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Investigation on site conditions for seismic stations in Romania using H/V spectral ratio

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Abstract. This research evaluates the soil conditions for seismic stations situated in Romania using the horizontal-to-vertical spectral ratio (HVSR). The strong ground motion database assembled for this study consists of 179 analogue and digital strong ground motion recordings from four intermediate-depth Vrancea seismic events with $M_w \geq 6.0$. In the first step of the analysis, the influence of the earthquake magnitude and source-to-site distance on the H/V curves is evaluated. Significant influences from both the earthquake magnitude and hypocentral distance are found especially for soil class A sites. Next, a site classification method proposed in the literature is applied for each seismic station and the soil classes are compared with those obtained from borehole data and from the topographic slope method. In addition, the success and error rates of this method are computed and compared with other studies from the literature. A more in-depth analysis of the H/V results is performed using data from seismic stations in Bucharest and a comparison of the free-field and borehole H/V curves is done for three seismic stations. The results show large differences between the free-field and the borehole curves. As a conclusion, the results from this study represent an intermediary step in the evaluation of the soil conditions for seismic stations in Romania and the need to perform more detailed soil classification analysis is highly emphasized.

Keywords: soil class; strong ground motion records; Vrancea subcrustal earthquakes; spectral amplification; fundamental frequency

1. Introduction

The local site conditions influence to a great extent the characteristics of the recorded ground motion in a particular site. The estimation of site effects has become a major challenge for the quantification of seismic hazard and seismic risk, especially after the Michoacan (1985), Northridge (1994), Kobe (1995) or Kocaeli (1999) earthquakes. Many methods and techniques are available for the evaluation of site effects. Among these methods, the horizontal-to-vertical spectral ratio (HVSR) proposed by (Nakamura 1989) is one of the most used.

The Vrancea intermediate-depth seismicity occurs in a region of continental collision centred at the South-Eastern Carpathians Arc bend, where European plate, Moesian sub-plate and Intra-

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Alpine sub-plate come into contact. Earthquakes with magnitude up to M_w~8.0 are generated at mantle depths (60 to 170 km) in an extreme narrow high-velocity lithospheric volume. Analysis of focal mechanisms of the Vrancea seismic events shows a thrust type of motion, with horizontal compression and vertical extension. The predominant type of motion is characterized by a rupture plane oriented on the NE-SW direction and maximum compression in the perpendicular direction. This is the typical mechanism for all the earthquakes with magnitude ~7 or larger. Radulian *et al.* (2000) shows the predominance of reverse faulting mechanisms for earthquakes with $M_w \geq 5.0$. The strongest Vrancea seismic events which occurred in the past 100 years (10 November 1940, M_w=7.7; 4 March 1977, M_w=7.4; 30 August 1986, M_w=7.1) have caused significant casualties and damage reported in Romania and in Bulgaria, Serbia, Rep. of Moldova and Ukraine, as well. Nevertheless, a thorough description of the seismological features of the Vrancea seismic source is beyond the scope of this article and can be found elsewhere (e.g., Ismail-Zadeh *et al.* 2012, Radulian *et al.* 2000).

The horizontal-to-vertical spectral ratio (HVSR) method has been used intensively in studies performed in the last decades and related to the evaluation of site conditions. In some studies, such as (Garcia-Jerez *et al.* 2007, Guillier *et al.* 2007, Fitzko *et al.* 2007, Mundepi *et al.* 2010, Goded *et al.* 2012, Garcia-Fernández and Jiménez 2012) the HVSR method is applied on ambient noise measurements, while in other studies (e.g., Yamazaki and Ansari 1997, Lozano *et al.* 2009, Ruizhi *et al.* 2011, Di Alessandro *et al.* 2012, Nunziata and Costanza 2014) the HVSR method is applied on strong ground motion recordings or on microtremor data (Haghshenas *et al.* 2008, Paudyal *et al.* 2012). Zhao *et al.* (2006) proposed a site classification index using the mean H/V spectral ratios over a broad range of periods for seismic stations in Japan. Fukushima *et al.* (2007) perform a site classification based on the predominant period from the H/V curves and using data from seismic stations in Japan, California and Europe. Ghasemi *et al.* (2009) evaluate the index proposed by Zhao *et al.* (2006) using a database from Iran and develop a new site index term based on H/V spectral ratios. Di Alessandro *et al.* (2012) propose a site classification scheme comprising of six classes for seismic stations in Italy based on H/V curves. Haghshenas *et al.* (2008) perform an evaluation of the capabilities of HVSR method to provide accurate information related to the site conditions. The authors conclude that HVSR method can provide good estimates of the fundamental frequency and can’t provide good estimates of the site amplification. Actually, the site amplification given by HVSR method can be regarded as a lower bound estimate of the actual site amplification. Theodoulidis *et al.* (2008) check whether the HVSR method correlates with the observed damage pattern for five European cities. The results obtained by the authors are mixed: in some cases the damage distribution is correlated with the soil conditions, while in some other cases the results are not so obvious. On the contrary, Herak *et al.* (2010) obtained a good correlation between the damage distribution in the city of Ston (Croatia) and the site amplification and its corresponding fundamental frequency. Hellel *et al.* (2010) correlate the damage distribution from the city of Boumerdes in Algeria which was affected by the 2003 earthquake with the results of HVSR method. The authors show that heavier damage was encountered in regions in which the H/V curves do not show clear peaks, while lighter damage was observed in zones which exhibited clear peaks on H/V curves. Oubaiche *et al*. (2012) perform a comparison between H/V spectral curves obtained using ambient vibrations and downhole velocity profiles and find that the peak of the H/V curves is due to a shear-wave velocity contrast of an upper soft sediment layer and an underlying harder layer. Ducellier *et al.* (2013) make a series of inversions of underground structure using genetic algorithms and compare the obtained H/V curves with the target ones for a series of sites in Japan. Barani *et al.* (2008) investigate the reliability and accuracy of classifying soils as a function of the average shear-wave velocity on the upper 30 m of soil layers - $v_{s,30}$ for several sites in Italy. They also compute H/V curves based on earthquake recordings and on microtremors and find out that the curves based on microtremors point out only the fundamental frequency and do not provide reliable site amplification levels. The HVSR method was also applied by various researchers for seismic stations in Romania (e.g., Aldea *et al.* 2004, Aldea *et al.* 2007, Grecu *et al.* 2007, Bala *et al.* 2009, Grecu *et al.* 2011). For instance, Aldea *et al.* (2004, 2007) computed H/V curves using both free-field and borehole strong ground motion recordings from Bucharest, while Yamanaka *et al.* (2007) used microtremor data for the evaluation of H/V curves also for Bucharest.

In this study, the horizontal-to-vertical spectral ratio (HVSR) method (Nakamura 1989) is used for the assessment of site conditions for seismic stations situated in the eastern and southern part of Romania through the analysis of strong ground motion recordings from four intermediate-depth Vrancea earthquakes. In addition, the site index of Zhao *et al.* (2006) is computed in order to check the validity of the HVSR results. Finally, a comparison of the HVSR results in borehole and at free surface is performed using data from three boreholes in Bucharest.

2. Strong ground motion database and soil conditions

The strong ground motions used in this study were recorded during four intermediate-depth Vrancea seismic events in 117 seismic stations. These four seismic events represent the largest earthquakes produced in the intermediate-depth Vrancea seismic zone in the past 30 years. The characteristics of these earthquakes (e.g., magnitude and focal depth), as well as the corresponding number of recorded triaxial accelerograms for each event are provided in Table 1.

The geographical distribution of the 117 seismic stations and their corresponding soil conditions according to EN 1998-1 (2004) - soil classes A, B or C, as well as the position of the epicentres of Vrancea intermediate-depth earthquakes are given in Fig. 1. In EN 1998-1 (2004), the site classes are defined according to the average shear wave velocity on the upper 30 m of soil layers - $v_{s,30}$. The following $v_{s,30}$ limits are specified in EN 1998-1 (2004): for soil class A - $v_{s,30}$ > 800 m/s, for soil class B - $v_{s,30}$=360 m/s - 800 m/s and for soil class C - $v_{s,30}$=180 m/s - 360 m/s The soil conditions for all the seismic stations are initially assigned based on the topographic slope method of Wald and Allen (2007) and on borehole data assembled within the BIGSEES national research project.

All the analysed strong ground motions are collected for the BIGSEES research project and were recorded by four seismic networks: INCERC (Building Research Institute), INFP (National Institute of Earth Physics), NCSRR (former National Centre for Seismic Risk Reduction, current Seismic Risk Assessment Research Centre) and GEOTEC (Institute for Geotechnical and

Table 1 Characteristics of considered seismic events

Earthquake date	M_W	*h* (km)	No. of triaxial accelerograms
30.08.1986	7.1	131	35
30.05.1990	6.9	91	47
31.05.1990	6.4	87	31
27.10.2004	6.0	105	66

Geophysical Studies). The database contains both analogue and digital strong ground motion recordings. All the recordings from the three largest Vrancea seismic events ($M_W \geq 6.4$) in the database are analogue, while over 95% of the recordings from the October 2004 event were obtained on digital instruments. In the case of analogue recordings only the processed waveforms were available in the database, so no processing was performed by the authors. The processing of all the analogue recordings was generally performed using an Ormsby band pass filter with cut-off frequencies of 0.15 - 0.25 Hz and 25 - 28 Hz. The digital recordings, for which the raw data are available in the database, were processed according to the procedures given in the literature (e.g., Akkar and Bommer 2006, Boore and Bommer 2005) and using a band-pass Butterworth filter of 4^{th} order with cut-off frequencies of 0.05 Hz and 50 Hz.

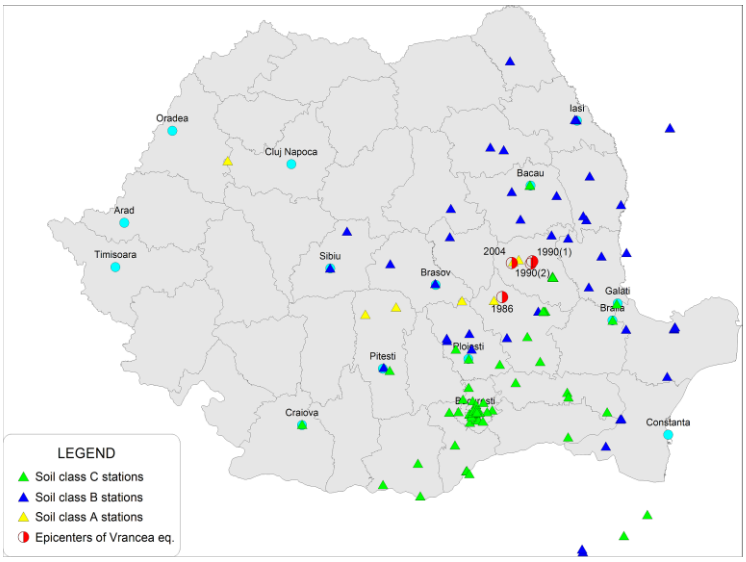

Fig. 1 Distribution of recording seismic stations and their corresponding soil conditions according to EN 1998-1 and position of earthquake epicentres

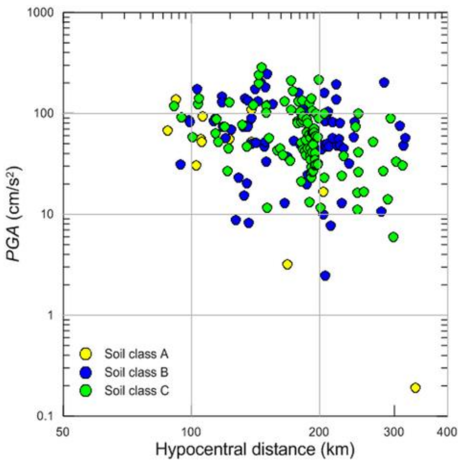

Fig. 2 Distribution of the peak ground acceleration with the hypocentral distance of the seismic stations

The distribution of the peak ground acceleration (*PGA*) with the hypocentral distance of the recording seismic stations is shown in Fig. 2. It is noteworthy the fact that there are very few recordings from hypocentral distances smaller than 100 km and that most of the strong ground motions were recorded at hypocentral distances in the range 100 - 200 km.

3. Results of HVSR method

The HVSR (horizontal-to-vertical spectral ratio) method (Nakamura 1989) is applied on a strong ground motions database of 179 triaxial accelerograms in order to validate the soil conditions for 117 seismic stations in Romania. As previously mentioned, the soil conditions were already assigned for the analysed seismic stations using borehole data collected within the BIGSEES national research project and using the topographic slope method of Wald and Allen (2007).

The histograms of site fundamental frequency and the amplifications corresponding to the fundamental frequencies obtained by applying the HVSR method on the entire strong ground motions database are presented in Fig. 3.

One can notice from Fig. 3 that about two thirds of the computed site fundamental frequencies are in the range 1-3 Hz and around 60% of the corresponding amplifications are in the range

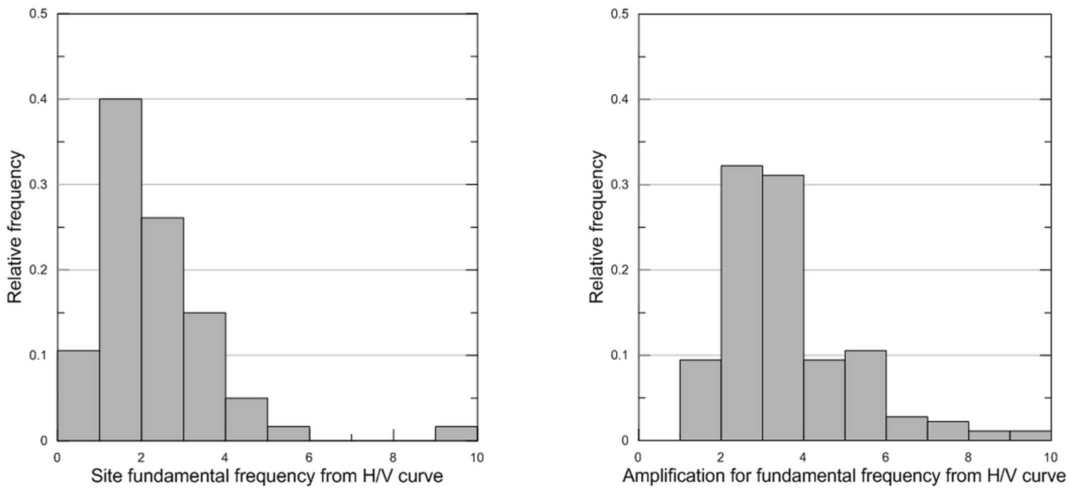

Fig. 3 Histograms of site fundamental frequency and amplifications corresponding to fundamental frequency from H/V curves

Table 2 Mean site fundamental frequencies and site amplifications for each soil class

Soil class	Site fundamental frequency (Hz)		Amplifications corresponding to fundamental frequency	
	Mean	COV	Mean	COV
A	2.94	0.44	3.53	0.74
B	2.73	0.66	3.99	0.45
C	1.99	0.33	3.34	0.13

2-4. The mean fundamental frequencies and the amplifications corresponding to the site fundamental frequency and their coefficients of variation (COV) are reported in Table 2 for each soil class. The lowest site fundamental frequencies are encountered for soil class C sites, as expected and the corresponding variability is also the smallest among all three soil classes. There is no clear trend for the mean values of corresponding amplification, but one can notice the sharp decrease of the COV from soil class A to C.

The mean H/V curves and the corresponding coefficients of variation (COV) are plotted in Fig. 4 for each soil class - A, B and C (EN 1998-1) and using all the strong ground motion recordings in the database. It is noteworthy the fact that the largest values of the amplifications corresponding to fundamental frequency are encountered for soil class B sites, while the smallest values are obtained for the soil class C sites. The almost constant plateau of H/V amplifications for soil class C sites situated in the spectral period range of 0.3-1.0 s is to be emphasized. The distribution of the coefficients of variations for the three soil classes appears to be quite random. However, one can notice a higher variability for soil class C sites for the short spectral period range (up to 0.2 s) and the larger variability for soil class A and B sites in the medium-long spectral period range (over 0.5 s).

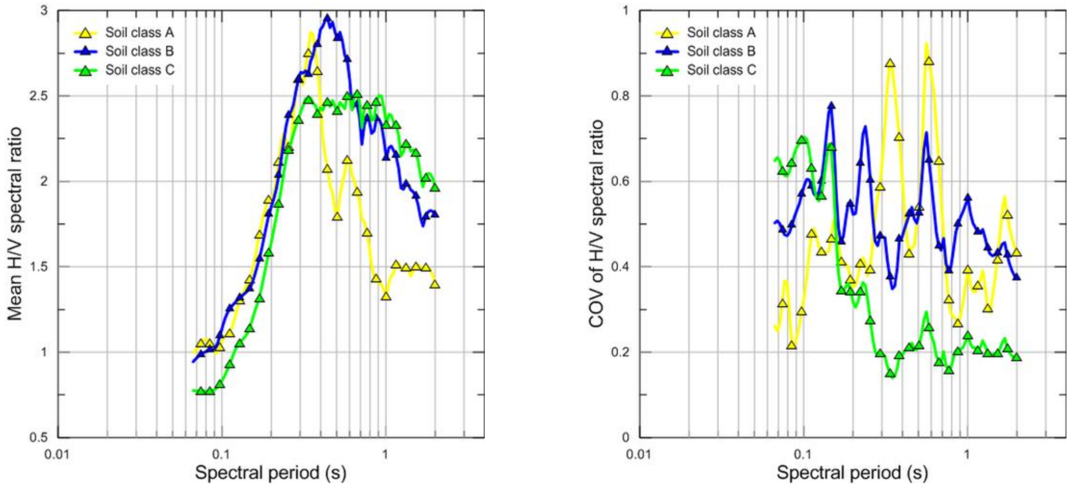

Fig. 4 Mean H/V spectral ratio curves and corresponding COV for each foil class and for all data

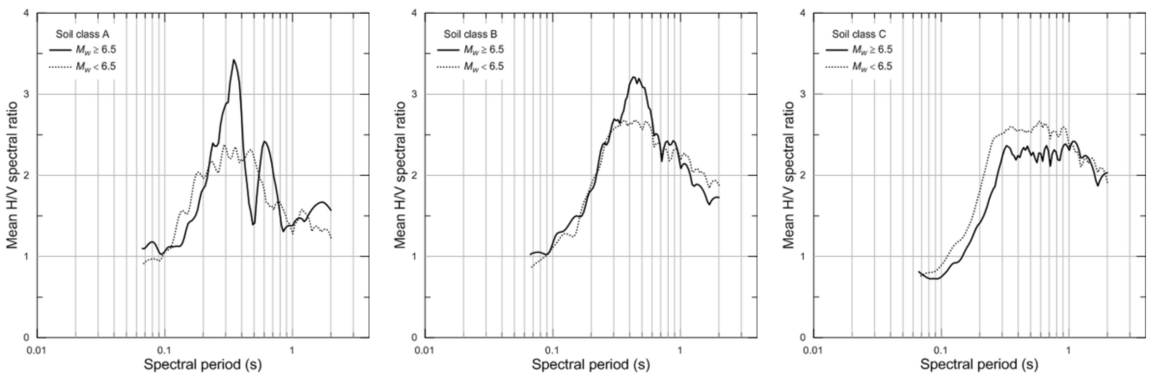

Fig. 5 Variation of mean H/V curves with earthquake magnitude for the three soil classes

In the next step of the analysis, the influence of the earthquake magnitude and of the source-to-site distance of the seismic stations on the H/V curves is investigated. Fig. 5 shows the H/V curves computed for all three soil classes as a function of the earthquake magnitude (earthquakes with $M_W \geq 6.5$ and earthquakes with $M_W < 6.5$). The first bin (earthquakes with $M_W \geq 6.5$) contains two seismic events and 82 strong ground motions; the second bin (earthquakes with $M_W < 6.5$) contains the other two seismic events and 97 strong ground motions.

The results from Fig. 5 show a significant influence of the earthquake magnitude on the H/V curves, especially for soil classes A and B sites. One can notice larger mean values for seismic events of larger magnitude and a larger plateau of nearly constant maximum values in the case of lower magnitude earthquakes. In the case of soil class C sites, the two H/V curves have almost similar shapes; the plateau of nearly constant maximum values is larger than for soil classes A and B and the higher mean values are encountered for lower magnitude seismic events. This result is opposite to that obtained by Zhao *et al.* (2006), which shows negligible influence of the earthquake magnitude on the H/V curves for all soil classes. The reason for the larger differences encountered for soil class A sites might be due to the small number of available recordings in the database for this type of soil class. As such, further studies should be conducted for the evaluation of HVSR curves for soil class A sites.

Fig. 6 displays the mean H/V curves for each soil class as a function of the hypocentral distance of the recording seismic stations ($R \leq 120$ km, 120 km$< R \leq 180$ km and $R > 180$ km). In this case too, the largest differences between the H/V curves are encountered for soil class A and B sites, while for the soil class C sites, the H/V curves are almost similar. The reason for the larger influence of the epicentral distance on the H/V curves for soil class A sites is related again to the very limited number of available strong ground motion recordings. It is also noteworthy the fact that no influence or very limited influence of the source-to-site distance or magnitude can be observed for soil class C sites.

The combined influence of the earthquake magnitude and source-to-site distance on the H/V curves is evaluated in Fig. 7 only for soil classes B and C for which there is a significant number of strong ground motion recordings available. One can notice very large differences between the mean H/V curve for $M_W < 6.5$ and $R \leq 120$ km as compared with the mean curve for $M_W \geq 6.5$ and $R > 180$ km for soil class B stations. In the case of soil class C stations, the differences between the two curves are much smaller.

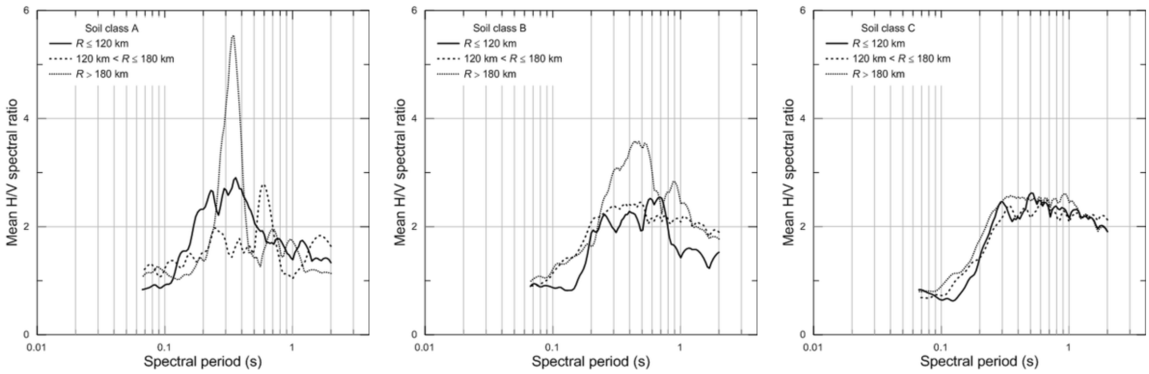

Fig. 6 Variation of mean H/V curves with hypocentral distance of the seismic station for the three soil classes

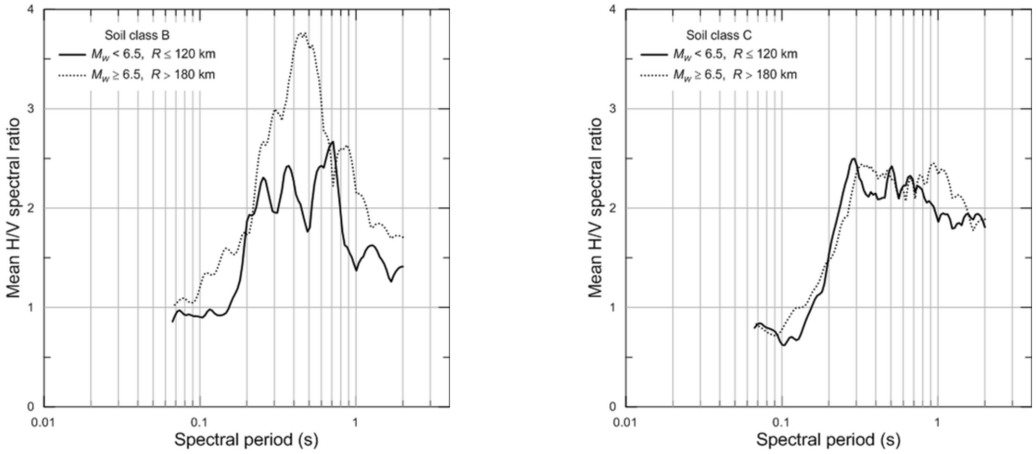

Fig. 7 Combined influence of the earthquake magnitude and source-to-site distance on H/V curves for soil classes B and C

Subsequently, the site classification index defined by Zhao *et al*. (2006) and shown in equation (1) is computed for all the available Vrancea strong ground motion recordings. This index shows, based on the computed H/V curves, the corresponding soil condition for a particular site of interest. The site classification index is calculated for each site and for each of the three possible site classes and the site class having the largest *SI* value (either A, B or C) is assigned to the site of interest

$$SI_k = \frac{2}{n}\sum_{i=1}^{n} F\{-abs[\ln(\mu_i) - \ln(\mu_{ki,\,mean})]\} \tag{1}$$

In Eq. (1) k is the site class (A, B or C), n is the total number of periods, $F(\ )$ is the cumulative normal distribution, μ_i is the mean H/V ratio for the site of interest for the ith period and $\mu_{ki,\,mean}$ is the mean H/V ratio for site class k averaged for period i over all considered period.

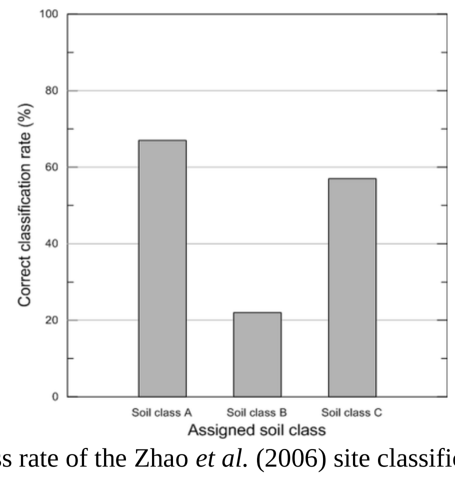

Fig. 8 Success rate of the Zhao *et al.* (2006) site classification method

This classification scheme is tested against the initial soil classification based on borehole data and on the topographic slope method of Wald and Allen (2007). The corresponding success rates for each soil class are given in Fig. 8.

One can observe that the higher success rates correspond to soil classes A and C. This result is similar with the results obtained by Zhao *et al.* (2006) and Ghasemi *et al.* (2009), albeit the fact that the success rates are lower in the present study, perhaps due to the smaller number of strong ground motion recordings used in the analysis. The corresponding error rates of the classification method proposed by Zhao *et al.* (2006) are given in Fig. 9 for each soil class. The soil class A sites are incorrectly assigned to soil class B in one-third of the cases, while the majority of soil class B sites are assigned to soil class A (46% as compared to 32% for soil class C). In the case of soil class C sites, they are incorrectly assigned in equal proportions to both soil classes A and B (18% and 25%, respectively).

A significant number of studies related to the evaluation of soil conditions for Bucharest, the capital city of Romania, can be found in the literature (e.g., Aldea *et al.* 2007, Grecu *et al.* 2007, Yamanaka *et al.* 2007, Bala *et al.* 2009). Using the available borehole data from Bucharest it can be concluded that a soil class C according to EN 1998-1 can be assigned for Bucharest (Lang *et al.* 2012, Pavel *et al.* 2013). The mean and mean ± standard deviation H/V curves are shown in Fig. 10 using all the strong ground motions recorded during the four analysed earthquakes in Bucharest.

The influence of the earthquake magnitude (earthquakes with $M_W \geq 6.5$ and earthquakes with $M_W < 6.5$) and hypocentral distance ($R \leq 185$ km and $R \geq 185$ km) on the H/V curves for Bucharest is evaluated in Fig. 10. Even though the influence of the earthquake magnitude and source-to-site distance on the H/V curves for soil class C sites when using the entire database of strong ground motion recordings in Romania was found to be less significant, in the case of Bucharest data the situation is somewhat different. As such, larger amplitudes can be noticed for lower magnitude earthquakes, while the hypocentral distance has a very small influence on the results.

Subsequently, a comparison between the H/V curves obtained from free-field and borehole recordings is performed for three seismic stations in Bucharest. The three analysed seismic stations are denoted as: PRI (Bucharest City Hall), PRC (Civil Protection Headquarters) and SMU (Municipal Hospital). These three seismic stations, which belonged to the former National Centre

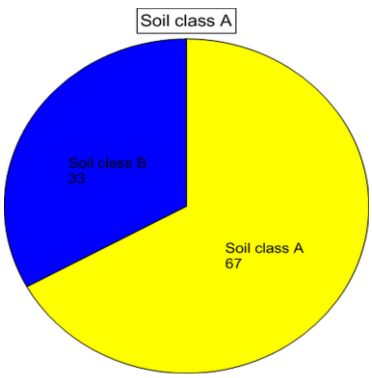

Fig. 9a Error rate of the Zhao *et al.* (2006) site classification method for soil class A sites

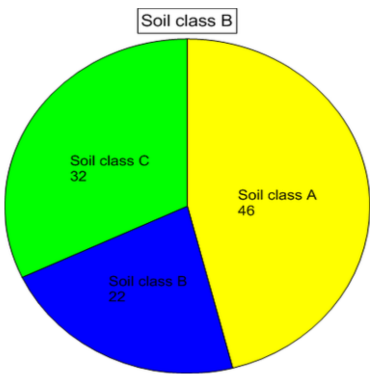

Fig. 9b Error rate of the Zhao *et al.* (2006) site classification method for soil class B sites

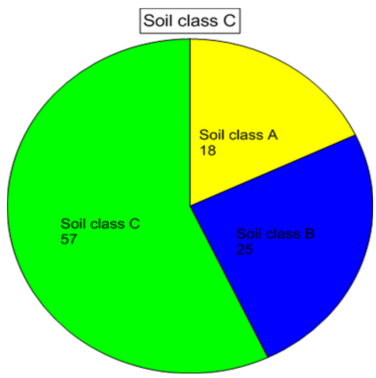

Fig. 9c Error rate of the Zhao *et al.* (2006) site classification method for soil class C sites

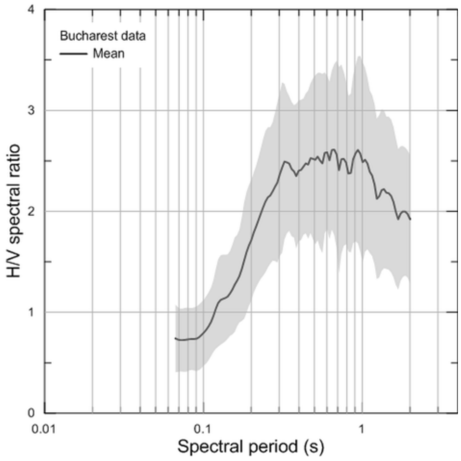

Fig. 10 Mean and mean ± standard deviation H/V curves for Bucharest. The shaded area corresponds to the region between the 16th and 84th percentile values

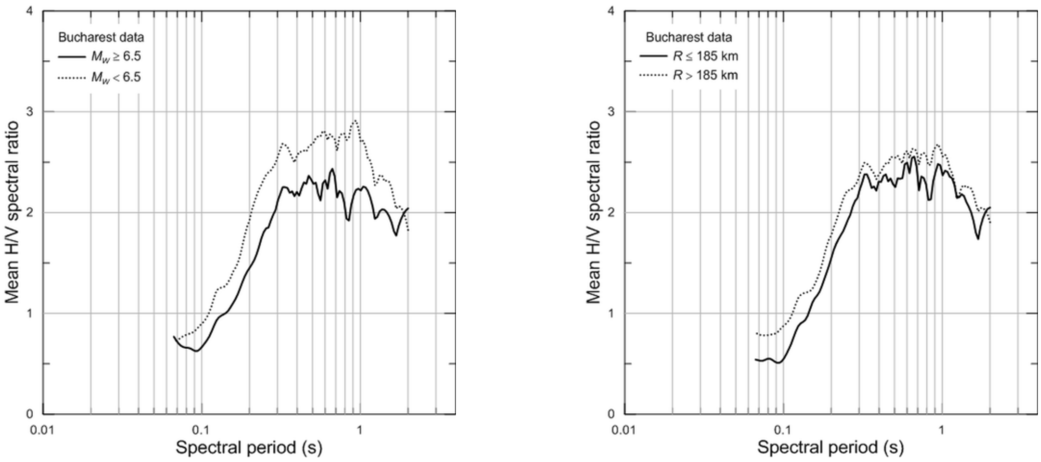

Fig. 11 Variation of mean H/V curves with earthquake magnitude and hypocentral distance of the seismic stations for Bucharest data

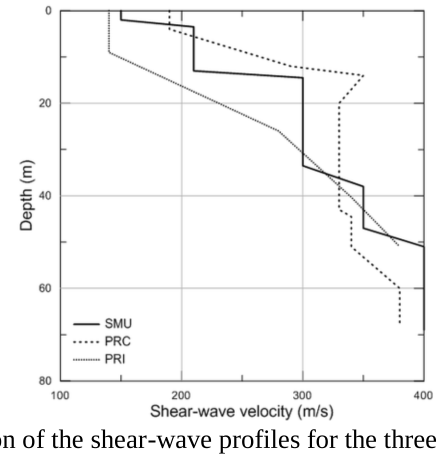

Fig. 12 Comparison of the shear-wave profiles for the three analysed boreholes

for Seismic Risk Reduction (currently Seismic Risk Assessment Research Centre) have recordings of the Vrancea October 2004 event both at the surface and at the bottom of the boreholes. The depth of the boreholes is 51 m for PRI station, 68 m for PRC station and 69 m for SMU station. However, the boreholes do not reach the bedrock level which for Bucharest is considered to be at a depth below 1000 m (Constantinescu and Enescu 1985). The shear-wave velocity profiles for the boreholes are given in Fig. 12.

One can observe from Fig. 13 that there are significant differences between the two H/V curves obtained from the free-field recording and from the borehole recording. Both the fundamental site frequency and the corresponding amplifications have different values. Larger amplifications are obtained at free-field level only for periods T>0.2 s (0.3 s). On the contrary, for T<0.2 s (0.3 s) the H/V curve obtained from the borehole recordings has larger amplitudes. In addition, the shape of the H/V curve differs significantly, especially for PRC and SMU stations, hence rendering a significant influence of the softer top soil layers on the ground motion at surface level. In the case of the PRI station, one can notice similar peaks for H/V curves, albeit the amplifications are different. These mixed results are obtained on three sites with the top 30 m average shear-waves velocities $v_{s,30}$ situated in a narrow range (250 m/s - 290 m/s), thus showing that in the case of Bucharest the site characterization performed using $v_{s,30}$ does not appear to be the most appropriate.

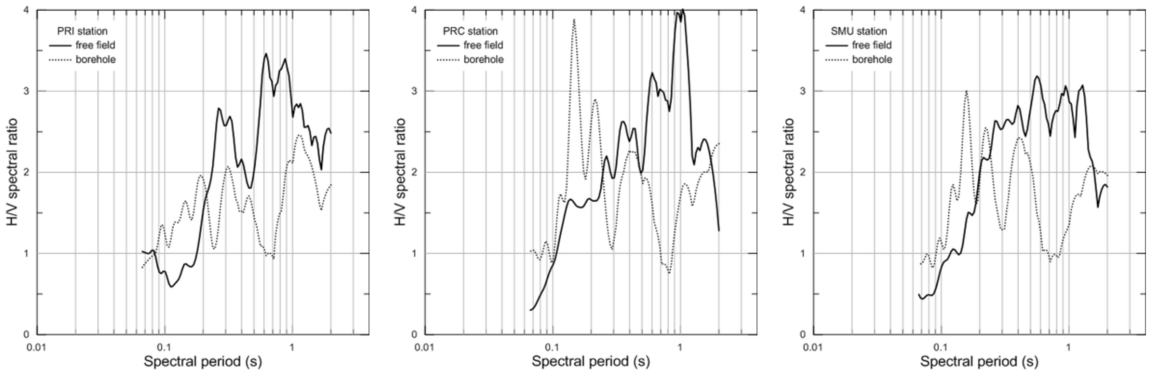

Fig. 13 Comparison of H/V curves at free-field and in borehole for three seismic stations in Bucharest

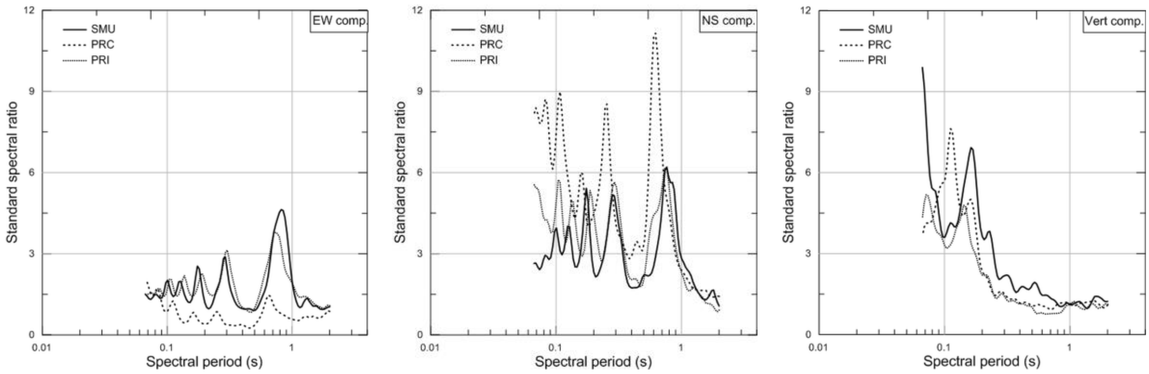

Fig. 14 Comparison of standard spectral ratios curves between free-field and borehole recordings for three seismic stations in Bucharest

The standard spectral ratio (Borcherdt 1970) between free-field and borehole is also computed for the three seismic stations in Bucharest. The results are shown in Fig. 14. One can notice that the standard spectral ratios are almost similar for the horizontal components in the case of the seismic stations PRI and SMU (which are situated in the same area of Bucharest). The larger standard spectral ratios are encountered for the NS and vertical components in all three cases. In addition, it is also noticeable that in the case of the PRC station situated in northern Bucharest, the differences between the two horizontal components (NS and EW) are very large. Generally, the standard spectral ratio between free-field and borehole has values larger than unity for spectral periods up to around 1.5 s. Nevertheless, the considerable influence of the top soil layers on the ground motion is confirmed by the computed standard spectral ratios (Borcherdt 1970).

5. Conclusions

The main focus of this study is the evaluation of site conditions for seismic stations in Romania using strong ground motion data from the four largest intermediate-depth Vrancea seismic events produced in the past 30 years. The HVSR (horizontal-to-vertical) spectral ratio method proposed by Nakamura (1989) is used for this purpose.

In the first step of the analysis the site fundamental frequencies and corresponding amplifications were computed and the results show that around two thirds of the site fundamental frequencies are in the range 1 - 3 Hz and the same proportion of amplifications are between 2 and 4. Next, the mean H/V curves were computed for each of the three soil classes (A, B or C as defined in EN 1998-1). The largest amplifications were obtained for soil class B sites, while the soil class C sites exhibit a plateau of constant acceleration in the spectral period range 0.3 - 1.0 s. Subsequently, the influences of the earthquake magnitude and hypocentral distance of the seismic stations were assessed. The computed H/V curves show significant influence from both the earthquake magnitude and source-to-site distance for soil class A and B sites and a very limited influence in the case of soil class C sites. Next, the site classification scheme proposed by Zhao *et al.* (2006) was also applied in order to assign a soil condition for a particular site of interest. This method was tested against the initial soil classification based on borehole data collected for the BIGSEES national research project and on the work of Wald and Allen (2007). The success rate of this method is lower in our study than in the studies of Zhao *et al.* (2006) or Ghasemi *et al.* (2009). In addition, the lowest success rate is encountered for soil class B sites, while the highest success rate is obtained for soil class A sites. In the subsequent step of the analysis, the H/V curves were computed using only strong ground motion data from Bucharest and the influence of the earthquake magnitude on the H/V curves was found to be significant. Finally, a comparison between the H/V curves derived from strong ground motions recorded at surface level and in boreholes was performed for three seismic stations in Bucharest. Significant differences between the two curves (surface vs. borehole) are noticeable, as well as larger amplifications observed on the H/V curve for surface level, thus showing a considerable influence of the top soil deposits on the ground motion characteristics at surface. The standard spectral ratios between surface and borehole for the two horizontal components (NS and EW) are similar for the seismic stations SMU and PRI, which are situated in the same area of Bucharest. Generally, the standard spectral ratio has values larger than unity for spectral periods $T<1.5$ s.

The analysis of the soil conditions for seismic stations in Romania using the HVSR method can be considered as an intermediary step and the results obtained in this study should be validated against an increased database of strong ground motion recordings. The results of the analysis and the mixed results obtained point to the stringent need for a national research project dealing with a more in-depth evaluation of the soil conditions for seismic stations in Romania.

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