GROUND RESPONSE ANALYSIS: COMPARISON OF 1D, 2D AND 3D APPROACH

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Abstract. Generally, one-dimensional (1D) wave propagation or ground response analysis (GRA) is preferred to evaluate the effect of local site conditions subjected to an earthquake ground motion [1]. For a site with complex and irregular stratigraphy, two-dimensional (2D) and three-dimensional (3D) ground response is preferred over 1D wave propagation for more realistic evaluation of ground response under seismic load.

In present study, 1D, 2D (plane-strain) and 3D (solid) finite element (FE) models are developed using Abaqus [2] considering two different soil profiles (with multilayer linear viscoelastic materials) of different dynamic characteristics. The kinematic constraints are used along the lateral boundaries of FE models, whereas the base is considered to be fixed in vertical direction. The maximum size of used elements is selected according to the recommendation of ASCE/SEI 4-98 [3] and ASCE/SEI 4-16 [4], for wavelength corresponding to 10 Hz. A recorded ground motion is applied at base of FE models (1D/ 2D/ 3D) and 1D wave propagation model developed in SHAKE2000 [5]. The simulated ground motions are compared in terms of transfer functions. On the other hand, a recorded ground motion is de-convoluted through the considered soil profiles using SHAKE2000 [5] separately and then de-convoluted ground motion is applied at the base of FE models. Again, the simulated ground motions (in terms of response spectra and acceleration time-history) of different FE models are compared with the recorded one. The results are found to be in excellent agreement for all the considered cases.

Keywords: Ground response analysis (GRA); Transfer function; Finite element analysis; Response spectra.

1 Introduction

Ground response analysis (GRA) is a method to assess or predict the dynamic response of a soil profile subjected to an earthquake excitation. When earthquake waves propagate from bedrock to soil profile, the overlying soil deposits behave as a filter and alter the actual ground motion characteristics, such as amplitude, frequency content and duration. GRA plays an important role in dynamic analysis of structures, as the dynamic response of a structure is highly influenced by propagated earthquake excitation through supporting geological media. In addition, stratigraphy or heterogeneity of site and subsurface material properties also influence the ground motion characteristics recorded at the soil site [1].

Over the period, several methodologies have been developed to perform GRA. These methodologies are generally classified based on the different site response parameters and dimension of the problems. Generally, 1D wave propagation or 1D GRA is preferred in practice to evaluate the effect of local site conditions on propagating earthquake motion. In 1D GRA, all boundaries are assumed perfectly horizontal, whereas extents of multilayered soil and bedrock in horizontal directions are assumed as infinite and homogeneous. In addition, 1D GRA can evaluate effective response in case of the leveled or gently sloping ground [6] with horizontal boundary conditions and is not efficient in case of complex and irregular soil stratigraphy. In such cases, 2D and 3D ground responses are preferred over 1D GRA for more realistic evaluation of GRA. More specifically, (a) 2D GRA is preferred for problems, in which one dimension is significantly larger than others such as earth dams, tunnels, cantilever retaining wall etc., (b) 3D GRA is preferred in cases, in which soil conditions and respective boundary conditions vary in all dimensions, such as soil-structure interaction (SSI) problems.

In the past, several researchers have evaluated the ground response, assuming two different material behaviour, viz. linear or equivalent-linear (EQL) and nonlinear (NL). However, the dynamic response evaluated from these assumptions on material behaviour can significantly vary, due to inherent differences in the numerical approaches. Initially, Idriss and Seed [7] proposed the EQL GRA approach which evaluates an approximate NL ground response based on linear analysis and material properties of soil are iteratively adjusted to incorporate the softening behaviour during earthquake excitation. This approach has an advantage of stabilized numerical integration during dynamic analyses assuming the superposition principle [8]. Further, Schnabel et al. [9] applied this methodology in the frequency-domain and developed a widely accepted computer program, SHAKE. Later on, Assimaki et al. [10] and Yoshida et al. [11], made modifications to the EQL methodology which did not gain practical importance. Further, several studies have also been carried out to explore the NL GRA [12-17]

In EQL and NL GRA, the boundary conditions at the base of the soil can be modelled either as reflecting or as transmitting type. Kwok et al. [18] and Mejia and Dawson [19] explained the process of selecting a proper boundary condition for performing GRA. The NL GRA requires a reliable constitutive model capable enough to simulate the hysteretic stress-strain behaviour of soil. However, Régnier et al. [17] suggested to perform linear GRA before any complex NL ground response simulation and for accurate estimation of equivalent viscoelastic material parameters of corresponding soil.

Most of the earlier studies have considered 1D GRA using EQL and NL material properties. However, the effect and comparison of model dimensions on GRA are rarely discussed in literature. To this end, the present study has been performed to compare the ground responses of FE models with different dimensions (1D/2D/3D) using Abaqus [2]. This study consists of a series of dynamic analyses (linear GRA) conducted on FE models having two different soil profiles with appropriate dynamic boundary conditions. The responses obtained from FE models (1D/2D/3D) are compared with the results obtained from 1D wave propagation (1D GRA) using SHAKE2000 [5] and an analytical solution [1] for considered soil profiles. The outcomes of this study are being presented in terms of transfer functions, acceleration time-history and response spectra for each profile, respectively.

2 Description of Soil Profiles

In the present study, two generic soil profiles (denoted as ‘I’ and ‘II’) has been considered as shown in Fig. 1 and Fig. 2. The considered soil profiles consist of a similar geometrical configuration and multilayer (six) linear viscoelastic material properties with different dynamic characteristics. These soil profiles belong to site class ‘D’ as per the classification of ASCE/SEI 7-16 [20]. The reduction of shear modulus and damping with corresponding shear strain are unique characteristics of a particular soil type. To incorporate the nonlinear behaviour of soil in GRA, strain compatible shear modulus and damping have been considered in this study. To consider the effects of these parameters, fixed values of the modulus reduction factor $G = 0.7G_0$ [21] and damping ratio (5%) is considered for each soil profiles as per the recommendations of EPRI (1993) [22]. All pre-requisites parameters for each soil profile are shown in Table 1.

Table 1. Material properties of the soil profile I

Layers	Density (kg/m^3)		Poisson’s Ratio		Modulus of Elasticity (GPa)		Modulus of Rigidity (GPa)		Shear Wave Velocity (m/s)	
	I	II	I	II	I	II	I	II	I	II
1	2000		0.33		0.122	0.338	0.046	0.127	151	252
2	2000		0.33		0.188	0.441	0.071	0.166	188	288
3	2000		0.33		0.216	0.485	0.081	0.182	201	302
4	2000		0.33		0.239	0.521	0.089	0.196	212	313
5	2000		0.33		0.282	0.583	0.106	0.219	230	331
6	2000		0.33		0.336	0.659	0.126	0.248	251	352

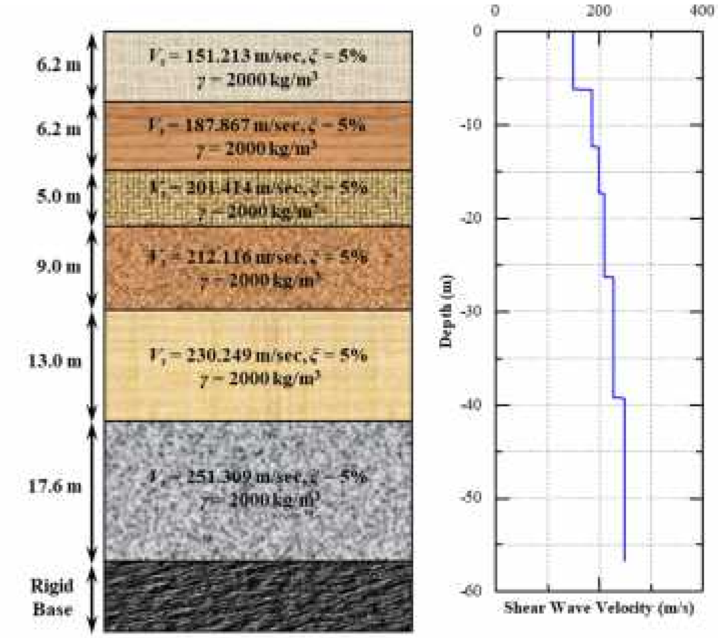

Fig. 1. Graphical representation and corresponding shear-wave velocity of soil profile I

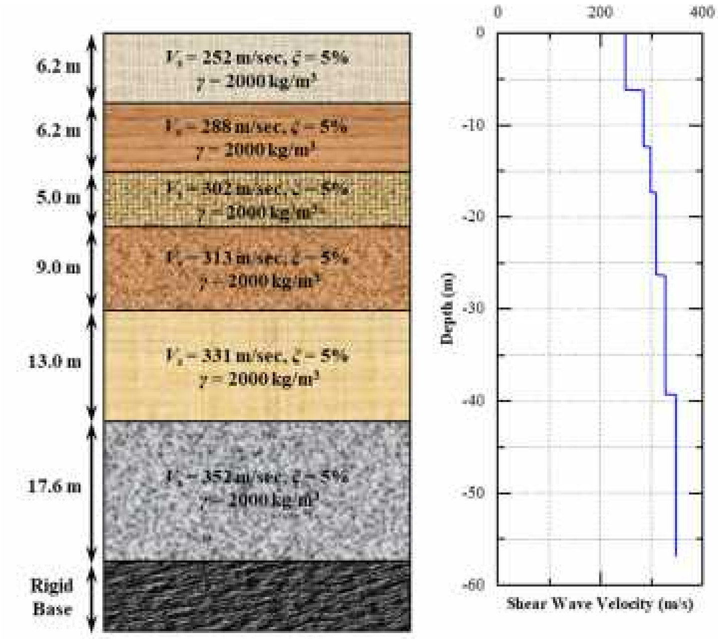

Fig. 2. Graphical representation and corresponding shear-wave velocity of soil profile II

3 Finite Element Modeling

In real practice, the geometrical configuration of the soil profile is defined with bore-log data obtained from a particular site and the sub-surface soil is merely found perfectly horizontal at larger extent. The FE model of each soil profile is developed in Abaqus [2] as 1D, 2D and 3D FE model, respectively (as shown in Fig. 3). The 1D and 2D FE models comprise of plane strain elements, while 3D FE models comprise of solid elements. More specifically, 1D and 2D FE models of soil mass have been discretized with 2D plane strain element CPE4R (4-noded bilinear plane strain quadrilateral, reduced integration, hourglass control), whereas 3D FE models have been discretized with 3D stress element C3D8R (8-noded linear brick, reduced integration, hourglass control) available in Abaqus element library [2]. To avoid wave reflection from model boundaries in 2D/3D FE models, a larger soil domain with extent of 170m in longitudinal and transverse directions has been considered through sensitivity analysis. The vertical extent of the FE models has been limited up to 57m as per the available depth of the soil profile layers [23]. A uniform dense mesh has been used to optimize computational effort and accuracy of developed 1D/2D/3D FE models. In order to avoid the numerical distortion of frequency content in simulation of wave propagation problems, maximum size (h) of the FE mesh has been estimated from Equation (1) as:

$$h \leq \frac{V_S}{a \times f_{\max}} \tag{1}$$

where, V_S = smallest shear wave velocity of interest, a = 5 as per ASCE/SEI 4-98 [3], 10 as per ASCE/SEI 4-16 [4] and f_{max} = maximum frequency of interest (≈ 10Hz).

In case of 1D FE model, the base has been considered fixed in vertical direction while static earth pressure has been applied at lateral boundary [24]. To simulate appropriate dynamic boundary condition in 2D/3D FE models, kinematic constraints [21] have been used along the lateral boundaries to avoid flexure mode of vibration of soil mass. These constraints allow the shear behaviour between neighboring soil layers and prevent the lateral spread of the soil mass from gravitational loads. At the base of 2D/3D FE models, fixed boundary in vertical direction has been applied, similar to 1D FE models. The mass and stiffness proportional Rayleigh damping expressed in terms of coefficients, α and β, have been used to account for the energy dissipation during the elastic response. Table 2 represents the first four natural frequencies of the soil profiles and Table 3 shows the corresponding Rayleigh damping coefficients (α, β) estimated using first and second frequency.

Table 2. Fundamental frequencies of studied soil profiles

Soil Profile	Frequency (Hz)			
	F1	F2	F3	F4
I	1.037	2.863	4.657	6.412
II	1.482	4.203	6.894	9.549

Table 3. Rayleigh damping coefficients used in this study

Soil Profile	Rayleigh damping coefficients	
	α	β
I	0.478	0.0041
II	0.688	0.0027

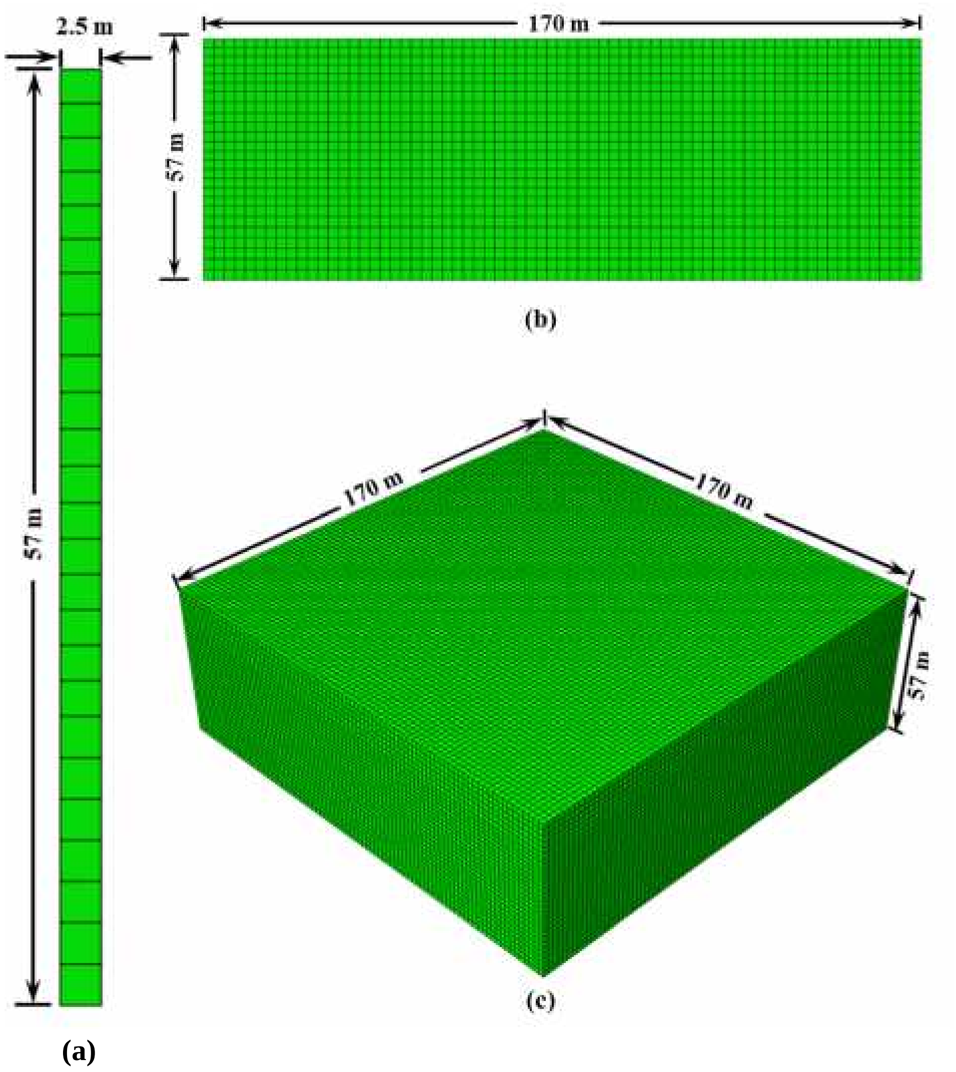

Fig. 3. FE models of a soil profile (a) 1D (b) 2D and (c) 3D

4 Seismic Input Motion

In this study, the seismic loading has been applied in terms of acceleration time-history in each dynamic analysis (GRA). The ground motion recorded at MZH (Japan) station due to Kobe earthquake on May 16, 1995 (Kobe-MZH-1995) has been used as seismic input. The acceleration time-history and Fourier spectrum of Kobe-MZH-1995 ground motion are shown in Fig. 4.

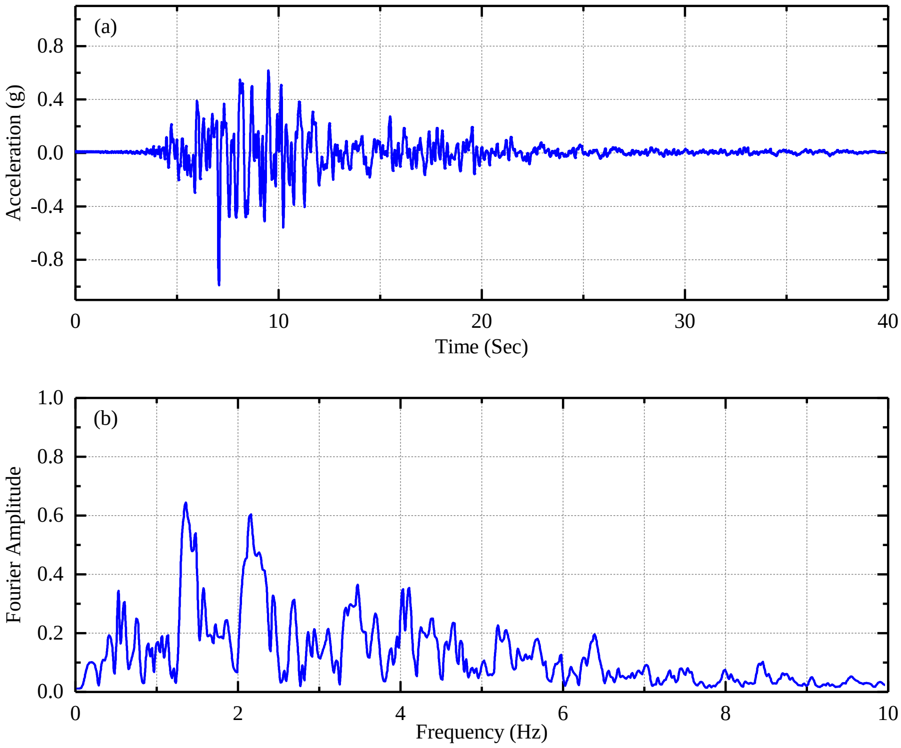

Fig. 4. Seismic input (Kobe-MZH-1995), (a) acceleration time history; (b) Fourier spectrum

5 Results

An acceleration time history of a recorded earthquake ground motion has been applied at the rigid base of FE models and recorded at the top. 1D wave propagation has been performed for the considered soil profile (I and II) using SHAKE2000 [5]. The transfer functions, defined as the ratio of the FFT of applied (at base) and recorded (at top) ground motion, have also been estimated for all considered soil profiles. The transfer functions obtained from FE models have been compared with 1D wave propagation using SHAKE2000 [5] and an analytical solution for multilayer system [1]. The transfer functions for soil profile I and II are shown in Fig. 5 (a) and Fig. 6 (a), respectively. It can be observed from the figures that, 1D/2D/3D FE models produce amplification pattern similar to 1D wave propagation and analytical solution, up to second mode of vibration. For higher frequency of interest (third mode onwards), the FE models produce lower amplification than other methods. As already mentioned that the damping of soil mass has been considered in term of Rayleigh damping coefficients corresponding to first and second frequency, which results in higher damping value for higher frequencies.

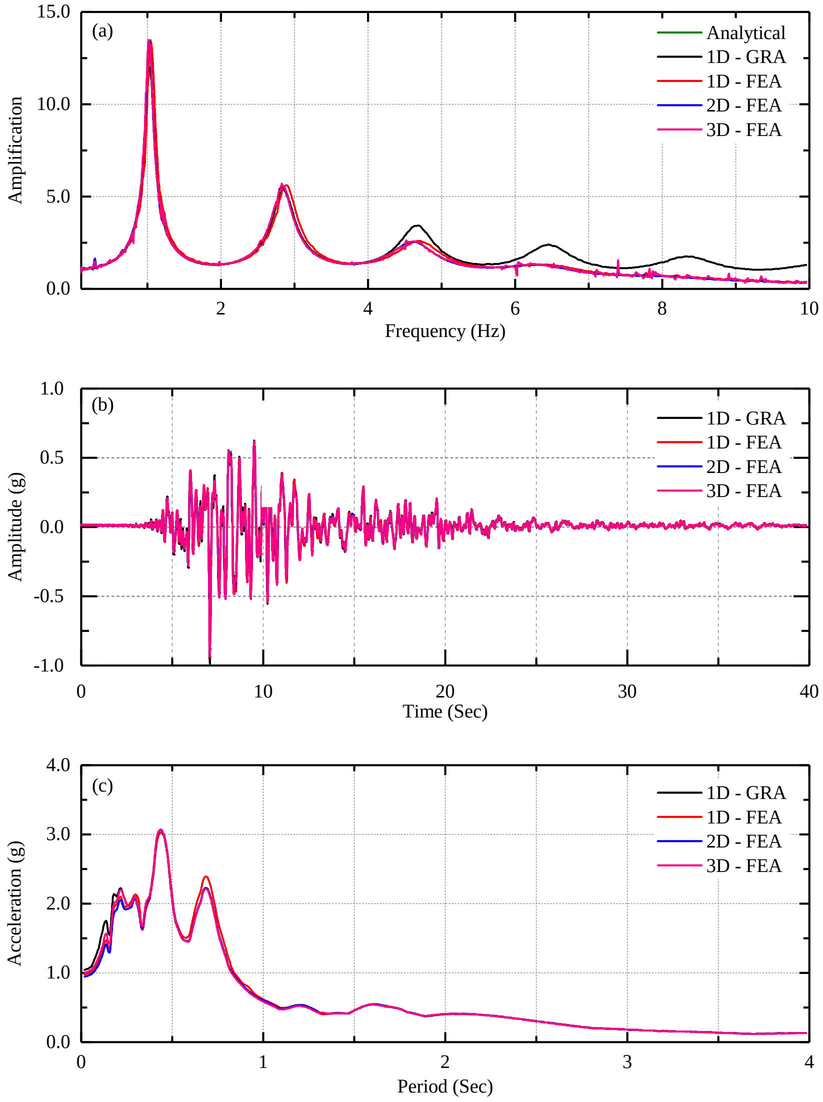

Fig. 5. Soil profile I (a) Transfer function (b) Acceleration time histories at the ground level (c) The surface-response spectra

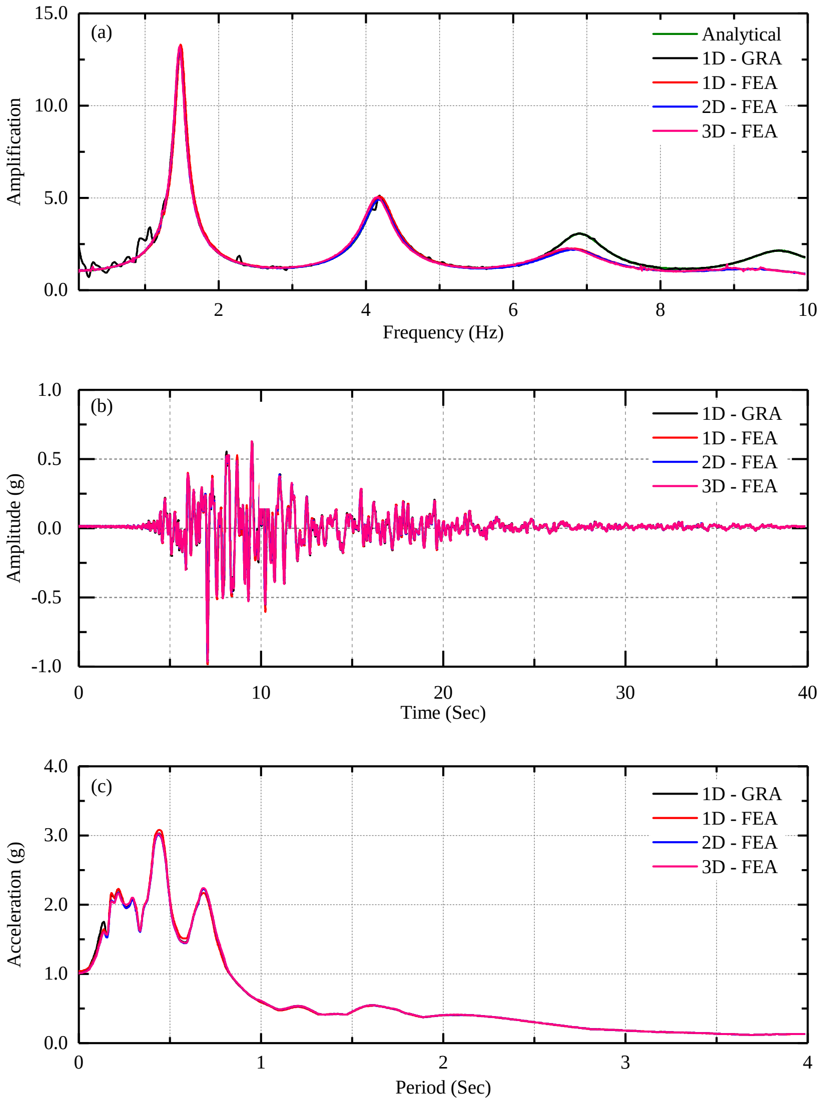

Fig. 6. Soil Profile II (a) Transfer function (b) Acceleration time histories at the ground level (c) The surface-response spectra

To investigate the accuracy of developed FE model for wave propagation simulation, the de-convolution (in frequency domain) and convolution (in time domain) analyses are performed [19]. Initially, a target ground motion has been de-convoluted to the actual depth of soil profile (within the last layer) through 1D wave propagation using SHAKE2000 [5]. Further, the de-convoluted ground motion has been applied at base of FE models and the simulated ground motion has been recorded at top of FE models [19]. The response of the simulated ground motions during convolution process using different FE models have been compared with target motion (the original de-convoluted ground motion) in terms of acceleration time history and 5% damped response spectrum. The acceleration time histories at the ground level for each soil profile has been shown in Fig. 5 (b) and Fig. 6 (b), respectively. Similarly, Fig. 5 (c) and Fig. 6 (c) show the surface-response spectra for soil profile I and II, respectively. It can be observed that the simulated acceleration time histories at top of the 1D/2D/3D FE models are in excellent agreement with the target motion.

6 Conclusions

The use of dynamic analyses to evaluate the seismic ground response of a soil profile depends on a proper simulation of numerical modeling and corresponding dynamic boundary condition. Before performing a dynamic analysis, calibration of the used boundary condition, numerical and material damping are essential to simulate a wave propagation problem. The primary objective of this study is to compare the response using 1D/2D/3D GRA. Two different soil profiles, having multilayer viscoelastic material properties, are considered. Initially, 1D/2D/3D FE numerical simulations are performed using Abaqus [2], while 1D wave propagation is performed using SHAKE2000 [5]. The results obtained from above simulations are compared with analytical solution [1]. It can be concluded that the analytical solution and 1D wave propagation slightly overestimates the ground response, as compared to the 1D/2D/3D FE models.

For each soil profile, 1D/2D/3D FE analyses predict amplification pattern similar to 1D wave propagation and analytical solution, up to second mode of vibration and underestimate at higher frequencies due to high Rayleigh damping. The simulated acceleration time histories and corresponding 5% damped response spectra recorded at top of the 1D/2D/3D FE models are in excellent agreement with the target motion. For accuracy and efficiency of developed FE model, it is suggested to compare GRA for different 1D/2D/3D geotechnical systems to predict reliable ground response. The present study considered perfectly horizontal soil profiles (which yield similar results in 1D/2D/3D) which is not representing the actual site condition in larger extent and hence the results obtained from the study is limited to similar soil profile only.

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