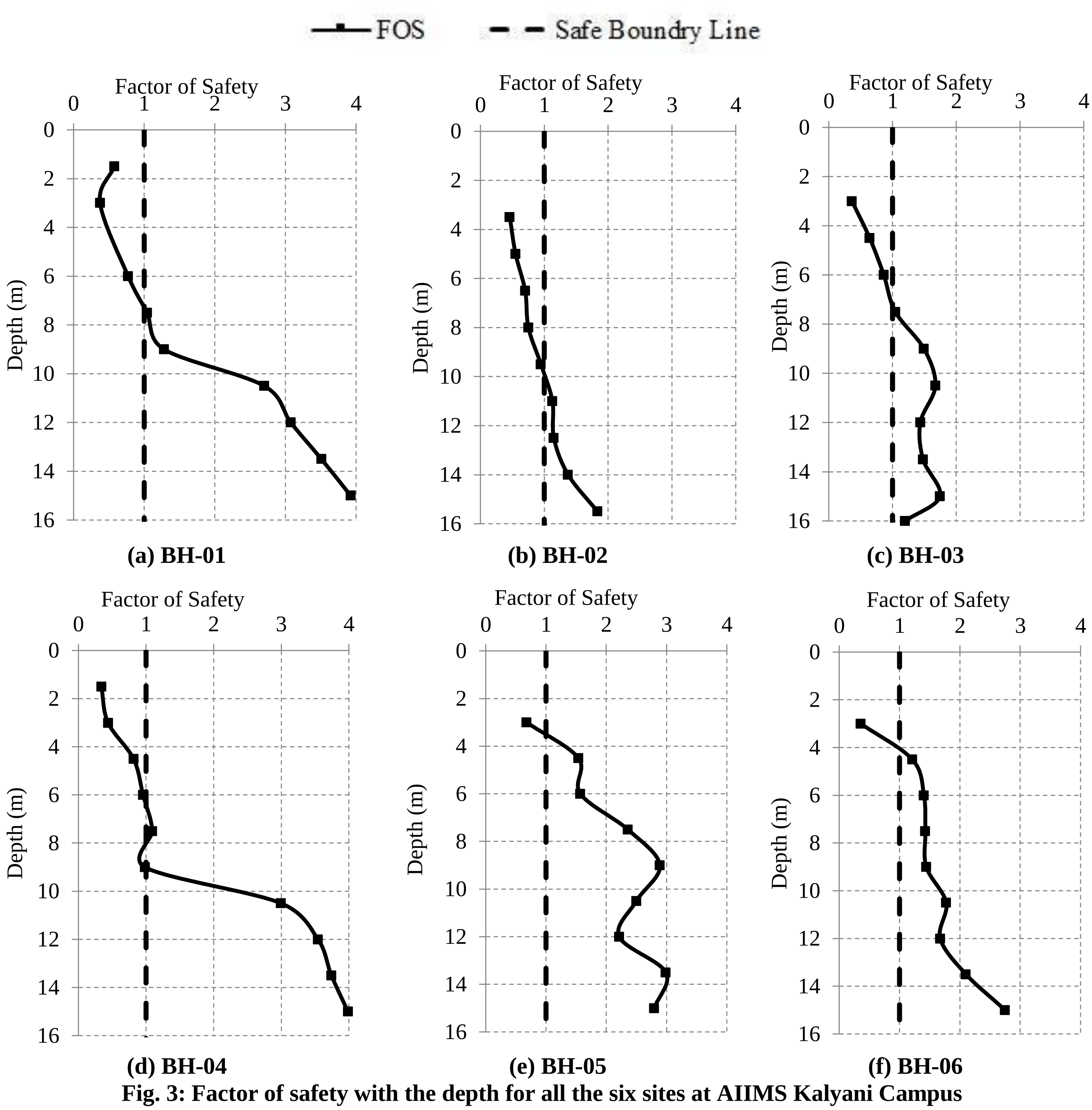


Fig. 3: Factor of safety with the depth for all the six sites at AIIMS Kalyani Campus (for Mw = 7.5 with a_{max} = 0.16g and the water table at ground surface)

Table 3
Computational of LPI of BH-02 for PGA = 0.16g, Magnitude of the Earthquake (M_w = 7.5) and the water table at ground surface

Depth (m)	CSR	CRR_{Vs}	FOS_{Vs}	Z	w(z)	F_i	LPI
3.5	0.23	0.11	0.46	1.75	9.13	0.54	17.24
5.0	0.23	0.12	0.55	4.25	7.88	0.45	5.31
6.5	0.22	0.16	0.70	5.75	7.13	0.30	3.19
8.0	0.22	0.16	0.75	7.25	6.38	0.25	2.38
9.5	0.21	0.20	0.95	8.75	5.63	0.05	0.43
11.0	0.21	0.23	1.13	10.25	4.88	0.00	0.00
12.5	0.20	0.23	1.15	11.75	4.13	0.00	0.00
14.0	0.18	0.25	1.37	13.25	3.38	0.00	0.00
15.5	0.17	0.32	1.83	14.75	2.63	0.00	0.00
	LPI = Σw(z).F .H						**28.55**

Table 4
LPI values of all six sites (for M_w = 7.5 and a_{max} = 0.16g)

S.N.	Site Identification	Bore Hole Depth (m)	LPI Value	Level of liquefaction severity (Iwasaki *et al.*[19])
1	BH-01	15.00	19.72	Very High
2	BH-02	15.50	28.55	Very High
3	BH-03	16.00	23.51	Very High
4	BH-04	15.00	19.77	Very High
5	BH-05	15.00	8.95	High
6	BH-06	15.00	17.84	High

The minimum value of Vs1 is 138 m/s for the BH-03 and BH-06 at the depth of 3 m corresponding to the minimum SPT N value and the maximum value of Vs1 is 216 m/s at the depth of 15 m for BH-04. It can be inferred from fig. 2 and N values that all the six sites are comprised of medium sand.

Results and Discussion

The CSR values at different depths were computed using the simplified method (Eq. 1) for all the six sites. The CRR was computed using eq. 2 given by Andrus and Stokoe[4].

Further, fig. 3 depicts the FoS against liquefaction with the depth for all the six sites based on Vs data. It can be observed from fig. 3 that three sites viz. BH-01, BH-02 and BH-03, are likely to be liquefied up to the shallow depth up to the 8.0 depth. From fig. 3b, it is clear that the BH-02 is the most susceptible site to liquefaction up to the depth of 10 m.

Like FoS, LPI values are also computed for all the six sites for Mw = 7.5 and a_{max} = 0.16g. Table 3 shows the values of LPI for the site BH-02 along the depth. Liquefaction susceptibility for sites with LPI > 15 is high and the liquefaction is unlikely at sites with LPI < 5. LPI value of 15 has a probability of 93% of showing surface manifestations of liquefaction; a location with an LPI value of 5 has a probability of 58%.[45] Also. LPI values at different sites are much sensitive to the location of water table rather that the magnitude of earthquake.

The LPI values evaluated from Vs based approach for all the six sites are given in table 4. It can be concluded from table 5 that for Vs based approach, all the borehole locations have LPI values greater than 15 excluding boreholes BH-05 and BH-06; thereby the level of liquefaction severity is very high for these sites. BH-05 and BH-06 have LPI index between 5 and 15 which means the level of liquefaction severity is high (less than 93% probability). Further, liquefaction potential index was also evaluated for different earthquake magnitudes based on shear wave velocity data.

For Kolkata site, for the earthquake magnitude of 6, the design PGA value obtained from the relationship given by Abrahamson and Litehiser[1] is 0.12g. The PGA values for other magnitudes of earthquake of Mw = 6.5 and Mw = 5.5 were found to be 0.1g and 0.01g respectively.[8]

For Mw = 5.5 and PGA = 0.16g, the susceptibility of all the six sites to liquefaction is very low (LPI = 0). For Mw = 6.0 and PGA = 0.12g, all the sites have LPI index < 5 i.e. low possibility of liquefaction (less than 58% probability). Further, for Mw = 6.5 and PGA = 0.14g, all the sites have LPI values between 5 and 15 i.e. less than 93% probability except the BH- 05 (LPI = 0). Figure 5 shows the liquefaction susceptible chart for all the six sites based on LPI values for different earthquake magnitudes.

Figure 4 shows the liquefaction susceptibility chart for all the six sites based on LPI values for different earthquakes magnitudes. From fig. 4, it can be observed that the liquefaction severity is lowest for the earthquake magnitudes of 5.5 and the severity of liquefaction increases as the magnitude of earthquake increases. Based on the analyses and results, liquefaction potential index mapping for AIIMS Kalyani region for different magnitudes of earthquake was prepared and is presented in figure 5.

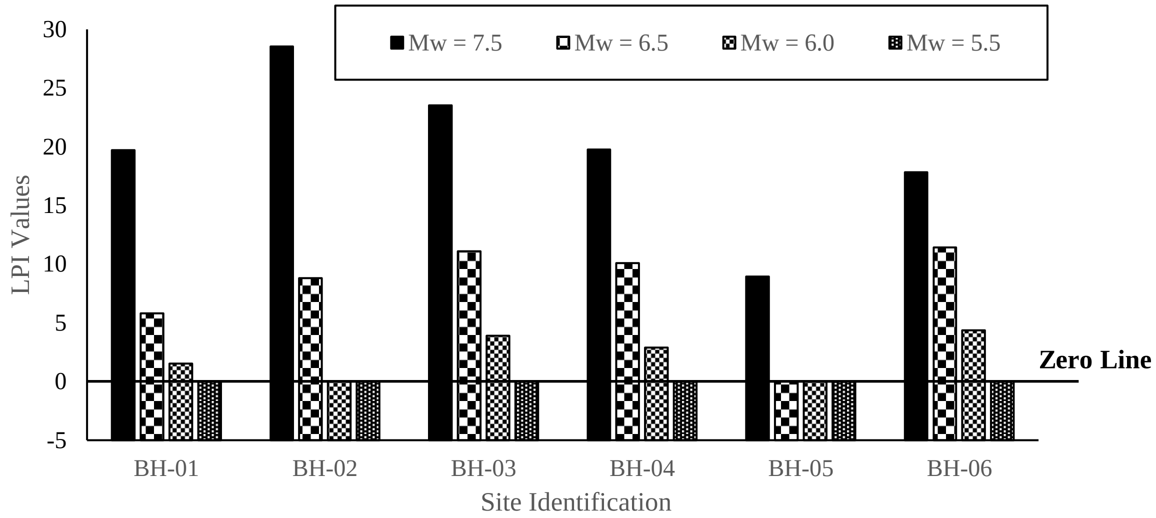
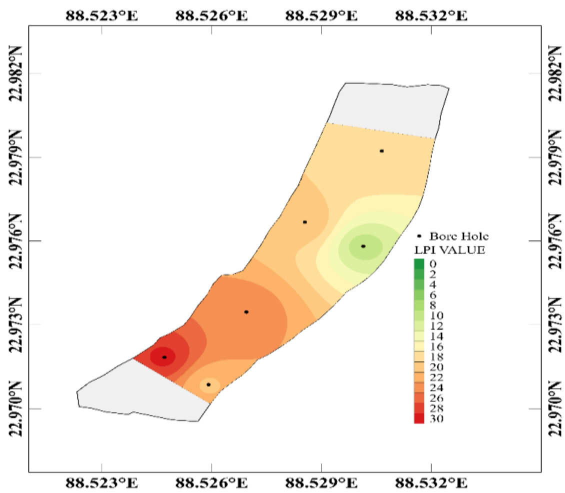
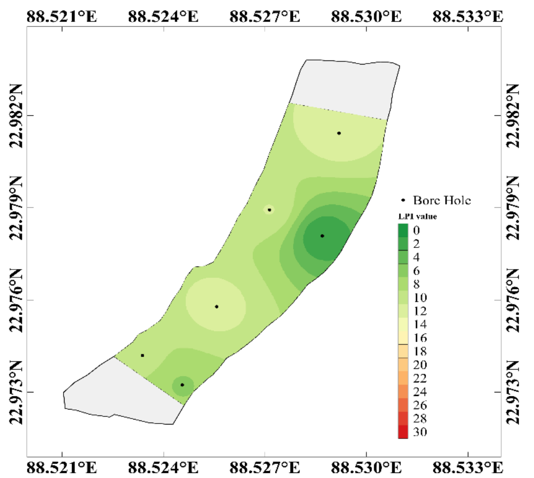


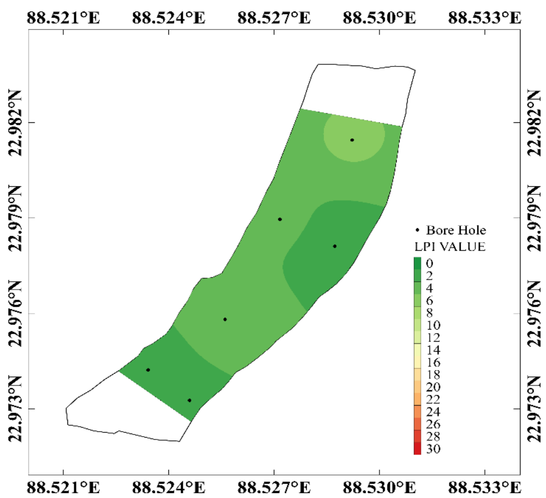
Fig. 4: LPI chart for all the six sites in AIIMS Kalyani Campus for different earthquake magnitudes



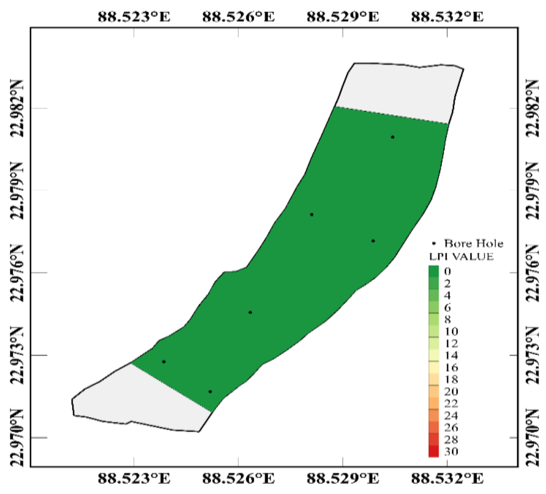
(a) LPI Map for Mw = 7.5 & PGA = 0.16



(b) LPI Map for Mw = 6.5 & PGA = 0.14



(c) LPI Map for Mw = 6.0 & PGA = 0.12



(d) LPI Map for Mw = 5.5 & PGA = 0.01

Fig. 5: LPI Mapping for AIIMS Kalyani Region for Different magnitudes of earthquake

Table 5
LPI value of all the six sites in AIIMS Kalyani Campus for different Earthquake Magnitude and PGA

Site Identification	Liquefaction Potential Index Values			
	M_w = 7.5 & PGA = 0.16	M_w = 6.5 & PGA = 0.14	M_w = 6.0 & PGA = 0.12	M_w = 5.5 & PGA = 0.01
BH-01	19.72	5.8	1.52	0
BH-02	28.55	8.81	0	0
BH-03	23.51	11.09	3.89	0
BH-04	19.77	10.08	2.89	0
BH-05	8.95	0	0	0
BH-06	17.84	11.42	4.37	0

Conclusion

The liquefaction potential of Kalyani Region has been analyzed using *in situ* tests data. The factor of safety against liquefaction is also determined using shear wave velocity data. Liquefaction potential is also compared with other *in situ* tests data i.e. SPT N-Values. Further liquefaction potential index is also evaluated for different magnitudes of earthquake.

Following conclusions can be drawn based on the analyses performed:

1. For PGA = 0.16g and M_w = 7.5, the factor of safety against liquefaction, assuming water table at the ground level, is less than one for most of the sites at shallow depths (up to 7.5m depth) except for one site (BH-05). Thus, all the sites are likely to be liquefied up to the shallow depths of 7.5 m based on the results.
2. Further, for the selected earthquake magnitude of Mw = 6.5 (PGA = 0.14g), the liquefaction potential index values, assuming water table at the ground level, lie between 5 to 15 i.e. there is high level of liquefaction severity at all the sites except BH-05 (LPI =0). Thus, all the sites are likely to be susceptible to liquefaction. Further, for Mw = 6.0 and PGA = 0.12g, all the sites are having LPI = 0 to 5 i.e. low possibility of liquefaction (less than 58 % probability) while in case of Mw= 5.5 and PGA = 0.01g, all the sites perform well i.e. LPI = 0. As the magnitude of earthquake increases, the severity of liquefaction increases.

The present study is done to evaluate the liquefaction potential of Kalyani region Kolkata. The finding of the present study is helpful to identify seismic liquefaction-prone areas in the Kalyani region. This knowledge can be used to take proper measures to mitigate liquefaction hazard. Results indicate that for all the important projects, the liquefaction analysis of a site based on shear wave velocity may be required for the comprehensive understanding. Though this outcome is based on limited data presented here and may require further investigation, the present study has direct practical application for the design of structures and foundations in the Kalyani region of Kolkata.

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References

1. Abrahamson N.A. and Litehiser J.J., Attenuation of vertical peak acceleration, *Bulletin of Seismological Society of America*, **79(3)**, 549-580 **(1989)**

2. Anbazhagan P. and Sitharam T.G., Seismic microzonation of Bangalore, India, *Journal of Earth System Science*, **117(Supplement 2)**, 833–852 **(2008)**

3. Andrus R.D. and Stokoe K.H. II, Liquefaction resistance based on shear wave velocity, Proc., NCEER Workshop on Evaluation of Liquefaction Resistance of Soils, Tech. Rep. NCEER-97-0022 National Center for Earthquake Engineering Research, Buffalo, 89–128 **(1997)**

4. Andrus R.D. and Stokoe K.H. II, Liquefaction resistance of soils from shear-wave velocity, *J. Geotech Geoenviron. Engg*., **126(11)**, 1015-1025 **(2000)**

5. Belloti R., Jamiolkowski J., Presti D.C.F. and O'Neill D.A., Anisotropy of small strain stiffness of Ticino sand, *Geotechnique London*, **46(1)**, 115–131 **(1996)**

6. Bierschwale J.G. and Stokoe K.H. II, Analytical evaluation of liquefaction potential of sands subjected to the 1981 Westmorland earthquake, Geotech. Engg Report 95-663, University of Texas, Austin, Texas **(1984)**

7. Centre for Advanced Engineering, Report on Geotechnical Investigation for Setting up of AIIMS at Kalyani West Bengal, Centre for Advanced Engineering, Kolkata, 1-77 **(2015)**

8. Chakarborty P., Pandey A.D., Mukharjee S. and Bhargava A., Liquefaction assessment for microzonation of Kolkata city, 13th World Conference on Earthquake Engineering Canada, Paper no. 2 **(2004)**

9. Dagar R., Shukla H., Muley P. and Syed N.M., Evaluation of the Soil Amplification Factor of Sites in Kalyani Region, Biswas S., Metya S., Kumar S. and Samui P., eds., In Advances in Sustainable Construction Materials, Lecture Notes in Civil Engineering, Springer, Singapore **(2021)**

10. de Alba P., Baldwin K., Janoo V., Roe G. and Celikkol B., Elastic-wave velocities and liquefaction potential, *Geotech. Testing J*., **7(2)**, 77–87 **(1984)**

11. Dixit J., Dewaikar D. and Jangid R., Assessment of liquefaction potential index for Mumbai city, *Natural Hazards and Earth System Sciences*, **12**, 2759–2768 **(2012)**

12. Dobry R., Stokoe K.H. II, Ladd R.S. and Youd T.L., Liquefaction susceptibility from S-wave velocity, Proc. of *In Situ* Tests to Evaluate Liquefaction Susceptibility, National Convention, ASCE, New York **(1981)**

13. Hanumantharao C. and Ramana G.V., Dynamic Soil Properties for Microzonation of Delhi, India, *Journal of Earth System Science*, **117(S2)**, 719-730 **(2008)**

14. Hasancebi N. and Ulusay R., Empirical correlations between shear wave velocity and penetration resistance for ground shaking assessments, *Bull. Eng. Geology and the Environment*, **66**, 203 – 213 **(2007)**

15. IS 1893 (Part-1) Criteria for earthquake resistance design of structure: general provisions and buildings, Bureau of Indian Standards (BIS) New Delhi **(2002)**

16. IS 1893 (Part-1) Criteria for earthquake resistance design of structure: general provisions and buildings, Bureau of Indian Standards (BIS) New Delhi **(2016)**

17. IS 2131 Method for standard penetration test for soils, Bureau of Indian Standards (BIS) New Delhi **(1981)**

18. Iwasaki T., Tatsuoka F., Tokida K. and Yasuda S., A Practical Method for Assessing Soil Liquefaction Potential Based on Case Studies at Various site in Japan, 5th Japan Earthquake Engineering Symposium, 641-648 **(1978)**

19. Iwasaki T., Tokida K., Tatsuoka F., Watanabe S., Yasuda S. and Sato H., Microzonation for soil liquefaction potential using simplified methods, Proceedings of 2nd International Conference on Microzonation, Seattle, 1319–1330 **(1982)**

20. Kayen R.E., Mitchell J.K., Seed R.B., Lodge A., Nishio S. and Coutinho R., Evaluation of SPT-, CPT- and shear wave-based methods for liquefaction potential assessment using Loma Prieta data. Proc., 4th Japan-U.S. Workshop on Earthquake Resistant Des. of Lifeline Fac. and Countermeasures for Soil Liquefaction, Tech. Rep.NCEER-92-0019, National Center for Earthquake Engineering Research, Buffalo, 177–204 **(1992)**

21. Kirar B., Maheshwari B.K. and Muley P., Correlation between shear wave velocity (Vs) and SPT resistance (N) for Roorkee Region, *Int J Geosynth Ground Eng*., **2(9)**, 1-11 **(2016)**

22. Kramer S.L., Geotechnical earthquake engineering, Prentice Hall Inc., Upper Saddle River **(1996)**

23. Kumar S., Srivastav T. and Muley P., Assessment of SPT-Based Liquefaction Potential of Kalyani Region, Kolkata, Patel S., Solanki C.H., Reddy K.R. and Shukla S.K., eds., In Proceedings of the Indian Geotechnical Conference 2019, Lecture Notes in Civil Engineering, Springer, Singapore **(2021)**

24. Lodge A.L., Shear wave velocity measurements for subsurface characterization, Ph.D. dissertation, University of California, Berkeley, California **(1994)**

25. Maheshwari R.U., Boominathan A. and Dodagoudar G.R., Use of surface waves in statistical correlations of shear wave velocity and penetration resistance of Chennai soils, *Geotech Geol Eng*., **28**, 119–137 **(2010)**

26. Mondal A., Prasad S. and Roy N., Liquefaction study of river channel deposit in Kolkata, In Proceedings of the Indian Geotechnical Conference, Guwahati **(2017)**

27. Muley P., Maheshwari B.K. and Paul D.K., Effect of Fines on Liquefaction Resistance of Solani Sand, 15th World Conference on Earthquake Engineering 2012, paper ID-1484, Lisbon, Portugal **(2012)**

28. Muley P., Maheshwari B.K. and Paul D.K., Liquefaction potential of Roorkee region using field and laboratory tests, *Int J Geosynth Ground Eng*., **1(37)**, 1-12 **(2015)**

29. Muley P., Maheshwari B.K. and Paul D.K., Assessment of Liquefaction Potential Index for Roorkee Region, 16th Symposium on Earthquake Engineering 2018, paper-ID 257, Indian Institute of Technology, Roorkee, India **(2018)**

30. Olsen R.S., Cyclic liquefaction based on the cone penetrometer test, Proc., NCEER Workshop on Evaluation of Liquefaction Resistanceof Soils, Tech. Rep. NCEER-97-0022 National Center for Earthquake Engineering Research, Buffalo, 225–276 **(1997)**

31. Rahmanian S. and Rezaie F., Evaluation of liquefaction potential of soil using the shear wave velocity in Tehran, Iran, *Geosciences Journal*, http://dx.doi.org/10.1007/s12303-015000 39-9 **(2015)**

32. Robertson P.K. and Campanella R.G., Liquefaction potential of sands using the CPT, *J. Geotech. Engg. ASCE*, **111(3)**, 384–403 **(1985)**

33. Robertson P.K., Woeller D.J. and Finn W.D.L., Seismic cone penetration test for evaluating liquefaction potential under cyclic loading, *Can. Geotech. J Ottawa*, **29**, 686–695 **(1992)**

34. Robertson P.K. and Wride C.E., Evaluating cyclic liquefaction potential using the cone penetration test, *Can. Geotech. J. Ottawa*, **35(3)**, 442–459 **(1998)**

35. Seed H.B. and Idriss I.M., Simplified procedure for evaluating soil liquefaction potential, *J Soil Mech. and Found. Div. ASCE*, **97(SM9)**, 1249–1273 **(1971)**

36. Seed H.B. and Idriss I.M., Ground motions and soil liquefaction during earthquake. Earthquake Engineering Research Institute, Berkeley, California **(1982)**

37. Seed H.B., Idriss I.M. and Arango I., Evaluation of liquefaction potential using field performance data, *J. Geotech. Engrg. ASCE*, **109(GT3)**, 458–482 **(1983)**

38. Seed H.B., Tokimatsu K., Harder L.F. and Chung R.M., The influence of SPT procedures in soil liquefaction resistance evaluations, *J. Geotech. Engrg. ASCE*, **111(12)**, 1425–1445 **(1985)**

39. Shukla H., Muley P. and Kumar S., Soil Amplification Study for Kalyani Region, Kolkata, Sitharam T.G., Jakka R. and Govindaraju L., eds., In Local Site Effects and Ground Failures, Lecture Notes in Civil Engineering, Springer, Singapore **(2021)**

40. Sonmez H., Modification of the liquefaction potential index and liquefaction susceptibility mapping for a liquefaction-prone area, *Environmental Geology*, **44** 862–871 **(2003)**

41. Stark T.D. and Olson S.M., Liquefaction resistance using CPT and field case histories, *J. Geotech. Engg ASCE*, **121(12)**, 856–869 **(1995)**

42. Stokoe K.H. II, Lee S.H.H. and Knox D.P., Shear moduli measurements under true triaxial stresses, Proc. Adv. in the Art of Testing Soil under Cyclic Conditions, ASCE, New York, 166–185 **(1985)**

43. Stokoe K.H. II, Rosset J.M., Bierschwale J.G. and Aouad M., Liquefaction potential of sands from shear wave velocity, Proc. of 9th World Conf. on Earthquake Engg., **III**, 213–218 **(1988)**

44. Tokimatsu K. and Uchida A., Correlation between liquefaction resistance and shear wave velocity, *Soils and Found Tokyo*, **30(2)**, 33–42 **(1990)**

45. Toprak S. and Holzer T.L., Liquefaction potential index: field assessment, *Journal of Geotechnical and Geoenvironmental Engineering*, **129(4)**, 315–322 **(2003)**

46. Ulusay R. and Kuru T., Adana-Ceyhan (Turkey) earthquake and a preliminary Microzonation based on liquefaction potential for Ceyhan town, *Natural Hazards*, **32**, 59-88 **(2004)**

47. Woods R.D., ed., Geophysical characterization of sites, Balkema, Rotterdam, The Netherlands **(1994)**

48. Youd T.L. and Idriss I.M., ed., Proceedings for the NCEER workshop on evaluation of liquefaction resistance of soils, Technical Report: NCEER-97-0022 National Center for Earthquake Engineering Research State, University of New York, Buffalo Engineering Research State, University of New York **(1997)**.

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