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2D nonlinear site response analysis of typical stiff and soft soil sites at shallow bedrock region with low to medium seismicity

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ABSTRACT

In this study, an attempt has been made to estimate 2D nonlinear seismic site response of a small scale basin on typical stiff and soft soil sites in Peninsular India (PI). Six survey sites were selected from three shallow bedrock regions such as Kalpakkam, Bangalore and Vizag for which subsurface profiles are generated at these locations using Multichannel Analysis of Surface Wave -2D (MASW-2D) method. The subsurface profiles generated are classified as stiff and soft sites based on average 30 m shear wave velocity and further used for the 2D nonlinear site response analysis using the commercial program FLAC -2D. Thirteen intraplate ground motions from all around the world are selected for the site response analysis based on seismicity of the region. Results of the site response analysis were expressed in terms of short-period amplification factor (Fc) and long period amplification factor (Fs) for the intraplate shallow bedrock region. The results show that the Fc gives higher values than Fs in the case of stiff soil and it is showing a reverse trend in the case of soft soil. The trend of Fc is becoming more complex than that of the Fs especially in the case of stiff soil sites. Also, the 2D site response results were compared with conventional 1D nonlinear site response results using the program DEEPSOIL and aggravation factors were generated. Further, a parametric study has been carried out to quantitatively evaluate the effect of amplitude of ground motion on 2D site response analysis. Parametric study results show that subsurface heterogeneity is very sensitive to the low amplitude of input motion, especially in the case of stiff soil sites.

1. Introduction

Earthquakes can cause tremendous damage to the structures and are one of the most destructive natural events in the world. Peninsular India (PI) is considered as a stable continental region for many years. But recent earthquakes like Bhuj (2001; Mw 7.6), Jabalpur (1997; Mw 5.8), Koyna (1967; Mw 7.6), and Latur (1993; Mw 6.1) happened for last few decades demanded a seismic study of Peninsular India. Also, many previous studies like Ganesha Raj and Nijagunappa, 2004, Anbazhagan et al., 2010, Boominathan et al., 2008, Menon et al., 2010, Singh et al., 2008, Jade, 2004, Sitharam et al., 2006, and Rao, 2000 pointed out that the seismic activity of Peninsular India has increased for recent years and cannot be considered as a stable continental region. All these are focusing on a seismic study and site response analysis of Peninsular India.

Site response analysis became an essential aspect for the geotechnical design of crucial structures as it gives the input parameters for the seismic soil-structure interaction by estimating the local site effects due to the propagation of ground motion generated during an earthquake shaking (Roesset, 1977; Idriss and Seed, 1968; Kockar and Akgun, 2012; Idriss, 1990, and Rodgers et al., 2006). Many previous studies like Boominathan et al., 2008, Anbazhagan and Sitharam, 2008, Jaya and Remmya, 2010, Maheswari et al., 2008 have presented one dimensional (1D) site response studies in PI with the assumption that soil layers are horizontal and homogenous. However, 1D shear models may not represent the local amplification due to variation of soil layer thickness and stiffness variation in a 2D geometry. Several researchers have pointed out the insufficiency of 1D site response analysis for accounting the heterogeneity in the subsurface layers (Bakir et al., 2002, Iyisan and Hasal, 2007, Hasal and Iyisan, 2012). For better estimation of site response of heterogeneous sites, 2D site response analysis is necessary as it can account for the effect of spatial variability of subsurface layers thickness and stiffness. Many researchers have done 2D site response analysis in the past (Heymsfield, 2000, Kamiyama and Satoh, 2002, Finn et al., 2003, Khanbabazadeh et al., 2016). But most of these studies are focusing on large scale basins in which the length of the subsurface profiles is in the range of many kilometers. Site response analyses of the small-scale sites in meters are still in the preliminary stage, which are essential for design of shallow bedrock region like PI.

In this study, an attempt has been made to estimate a 2D nonlinear site response analysis of small scale sites selected at shallow bedrock locations in PI. Three shallow bedrock regions are selected for the study at Kalpakkam, Bangalore and Vizag which includes both stiff and soft soil

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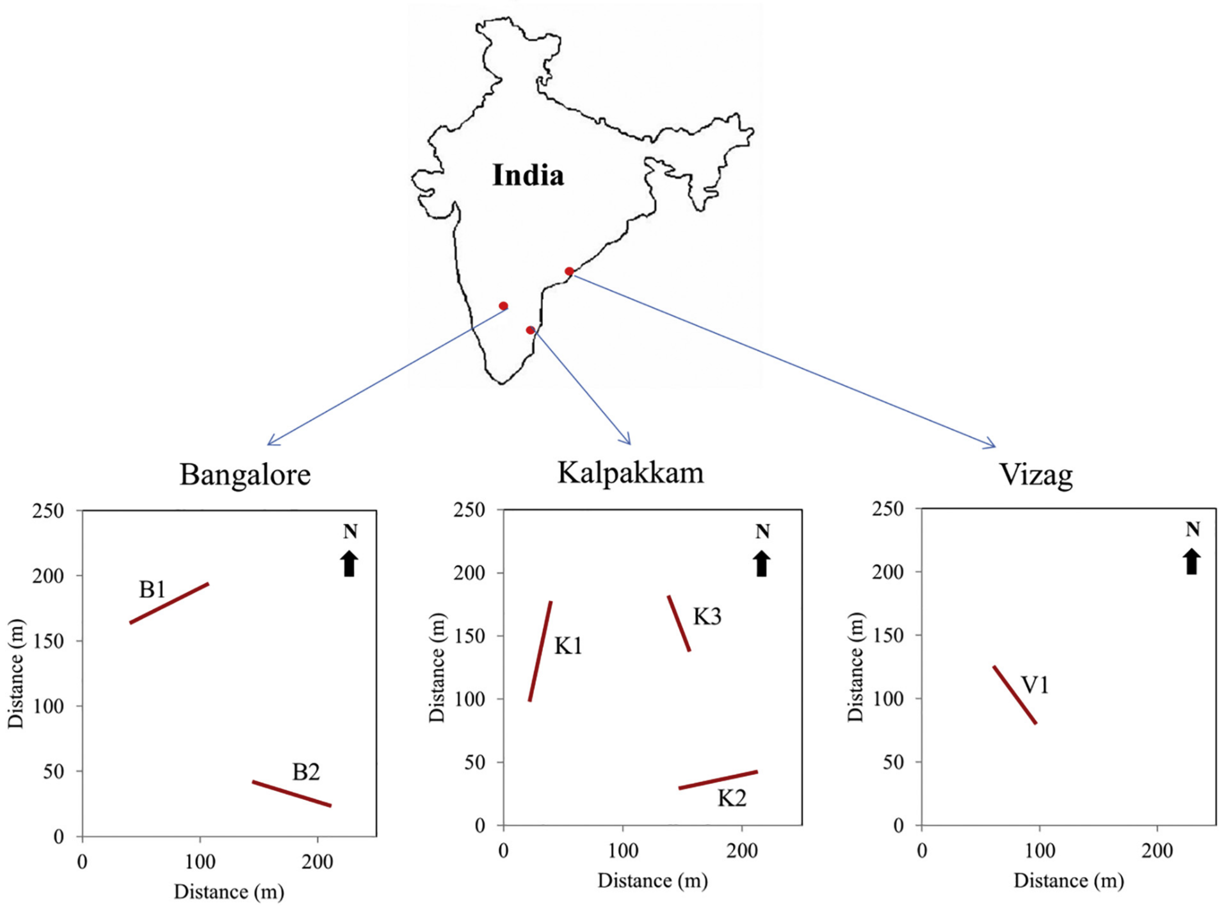

Fig. 1. Location of three selected sites Kalpakkam, Bangalore, and Vizag along with the survey lines.

sites. Multi-Channel Analysis of Surface Waves -2D (MASW- 2D) survey and conventional borehole data with Standard Penetration Test (SPT) were used for the subsurface characterization in 2D at these sites. MASW is a commonly used geophysical method for site characterization (Leucci et al., 2007; Steeples and Miller, 1993; Maheswari

Table 1
Typical soil profile at Kalpakkam site from the SPT borehole data.

BH no	Depth (m)		Thickness (m)	Average N value	Description
	From	To			
KBH 1	0	3	3	13	Loose silty sand
	3	5.5	2.5	20	Greyish silty sand
	5.5	15	9.5	>50	Weathered rock
	15	20	5	>50	Medium to very strong hard rock
KBH 2	0	3	3	15	Greyish silty sand
	3	11	8	>50	Weathered rock
	11	20	9	>50	Medium to very strong hard rock
KBH 3	0	0.5	0.5	8	Loose sand
	0.5	3	2.5	17	Silty sand
	3	12	9	>50	Weathered rock
	12	20	8	>50	Medium to very strong hard rock
KBH 4	0	3	3	20	Loose to dense silty sand
	3	10	7	>50	Weathered rock
	10	20	10	>50	Medium to very strong hard rock

Table 2
Typical soil profile at Bangalore site from the SPT borehole data.

BH no	Depth (m)		Thickness (m)	Average N value	Description
	From	To			
BBH 1	0	3	3	15	Greyish silty sand
	3	6	3	28	Medium dense sand
	6	10	4	>50	Disintegrated weathered rock
BBH 2	0	2	3	8	Loose silty sand
	2	4	3	20	Brownish silty sand
	4	10	4	>50	Disintegrated weathered rock
BBH 3	0	2	2	8	Loose silty sand
	2	8	6	15	Medium dense sand
	8	13	5	28	Dense sand
	13	15	2	>50	Weathered rock

Table 3
Typical soil profile at Vizag site from the SPT borehole data.

BH no	Depth (m)		Thickness (m)	Average N value	Description
	From	To			
VBH 1	0	2.5	2.5	9	Greyish loose silty clay
	2.5	5	2.5	14	Light yellowish silty clay
	5	12	7	30	Brownish medium dense clay
	12	15	3	>50	Highly weathered rock

et al., 2008; Park et al., 1999; Anbazhagan and Sitharam, 2009; Mahajan et al., 2007; Chandran and Anbazhagan, 2017). The subsurface profiles generated are used for the 2D nonlinear site response analysis by using the program FLAC 2D. One dimensional site response analysis is also done at selected points in the survey line using the program DEEPSOIL and the results were compared with the 2D response. Furthermore, a parametric study has also been carried out to quantitatively evaluate the effect of stiffness of subsurface profile on 2D site response analysis.

2. Study area

A stiff soil site at Kalpakkam and two soft soil sites, one at Bangalore and the other at Vizag were selected for the study. The number of survey lines selected at Kalpakkam, Bangalore and Vizag are three, two and one respectively. Locations of these sites along with the survey lines are shown in Fig. 1. The stiff and soft sites are classified based on average shear wave velocity of 30 m depth (Vs^{30}) of sites using the National Earthquake Hazards Reduction Program (NEHRP) (BSSC, 2001) and International Building Code 2009 (IBC, 2009) classification. Bangalore is a metropolitan city and capital of Karnataka state. Peninsular Gneiss Complex (PGC) which consists of gneisses, granites, and migmatites is one of the most predominant rock units in this area. Kalpakkam and Vizag sites are located near to the seashore. Borehole data shows that Kalpakkam and Bangalore sites consist of mainly sandy soil deposits and the Vizag site consists of clayey soil deposits (Tables 1, 2 and 3). Three survey lines selected at the Kalpakkam site are named as K1, K2, and K3. Two survey lines selected at the Bangalore site are named as B1 and B2. The survey line selected at the Vizag site is named as V1. Geophysical testing was carried out along these survey lines.

3. Methodology

The MASW 2-D survey was conducted at six selected locations shown in Fig. 1 and the data were collected. The data were collected by a geode seismograph of 24 channels with a sampling interval of 1 ms. Twenty-four geophones of frequency of 4.5 Hz are spaced at 1 m intervals for the survey (Anbazhagan et al., 2013). A software package of Surfseis (Ivanov and Brohammer, 2010) has been used to process the MASW data. During data analysis, each time-domain shot was converted to the frequency domain by using the fast Fourier transform approach (Park et al., 1999). Then, each transformed shot converted as dispersion curve (a plot of phase velocity versus frequency). A 1D-Vs profile is generated from the dispersion curve by using an iterative nonlinear inversion process (Park et al., 1999). The typical dispersion curve and inverted 1D velocity depth profile for the Kalpakkam site is shown in Fig. 2. All the 1D shear wave velocity profiles along the survey line are interpolated by using a Kriging algorithm in a shot station sequential order and the final continuous 2D-Vs profile was generated. Based on

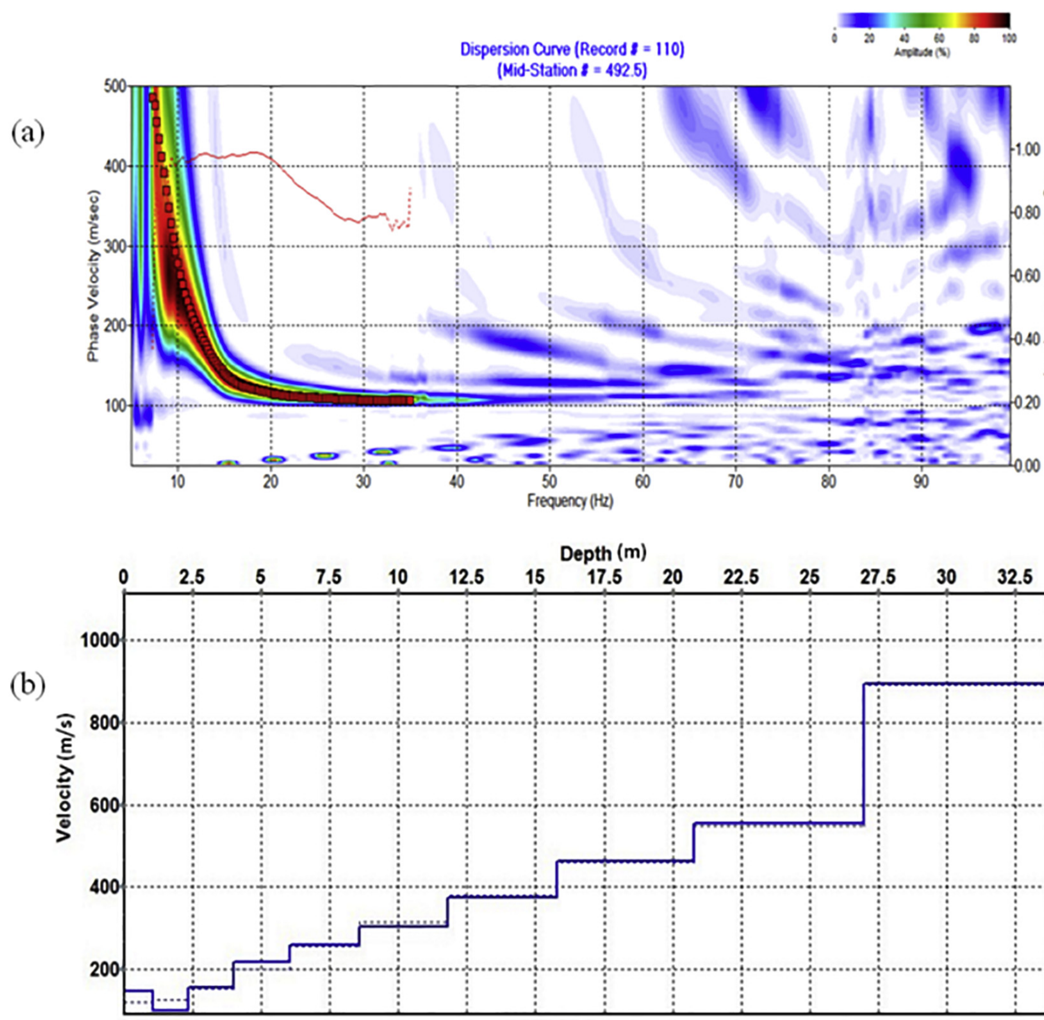

Fig. 2. Typical MASW 1D velocity model at the Kalpakkam site. (a) Extracted dispersion curve (b) Inverted 1D shear wave velocity profile.

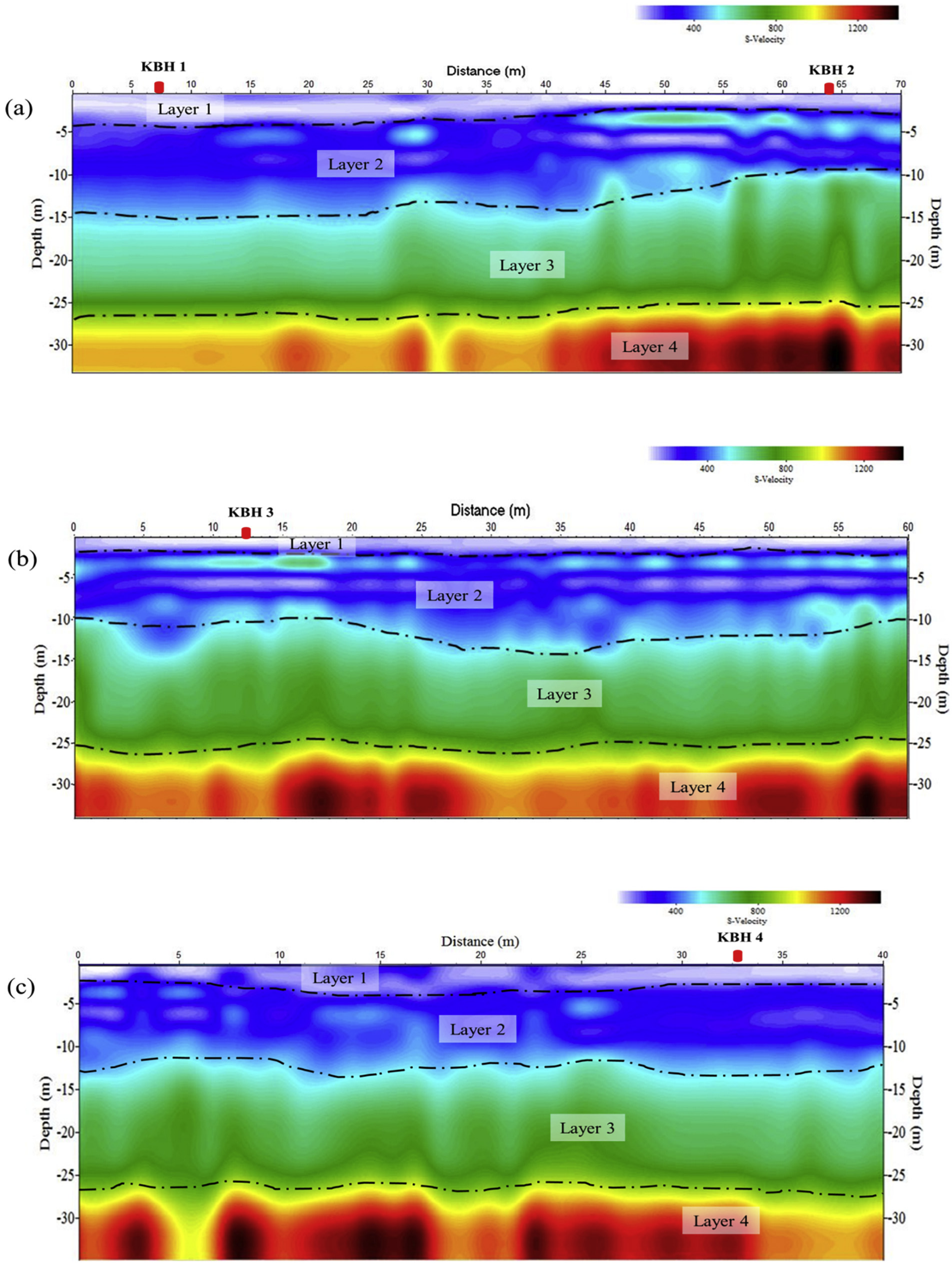

Fig. 3. MASW-2D profiles at Kalpakkam site (a) Line K1 (b) Line K2 (c) Line K3.

the spatial variation of shear wave velocity, different soil layers were interpreted. 2D-Vs profiles have been interpreted by following the previous studies of shear wave velocity (Vs) mapping by many researchers like Maheswari et al., 2008, Shaaban et al., 2013, Leucci et al., 2007, Mahajan et al., 2015, and Anbazhagan and Sitharam, 2009. MASW test results were correlated with borehole data and the final subsurface profiles were generated in 2D. These profiles were used to generate the 2D model for nonlinear site response analysis in the FLAC -2D program of

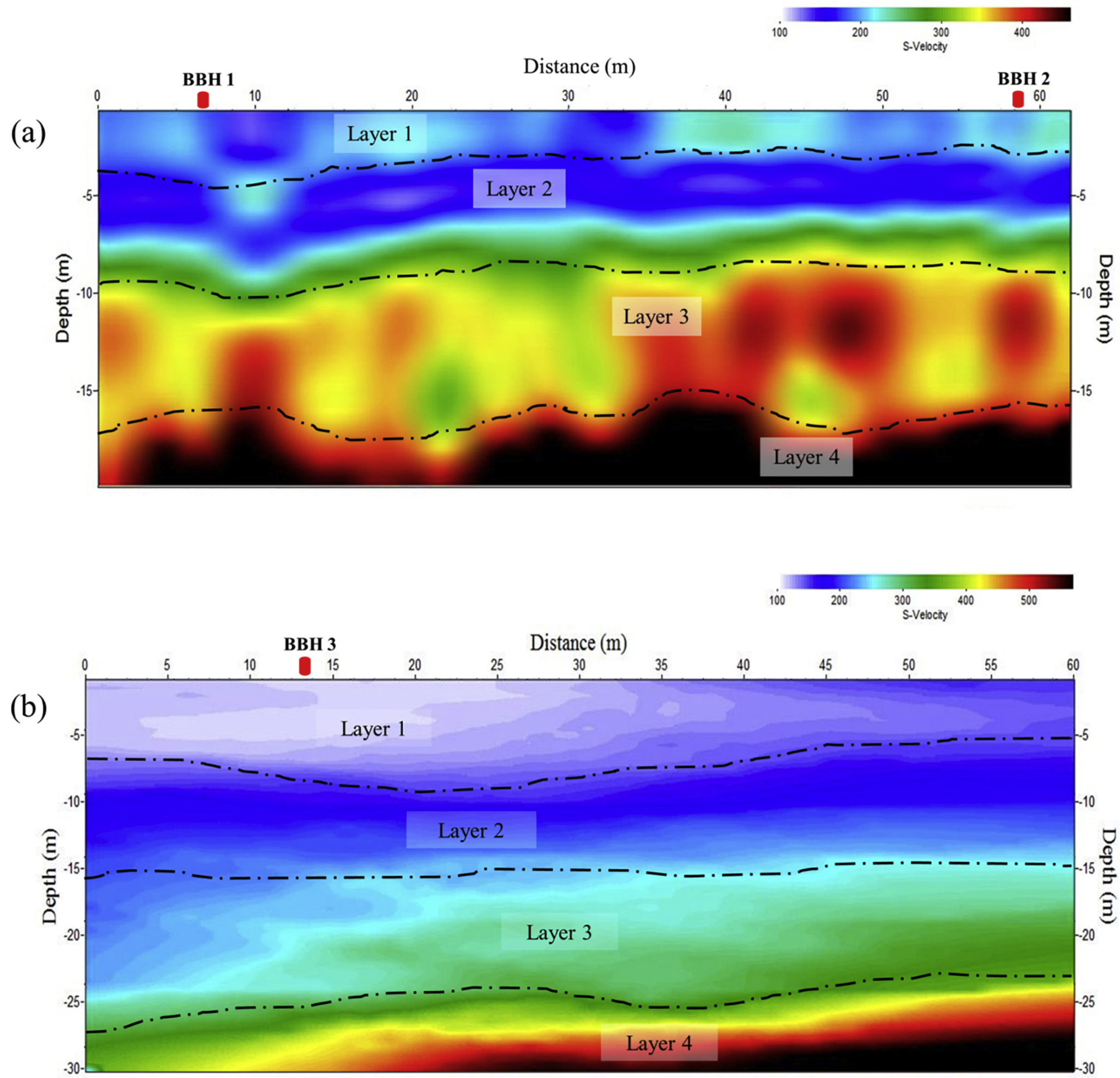

Fig. 4. MASW-2D profiles at Bangalore site (a) Line B1 (b) Line B2.

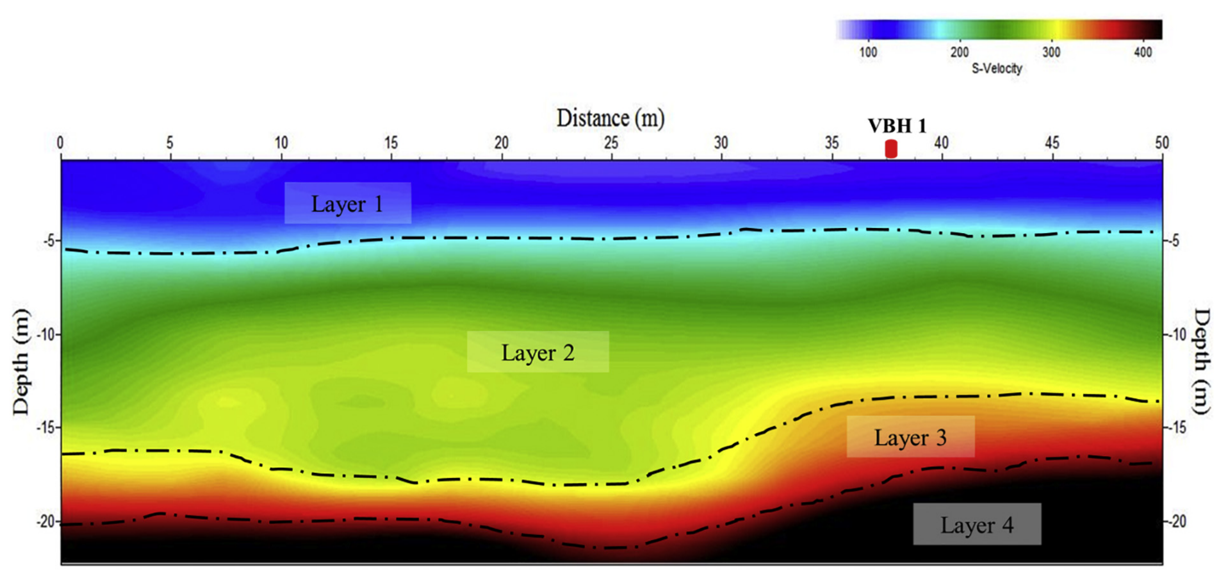

Fig. 5. MASW-2D profile at Vizag, Line V1.

Table 4
Subsurface layer properties selected for the site response analysis at the shallow sites.

Line no	Sub-surface layer	Vs (m/s)	Unit weight (kN/m^3)	Soil type	Modulus reduction curve and damping curve selected
K1	Layer 1	200	14.71	Sand	Seed and Idriss (1970), UL
	Layer 2	360	16.56	Rock	Schnabel (1973)
	Layer 3	800	19.42	Rock	Schnabel (1973)
	Layer 4	1200	21.06	Rock	Schnabel (1973)
K2	Layer 1	200	14.71	Sand	Seed and Idriss (1970), UL
	Layer 2	360	16.56	Rock	Schnabel (1973)
	Layer 3	750	19.17	Rock	Schnabel (1973)
	Layer 4	1200	21.06	Rock	Schnabel (1973)
K3	Layer 1	200	14.72	Sand	Seed and Idriss (1970), UL
	Layer 2	370	16.65	Rock	Schnabel (1973)
	Layer 3	780	19.32	Rock	Schnabel (1973)
	Layer 4	1200	21.06	Rock	Schnabel (1973)
B1	Layer 1	150	12.81	Sand	Seed and Idriss (1970), UL
	Layer 2	260	15.51	Sand	Seed and Idriss (1970), UL
	Layer 3	360	16.56	Rock	Schnabel (1973)
	Layer 4	425	17.11	Rock	Schnabel (1973)
B2	Layer 1	120	13.29	Sand	Seed and Idriss (1970), UL
	Layer 2	180	14.41	Sand	Seed and Idriss (1970), UL
	Layer 3	350	16.46	Rock	Schnabel (1973)
	Layer 4	500	17.68	Rock	Schnabel (1973)
V1	Layer 1	120	13.29	Clay	Sun et al. (1988), UL
	Layer 2	250	15.39	Clay	Sun et al. (1988), UL
	Layer 3	360	16.56	Rock	Schnabel (1973)
	Layer 4	420	17.07	Rock	Schnabel (1973)

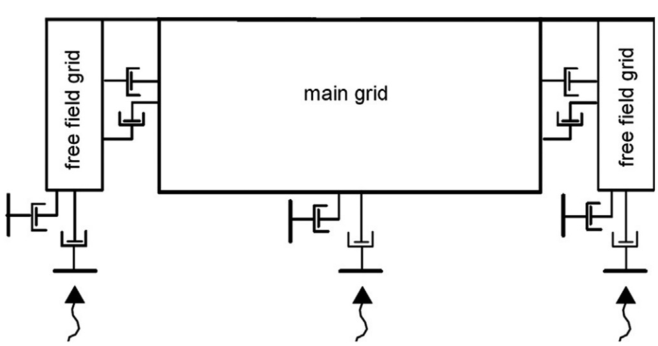

Fig. 6. Schematic illustration of finite difference main grid coupling to free-field grids by viscous dashpots (Khanbabazadeh and Iyisan, 2014).

version 7.0 (Itasca 2013). Further, 1D site response analysis also done at specific points (every 10 m distance) in the survey lines using DEEPSOIL program of version 6.0 (Hashash et al., 2015) and the results were compared with the 2D site response results.

4. Subsurface 2D shear wave velocity profiles

Shear wave velocity profiles generated at Kalpakkam, Bangalore and Vizag are shown in Figs. 3, 4 and 5 respectively. Based on the spatial variations in the shear wave velocity, different soil layers were interpreted. The borehole data summary of these sites Kalpakkam, Bangalore and Vizag were shown in Tables 1, 2 and 3 respectively. Standard Penetration Test (SPT) has been conducted at each borehole by following IS 2131 (1981) and SPT N value has been recorded. Table 1 shows that, at Kalpakkam site sandy soil is available nearly up to 3 m depth and after that weathered rock starts. In the Bangalore site, sandy soil is present till deeper depth and after that weathered rock begins (Table 2). In the Vizag site, clayey soil is present till deeper depth and after that weathered rock starts (Table 3). The locations of these boreholes are marked in the 2D Vs profiles (Figs. 3, 4 and 5) and used to correlate the geophysical test results. Typical 2D Vs profile at the line K1 is shown in Fig. 3a. The locations of the boreholes are marked in this profile. The 2D- Vs profile shows four sub-surface layers that are marked using black dotted lines. The layer 1 (2–5 m thick) has an average shear wave velocity of 200 m/s, whereas the layer 2 located at the depth range 10–15 m has an average shear wave velocity of 360 m/s. Layer 3 is extended up to 26 m depth and is having an average velocity range of 800 m/s. The last layer i.e. layer 4 is extended up to a depth of 33 m with an average velocity of 1200 m/s. Top layer 1 most likely corresponds to the sandy soil at the top and layer 2 mostly corresponds to the weathered rock in the borehole data (Table 1). Hence the borehole data is matching well with the geophysical test results. MASW 2D profiles for lines K2, K3, B1, B2, and V1 are also interpreted similarly and are shown in Fig. 3b, c, 4a, b and 5 respectively. MASW 2D profiles at these lines also have a four-layered structure similar to the line K1. The layer properties interpreted from all these 2D profiles and SPT borehole data for numerical modeling are presented in Table 4.

5. 2D dynamic modeling parameters and input ground motions

Two-dimensional dynamic analysis has been done for all the six profiles using the program FLAC- 2D (Itasca, 2013). FLAC is an explicit finite difference program that performs Lagrangian analysis to model the soil profile (Itasca, 2013). The materials are assumed to be elastic and dry. A combination of two advanced dynamic boundary conditions, one at the

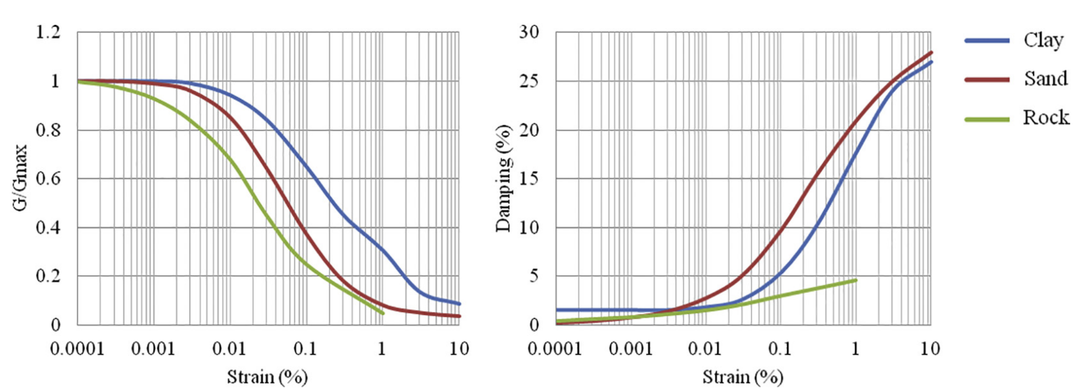

Fig. 7. Shear modulus and damping curves used for sand, clay and rock layers.

Table 5
Intraplate earthquake motion selected for the site response analysis from Anbazhagan et al. (2017).

Earthquake	Station	Motion code	PGA (g)	Epi dist (km)	Predominant period, Tp (Sec)	Magnitude
Saguaney 1988	St.-Ferreol	A1-enr	0.121	115.827	0.15	5.6
Saguaney 1989	Quebec	A2-enr	0.0506	147.615	0.1	5.6
Saguaney 1990	Baie-St-Paul	A7-ent	0.174	105.068	0.2	5.6
Saguaney 1991	La	A8-enr	0.124	124.192	0.15	5.6
Saguaney 1992	St.-Pascal	A9-en2	0.0558	164.996	0.15	5.6
Saguaney 1993	Riviere-Ouelle	A10-ent	0.057	148.398	0.15	5.6
Saguaney 1994	Chicoutimi	A16-ent	0.131	45.142	0.04	5.6
Saguaney 1995	Andre-Lac-Jean	A17-enr	0.156	91.847	0.04	5.6
Saguaney 1996	Les	A20-enr	0.126	112.94	0.2	5.6
Quebec 2005	A61–2005	A61–2005	0.07	29.696	0.04	5.4
Quebec 2006	A21–2005	A21–2005	0.084	13.3	0.05	5.4
Alaska 2008	A21–2008	A21–2008	0.077	5.553	0.03	4.7
Virginia 2011	VA	Virginia	0.098	53.5	0.05	5.8

base and other at the sides, was used at the model boundaries. To simulate the real situation of interaction between the bedrock and the soil, quiet boundaries were used at the base of the model (Lysmer and Kuhlemeyer, 1969). The quiet-boundary scheme involves dashpots attached independently to the boundary in the normal and shear directions. The dashpots provide viscous normal and shear tractions given by.

$$t_n = -\rho C_p\, v_n \tag{1}$$

$$t_s = -\rho C_s\, v_s \tag{2}$$

where v_n and v_s are the normal and shear components of the velocity at the boundary; ρ is the mass density; and C_p and C_s are the p- and s-wave velocities. These viscous terms are not introduced directly into the equations of motion of the grid points lying on the boundary, but the normal and shear tractions are calculated and applied at every time step in the same way as boundary loads are applied. As a result, it prevents the reflection of outward propagating waves back into the model and allows the necessary energy radiation.

Free-field boundaries were set at the vertical boundaries to simulate the infiniteness of the media at the sides (Cundall, 1980). The procedure is to “enforce” the free-field motion in such a way that vertical boundaries retain their non-reflecting properties. This approach used in the continuum finite-difference code NESSI (Cundall, 1980) is developed for FLAC via Free-Field boundary condition which involves the execution of free-field calculations in parallel with the main-grid analysis.

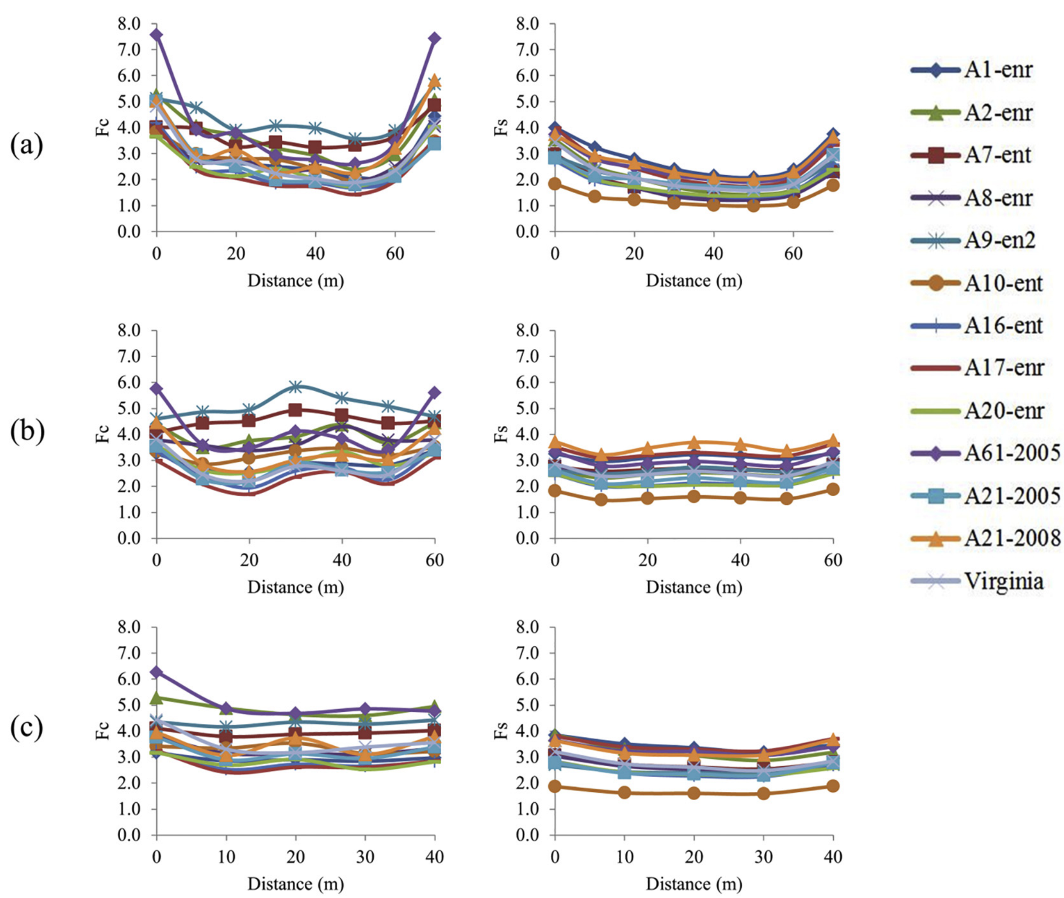

Fig. 8. Variation of average spectral amplification factors correspond to the stiff soil sites (a) Line- K1 (b) Line- K2 (c) Line- K3.

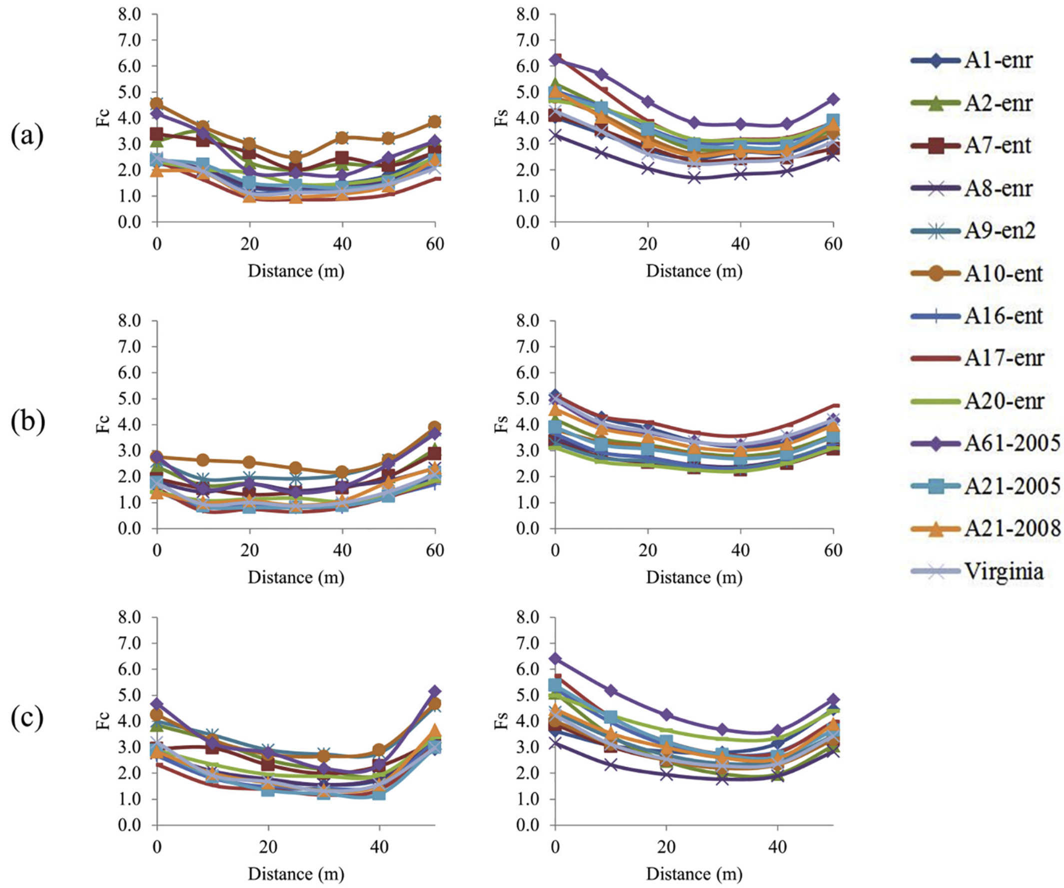

Fig. 9. Variation of average spectral amplification factors correspond to the soft soil sites (a) Line- B1 (b) Line- B2 (c) Line- V1.

The unbalanced forces applied from free-field grid to the main grid are as:

$$F_x = -\rho C_p \left(v_x{}^{m} - v_x{}^{ff}\right) A + F_x{}^{ff} \tag{3}$$

$$Fy = -\rho C_s \left(v_y{}^{m} - v_y{}^{ff}\right) A + F_y{}^{ff} \tag{4}$$

where ρ denotes the material density along the vertical model boundary and A is the influence area of the free-field gridpoint. C_p and C_s are the p and s-wave speed at the side boundary, respectively. The denotations of the other parameters are as follow:

v_x^m, v_y^m = x and y gridpoint velocity in the main grid at side boundary;

v_x^{ff},v_y^{ff} = x and y gridpoint velocity in the side free-field;

Fx^{ff}, Fy^{ff} = free-field gridpoint force with contributions from σ_{xx}^{ff} and σ_{xy}^{ff} stresses of the free-field zones around the gridpoint;

A combination of these two advanced formulations is used in this research. Fig. 6 shows the schematic coupling of the main grid to free-field grids by viscous dashpots.

To prevent the numerical distortion related to the frequency content of input motion, the size of the spatial element was selected smaller than one-tenth of the wavelength associated with the highest frequency component of the wave (Kuhlemeyer and Lysmer, 1973). Hysteretic damping is used for the energy dissipating response. The backbone curves selected are Seed and Idriss (1970) upper limit (UL) curve for the sand, Sun et al. (1988) upper limit (UL) curve for the clay, and Schnabel (1973) curve is used for the rock as per Bajaj and Anbazhagan (2019). Table 4 column 6 gives details of shear modulus and damping curves used for site response analysis (Fig. 7).

All the three regions considered in this study are coming in the PI, which is considered as a "Stable Continental Region (SCR)". Many damaging earthquakes are reported in this region, e.g. Bhuj (2001, Mw 7.6), Latur (1993, Mw 6.1), Koyna (1967, M 6.5), and Jabalpur (1997, Mw 5.8). These are intraplate earthquakes which caused considerable damages. However, due to poor instrumentation, the recordings of these earthquake events are not available. Also, many seismic hazard analyses are presented for PI by various researchers (Kumar et al., 2012; Vipin et al., 2009; Anbazhagan et al., 2009; Raghukanth, 2011; Ramanna and Dodagoudar, 2012). These studies show that selected sites may have the potential for ground motion of PGA (Peak ground acceleration) 0.05 g to 0.2 g. Hence thirteen intraplate recordings for site response analysis from Anbazhagan et al. (2017) have been selected. The summary of these earthquake data is presented in Table 5.

6. 2D site response analysis and amplification factor

The dynamic analysis of six locations in Peninsular India is presented here. 2-D nonlinear site response analyses are performed by using FLAC -2D on all six locations subjected to thirteen input motions. Subsurface layer properties and backbone curves selected for the three locations are shown in Table 4. The unit weight of the material corresponds to each layer is measured from the density Vs correlation by Anbazhagan et al., 2016. Responses are recorded at many observation points (every 10 m) at the surface of the soil profile and acceleration response spectra are generated with a 5% damping. Amplification of ground motion at various portions of the spectrum is conveniently expressed as

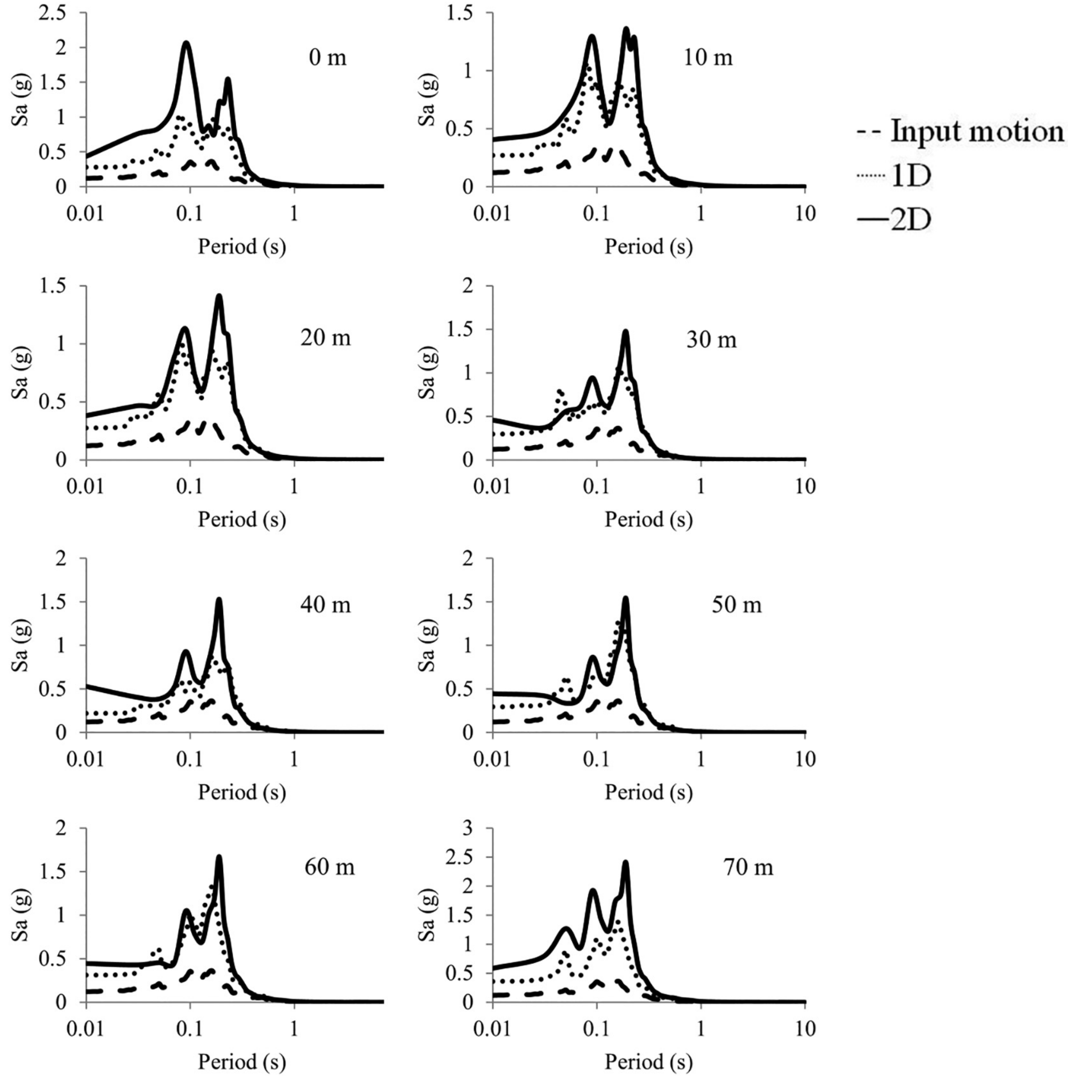

Fig. 10. Comparison between 2D and 1D response spectra at different observation points at the surface along the survey line K1.

the amplification factor or site coefficient. Newmark and Hall (1982) suggested amplification factors corresponding to acceleration, velocity and displacement response for different damping values, calculated from acceleration time history. They used the ratios between spectral values and peak ground-motion parameters (accelerations, velocity, and displacement) to determine the average amplification factors used in the construction of smooth-response spectra. Hall et al. (1975) assumed that the Spectral accelerations (SAs) for periods <0.33 s is sensitive to acceleration region, those for periods between 0.33 s and 3.33 s are sensitive to velocity region, and the rest is sensitive to displacement region. IBC (2009) suggested the site coefficients as a short period amplification factor (corresponding to 0.2 s time period) Fa and long period amplification factor (corresponding to 1 s time period) Fv. The coefficients were calculated using the ratio of response spectra (RRS) or ratio of Fourier spectra (RFS) of the soil and corresponding rock records. The coefficients are provided as a function of site class and mapped spectral acceleration, where site class is determined according to the shear velocity, SPT N or undrained shear strength. Dobry et al., 2000 suggested three types of site coefficients as short-period (0.01–0.1 s) amplification factor, F1, mid-period (0.1–0.5 s) amplification factor, F2 and long-period (0.4–2 s) amplification factor, F3. Factors F1, F2 and F3 using a ratio of response spectra. Most of these studies, region was arrived based on earthquake data from active region and very limited intraplate ground motion data were used to arrive control period. Aditya (2014) studied cut of period and amplification of shallow bedrock sites in PI. In this study, a short-period amplification factor (Fc) range from 0.01 s to 0.06 s and long period amplification factor (Fs) range from 0.05 s to 1 s are taken similar to Aditya (2014) for the intraplate earthquake data. Factors Fc and Fs can be calculated using equations as follows

$$Fc = \frac{Rsoil}{Rrock}\frac{1}{0.05}\int_{0.01}^{0.06}\frac{RSsoil(T)}{RSrock(T)}dT \quad (5)$$

$$Fs = \frac{Rsoil}{Rrock}\frac{1}{0.95}\int_{0.05}^{1}\frac{RSsoil(T)}{RSrock(T)}dT \quad (6)$$

where, RSsoil and RSrock are response spectra on soil and rock at a given period T, and Rsoil and Rrock are the hypocentral distances of soil and rock stations. The ratio of Rsoil/Rrock was assumed to be 1.0 in this study as rock and surface spectral hypocentral distance is similar.

Variations of average spectral amplification factor in terms of Fc and Fs with distance at the stiff soil sites correspond to thirteen ground motions are shown in Fig. 8. Results show that the average spectral amplification curves are changed with the different ranges of the period of the ground motion. It shows that the values of short-period amplification

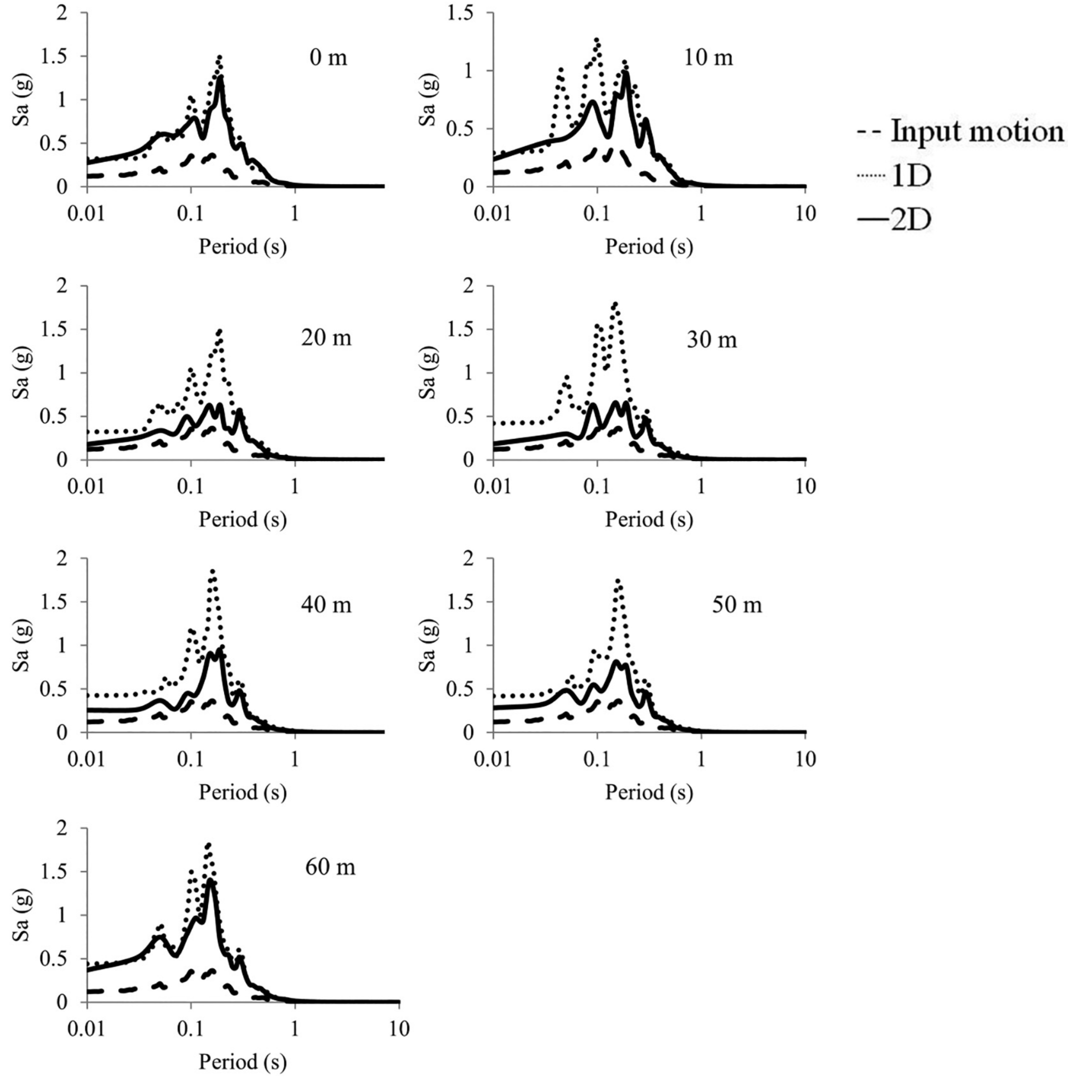

Fig. 11. Comparison between 2D and 1D response spectra at different observation points at the surface along the survey line B1.

factor Fc are relatively higher than the values of long period amplification factor Fs. The trend of Fc with distance is more complex and undulating than Fs. The trend of Fs is showing almost uniform values throughout the profile especially in the case of lines K2 and K3. The amplification pattern in terms of Fc is showing a different trend for different ground motions. But in the case of Fs, the trend is almost the same for most of the ground motion. This shows that 2D geometry is more sensitive to higher frequency content (short-period) of input motion in the case of stiff soil.

Fig. 9 shows the variation of average spectral amplification factors for the soft soil sites. It shows that the Fc values are relatively lower than Fs values. In this case, it is not possible to clearly distinguish the higher complexity in the trend of Fc than Fs as in this case of stiff soil site. But still, the result shows that the trend of Fc with distance is relatively more undulating than Fs. From Figs. 8 and 9 it is clear that the trend of Fs values with distance at the soft soil site is relatively more complex than that of the stiff soil sites. Hence it is showing that the 2D geometry is sensitive to both higher and lower frequency content of input motion in the case of soft soil site.

7. Comparison with 1D site response analysis and aggravation factor

1D site response analysis was carried out at the selected observation points (every 10 m distance) in the survey lines using the DEEPSOIL program and the results were compared with the 2D response results. All input parameters are the same for both 1D and 2D analysis. Typical acceleration response spectra correspond to an input motion A2-enr for the stiff soil sites at K1 (Kalpakkam) is shown in Fig. 10. It can be observed that 2D spectral accelerations are comparatively higher than 1D in the case of stiff soil site Kalpakkam. The acceleration response spectra correspond to the other stiff soil sites at K2 (Appendix Fig. 18) and K3 (Appendix Fig. 19) is also showing a similar trend as that of K1. Fig. 11 shows the typical acceleration response spectra correspond to an input motion A2-enr for the soft soil sites at B1 (Bangalore). But in this case, the trend of spectral signature shows a reverse trend such that 1D response seems to be greater than that of 2D. The acceleration response spectra correspond to the other two soft soil sites at B2 (Appendix Fig. 20) and V2 (Appendix Fig. 21) also shows a similar trend as that of B1.

To compare the 2D amplification factors with 1D, aggravation factors (AG) were generated. Aggravation factor (AG) is defined as the ratio of 2D acceleration or amplification factor to the corresponding 1D acceleration or amplification factor at a point (Iyisan and Khanbabazadeh, 2013). The aggravation factor in terms of Fc (AG_{Fc}) and Fs (AG_{Fs}) corresponds to stiff and soft soil sites were generated as follows:

$$AG_{Fc} = Fc_{2D}/Fc_{1D} \tag{7}$$

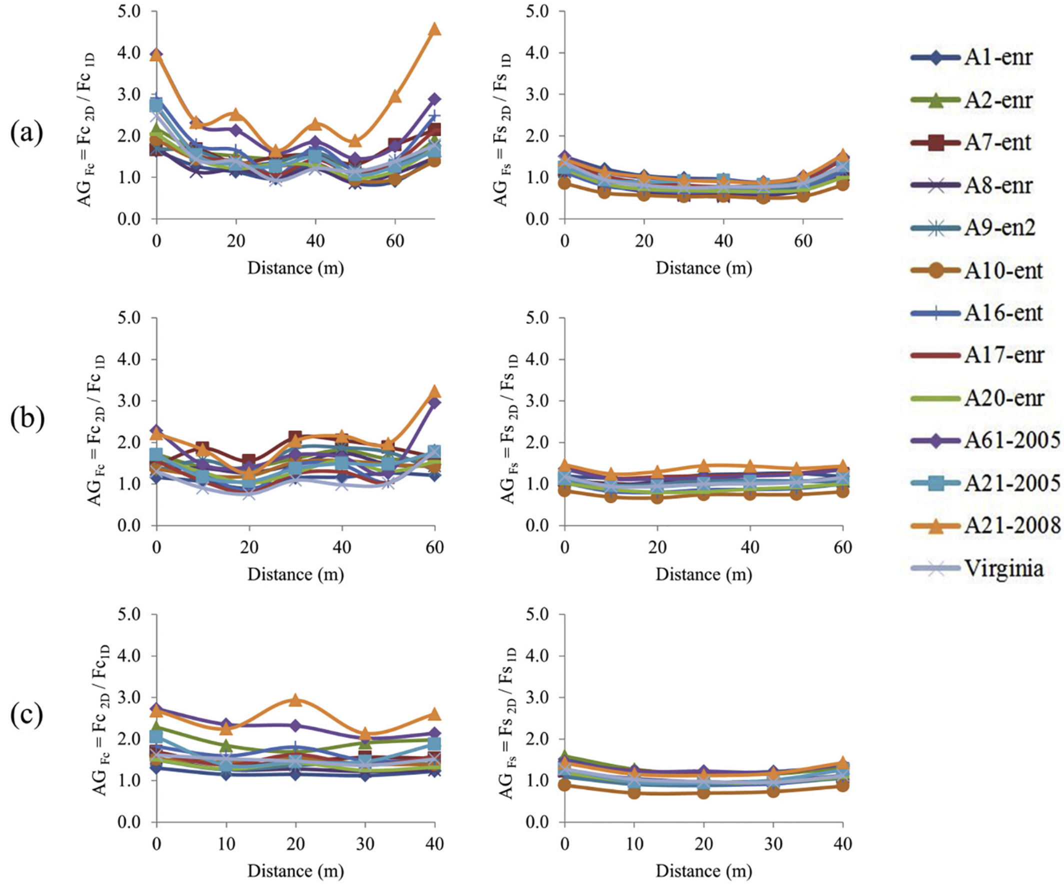

Fig. 12. Aggravation factor variation at the stiff soil sites (a) Line- K1 (b) Line- K2 (c) Line- K3.

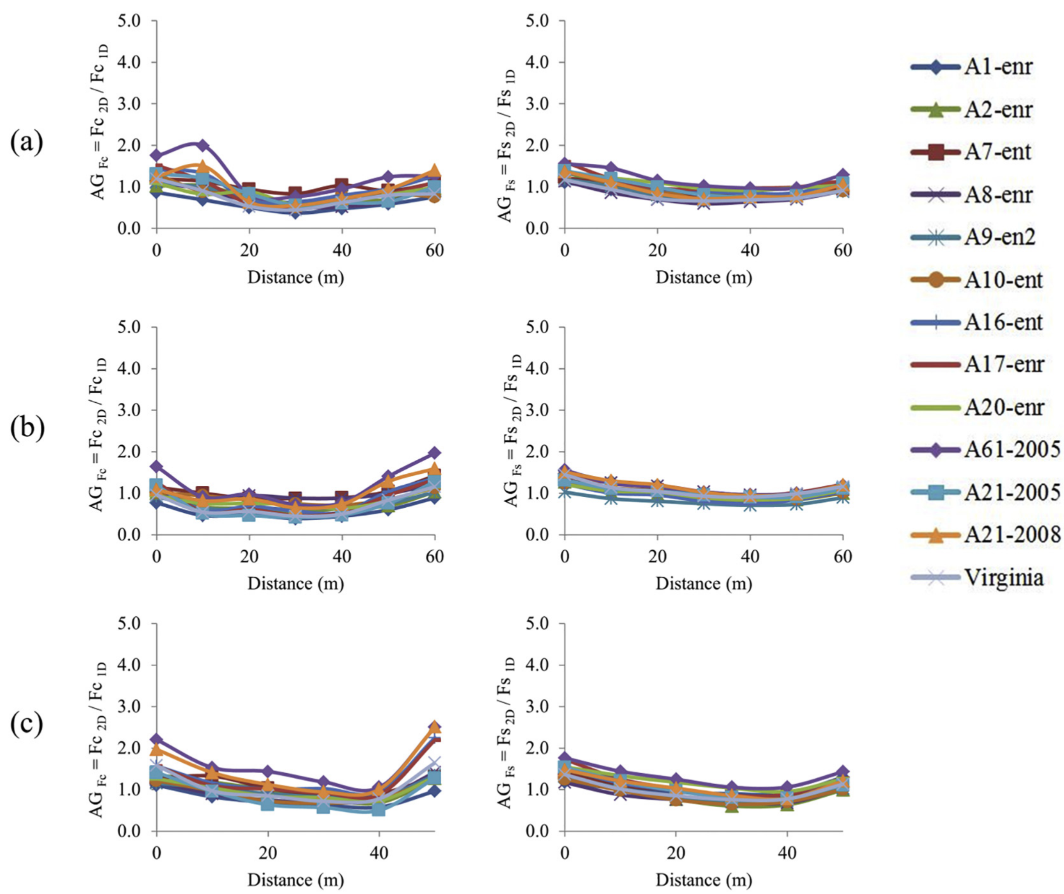

Fig. 13. Aggravation factor variation at the soft soil sites (a) Line- B1 (b) Line- B2 (c) Line- V1.

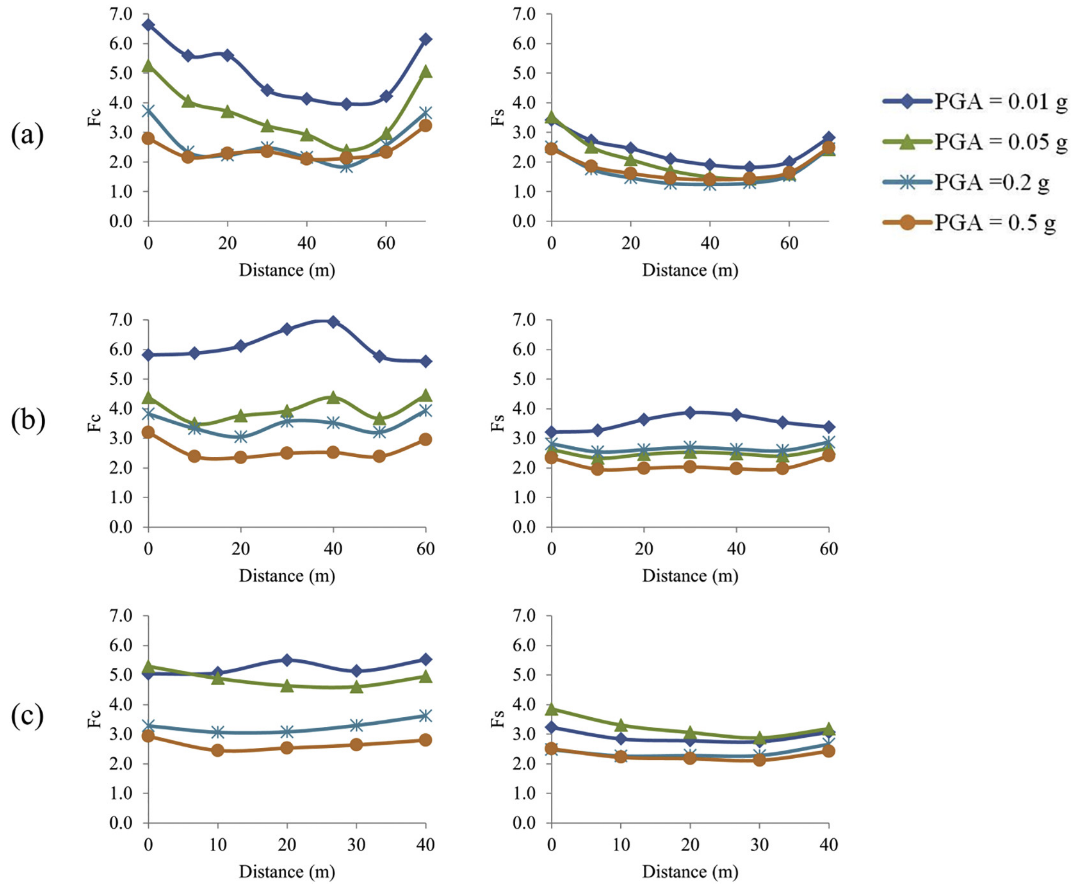

Fig. 14. Variation of average spectral amplification factors correspond to different amplitudes of input motion A2-enr at the stiff soil sites (a) Line- K1 (b) Line- K2 (c) Line- K3.

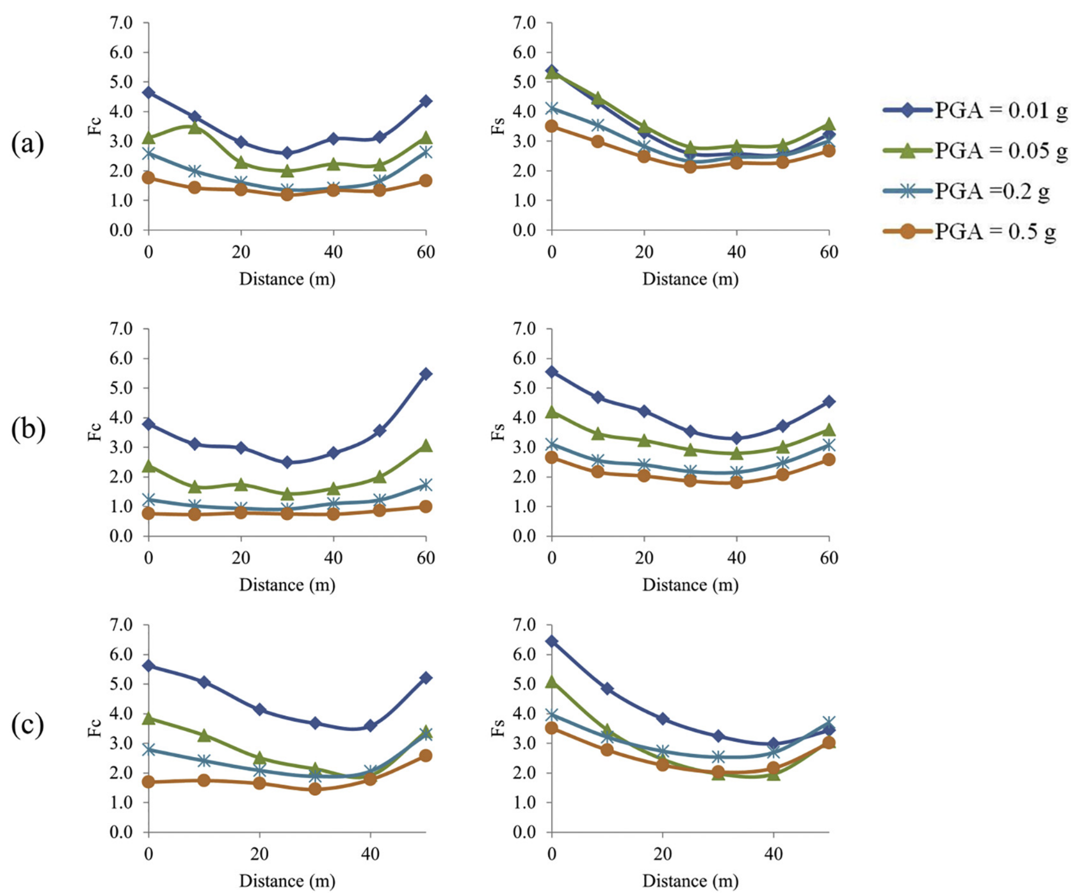

Fig. 15. Variation of average spectral amplification factors correspond to different amplitudes of input motion A2-enr at the soft soil sites (a) Line- B1 (b) Line- B2 (c) Line- V1.

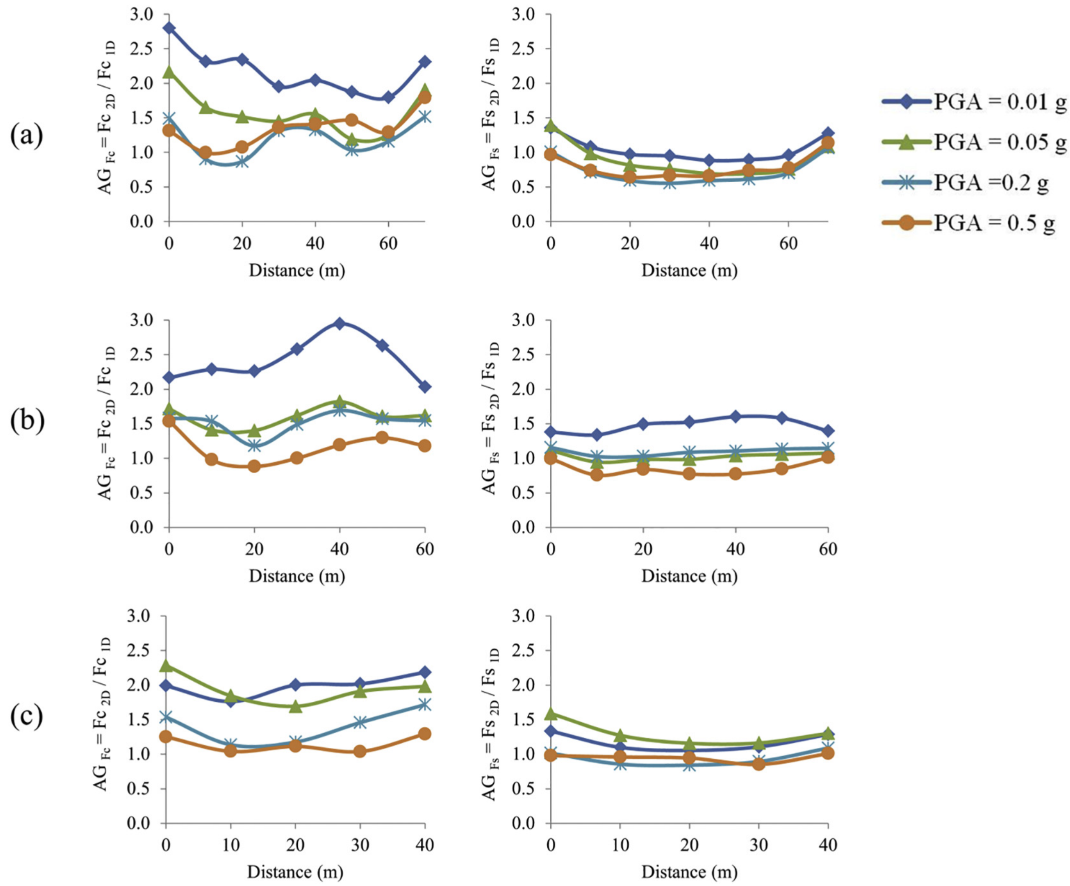

Fig. 16. Aggravation factor variation correspond to different amplitudes of input motion A2-enr at the stiff soil sites (a) Line- K1 (b) Line- K2 (c) Line- K3.

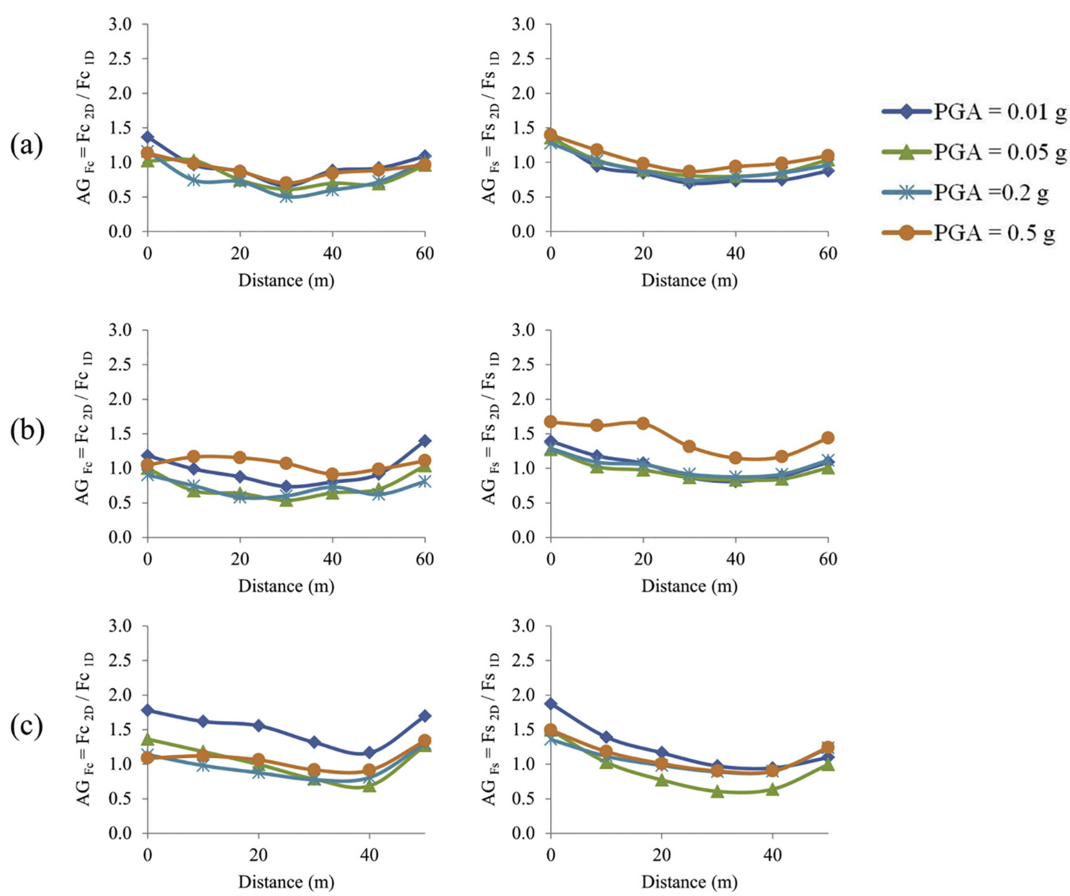

Fig. 17. Aggravation factor variation correspond to different amplitudes of input motion A2-enr at the soft soil sites (a) Line- B1 (b) Line- B2 (c) Line- V1.

$$AG_{Fs} = Fs_{2D}/Fs_{1D} \quad (8)$$

The variation of AG $_{Fc}$ and AG $_{Fs}$ corresponds to stiff soil site is shown in Fig. 12. The results show that in the case of stiff soil sites, the overall behavior pattern of AG $_{Fc}$ is very complex and also showing higher values than one. But in the case of AG $_{Fs,}$ it is showing an almost uniform trend throughout the profile and showing a value close to one. Hence the results show that in the case of stiff soil sites, the 2D amplifications are more dominant and higher than 1D corresponds to the higher frequency content of ground motion. Also, the 2D amplifications are less sensitive to low-frequency content of ground motion and showing almost similar amplification values as that of 1D.

The variation of AG $_{Fc}$ and AG $_{Fs}$ corresponds to soft soil site is shown in Fig. 13. The results show that in the case of soft soil sites, the trend of AG $_{Fc}$ is less complex than that corresponds to stiff sites. But at the same time, the trend of AG $_{Fc}$ is relatively more undulating than the trend of AG $_{Fs.}$ The trend of AG $_{Fs}$ is less complex and showing almost a uniform curve. The values of aggravation factors are showing almost equal to one or lesser values than one in many cases. Hence it is showing that the 2D amplifications are not differing much with 1D amplification in the case of soft sites when compared to stiff sites.

8. Parametric study

It is noticed from the above section that, the stiff soil sites undergo more spectral amplification than the soft soil sites in the case of short-period (0.01 s - 0.06 s) of ground motion and a reverse trend is occurring in the case of the long period (0.05 s – 1 s) of ground motion. Further, a parametric study has been carried out to quantitatively evaluate the effect of different intensities of ground motion on the 2D site response. A typical intraplate ground motion A2-enr has been selected and it is scaled to four different amplitudes of 0.01 g, 0.05 g, 0.2 g, and 0.5 g through linear scaling method. It is done by applying suitable scaling factors to the amplitude axis of the record (Jaramillo, 2003; Watson-Lamprey, 2007). A2-enr is selected and it is scaled to four different PGA values 0.01 g, 0.05 g, 0.2 g, and 0.5 g by multiplying every data of acceleration record by a scale factor of $0.01/PGA_{A2\text{-}enr}$, $0.05/PGA_{A2\text{-}enr}$, $0.2/PGA_{A2\text{-}enr}$ and $0.5/PGA_{A2\text{-}enr}$ respectively. All the four input motions with different amplitude values were used for the site response analysis and the amplification factors correspond to the stiff and soft soil sites are shown in Figs. 14 and 15 respectively. The result shows that 2D amplifications are increasing with the decrease in the amplitude of ground motion. The maximum amplification is occurring for 0.01 g and minimum amplification occurs for 0.5 g. Also, the 2D amplification pattern seems to be uniform when the intensity of ground motion increases to 0.5 g and it became very undulating when the amplitude decrease to 0.01 g. In the case of stiff soil, short-period amplifications (Fc) are relatively higher than long period amplification (Fs) (Fig. 14) and a reverse trend is occurring in the case of soft soil (Fig. 15).

Aggravation factor (AG) variations correspond to different amplitudes of input motion A2-enr at the stiff and soft soil sites are shown in Figs. 16 and 17 respectively. The results show that in the case of stiff sites the values of aggravation factors are increasing with the decrease in the amplitude of input motion especially in the case of AG $_{Fc}$ (Fig. 16). The trend of AG $_{Fc}$ seems to be more complex than the trend corresponds to AG $_{Fs}$ (Fig. 16). This shows that in the case of stiff soil sites subsurface heterogeneity has very less effect in site response if the ground motion intensity is very high and vice versa. In the case of soft soil sites, there is no specific trend observed in the values of aggravation factor with the variations in the amplitude of input motion as in the case of stiff soil sites (Fig. 17). It is showing that the values of aggravation factors are almost close to one and less complex than correspond to the stiff soil sites especially in the case of AG $_{Fc}$ (Fig. 17). This shows that amplitude of input motion is more sensitive to 2D geometry of subsurface in the case of stiff soil and it is relatively less sensitive in the case of soft soil.

9. Summary and conclusions

In this study, subsurface profiling is done at three shallow bedrock sites in Peninsular India such as Kalpakkam, Bangalore and Vizag using the MASW-2D method. Three survey lines were selected from the stiff soil site at Kalpakkam and three survey lines selected from the soft soil sites at Bangalore and Vizag. By correlating the geophysical test results with the conventional SPT borehole data, the final subsurface layer properties were generated to model site response.

Two-dimensional dynamic analysis was done on all the six profiles using FLAC-2D through proper boundary conditions and includes hysteresis damping. Thirteen intraplate ground motions were selected as input for the analysis. Results of the site response analysis are expressed in terms of short-period amplification factor (Fc) and long period amplification factor (Fs). In the case of stiff soil sites short-period amplification factor is showing higher values than the long period amplification factor and it is reversed in the case of soft soil site. The results of 2D dynamic analysis was compared with 1D analysis using DEEPSOIL and aggravation factors were generated. The aggravation factors show that in the case of stiff soil sites the 2D amplifications are seemed to be higher than 1D, especially for Fc. In the case of soft soil, it is showing a trend such that the 2D amplifications are almost equal to or lower than 1D amplification for most of the cases. Hence it is showing that the 2D response is less sensitive to ground motions in the case of soft sites when compared to stiff sites.

A parametric study has been done to quantitatively evaluate the effect of different amplitudes of input motion on the 2D site response. A typical intraplate ground motion A2-enr has been selected and it is scaled to four different amplitudes of 0.01 g, 0.05 g, 0.2 g, and 0.5 g through linear scaling method and used as the input motions for the site response analysis. The result shows that 2D amplifications are increasing with the decrease in the amplitude of ground motion. Also, the amplification pattern is becoming more complex corresponds to the low amplitude of the ground motion. The values of aggravation factors showing an increasing trend with the decrease in the amplitude of ground motion in the case of stiff soil sites and in the case of soft soil sites it is not showing any specific trend. Hence the parametric study shows that subsurface heterogeneity is highly sensitive to low-intensity ground motions especially in the case of stiff soil sites.

Author statement

Deepu Chandran and Anbazhagan P

- The corresponding author, Prof. P. Anbazhagan - is responsible for ensuring that the descriptions are accurate and agreed by all authors.
- Deepu Chandran carried out Field, studies, data processing, analysis and drafted paper
- Anbazhagan is obtain funding for the study, equipment's and software required for the study, permission for the field work and financial support for entire study. He also corrected draft paper prepared by Deepu Chandran and supervising his research work as PhD guide.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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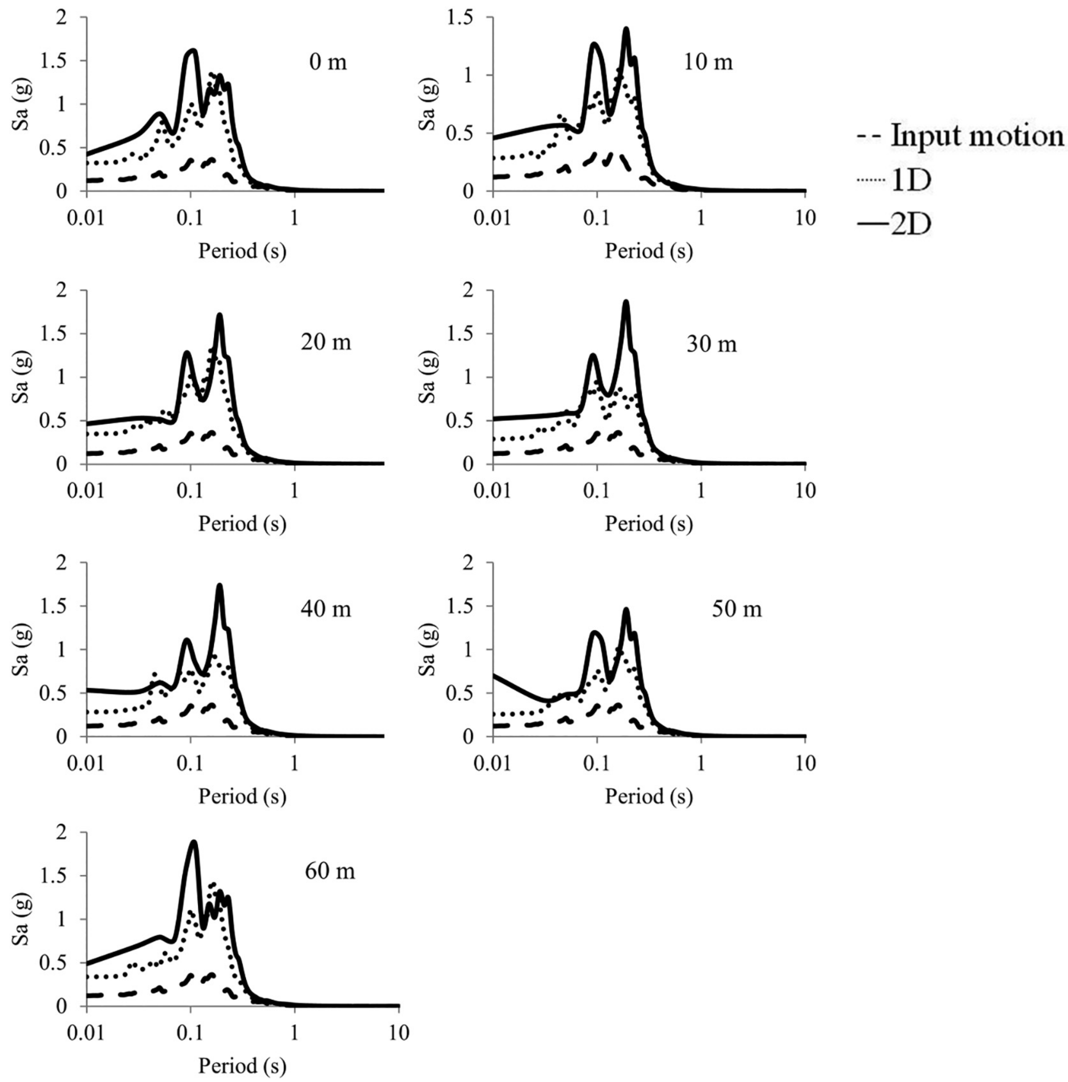
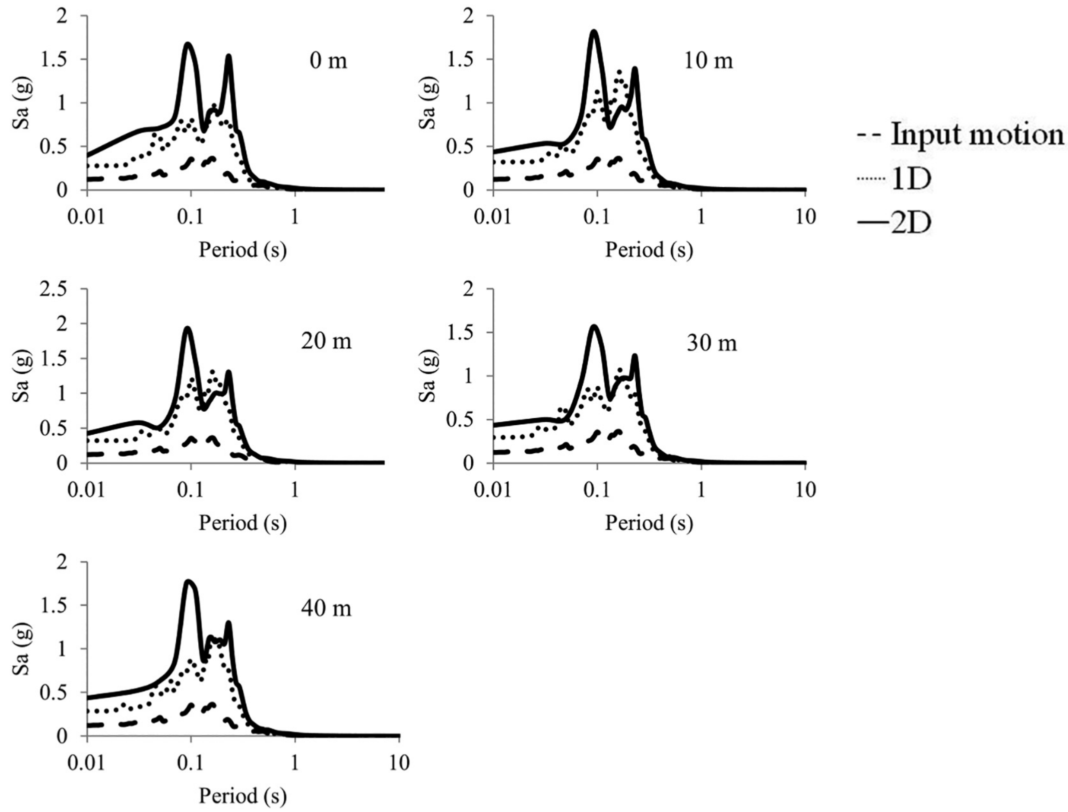
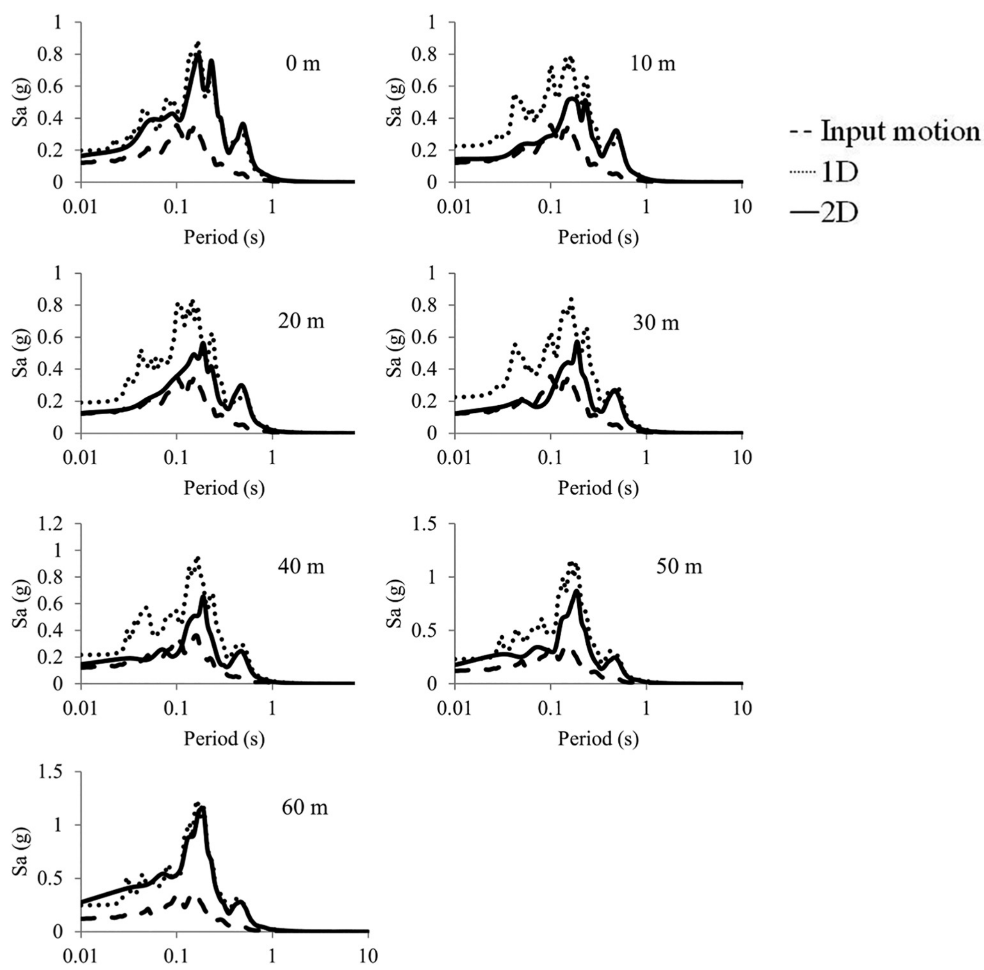
Appendix A



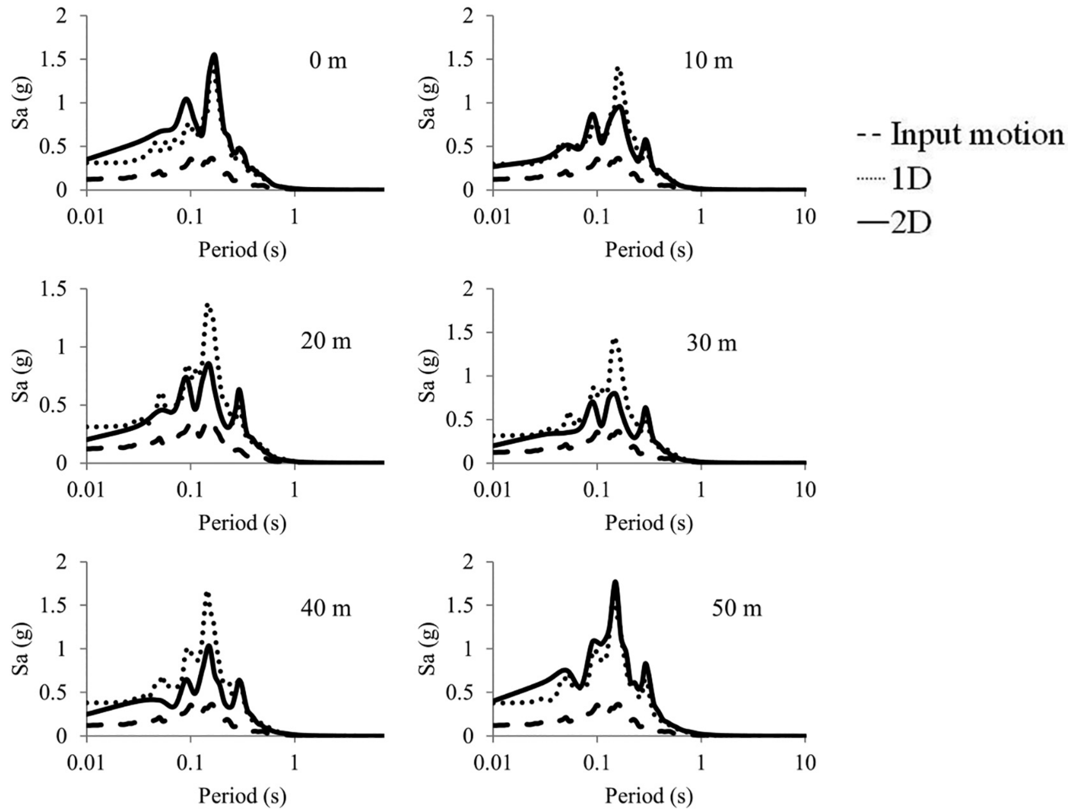
Appendix Fig. 18. Comparison between 2D and 1D response spectra at different observation points at the surface along the survey line K2.



Appendix Fig. 19. Comparison between 2D and 1D response spectra at different observation points at the surface along the survey line K3.



Appendix Fig. 20. Comparison between 2D and 1D response spectra at different observation points at the surface along the survey line B2.



Appendix Fig. 21. Comparison between 2D and 1D response spectra at different observation points at the surface along the survey line V1.

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