Kochi Chapter

Indian Geotechnical Conference
IGC 2022
15th – 17th December, 2022, Kochi

Prediction of Liquefaction Probability Based on Simplified and Ground Response Analysis Method

Shiva Shankar Choudhary[1], Avijit Burman[2] and Sanjay Kumar[3]

Department of Civil Engineering, National Institute of Technology Patna, Patna-800005, India
[1]shiva@nitp.ac.in; [2]avijit@nitp.ac.in; [3]sanjay@nitp.ac.in

Abstract. The objective of the present study is to predict the probability of liquefaction using a simplified method (based on standard penetration test) and ground response analysis method (based on the correlations between SPT and shear wave velocity) at IIT Patna campus site. IIT Patna is located along the banks of the Ganga River at Bihta City, 35 km from Patna (India). The district lies in seismic zone IV. Thus, it becomes necessary to assess the liquefaction potential in order to design civil engineering projects and their foundations in the campus or district. At the present site, cyclic resistance ratio and the factor of safety against liquefaction is evaluated by both the above-mentioned approaches and also compared with liquefiable depths. The results indicate that the ground response analysis method predicts slightly lesser factors of safety against liquefaction as compared to the simplified method. Therefore, ground response analysis is found to be a more appropriate method for evaluating liquefaction as more soil layers are found to be liquefiable. As a result more safety or precaution is required in this region before the construction of any heavy structure or structural foundation.

Keywords: Liquefaction Potential; Standard Penetration Test; Shear Wave Velocity; Empirical Formula; Ground Response Analysis Method.

1 Introduction

The presence of soil deposits at a place has a considerable impact on the features of an seismic condition. The seismic motion characteristics are assessed using either a basic site categorization approach or a thorough ground response study relevant to the site. The most essential parameter in all of these approaches is shear wave velocity (V_s), which measures the stiffness of the soil layers. Wave propagation experiments are commonly used to determine the shear wave velocity profile at a given location. However, it is not cost-effective to undertake these tests at all locations. However, for many sites where geotechnical investigations are conducted, the numbers of blows (N) from standard penetration tests (SPT) are easily available. In this view, a reliable empirical correlation between shear wave velocity and N-values from standard penetration tests would be of considerable advantage. Many attempts have been made worldwide and in India to connect V_s values with accessible soil factors such as N-value. Boominathan et al. [1] calculated the V_s for Chennai city using available data on soil N-value and JRA [2] correlations. The last few decades have seen the emergence of multichannel analysis of surface waves (MASW) as a potential method for determining the V_S of near-surface material for seismic site categorization. For the purpose of classifying seismic sites outside of the study area, several researchers (e.g. Sitharam and Anbazhagan [3], Orubu et al [4], Karabulut [5], etc.) used the MASW approach to determine the V_S profiles. Maheshwari et al. [6] conducted MASW and SPT for two locations in the Ganga Basin, Dhanauri and Roshnabad, and generated V_s and N-value correlations. Hanumantharao and Ramana [7] assessed shear wave velocity using SASW for 80 places in Delhi city, to a depth of 20-32 m, and generated V_s and N-value correlations. Considering Indian scenarios and site-specific properties of different districts or cities, many studies have already been done under liquefaction [8, 9, 10]. Because of the easy and quick availability of the SPT-N dataset from the geotechnical site reports, estimating V_S from SPT-N value is widely used in these studies. Although it is a straightforward process to estimate the shear wave velocity at a site using a certain correlation, choosing the right correlation and borehole data can be difficult and challenging for geotechnical or site engineers. In the case of the Patna region, there is no literature or investigation done under liquefaction considering V_s and N-value. It is primarily located on the Ganges' southern bank. The study area, i.e., the IIT Patna campus site, is quite vulnerable to liquefaction because it lies in a high seismic zone, i.e., zone IV as per IS Code [11], and also at this site, the Sone river flows on its western side. Therefore, it is necessary to evaluate soil liquefaction for the safety of any heavy structure or structural foundation in the city or at the campus. This study explores the V_s - N correlations provided by different researchers for five different site locations of the IIT Patna campus. The factor of safety against liquefaction is determined using Simplified Method (SM) and Ground Response Analysis (GRA) method. A comparison is also made between the factors of safety against liquefaction obtained from SM and GRA.

2 Geotechnical Investigation

Many borehole tests are carried out at IIT Patna campus (India). However, in the present study, the SPT - N values and soil properties of five borehole data sets are investigated to understand soil behaviour under liquefaction conditions. The site locations, ground water table (GWT), and borehole depth are listed in Table 1, and the site locations are presented in Fig. 1.

Table 1. Soil properties at IIT Patna campus.

S. no.	Sites	Longitude	Latitude	GWT (m)	BH depth (m)
1.	BH-1	84°50'56.2"E	25°31'58.7"N	5.0	15
2.	BH-2	84°51'05.1"E	25°32'09.4"N	6.0	15
3.	BH-3	84°51'16.2"E	25°32'28.8"N	6.8	15
4.	BH-4	84°51'11.3"E	25°32'41.9"N	6.0	15
5.	BH-5	84°50'47.5"E	25°32'39.3"N	6.0	15

SPT is performed at the site locations to obtain N-values, and geotechnical laboratory tests are performed on the collected soil samples at NIT Patna (India) to determine the soil properties at the site. The test results indicate the soil layers mainly consist of sandy soil. The soil properties and *N*-values with varying depths are presented in Fig. 2.

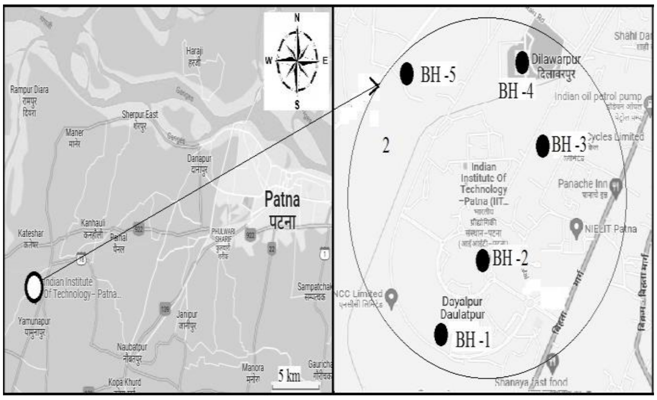

Fig. 1. Location of the boreholes at IIT Patna campus.

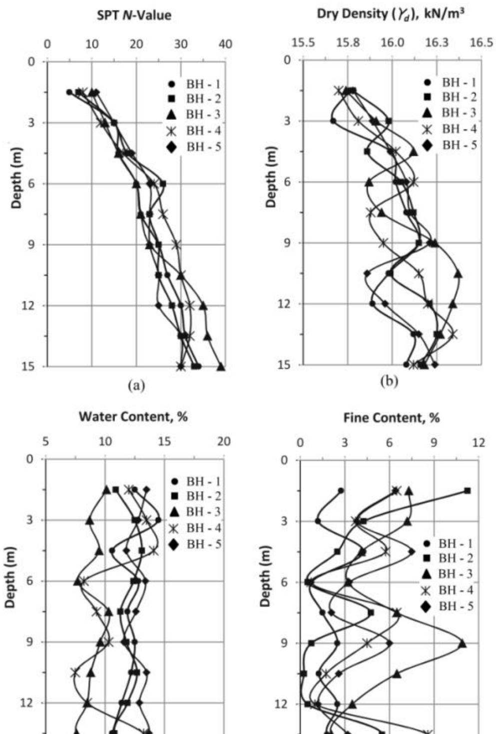

Fig. 2. Soil properties and SPT *N*-value of different boreholes.

3 Evaluation of Soil Liquefaction

For the determination of factors of safety against liquefaction (FS) and liquefaction potential index, semi-empirical formulations for SPT, CPT, and V_s are commonly used by geotechnical or site engineers. In the present study, the simplified method (based on SPT) and the ground response analysis method [based on the average shear wave velocity (V_{s-avg}) obtained from an correlations between SPT and shear wave velocity] are used to investigate the soil liquefaction at different depths of soil layers. Evaluation of Cyclic Shear Ratio (CSR) by SM and GRA procedures is based on Youd et al. [12]. The FS values are calculated by comparing the seismic demand in form of cyclic stress ratio (CSR) to the soil's liquefaction resistance capacity stated in terms of cyclic resistance ratio (CRR). The seismic demand generated by a given earthquake is measured using CSR, which is based on ground motions and is calculated from peak ground surface acceleration. CRR requires fine content (FC) to calculate the corrected SPT blow count $(N_1)_{60}$ to an equivalent clean sand standard penetration resistance value $(N_1)_{60cs}$.

Using Simplified Method;

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

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

where a_{max} is the maximum horizontal acceleration at the ground caused by the earthquake, g is gravity's acceleration, σ_v and σ'_v are total and effective vertical overburden stresses, and r_d is the stress reduction coefficient (evaluate relation given by Youd et al. [12].

Using Ground Response Analysis (Based on V_s - N correlations);

The average values obtained using the empirical equations reported in Table 2 is used to obtain the shear wave velocity profiles with depth for all in-situ locations. Those empirical correlations provided by six different researchers (Imai and Yoshimura [13], Imai [14], Seed and Idriss [15], Sisman [16], Jafari et al [17], and Kiku et al [18]) can be used on any type of soil. The comparisons between different empirical correlations with different boreholes are presented in Fig. 3. The pattern of each correlation indicates a similar type of variation for all five borehole datasets. For all locations and correlations, the minimum V_s is found at 74.5 m/s at 1.5 m depth (BH-1) and the maximum is found at 495.3 m/s at 15 m depth (BH-3) from ground level. However, in the case of V_{s-avg}, the minimum values are found at 120 m/s at 3.0 m depth and a maximum of 150 m/s at 15 m depth. The V_{s-avg} values are used for the calculation of CRR in the following equation described by Youd et al [12].

$$CRR = a\left(\frac{V_{S1}}{100}\right)^2 + b\left(\frac{1}{V_{S1}^*-V_{S1}} - \frac{1}{V_{S1}^*}\right) \tag{3}$$

where V_{S1}* is the limiting upper value of V_{s1} for liquefaction occurrence; and a and b are curve fitting parameters.

Table 2. Correlations between V_S and SPT *N*-Values.

S. no.	Author(s)	V_s (m/s)
1.	Imai and Yoshimura (1970)	$V_S = 76\ N^{0.33}$
2.	Imai (1977)	$V_S = 91\ N^{0.337}$
3.	Seed and Idriss (1981)	$V_S = 61\ N^{0.5}$
4.	Sisman (1995)	$V_S = 32.8\ N^{0.51}$
5.	Jafari *et al.* (1997)	$V_S = 22\ N^{0.85}$
6.	Kiku *et al*. (2001)	$V_S = 68.3\ N^{0.292}$

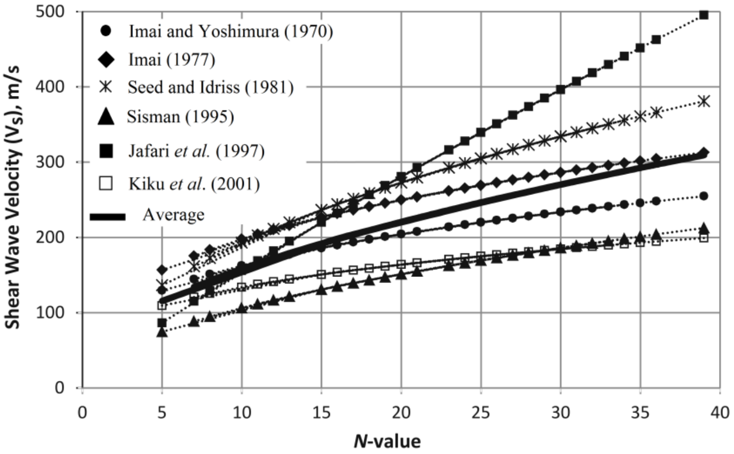

Fig. 3. Comparison between previous correlations.

4 Results and Discussion

For the calculation of the factor of safety against liquefaction (FS), an earthquake magnitude of 7.5 with a peak ground acceleration level of 0.24g is considered. Two basic criteria are used in this investigation to distinguish soil liquefaction in terms of FS. First, if FS ≤ 1.0, soil will liquefy, and if FS > 1.0, soil will not liquefy. However, in many cases or based on the different literature, it is not essential that the values of FS just below 1.0 will conformably liquefy, and in the case of just above 1.0, it will not, as it may depend upon the methodology and desired safety level. In the present case, the soil profiles of all five locations show sandy soil with a variation of 5.0 m to 6.8 m GWT. The CSR and CRR based on the simplified method and ground response analysis method are summarized in Table 3. It is found from the tabular results that the CRR values of the GRA method are estimated at higher values as compared to the SM and due to that, the FS values are found higher in the GRA method.

Table 3. Table Comparison of CRR between SM and GRA.

Depth (m)	γ_d (kN/m^3)	r_d	MSF	C_N	σ'_v (kPa)	CSR	CRR	
							SM	GRA
BH - 1								
0.0 - 1.5	15.76	0.99	1.0	1.70	23.64	0.15	0.08	0.16
4.5 - 6.0	16.02	0.95	1.0	1.01	98.61	0.16	0.18	0.25
9.0 - 10.5	15.98	0.89	1.0	0.86	134.31	0.20	0.22	0.42
13.5 - 15.0	16.08	0.77	1.0	0.77	166.74	0.19	0.25	0.38
BH - 2								
0.0 - 1.5	15.78	0.99	1.0	1.70	23.67	0.15	0.09	0.15
4.5 - 6.0	16.05	0.95	1.0	1.02	96.30	0.15	0.24	0.32
9.0 - 10.5	15.99	0.89	1.0	0.83	145.07	0.18	0.19	0.39
13.5 - 15.0	16.16	0.77	1.0	0.73	186.11	0.18	0.23	0.41
BH - 3								
0.0 - 1.5	15.74	0.99	1.0	1.70	23.61	0.15	0.14	0.15
4.5 - 6.0	15.87	0.95	1.0	1.02	95.22	0.15	0.18	0.24
9.0 - 10.5	16.37	0.89	1.0	0.81	187.01	0.17	0.23	0.42
13.5 - 15.0	16.18	0.77	1.0	0.73	268.43	0.17	0.29	0.49
BH - 4								
0.0 - 1.5	15.70	0.99	1.0	1.70	23.55	0.15	0.10	0.12
4.5 - 6.0	16.12	0.95	1.0	1.02	96.72	0.15	0.22	0.24
9.0 - 10.5	16.15	0.89	1.0	0.85	138.15	0.18	0.24	0.42
13.5 - 15.0	15.12	0.77	1.0	0.72	194.14	0.18	0.26	0.39
BH - 5								
0.0 - 1.5	15.78	0.99	1.0	1.70	23.67	0.15	0.09	0.14
4.5 - 6.0	16.08	0.95	1.0	1.02	96.48	0.15	0.15	0.20
9.0 - 10.5	15.86	0.89	1.0	0.83	144.87	0.18	0.14	0.19
13.5 - 15.0	16.24	0.77	1.0	0.74	184.05	0.18	0.19	0.30

The comparison of the FS of different boreholes using the SM and GRA methods is presented in Fig. 4. From the figure, it is found that the GRA method estimated a less liquefiable soil layer as compared to SM. The lesser FS value (FS < 1) indicates that the soil liquefaction vulnerability is increased in the case of the simplified method, which is based on SPT *N*-value. In the present study, it is found that liquefaction may occur at all five borehole locations up to a depth of 4.5 m. However, in the case of BH-2, it may occur upto a depth of 3.0 m considering the higher FS value from both the SM and GRA methods. The FS values show approximately similar results to SM and GRA up to a depth of 4.5 m. The values of CRR from the GRA method are found to be approximately 30 - 40% higher as compared to the SM method up to a depth of 4.5 m comparing all borehole data sets. In the case of FS, the variation range is high (4 - 50%) compared to SM and GRA. The site shows a liquefaction-susceptible area, indicating the possibility of damage during a strong earthquake. Therefore, mitigation techniques such as densification methods, modification of site geometry, or drainage to lower the groundwater table are needed for these locations.

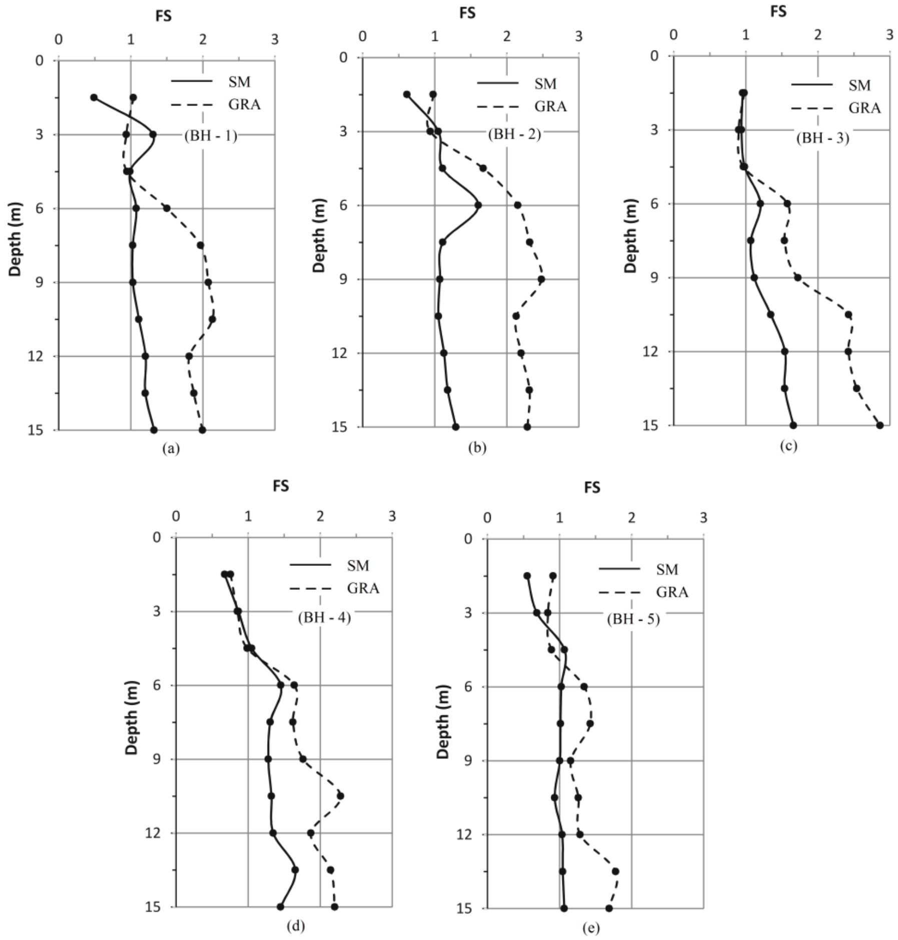

Fig. 4. Variation of SM and GRA in terms of FS.

5 Conclusions

The factor of safety (FOS) against liquefaction at IIT Patna site has been determined using two different methods (simplified method, SM and ground response analysis, GRA). It is found from the present study that liquefaction can occur in all five borehole locations up to a depth of 4.5 m, except BH-2 (where it may occur up to a depth of 3.0 m). The CRR values obtained from SM are slightly less than the GRA at all the depths. The minimum difference in CRR obtained by both methods at shallow depths is more than 7%. In the case of FS against liquefaction, GRA is found to be higher than the SM method, which indicates that the SM method predicts more liquefiable soil layers as compared to GRA. Therefore, the SM method may be adopted for this region to check the liquefaction susceptibility under strong earthquake conditions. All these site locations are found to be susceptible to liquefaction. Therefore, proper ground improvement measures should be taken before the construction of any heavy structure or structural foundation.

References

1. Boominathan, A., Dodagoudar, G. R., Suganthi, A., Uma Maheswari, R.: Seismic hazard assessment considering local site effects for microzonation studies of Chennai city. Proceedings of the workshop on microzonation, pp 94-104. Interline Publishing, Bangalore (2007)
2. Japan Road Association (JRA): Specification and interpretation of bridge design for highway-part V: Resilient design (1980).
3. Sitharam, T. G., Anbazhagan, P.: Seismic hazard analysis for the Bangalore region. Natural Hazards 40, 261-278 (2007).
4. Orubu, A., Khalil, M. A., Rutherford, B., Shaw, G., Gebril, A., Carsarphen, C.: Geophysical investigation of dewatering in Lolo Creek, Southwest Missoula, Montana, USA. Journal of Applied Geophysics 155, 149-161 (2018).
5. Karabulut, S.: Soil classification for seismic site effect using MASW and ReMi methods: a case study from western Anatolia (Dikiliizmir). Journal of Applied Geophysics 150, 254-266 (2018).
6. Maheshwari, B. K., Mahajan, A. K., Sharma, M. L., Paul, D. K., Kaynia, A. M., Lindholm, C.: Relation between shear velocity and SPT resistance for sandy soils in the Ganga basin. International Journal of Geotechnical Engineering 7(1), 63-70 (2013).
7. Hanumantharao, C., Ramana, G. V.: Dynamics soil properties for microzonation of Delhi, India. Journal of Earth System Science 117, 719-730 (2008).
8. Singh, M., Duggal, S. K., Pallav, K., Sharma, K. K.: Correlation of shear wave velocity with standard penetration resistance value for Allahabad city. In: Advances in Computer Methods and Geomechanics: IACMAG Symposium 2019. Gandhinagar: Springer (2020).
9. Kirar, B., Maheshwari, B. K., Muley, P.: Correlation between shear wave velocity (VS) and SPT resistance (N) for Roorkee region. International Journal of Geosynthetics and Ground Engineering 2(9), 1-11 (2016).
10. Roy, N., Shiuly, A., Sahu, R. B., Jakka. R. S.: Effect of uncertainty in VS−N correlations on seismic site response analysis. Journal of Earth System Science 127(7), 1-21 (2018).
11. IS 1893-Part 1: Criteria for earthquake resistance design of structures: general provisions and buildings, Bureau of Indian Standards (BIS) New Delhi (2016).
12. Youd, T. L., Idriss, I. M., Andrus, R. D., Arango, I., Castro, G., Christian, J. T., Dobry, R., Finn, W.D.L., Harder, L. F. Jr, Hynes, M. E., Ishihara, K., Koester, J. P., Liao, S. C., Marcuson, W. F. III, Martin, G. R., Mitchell, J. K., Moriwaki, Y., Power, M. S., Robertson, P. K., Seed, R. B., Stokoe, K. H. II,: Liquefaction resistance of soils: summary report from the1996 NCEER and 1998 NCEER/NSF workshops on evaluation of liquefaction resistance of soils. Journal of Geotechnical and Geoenvironmental Engineering ASCE127(10), 817-833 (2001).
13. Imai, T., Yoshimura, Y.: Elastic wave velocity and soil properties in soft soil. Tsuchito-Kiso 18(1), 17-22 (1970).
14. Imai, T.: P and S wave velocities of the ground in Japan. In: Proceedings of the IX international conference on soil mechanics and foundation engineering, vol 2, pp 127-132. Japan, (1977).

15. Seed, H. B., Idriss, I. M.: Evaluation of liquefaction potential sand deposits based on observation of performance in previous earthquakes. 81-544, in situ testing to evaluate liquefaction susceptibility, ASCE National Convention, pp 81-544. Missouri (1981).
16. Sisman, H.: An investigation on relationships between shear wave velocity and SPT and pressuremeter test results. M.Sc. Thesis, Ankara University, Geophysical Engineering Department, Ankara (1995).
17. Jafari, M. K., Asghari, A., Rahmani, I.: Empirical correlation between shear wave velocity (Vs) and SPT-N value for south Tehran soils" In: Proceedings of the 4th international conference on civil engineering, Tehran, Iran (1997).
18. Kiku, H., Yoshida, N., Yasuda, S., Irisawa, T., Nakazawa, H., Shimizu, Y., Ansal, A., Erkan, A.: In situ penetration tests and soil profiling in Adapazari, Turkey" In: Proceedings of the ICSMGE/TC4 satellite conference on lessons learned from recent strong earthquakes, pp.259–265 (2001).