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Seismic Ground Response Analysis using Continuum Approach

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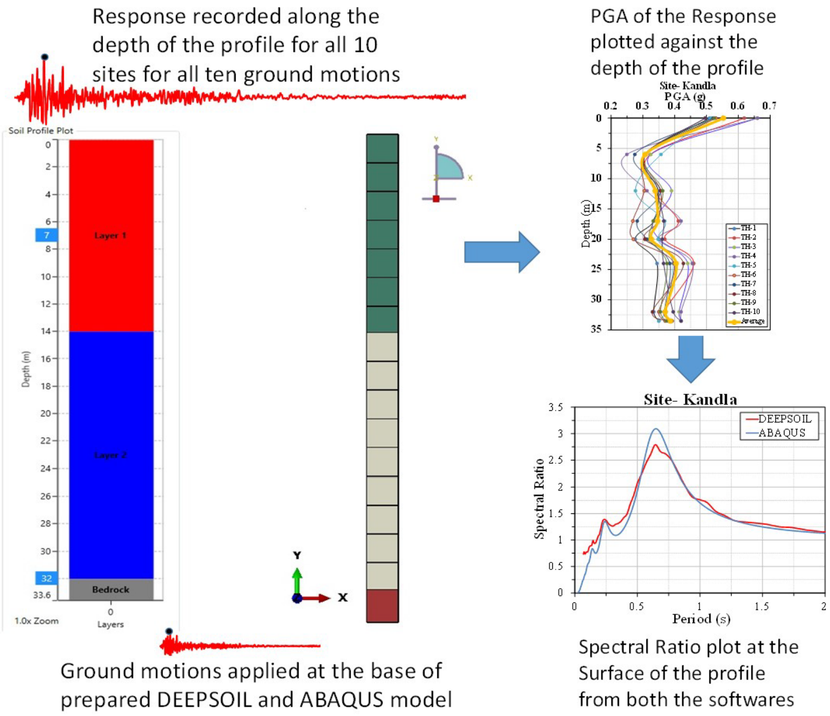
Abstract

Conventionally, Ground Response Analysis (GRA) is carried out using a discrete approach in which a layered soil column is idealized as a multidegree of freedom lumped mass system. In this approach equivalent-linear or nonlinear soil model is used and the soil layers are assumed to be horizontal and infinitely extended. However, when these conditions are not met, the continuum approach to model soil column using finite elements is more realistic. Further, depending on the soil test data availability, the soil model may be chosen as linear, equivalent-linear or nonlinear. When the phenomenon of ground response analysis is numerically simulated, the boundary conditions of the numerical model and the input ground motions play an important role. The present study, aims to compare the results of 1D GRA using discrete and continuum approach. For this purpose ten different real Indian sites are considered and modeled in DEEPSOIL and ABAQUS. The results show a good agreement between the approaches adopted for 1D GRA. This study is a step forward to use continuum approach to carry out 1D and 2D ground response analysis.

Keywords

Ground Response Analysis, Response Spectra, Amplification Factor, Numerical Modelling, ABAQUS, DEEPSOIL.

Graphical Abstract



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INTRODUCTION

An earthquake is a natural event that happens when the tectonic plates in the earth's crust shift and unleash a massive amount of energy, which travels in the form of seismic waves and leads to damage of infrastructure and life loss. The intensity of ground motion during an earthquake varies from location to location based on the seismic zone and the soil type beneath the surface. Soft soil layers, such as those composed of clay or silt, are more susceptible to amplifying ground motion than stiff soil layers, such as sand or gravel. The fundamental period of soil column, impedance contrast between layers and the depth of soil layers are also very important parameters in this regard (Kramer, 2013), (GovindaRaju et al., 2004). Several literatures are available on the effect of soil depth on seismic response (Adhikary, 2014; Adhikary et al., 2014; Deoda & Adhikary, 2020, 2022; Kamatchi et al., 2010). Further, Deoda & Adhikary 2022 suggested that the soil depth should be a parameter for classification of sites for Indian Seismic Design Code. Similar studies have been conducted by (Kamatchi et al., 2010). They studied the effect of performance of buildings for site-specific earthquakes with different depth of subsoil. He has conducted his study to examine the effect of eight different depths under the soil surface viz. 10m, 20m, 30m, 50m, 75m, 100m, 150m and 200m. They concluded that the depth of soil stratum has significant influence on displacement and base shear in buildings and claimed that just considering any depth over bedrock may not ensure safe seismic performance of structures.

Ground Response Analysis (GRA) is a popular method used in seismic engineering to predict the response of soil layers to ground motion. It involves using mathematical models to simulate the behaviour of soil and can be used to assess the reliability of the soil. GRA typically involves the use of computer software to model the behaviour of soils and bedrock under different loading conditions. The software takes into account factors such as the strength, stiffness, depth and geometry of the soil profile. The results of GRA can be used to determine the expected settlement, the stress and strain in the soil, and the risk of soil liquefaction or other types of soil failure. Ground response analysis is an essential assessment in geotechnical engineering and is used in a wide range of engineering applications. Professor Seed have developed the first computer program SHAKE (Ordóñez, 2012) to carry out ground response analysis. The software uses a 1D approach to model the seismic response of horizontally layered, infinitely extending soil layers. From then, researchers further expanded the first computer code of GRA and developed more sophisticated 1D GRA tool incorporating various numerical methods and considering a broader range of soil behaviors. With time and advancements in computer technology and computational methods, these computer codes got upgraded and now are an essential part in geotechnical engineering practices. Today, there are various GRA software packages available which have been developed by different research institutions. Down the line, initially SHAKE, later on ProSHAKE was introduced, then DEEPSOIL, SPECTRA etc. were developed incorporating multilayer soil profiles modelling and nonlinear soil analysis capability.

Researchers worldwide have been using different softwares to perform GRA in their studies. After the 2001 Bhuj earthquake in Gujarat, India, GovindaRaju et al. (2004) employed SHAKE91 to undertake GRA of the Gujarat site and underlined the significance and challenges of the procedure. They further emphasized the need to include guidelines on conducting GRA for geotechnical structures in the current IS code provisions. Ranjan (2004) used SHAKE2000 for GRA of 31 sites of Dehradun, India. The shear wave velocity profiles of those sites were determined by the Multi-Channel Analysis of Surface Waves method (MASW). In the study, the entire city was divided into different seismic zones on the basis of the obtained shear wave velocity and spectral acceleration. Similar studies have been conducted in other cities of India, viz. Kolkata city (Chatterjee and Choudhury, 2018) and Bangalore city (Anbazhagan and Sitharam, 2008) as well. Shukla and Choudhury (2012) provided valuable information about the potential seismic hazard in the region around the ports in Gujarat, India, by developing site-specific ground motions for different levels of shakings. They assessed the vulnerability of the structures in the vicinity of these ports using SHAKE2000 (Ordóñez, 2012). Additionally, this study highlighted the importance of considering local seismic conditions when designing and building structures in seismically active regions. Desai and Choudhury (2015) used SHAKE2000 for their 1D equivalent linear ground response analysis of various soil profiles from Mumbai, India. They found that certain sites among a few were prone to earthquakes in the city. Borja et al. (2002) compared another algorithm by performing a total stress analysis for ground response on a major earthquake-hit site in Lotung, Taiwan, using an equivalent linear analysis code SHAKE and a nonlinear finite element program SPECTRA. Both these softwares presented surface response well in range. This study highlighted the importance of understanding the ground response to earthquakes, and using different methods of analysis. Deoda and Adhikary (2020), Deoda and Adhikary (2022) used both equivalent linear and nonlinear ground response analysis options of DEEPSOIL software (Hashash et al., 2020) for the development of site classification and amplification factors which may be used for the revision of the site amplification provisions of the IS: 1893 (Part 1) - 2016.

With the advancements in computation technology several researchers have performed 1D and 2D GRA using finite element softwares which are capable to model nonlinear behaviour of soil and analyze complex stratigraphy of the soil deposits. Aki and Larner (1970) developed an empirical relation which proved to be a valuable tool for estimating the fundamental frequency of soil deposits spread in varying geological characteristics. Bard and Bouchon (1985) and Kumar and Narayan (2018) demonstrated the importance of studying the fundamental frequency of soil deposits to better understand their behaviour during earthquakes using both 1D and 2D GRA. They concluded that the 2D frequencies and amplification values differ significantly from their 1D counterparts. Further, the work by Kumar and Narayan (2018) showed that the same relation could be improved through regression analysis, taking into account the shape of the subsoil basin. These studies highlight the importance of considering both the depth-to-width ratio of the subsoil basin and its shape when estimating the fundamental frequency of soil deposits. Free-field boundary conditions were used in the GRA analysis following the guidelines of Volpini et al. (2021) where they compared different boundary conditions of 1D and 2D models prepared in finite-element software ABAQUS and finite-difference program FLAC3D and recommended free-field boundary for 2D analyses over tied boundary for efficient results. They also compared these GRA results with 1D Site Response Analysis software STRATA by adopting different boundary conditions, mesh element sizes and damping of the system.

Visone et al. (2010) performed time domain dynamic analysis of viscoelastic soil layers subjected to seismic loading using the finite element program-Plaxis2D. The study included a comparison of the response outcomes of the Plaxis2D analysis with the EERA code. The research examined the key parameters affecting seismic reaction of these layers through numerical modelling. The study provided a method to reduce undesirable effects in order to solve potential inaccuracies related to numerical modelling. A method for calibrating the Rayleigh damping coefficients and the ideal position for the lateral boundaries in dynamic finite element analysis was described in the study. It was concluded that the suggested method improved the dependability of dynamic finite element analyses. This improvement proved particularly noteworthy when working with codes which demand the determination of Rayleigh damping parameters and requires viscous absorbent boundaries. Amorosi et al. (2010) used PLAXIS2D (Bentley Systems, 2014) to conduct GRA of a cohesive deposit using linear cum viscoelastic and visco-elasto-plastic constitutive soil models. They performed their parametric study by altering the Rayleigh damping and boundary conditions. Discrete solver EERA was used to perform 1D equivalent-linear, frequency domain analyses on three soil profiles with four earthquake transient motions. Later, these PLAXIS2D results were compared with the ones obtained using EERA by altering the simulation parameters. Finally concluded that, by following the traditional approach to calibrate the damping coefficients may lead towards the overestimation the response. Bolisetti et al. (2014) conducted equivalent linear and nonlinear site response analyses using various numerical platforms, i.e. LS-DYNA, DEEPSOIL, SHAKE, etc. and have examined the differences between the responses obtained from different programs to determine which model was the most accurate. Karatzetzou et al. (2014) performed a similar study and compared the elastic and non-linear response of two soil profiles using various numerical simulation codes, i.e. LS-DYNA, DEEPSOIL, OPENSEES and ABAQUS with their appropriate, available soil and constitutive models. One profile was a 20 meter deep single-layer soil deposit with a constant shear wave velocity, while the other was a 100 meter deep soil profile with a parabolic shear wave velocity distribution. Both profiles were subjected to several different motions. Results were expressed in the form of acceleration time histories, shear stresses, and strains, and have compared the elastic and non-linear responses obtained from the four codes. These studies concluded that these codes produces identical results for low intensity ground motions and lesser frequencies. However, the results differ from one other when shear strain or applied frequency exceeds the limits followed in engineering practice. Kaklamanos et al. (2015) used 191 ground motions observed at six locations and utilized the equivalent-linear site response program SHAKE, the nonlinear discrete site response program DEEPSOIL, and finite element program ABAQUS for nonlinear analysis. These six locations cover a variety of geological conditions and were chosen because they were suitable for validating and calibrating 1D nonlinear soil models. Providing an insight into choosing the suitable program for the best results was the objective of their study. Compared to linear analysis, the equivalent linear and nonlinear analysis gave better results depicting equivalent linear and nonlinear analysis model predicts surface motion accurately. Bordoni et al. (2023) has conducted site-specific seismic response studies for near-fault regions based on different scenario-based approaches for the same site. They have emphasized on adopting the scenario-based spectrum-compatible accelerograms for seismic response studies. The study was performed using FLAC3D finite difference analysis software, and validated with the LSR2D code. Researchers concluded that the shear strain developed in the soil column above 0.1% is inadequate to be performed in SHAKE. Non-linear DEEPSOIL or LS-DYNA were to be favoured above the said limit of shear strain (O'Riordan et al., 2018). They concluded that since real earthquakes do not produce a 1D wave field, robust validation of these programs is required in large-scale trials.

In the present study, 1D GRA is conducted using both discrete and continuum approaches. In the DEEPSOIL software the equivalent linear frequency domain analysis is carried out for this purpose, while in the commercially available finite element software ABAQUS (Dassault Systemes, 2017) the soil column is modeled using 2D plane strain elements along with proper boundary conditions. The comparison of results between the two approaches is crucial to determine the accuracy of the equivalent linear GRA method. The comparison is made, keeping the spectral ratio as the judgement parameter, which gives the ratio of the spectra of the surface response to the spectra of the applied motion. The response spectra gives an idea of the spectral acceleration at different frequencies and how the soil behaves under dynamic loads, while the amplification curve shows the relationship between the response of the soil and the ground motion. This study is in continuation with the author's previous research work (Sharma and Adhikary, 2023).

2 SITES CONSIDERED FOR THIS STUDY

The objective of the study is to analyse the ground response at a few chosen places in India. For this purpose, the well-documented Indian locations found in literature were chosen. The ports of Hazira, Kandla, and Mundra are all in Gujarat, while Site 1, 2, and 4 are all in Dehradun, Uttarakhand. On the other hand, Silchar soil site is situated in the Indian state of Assam, and BH-1 Park Street, BH-3 Rajarhat, and BH-7 Panditya Road are all in Kolkata, West Bengal. Depending on the site information and experimental data available the selected sites were first classified as per the existing provisions of the Indian Standard (IS 1893 (Part-1), 2016) and the recent provisions of site classification scheme developed by Deoda and Adhikary (2022) as shown in Table 1. A particular site named "Kandla" is briefly explained with its layer-wise material properties and the details are provided in Table 2.

Damage observed in Bhuj earthquake has given an insight to various weak prospects in the field of geotechnical engineering. Sitharam and Govindaraju (2004) has examined and evaluated the aftermath on site and the report were prepared for the faulty designs and inadequate soil strength and was submitted to the authorities. Site exploration study was conducted in the banks of river Brahmaputra (Dammala and Krishna, 2022) in order to derive the site specific soil properties. Three sites were investigated in Assam, India with varying stratification. It was found that loose or soft soil deposits in the region are prone to amplifying incoming seismic waves. Exploration of a proposed bridge site over Barak River along Silchar Bypass Road (Sil and Haloi, 2018) was conducted to observe the local site effects of underlying soil. The shear wave velocity profiles were estimated using the SPT-N value, and the sites considered were classified as per the state provisions.

Table 1 Soil Profiles and Classification followed in the study (Sharma and Adhikary, 2023).

Author(s)	Site	Depth of Profile (m)	Avg. Shear Wave Velocity, $V_{s,avg}$ (m/s)	Fundamental Period (s)	Site Class as per IS 1893:2016	Site Class as per (Deoda and Adhikary, 2020)
(Ranjan, 2004)	Site 1	31.7	406.97	0.31	I	B
	Site 2	29.96	334.65	0.36	I	B
	Site 4	31.94	318.69	0.4	I	B
(Shukla and Choudhury, 2012)	Hazira	30	234.32	0.51	II	C
	Kandla	32	236.45	0.45	II	C
	Mundra	30	237.26	0.42	II	C
(Chatterjee and Choudhury, 2018)	BH-1 Park Street	31	258.54	0.48	III	D
	BH-3 Rajarhat	40.5	228.00	0.71	III	D
	BH-7 Panditya Road	40	210.53	0.76	III	D
(Sanjay Paul and Ashim Kanti Dey, 2008)	Silchar	75	239.06	1.25	III	D

Table 2 Soil Properties for "Kandla" soil profile.

Site- Kandla	Thickness of Layer (m)	Density, ρ (kg/m3)	Shear Wave Velocity, Vs (m/s)	Modulus of Elasticity, E (MPa)	Poisson's Ratio, μ	Cohesion, C (kPa)	Friction Angle, ϕ (deg)	Shear Strength S (kPa)
Layer 1	17	1529	200	118.5	0.3	0.174	25.7	61.5
Layer 2	3	1529	250	214.0	0.3	0.046	20.8	105.4
Layer 3	4	1835	300	144.6	0.3	0.188	18.4	111.9
Layer 4	8	1733	320	191.1	0.3	0.358	15.1	118.3

3 SELECTION OF GROUND MOTIONS

Selecting appropriate ground motions is a crucial aspect when conducting GRA for any site. Regarding the effect of type of earthquake, several literatures viz. (Katsanos et al., 2010) discussed the method of selection of time histories to study seismic response of structures. However, (Adhikary et al., 2014) demonstrated that the use of different types of earthquake records (i.e. recorded and spectrum compatible ground motions) may change the response spectra pattern of any soil site but doesn't affect the amplification factor of it. Therefore, in the present study spectrum compatible earthquake motions are used. For the highest seismic zone, 0.36g (Zone V), SeismoMatch software (SeismoSOFT ltd., 2022) was used to make ten naturally occurring ground motions compatible with Type-I spectra of IS: 1893 (part-1) 2016 for this investigation. These earthquake motion recordings were selected from the COSMOS-Virtual Data Center and PEER database. In order to match a target response spectrum, SeismoMatch adjusts earthquake accelerograms using the wavelets algorithm developed by Al Atik and Abrahamson (2010) and Hancock et al. (2006). It can match multiple accelerograms simultaneously and combine them to provide a mean spectrum that complies with user-specified misfit criteria. The specifics of these ground motions are given in Table 3, and Figure 1 illustrates their spectral compatibility with Type-1 spectra of IS: 1893 (part-1) 2016 for 0.36g.

Table 3 Strong Ground Motions considered in the study (Sharma and Adhikary, 2023).

Earthquake Parameters					
Earthquake	Recording Station	Year of Occurrence	Magnitude	Distance from Source (km.)	Duration of Earthquake (s)
India-Burma Border	Umsning	1988	6.1	343.8	70.52
India-Burma Border	Umsning, India	1997	5.6	106.8	27.28
NE India	Pynursla	1986	4.5	48.2	18.52
Loma Prieta	Gilroy Array #1	1989	6.93	8.84	79.89
Landers	Lucerne	1992	7.28	2.19	96.16
Kobe, Japan	Kobe University	1995	6.9	0.9	31.96
India-Bangladesh Border	Nongkhlaw	1988	5.8	117.3	45.2
Uttarkashi	Uttarkashi	1991	7	34	39.84
El Mayor-Cucapah, Mexico	Blythe	2010	7.2	164.38	120.01
San Simeon, CA	Diablo Canyon Power Plant	2003	6.52	37.92	29.43

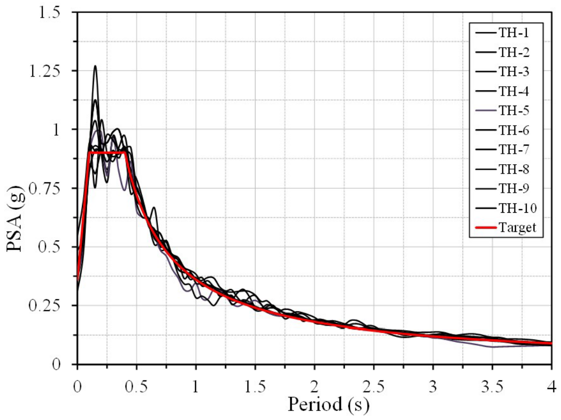


Figure 1 Response Spectra of all selected ground motions compatible with Type-1 Spectra as per IS: 1893-2016.

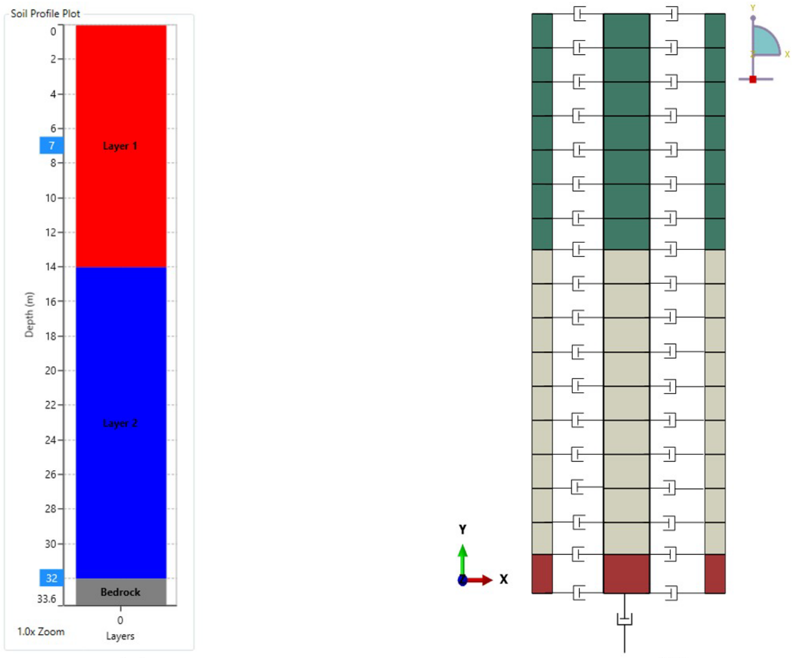
4 GROUND RESPONSE ANALYSIS

Before beginning any construction, various soil tests for structural integrity and soundness are performed on the proposed site. One such necessary test is to determine the shear wave velocity of the surrounding soil profile underneath the surface. This test can be performed on the field using surface equipments, analytical procedures, or some programs that solve some consecutive analytical equations. Field or analytical methods are generally suited if the soil is uniform in the vertical direction, and software programs are used when the soil has a varied profile along the depth.

Ground response analysis is a type of study that aims to predict the response of soil layers to an applied excitation. The analysis typically involves creating a numerical model of the soil layers and using this model to simulate the motion of the soil during the excitation. Liu et al. (2021) have performed a detailed study involving the use of response surface method in GRA. The goal of their study was to understand the effects of soil-structure interaction on the response of the structure, including factors such as soil deformations and vibrations. This information can be used to evaluate the seismic safety of structures, to design and to develop mitigation strategies, to reduce the potential damage during an earthquake or other seismic event.

Various open-source programs are available based on different algorithms that perform GRA study viz. SHAKE, SPECTRA and DEEPSOIL. These programs carry out GRA in a 1-dimensional framework using the strength parameters and strain-dependent characteristics of soil, such as the damping ratio curve and shear modulus reduction curve. Similar methodology has been applied to numerous design projects employing the 1D GRA. Among other engineering outcomes, GRA is used to obtain site's natural period, develop spectra for the location, examine ground amplification, and gauge the likelihood of liquefaction. 1D equivalent-linear, visco-elastic, frequency-domain analyses can be performed in DEEPSOIL. This analysis procedure uses the shear wave velocity profile along the depth, the modulus reduction curve that shows how shear modulus ***(G)*** varies with shear strain ***(ε)***, and the damping ratio curve that shows how damping ***(ξ)*** varies with shear strain.

In this study, one dimensional equivalent linear analysis (1D-EQL) is carried out in the FEM model prepared for one dimensional analysis in ABAQUS and the outcomes from the continuum analysis are then compared with discrete software DEEPSOIL. GRA can be performed in one, two, or three dimensions using either a linear, equivalent linear, or nonlinear technique. For the induced level of extremely small shear strain in each layer, the linear technique requires constant soil parameters of ***G*** and ***ξ***, whereas the nonlinear technique uses cyclic stress-strain models utilizing damping ratio curve and modulus reduction curve to represent the irregularity in the material characteristics. To obtain values for consecutive ***G*** and ***ξ*** that are compatible with the actual shear strains in each layer, the equivalent-linear technique determines soil response through an iterative process for shear modulus, and damping with respect to cyclic shear strain. In this article 1D-EQL analysis is performed in DEEPSOIL using discrete approach and in ABAQUS using continuum approach. The respective numerical models are shown in Figure 2.



(a) *(b)*

Figure 2 Numerical model of a typical soil profile prepared in (a) DEEPSOIL and (b) ABAQUS.

4.1 1D Equivalent Linear using DEEPSOIL

DEEPSOIL is primarily a 1-dimensional tool used to perform ground response analysis either as frequency-dependent 1D equivalent-liner analysis or as time-dependent 1D nonlinear analysis. DEEPSOIL requires the soil profile data, which describes the properties of the soil layers at the site, and the seismic input data, which describes the characteristics of the earthquake ground motions. The software utilizes the Kelvin-Voigt model, which is represented as an assembly prepared by a viscous spring and a viscous damper, thus providing the property of elasticity and viscosity. DEEPSOIL solves the equations of motion for each soil layer, taking into account the characteristics of the soil profile and the seismic input data. The output from the analysis includes ground motion response spectra, response time histories of ground motion, and soil characteristics (e.g. shear strain levels). Successive iterations of plastic strain gives the exact solution of the wave equations representing the vertical propagation of shear-horizontal waves. Bolisetti et al. (2014) and Karatzetzou et al. (2014) have also performed such studies using several but different codes, including DEEPSOIL and have compared the results for the performance of codes.

Performing GRA in DEESPSOIL is simple, starts with the selection of the method of integration, generation of soil profile, application of the selected ground motion and selection of all the required output variables. The thickness of the soil profile along with all the soil properties like density, shear wave velocity, damping ratio and dynamic soil properties of individual layers completes the soil column modelling. DEEPSOIL offers a variety of integration methods to choose from; all work differently and has to be selected with caution (Hashash et al., 2020). After applying the input ground motion(s), the responses of each layers are displayed. The results tab includes the response time history of each layer, their response spectra, fourier amplitude, and amplification factor.

Ten selected number of soil columns were prepared in DEEPSOIL software with the given material properties and selecting the appropriate damping ratio and modulus reduction curves for equivalent analysis. 5% material damping is considered for the analysis. The ten recorded ground motions were applied to the bottom of the soil column and the response is observed at the surface of all the layers of the soil column. Hence, a total of 100 analyses were carried out using DEEPSOIL. The peak ground acceleration, strain and displacement is determined from the responses and the respective plots are prepared.

4.2 Numerical Simulation using ABAQUS

ABAQUS software has been employed with the aim of continuum modelling of a 1D soil profile. Utilizing the strain observed during the 1D DEEPSOIL analysis, the dynamic soil parameters, such as the modulus reduction and damping ratio curves, were appropriately used for each soil layer. Nautiyal et al. (2021) followed the same approach for their study, using ABAQUS software and have prepared and analyzed two soil models. They have compared the 1D, 2D and 3D analysis approach utilizing the soil characteristics and shear wave velocity profile down the depth of two sites using ABAQUS, and their results were found to be in perfect agreement with the field experiments.

In this study, the model prepared for the 1D analysis in ABAQUS is a slender column of a predefined depth and one and a half meter thick, with 4-noded plane strain elements (CPE4R) connected with dashpots with 1 degree of freedom on either direction of the node (along X and Y axes) originally proposed by Lysmer and Kuhlemeyer (1969) with the dashpot coefficients (Tidke & Adhikary, 2021) calculated using equations (1) and (2), and dependent upon the material properties of the entire soil profile. These dashpots are used as an artificial boundary on either side of the horizontal section to dissipate the enormous amount of energy produced in soil due to earthquake motion. Such arrangement is known as viscous boundary as it helps in the fluent passage of earthquake waves from the soil and prevents reflecting inside the model.

$$C_n = A_1 \, \rho \, c_p \qquad \text{eq. (1)}$$

$$C_t = A_2 \, \rho \, c_s \qquad \text{eq. (2)}$$

where, $\boldsymbol{C_n}$ and $\boldsymbol{C_t}$ are the normal and tangential direction dashpot coefficients, $\boldsymbol{\rho}$ is the mass density of the soil, $\boldsymbol{c_s}$ and $\boldsymbol{c_p}$ are the shear wave and compressional wave velocity which can be determined using equation (3) and (4), and $\boldsymbol{A_1}$ and $\boldsymbol{A_2}$ are the cross sectional area of the bar which can be determined using equation (5) and (6).

$$c_s = \sqrt{\frac{G}{\rho}} \qquad \text{eq. (3)}$$

$$c_p = \sqrt{\frac{E(1-\mu)}{(1+\mu)(1-2\mu)\rho}} \qquad \text{eq. (4)}$$

where, $\boldsymbol{G}$, $\boldsymbol{E}$ and $\boldsymbol{\mu}$ are the shear modulus, elastic modulus and poisson's ratio respectively.

$$A_1 = \frac{8\pi}{15}(5 + 2S - 2S^2) \qquad \text{eq. (5)}$$

$$A_2 = \frac{8\pi}{15}(3 + 2S) \qquad \text{eq. (6)}$$

where,

$$S = \sqrt{\frac{(1-2\mu)}{(1+\mu)}} \qquad \text{eq. (7)}$$

Mohr-Coulomb failure criteria for soil was chosen to model these profiles as this was well suited to describe the behaviour of soils under stress (Shamsabadi et al., 2007), (Zhan et al., 2012). The model assumes that the shear strength of soil is dependent on the normal stress acting on the plane of failure and the frictional resistance of the material. The study was performed without considering the groundwater table in the soil profile, as this model doesn't account for the effect of pore water pressure on the shear strength of the soil. The model incorporates all the material and dynamic properties and is very much suitable for such studies (Nautiyal et al., 2021). Fixed values of the dynamic properties can be calculated based on the observed shear strain in the soil layer to perform an equivalent-linear analysis. Dynamic properties include shear modulus reduction curve and damping ratio curve, which can be generated with popular reference curves developed by Darendeli (2001) or Seed and Idriss (1970) (for sands and clays) and (Vucetic and Dobry (1991) for clays (Kwok et al., 2007, 2008; Phanikanth et al., 2011). The modulus reduction and damping ratio curves obtained for one particular site to include plasticity and overburden pressure in soil are shown in Figure 3.

Structural damping is the most important parameter in the numerical modelling of dynamic analysis with the structures. Our soil profile itself is a structure of a kind with distinct material properties. Damping restricts the unwanted noise generated in the structure by providing a resistance for itself. Rayleigh damping is used in the numerical modelling of all the soil profiles, which takes structural damping into account in terms of mass and stiffness proportional coefficients, i.e. α and β corresponding to the first and second modal natural frequencies of the soil profile and is determined for each layer of all the profiles using equations (8) and (9).

$$\alpha = \xi \frac{2\,\omega_i\,\omega_j}{\omega_i + \omega_j} \qquad \text{eq. (8)}$$

$$\beta = \xi \frac{2}{\omega_i + \omega_j} \qquad \text{eq. (9)}$$

where $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are the mass proportional and stiffness proportional damping coefficients, respectively, ξ is the damping ratio (5% damping ratio is considered), $\boldsymbol{\omega_i}$ and $\boldsymbol{\omega_j}$ are the first and second natural modal frequencies of the system.

As the soil column is prepared and the sections are assigned to the respective layers, the analysis can be started by applying the ground motion at the base of the model keeping the vertical sides attached to the dashpots and rollers at the bottom. The response at the surface of every layer will then be recorded, and the required plots will be prepared for comparison. This procedure is repeated with every selected soil profile and ground motion.

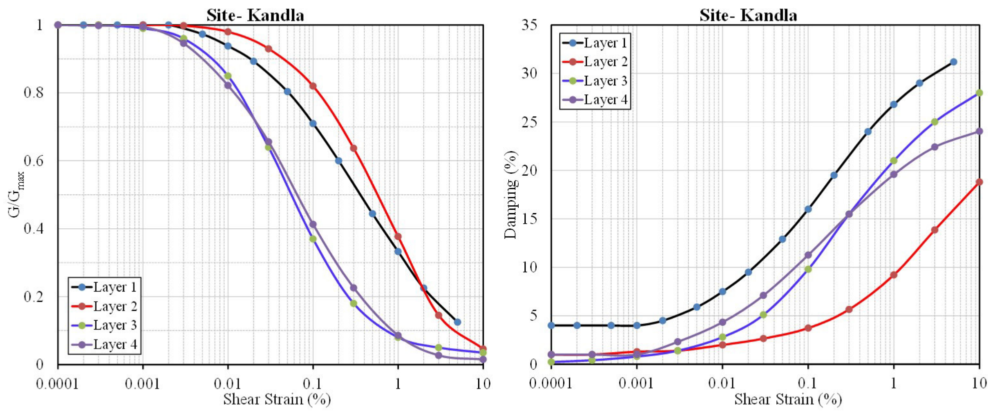


Figure 3 Shear Modulus Reduction Curve and Damping Ratio Curve obtained for Kandla site (Shukla and Choudhury, 2012).

4.3 Validation Study, Sensitivity Analysis and Free Vibration Analysis

Before performing numerical analysis on a large scale with various models and large inputs, a validation study is performed to check the prepared model for discrepancies. Validation of a numerical model involves comparing the model's predictions with experimental data or other researchers' work to assess the accuracy of the model. This process is essential to ensure that the model is reliable and can be used to make further predictions confidently. The model is considered valid if it can accurately reproduce the trends and patterns observed in the data and predict future outcomes with acceptable levels of accuracy. The validation process includes the sensitivity analysis with the model being refined and re-validated until the desired level of accuracy is achieved. Sensitivity analysis is performed to understand the effect of changes in input parameters or assumptions on the output of a model or analysis. This helps identify which input parameters or assumptions impact the model output most and which are least important. By performing sensitivity analysis, the robustness and reliability of the model can be improved, uncertainty can be reduced, and understanding of the implications of the model results can be made better.

Two sites were selected for the validation study. The first site was the Mumbai port of Maharashtra which was studied in detail by Desai and Choudhury (2015) using SHAKE2000 and further re-researched by Deoda and Adhikary (2020). The second site was in Silchar, Assam (India) which was studied in detail by Sanjay Paul and Ashim Kanti Dey (2008) and studied further by Deoda and Adhikary (2020). GRA of the Mumbai port site was conducted by utilizing the time history record of the 2001 Bhuj earthquake, which was made compatible with the Uniform Hazard Spectra (UHS) for Operating Level Earthquake (OLE). The Assam site was subjected to the 1997 North-East India earthquake time history. These two sites were modeled in DEEPSOIL using the discrete approach and in ABAQUS using the continuum approach. The response of each site was recorded and the ratio of the fourier amplitude of the output motion to the fourier amplitude of the input motion was defined as the Amplification Factor (Deoda and Adhikary, 2020). Figure 4 shows the results in terms of amplification factor as obtained by Desai and Choudhury, Deoda and Adhikary and the present study. It is clearly observed that the present study using DEEPSOIL is a perfect match to the already published details of the site. Moreover, as expected the continuum modeling in ABAQUS for the Mumbai port site leads to less response, nevertheless, the peak is observed at the fundamental period of the soil site.

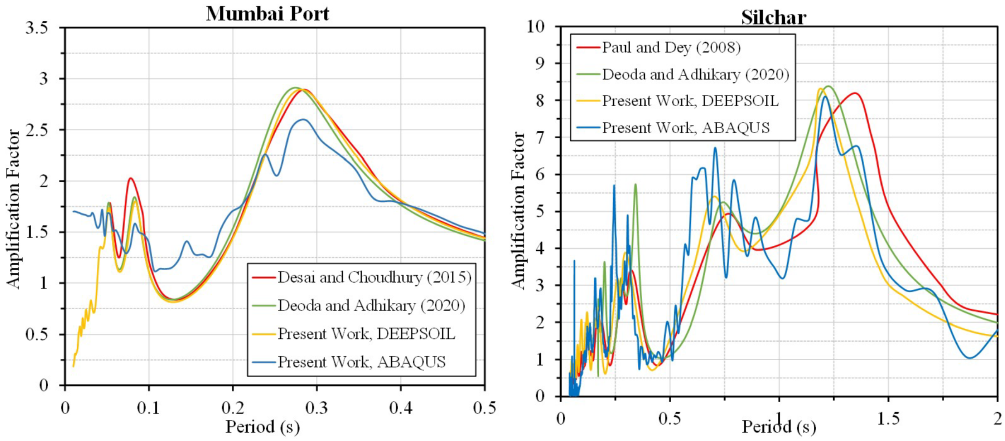


Figure 4 Amplification Factor curves obtained for (a) Mumbai Port (Desai and Choudhury, 2015) and (b) Silchar site (Sanjay Paul and Ashim Kanti Dey, 2008) in the validation study.

Sensitivity analysis was performed to determine the maximum size of the 4-noded element which should be used to prepare the soil column. The other way to determine the size of the element, is to use the following well-known equation given as,

$$h_{max} = \frac{V_s}{10 \times f_{max}} \qquad \text{eq. (10)}$$

where, $\boldsymbol{V_s}$ is the shear wave velocity, 10 is the consideration of the maximum number of elements in the model (layer in this case), and $\boldsymbol{f_{max}}$ is the maximum frequency of concern allowed to pass through the soil, generally considered 10 Hz. One can choose any method, but a random size should not be selected, and uniformity should be maintained (Bolisetti et al., 2014; Bordoni et al., 2023; Dassault Systemes, 2017; Volpini et al., 2021).

Several arbitrary element sizes were selected for sensitivity analysis, starting from 2.5 meters to 0.5 meters with an interval of 0.5 meters, to determine the largest element size that can be used for the numerical simulation in ABAQUS. With all these models, with different element sizes and a particular soil profile, ground response analysis was performed, and the Peak Ground Acceleration (PGA) of the response at each layer was recorded and plotted. Figure 5 shows the result as PGA(g)-depth profile of the selected site with the earthquake motion applied at the bottom with different element sizes, thus generating this plot. As it can be observed from the figure, on reducing the size further more than 1 meter, the curves converge over one-another, suggesting that further decrease in element size may not be necessary. This concludes that the maximum size should be at most 1 meter to get exact results in numerical modelling. Thus one-meter element size was selected for the numerical simulation in ABAQUS.

Free vibration analysis was performed for the numerical model developed in ABAQUS to obtain all the natural vibration modes and frequencies of the soil column. The deformed shape of the soil profile in the first fundamental mode of vibration is shown in Figure 6. DEEPSOIL uses simple analytical equation (refer equation 11) to determine the natural frequency of soil column using the depth of the profile and shear wave velocity as governing parameters and provides only the first mode of vibration frequency. Natural frequencies from both the softwares are in very good agreement with each other as they employ the material properties of the individual soil profiles, which were eventually the same in both the softwares. Natural frequencies of all the ten sites are tabulated in table 4.

$f_o = \frac{V_s}{4H}$eq. (11)

where, $\boldsymbol{V_s}$ is the shear wave velocity through the soil and $\boldsymbol{H}$ is the height/depth of the soil column.

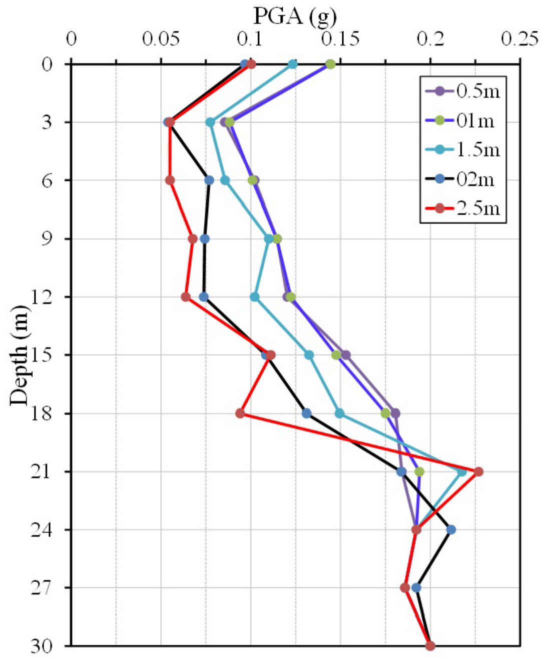


Figure 5 PGA(g)-depth profile obtained in the Validation study using ABAQUS software.

Table 4 Results of Free Vibration Analysis performed in DEEPSOIL and ABAQUS software.

Sites	DEEPSOIL		ABAQUS	
	Frequency (Hz)	Period (s)	Frequency (Hz)	Period (s)
Site 1	3.21	0.31	3.14	0.32
Site 2	2.8	0.36	2.57	0.39
Site 4	2.5	0.4	2.23	0.45
Hazira	1.95	0.51	1.87	0.53
Kandla	1.85	0.54	1.76	0.57
Mundra	1.98	0.50	1.87	0.53
BH-1 Park Street	2.08	0.48	1.92	0.52
BH-3 Rajarhat	1.41	0.71	1.34	0.75
BH-7 Panditya Road	1.31	0.76	1.24	0.81
Silchar	0.8	1.25	0.73	1.37

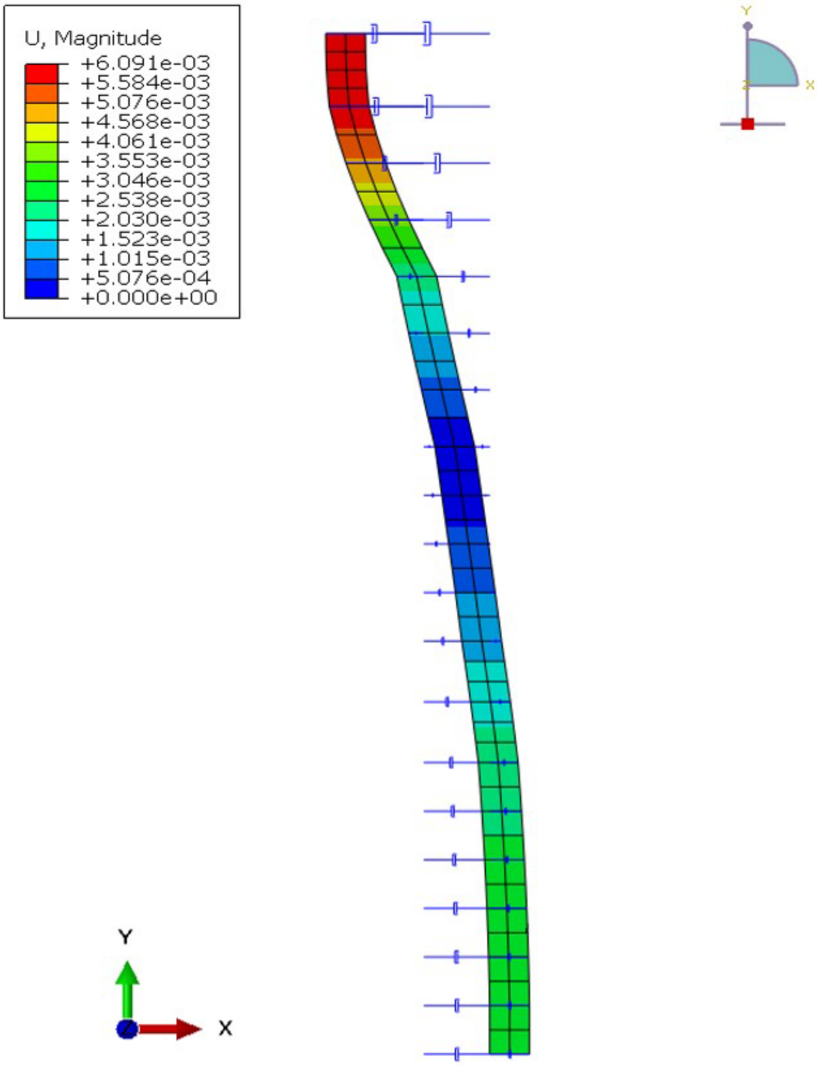


Figure 6 Deformed shape of soil profile in the fundamental mode obtained using ABAQUS software.

5 RESULTS IN TERMS OF RESPONSE SPECTRA AND AMPLIFICATION FACTOR

Results include a comparison between the shear strain in the layers, displacement, PGA(g)-depth profile and the spectral ratio plots for all the considered sites with different earthquake motions. Spectral ratio is the ratio of spectral acceleration at the surface of the soil site to the input spectral acceleration at the rock outcrop. Each soil profile being studied has time histories of ground motion applied at the bottom, and the reaction time history at the soil layer's surface is observed. GRA is the process of applying seismic motion at the base to observe how the soil layer on the surface responds. For the 1D case model in ABAQUS, the analysis was performed a hundred times using ten carefully chosen earthquake motions at ten predetermined sites. The outcomes of these hundred analyses were compared with those of the 100 comparable analyses carried out using the DEEPSOIL software.

The results are plotted considering the mean response of all the ten earthquake motions recorded at the surface of all the layers of the ten sites in DEEPSOIL and ABAQUS software. Figure 7(a) shows the results obtained for the PGA-depth profile curve of a particular soil profile after conducting ground response analysis. All ten strong ground motions were applied at the profile one after another, and the response was recorded at the surface of each layer and PGA of each response was determined and plotted for each layer with depths as shown in figure. The results in this entire study is presented as an average curve of the response of all the ten earthquake motions as one, hence an average line is plotted with all the curves. Similarly, a comparison among the softwares is also presented in Figure 7(b) for the strain, Figure 7(c) for the displacement and Figure 7(d) for the time history observed at the top surface with both the softwares for the same site and TH-5 earthquake ground motion which was the closest match with the obtained average record.

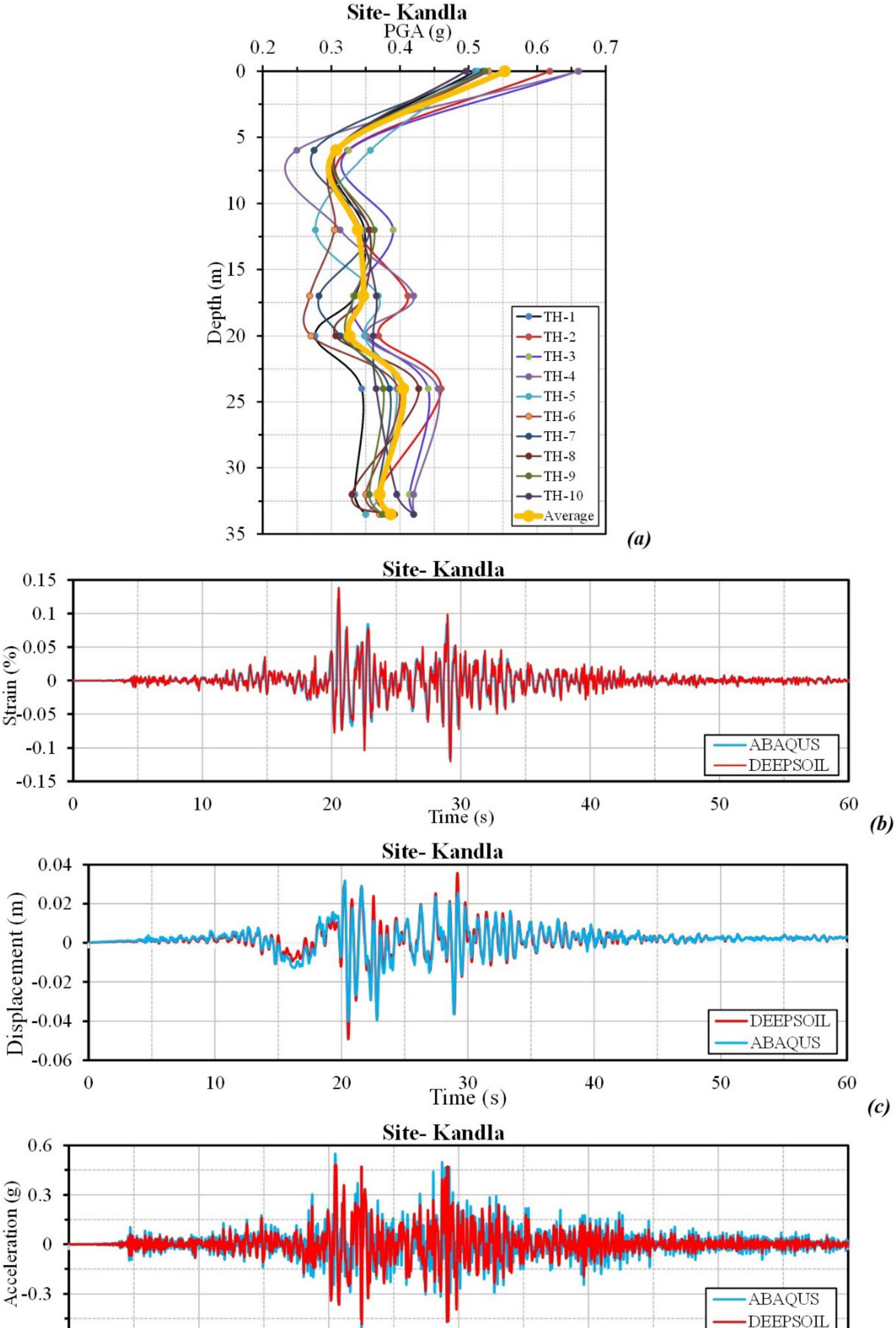


Figure 7 (a) PGA profile with all ten ground motions in ABAQUS; Comparison of **(b)** Strain observed at the top layer **(c)** Displacement observed at the surface of the top layer **(d)** Acceleration time history observed at the surface of top layer.

DEEPSOIL software gives change in shear strain (%), the maximum displacement (m) and the PGA(g)-depth profile at the end of the ground response analysis. Similar results are plotted with ABAQUS software at the same points for all the soil profiles and are shown next to those obtained using DEEPSOIL software. Since DEEPSOIL gives the shear strain at the center of the individual layers, the curve is not extending till the very depth of the profile. However, it was possible in the finite element tool ABAQUS to determine the same at any node. But, determining the strain in the last layer (rock layer) makes no sense. Hence, in the case of ABAQUS, the results are only extended to the center of the last soil layer. As you can see in Figure 8, the strain obtained with DEEPSOIL software match very well with those obtained from ABAQUS software. However, there are a few sites where some variation in the results can be noted. The maximum value of shear strain (%) achieved is 0.86% in the case of Park Street site and Silchar site. These higher values of the strain are due to the poor properties of the soil layer, as they fall in the soil class D category. With this array of soil profiles, it can broadly be said that the soils that belongs to lower site classes have higher values of shear strain. Uniformity in the shear strain results can be seen in the profiles that belong to site classes B and C, and discripancy in the results is observed in the profiles that belong to site class D. In all these soil profiles, the results from DEEPSOIL software is giving slightly more values in most cases, but the results match from both the softwares, which is of utmost importance for a comparative study.

Figure 9 shows the results of maximum displacements at the surface of each layer of the soil profile obtained using DEEPSOIL software. These displacement values are the maximum displacements achieved anytime throughout the ground excitation. Hence, these curves should not be misunderstood as the maximum displacement of the entire profile at any time of the ground excitation. Similar displacement plots has been obtained uisng finite element software ABAQUS at the same depths and at the bottommost depth too. As it can be seen in Figure 9, the maximum displacement obtained using DEEPSOIL software match those obtained using ABAQUS software very well. The maximum displacement is observed to be 0.13 meters for the Silchar site which is maximum among all the selected sites. This huge displacement must be possible due to its deep profile with poor soil properties.

Acceleration response time history is obtained for each layer at the surface of the each soil profile and the peak ground acceleration of the response is determined for all the obtained responses. Figure 10 shows the peak acceleration value of the response and plotted against the depth of the soil profile obtained using DEEPSOIL and ABAQUS software. These PGA-depth profiles are starting from different depths as per the soil profile, but the response PGA at the bottom layer is same (~0.4g), as is the mean value of all the input ground motions. Depending upon the characteristics of the profile, the PGA is either increasing or decreasing towards the surface of the soil profile. As Figure 10 indicates, the results from ABAQUS software is in perfect agreement with the results of 1D analysis obtained using DEEPSOIL software and are matching with insignificant variation in their PGA values. Hence, this can be said with certainty that, the continuum approach ABAQUS software can definitely be used for performing ground response analysis.

To help with the comprehension of the spectrum amplification of soil response, Figure 11 shows the Spectral Ratio of the response observed at the surface of the soil profile. The plot shows the ratio of the response spectra at the surface of the soil to the spectra of the applied input motion. These figures clearly show that, the spectral ratio from DEEPSOIL and ABAQUS software has the same amplitude at the same periods. This is because of the fact that, DEEPSOIL considers the average shear wave velocity, $\boldsymbol{V_{s,avg}}$, and depth of the profile while ABAQUS determines the natural frequency of the soil column by also taking into account the material properties and stiffness. These figures show very good match between the results obtained using DEEPSOIL and ABAQUS software and are identical in nature. Since the natural period of the soil profile obtained using ABAQUS software is slightly larger than DEEPSOIL software, as can be observed from Table 4, the peak of the spectral ratio obtained using ABAQUS software is also higher than that of DEEPSOIL software. And the peak of the spectral ratio curves is achieved at the natural period of the soil profiles (Deoda & Adhikary, 2020).

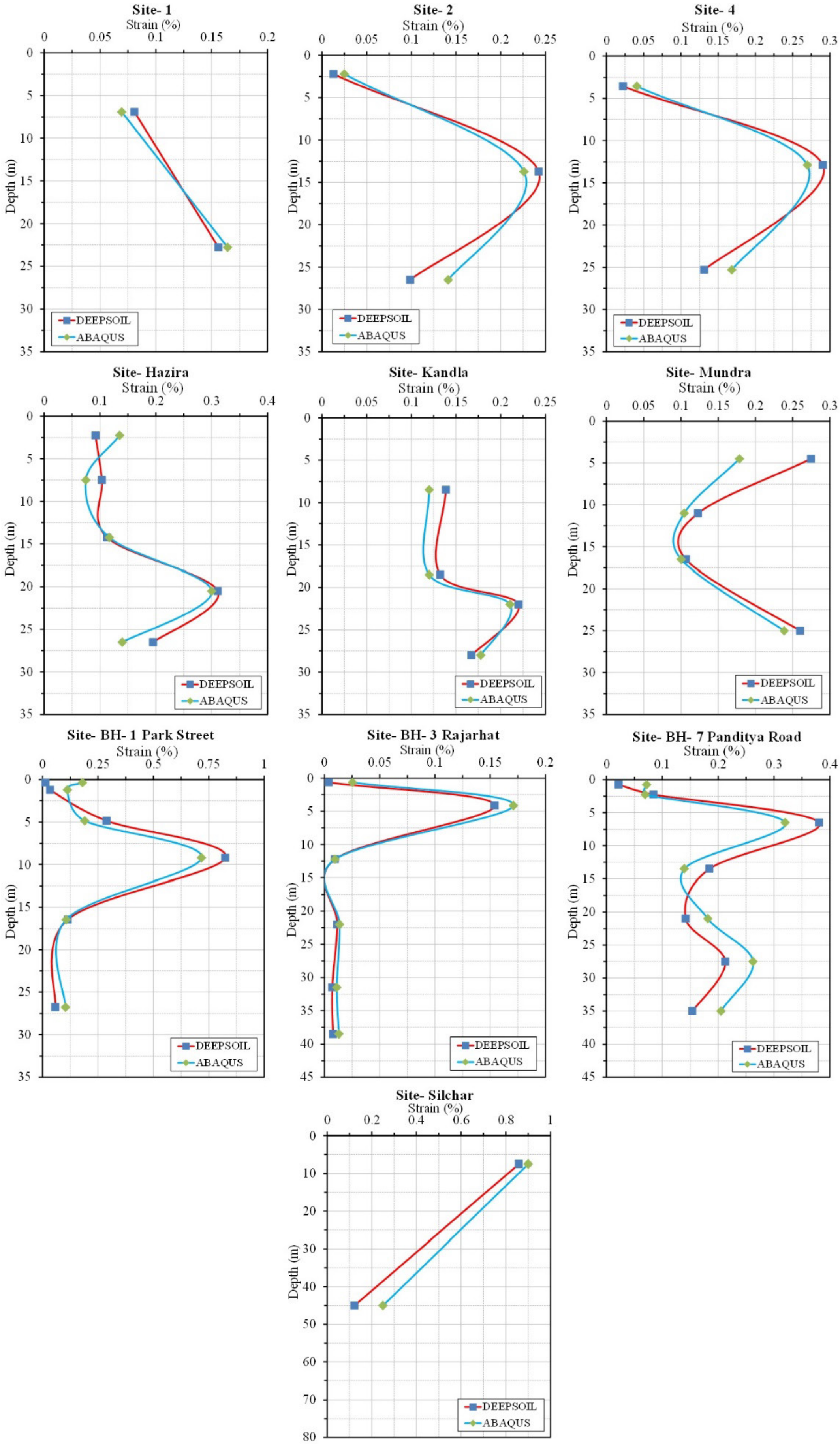


Figure 8 Shear strain profile obtained from the GRA using DEEPSOIL and ABAQUS for all the considered sites.

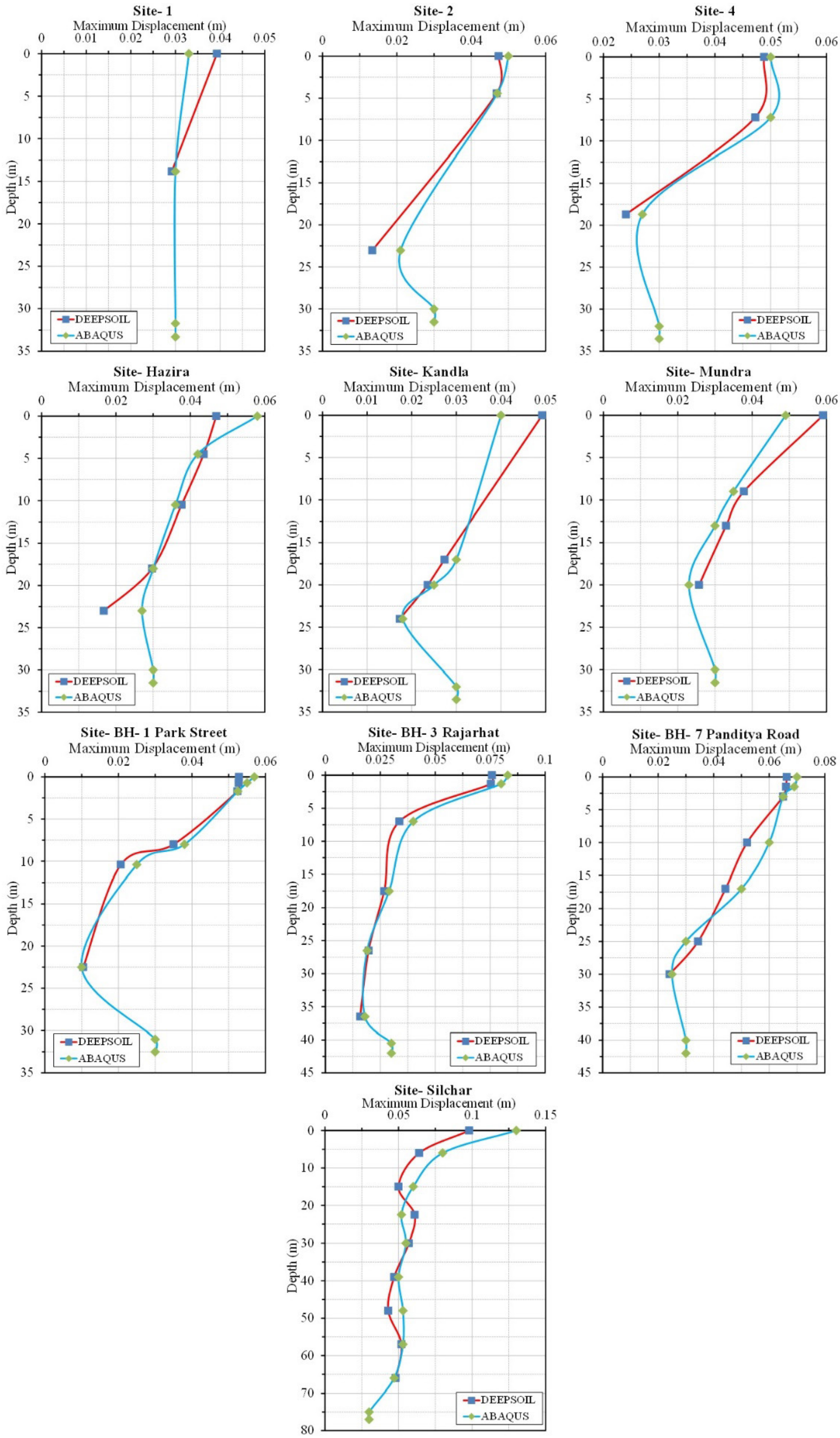


Figure 9 Maximum displacement profile obtained from the GRA using DEEPSOIL and ABAQUS for all the considered sites.

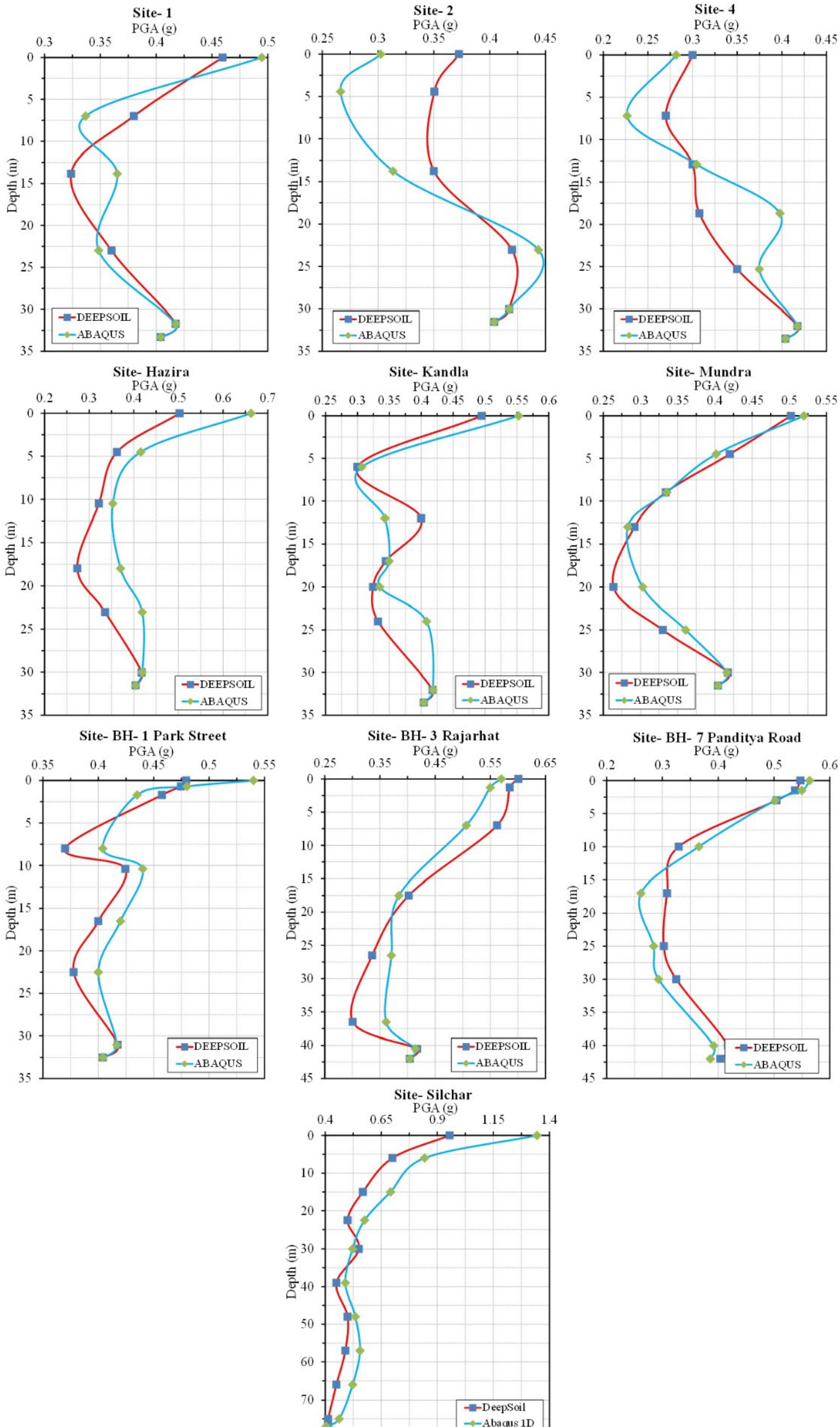


Figure 10 PGA-depth profile obtained from the GRA using DEEPSOIL and ABAQUS for all the considered sites.

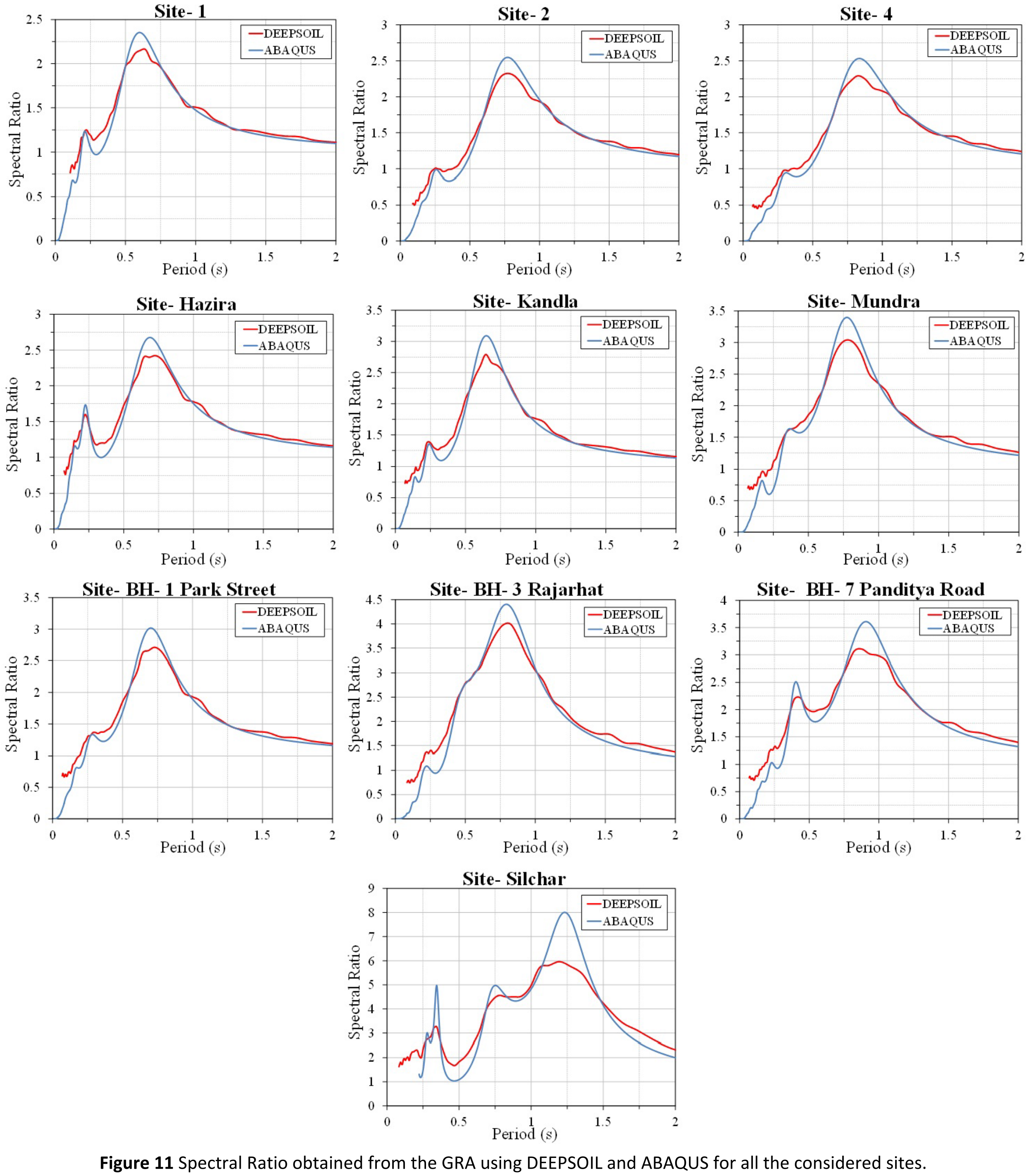


Figure 11 Spectral Ratio obtained from the GRA using DEEPSOIL and ABAQUS for all the considered sites.

6 CONCLUSION

In the existing civil engineering industry 1D GRA is popularly carried out using SHAKE/DEEPSOIL. This gives good result for horizontally layered, infinitely extending soil layers. The present study aims to carry out one dimensional ground response analysis using a continuum approach. For this purpose the commercially available ABAQUS software has been chosen. Hence, an attempt has been made to understand the steps required in numerical modelling of any soil site using ABAQUS for the purpose of GRA. The authors believe this step is important to get the transition from 1D GRA using discrete approach to 2D GRA using continuum approach. This study is carried out in continuation with the author's previous work. The study includes numerical analyses on various actual sites in India using different earthquake motions to determine the response at different depths. For the ground response analysis the open source software DEEPSOIL was used as a discrete approach, and the commercially available software ABAQUS was used as a continuum approach for the analyses. The results from 1D continuum approach are in good agreement with the 1D discrete approach. This suggests that both approaches are capturing the physical behavior accurately with their respective approximations and the inputs. After observing the results, following findings can be stated.

- The results from 1D continuum approach shows excellent agreement with the results from 1D discrete approach at every depth of the profile.
- The spectral ratio with continuum approach is slightly more than the ones with the 1D discrete approach at the natural frequency of the soil profile.

The discrete approach was found to be efficient in capturing GRA for most of the site profiles, however, continuum approach is recommended for spatial variation and heterogeneity in soil profile.

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Editor: Pablo Andrés Muñoz Rojas

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