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Effects on amplification of strong ground motion due to deep soils

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Abstract. Many seismically vulnerable regions in India and worldwide are located on deep soil deposits which extend to several hundred meters of depth. It has been well recognized that the earthquake shaking is altered by geological conditions at the location of building. As seismic waves propagates through uppermost layers of soil and rock, these layers serve as filter and they can increase the duration and amplitude of earthquake motion within narrow frequency bands. The amplification of these waves is largely controlled by mechanical properties of these layers, which are function of their stiffness and damping. Stiffness and damping are further influenced by soil type and thickness. In the current study, an attempt has been made to study the seismic site response of deep soils. Three hypothetical homogeneous soil models (e.g., soft soil, medium soil and hard soil) lying on bedrock are considered. Depth of half space is varied from 30 m to 2,000 m in this study. Controlled synthetic motions are used as input base motion. One dimensional equivalent linear ground response analyses are carried out using a computer package DEEPSOIL. Conventional approach of analysing up to 30 m depth has been found to be inadequate for deep soil sites. PGA values are observed to be higher for deeper soil profiles as compared to shallow soil profiles indicating that deeper soil profiles are more prone to liquefaction and other related seismic hazards under earthquake ground shaking. The study recommends to deal the deeper soil sections more carefully for estimating the amplification factors for seismic hazard assessment at the surface.

Keywords: deep soil; ground response analysis; synthetic controlled motion; PGA; amplification

1. Introduction

The availability of fertile land and water has lead to the development of civilisations around soil deposits of rivers which are mostly the fan areas near mountains. The seismic activities in such areas make them more vulnerable to damages due to the local site effects. Further, the rapid growth of world's population in last few decades has led to concentration of population, buildings and infrastructure in urban areas located on deep soil deposits. The tendency of urban areas to be

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developed on sedimentary deep soil sites has increased their vulnerability to earthquake hazard. Earthquake such as the 1985 Mexico event, the 1988 Spital, Armenia event, the 1989 Loma-Prieta event and Bhuj 2001, events have clearly demonstrated that deep soil conditions have significant influence on the strong ground motion and damage pattern (Field and Petersen 2000, Finn and Nichols 1985, Finn *et al*. 1993). To minimize the vulnerability of economic and human losses in such areas due to earthquakes, it is necessary to estimate seismic hazard accurately and provide earthquake resistant structural design to withstand the anticipated earthquake hazard.

In general, if the soil cover extends below 30 m from the ground surface, it is termed as deep soil. Seismic site response analysis is commonly carried out considering top 30 m soil cover. There are many studies available even on Indian soils, where only top 30m soil cover is considered (e.g., Jishnu *et al*. 2013, Kumar *et al*. 2012, Phanikanth *et al*. 2011). Kumar *et al*. (2012) presented a site specific seismic site response analysis of Lucknow city soil, while Jishnu *et al*. (2013) has presented site response analysis of Kanpur soil. Both Lucknow and Kanpur are along Indo-Gangetic plain, where the soil cover extends deep below 30m. Studies on deep soils considering full soil thickness are very scanty. Huang *et al*. (2009) presented a seismic site response analysis of deep saturated soil of Shanghai with the help of constitutive modelling and capture fundamental seismic aspects of the deep saturated soil. Chen *et al*. (2011) also presented dynamic response analysis of deep Shanghai soil under multidirectional earthquake loading. Ashford *et al*. (2007) presents the results of a study on the amplification of earthquake ground motions in Bangkok which concluded that the Bangkok soil has ability to amplify ground motion up to 5 times the input motion. There is similarity of level of amplification of Bangkok soil with 1985 Mexico City soft soil, and San-Francissco Bay mud area. Luke *et al*. (2001) investigated seismic response of deep dry sandy soil and found that acceleration amplitude decreased and predominant period increased with depth. Areas underlain by deep soil deposits often comes under large scale loss of structure and lives due to moderate to large earthquakes. The damage to the building and structures during some important earthquakes such as the great Mexico earthquake in 1985, San Francisco earthquake in 1989, Bhuj earthquake 2001 was found to be confined in the areas underlain by deeper soft soil deposits. Many of these areas are on soft deep soil and are located as much as 350 km far from epicentre of the earthquake. These evidences related to deep soil effects are forcing to investigate deep soil and its effects on strong ground motion.

It has been recognized that the earthquake response is altered by geological condition at the location of building, which is known as “site effect”. As seismic waves propagates through uppermost layers of soil and rock, these layers serve as filter that can increase duration and amplitude of earthquake within narrow frequency band. The amplification of these waves is largely controlled by mechanical properties of these layers. The maximum amplification of seismic wave occurs at resonance frequency; which is function of thickness of soil deposits and shear wave velocity. The frequency dependency of maximum amplification is due to trapped seismic waves within the soil layers. Fundamental frequency of soil deposit is estimated by using total thickness of soil deposits and average shear wave velocity. The most significant site amplification can be expected at this frequency. Amplification may also occur at higher natural frequencies of other modes of vibration of soil deposit as well.

The main objective of study is to investigate these fundamental aspects of influence of deep soil effects on strong ground motion and quantify the potential of amplification of earthquake ground motions due to deep soil effects. In this study, three hypothetical sites with deep soil deposits are considered. Their response is investigated under controlled wave motions.

2. Evaluation of deep soil effects

Response of soil deposits under dynamic loading such as earthquake loading is estimated by seismic site response analysis. There are various methods available to evaluate seismic site response which can be grouped as: (i) Experimental methods; (ii) Empirical methods; (iii) Theoretical methods; and (iv) Hybrid methods. Experimental methods use the ground motion records to estimate response usually in frequency domain. Empirical methods usually estimate some important parameters such as peak ground acceleration, peak ground velocity, peak ground displacement and response spectra for particular site classification. In theoretical methods, 1D, 2D and 3D wave propagation models are used to estimate site effects. A number of computer packages such as SHAKE-2000, DEEPSOIL, DESRA, CHARSOIL, etc are available for carrying out ground response analysis (Schnabel *et al*. 1972, Lee and Finn 1978, Park and Hashash 2003). In present study, one dimensional equivalent linear ground response analysis has been used by using commuter package DEEPSOIL (Hashash 2012). Hybrid methods combines different category of methods to estimate site effects.

Despite the fact that seismic waves travel tens of kilometers through rock and often less than 100 m through soil, soil plays much more significant role in determining the characteristics of surface ground motion. The three important factors which affect the ground motion are the source, path and the site characteristics. The identification and removal of these effects from site response is greatest challenge. So, synthetic ground motion has been generated and used in the present study. In this study, first homogeneous deep soil profile is modeled as 1D soil column. Synthetic sinusoidal harmonic motion with 0.1 g amplitude and frequency corresponds to its site characteristic frequency (i.e., Vs/4H) is applied and then ground response is obtained. It has been found that acceleration amplitude decreases and predominant period increases with increase in soil profile thickness. One interesting thing is observed that amplification ratio is maximum at a frequency lower than the computed soil site characteristic frequency. Then the analysis has been again carried out with a new motion prepared at this frequency and then response is obtained. This procedure enables the identification of maximum response of the considered profile at its actual fundamental frequency as explained in the introduction.

Since the behavior of soil is nonlinear, linear approximation in ground response analysis may not be proper to use. Here in this study, ground response analyses is carried out using DEEPSOIL implementing equivalent linear approximation of non-linear behavior of soil. Equivalent linear analysis is most commonly adopted for the site response analysis for accounting nonlinear effects of the soils. Equivalent linear analysis accurately approximates the non-linear analysis without need for consideration of complex soil models. It accounts the nonlinear behaviour by means of modulus reduction and damping variations with shear strain. It is well known and proven method of analysis for studying simple nonlinear effects.

Current study mainly consists of two parts; first part presents the study of deep soil deposit with varying soil cover thickness and second part covers the analyses of three different types of deep homogeneous soil deposits.

Site amplification controls the damage in urban areas during large earthquakes. Many studies have demonstrated the role played by the surface geology on altering the surface motions. To investigate the deep soil effects, three different types of soils have been considered. Bedrock properties have been kept the same for all cases. Unit weight, shear wave velocity are taken as 24 kN/m^3 and 1,200 m/sec respectively. The unit weight and shear wave velocities for three types of soils considered are given in Table 1.

Table 1 Properties of soil models considered

Si. No.	Type of soil	Unit Wt. (kN/m^3)	V_s in soil(m/s)
1	Soft soil	18	150
2	Medium soil	20	250
3	Hard soil	21	500

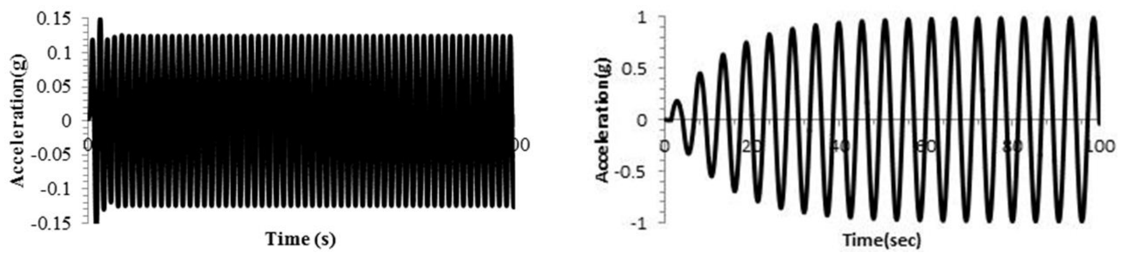
Response of deep soil deposits also depends upon applied input motion. Since very little recorded earthquake motions are available, particularly on deep soil sites, synthetic input motions are used here for investigating deep soil effects. Controlled synthetic motions further help to avoid the influence of frequency variations of earthquake motion on the study of deep soil effects. Sinusoidal synthetic harmonic motions are considered as input motion for the analyses.

Initially sinusoidal ground motion is generated at the computed soil site characteristic frequency (V_s/4H). Based on the response, actual site characteristic frequency is identified. Frequency of sinusoidal motion is then modified accordingly and then used in the analysis to get the maximum amplitude corresponding to resonance frequency. In present study, appropriate input motions are generated for all the sites for different level of shaking (0.0001 g~1.0 g) and the applied generated motion at the bedrock.

3. Effects of thickness of soil cover

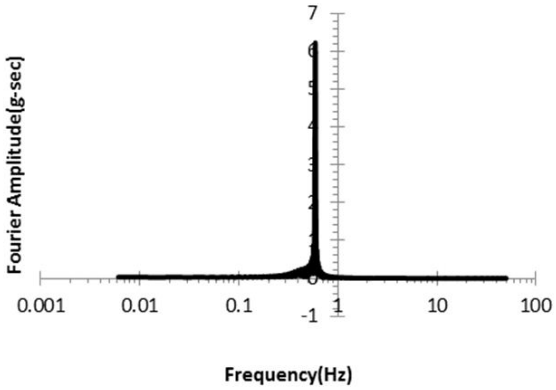
To investigate the influence of depth of soil on strong ground motion, six hypothetical cases have been assumed with the depth of soil ranging from 30 m to 2,000 m. Soft soil is considered in all the cases, whose unit weight and shear wave velocities are 18 kN/m^3 and 150 m/s. Bed rock properties are also kept constant for all the six cases. The unit weight and the shear wave velocity of the bed rock are chosen as 24 kN/m^3 and 1,200 m/s respectively. Depth of soil has shown significant influence on strong ground motion. To understand these effects typical results for two depths 30 m and 200 m are presented here in Figs. 1 to 4, under 0.1 g intensity of shaking.

As discussed earlier, results presented here correspond to the actual site frequency of the considered profiles. Thus, maximum possible response is obtained for the considered soil profile under the considered ground motion. The resulted ground motion shown in Figs. 2 and 3, reveals frequency shift towards low frequency for the deeper soil. Predominant frequency for 200m soil is



(a) (b)

Fig. 1 Resulted ground motions: (a) 30 m thick soil profile; and (b) 200 m thick soil profile



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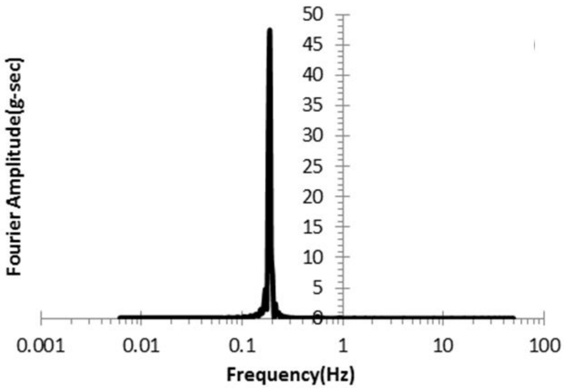

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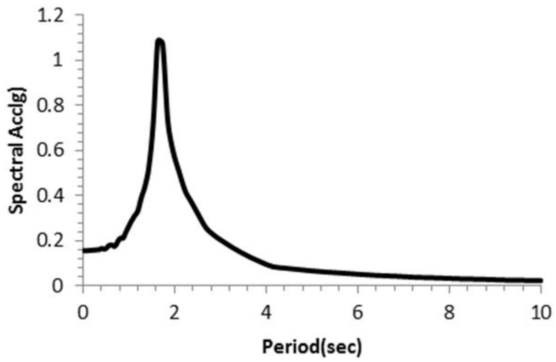
Fig. 2 Fourier amplitude spectra for (a) 30 m; and (b) 200 m



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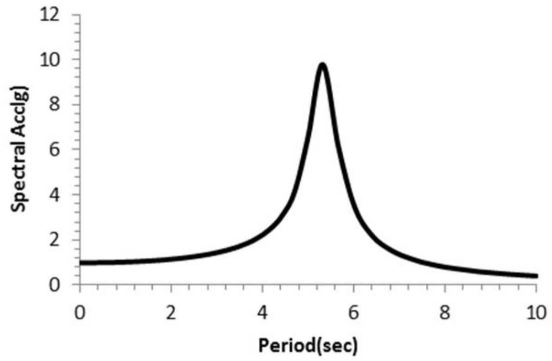
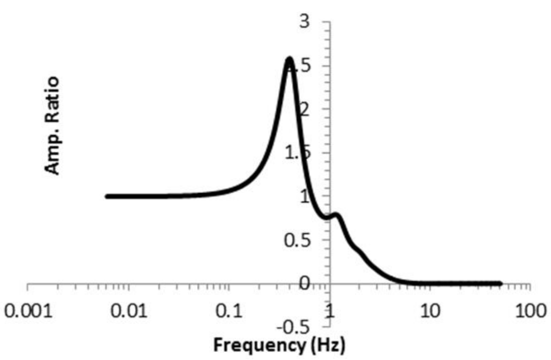


(b)

Fig. 3 Response spectra for (a) 30 m; and (b) 200 m



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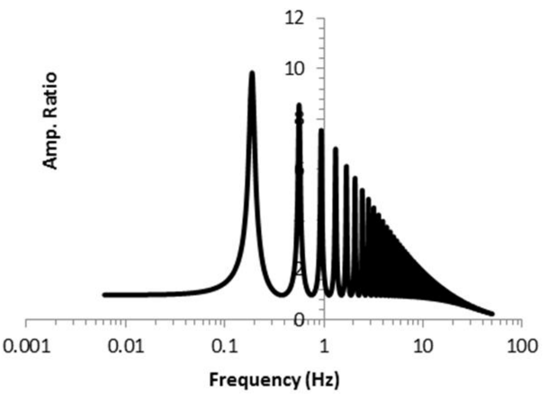

(b)

Fig. 4 Amplification ratio for (a) 30 m; and (b) 200 m

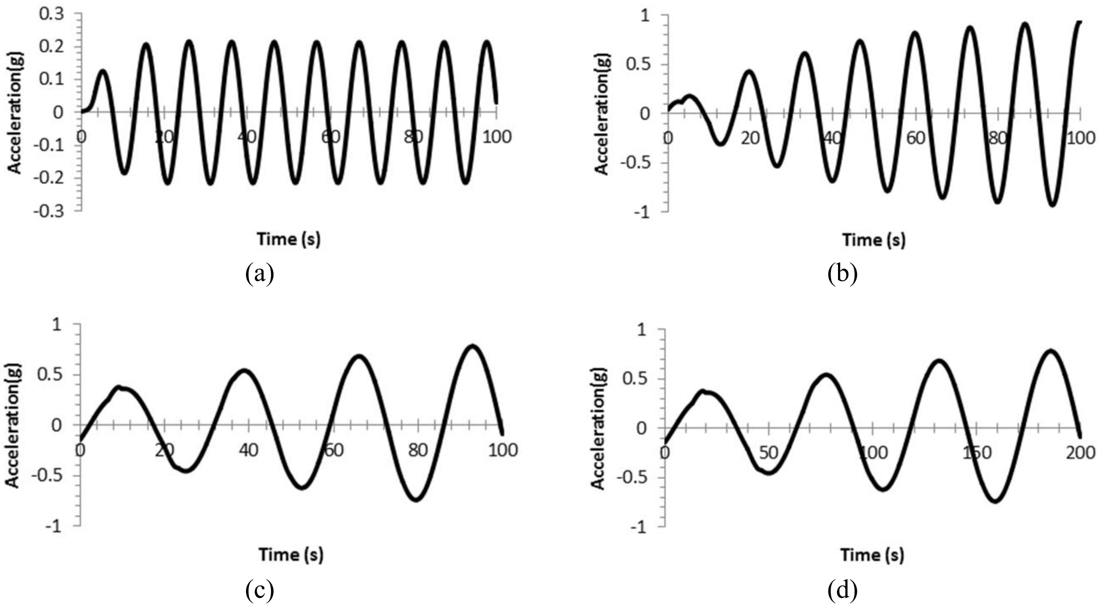

Fig. 5 Surface ground motions for (a) 100 m; (b) 500 m; (c) 1,000 m; and (d) 2,000 m soil covers

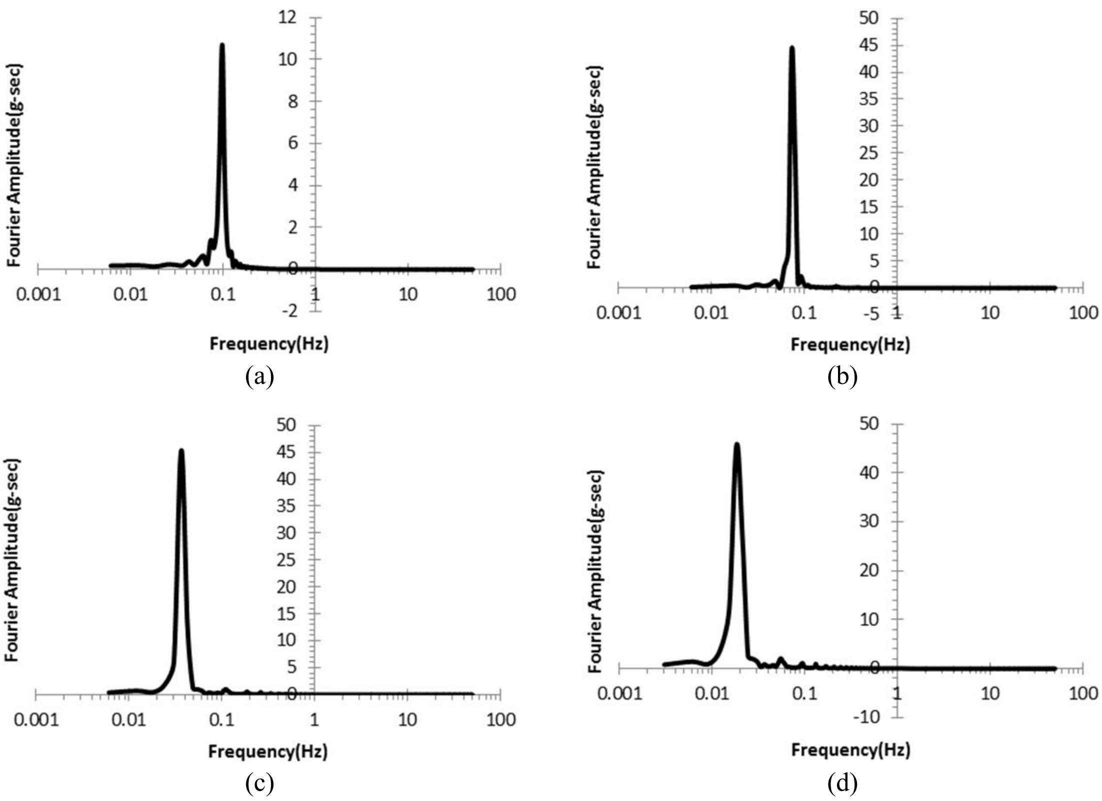

Fig. 6 Fourier amplitude spectra for (a) 100 m; (b)500 m; (c) 1,000 m; and (d) 2,000 m

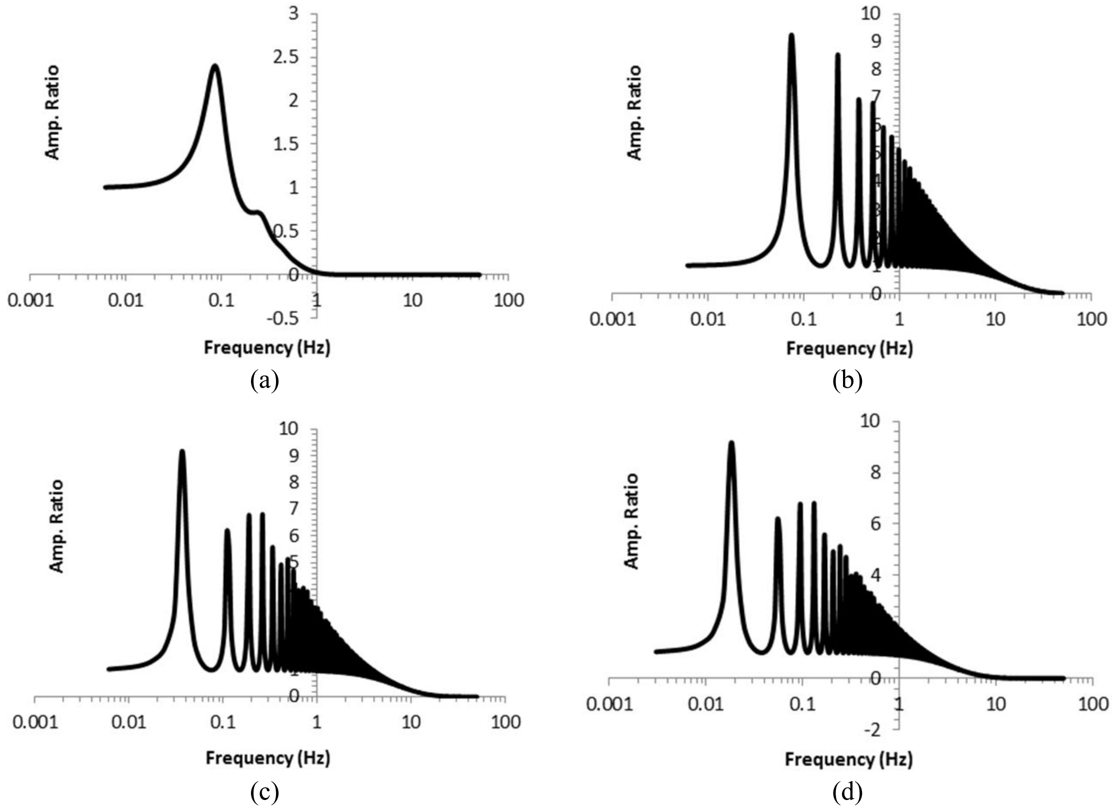

Fig. 7 Amplification ratio for (a) 100 m; (b) 500 m; (c) 1,000 m; and (d) 2,000 m

shifted to 0.2 Hz from 0.4 Hz. Similar frequency shifts are observed in amplifications as well (See Fig. 3). However, amplification has been observed to be increased from 2.5 to about 10 in case of deeper soil. Results for other soil cover thicknesses (e.g., 100 m, 500 m, 1,000 m and 2,000 m) are presented in Figs. 5, 6 and 7. Surface ground motions are shown in Fig. 5. Fourier spectra correspond to surface ground motions of various cases are shown in Fig. 6. Amplification ratios for these cases are plotted in Fig. 7.

The results presented for these cases in Figs. 5 to 7 are compared with the previous two cases (e.g., 30 m & 200 m soil cover) presented in Figs. 1 to 4, to validates the previous interpretations. There is clear indication of shift of predominant frequency of ground motion with increase in the soil cover thickness (See Fig. 6). Similarly, shift of predominant frequencies can also be observed in amplification spectra as well. (See Fig. 7), However, some differences are observed in amplitudes of amplification spectra with increase in soil cover thickness unlike previous cases. Amplification is found to be increased initially with increase in soil cover thickness and reached saturation afterwards.

4. Influence of type of soil

To study the effect of type of deep soil on strong ground motion, three hypothetical cases have

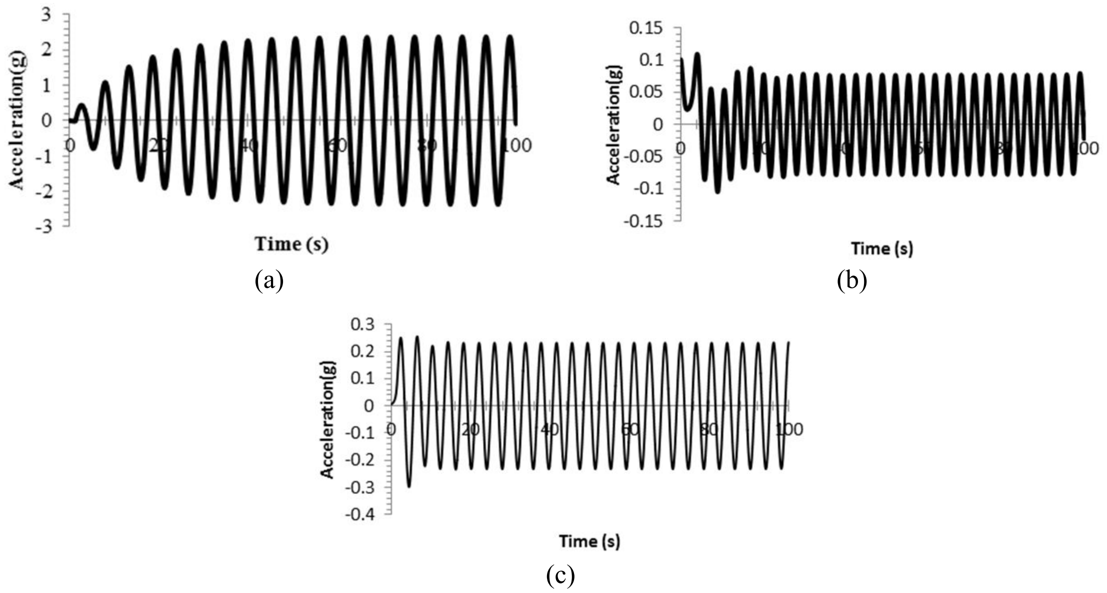

Fig. 8 Surface ground motions for (a) soft; (b) medium; and (c) hard soil

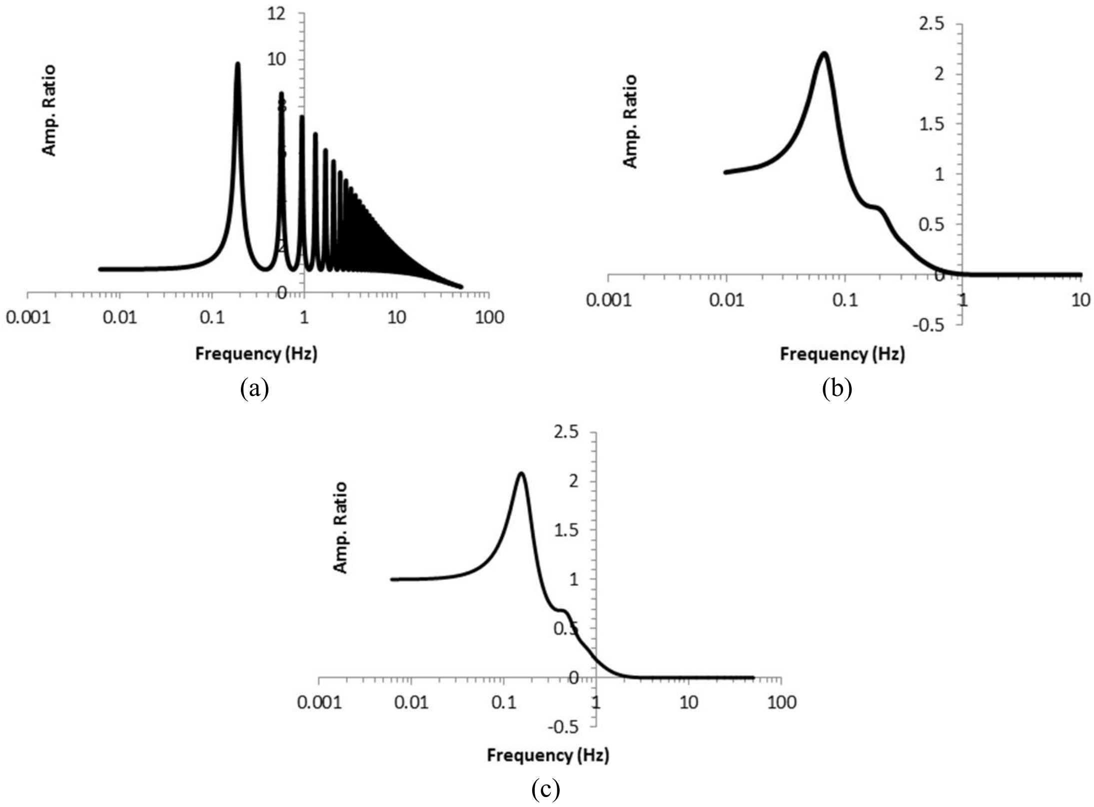

Fig. 9 Amplification ratio for (a) soft; (b) medium; and (c) hard soil

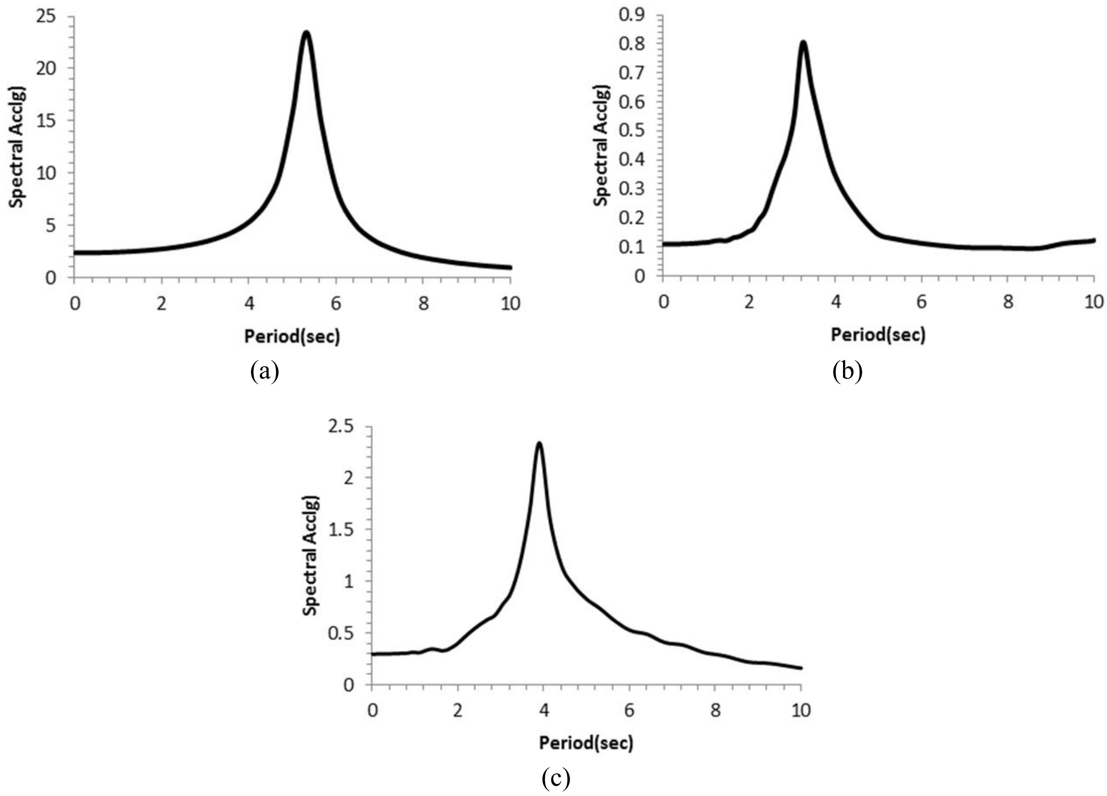

Fig. 10 Response spectra for (a) soft; (b) medium; and (c) hard soil

been studied considering three different types of soils. Soil properties are given in the Table 1.The soil type assumed in first case is soft soil with unit weight of 18 kN/m^3 and shear wave velocity of 150 m/s. For the second case, medium soil with unit weight of 20 kN/m^3 and shear wave velocity of 250 m/s is considered. Very hard soil representing very dense sand or hard clay with unit weight of 21 kN/m^3 and shear wave velocity of 500 m/s has been considered for the third case. In all the cases, 200 m thick soil cover is considered. Bedrock properties are kept constant for all the cases. The modulus reduction curve and the damping ratio curve for the materials are chosen directly from the database of DEEPSOIL. Sinusoidal motion of intensity 0.24 g is prepared at an appropriate frequency corresponding to the actual site characteristic frequency for each case and used in the analysis. 0.24 g intensity is the expected level of ground shaking for seismic zone IV in India as per Indian seismic code [IS1893 (Part 1): 2002]. Obtained response for these three considered cases are shown in Figs. 8 to 11.

Results shown in Figs. 8 to 11 are clearly demonstrating the influence of deep soil stiffness on strong ground motion. Fig. 8 shows resultant surface ground motions for soft, medium and hard soils. As seen in these plots soft soils are experiencing higher peak ground accelerations (PGA). Amplification ratio plots for the three cases are shown in Fig. 9. Amplification of input motions is clear for soft soils even from these plots. Peak amplification is observed at lower frequency for soft soil compared to stiffer soils. Figs. 10 and 11 show response spectra and Fourier amplitude spectra for the considered three cases. Plots in Figs. 10 and 11 further support the observations

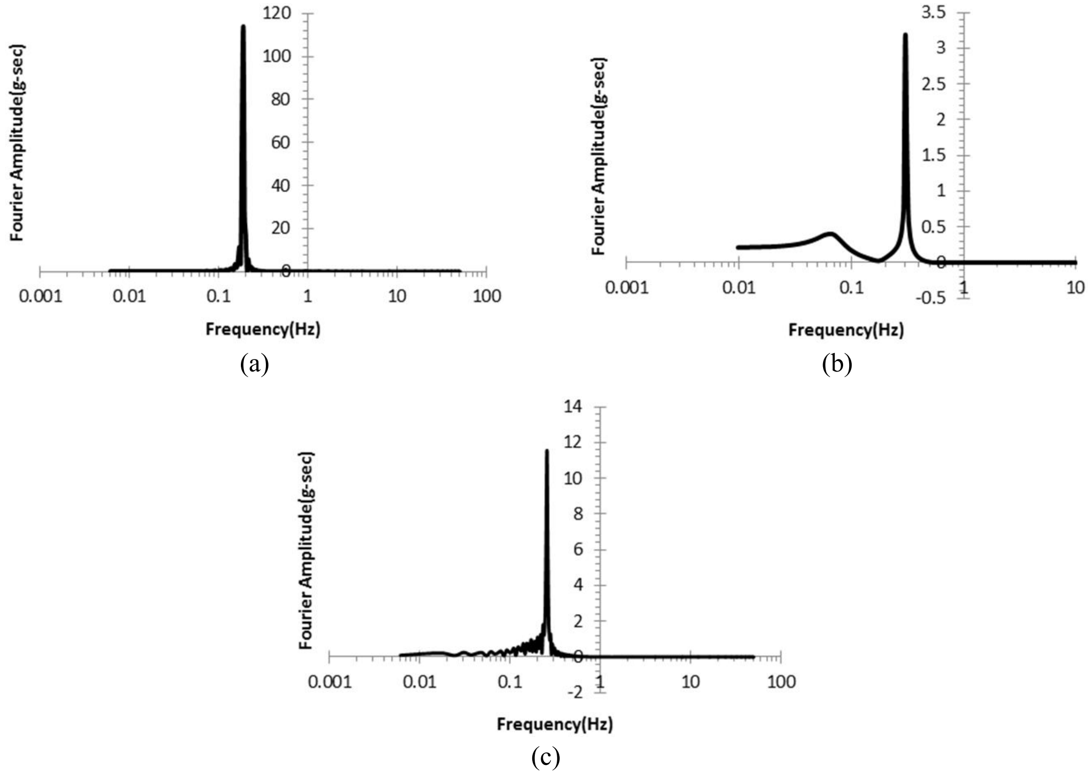

Fig. 11 Fourier amplitude spectra for (a) soft; (b) medium; and (c) hard soil

Table 2 PGA and amplification ratio for different depths of soft soil layer

Depth (m)	30	100	200	500	1000	2000
PGA (g)	0.15	0.20	0.98	0.93	0.78	0.78
Amplification ratio	2.5	2.4	9.8	9.1	9.1	9.1

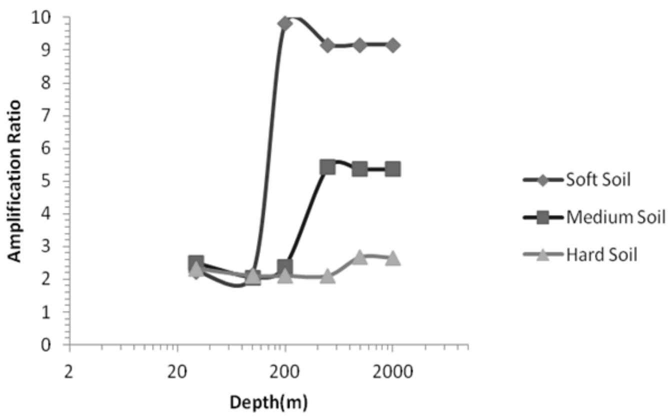

Fig. 12 Variation of amplification ratio with depth for three types of soil

from Figs. 8 and 9. Soft soils exhibited higher spectral and Fournier amplitudes. Peak spectral and Fourier amplitudes are observed at lower frequency for soft soils.

5. Discussions and Conclusions

One of the most challenging issues in seismic hazards assessment is to predict deep soil effects on strong ground motion at a given site. It is necessary to consider deep soil effects for seismic design, as their mechanical characteristics changes with the increase in thickness of soil cover. Extrapolations in such cases are not reliable for the seismic design due to inclusion of non linearities. So it is important to consider deep soil effects for the purpose of seismic design. Current study focuses on investigation of these affects on response of deep soils. Two important factors have been studied here: (i) influence of soil cover; and (ii) influence of soil type on deep soil response. The influence of deep soil conditions on strong ground motion has been studied through the perspective of theoretical one dimensional ground response analysis. For six different soil cover thicknesses, seismic site response analyses have been carried out and deep soil effects have been investigated. It has been observed that ground motions are amplified up to certain depth; thereafter amplification factor of ground motion is saturated. Table 2 shows the variation of PGA and amplification ratio for 0.1 g intensity of shaking, which is corresponds to level of shaking expected in seismic zone 2 of India.

As depth of soil increases, peak ground acceleration (PGA) also increases with depth. Deeper soil profile shows higher response as compare to shallow soil profile. There is frequency shift towards lower values with depth; this is due to increase of predominant period with increasing soil layer thickness. The depth of half space should be placed as deep as possible within the soil profile for accurate estimation of deep soil site response. Conventional approach of analysing up to 30m depth is found to be inadequate for deep soil sites. PGA is higher for deeper soil profile as compared to shallow soil profile; which indicates that deeper soil profile are more prone to liquefaction and post liquefaction settlement under earthquake ground shaking. In present study, variation of amplification for three types of soils is worked out under the considered synthetic motion and a plot of amplification ratio versus depth is plotted in Fig. 12.

The result shows variation in amplification due to depth of soil, soil stiffness and level of shaking. Amplification is higher for soft soil and for greater soil thickness. Soft soil sites amplify ground motion to greater extent; the amplification in soft soil sites ranges from 2 to 10. As thickness of soil cover increases, amplification factor increases but after certain depth the amplification saturates. Amplification also depends upon soil stiffness; in medium soil amplification ranges from 2 to 5, while for hard soil it ranges from 2 to 2.7 only. Finally it is to be noted that deep soil act as filter and will modify the ground motion significantly. For an accurate estimation of seismic hazard, it is required to account these deep soil effects.

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