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PROBABILISTIC NONLINEAR GROUND RESPONSE ANALYSIS OF NEWTOWN SUBURB, KOLKATA, INDIA

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Abstract. Ground response analysis (GRA) helps immensely in the assessment of seismic hazards on the surface of any region, as it captures the influence of local soil conditions on the ground surface motion. In this study, a probabilistic one-dimensional (1-D) nonlinear GRA (NGRA) is performed for Newtown, Kolkata, using DEEPSOIL software. The methodology incorporates soil nonlinearity, variations in soil properties, and water table fluctuations to achieve a more realistic seismic response than conventional equivalent linear GRA (ELRA). Although ELRA methods are widely used due to simplicity, they may underestimate soil behavior under strong shaking or liquefaction-prone conditions. Thus, a comparison of results from ELRA and NGRA reveals significant differences in predicted peak ground acceleration (PGA), highlighting the need to capture nonlinear soil behavior for robust seismic design and risk assessment. However, the nonlinear approach being the most appropriate method for GRA, its performance largely depends on the input parameters used in the analysis. For lower discrepancy and faster convergence, a quasi-Monte Carlo Simulation (QMCS) technique is adopted to sample uncertain input parameters, including shear wave velocity, shear strength, shear modulus, damping ratio, and soil density, based on their probabilistic distributions, and this uncertainty is subsequently reflected in the probabilistic ground response analysis (PGRA). Eleven spectrum-compatible bedrock motions with PGA varying between 0.16g to 0.24g are used as seismic input at the base of the soil column, representing a range of earthquake scenarios. Dynamic soil properties, including modulus reduction and damping curves, are calibrated considering the effect of overburden pressure, plasticity index, and geologic age against local field and laboratory data to ensure reliable analysis. The variation of PGA across the soil profiles is captured, and the amplification ratio of surface PGA and bedrock PGA in Newtown is in the range of 1.5-2.5. The PGA at surface level obtained from the PGRA corresponding to a bedrock PGA of 0.17g is 0.356 ± 0.03g and 0.5 ± 0.035g from nonlinear and equivalent linear approaches, respectively. The developed hazard curves will enable practicing engineers to establish the probability-based response spectra for seismic response analysis of structures and to make risk-informed decisions in seismically active regions.

Keywords: Nonlinear ground response analysis, DEEPSOIL, uncertainties, quasi-Monte Carlo simulation, PGA, probability distribution.

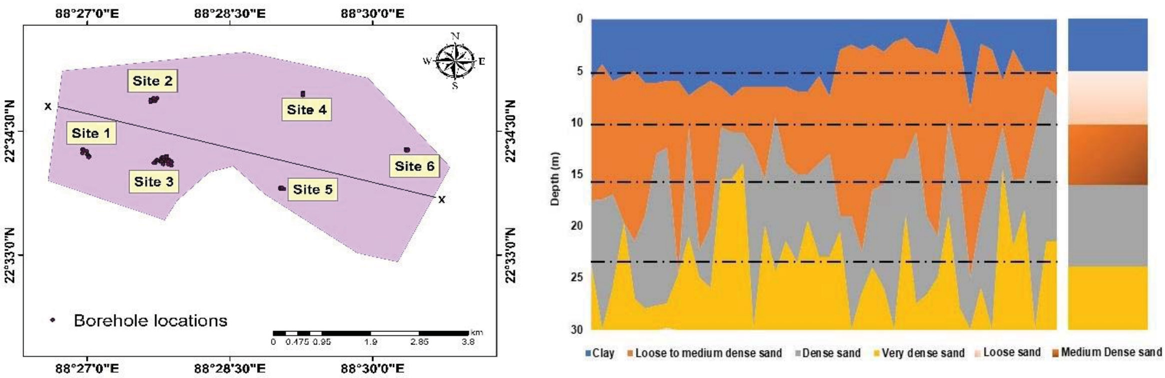
1. Introduction

Ground response analysis (GRA) is most often performed by the one-dimensional (1-D) propagation of horizontally polarized shear waves (SH) through soil layers over bedrock. Conventionally, 1-D GRA is performed using linear and equivalent linear approaches. However, soils tend to exhibit nonlinear behaviour even at small strains, and the use of linear and/or equivalent linear methods is not applicable in modelling the nonlinear soil behaviour during earthquakes. These approaches use maximum and effective strains, respectively, to define the material properties in the analyses. However, the inadequacy of the above methods is observed when a large shear strain develops in the soil layer due to seismic shaking (Hashash and Park 2001). In the Nonlinear ground response analysis (NGRA), the mechanical properties of the soil are updated in each time increment, thereby capturing the nonlinear response of the ground during an earthquake (Rathje and Kottke 2011).

Over the years, site-specific ground response studies for Kolkata city have been carried out using equivalent linear ground response analysis (ELRA) (Shiuly and Narayan 2012, Nath 2016). A nonlinear soil amplification study is attempted by Bandyopadhyay et al. (2021) for Kolkata city, considering uncertainty in plasticity characteristics and shear wave velocity (V_s). Recently, deterministic GRA for the Newtown location for a moment magnitude (M_w) of 7 and input peak ground acceleration (PGA) at the bedrock level of 0.16 – 0.183g was carried out utilizing the data from standard penetration test (SPT) and Seismic Dilatometer Marchetti Test (SDMT) by Mistry et al. (2024) and Das et al. (2024), respectively. However, these studies have not considered the uncertainty in input parameters for the NGRA. The present study has adopted the total stress-based NGRA using DEEPSOIL program for the probabilistic nonlinear GRA (PNGRA) of Newtown suburb of Kolkata city and assesses the local site effects due to the presence of potentially liquefiable layers at the shallow depth of the study area. The values of the target shear strength and friction angles are corrected for the entire soil profile to avoid erroneous responses from the response analyses. The results of the PNGRA are compared to those obtained from the probabilistic ELRA. It is noted from the results of the PNGRA that the manifestation of liquefaction is observed in the form of alteration of frequency content.

2. Study area and subsoil characteristics

Kolkata is the oldest metropolitan city and a significant commercial hub of eastern India. A suburb, Newtown, is located in the eastern part of Kolkata. The Newtown suburb is undergoing rapid urbanization compared to other parts of the city to accommodate the growing population. The rapid urbanization and overpopulation caused the city to expand, which led to the filling up of extensive areas with dredged alluvial soil from the Ganges River. Previous seismic microzonation studies indicate that the subsoil at depths of 12-13 m is predominantly unconsolidated, potentially liquefiable, highly variable, with very low SPT blow count (N) values up to 5 along this depth. A sudden increase in N value of 16 to 18 is observed on average for the entire city, indicating the demarcation between Holocene and Pleistocene deposits (Nandy 2007). The soil strata beyond 30 m depth are observed to be very hard, and as the depth reaches 75 m, the N value also progressively increases to a maximum value of 100. The alluvial nature of Kolkata soil is prone to significant alterations in ground motion characteristics during earthquake shaking. The sites considered for the response study and the typical subsoil profile along the section x-x (approximately 6 km between Site 1 and Site 6) are depicted in Fig. 1.



(a) (b) (c)

Fig. 1. (a) Location of the sites considered in the study area (b) variation of subsoil along section x-x, and (c) idealised soil profile considered for PNGRA

3. Quantification of Uncertainty in Geotechnical Parameters

The response of soil to the input ground motion is influenced by several geotechnical parameters, each having a unique effect on the propagation of the seismic waves through the soil. The ground response, particularly at the surface, is sensitive to slight variations in the soil properties. The subsoil profile at the study area comprises loose to medium dense sand overlain by clay of soft to stiff consistency. Dense to very dense sands with higher N values (N > 50) are present at depths greater than 15 m. Figure 1 shows the spatial variability of the subsoil with depth that warrants a probabilistic approach to quantify the variation in responses. The uncertainty in shear wave velocity (V_s), unit weight (γ), plasticity index (PI), shear strength (S_u), water table and dynamic soil properties like maximum shear strain modulus (G_{max}) and damping (ξ) is considered to obtain the expected value of the nonlinear (NL) and equivalent linear (EL) ground response quantities at any depth for different soil profiles. The study area lies in Zone III/Zone IV as per IS 1893 seismic microzonation of India and can experience a ground motion with PGA in the range of 0.16g-0.24g. The recent draft version of IS 1893 Part 1 (2023) has emphasized the use of spectrum-compatible ground motions for areas that lack reliable earthquake records. In this study, the ground motions compatible with the IS code spectrum of hard soil have been obtained by following the methodology of Mandal et al. (2025a, b) and are denoted as GM1 to GM11. The ground response is evaluated using these 11 ground motions, having varying PGA, frequency content, and duration.

The uncertainty in the input parameters is quantified using Quasi-Monte Carlo (QMC) simulations using sobol sequence for sampling from the probability density function (pdf) of the random variables. Unlike the conventional Monte Carlo simulation (MC), the QMC samples the data in a sequence, resulting in lower discrepancy and faster convergence (Shinoda 2007, Liu and Cheng 2018). The input soil parameters used in the GRA are modelled as normal random variables, and their corresponding pdf are developed from the data acquired from the field and laboratory tests. Data from 62 boreholes within a radius of 3 km from the Newtown suburb have been analyzed, and the sample space, mean, and standard deviation to be used for QMC sampling are established and presented in Table 1. Due to the non-availability of the measured V_s values, N-based empirical correlations (Ohsaki and Iwasaki 1973, Imai and Tonouchi 1982, Iyisan 1996, Hasancebi and Ulusay 2007, Dikmen 2009) are used for determining the V_s values. The uncertainty in N values is assumed to reflect the randomness in V_s. The uncertainty in dynamic soil properties is evaluated using the approach of Zhang et al. (2005) by considering variations in cohesion (c_u) and PI for clays and variation in angle of internal friction (ϕ) for sands. The Zhang et al. (2005) model considers the age and shear strength characteristics of the soil deposits. In order to reflect these aspects, the variations in the above parameters are considered to quantify the uncertainties in the dynamic properties. This is the usual procedure adopted to reflect the age and shear strength characteristics of the soil. In all, 245 QMC samples are generated from the pdf, and the probabilistic ground response analysis (PGRA) is carried out using DEEPSOIL V.7.1 by adopting NL and EL approaches.

Table 1 Statistical parameters of the subsoil profile considered for QMCS.

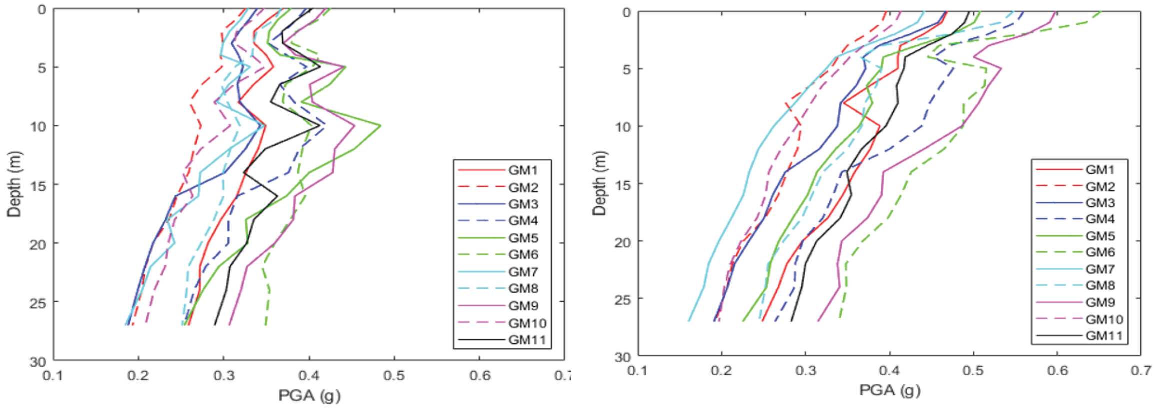
Property	Min Value	Max Value	Mean	Coeff. of Variation
Clay				
Cohesion (kN/m^2)	12	83	31.2	0.570
Plasticity index (PI)	8	52.0	21.23	0.530
Unit weight (kN/m^3)	15.54	20.72	18.08	0.080
Shear wave velocity (m/s)	110	193	138.6	0.163
Loose silty sand				
Angle of internal friction (°)	20	30	28	0.100
Unit weight (kN/m^3)	14.47	21.29	17.92	0.067
Shear wave velocity (m/s)	125	206	173.7	0.137
Medium dense silty sand				
Angle of internal friction (°)	22	32	30	0.100
Unit weight (kN/m^3)	14.55	21.34	17.98	0.116
Shear wave velocity (m/s)	166	316	231.6	0.124
Dense silty sand				
Angle of internal friction (°)	25	36	34	0.090
Unit weight (kN/m^3)	14.52	21.32	17.96	0.122
Shear wave velocity (m/s)	195	370	302.3	0.140
Very dense silty sand				
Angle of internal friction (°)	31	39	36	0.041
Unit weight (kN/m^3)	14.52	21.32	17.96	0.122
Shear wave velocity (m/s)	217	453	364.4	0.165
Depth of GWT (m)	1.0	10.5	4.9	0.461

4. Nonlinear Ground Response Analysis using DEEPSOIL

The soil profile for GRA is discretized into many layers of different thicknesses as per the DEEPSOIL program. The dynamic soil properties (i.e., shear modulus (G) and damping ratio (ξ)) with increasing cyclic shear strain (γ) amplitudes are usually obtained from resonant column test, cyclic triaxial test, etc. Due to a lack of laboratory test data, the normalized modulus reduction (G/G_{max}) and damping ratio curves are obtained using the empirically derived expressions in the present study. The procedure given by Zhang et al. (2005) is adopted for the Quaternary deposit of the study area. A General Quadratic/ Hyperbolic (GQ/H) model (with shear strength control) proposed by Groholski et al. (2016) is used to model the response of soil. The primary input parameters for the GQ/H model are the undrained shear strength and V_s of the soil layers. The GQ/H model implemented in DEEPSOIL uses a curve-fitting routine that provides the parameters for calculating the strength-corrected dynamic properties. The shear strength correction procedure by Hashash et al. 2015 enables the GQ/H model to capture the modulus reduction, increase in damping, and shear strength at large strains. The non-Masing model, i.e., modulus reduction and damping formulation (MRDF) Pressure-Dependent Hyperbolic model (Philips and Hashash 2009) is implemented as the MRDF-UIUC reduction factor in the DEEPSOIL program. This reduction factor is introduced in the soil model, and the G/G_{max} and damping curves are fitted and compared with the reference curves of Zhang et al. (2005) to obtain the fitting parameters. After an initial fit, the shear strength and friction angle estimated by the fitting parameters are corrected to match the target shear strength and friction angle of all the layers to avoid overestimation or underestimation of the G/G_{max} and damping values at higher strain. The fitting procedure is done iteratively to obtain the best-fitted G/G_{max} and damping ratio curves, which are used in the ELRA and NLRA. The bedrock is modelled as a rigid half-space.

5. Results and Discussion

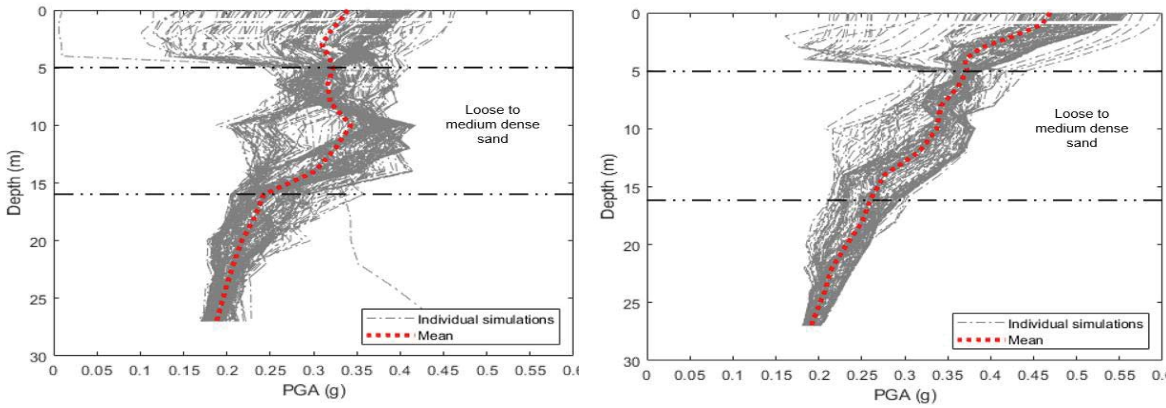
Figures 2(a) and 2(b) depict the mean variation of the responses from equivalent and nonlinear GRA with depth for different bedrock motions. The PGA values of the input motion at any depth from the equivalent linear approach are found to be higher than those evaluated from the nonlinear approach. Both methods indicated an amplification in the PGA up to a depth of 10 m below the ground surface. Thereafter, attenuation of the PGA at depths between 5 m and 10 m is recorded from the nonlinear analysis. However, in the EL approach, no such variation in the PGA is noticed for most ground motions. The attenuation of the PGA between 5 m and 10 m may be attributed to the potential liquefaction of the sand under seismic loading. Zhan and Chen (2022) observed that the liquefaction manifestation from the effective stress-based NGRA is indicated by the decreasing values of the PGA from the bottom of the liquefiable layer to the ground surface. Although the total stress NGRA may not capture this variation effectively, the reduction of PGA values within a loose to medium dense sand provides an indication of potential liquefaction, which the ELRA is not able to capture.



(a) (b)

Fig. 2. Variation of mean PGA for the 11 ground motions along the depth from (a) NL and (b) EL analysis.

The results of the PGRA of the study area corresponding to GM3 are further illustrated. Figures 3(a) and 3(b) indicate the variation in response of the subsoil from the NL and EL methods with varying soil properties. The band of variation in the response increases from the bedrock towards the surface, with maximum variation noticed at the surface. This indicates the sensitivity of the surface response to minor variations in the soil properties. The presence of potentially liquefiable loose to medium dense sand between 5 m to 12 m has significantly altered the ground motion as indicated by the increased variations at this depth. This substantiates the need for PNGRA for sites with potentially liquefiable soils, as it aids in evaluating the soil properties that can trigger liquefaction. As the surficial response is highly variable, developing a pdf of the surface response to a particular ground motion can provide information about the expected value under different soil conditions.

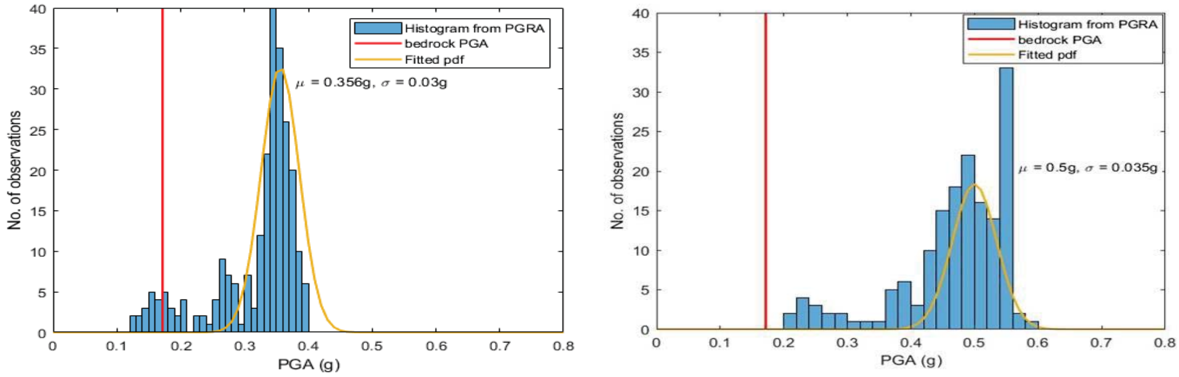


(a) (b)

Fig. 3. Variation of PGA along the depth for GM3 from (a) NL and (b) EL analysis.

Figures 4(a) and 4(b) outline the surficial response to GM3 from nonlinear and equivalent linear analysis. The histogram indicates a probable surface PGA of 0.34g - 0.36g and 0.5g-0.56g from NL and EL methods for an input ground motion with bedrock PGA of 0.171g. A normal distribution curve is fitted to the histogram to develop the corresponding pdf of the ground surface motion. A pdf with a mean (μ) of 0.356g and standard deviation (σ) of 0.03g is fitted to the histogram corresponding to the NL response, and a pdf with μ = 0.5g and σ

= 0.035g is fitted to the EL response. The μ and σ of the pdfs are so selected to cover the maximum area of the histogram. The results of the probabilistic ground response analysis are compared with the results available in the literature for Kolkata city. The expected values from the developed pdf are in accordance with the results reported by Mistry et al. (2024) and Das et al. (2024). Further, a surface PGA hazard curve (see Fig. 5) indicating the probability of exceedance of PGA is developed. By referring to these curves, engineers can assess the probability of different PGA levels occurring at the ground surface during seismic events. This information enables practitioners to implement risk-based design strategies by considering the expected PGA values in their structural analysis and design processes.



(a) (b)

Fig. 4. Probability density function of surface PGA for GM3 from (a) NL and (b) EL analysis

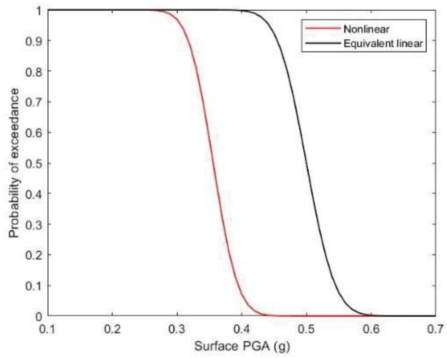


Fig. 5. Probability of exceedance vs surface PGA from NL and EL GRA

6. Conclusions

Probabilistic nonlinear ground response analysis was carried out for the Newtown suburb of Kolkata, India, through the quantification of variability in the input parameters such as shear wave velocity, unit weight, shear strength, water table, and dynamic soil properties. The uncertainties are quantified using Quasi-Monte Carlo simulations, and the nonlinear and equivalent linear responses are evaluated for 11 IS spectrum-compatible ground motions. The following are the conclusions drawn from the analysis.

(i) The 1-D total stress-based PNGRA adopted for the Newtown suburb has provided a comparatively realistic variation of amplitude, duration, and frequency of ground motion within the subsurface profile in the study region.

(ii) Nonlinear ground response analysis performed better in capturing the manifestation of probable liquefaction through the attenuation of the PGA compared to the equivalent linear approach, which yielded overestimated values of surface PGA.

(iii) The expected values of surface PGA at the study area for an input bedrock motion of 0.171g are 0.356±0.03g and 0.5±0.035g from nonlinear and equivalent linear approaches, respectively.

Though these analyses are computationally intensive and require nonlinear constitutive models within the framework of numerical modeling, they are reliable for implementation in practice for site-specific nonlinear ground response studies. The limited efficiency of the total stress-based NGRA approach in capturing the variation in site response due to PGA-altering phenomena, such as liquefaction, is limited and therefore tends to slightly overpredict the responses compared to the effective stress-based NGRA, particularly at the surface. Therefore, the current study is further extended to evaluate the probabilistic site response within a framework of effective stress-based NGRA. Further, sensitivity analysis will be carried out to determine the most influential soil parameter on the ground response (displacement and shear stress) along the soil profile of the study area. The site response studies of the selected location in the Kolkata region on these lines are currently underway, and the results will be provided subsequently.

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