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Integrated liquefaction hazard assessment using empirical and numerical approaches for a project site in Sonarpur, Kolkata, India

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ABSTRACT: This study presents a detailed liquefaction hazard assessment for a project site in Sonarpur, Kolkata, located in Zone IV of the seismic microzonation map of India, which exhibits moderate to high seismicity. The analysis is performed using ten hard-soil or rock spectrum-compatible ground motions defined in the latest IS 1893 Part I (2025), with peak ground accelerations (PGAs) ranging from 0.16 to 0.24g. The analysis is carried out using both empirical and numerical approaches, providing an in-depth assessment of the liquefaction-associated hazard. Three in-situ field tests, namely the Standard Penetration Test (SPT), Cone Penetration Test (CPT), and Dilatometer Marchetti Test (DMT), are employed for the empirical evaluation of liquefaction potential. Data from SPT, CPT, and DMT are compared and further utilized to determine field parameters and soil properties, enabling a liquefaction hazard analysis across the study area in terms of the factor of safety against liquefaction (FOS), liquefaction potential index (LPI), and probability of liquefaction (P_L). The obtained results indicate that the study area exhibits high susceptibility to liquefaction. For a more detailed and confirmed assessment, the well-characterized data related to shear strength and index properties are utilized to perform one-dimensional effective stress-based nonlinear ground response analysis (NGRA) using DEEPSOIL v7.1.8. It is observed that the excess porewater pressure (EPP) builds up significantly during shaking, attaining an EPP ratio (r_u) of 0.99 at soil layers susceptible to liquefaction, along with an alteration in the frequency content of the surface response estimates, where the FOS against liquefaction is less than 1. Overall, the combination of empirical and numerical procedures corroborates the finding that the study area is highly susceptible to liquefaction. The integration of DMT, CPT, and SPT data within an advanced numerical modeling framework provides an inclusive and robust framework for identifying critical layers susceptible to liquefaction, evaluating the associated potential to cause surface manifestations, and thereby helping to adopt suitable countermeasures against liquefaction.

KEYWORDS: Liquefaction susceptibility, in-situ field tests, Nonlinear response analysis, DEEPSOIL v7.1.8, liquefaction hazard analysis.

1 INTRODUCTION

Earthquake-induced ground shaking is significantly influenced by local geological conditions. The variation in soil stiffness can amplify seismic waves, resulting in site-specific effects such as liquefaction, slope failures, and structural damage during strong shaking.

Kolkata falls within Seismic Zone IV, as classified by IS 1893 Part I: (2025), indicating moderate to high seismic hazard. The city has experienced several notable earthquakes, including the 1897 Shillong event, the 1906 and 1964 Calcutta earthquakes, the 2006 Sikkim earthquake, and the 2015 Nepal earthquake, highlighting its susceptibility to seismic activity (Nath et al., 2014). Geologically, the region is part of the Bengal Basin and is underlain by thick layers of Quaternary alluvial deposits, comprising clay, silt, and sand. These soil types are known to alter the ground motion. Additionally, rapid urbanization in areas such as Sonarpur (the present study area) (Figure 1) has driven urban settlement over a fine-rich, sand-like soil-dominated stratigraphy (Mandal et al., 2025c), and therefore, a comprehensive assessment of seismic vulnerability is warranted.

Subsoil investigations in parts of Kolkata reveal the presence of unconsolidated layers at depths of 12–13 m, which are characterized by abrupt changes in soil properties, low standard penetration test (SPT) blow count (N) values (≤5), and susceptibility to liquefaction. A transition to Pleistocene deposits occurs below this depth, with N-values increasing to 16–18, and dense soil layers (N ≈ 100) prevailing beyond 24 meters (Nandy 2007). Reliability-based studies of liquefaction at various locations in Kolkata city indicate high susceptibility to liquefaction between 7–15 meters, considering the annual average depth of the water table at 3 meters from the ground surface (Sett et al., 2023, 2024). In recent times, the loosely coupled pore pressure generation model for a 1-D effective stress-based NGRA and the total stress-based probabilistic GRA, utilizing data from SPT and Seismic Dilatometer Marchetti Test (SDMT) tests, have been extensively carried out (Mandal et al, 2025a; Das et al., 2025a, b; Mistry et al., 2025) for the Newtown region of Kolkata as part of site-specific liquefaction-based response studies. These studies highlight the need for a comprehensive assessment of liquefaction potential in similar urbanizing regions of the city. Extending these efforts to the Sonarpur region necessitates an evaluation that builds from fundamental geotechnical site characterization.

Based on the above context, a detailed liquefaction hazard assessment of the study area is performed using existing empirical approaches, incorporating advanced in-situ tests such as DMT, SPT, and cone penetration test (CPT) (Figure 2). Indices such as factor of safety (FOS) and probability of liquefaction (P_L) have been assessed to categorize each shallow litho-stratum as safe or unsafe. Along with this, an effective stress-based nonlinear GRA (NGRA) was also performed for the study area to capture the on-site effects of liquefaction. In Kolkata, particularly in the Sonarpur area, the presence of extensive alluvial sandy deposits necessitates careful evaluation of liquefaction potential and risk zonation. A project similar to the European H2020 LIQUEFACT initiative (Ferreira et al., 2020) could be envisioned, where the current site (Figure 3) in Sonarpur serves as a reference location of a seismic program, enhancing long-term monitoring, improving regional hazard models, and supporting data-driven liquefaction risk mitigation strategies.

(a)

(b)

Figure 1. Urbanization of the study area since (a) 2011, and (b) at present in 2025 (Source: Google Earth)

2 GEOTECHNICAL INVESTIGATIONS

The study area is extensively characterized using data from multiple field tests, including SPT, CPT, DMT, and SDMT. A total of six SPTs (Figures 4 and 5) and CPTs, as well as three numbers each of DMT and SDMT, were performed for the geotechnical characterization of the subsoil profile.

Figure 2. CPT, SDMT, and DMT tests being carried out during the in-situ test campaign at the study area.

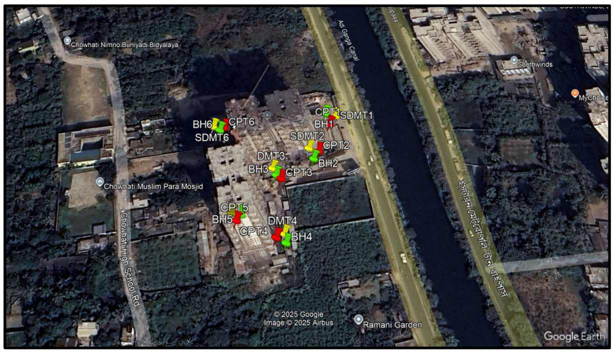


Figure 3. Locations of the in-situ tests conducted at the study area. (Source: Google Earth)

Based on the borehole data, the typical subsurface profile in the Sonarpur area reveals the presence of a loose to medium-stiff silty clay or clayey silt layer (classified as CL according to the Unified Soil Classification System, USCS), extending to depths of 3 to 4 meters below the ground surface. The DMT and CPT tests conducted in the vicinity of the boreholes indicated an approximately 4m thick loose silty sand layer. These are overlaid by medium-dense to dense sand deposits, which at least extend up to 20 m from the ground surface (Figure 6). These in-situ tests were conducted in close proximity to the study area to ensure consistency in interpreting the subsurface conditions. Across all tests, a groundwater table was assumed at a depth of 1.5 m, based on the p_2 values detected by the DMT in thin sand layers.

Borehole No.	Depth of sample Below G.L. (m)	Stratum	NMC (%)	Density (gms/cc)		Atterberg Limit(%)		Specific Gravity	Shear Test			Consolidation Test ($C_c/1+e_0$)
				Bulk	Dry	L.L.	P.L.		Type of Test	Cohesion (Kg/cm^2)	Friction (Degree)	
1	1.50 – 1.95	II	28	1.90	1.48	47	21	2.69	UU	0.33	3	0.058
	6.00 – 6.45	III	26	1.94	1.54	Non Plastic		2.65	DS	0.04	29	-
	10.50 – 10.95	III	25	1.97	1.58	Non Plastic		2.65	DS	0.00	30	-
2	2.50 – 2.95	II	29	1.89	1.46	48	21	2.69	UU	0.34	4	0.056
	8.00 – 8.45	III	26	1.97	1.56	Non Plastic		-	DS	0.05	28	-
	14.00 – 14.45	III	25	1.97	1.58	Non Plastic		2.65	DS	0.00	32	-
3	2.50 – 2.95	II	28	1.90	1.48	48	21	2.69	UC	0.35	-	0.058
	5.50 – 5.95	III	25	1.97	1.58	Non Plastic		-	DS	0.04	27	-
	8.50 – 8.95	III	25	1.97	1.58	Non Plastic		2.65	DS	0.00	30	-
4	3.50 – 3.95	III	26	1.94	1.54	Non Plastic		-	DS	0.00	25	-
	11.00 – 11.45	III	25	1.97	1.58	Non Plastic		2.65	DS	0.00	30	-
5	2.50 – 2.95	II	28	1.90	1.47	47	21	2.69	CU	0.34	8	0.056
	5.00 – 5.45	III	26	1.94	1.54	Non Plastic		-	DS	0.00	26	-
	9.50 – 9.95	III	26	1.94	1.54	Non Plastic		2.65	DS	0.00	30	-
6	1.50 – 1.95	II	28	1.90	1.47	48	21	2.69	UU	0.34	3	0.060
	7.00 – 7.45	III	25	1.97	1.58	Non Plastic		2.65	DS	0.04	29	-

Figure 4. Typical borehole data and the results from the laboratory tests on the retrieved samples

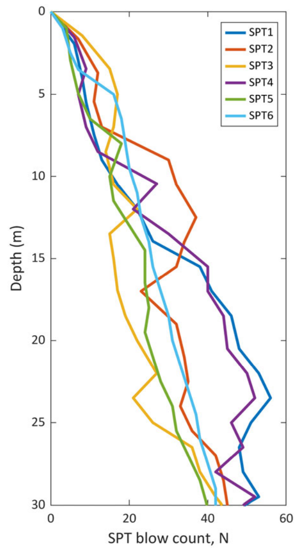
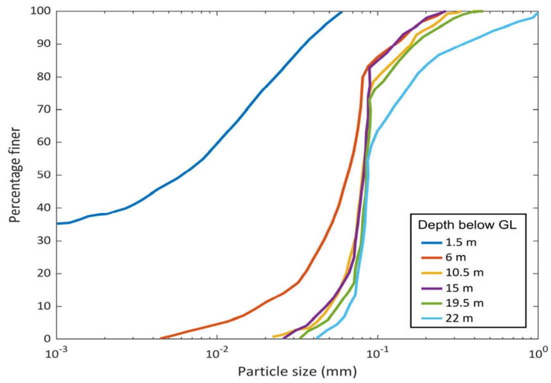
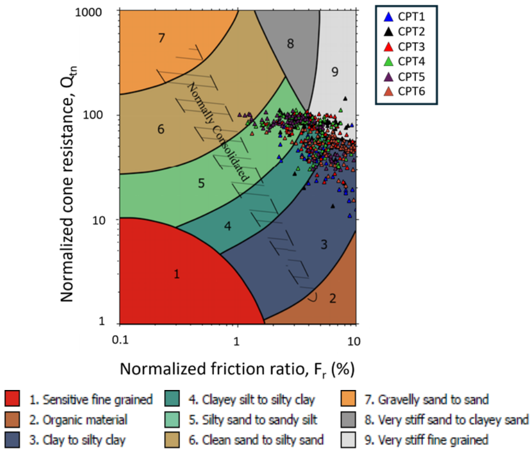


Figure 5. Variation of the SPT-N along depth at various BH locations in the selected site.

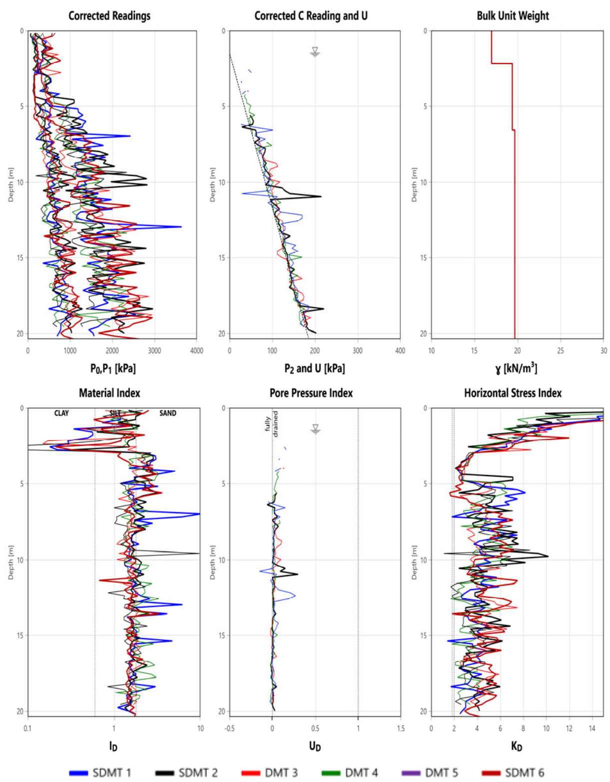


(a)



(b)

Figure 6. (a) Averaged grain size distribution curves, and (b) soil behaviour type (SBT) index, of the subsoil strata at various depths.



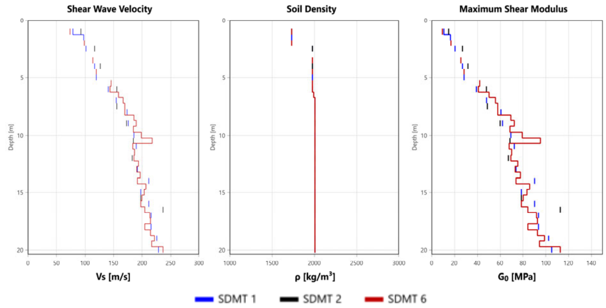


Figure 7. Results of DMT and SDMT in the selected site

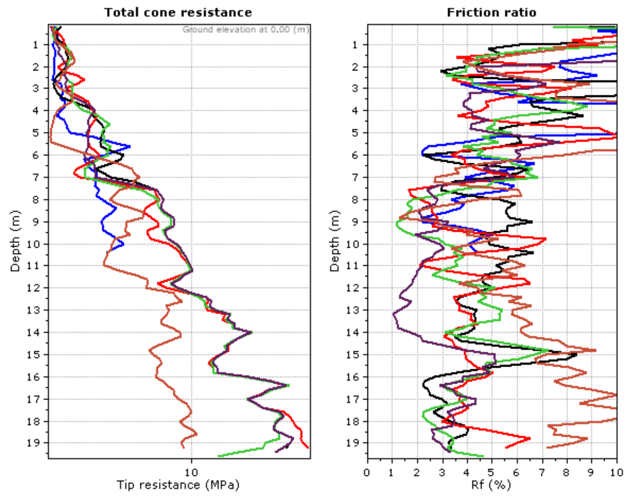


Figure 8. Results of CPT in the selected site

3 LIQUEFACTION HAZARD ANALYSIS USING EMPIRICAL APPROACHES

3.1 Factor of safety against liquefaction

The liquefaction potential of the study area is assessed in terms of a factor of safety (FOS) evaluated using the data from SPT, CPT, and DMT tests.

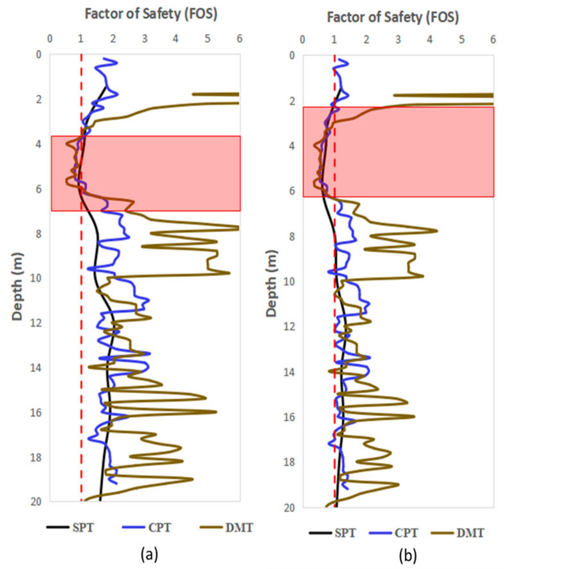


Figure 9. FOS against liquefaction for the representative subsoil profile, evaluated along the depth using SPT, CPT, and DMT data for input PGAs of (a) 0.16g and (b) 0.24g.

The FOS for sand-like soils is determined according to Marchetti (2016) using DMT data (Figure 7). For both clay-like and sand-like soils, the Boulanger and Idriss (2004, 2014) equations are used, utilizing SPT and CPT data (Figure 8). The analysis is carried out for a moment magnitude (M_w) of 6.7 and peak ground accelerations of 0.16 and 0.24g. It is observed from Figure 9 that all three in-situ tests, SPT, DMT, and CPT, indicate that the subsoil in the study area, from 3.0 m to 6.0 m, is susceptible to liquefaction triggering and associated surface manifestations under both seismic scenarios.

3.2 Liquefaction potential index

To determine the severity of liquefaction at the ground surface, the liquefaction potential index (LPI) is evaluated according to Iwasaki et al. (1978, 1982) using the FOS determined in Section 3.1. Iwasaki et al. (1978, 1982) developed the LPI to assess the severity of liquefaction hazards within the top 20 m of a subsoil profile. The concept of LPI incorporates three main factors: the thickness of the liquefied soil layer, its proximity to the ground surface, and how much the FOS against liquefaction falls below unity. These parameters are combined in a weighted integral to quantify the severity of liquefaction at a site (Iwasaki et al., 1978, 1982).

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

Here, n represents the total number of soil layers within the upper 20 m of the soil profile, and w denotes a depth-dependent weighting function that reflects the influence of liquefaction occurrence relative to the depth. This function was proposed to capture the decreasing impact of deeper liquefied layers on surface manifestations (Iwasaki et al., 1978, 1982).

$$w = 10 - 0.5z \tag{2}$$

In this context, z refers to the depth of each soil layer in m, H indicates the thickness of the individual layer, and S is calculated using the following approach. Maurer et al. (2014) introduced the LPI range, which is presented in Table 1.

$$S = \begin{cases} 0, FOS > 1 \\ 1 - FOS, FOS < 1 \end{cases} \tag{3}$$

Table 1. Severity of surface manifestation based on LPI

LPI Range	Severity of surface manifestation
< 4	No manifestation
4-8	Marginal
8-15	Moderate
≥ 15	Severe

Table 2. LPI obtained using FOS evaluated from SPT, CPT, and DMT tests

In-situ Test	LPI	
	0.16 g	0.24 g
SPT	1.00	9.52
CPT	2.28	9.27
DMT	4.27	10.5

The LPI was evaluated using the FOS obtained from Section 3.1 for PGAs of 0.16 and 0.24g, as presented in Table 2. From Table 2, it is observed that the maximum LPI of the study area is 4.27 and 10.5 for an input PGA of 0.16*g* and 0.24*g*, respectively. As per Table 1, the area is prone to marginal liquefaction manifestation for a PGA of 0.16g and moderate surface manifestation for a PGA of 0.24*g*.

3.3 Liquefaction severity number

Besides the LPI, the liquefaction severity number (LSN) is also determined to assess the susceptibility of the study area to ground damage due to potential liquefaction. The LSN is proposed by Tokin and Taylor (2013) and is calculated as

$$\text{LSN} = 1000 \int_0^{20} \frac{\epsilon_v}{z}\,\text{dz} \tag{4}$$

where ϵ_v is the post-liquefaction volumetric strain, and z is the depth (in m). The severity of the ground damage based on the LSN is presented in Table 3

Table 3. LSN computed from SPT, CPT, and DMT tests

In-situ test	LSN	
	0.16 g	0.24 g
SPT	24.02	57.26
CPT	25.05	48.32
DMT	28.28	43.9

The LSN values in Table 3 indicate that the study area is prone to moderate and major to severe damage under PGA of 0.16 g and 0.24 g, respectively. The post-liquefaction volumetric strains are calculated based on the FOS using the method of Zhang et al. (2002), and subsequently, the LSN is evaluated and tabulated in Table 4.

3.4 Probability of liquefaction

The FOS only categorizes soil layers as either safe or unsafe with respect to liquefaction potential and does not provide practitioners with sufficient information for making risk-based decisions. Therefore, the probability of liquefaction (P_L) is also evaluated to complement the FOS. Since the SPT-based method produced the lowest FOS values compared with CPT and DMT, the P_L is computed using the SPT data and the Idriss and Boulanger (2010) equation (eq. 4) for the selected earthquake scenarios.

$$\text{CRR} = \exp([(N_1)_{60}.(1+0.004FC) + 0.05FC - 29.53\ \ln(M_w) - 3.70\ln(\frac{\sigma_v'}{P_a}) + 16.85 + 2.70\Phi^{-1}(P_L)]/13.32) \tag{3}$$

Additionally, the P_L is also calculated from the SPT-derived FOS using the correlation developed by Sett et al. (2023) for typical soils in Kolkata. Both approaches indicate P_L values of approximately 50% for a PGA of 0.16g and 80% for a PGA of 0.24g. This suggests that liquefaction and non-liquefaction are equally probable at a PGA of 0.16g, whereas liquefaction is highly likely to occur at a PGA of 0.24g.

4 LIQUEFACTION HAZARD ASSESSMENT USING NUMERICAL ANALYSIS

Empirical liquefaction hazard analysis can only provide the FOS against liquefaction, and based on this FOS, it can give a probable estimation of liquefaction susceptibility in terms of LPI and P_L. But none of these probabilistic parameters captures the subsoil behavior against liquefaction. Regarding this, the NGRA liquefaction analysis effectively captures the effects of onsite liquefaction, which is portrayed in terms of surface PGA, PSA, and Excess PWP. In this study, DEEPSOIL v7.1.8 is used to perform the NGRA, and the framework required for effective stress-based analysis is adopted from Mandal et al. (2025c).

4.1 Selection of spectrum-compatible ground motions

Site-specific ground motion selection is crucial for seismic response analysis, particularly in regions with limited recorded earthquake data. For Kolkata, both long-term earthquake records and region-specific seismotectonic maps or site classification schemes are scarce. The recent IS 1893 Part I: (2025) allows the use of spectrum-compatible ground motions for conducting site response studies. One effective approach involves selecting recorded bedrock motions from tectonically similar regions and modifying them to match the target hazard level of Kolkata. Key parameters for ground motion selection include earthquake magnitude, fault distance, PGA values near the target, and comparable site conditions. Historical data indicate that seismic influences on Kolkata originate from the Arakan-Yoma range and the Himalayan front, with potential thrust fault activity within the Bengal Basin. According to IS 1893 Part I: (2025), Kolkata falls in Seismic Zone IV. In this study, the seismic hazard of the study area is assessed by considering past seismic events originating from seismic sources located within 20° N to 31° N and 80° E to 97° E, as outlined in previous seismic microzonation studies for Kolkata city (Mohanty and Walling, 2008; Nath et al., 2014). These studies partitioned the region into five different zones, providing the basis for a quasi-probabilistic approach to determine the maximum magnitudes (M_{max}) and corresponding seismic hazard (PGA).

The M_{max} suggested in IS 1893 Part I (2025) for site-specific hazard assessment in the Bengal Basin lies between 6.8 and 7.5. Therefore, in this study, ten ground motion records (M_w ranging from 6.5 to 7) at rock sites ($V_s > 750$ m/s, as per IS 1893 Part I: 2025) were selected from the PEER database (PEER, 2024). Site classification, based on SDMT-derived V_s at Sonarpur, identifies the soil as NEHRP Class D, with SPT N values ranging from 15 to 50 and V_s values between 183 and 366 m/s. Seismomatch software was used to decompose and scale the selected accelerograms to match the response spectrum for Kolkata's hard soil conditions, following the methodology outlined by Mandal et al. (2025b, c). Five compatible motions (GM 1 to GM 5) with PGA of 0.16g, and an additional five (GM 6 to GM 10) GMs with PGA of 0.24g are used in the analysis (Figure 10).

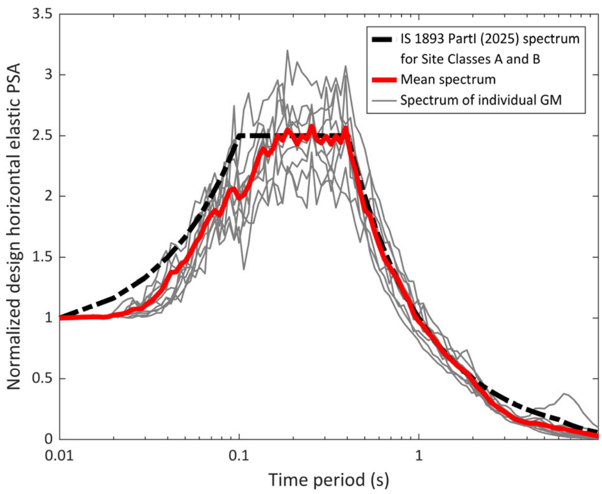
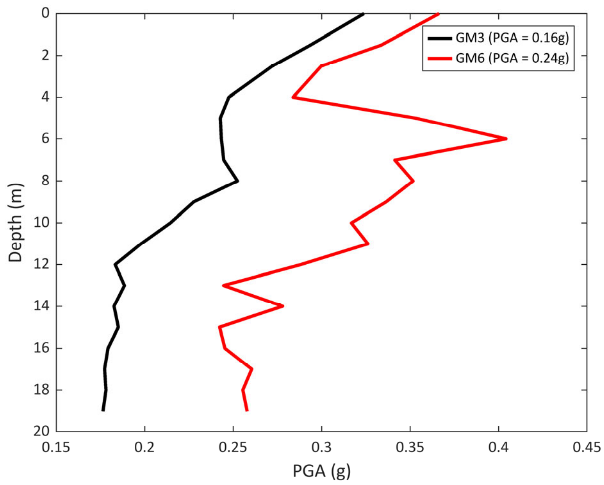


Figure 10. Spectra of the ground motions compatible with the IS 1893 Part 1 (2025) spectrum for Site Classes A and B.

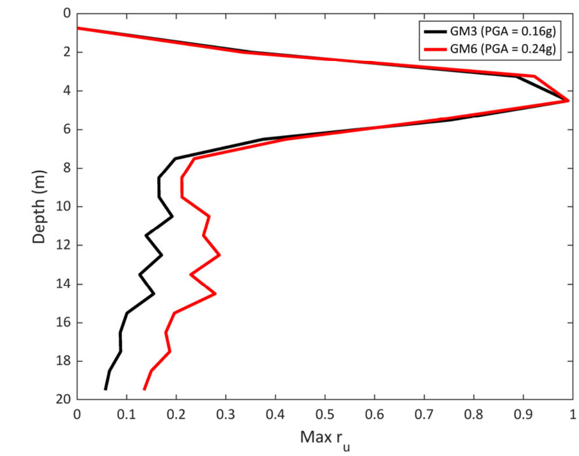
4.2 Ground response analyses: Results and Discussions

All ten ground motions were employed in the site response analysis conducted for the selected metropolitan area of Kolkata. For brevity in this paper, detailed results are presented only for the input time histories: GM3 (PGA = 0.16 g) and GM6 (PGA = 0.24 g). The average PGA at the surface, obtained through nonlinear ground response analysis (NGRA), was found to be 0.314g for ground motions GM1 to GM5, and 0.349g for GM6 to GM10.

A consistent upward trend in PGA values is observed from the bedrock to approximately 6 meters below the ground surface. At this depth, the soil undergoes liquefaction, resulting in a sharp decline in PGA values from 6 meters to the surface, as illustrated in Figure 11a. The NGRA has proven effective in estimating the excess pore water pressure (PWP) in the potentially liquefiable layers located between depths of 3 to 6 meters. The variation of the maximum PWP ratio with depth for GM3 and GM6 is depicted in Figure 11b.



(a)



(b)

Figure 11. (a) PGA variation (b) Max PWP ratio, along depth.

For the Sonarpur region, the average peak pseudo-spectral acceleration (PSA) values derived from the NGRA approach are 1.45g and 1.16g, corresponding to input motions of 0.24g and 0.16g, respectively. The associated average spectral periods range between 0.27 and 0.42 seconds, as illustrated in Figure 12. This figure also presents a comparison between the normalized response spectra for GM3 and GM6 at 5% damping and the design response spectrum for hard soil conditions specified in IS 1893 Part I: (2025) at the same damping level. These findings are valuable for structural engineers in selecting suitable ground motions for seismic response analysis.

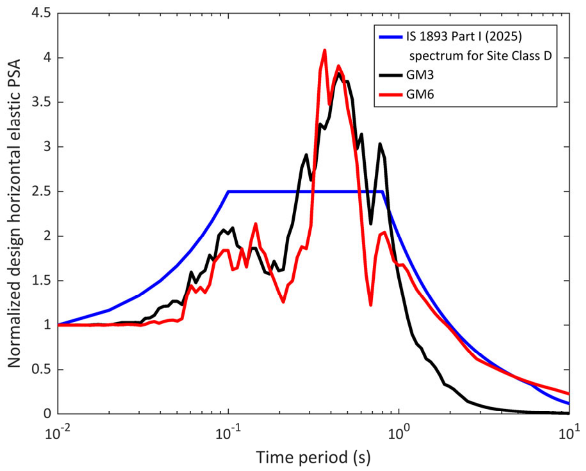


Figure 12. Comparison of the surface response spectra from GRA with the IS 1893 Part 1 (2025) recommended design spectrum for Site Class D.

5 CONCLUSIONS

This study presents a comprehensive approach for assessing the liquefaction hazard in the investigated area. Empirical analyses indicate that the loose silty sand layer, located between depths of 3.0 m and 6.0 m, is vulnerable to liquefaction under seismic events with PGA levels of 0.16g and 0.24g, showing a likelihood of marginal to moderate liquefaction triggering with probabilities of approximately 50% and 85%, respectively. The results are further complemented by the estimation of LPI and LSN, which are quantitative measures of surface manifestations caused by liquefaction. However, these approaches do not adequately represent the depth-wise variation in PGA or the progressive increase of the EPP ratio.

In contrast, the additionally performed NGRA effectively captured the site-specific stratigraphy and identified the onset of liquefaction by accurately modeling the progressive buildup in EPP and the evolution of the maximum EPP ratio within the silty sand layers. Overall, the integration of empirical approaches with effective stress-based response studies provides a reliable method for identifying critical layers susceptible to liquefaction, thereby improving site-specific hazard characterization.

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