Assessment of Soil Liquefaction Safety Factors Under Different Earthquake Magnitudes

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Abstract In the present study, seismic soil liquefaction in terms of factor of safety against liquefaction (FS) is evaluated by the IS Code: (Criteria for earthquake resistant design of structures. Bureau of Indian Standards, New Delhi [5]) (Part-I, 2016) for a site of IIT Patna campus. The FS values against liquefaction are evaluated under three different earthquake magnitudes, namely, $M_w = 6.0$, 6.5 and 7.0. A design peak ground acceleration of 0.24 g used as the Patna city lies in the Zone IV of the seismic zoning map of India as per IS code. In this paper, an evaluation of the severity of liquefaction in the form of liquefaction potential index (LPI) is also determined. The LPI is determined at a single borehole location from the obtained factors of safety (FS) to predict the potential of liquefaction to cause damage at the site of interest. The evaluated FS and LPI values from IS Code are compared with Idriss and Boulanger (Soil Dyn Earthq Eng 26:115–130 [4]) procedures to investigate the liquefaction behavior for cohesionless soils. The FS and LPI results of both SPT-based semi-empirical procedures indicate that the soil liquefaction probability increases during earthquakes with magnitude ≥7.0 at this site. It is also observed that the values of FS from IS code match with Idriss and Boulanger (Soil Dyn Earthq Eng 26:115–130 [4]) results under high earthquake magnitude.

Keywords Earthquake magnitudes · IS code · Liquefaction potential index · Soil liquefaction

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1 Introduction

Soil liquefaction can be defined as a temporary loss in shear strength of saturated sandy and silty soil due to the significant swelling in the pore-water pressure loudening under the influence of cyclic/dynamic loading generated due to incoming stress waves reaching the site in the form of seismic loading. Liquefaction is generally observed in the case of saturated cohesionless soil; however, the clayey soil may also undergo huge deformation/spreading. Liquefaction could cause serious damage to the buildings, earth structures, and sloping grounds due to the loss of strength of the soil, which eventually leads to the failure of the structure. The failure of the soil may be in the form of vertical ground settlements and slope instability, sand boil, and lateral spreading. To quantify the severity of soil liquefaction an index known as liquefaction potential index (LPI) could be computed for the determination of the degree of severity of liquefaction.

The liquefaction potential index (LPI) and factor of safety against liquefaction (FS) provide a technique to assess the level of risk of liquefaction-induced damage to the foundation of a structure. It is the basic and initial investigation from a geotechnical point of view and it is more important when the structural project site is under a higher seismic zone or near river/sea. The potential for soil liquefaction to occur at a certain depth at a site is quantified in terms of the factors of safety against liquefaction (FS). Seed and Idriss [9] suggested a simplified approach to evaluate the liquefaction resistance of soils in terms of factor of safety against liquefaction by taking the ratio of the capacity of a soil element to resist soil liquefaction to the seismic demand imposed on it. The liquefaction potential index (LPI) as proposed by Iwasaki et al. [6] was also used to illustrate the liquefaction vulnerability, which takes into account the effect of thickness and depth along with the FS of the liquefiable layer. Capacity to resist soil liquefaction is computed as the cyclic resistance ratio (CRR), and seismic demand is computed as the cyclic stress ratio (CSR). Factor of safety of a soil layer can be calculated with the help of several field tests such as standard penetration test (SPT), conic penetration test (CPT), Becker penetration test (BPT), and shear wave velocity (V_s) test. Factor of safety along the depth of soil profile is generally calculated using the surface-level peak ground acceleration (PGA), earthquake magnitude (Mw), and SPT data, namely, SPT blow counts (N), overburden pressure, fines content (FC), liquid limits and grain size distribution which is discussed by many researchers [7, 10, 12, 11]. Bao et al. [1] and Bwambale and Andrus [2] analyzed and discussed the characteristics of the newly developed methods including the mitigating mechanism and effectiveness, and possible executive problems to understand the progress of liquefaction resistance. Olson et al. [8] performed a broad parametric study to assess the viability of using nonlinear site response analysis with validated constitutive and pore-water pressure generation models to evaluate level-ground liquefaction. In this study, the nonlinear site response analysis with pore-water pressure generation correctly predicted liquefaction for dynamic centrifuge tests and field cases, demonstrating that this approach can assess level ground liquefaction while avoiding highly uncertain correction factors required in the cyclic stress method. An approach for

soil liquefaction evaluation using a probabilistic method based on the SPT databases has been presented by Goharzay et al. [3]. In this paper, the uncertainties of the parameters for liquefaction probability have been taken into account. A calibrated mapping function is developed using Baye's theorem in order to capture the failure probabilities in the absence of the knowledge of parameter uncertainty.

To study the liquefaction vulnerability with different earthquake magnitudes for possible building construction and design at the Indian Institute of Technology Patna (IITP) site, initial liquefaction check is done in terms of FS and LPI. Patna (Bihta) city falls under seismic zone IV and established near the Ganga River. So, it is absolutely necessary to make foundation soil improve before construction to eliminate the liquefaction risk. There are many empirical relations are developed based on in situ and laboratory test results. In the current study, two different SPT-based semi-empirical procedures [4, 5] are used for the liquefaction vulnerability check under earthquake magnitude (M_w) of 6.0, 6.5, and 7.0.

2 Site Location and Soil Condition

Soil sample of Indian Institute of Technology Patna campus site (located at Bihta and 35 km from Patna) is investigated. The borehole site lies in the latitude of 25° 32′ 03.1″ North and longitude of 84° 50′ 54.5″ East. The borehole location and soil property with varying depth is presented in Fig. 1 and Table 1, respectively.

At this site, many borehole tests are performed. However, in this study, one borehole test data is used for the investigation of soil liquefaction potential. The standard penetration test (SPT) is performed up to the depth of 15 m in order to determine the SPT-N values in the field. The laboratory tests are also performed on collected soil
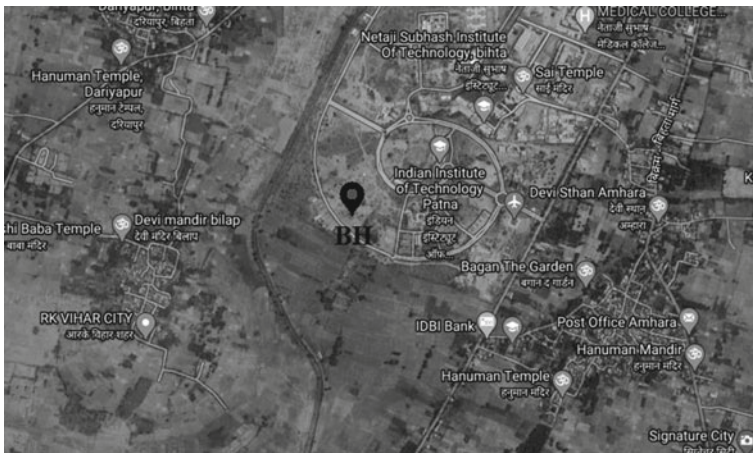

Fig. 1 Borehole location at IIT Patna campus site

Table 1 Soil properties at IIT Patna campus

Depth (m)	Fine Content, FC (75 η)	$Υ_d$ (g/cc)	W (%)	SPT-N value
0–1.5	6.50	1.570	12.00	8
1.5–3.0	3.75	1.581	13.50	12
3.0–4.5	5.75	1.602	14.10	17
4.5–6.0	0.75	1.612	8.20	24
6.0–7.5	6.50	1.588	9.30	26
7.5–9.0	4.50	1.595	10.30	29
9.0–10.5	1.75	1.615	7.50	30
10.5–12.0	1.00	1.620	8.50	32
12.0–13.5	88.60	1.534	23.25	32
13.5–15.0	87.30	1.512	24.53	30

samples at the National Institute of Technology Patna (NIT Patna) to determine the soil properties at different depths. From the SPT and laboratory tests, it is found that the subsurface soil layers mainly consist of sandy soil.

3 Evaluation of Soil Liquefaction Potential

The empirical relations based on SPT and CPT are widely used in practice for the determination of factors of safety against liquefaction (FS) and liquefaction potential index (LPI). In this paper, empirical relations based on the SPT test [4, 5] are used. The values of FS are determined by comparing the seismic demand expressed in terms of cyclic stress ratio (CSR) to the capacity of liquefaction resistance of the soil expressed in terms of cyclic resistance ratio (CRR). CSR distinguishes the seismic demand produced by a given earthquake and it is evaluated from peak ground surface acceleration that is based upon the ground motions. CRR requires fines content (FC) of the soil to correct updated SPT blow count $(N_1)_{60}$ to an equivalent clean sand standard penetration resistance value $(N_1)_{60cs}$.

From IS Code: [5] (Part-I), 2016,

$$CSR = 0.65\left(\frac{a_{\max}}{g}\right)\left(\frac{\sigma_v}{\sigma_{v'}}\right)r_d \tag{1}$$

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

From Idriss and Boulanger [4],

$$CSR = 0.65 \left(\frac{a_{\max}}{g} \right) \left(\frac{\sigma_v}{\sigma_v'} \right) r_d \frac{1}{MSF} \frac{1}{K_\sigma} \qquad (3)$$

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

where $a_{\max}$ = peak horizontal ground acceleration; = acceleration due to gravity; r_d = depth-dependent stress reduction factor; σ_v and $\sigma_{v'}$ = total vertical overburden stress and effective vertical overburden stress, respectively, at a given depth below the ground surface; MSF = magnitude scaling factor and K_σ = overburden correction factor. For the soil profiles with the depth less than 20 m, LPI is calculated using the following expression:

$$LPI = \sum_{i=1}^{n} \omega_i F_i H_i \ with \left\{ \begin{array}{l} F_i = 1 - FS_i \ for \ FS_i < 1.0 \\ F_i = 0 \ for \ FS_i \geq 1.0 \end{array} \right\} \qquad (5)$$

where H_i = thickness of the discretized soil layers; n = number of layers; F_i = liquefaction severity for i-th layer; FS_i = factor of safety for i-th layer; w_i = weighting factor (=10–0.5 z_i); and z_i = depth of i-th layer.

4   Results and Discussion

In this study, FS and LPI for earthquake magnitudes (Mw) of 6.0, 6.5, and 7.0 are determined with the use of SPT-based IS code: [5], 2016 and Idriss and Boulanger [4] methods. For calculation of soil liquefaction potential, the earthquake magnitudes with a peak ground acceleration level of 0.24 g are considered. Two basic definitions of factors of safety against liquefaction (FS) for soil liquefaction potential are used in the present study: liquefiable (FS ≤ 1.0) and non-liquefiable (FS > 1.0). However, it cannot be established that FS just below 1.0 will certainly liquefy or FS above 1.0 will not, as it may vary based on the method adopted and the level of safety desired. From in situ and laboratory tests, the typical subsoil profiles of the existing site indicate sandy soil and the groundwater table is found at a depth of 3.0 m.

The type of soil most susceptible to liquefaction is one in which the resistance to deformation is mobilized by friction between particles. The LPI and FS with three different earthquake magnitudes are summarized in Tables 2 and 3 for IS code: [5] and Idriss and Boulanger [4], respectively. It is found from Tables 2 and 3 that the values of factor of safety against soil liquefaction are decreases with the increase of seismic magnitude. This type of increasing pattern indicates that the soil liquefaction vulnerability increases with an increase in the intensity of seismic events.

The FS values with M_w = 6.0 and 6.5 indicate no zone of liquefaction and M_w = 7.0 indicate two zones of potential liquefaction in the poorly graded sand layer at depths of 3.0 m from ground surface as per IS code. However, in case of

Table 2 Factors of safety (FS) against soil liquefaction potential [5]

Depth (m)	CSR	CRR$_6$	CRR$_{6.5}$	CRR$_7$	FS			LPI		
					$M_w =$ 6	$M_w =$ 6.5	$M_w =$ 7	$M_w =$ 6	$M_w =$ 6.5	$M_w =$ 7
1.5	0.15	0.18	0.15	0.15	1.19	0.97	0.80	–	–	2.71
3.0	0.15	0.22	0.18	0.15	1.45	1.18	0.98	–	–	0.27
4.5	0.18	0.29	0.24	0.19	1.57	1.28	1.06	–	–	–
6.0	0.21	0.45	0.37	0.30	2.17	1.76	1.46	–	–	–
7.5	0.22	0.46	0.38	0.31	2.08	1.69	1.40	–	–	–
9.0	0.23	0.48	0.39	0.32	2.08	1.70	1.40	–	–	–
10.5	0.23	0.51	0.42	0.35	2.20	1.79	1.48	–	–	–
12.0	0.23	0.52	0.42	0.35	2.26	1.84	1.52	–	–	–
13.5	0.21	0.62	0.51	0.42	2.93	2.38	1.97	–	–	–
15.0	0.21	0.51	0.42	0.34	2.46	2.01	1.66	–	–	–
$LPI = \Sigma_{wi} F_i H_i =$								0.00	0.00	2.98

Table 3 Factors of safety (FS) against soil liquefaction potential [4]

Depth (m)	CRR	CSR$_6$	CSR$_{6.5}$	CSR$_7$	FS			LPI		
					$M_w = 6$	$M_w = 6.5$	$M_w = 7$	$M_w = 6$	$M_w = 6.5$	$M_w = 7$
1.5	0.10	0.13	0.10	0.08	1.34	1.03	0.79	–	–	2.91
3.0	0.11	0.18	0.14	0.10	1.65	1.25	0.93	–	–	0.89
4.5	0.16	0.29	0.22	0.15	1.80	1.40	0.93	–	–	0.81
6.0	0.16	0.38	0.29	0.21	2.40	1.84	1.33	–	–	–
7.5	0.17	0.40	0.30	0.23	2.38	1.78	1.33	–	–	–
9.0	0.17	0.44	0.32	0.24	2.60	1.89	1.41	–	–	–
10.5	0.15	0.41	0.31	0.23	2.70	2.06	1.52	–	–	–
12.0	0.19	0.52	0.38	0.27	2.73	2.00	1.41	–	–	–
13.5	0.20	0.73	0.53	0.38	3.67	2.65	1.88	–	–	–
15.0	0.20	0.64	0.48	0.32	3.20	2.40	1.59	–	–	–
$LPI = \Sigma_{wi} F_i H_i =$								0.00	0.00	4.61

Mw = 7.0, top three layers (up to 4.5 m depth) are found liquefiable as per Idriss and Boulanger [4] calculation. The results of soil liquefaction potential indicated that soil liquefaction probability increases when the $M_w \geq 7.0$, whereas the higher the seismic magnitude, the greater the liquefaction potential and the more damage it causes. Comparisons of FS values evaluated from IS code and Idriss and Boulanger [4] method is presented in Fig. 2 for different earthquake magnitude (M_w). It is found from the comparison curves that the evaluated values of FS from IS code are similar to Idriss and Boulanger [4] results for $M_w = 7.0$. Liquefaction susceptibility for
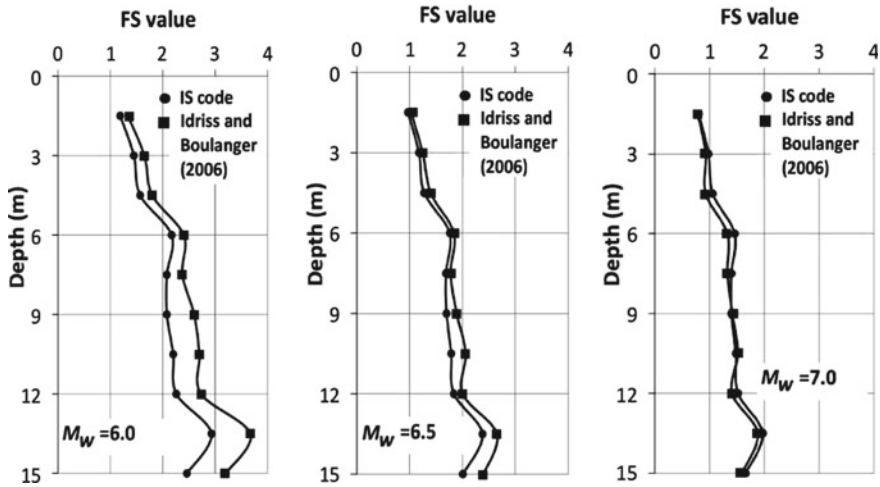
Fig. 2 Comparison of FS values between IS code and Idriss and Boulanger [4]

sites with LPI > 15 is very high, and the liquefaction is very unlikely at sites with LPI < 5. From this study, it is found that the site is in a liquefaction-susceptible area, indicating the possibility of damage during high earthquake.

5 Conclusions

In the present study, SPT-based semi-empirical procedures [4, 5] are used to evaluate the liquefaction potential of cohesionless soils with three different earthquakes magnitude (M_w = 6.0, 6.5, and 7.0). The SPT-based soil liquefaction in terms of FS and LPI, revealed that the soil liquefaction probability increases during earthquakes with a magnitude greater and equal to 7.0 at the IIT Patna campus site. So, mitigation techniques such as densification methods, modification of site geometry, or drainage to lower the groundwater table are needed for this site. It is also found that the values of FS from IS code matches with Idriss and Boulanger [4] results under higher earthquake magnitude.

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