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ORIGINAL RESEARCH

Investigation on site-specific seismic response analysis for Bucharest (Romania)

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Abstract
In this study, the nonlinear seismic response analysis of five sites with deep boreholes in Bucharest (Romania) is performed. A ground motion database consisting of recordings obtained during several Vrancea intermediate-depth earthquakes is compiled for the analyses. The results of the nonlinear site response analysis show that significant long-period spectral amplifications occur for all five sites and that the level on input peak ground acceleration influences in a significant manner the spectral amplifications, both as median value and variability. In addition, the differences in terms of site amplification factors between the five analysed sites also increase with the level of the input peak ground acceleration levels. The median site amplifications decrease with the increase of the peak ground acceleration for spectral periods of up to 2.0 s, while for longer periods the median site amplifications increase. The results of the nonlinear site response analysis were also validated by using real ground motions recorded in the same area during recent Vrancea intermediate-depth earthquakes.

Keywords Vrancea intermediate-depth seismic source · Site amplification factors · Ground motion recordings · Shear wave velocity · Peak ground acceleration · Seismic hazard

1 Introduction

Bucharest, the capital of Romania has been historically affected by earthquakes originating in the Vrancea intermediate-depth seismic source, situated at the bend of the Carpathian Mountains, at epicentral distances ranging between 100 and 180 km. The focal depths of most of the Vrancea intermediate-depth earthquakes are in the range 70–180 km. The combination between the local geology and the large magnitude (e.g. moment magnitude $M_W \geq 7.0$) of the Vrancea earthquakes has generated long-period spectral amplitudes

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observed at several sites in Bucharest during the Vrancea earthquakes of March 1977 and August 1986.

The local geology of Bucharest has been discussed in several papers (e.g. Wirth et al. 2003; Sokolov et al. 2004; Bala et al. 2006, 2009, 2011; Pavel et al. 2018). It has been observed that the Quaternary deposits in Bucharest area can be divided into seven main layers, among which the first one consists of backfill, the second and the sixth layer are a mix of clayey and sandy deposits, the third, fifth and seventh layers consist of sands and gravels (they are the three aquifers of Bucharest), while the fourth one is composed mainly of clays (Bala et al. 2006, 2009). Among the most interesting features of the local geology of Bucharest, the bedrock depth greater than 500–700 m and the alternation down to 300 m in depth of Quaternary sandy and clayey (or gravel) deposits are the most noteworthy. The engineering bedrock can be considered as a marl layer situated below the last sandy and gravel layers. However, there are no velocity measurements performed in boreholes which extend up to that depth. It has also been noticed that the thickness of the last two deposits decreases from the north part of the city from 200 to 300 m towards the southern part where the thickness reaches 100–150 m (Bala et al. 2011). Liteanu (1961) drew a map of the limit between tertiary and quaternary deposits in the Romanian Plain (where Bucharest is situated) and the limit depth is in the range 200–300 m for Bucharest area. A similar value was proposed for INCERC site by Constantinescu and Enescu (1985) and Yamanaka et al. (2007) using genetic algorithms inversion. Manea et al. (2016) have found depths up to the cretaceous bedrock ranging from 1200 m in the northern part of the city up to about 700 m in the southern part. The current seismic design code of Romania P100-1/2013 (2013) uses as proxy for the soil conditions the control period T_C. As such, Bucharest is characterised by $T_C = 1.6$ s, which represents one of the largest control periods encountered in the world (larger values can be encountered for instance in Mexico-City as shown by Ordaz and Meli 2004).

In this paper, we perform the first nonlinear site response analyses for five sites with deep boreholes situated in Bucharest area. The nonlinear site response analyses are performed using as input the shear waves' velocity profiles up to a depth of 150 m or even 200 m (Bala et al. 2011; Calarasu 2012). These velocity profiles are among the deepest currently available for sites situated in Bucharest area. A sensitivity analysis using uncertain soil parameters is also performed for a selected soil model (INC). A validation of the results obtained thorough nonlinear site response analysis is also performed using ground motions recorded at four different seismic stations in Bucharest area during several recent Vrancea earthquakes.

2 Description of analysed sites

A total of three categories of sites are used in this paper:

- Five sites with deep boreholes (denoted as IMGB, INC, OTP, POLI and VIC) for which the velocity profiles are available;
- Four sites with recordings at stations at surface and at borehole (PRC, SMU, UTC1, UTC2) for which the velocity profiles are available;
- Eight sites (GRG, PIT, VLM, VRN, CRC, CVD, BAA, TLC) which are not in Bucharest are and which were taken from Pavel et al. (2019) for which only the horizontal-to-vertical spectral ratios (HVSR) are available.

The use of each category of sites is described in this section and in the subsequent one. The position of the five studied deep boreholes (IMGB, INC, OTP, POLI and VIC) are situated in shown in Fig. 1. In addition, also in Fig. 1 are shown the positions of four sites (PRC, SMU, UTC1, UTC2) where ground motions were recorded at surface and in boreholes during the Vrancea earthquake of October 27, 2004.

The shear wave velocity profiles of the five analysed sites with deep boreholes are illustrated in Fig. 2, and are taken from the works of Bala et al. (2011) and Calarasu (2012). It can be observed that with the exception of the IMGB borehole which is the most southern situated among the five sites, the shear wave velocity at the bottom of the borehole is smaller than 600 m/s. The depth of each borehole, as well as the average shear wave velocity in the upper 30 m of soil deposits ($v_{s,30}$) and on the entire depth of the boreholes are given in Table 1.

According to the criteria given in Eurocode 8 (CEN 2004) for $v_{s,30}$ ranges, the sites can be classified as soil class C (four sites) or soil class B (IMGB site). However, one can also notice that the difference in terms of average shear wave velocities computed on the entire depth of the borehole is much smaller than in the case of the $v_{s,30}$ metric. In addition, the slow increase of the shear wave velocity with the depth is also noteworthy, as well as the intercalation of softer layers at various depths visible in the case of all five boreholes.

Fig. 1 Locations of the five sites with deep boreholes and locations of the sites in which ground motions were recorded during the 2004 Vrancea earthquake

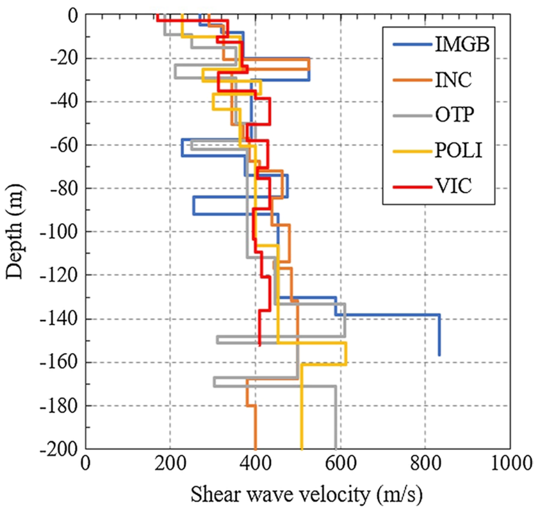


Fig. 2 Shear wave velocity profiles of the five analysed deep boreholes from Bucharest area (Bala et al. 2006; Calarasu 2012)

Table 1 Depths and average shear wave velocities for the five deep boreholes

Name	Depth (m)	$v_{s,30}$ (m/s)	$v_{s,borehole}$ (m/s)
IMGB	155	368	411
INC	205	341	412
OTP	200	238	380
POLI	200	285	403
VIC	152	314	387

3 Site-specific seismic response analysis

The DeepSoil (Hashash et al. 2016) code is used for performing the nonlinear site-specific seismic response analyses. The Pressure-Dependent Modified Kondner Zelasko (MKZ) soil model and the Non-Masing hysteretic model (MRDF Pressure-Dependent Hyperbolic) as incorporated in DeepSoil code (2016) are used for the nonlinear analyses. The following G-γ curves were used:

- Vucetic and Dobry (1991) for clayey deposits;
- Seed et al. (1986) for gravel deposits;
- Seed and Idriss (1969)—mean values for sandy deposits.

A ground motion database consisting of recordings obtained during four Vrancea i earthquakes (the events of 1986, 1990—two events and 2004) are used in the analysis. The characteristics of the ground motion database are given in Table 2. The relation between the peak ground acceleration and the hypocentral distance of the recording stations is illustrated in Fig. 3. The selection of the ground motion recordings was performed based on the following criteria:

Table 2 Characteristics of the ground motion events used for nonlinear site response analyses

Earthquake date	Magnitude M_W	Focal depth (km)	Stations	Hypocentral distance (km)	PGA range (g)
30.08.1986	7.1	131	7	138–235	0.03–0.19
30.05.1990	6.9	91	7	134–244	0.05–0.17
31.05.1990	6.4	87	6	133–245	0.01–0.07
27.10.2004	6.0	105	3	174–247	0.01–0.08

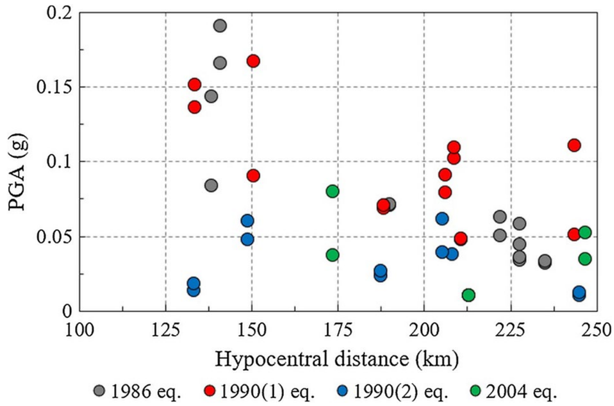


Fig. 3 PGA vs hypocentral distance for the ground motion recordings used for nonlinear site response analyses

- The hypocentral distance for each recording should be in the range of values (140–250 km) expected for sites situated in Bucharest area in the case of earthquakes originating in the Vrancea seismic source.
- The peak ground acceleration (PGA) of all the horizontal components should be larger than 0.01 g.
- The site conditions of the seismic station should be similar to those encountered at the bottom part of the borehole. Unfortunately, there are very few seismic stations in Romania (with the exception of those situated in Bucharest) for which the measured shear wave velocity profiles are available. As such, in order to evaluate the $v_{s,30}$ for each seismic station we used the topographic slope method of Wald and Allen (2007). Thus, the $v_{s,30}$ values for each seismic station are only inferred. Next, we checked the site amplification factors computed from horizontal-to-vertical spectral ratios (HVSR) of the ground motions recorded on each individual site.

The final database complied for this study consists of 46 horizontal components recorded during the four above-mentioned seismic events in eight different stations. Based on the topographic slope method of Wald and Allen (2007), the inferred $v_{s,30}$ for each seismic station is in the range 400–600 m/s.

The mean HVSR curves for the eight above-mentioned sites were taken from the recent work of Pavel et al. (2019) and are illustrated in Fig. 4. It can be noticed that clear site fundamental periods can be observed from the mean HVSR curves for all the sites, and that the site fundamental period does not exceed 0.6 s. Consequently, according to the criteria of Pitilakis et al. (2018) related to the site fundamental period, the eight sites can be classified as being class A, B1 or B2. Next, the normalized acceleration

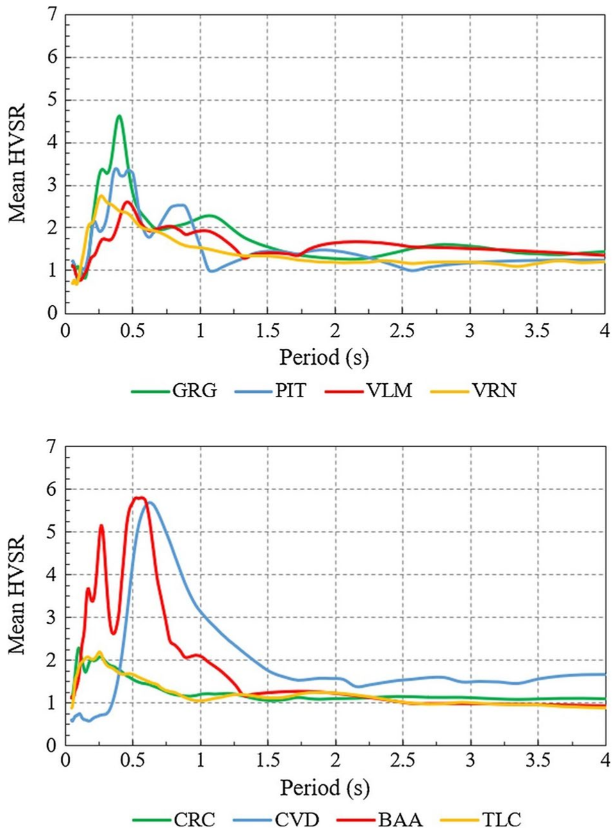


Fig. 4 Mean HVSR curves taken from Pavel et al. (2019) for the sites with ground motion recordings used in nonlinear site-specific seismic response analysis

response spectra (ratio between the spectral acceleration and the peak ground acceleration) for all 46 horizontal components recorded at the eight sites, as well as the mean and mean ± one standard deviation normalized acceleration response spectra are shown

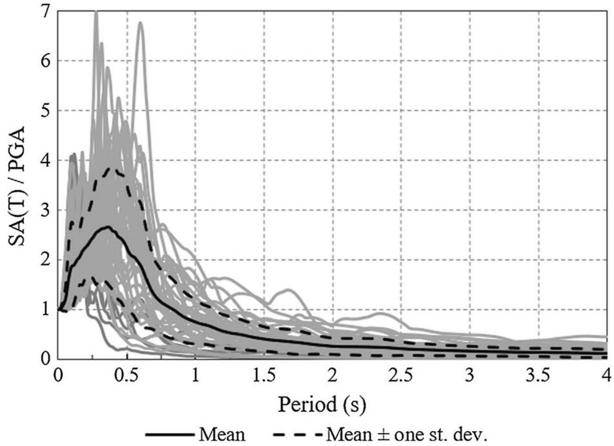


Fig. 5 Individual normalized acceleration response spectra for 46 horizontal components used in nonlinear site-specific seismic response analysis. The mean and mean ± one standard deviation normalized acceleration response spectra are also shown

in Fig. 5. It can also be noticed that the largest spectral amplifications occur for periods smaller than 0.6 s (as in the case of the site fundamental period).

The following hypotheses were applied for the nonlinear site-specific seismic response analysis:

- All the recordings are scaled as a function of the PGA in the range 0.05–0.45 g (with an increment of 0.1 g). The upper limit of the scaling factors for each horizontal component is 10. As such, for larger values of peak ground acceleration, the number of useable horizontal components is smaller than 46 (the minimum number is 29 for PGA = 0.45 g).
- The horizontal components were applied at the bottom part of each borehole, with the exception for the IMGB profile for which the horizontal components were applied in the softer layer overlaying the last one.
- For each analysis, the amplification factors computed as the ratio of the spectral accelerations at surface and the spectral accelerations at various depths of the borehole were obtained.

The median site amplification factors computed for the entire depth of the borehole and as a function of the input level of the peak ground acceleration are shown in Fig. 6. The variation in the shape of the spectral amplifications as a function of the input level of the peak ground acceleration, as well as the shift of the maximum spectral amplification towards longer periods as the input PGA increases are several noteworthy aspects from Fig. 6. The corresponding standard deviations of the site amplification factors as a function of the input peak ground acceleration are also illustrated in Fig. 6. As in the case of the median site amplification factors, there is a shift towards longer period range of the larger values of the standard deviations for all considered sites.

Subsequently, the median site amplification factors for three levels of input peak ground acceleration (e.g. 0.05 g, 0.25 g and 0.45 g) are shown in Figs. 7, 8 and 9. The median site amplifications are computed for each site as the ratio of the spectral accelerations at the surface and the ones at 30 m (Fig. 7), 90 m (Fig. 8) and 150 m (Fig. 9). The results show differences between the median site amplification factors for all three depths which increase with the level of the input peak ground acceleration. In the case of the larger input peak ground acceleration it can be observed that the median site amplification when considering 150 m of the borehole is different in the case of IMGB site (the one situated in the southern part of Bucharest) as compared to the other four sites. This issue can be also due to the significant shear wave velocity contrast encountered at the bottom part of IMGB borehole. Moreover, it can be observed that there are differences between the five sites when considering also the first 30 m or 90 m of the boreholes. It is also noticeable that the site amplifications for INC, POLI and VIC stations which are situated at approximately the same latitude are very similar both for the depth range 0–90 m, as well as for 0–150 m. The variation of the median site amplification as a function of the input peak ground acceleration and of the spectral period for all five analysed sites is shown in Fig. 10. One can notice that the median site amplification for spectral periods of up to 2.0 s decrease with the increase of the input peak ground acceleration. However, for longer spectral periods, the trend is reversed, an increase of the median site amplifications being observed with the increase of the input peak ground acceleration.

The considerable influence of the input level of the peak ground acceleration on the site amplifications is also another important aspect.

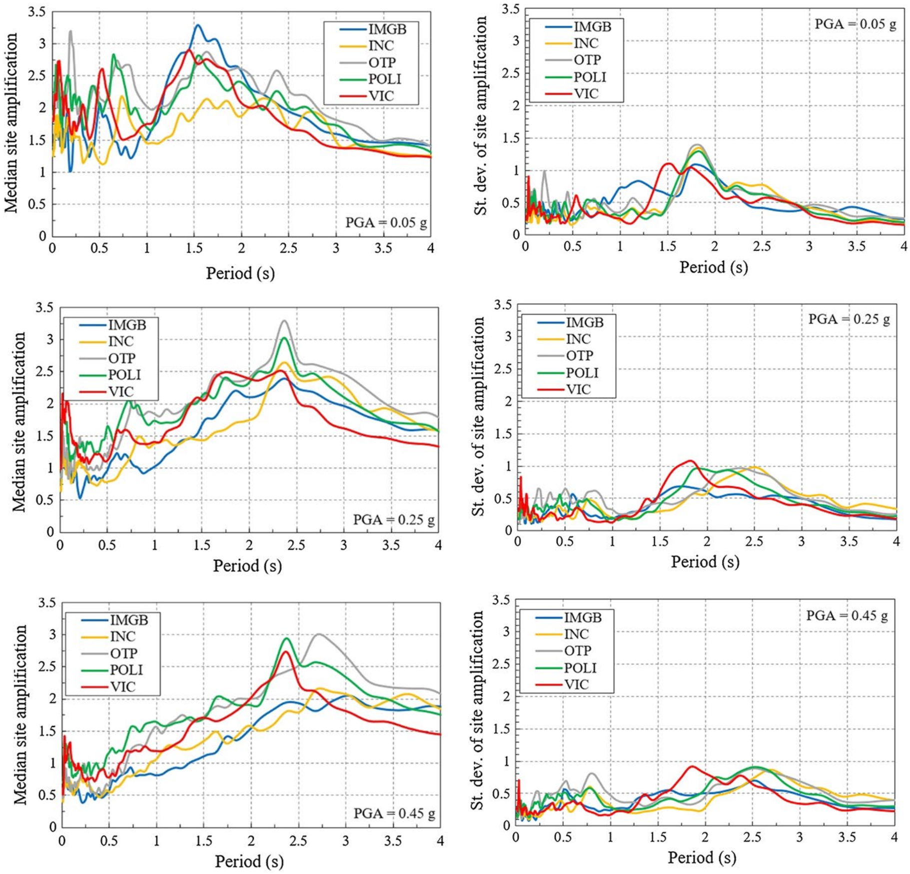


Fig. 6 Median and standard deviation of the site amplification factors for the five analysed sites as a function of the input level of PGA

4 Effect of variability of soil properties on site amplification

The sensitivity analysis for a soil model to uncertain soil parameters for most practical engineering applications is generally acknowledged. Various studies have been carried out through sensitivity analyses to uncertain soil parameters in site response characteristics. Faccioli (1976) developed a stochastic approach to soil amplification, Roblee et al. (1996) addressed the variability in site specific seismic ground-motion design predictions, Bazzurro and Cornell (2004) studied ground motion amplification in nonlinear soil sites with uncertain properties and Toro (1995) develop realistic stochastic fields of elastic and nonlinear dynamic soil properties. A common method to account for epistemic uncertainty in soil properties (Vs and damping characteristics) when performing site response analyses is to use a median/base-case profile along with upper—(i.e., stiffer) and lower-boundary (i.e., softer) profiles as well randomization procedures to develop a suite of soil models that account for aleatory variability.

In this study, a representative site (INC) is considered to incorporate the uncertainties of soil properties through randomization using the code DeepSoil (Hashash et al.

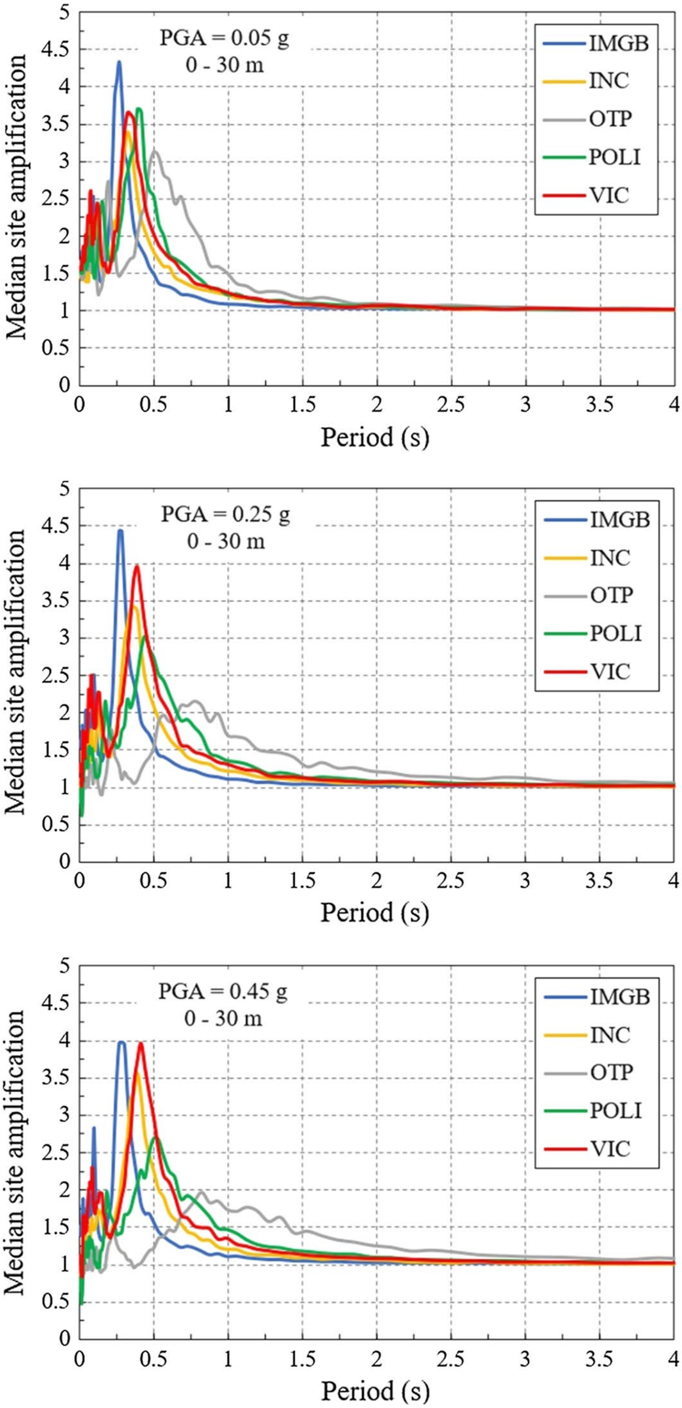


Fig. 7 Comparison of the median site amplification factors computed for the five analysed sites between 0 and 30 m for three levels of peak ground acceleration (0.05 g, 0.25 g and 0.45 g)

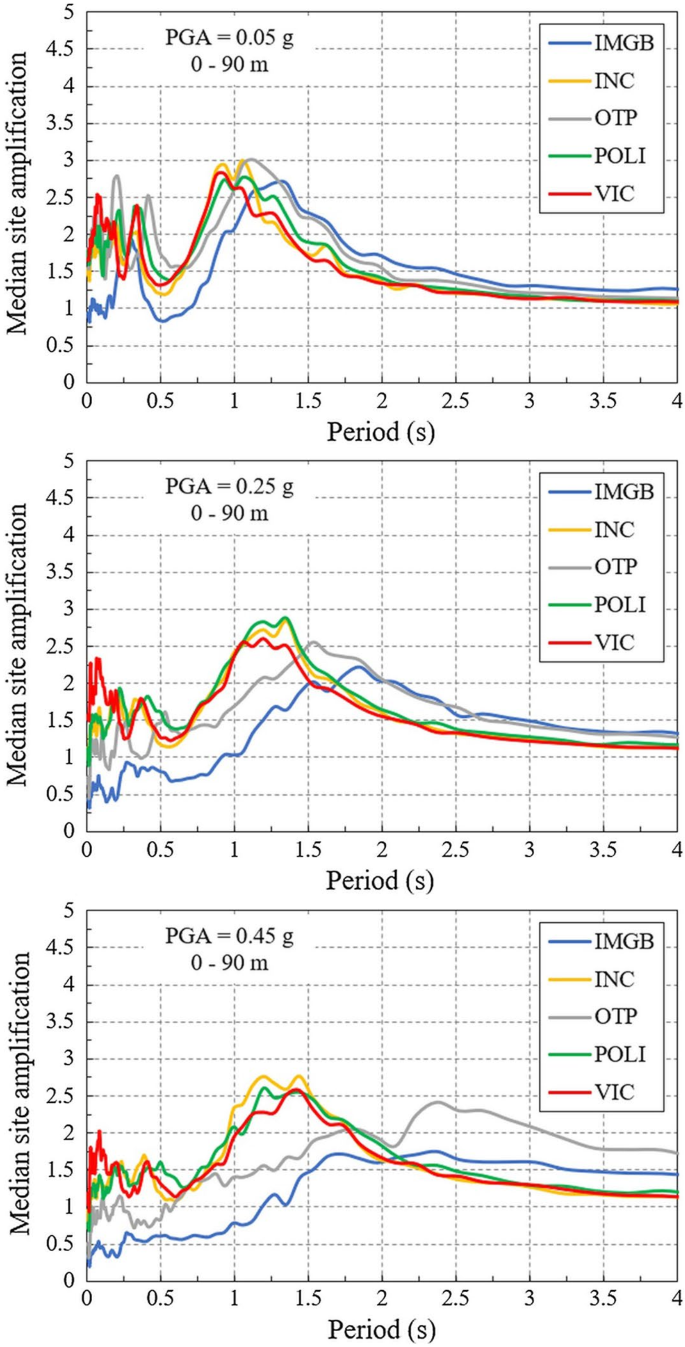


Fig. 8 Comparison of the median site amplification factors computed for the five analysed sites between 0 and 90 m for three levels of peak ground acceleration (0.05 g, 0.25 g and 0.45 g)

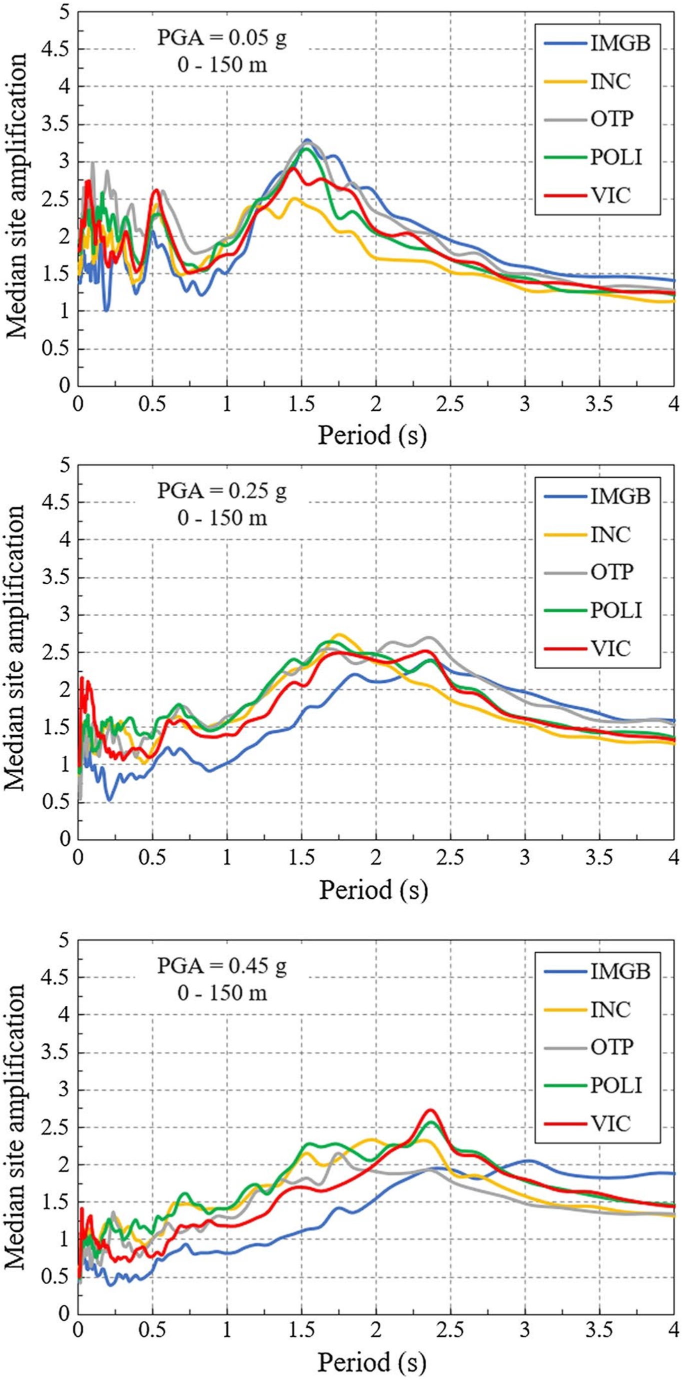


Fig. 9 Comparison of the median site amplification factors computed for the five analysed sites between 0 and 150 m for three levels of peak ground acceleration (0.05 g, 0.25 g and 0.45 g)

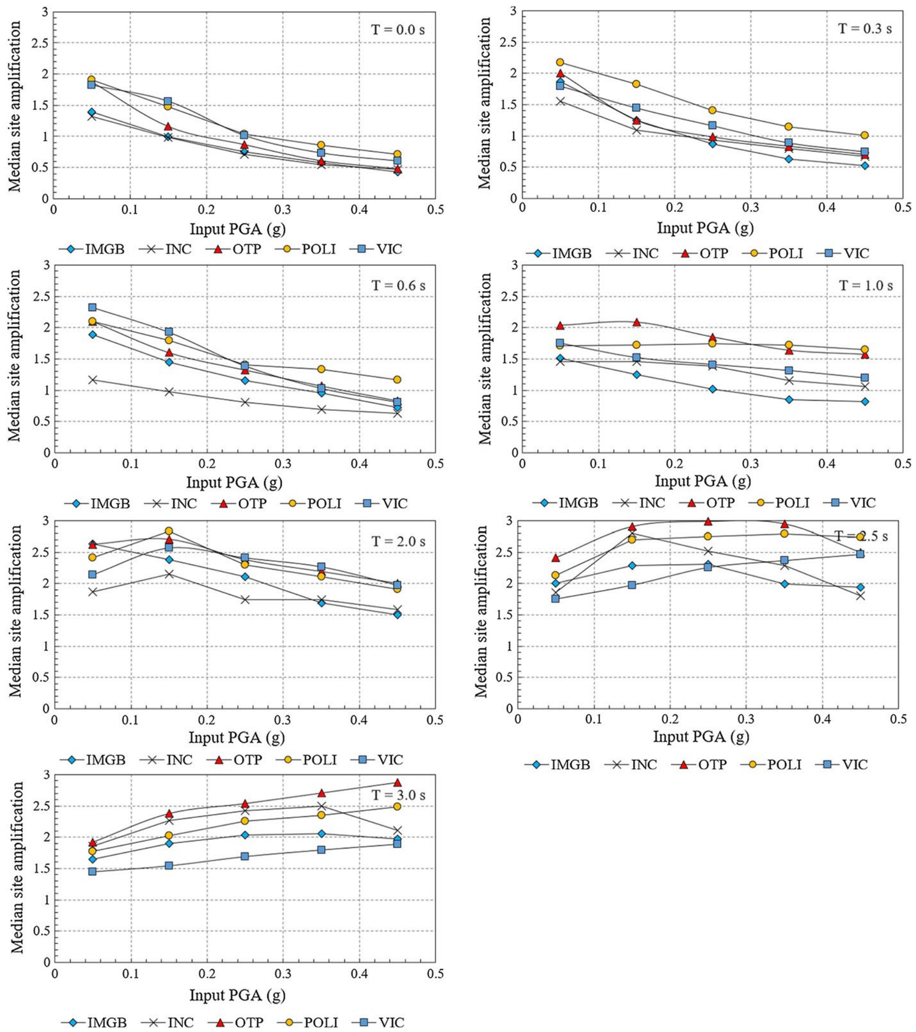


Fig. 10 Variation with the input peak ground acceleration and with the spectral period of the median site amplification for the five analysed sites in Bucharest

2016). The model for velocity variation proposed by Toro (1995) is used to represent the variability in shear wave velocity of the soil profile above the bottom of the borehole as well as for the shear modulus and damping variation with shear strain. Two cases are examined. In the first case the variability in shear wave velocity is modeled with a standard deviation $\sigma = 0.38$ ($\Delta = 8.0$, $\rho_0 = 0.99$, $\rho_{200} = 1.0$, $\beta = 0.0$, $h_0 = 0.16$) and in the second case the modulus-damping curves is modeled with $\sigma = 1.5$ ($\rho_1 = -1$, $\rho_1 = 1$). In total twenty random profiles are generated in each case. Figure 11 depicts the representative set of randomized velocity profiles and Fig. 12 shows representative shear modulus and damping ratio degradation randomization curves limits at a depth of 33 m. Ground response analysis is performed with a smaller set of input motions, comprising

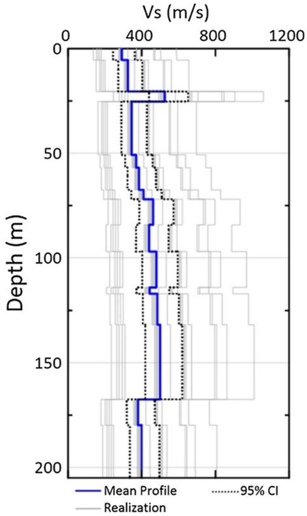


Fig. 11 Shear wave velocity for the site INC (blue line) and randomized velocity profiles (grey lines) along with their 95% confidence interval of 95% (thick black dashed line)

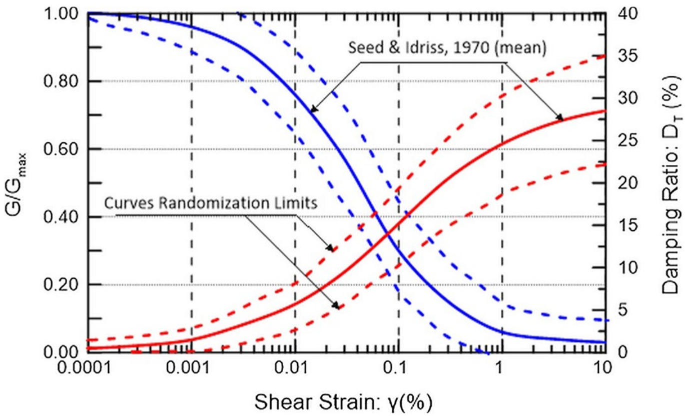


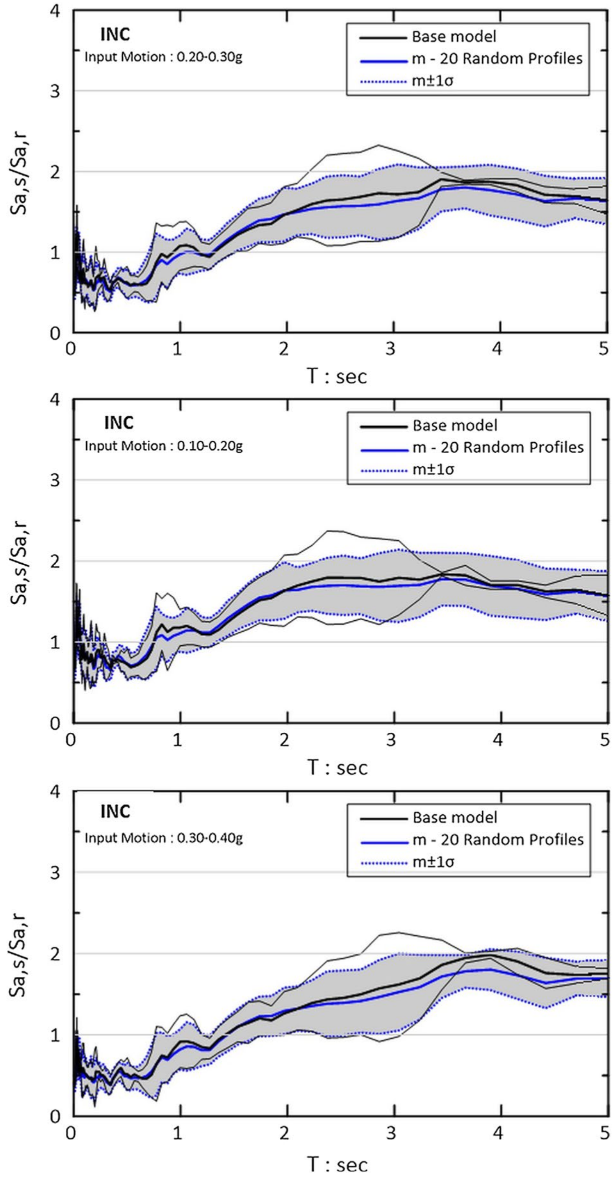
Fig. 12 Variability of shear modulus and damping curves for the soil at depth of 33 m

nine time histories with peak values from 0.1 to 0.4 g, and site amplification functions at the surface of the soil profile are obtained.

Figure 13 depicts the resulting values of site factors for three levels of input ground motion calculated with the twenty randomized Vs profiles. Mean site amplification values calculated for randomized sites is well compared to the mean values resulted for the base soil model. At spectral values up to 3.5 s the resulted amplification values are within the limits (median $\pm$ 1σ − standard deviation) calculated for the base soil model. However, for longer spectral periods and for lower values of applied input motion, the variability of Vs affects more significantly the values of amplification.

Figure 14 shows the effect of variability of shear modulus and damping ratio values on site amplification factors for three levels of input ground motion resulted from twenty site profile realizations. Median (m) calculated values as well m + 1σ values of the random sites are compared well with the derived values of the base model at

Fig. 13 Effect of Vs variability on site amplification factors for three levels of input ground motion (0.10–0.20 g, 0.20–0.30 g, 0.30–0.40 g) at site INC



spectral values up to 5.0 s. Moreover, at spectral periods higher than 2.0 s an increase of the site amplification is observed with the increase of the input ground acceleration.

Therefore, based on the results in a representative site (INC) it is recognized that the effect of variability of soil properties on site amplification is important but follows the trend of derived values at the base model. The effect of Vs variability is more important at spectral values higher than 3.5 s.

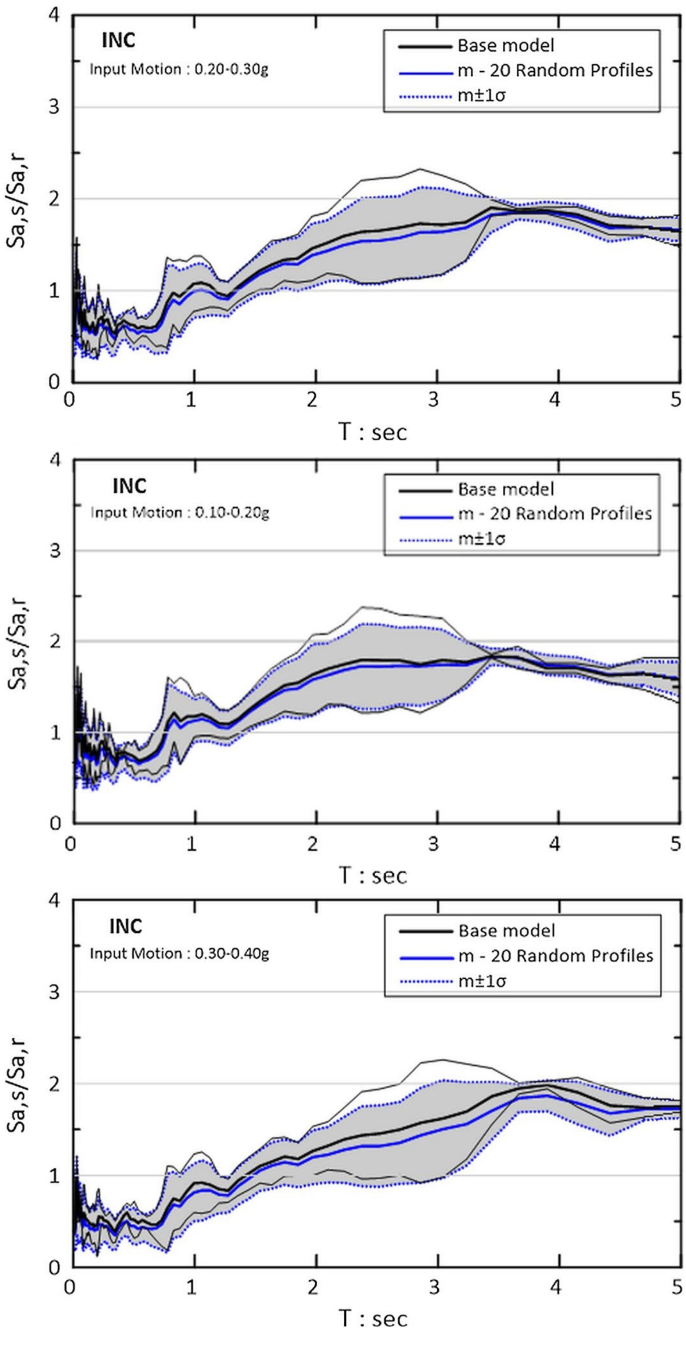


Fig. 14 Effect of shear modulus and damping variability on site amplification factors for three levels of input ground motion (0.10–0.20 g, 0.20–0.30 g, 0.30–0.40 g) at site INC

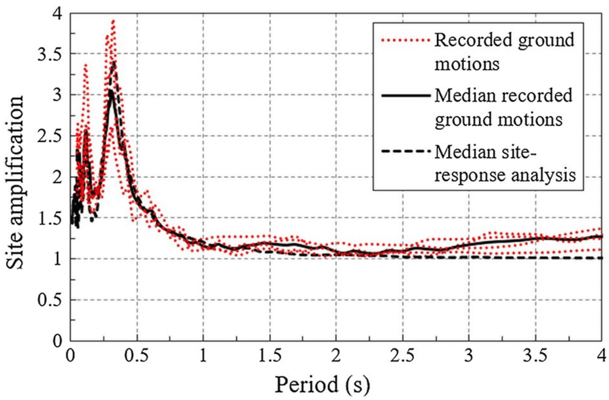


Fig. 15 Comparison between the median site amplification factors for the first 30 m of soil deposits for INCERC site obtained from ground motion recordings and from nonlinear site response analysis

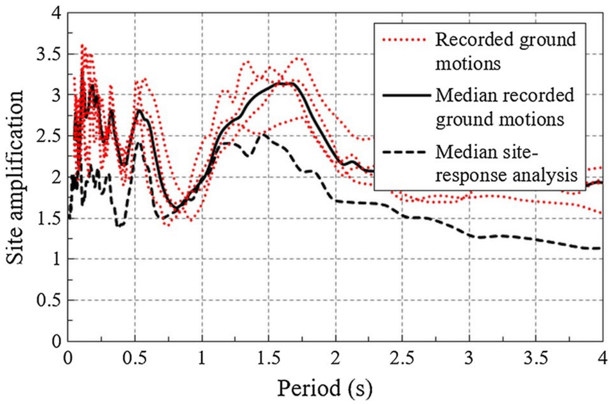


Fig. 16 Comparison between the median site amplification factors for the 150 m of soil deposits for INCERC site obtained from ground motion recordings and from nonlinear site response analysis

5 Validation of site response analysis with ground motion recordings from Vrancea earthquakes

During the Vrancea intermediate-depth earthquake of October 27, 2004 (moment magnitude $M_W = 6.0$ and focal depth h = 105 km according to ROMPLUS earthquake catalogue), a series of ground motion recordings were obtained in various sites situated in Bucharest area using sensors situated both at surface level and in boreholes (the sites are mentioned in Fig. 1). In addition, three more ground motion recordings obtained during the Vrancea intermediate depth seismic events of May 14, 2005 ($M_W = 5.5$, h = 149 km), June 18, 2005 ($M_W = 5.2$, h = 154 km) and April 25, 2009 ($M_W = 5.4$, h = 110 km) obtained at INCERC (denoted as INC in Fig. 1) station were also analysed in the previous section.

Figures 15 and 16 compare the median site amplification factors obtained at INCERC site (INC) during the four above mentioned seismic events with the results (median values) from nonlinear site response analysis for the smallest considered input peak ground acceleration (0.05 g), due to the fact that the recorded peak ground accelerations are smaller than this threshold value. The site amplifications of the recorded ground motions were computed as the ratio (geometrical mean of the two horizontal components) between the spectral accelerations recorded at ground surface and the spectral accelerations at a depth

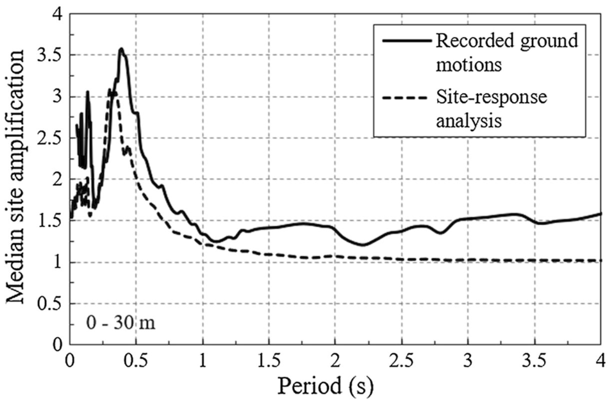


Fig. 17 Comparison between the median site amplification factors for the first 30 m of soil deposits for PRC, SMU, UTC1 and UTC2 sites obtained from ground motion recordings and the median site amplification factors for the first 30 m of soil deposits for IMGB, INC, OTP, POLI and VIC sites from nonlinear site response analysis

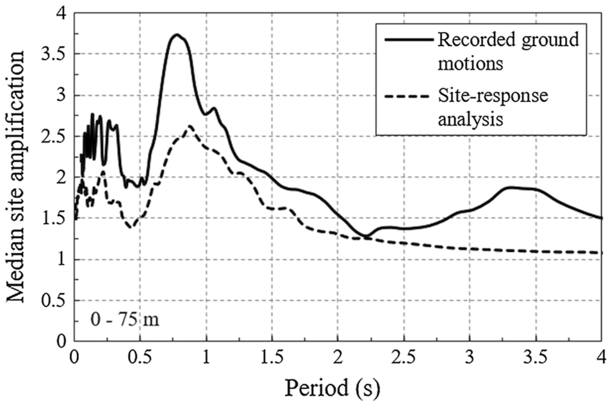


Fig. 18 Comparison between the median site amplification factors for the entire borehole depth for PRC, SMU, UTC1 and UTC2 sites obtained from ground motion recordings and the median site amplification factors for the first 75 m of soil deposits for IMGB, INC, OTP, POLI and VIC sites from nonlinear site response analysis

of 30 m and at a depth of 150 m where the two borehole sensors were placed. It is noticeable from Fig. 15 that both median site amplification factors (obtained from ground motion recordings and from nonlinear site response analysis) for the first 30 m of soil deposits are similar. However, in the case of the results for the entire 150 m borehole at INCERC site, it can be observed that the median site amplification factors obtained from nonlinear site response analysis are smaller than the ones from ground motion recordings, albeit its variation is somewhat similar.

Besides, the ground motion recordings at surface and at various depths in a borehole at INCERC site, some additional ground motion recordings of the Vrancea intermediate-depth earthquake of October 2004 were obtained in four additional sites (PRC, SMU, UTC1 and UTC2) in Bucharest having boreholes with depths in the range 66–78 m. These sites are also shown in Fig. 1 and have $v_{s,30}$ values in the range 245–309 m/s. An extensive analysis of these ground motion recordings can be found in the papers of Aldea et al. (2006, 2007). Figures 17 and 18 compare the median site amplification factors obtained at the four-above mentioned sites with the results (median values) from nonlinear site response analysis for the smallest considered input peak ground acceleration (0.05 g) for all five sites in Bucharest (IMGB, INC, OTP, POLI and VIC) for the first 30 m of soil deposits and for the entire soil profile (in this case we use the average of the results of the nonlinear site-response analysis obtained at 60 m and at 90 m). It can be observed that there is quite a good match between the results obtained from ground motion recordings and the results from nonlinear site response analysis for the first 30 m of soil deposits. Moreover, as in the case of the results for INCERC site shown previously, it can be observed that the median site amplification factors obtained from nonlinear site response analysis are smaller than the ones from ground motion recordings. This issue of underprediction of site amplification factors obtained from real ground motion recordings through nonlinear site response analysis has also been recently discussed by Faccioli et al. (2018).

Finally, the computed site amplifications are also compared with the ones obtained from six ground motions recorded at IMGB (two recordings), INC (three recordigns) and OTP (one recording) sites during the recent Vrancea earthquakes from 1977, 1986 and 1990. The site amplifications from ground motion recordings are obtained by dividing the acceleration response spectra of the recorded ground motions with the acceleration response spectra obtained using a ground motion prediction equation (e.g. BC Hydro ground motion model developed by Abrahamson et al. 2016). The results for the three sites in terms of median ± one standard deviation of the site amplification computed from site-specific seismic response analysis and from ground motion recordings are illustrated in Figs. 19, 20 and 21. One can notice that in most of the cases there is an underestimation of the site amplifications obtained from recordings, as discussed in the previous section. Thus, it is clear that, as mentioned by Faccioli et al. (2018), the reliability of the site-specific amplification levels obtained critically depends on the quality of the soil profile model available. As such, it is likely that the values of some input parameters used in the nonlinear site-response analysis are not as reliable as they should and should be further investigated in the future.

6 Conclusions

In this study, the first nonlinear site response analyses for five sites with deep profiles situated in Bucharest area is performed. The depth of all the selected boreholes is in the range of 150–200 m. A ground motion database consisting of recordings from Vrancea intermediate-depth earthquakes is used for the nonlinear site-specific seismic response analysis which uses as input the data from the five analysed boreholes. The results of the analyses show that long-period spectral amplifications occur for all five analysed sites. In addition,

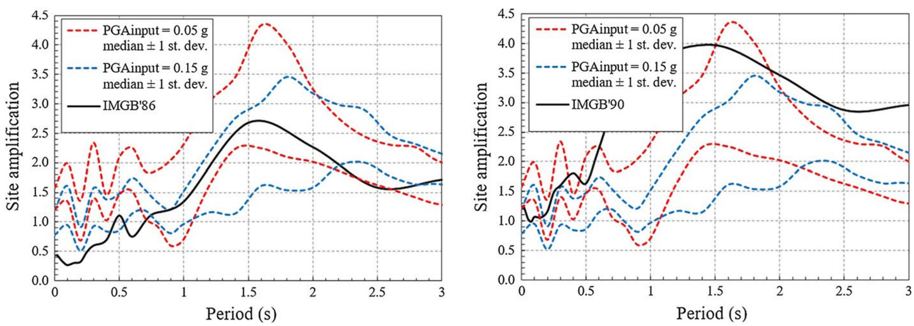


Fig. 19 Comparison between the site amplifications for IMGB site obtained from site-specific seismic response analysis and from the ground motions recorded during the Vrancea earthquakes of 1986 and 1990

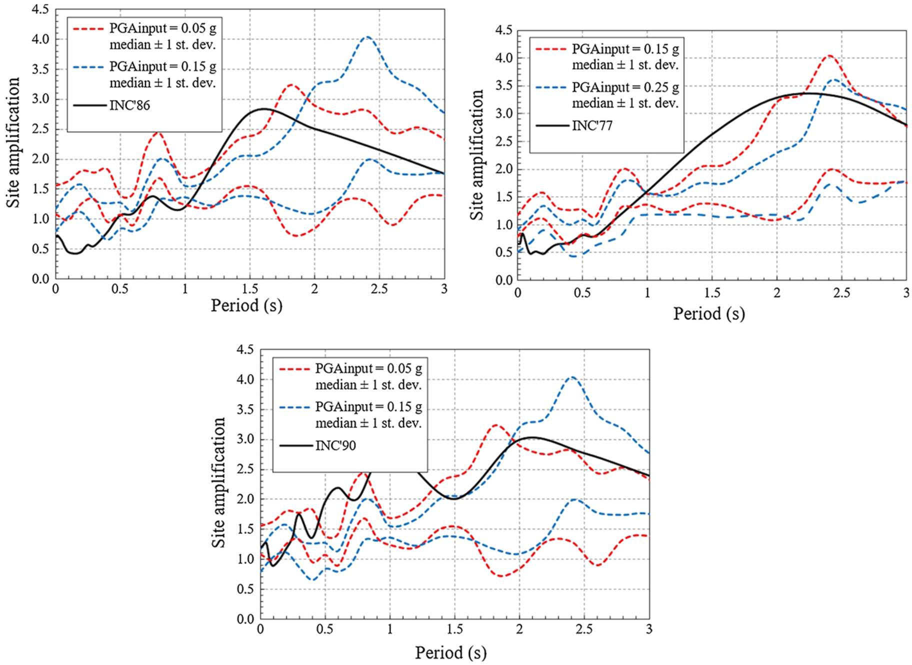
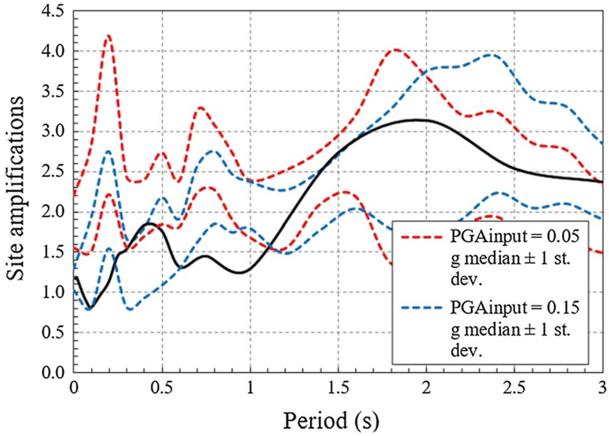


Fig. 20 Comparison between the site amplifications for INC site obtained from site-specific seismic response analysis and from the ground motions recorded during the Vrancea earthquakes of 1977, 1986 and 1990

Fig. 21 Comparison between the site amplifications for OTP site obtained from site-specific seismic response analysis and from the ground motions recorded during the Vrancea earthquake of 1986



the amplification factors both in terms of median values and standard deviations are significantly influenced by the level of the input peak ground acceleration. As such, the differences in terms of median site amplification factors observed between the five sites for three depths also increase with the level of the input peak ground acceleration. The median site amplifications decrease with the increase of the peak ground acceleration for spectral periods of up to 2.0 s, while for longer periods an increase of the median site amplifications is clearly noticeable. The comparison of the results of nonlinear site response analysis with those obtained from the analysis of real ground motions recorded in Bucharest area during several recent Vrancea earthquakes shows that there is quite a good match of the results when considering the first 30 m of the boreholes, and an underprediction when considering deeper portions of the boreholes. Thus, as mentioned by Faccioli et al. (2018), the reliability of the site-specific amplification levels obtained critically depends on the quality of the soil profile model available. More extensive investigations are necessary for all the sites in the southern part of Romania in order to shift from the current code soil characterization define din terms of the control period T_C to another one (e.g. based on site fundamental period). Moreover, the site-specific seismic hazard assessments performed for sites situated in the southern part of Romania (including Bucharest) should take into account the nonlinear site response. Thus, a critical issue which should be addressed is how reliable is a uniform hazard response spectrum for such sites?

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