# Site-Specific Liquefaction Analysis for Newtown, Kolkata, Using Dilatometer Marchetti Test (DMT) Calibrated UBC3D-PLM Model

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## ABSTRACT

This study presents a detailed one-dimensional (1D) analysis of liquefaction susceptibility for a project site in Newtown, Kolkata, under a scenario earthquake characterized by a moment magnitude ($M_W$) of 7 and a peak ground acceleration ($a_{max}$) of 0.24$g$. The liquefaction response is predicted using the UBC3D-PLM constitutive model implemented within the finite element (FE) software, PLAXIS 2D. In prior research, the model required input from corrected Standard Penetration Test (SPT) blow counts. However, the DMT is more sensitive than the SPT to factors influencing liquefaction resistance, such as aging, stress history, overconsolidation, and horizontal earth pressure. Therefore, this study introduces a new approach to calibrate the UBC3D-PLM model parameters, derived from the horizontal stress index ($K_D$) of the DMT. These DMT-based calibrated parameters are validated using results from cyclic direct simple shear (CDSS) tests in the PLAXIS 2D Soil Test Facility. Finally, these calibrated parameters inform the 1D liquefaction analysis for the study area, evaluating liquefaction susceptibility in terms of excess pore water pressure ratio criterion ($r_u > 0.9$) and maximum shear strain criterion ($\gamma_{xy} = 3\%$) of liquefaction triggering, respectively.

## INTRODUCTION

Ground shaking during earthquakes is strongly influenced by local soil conditions, where contrasts between soft sediments and underlying bedrock cause significant "site effects". These effects can lead to hazards such as liquefaction, landslides, and structural damage, especially under strong shaking. Thus, accounting for site effects through Ground Response Analysis (GRA) is crucial for accurate seismic design.

Kolkata, situated within Seismic Zones III and IV (IS 1893 Part 1: 2016), faces notable seismic risk. Historical earthquakes—including the 1897 Great Shillong, 1906 and 1964 Calcutta, 2006 Sikkim, and 2015 Nepal events—underscore the city's vulnerability (Nath et al. 2017). Geologically, Kolkata lies within the Bengal Basin and is underlain by Quaternary fluvio-deltaic sediments of clay, silt, and sand, which amplify its seismic vulnerability. Rapid urban expansion

into areas like Newtown (study area) (see Figure 1), built on reclaimed Ganges alluvial soil, further heightens the risk



(a)                                                                (b)

**Figure 1. (a) Study area in the year 2012 (b) Study area in the year 2025 (Source: Google Earth Pro)**

Subsoil investigations in Kolkata reveal unconsolidated layers prone to liquefaction at depths of 12–13 meters, marked by abrupt changes in soil properties and low SPT 'N' values (≤5). A transition to more geologically old aged Pleistocene deposits occurs below this depth, with N-values increasing to 16–18, and dense layers (N ≈ 100) appearing beyond 30 meters (Nandy 2007). Reliability-based liquefaction assessment studies show high susceptibility between 7–15 meters from the ground surface, and it decreases beyond 25 meters (Sett et al. 2023, 2024). These results emphasize the importance of site-specific Ground Response Analysis (GRA) to address local risks (Mohanty et al. 2008). Nonlinear GRA is vital for estimating surface ground motion and generating design spectra (Kramer 1996). GRA-based microzonation studies have been widely conducted in urbanized Indian cities including Delhi, Mumbai, Bangalore, Chennai, and Kolkata (Mohanty et al. 2008; Raghukanth et al. 2006; Anbazhagan et al. 2008; Boominathan et al. 2008; Hanumantharao and Ramana 2008; Govindaraju and Bhattacharya 2012; Mandal et al. 2025a). In Kolkata, equivalent-linear response analyses (EQLRA) have been performed (Shiuly and Narayan 2012) along with nonlinear amplification studies that considers uncertainty in shear wave velocity and plasticity characteristics (Bandyopadhyay et al. 2021). Scenario-based spectrum-compatible accelerograms were developed and used at the Case Pente site in Italy to demonstrate the importance of utilizing advanced constitutive models within the framework of numerical modeling for site-specific response analyses (Bordoni et al. 2023; Mandal et al. 2025b).

This study focuses on addressing seismic challenges through in-situ testing in Newtown, a rapidly urbanizing suburb of Kolkata. The study area is located in the city's northeastern expansion through Rajarhat and Newtown. In-situ geotechnical testing data is utilized to evaluate the liquefaction potential for futuristic seismic scenarios, and this location is strategically selected to address earthquake risks because of the rapid increasing urban development and expansion of this area. Liquefaction susceptibility in the region was evaluated by means of nonlinear dynamic analysis (NDA) using data from in-situ tests such as the DMT. Soil parameters obtained from the DMT include cohesion ($c_u$), angle of internal friction ($\varphi$), horizontal stress index ($K_D$), and vertical drained constrained modulus ($M_{DMT}$). Additionally, shear wave velocity ($V_s$) was derived from the Seismic Dilatometer Marchetti Test (SDMT). These parameters were used to assess liquefaction

potential under seismic conditions characterized by a moment magnitude ($M_w$) of 7 and a peak ground acceleration (PGA) of 0.24$g$. Subsequently, a spectrum-compatible ground motion was utilized as input to perform detailed nonlinear site-specific ground response analysis (GRA) of the selected study area in the Kolkata metropolitan area. The liquefaction analysis was conducted using the UBC3D-PLM model within the PLAXIS 2D software.
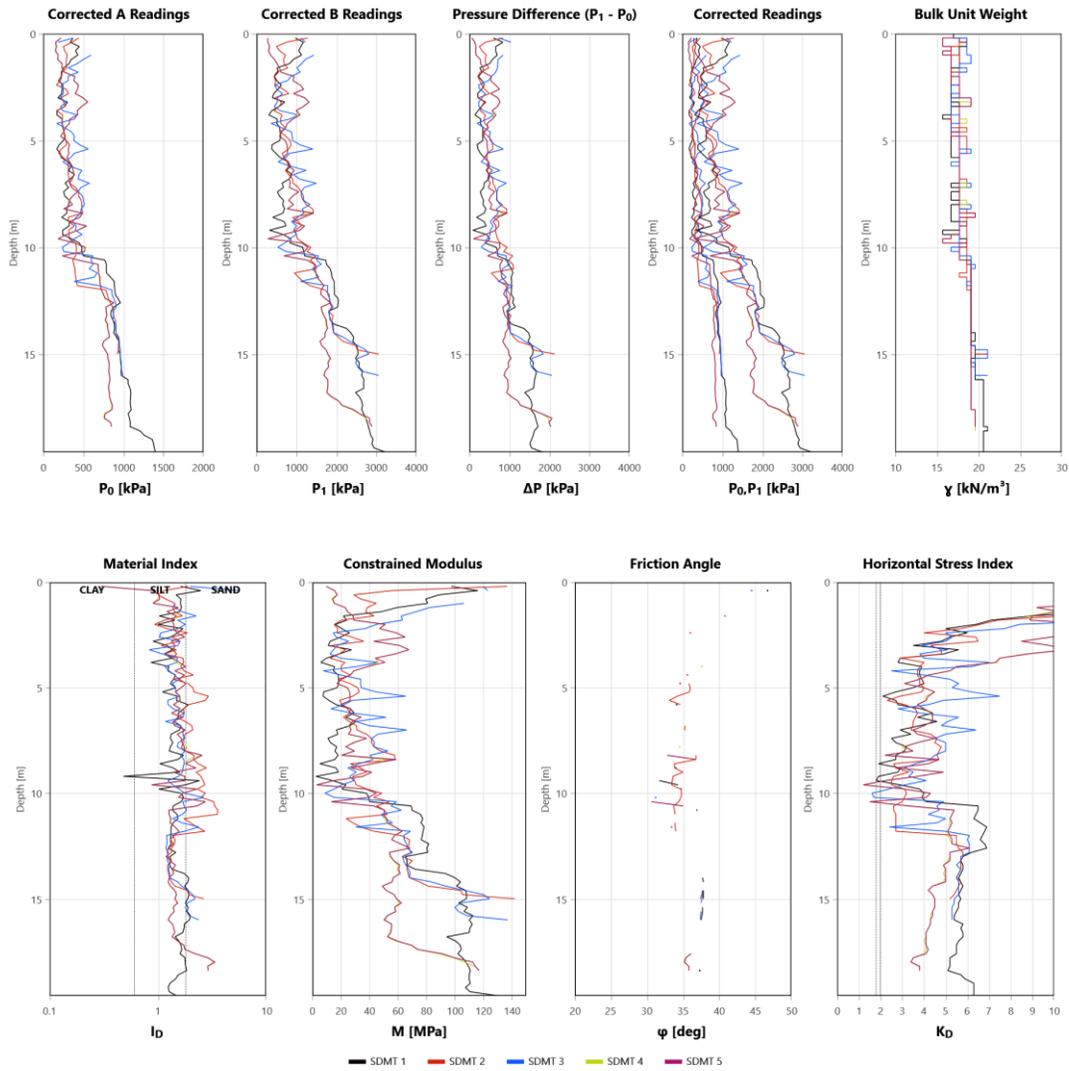
**STUDY AREA AND GEOTECHNICAL INVESTIGSTION**

In Kolkata, more than 100 DMT tests have been performed for various geotechnical purposes like site characterization, determination of shear parameters, settlement analysis, etc. In the present study, five SDMT tests were selected (Bandyopadhyay et al. 2022; Das et al. 2024). The advanced DMT tests provided the $c_u$, $\varphi$, $K_D$, and $M_{DMT}$. The study focused on the Newtown area (see Figure 2) of the Kolkata metropolitan region (22°35'03.33" N,88°29'38.28" E). The test locations are depicted in Figure 2.
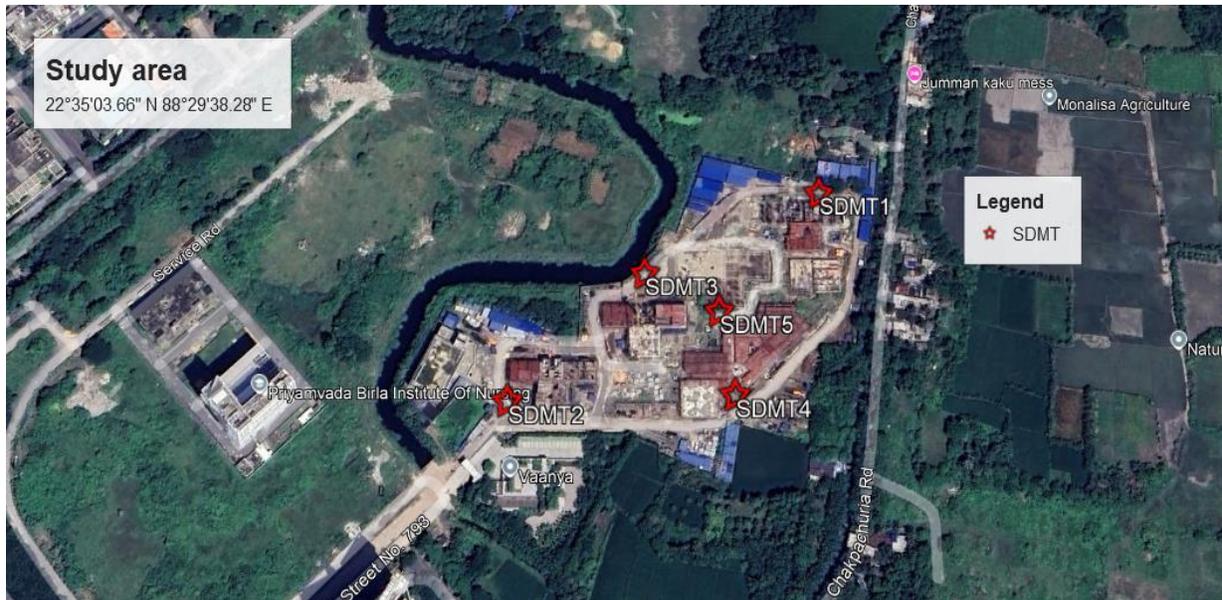


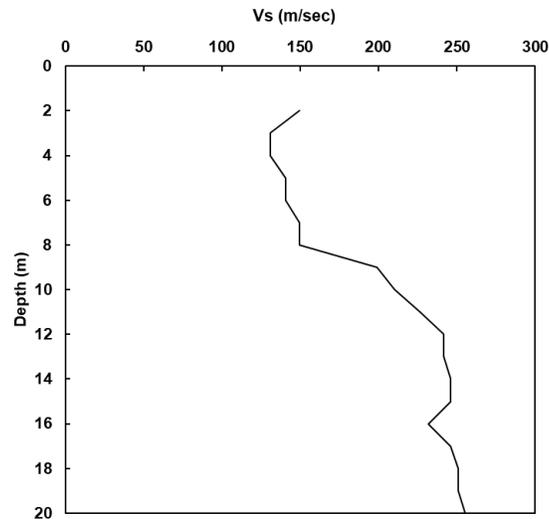**Figure 2. Testing Locations (Source: Google Earth Pro)**

A detailed analysis of the subsoil profiles in the Newtown area reveals a fill layer at approximately 2 m depth, beneath which lie strata of loose to medium fine silty sand [i.e. classified as SM/ML according to the Unified Soil Classification System (USCS)] extending to about 10 m. Below this, layers of loose to dense silty sand (SM as per the USCS) are observed down to a test termination depth of 20 m. The in-situ test data obtained from previous borehole investigations of this area by Mandal et al. (2025a), were also compared with the SDMT results, revealing a similar soil stratigraphy (see Figure 3). This consistency affirms the reliability of the data and thereby provides good geotechnical site characterization. Overall, based on the site characterization, the study area is identified to be predominantly sand-like soil deposits. Figure 4 depicts the typical representative $V_s$ profile of the subsoil in the study area.

**Figure 3. Subsoil Profile**

**Figure 4. Representative $V_s$ of Subsoil Profiles in the Study Area**

## LIQUEFACTION SUSCEPTION OF THE STUDY AREA BY MEANS OF NDA

The interaction of subsoils within a stratigraphy significantly contributes to the overall seismic response of a site, a phenomenon known as multi-layer effects. Nonlinear dynamic analysis (NDA) methods are particularly effective in capturing the soils' nonlinear mechanical behavior, including hysteretic behavior and pore water pressure generation. These approaches can model multi-layer effects by considering the interaction between adjacent soil interfaces. Recent developments in advanced constitutive models analyzing liquefaction phenomenon help to conduct detailed NDA investigations for non-plastic sandy soils, as demonstrated in this study. To accurately capture the multilayer effects of liquefaction at the study site, the loose sandy silt and silty sand layers were modeled using the UBC3D PLM model.

The UBC3D-PLM model is an effective-stress-based elastoplastic framework designed to replicate the liquefaction behavior of sandy soils under dynamic loading conditions. It is an advancement of the original UBCSAND model, initially developed by Beaty and Byrne (1997); and subsequently improved by (Tsegaye 2010; Petalas and Galavi 2013). The model is grounded in classical plasticity theory and employs a hyperbolic strain-hardening approach based on the modified Duncan–Chang formulation. Moreover, it incorporates the Drucker–Prager flow rule. The key distinction between UBCSAND and UBC3D-PLM lies in the latter's three-dimensional formulation, which integrates the Mohr–Coulomb yield criterion within a 3D principal stress framework, enabling more comprehensive modeling of soil behavior under complex stress states.

In many cases, only in situ test data are available for analysis. Among these, the Cone Penetration Test (CPT) and Standard Penetration Test (SPT) are the most commonly used methods for evaluating liquefaction resistance. To address this, Beaty and Byrne (2011) developed specific correlations linking the model parameters of the UBCSAND model (Version 904aR) to corrected SPT blow counts, $(N_1)_{60}$, for general calibration purposes. Subsequently, Makra (2013) revised these correlations for application to the UBC3D-PLM soil model, resulting in updated equations.

$$k_G^{*e} = 21.7 \times 20 \times (N_1)_{60}{}^{0.3333} \tag{1}$$

$$k_B^{*e} = 0.7 \times k_G^{*e} \tag{2}$$

$$k_G^{*p} = k_G^{*e} \times (N_1)_{60}^2 \times 0.003 + 100 \tag{3}$$

$$\varphi_p = \varphi_{cv} + \left(\frac{(N_1)_{60}}{10}\right) + \max\left(0; \frac{(N_1)_{60} - 15}{5}\right) \tag{4}$$

$$R_f = 1.1(N_1)_{60}^{-0.15} < 0.99 \tag{5}$$

The constant volume frictional angle $\varphi_{cv}$, is to be set as 33, when specific test data is insufficient.

In this paper an effort has been made to obtain the UBC3D-PLM constitutive model input parameters directly from DMT tests based on an initial work by Reyna and Chameau (1991). First the relative density ($D_r$) of the sandy soils had been obtained making use of $K_D$, from Eq. 6, and then Eq. 7 (Idriss and Boulanger 2008) is used to obtain $(N_1)_{60}$ from $D_r$.

$$K_D = 0.0007(D_r)^2 - 0.0186(D_r) + 1.3939 \tag{6}$$

$$D_r = \sqrt{\frac{(N_1)_{60}}{C_d}} \tag{7}$$

$C_d$ is a correlation constant between the $D_r$ and $(N_1)_{60}$ and it is taken equal to 46 for sand-like soils (non-plastic silty sand or sandy-silt) as per Idriss and Boulanger (2008). Based on these equations, UBC3D PLM model input parameters for the NDA had been obtained. Utilizing the input parameters, the model was further calibrated to simulate the onset of liquefaction in sand-like soils, focusing on the element-level undrained CDSS test response for attaining either of the liquefaction triggering criterion (i.e., strain = 3% or the excess porewater pressure ratio ($r_u > 0.9$) (Ishihara 1993) (see Figure 5).
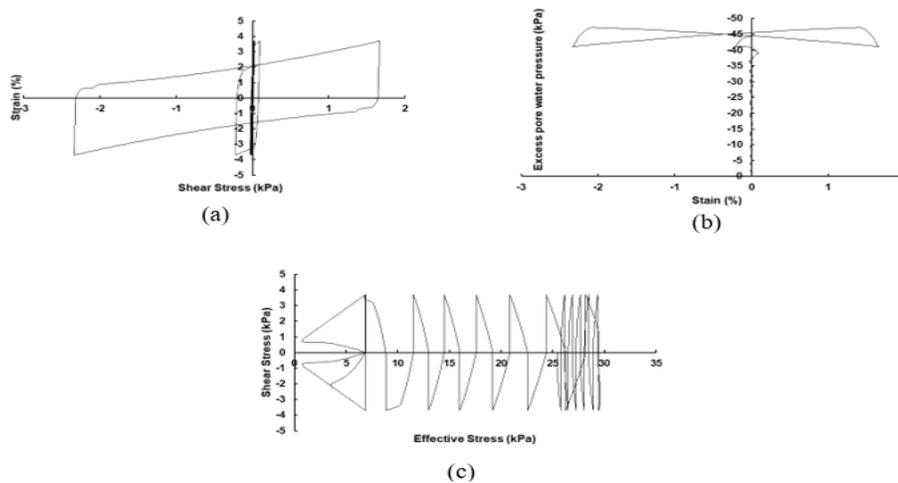


**Figure 5. Typical Example of Element Level Undrained CDSS Test Results obtained for L3 Medium Dense Sandy silt: (a) Shear stress vs Strain (%) (b) $p_{excess}$ vs Strain (%) (c) Shear stress vs Excess pore pressure at $M_W = 7$**

**Selection of Spectrum Compatible Ground Motion**

Selecting appropriate ground motions is essential for seismic response analysis, especially in regions like Kolkata where recorded earthquake data are sparse. The lack of reliable seismotectonic maps and site classification further complicates the process. A recent draft of the Indian Standards (IS) recommends using spectrum-compatible ground motions in such data-scarce regions. To address these challenges, ground motions from tectonically similar regions are selected and modified to reflect local hazard levels. Key selection criteria include magnitude, fault distance, PGA, and site conditions. Seismic activity in Kolkata has historically originated from the Arakan-Yoma ranges, the Himalayan front, and local thrust faults in the Bengal Basin. As per the draft code, Kolkata lies in Seismic Zone IV with a zone factor of 0.24g (PGA ≈ 0.253g), indicating considerable seismic risk. The methodology to select ground motions is adopted, such that it is similar to the procedure by Mandal et al. (2025c). For this study, a $M_w$ of 7 ground motion recorded at a rock site (Vs > 750 m/s) with a near-fault distance of around 30 km was selected from the PEER database. SDMT results from Newtown classify the site as site Class D as per NEHRP, with SPT N-values of 15–50 and $V_s$ ranging from 183 to 366 m/s.

The DEEPSOIL software was used to scale the obtained accelerogram and apply baseline correction. The time history was appropriately scaled to match Kolkata's target response spectrum for rock-like conditions. As part of this study, a ground motion that conforms to the IS code spectrum (IS 1893 Part I: 2016) for hard soil or rock-like conditions was generated, with the representative ground motion designated as GM1 (see Figure 6)



(a)                                                                                                    (b)
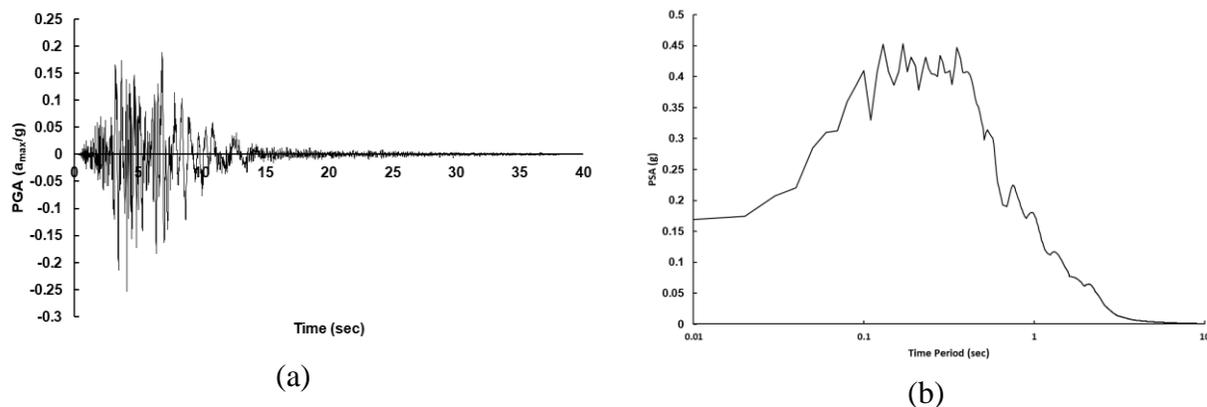
**Figure 6. Spectrum-compatible ground motion: (a) Time vs Acceleration plot (b) Response Spectrum plot**

**RESULTS AND DISCUSSION**

After constructing the FE modeled 1-D soil profile of the selected site and calibrating the constitutive model (see Figure 7), the 1-D soil column was seismically excited to GM1. The site liquefaction response was evaluated in terms of surface PGA and surface PSA, along with variation in maximum shear strain and excess pore water pressure ratio with depth.

Figure 8(a) shows the surface acceleration-time history computed from the NDA, with a peak PGA of 0.316g at 3.74 seconds. Figure 8(b) shows PSA values at ground surface level, with a peak of 1.29g at 0.50 seconds. Huge variations in surface PSA arise from pore pressure buildup in

liquefiable layers under dynamic loading with the peak PSA obtained between 0.1–1 s, thereby indicating elongation of the site period.
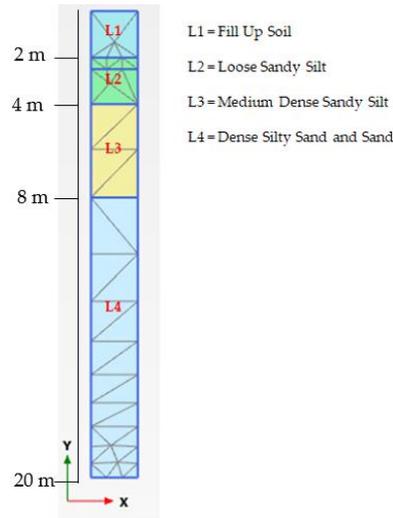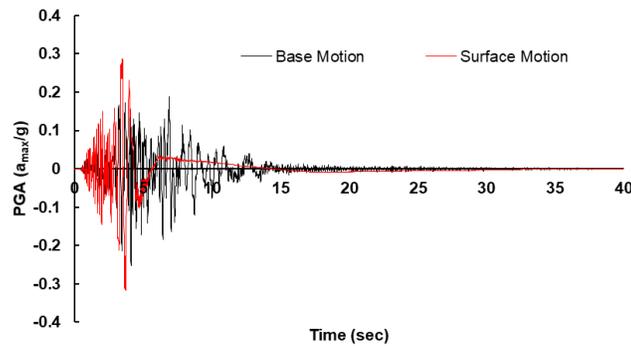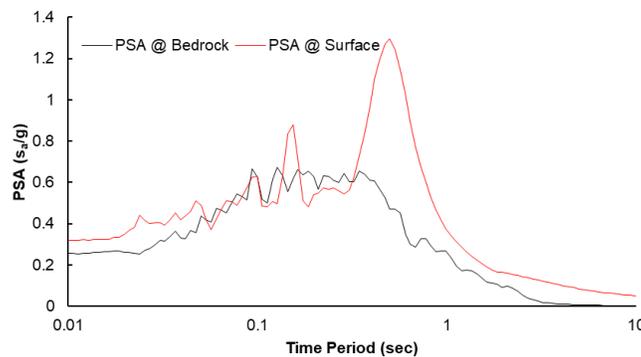
**Figure 7. 1-D representative soil column of the Study Area**

(a)

(b)

**Figure 8. Surface Response obtained from NDA for the study area: (a) Time vs Acceleration plot (b) Response Spectrum plot**

Figure 9 illustrates the evolution of excess porewater pressure ratio ($r_u$) at 4 – 8 m depth during shaking. The $r_u$ exceeds 0.9 throughout the 40-second motion, with a rise in porepressure buildup initiated around 4 sec. This sustained rise indicates a high potential for surface instability and ground failure in liquefiable layers.
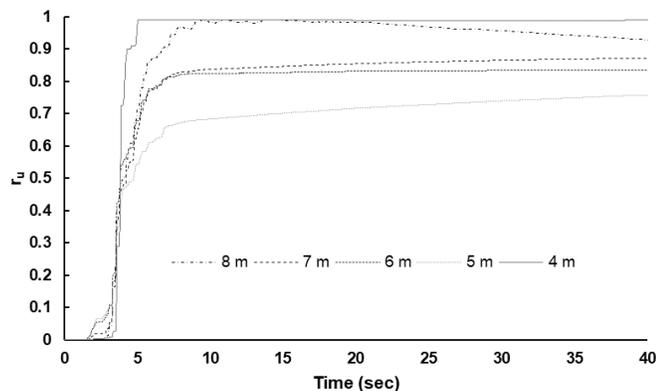
**Figure 9. Predicted $r_u$ at Different Depths for the Study Area**

Figure 11 shows $r_u$ propagation up to t = 40 s, highlighting pore pressure buildup in Layers 2 and 3 due to cyclic failure, as indicated by red and yellow zones. Additionally, $r_u > 0.4$ in the dense bottom sand layer suggests every possibility of the onset of shear-induced dilation.
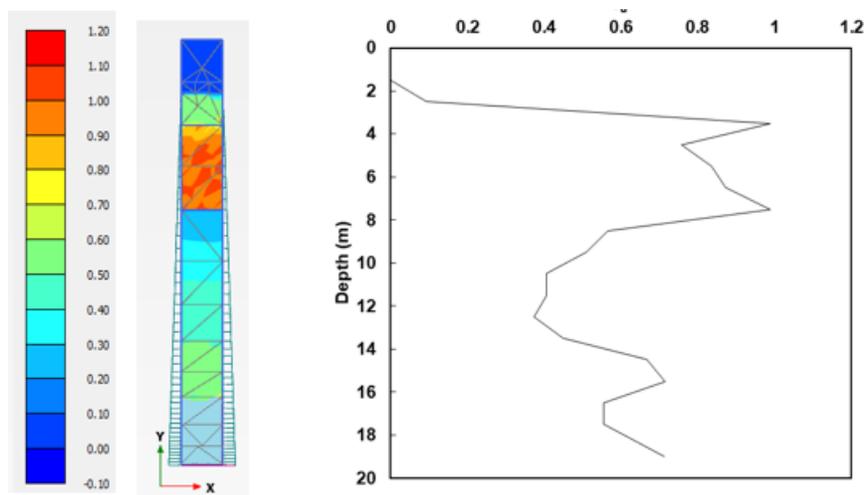
**Figure 10. $r_u$ value along the depth of the selected Site.**

Figure 11 presents the strain along the depth of the site as shown by the NDA. The NDA response from PLAXIS 2D for the maximum $\gamma_{xy}$ vs. depth plot aligns very well, both, with the shear strain criterion and also the $r_u > 0.9$ criterion in Fig. 10, where cyclic liquefaction is very likely to occur in non-plastic sand-like soils under an earthquake. The results of the NDA are in accordance with the surface PGA and surface PSA estimates obtained from quasi-coupled effective stress-based GRA studies performed at nearby locations as that of the study area (Mistry

et al. 2025; Das et al. 2025). These observations highlight the efficacy of the preliminary approach adopted in the current study for futuristic comprehensive site-specific response studies.
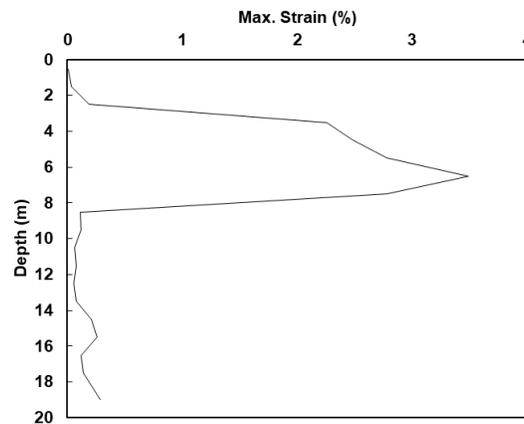


**Figure 11. Shear Strain (%) along the depth of the selected Site.**

## CONCLUSION

The UBC3D-PLM model, when calibrated with parameters that directly correlate in-situ SPT-based parameters with in-situ DMT-based parameters evaluates satisfactory liquefaction response. The response is captured well for both the $r_u > 0.9$ and shear strain ($\gamma_{xy} > 3\%$) criteria in non-plastic sand-like soils. The UBC3D-PLM model, calibrated using DMT data, effectively captures the liquefaction triggering in terms of amplification/attenuation of ground motion, surface PGA estimate and development of excess pore pressure in the sand-like soils. However, the current study only uses a correlation that is directly associated with an in-situ state parameter ($D_r$) linking both SPT and DMT data. Various other proposed correlations in literature and data from calibration chamber tests will provide more insights into the predictive capability of the UBC3D-PLM model to evaluate reliable liquefaction response of sand-like soils utilizing the DMT obtained field parameters.

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