Evaluation of Site-Specific Seismic Response of Subsoil in Kolkata Suburb, Based on Seismic Dilatometer (SDMT) and DEEPSOIL: A Deterministic Approach

Das Kaustav, Mandal Shiladitya, Rajak Sayandeep, Sarkar Arindam, and Bandyopadhyay Kaushik

Abstract While West Bengal experienced moderate seismic activity with five earthquakes exceeding magnitude 3.0 in the past year, its location on the Zones III-IV boundary with an average zone factor of 0.16 *g* warrants cautious planning, particularly for high-rise projects on the outskirts of Kolkata. The primary concern from a geotechnical point of view for the subsoil stratigraphy in the outskirts of Kolkata region is the presence of loose, cohesionless soil beneath these new constructions which makes them susceptible to liquefaction even during moderate earthquakes. Therefore, determining site-specific seismic parameters becomes crucial for geotechnical engineers to assess potential liquefaction risks. This study proposes a unique approach utilizing sophisticated in-situ test like SDMT to precisely measure shear wave velocities and compressibility characteristics of the Kolkata subsoil. These geotechnical parameters are incorporated in the DEEPSOIL software to generate site-specific seismic responses for various earthquake scenarios ($M_w = 6.9$ and 7.5). The study reveals that the site-specific peak ground acceleration (PGA) values are quite alarming when compared with previous research works. The resulting spectral acceleration (S_a/g) values at surface level are compared with the response spectrum specified in IS 1893 (Part 1): 2016 for medium soil. The study concludes that this combined approach of advanced in-situ testing and DEEPSOIL analysis simplifies the process of conducting site-specific seismic response analysis, allowing for more informed and safer design decisions for high-rise buildings.

Keywords DEEPSOIL · Liquefaction · PGA · S_a/g · SDMT

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1 Introduction

Observations from past earthquakes highlight the substantial influence of subsoil physical and mechanical properties on ground shaking response, leading to amplification or attenuation of surface motion and alterations in frequency content compared to bedrock levels. These phenomena contribute to structural failures and liquefaction risks as seen in Fig. 1. Thus, incorporation of local subsoil properties in ground response analysis (GRA) is crucial for improving outcomes.

Recent earthquakes underscore the pronounced ground-motion amplification for weak motions compared to strong motions due to nonlinear soil behavior [28]. West Bengal's seismic history, spanning three centuries, highlights seismic activity in the Himalayan ranges and Bengal fan, with Kolkata's vulnerability due to its proximity to fault lines by Parvez et al. [26]. Kolkata, falling in seismic Zones III to IV, faces high seismic risk (IS 1893 Part I: 2016). Historical seismic events, including the Great Shillong earthquake (1897) and Nepal earthquake (2015), underscore Kolkata's susceptibility to seismic shaking [4]. The Bhuj earthquake (2001), although triggered in Zone V, caused massive infrastructural damage and loss of human lives in Ahmedabad (a city in seismic Zone III) signifying the importance of considering "local site effects" while performing ground response analysis (GRA). This observation also emphasizes seismic preparedness of Kolkata city especially due to the vicinity of nearby earthquake sources. Kolkata's geological setting, within the Bengal basin, comprises Quaternary fluvio-deltaic sediments, with extensive urban expansion contributing to significant alterations in ground motion characteristics as per Govindaraju and Bhattacharya [6]. Site exploration indicates potentially liquefiable soil up to 12–13 m depth, with abrupt changes beyond, amidst surrounding active faults [24]. The geological characteristics of Kolkata, including its unconsolidated foundation soil and susceptibility to liquefaction, emphasize the need for comprehensive GRA [23].

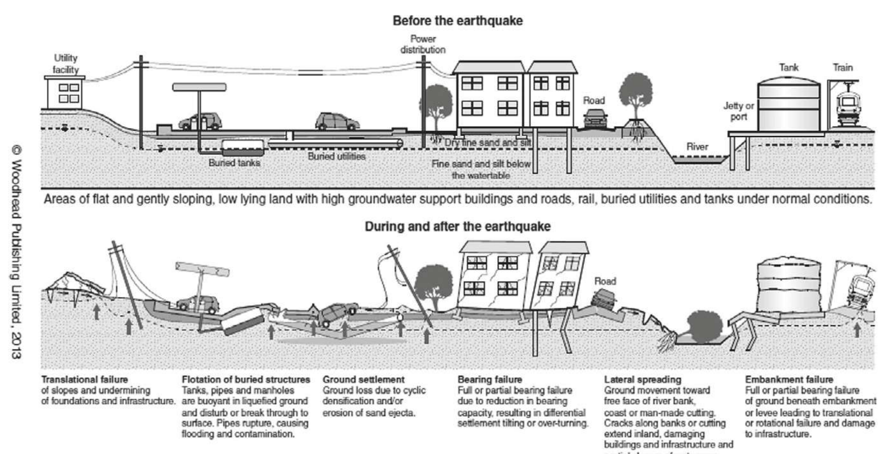

Fig. 1 Effect of ground shaking. Adapted from Milan et al. [22]

Reliability based liquefaction hazard maps and finite element analysis-based studies for subsoil profiles in Kolkata region also reveal liquefaction susceptibility at depths of 7–15 m for seismic conditions of $M_w = 7$ and $a_{max} = 0.17$ g [15, 30].

Constructing high-rise buildings in urban areas requires civil engineers to ensure safety and economic efficiency, especially in earthquake-prone regions. Earthquake-induced liquefaction poses significant concerns, including excessive ground deformations or failure and adverse seismic wave modification due to ground softening. However, there is limited guidance for practicing engineers on the influence of soil softening and liquefaction on ground response [13]. Given the well-known nonlinearity of soil behavior, accurately estimating site response remains a challenging aspect in geotechnical earthquake engineering. These aspects have motivated researchers to continuously explore the limitations from previous experiences and thus conduct microzonation studies for various urban locations focusing on site-specific GRA.

Seismic GRA is a vital tool for assessing the impact of seismic motion before earthquakes occur. It evaluates how seismic waves affect the surface level by considering soil characteristics and bedrock motions. GRA is crucial for understanding potential amplifications of bedrock motion at the surface, essential for designing structures to withstand ground shaking. GRA can be conducted through one-dimensional or two-dimensional analysis employing equivalent linear (frequency-domain analysis) and nonlinear (time-domain analysis) methods [14]. Advanced GRA computer programs (i.e., SHAKE 2000, DEEPSOIL v7.0.34, etc.) can be used effectively to obtain seismic ground response. These computer programs estimate the surface motions by employing equivalent linear (frequency-domain analysis) (ELRA) and nonlinear (time-domain analysis) (NLRA) in terms of peak ground acceleration (PGA), peak spectral acceleration (PSA), strain percentage (γ%) and excess pore water pressure ratio (r_u). Researchers over the years [6, 25, 29, 31, 32] have conducted site-specific ELRA and NLRA studies for various locations in the Kolkata region. However, NLRA analysis that includes effective stress based-analysis by modeling the pore water pressure generation and dissipation for the study area is rare.

This study addresses the above-mentioned challenge through a simplified methodology incorporating thorough in-situ testing in Kolkata's outskirts (i.e. Newtown area) where urbanization is rapid. Newtown area spans between latitude N 22° 35.01′ to longitude E 88° 29.658′. Soil parameters, including undrained shear strength (c_u), angle of internal friction (φ), horizontal stress index (K_d), vertical drained constrained modulus (M_{DMT}), and shear wave velocity (V_s) are obtained through advanced in-situ tests like Dilatometer (DMT) and Seismic Dilatometer (SDMT). Prior to the locations where DMT and SDMTs were performed, Standard Penetration Tests (SPTs) were carried out and geotechnical properties of subsoil from borelog data are also utilized in the study. Subsequently, numerically modeled nonlinear site-specific GRA has been carried out using the computer program DEEPSOIL v7.0.34 to gauge the surface ground response with respect to various earthquake scenarios (M_w 7.5, 6.9).

2 Geotechnical Investigation

Bandyopadhyay et al. [1] have extensively carried out the DMT in various locations of the Kolkata metropolitan to determine soil parameters: c_u, φ, K_d, and M_{DMT} for detailed subsoil investigations, evaluation of subsoil properties under heritage structures for retrofitting purposes and upcoming high-rise construction projects. In the study area, 20 DMTs were carried out as part of subsoil exploration program for various high-rise construction projects. The DMTs were carried out adjacent to the locations in the study area where over 30 SPTs were conducted. The borelog data from the SPTs provided important geotechnical properties of subsoil such as natural moisture content, bulk density, Atterberg limits, grain size distribution characteristics, shear strength parameters, and fines content.

According to soil exploration reports, a representative subsoil profile (see Fig. 2) is prepared. The top layer in the study area mostly comprises silt with a c_u of 30 kPa, extending on average to a depth of 4 m. Below this layer, there is loose silty sand/sandy silt extending to an average depth of 10.0 m, with Standard Penetration Test (SPT) N values ranging from 8 to 10, φ of 27° and M_{DMT} of 19 MPa. Further down, there is a dense silty sand layer extending to the termination level, with SPT N values ranging from 18 to 40, φ ranging from 30 to 33° and M_{DMT} of 30 MPa.

The presence of unconsolidated sediments above bedrock significantly alters surface ground motion characteristics, impacting seismic wave propagation. V_s is a crucial parameter reflecting soil stiffness, typically determined through various field methods like cross-hole tests, down-hole tests, and surface wave tests [14]. Surface wave testing stands out as a straightforward and efficient technique, although conducting shear wave velocity measurements may not always be economically feasible, particularly in urban areas.

In this study, seismic dilatometer test (SDMT) was used for measuring the V_s of the subsoil profile. The SDMT integrates the mechanical flat Dilatometer (DMT) with a seismic module for V_s measurement [17–19]. Recent advancements in SDMT technology have enhanced its effectiveness. The seismic module consists of a cylindrical element with two receivers spaced 0.50 m apart above the DMT blade. A shear wave source, typically a hammer, generates a shear wave by striking a steel plate pressed against the soil. V_s yields as the difference in distance between the source and receivers divided by the delay [16] (see Eq. 1). The V_s values obtained from the SDMT tests are given below (see Fig. 3):

$$V_s = \frac{s_2 - s_1}{\Delta t} \tag{1}$$

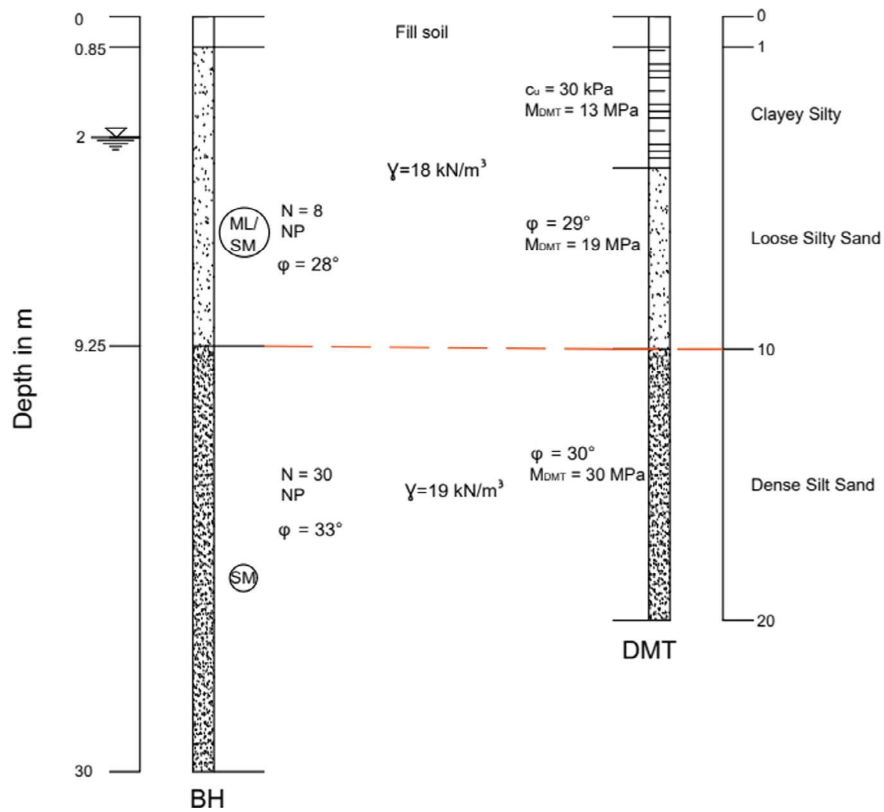

Fig. 2 Representative subsoil profile from, **a** SPT borelog and **b** DMT data for Newtown area

3 Ground Response Analysis (GRA)

The DEEPSOIL software replicated an identical subsoil profile based on obtained site-specific geotechnical characteristics. Nonlinear time-domain analysis, including a pore water pressure (PWP) generation model, was employed. Each layer's thickness ensured a maximum frequency exceeding 30 Hz. Ground motions of moderate and high magnitudes ($M_w = 6.9$ and 7.5) from the PEER database, yielding PGAs of 0.17 *g* and 0.28 *g*, respectively, are provided as base input motion for analysis (PEER 2024).

The General Quadratic/Hyperbolic model with shear strength control (GQ/H) by Groholski et al. [7] was applied to each layer of the modeled subsoil profile for the precise representation of soil's elastoplastic behavior. This model was coupled with an advanced PWP generation model developed by Vucetic and Dobry [33], forming the $(GQ/H) + u$ combination, as coined by Mei et al. [20].

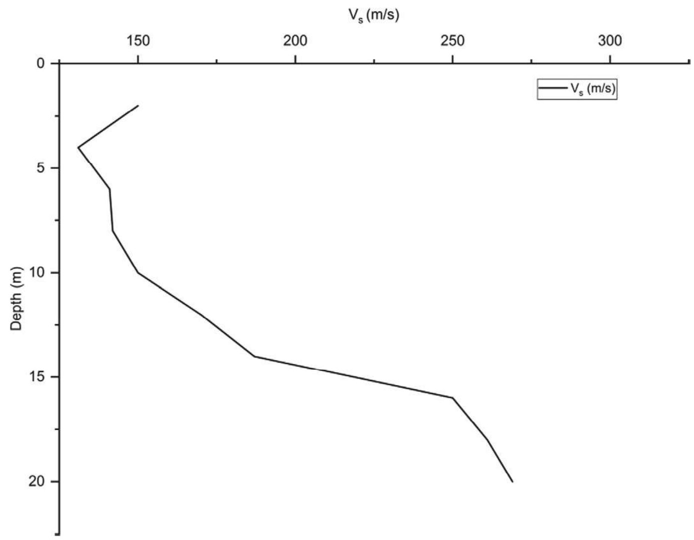

Fig. 3 Variation of V_s with depth for representative subsoil profile in Newtown area

In one-dimensional (1D) site response analysis, estimating dynamic soil properties like shear modulus (G) and soil damping (ξ) with shear strain (γ) is crucial. Small-strain V_s reflects small-strain shear modulus (G_{max}), indicating soil stiffness. While conducting GRA, obtaining shear modulus and damping requires field measurement and laboratory testing to determine their variation with shear strain. However, due to cost constraints, laboratory tests are often limited to unique soil conditions or critical projects. In the absence of site-specific dynamic soil properties, constitutive model parameters are calibrated using laboratory-derived or empirically normalized modulus reduction and damping curves, such as those provided by Zhang et al. [34]. The variation of normalized shear modulus (G/G_{max}) is influenced by several key factors including shear strain (γ) mean effective confining stress ($\acute{}\sigma_m$), soil type, overconsolidation ratio (OCR), and plasticity index (PI). Equations for estimating (G/G_{max}) and damping ratio (ξ) variation with shear strain (γ) for sandy to clayey soils across Quaternary, Tertiary, and residual soil geologic age groups are provided by Zhang et al. [34].

To capture realistic hysteretic nonlinear unload-reload behavior, non-Masing criteria were employed in this study. The Modulus Reduction Damping Formulation (MRDF) proposed by Phillips and Hashash [27], offers improved agreement with empirical modulus reduction and damping curves at large shear strains (1–10%). Furthermore, for layers characterized by silty sand/sandy silt compositions, implied friction angles were adjusted following the approach by Hashash et al. [8]. The target shear strength is based on the input for the GQ/H model, i.e., c_u for clay-like soils and φ for sand-like soils. The modeled profile and the implied shear strength correction with respect to the input target shear strength for clay-like and sand-like soils, are depicted in Fig. 4.

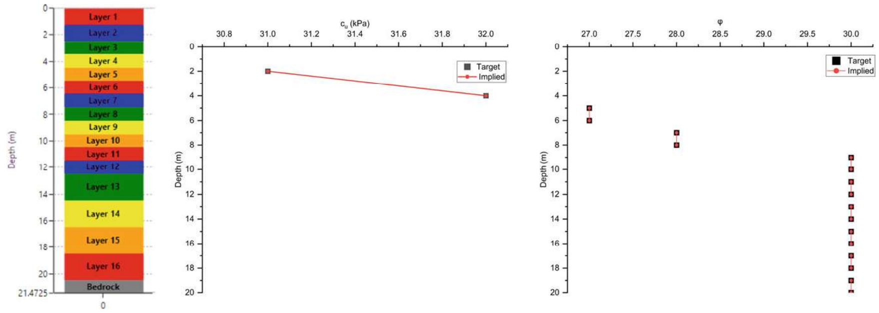

Fig. 4 Implied c_u/φ correction of the constitutive model

For PWP generation in sand-like layers, the Vucetic and Dobry [33] model was utilized for both silty sand and sandy silt layers. Vucetic and Dobry [33] proposed a unique relationship between the residual excess PWP ratio r_u, N at cycle N and cyclic shear strain (γ_c%), based on undrained, strain-controlled cyclic triaxial (CTX) tests. This relationship expresses as a function of and the equivalent number of loading cycles.

$$r_{u,N} = \frac{pfN_c F\left(\gamma_c - \gamma_{tvp}\right)^s}{1 + fN_c F\left(\gamma_c - \gamma_{tvp}\right)^s} \quad (2)$$

p, F, and s are fitting constants; f is 1 depending on one-directional cyclic loading being applied. γ_{tvp} is volumetric threshold shear strain (that shear strain below which no significant PWP is generated during undrained cyclic loading) and taken as 0.01%. The recommendation by Mei et al. [20] to assign a value of F based on factors such as fines inclusion, relative density (D_r), uniformity coefficient (C_u), and grain shape, with $p = s = 1$, was implemented for the profile below a depth of 4 m. The relative density of the sand-like layers was determined using correlations between SPT N and D_r values provided by Cubronivski and Ishihara [5]. Given that the sand below 4 m contains very few fines (8–12%), it was modeled according to the aforementioned recommendation.

4 Numerical Analysis, Results and Discussion

The PGA values obtained from Equivalent Linear Analysis (EQL) and Effective Stress Nonlinear Response Analysis (ES NLRA) for earthquakes of $M_w = 7.5$ and 6.9 are as follows: EQL—0.51 and 0.42 g, ES NLRA—0.29 g and 0.28 g, respectively. Additionally, the average peak PSA values obtained from both GRA methods for

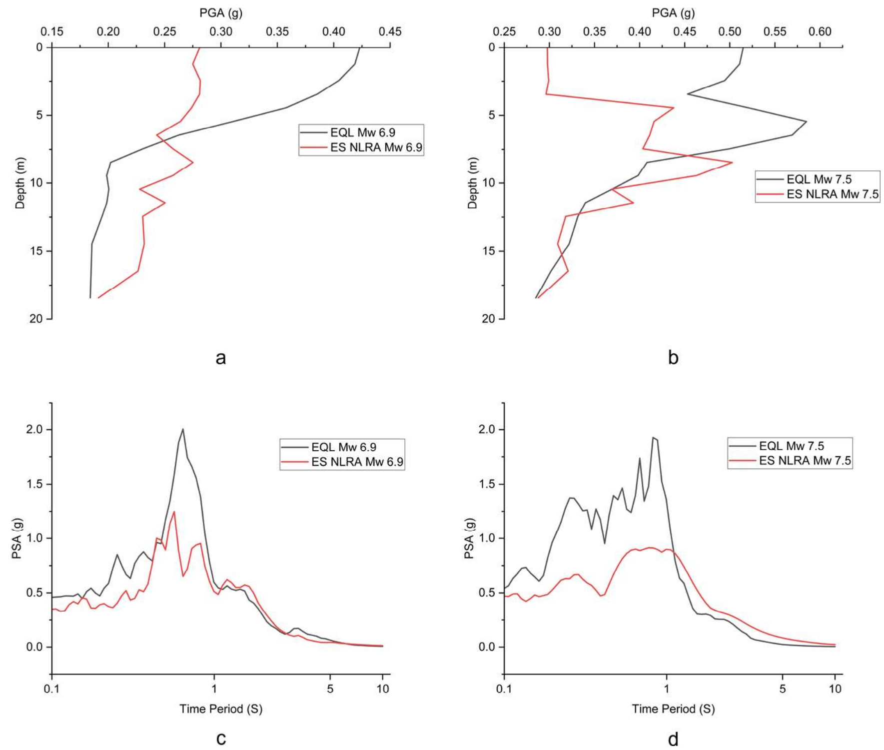

Fig. 5 Time histories of GRA of M_w 6.9, 7.5. **a** PGA (M_w 6.9), **b** PGA (M_w 7.5), **c** PSA (M_w 6.9), **d** PSA (M_w 7.5)

earthquakes of $M_w = 7.5$ and 6.9 are as follows: EQL—2.01 and 1.92 g, ES NLRA—1.24 g and 0.91 g, respectively, corresponding to an average period range of 0.5–0.6 s (see Fig. 5).

The Vucetic–Dobry PWP generation model was calibrated based on recommendations by Mei et al. [20], utilizing relevant data such as uniformity coefficient, grain size characteristics, plasticity characteristics, and relative density estimates from laboratory-tested samples collected from boreholes. These parameters were incorporated into ES NLRA due to an insignificant amount of fines content observed in the soil sample composition.

Excellent estimates of PWP were obtained in the loose silty sand layer (4–8 m) indicating the occurrence of seismic liquefaction, as seen in Fig. 6. The buildup of PWP for the dense sand-like soil at depths greater than 10 m also attained a r_u of 0.4–0.6, accurately indicating the likelihood of shear-induced dilation phenomenon. The assessment of this phenomenon is of vital importance while evaluating the seismic response of stratified deposits especially when the effect of higher overburden pressures from superstructures and initial static shear stresses are considered. The response of subsoil conditions not only at shallow depths but also at greater depths

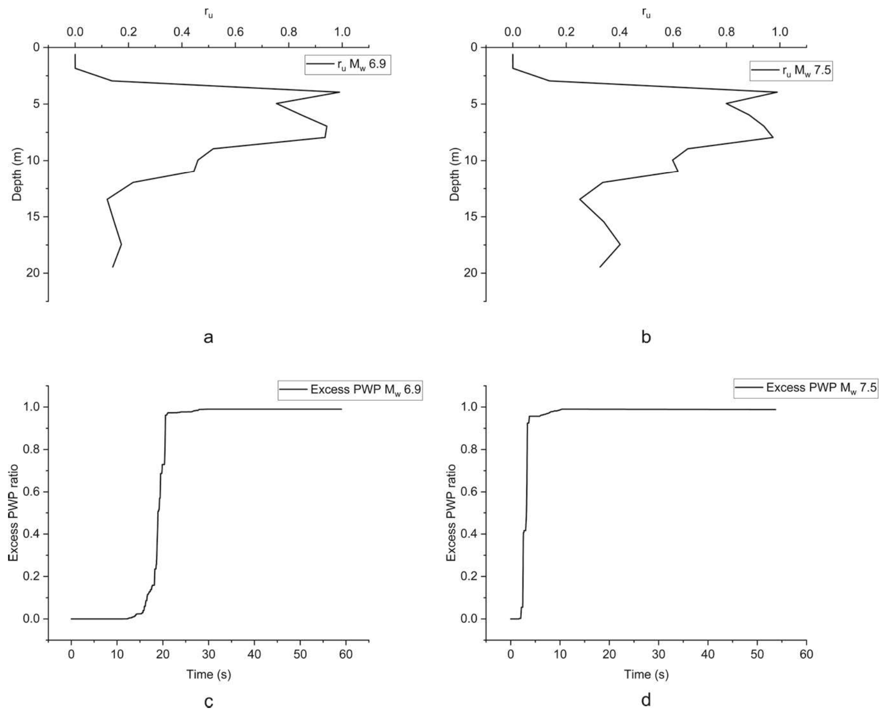

Fig. 6 Time histories of GRA of M_w 6.9, 7.5. **a** r_u (M_w 6.9), **b** r_u (M_w 7.5), **c** r_u at 4 m (M_w 6.9), **d** r_u at 4 m (M_w 7.5)

impart preparedness for engineers to implement liquefaction countermeasures for such subsoil conditions in the case of sequential earthquakes as well.

5 Validation Study

Holzer et al. [11] conducted a detailed analysis of data from the Wildlife Liquefaction Array (WLA) during the 1987 Superstition Hill earthquake sequence. They observed nonlinear soil behavior leading to liquefaction, resulting in attenuation of horizontal acceleration compared to bedrock motion. The sequence included a foreshock of Mw 6.2 followed by the mainshock (Mw 6.6), which induced liquefaction in a 4.3 m thick sand layer. Only the mainshock triggered liquefaction, causing eruption of muddy sediment and water covering a significant area. Piezometer P5, buried in sandy silt, exhibited excess pore water pressure development at 13.6 s, coinciding with peak horizontal acceleration. The North–South accelerometer recorded a PGA of 0.21 g, while down-hole PGA at 7.5 m depth was 0.17 g [9]. Subsurface conditions and geotechnical properties were evaluated by Bennett et al. [2] and

Vucetic and Dobry [33], revealing a stratigraphy with a 2.5 m layer of lean clay to silt overlying the liquefiable silty sand layer. The upper 1 m of the liquefiable layer consisted of sandy silt with an average fines content of 78%, while the lower 3.3 m was silty sand with an average fines content of 36% [9].

Simulations assessed PGA and maximum PWP variations with depth at the Wildlife Liquefaction Array (WLA) site. An Effective Stress Nonlinear Response Analysis (ES NLRA) integrated with a constitutive model for pore water pressure (PWP) generation is employed to assess the variation in maximum PWP with depth. The GQ/H constitutive model, when coupled without a PWP generation model, yielded total stress-based nonlinear GRA (TS NLRA). Equivalent Linear Analysis (EQL) and TS NLRA did not provide maximum PWP depth variation.

Maximum PWP reached 0.99 at 3.8 m depth, while P5 recorded 1 in the sandy silt layer, indicating liquefaction at 3.3 m depth. Computed surface acceleration-time history matched field data (0.21 g at 13.6 s), capturing post-liquefaction frequency content alteration. Peak PSA at the surface (0.78 g, 0.3 s) matched field data. PSA values slightly underestimated at 0.3–1 s and slightly overestimated thereafter, indicating model incapability to capture dilation phenomena [21] (see Fig. 7). Proper calibration of model parameters enables accurate application of the chosen models for site-specific response analysis, as demonstrated in the validation study of GRA at the WLA site.

6 Conclusions

- The numerically modeled effective stress-based nonlinear analysis (ES NLRA) results were validated against the Wildlife Liquefaction Array (WLA) site during the 1987 Superstition Hills earthquake. Demonstrated exceptional agreement with previous literature findings by Holzar and Youd [9]. Key parameters such as peak ground acceleration (PGA), peak spectral acceleration (PSA), and pore water pressure (PWP) development closely mirrored those observed in earlier studies.
- The numerical modeling of effective stress-based nonlinear analysis (ES NLRA) conducted for the Newtown region, specifically targeting loose silty sand layers, revealed crucial insights. Across both earthquakes studied, the analysis highlighted an excess PWP ratio (r_u) of 0.99, underscoring the vulnerability of these layers to liquefaction. Additionally, the average PGA calculated through ES NLRA stood at 0.28 *g*. In contrast, the EQL analysis yielded a notably higher average PGA of 0.47 *g*.
- The frequency content of the ground motion changes once the soil is liquefied as it is evident in the form of alteration of high frequency content, while the low frequency content keeps propagating upwards, posing a huge risk to high natural period structures, especially high-rise construction projects and bridges. The response spectra obtained are more convincing for engineers to adopt while executing high-rise projects, especially as of the presence of potentially liquefiable soil deposits.

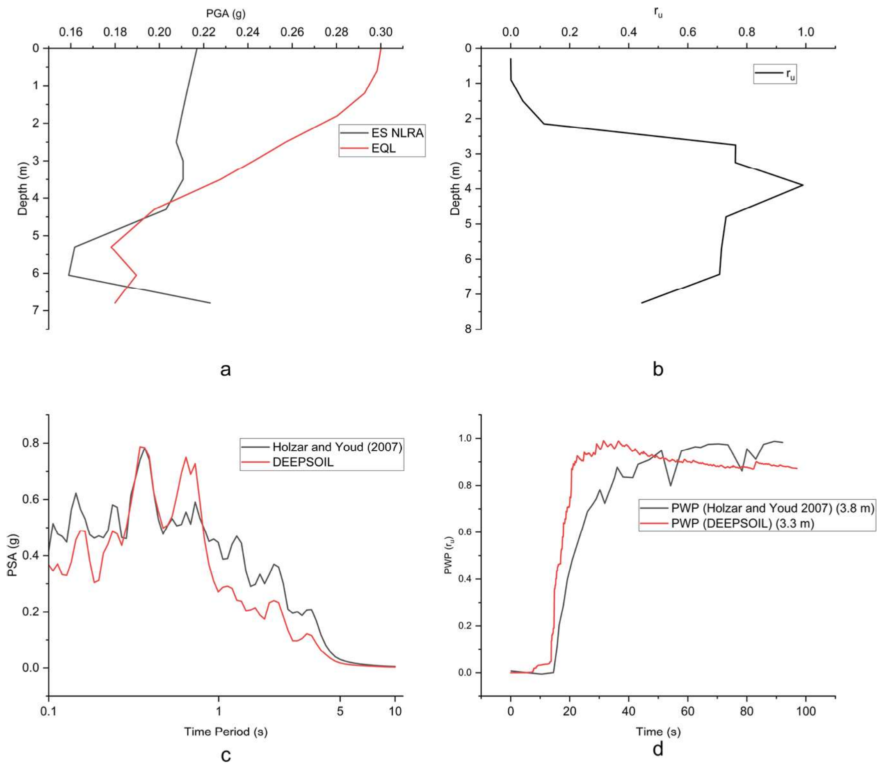

Fig. 7 Time histories of WLA. **a** PGA, **b** r_u, **c** PSA, **d** r_u at 3.8 and 3.3 m

- The efficiency and accuracy of the PWP generation model in ES NLRA hinge significantly upon several key factors. These include the fines content, precise shear wave velocity records, shear strength characteristics, and particle size distribution of the soil. However, this initial analysis is just the beginning; it sets the stage for more advanced and computationally extensive techniques, such as two-dimensional finite element methods. Looking ahead, the study aims to evolve toward a deterministic framework for 2D ES NLRA. This future scope underscores the commitment to enhancing the reliability and robustness of the analysis, ultimately contributing to more accurate and comprehensive assessments of seismic hazards and their implications for engineering projects.

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