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SITE EFFECT EVALUATION USING DIFFERENT TECHNIQUES: A CASE OF INTERMEDIATE DEPTH VRANCEA (ROMANIA) EARTHQUAKES

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SUMMARY

The soil response on earthquake ground motion was studied using ground-motion database collected in Romania. Almost all of the earthquakes occurred in Vrancea focal zone (SE-Carpathians), which is characterized by a high rate of occurrence of large earthquakes in a narrow focal volume. The epicentral region is confined to about 60 x 20 sq. km and the seismic activity ranges within an almost vertical stripe in depths between 70 and 170 km. The used database includes several tens of acceleration records obtained during three large (M 7.5, 7.2 and 6.9) earthquakes and several hundreds records from more than 120 small magnitude (M 3.5-5) earthquakes occurred in 1996-2001. The records were obtained at 23 stations; the local site conditions vary from metamorphic rock to deep soft soil deposits. The characteristics of soil response were evaluated in terms of frequency-dependent amplification using two techniques. One is a modification of the well-known horizontal-to-vertical Fourier spectral ratio of the S-wave phase, which was proposed for earthquake ground motion by Lermo and Chavez-Garcia (1994). The second one (Sokolov 1998) consists in calculating ratios between spectra of actual earthquake records (horizontal components) and those modeled for a hypothetical "very hard rock" (VHR) site. The VHR spectral model may be evaluated using the Vrancea earthquakes ground-motion database. Besides the local site response, the ratios include effects of source rupture peculiarities and inhomogeneous propagation path, too. However, when using a large enough number of events varying by magnitude, source depth and azimuth, the effects of focal mechanism and directivity are expected to be averaged out. In this paper we analyzed the ability of the techniques for intermediate-depth earthquakes of various magnitudes.

INTRODUCTION

Seismic hazard for almost half of the territory of Romania is determined by the Vrancea seismic region, which is situated beneath the southern Carpatian Arc in Romania. The region is characterized by a high rate of occurrence of large earthquakes in a narrow focal volume. The epicentral zone is confined to about

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60 x 20 sq. km and the seismic activity ranges within an almost vertical stripe in depths between 70 and 170 km. During the last century four major Vrancea earthquakes occurred on November 10, 1940 (M_W = 7.7), March 4, 1977 (M_W = 7.4), August 30, 1986 (M_W = 7.2) and May 30, 1990 (M_W = 6.9). The former two lead to disastrous impact on Romanian territory. According to official data (e.g. Sandi [1]) in the March 4, 1977 event, 1,570 people died, 11,300 were injured and 32,500 residential and 763 industrial units were destroyed or seriously damaged. According to World Bank estimates the total direct economic loss amounted to 2 billion US dollars.

Studies on strong ground motion excitation and attenuation during the Vrancea earthquakes based on available observed data have been performed, in application to seismic hazard assessment, by many seismologists (e.g. Gusev [2], Lungu [3], Oncescu [4], Moldovan [5]). A new seismic network (Figure 1) has been installed during recent years jointly by the Collaborative Research Center 461 'Strong Earthquakes' of Karlsruhe University (http://www-gpi.physik.uni-karlsruhe.de/) and the National Institute for Earth Physics, Bucharest (http://www.infp.ro). The network is centered in the Vrancea epicentral zone and covers an area with a diameter of up to 500 km. It consists of 44 free field stations, which are equipped with Kinemetrics K2-dataloggers with GPS timing systems and three-component accelerometers. Fifteen stations of the net were deployed in the Romanian capital Bucharest in nearly free field conditions. The accumulated database, which consists in hundreds of records obtained by several tens of stations during many small and moderate earthquakes, allows analyzing features of ground motion excitation and propagation in the region, including site response analysis (e.g. Bonjer [6], Wirth [7]). In this paper we concentrate on Fourier spectra and site response analysis.

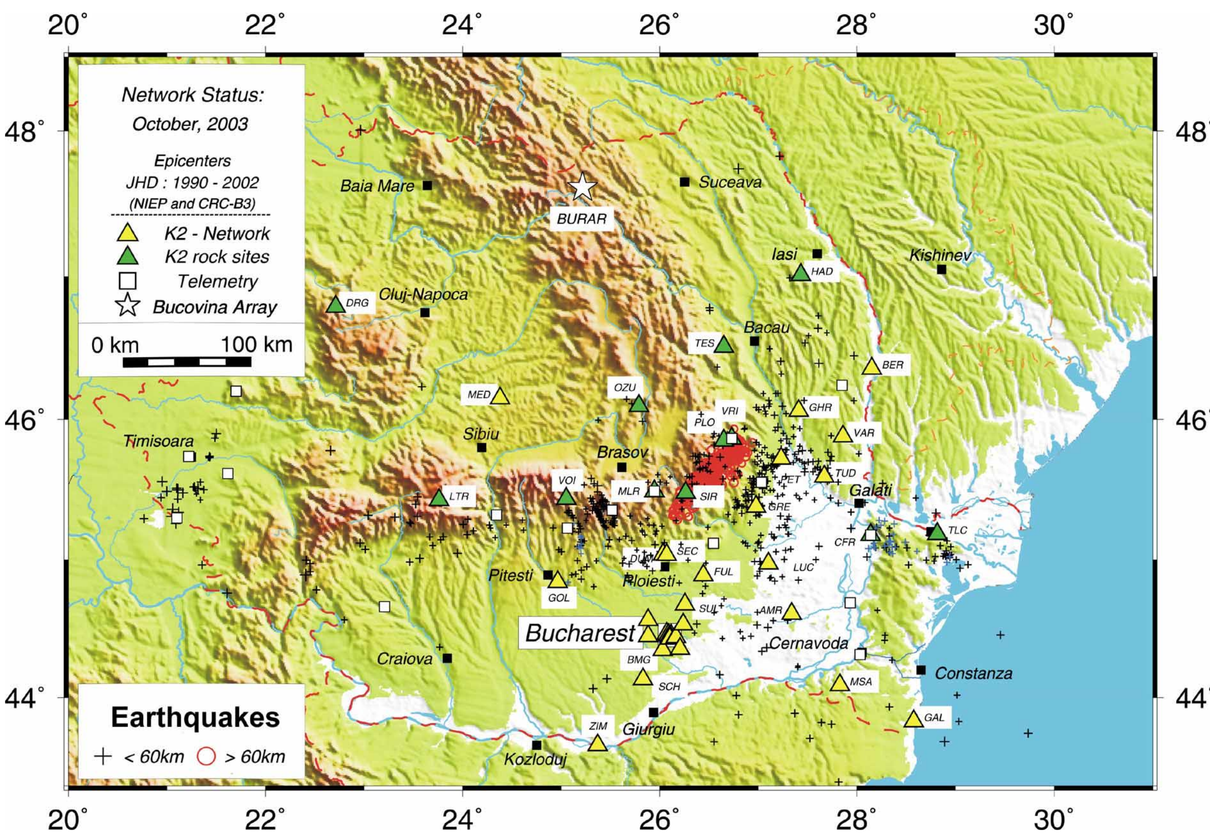

Figure 1. K2-network in Romania and location of the Vrancea seismogenic zone.

To estimate the site response from earthquake data it is necessary to remove the source and propagation path effects. Various site-response estimation techniques using the S-wave window have already been developed and studied (e.g. Bard [8]). One of them involves dividing the horizontal-component shear-wave spectra at each site by the vertical component spectra observed simultaneously at that site (Lermo [9]). This H/V technique has been widely studied and analyzed recently (e.g. Chen [10]; Bonilla [11], Field [12]). It has been found that the H/V method can reveal overall frequency dependence of site response and it is consistent with the general geological conditions of the recording sites. However, the general conclusion is that the technique fails in amplitude level, especially for high frequencies.

It was proposed recently (Sokolov [13-15]) to use so-called "very hard rock" (VHR) spectral model for the estimation of site response characteristics in terms of frequency dependent amplification (spectral ratios). The approach consisted in calculating spectral ratios between spectra of actual earthquake records (horizontal components) and those modeled for a hypothetical VHR site. Besides local site response, the spectral ratios include effects of source rupture peculiarities and inhomogeneous propagation path. When using a large enough number of events varied by magnitude, source depth and azimuth, the effects of focal mechanism and directivity are expected to be averaged out. The approach was applied for evaluation of characteristics of spectral amplification for particular sites in Taipei basin (Sokolov [14]) and for generalized site conditions in Taiwan (Sokolov [15]).

In this paper we analyzed records obtained at 23 stations, one of which a characterized as "hard rock" (VOI), eight – as "rock", and the others - as sediments or soft soil ones (Figure 1). The horizontal-to-vertical spectral ratio and very hard rock techniques were applied for characterization of site response in frequency range from 0.3-0.4 Hz to 10-15 Hz. The results were compared in order to assess advantages and shortcomings of the techniques. The analysis also allows evaluating of source scaling and attenuation model for ground motion spectra during intermediate depth earthquakes in the Vrancea source zone.

INPUT DATA AND TECHNIQUES

Data base and processing

The accelerograms of the strong Vrancea earthquakes of 1986 and 1990 are analog recordings of a SMA-1 network, operated by the National Institute for Earth Physics, Bucharest-Magurele (Oncescu [4]). The moderate size Vrancea earthquakes ($M < 5.5$, more than 60 events), used in this study, were recorded in 1996-2002 by the newly installed accelerometer K2-network (Figure 1). The site-specific amplification functions were evaluated for 23 stations, the local soil conditions at which vary from metamorphic rock to thick and water-saturated sedimentary formation.

Fourier amplitude spectra were calculated, using 10% cosine window, for selected parts (pre-event noise and S-wave window) of the records (Figure 2). The S-wave window contains the strongest part of the shaking. For the considered stations and small and intermediate size earthquakes, the length of the window was typically about or less than 10 seconds. We tried to keep the length of signal window as less as possible to avoid influence of surface waves. The Fourier spectra were smoothed twice within 0.2 Hz running window and the spectral amplitudes, for which the signal-to-noise ratio exceeded 2, were processed further. However, for the low-frequency range, besides level of noise, it is necessary to consider the effect of truncation in the time domain (e.g. Bath [16]). The truncation leads incorrectly to a too flat spectrum for long periods. It is recommended to use a time-domain-window length at least equal to twice the lowest analyzed wave period. Thus, combined effect of noise and truncation lead to different lower frequency values for various records. As a result, the number of analyzed spectral amplitudes in the low-frequency domain was smaller that that at the higher frequencies. For the case shown in Figure 2, the lower analyzed frequency is about 0.4-0.5 Hz

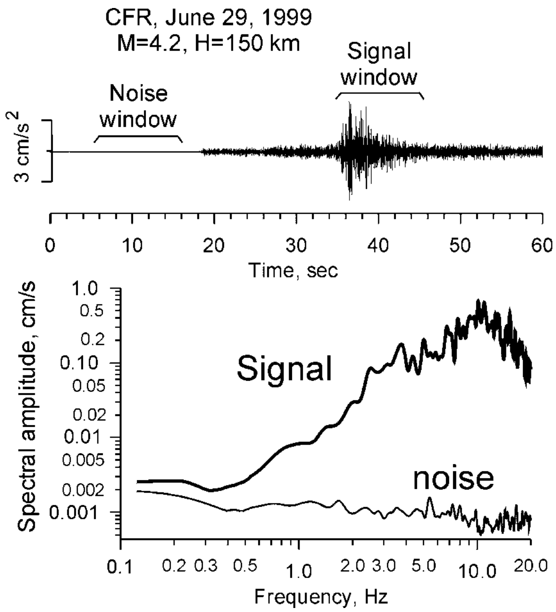

Figure 2. Example of evaluation of signal-to-noise ratio.

Technique for analysis

The details of the procedure of site amplification evaluation using horizontal-to-vertical spectral ratio (HVSR*)* may be found in many papers. Figure 3a shows example of evaluation of the HVSR function. In this section we describe in detail only the second technique – so-called Very-Hard-Rock ratio (VHR).

The general model for the Fourier acceleration spectrum A at frequency f is given by

$$A(f) = (2\pi f)^2 CS(f)D(R,f)I(f) \tag{1}$$

where C is the scaling factor*;* $S(f)$ is the source spectrum; $D(R, f)$ is the attenuation function, and $I(f)$ represents frequency-dependent and, strictly speaking, intensity- (magnitude and distance) dependent site response. For the case of "very hard rock" (VHR) spectrum, the function $I(f)$ should be equal to unity for the considered frequency range. Thus, the ratio between observed spectra A_O and the properly developed very hard rock spectral model *VHR* may be considered as site-specific amplification function I_{VHR} (Figure 3b)

$$I_{VHR}(f) = A_O(f) / VHR(f) \tag{2}$$

The specification of the "very hard rock" spectrum is of particular significance in the approach. One of our goals was to evaluate the ability of a simple spectral model to describe the seismic radiation from earthquakes in the region.

We constructed the VHR spectra as follows. The scaling factor C (equation 1) is calculated as

$$C = ([R_{\theta\phi}]FV)/(4\pi\rho\beta^3 R) \tag{3}$$

where $R_{\theta\phi}$ is the radiation coefficient, F is the free surface amplification, V represents the partitions of the vector into horizontal components, ρ and β are the density and shear velocity in the source region, R is the source-site (hypocentral) distance. A commonly used source function *S(f)* in the Brune [17] single-corner-frequency model is

$$S(f) = M_0 / [1 + (f / f_0)^2] \tag{4}$$

For the model, the source acceleration spectrum at low frequencies increases as f^2 and approaches a value determined by f_0 (corner frequency) and M_0 at frequencies $f > f_0$. The value of f_0 can be found from the relation $f_0 = 4.9 \times 10^6 \beta (\Delta\sigma / M_0)^{1/3}$. Here $\Delta\sigma$ is the stress parameter in bars, M_0 is the seismic moment in dyne-cm and β in km/sec.

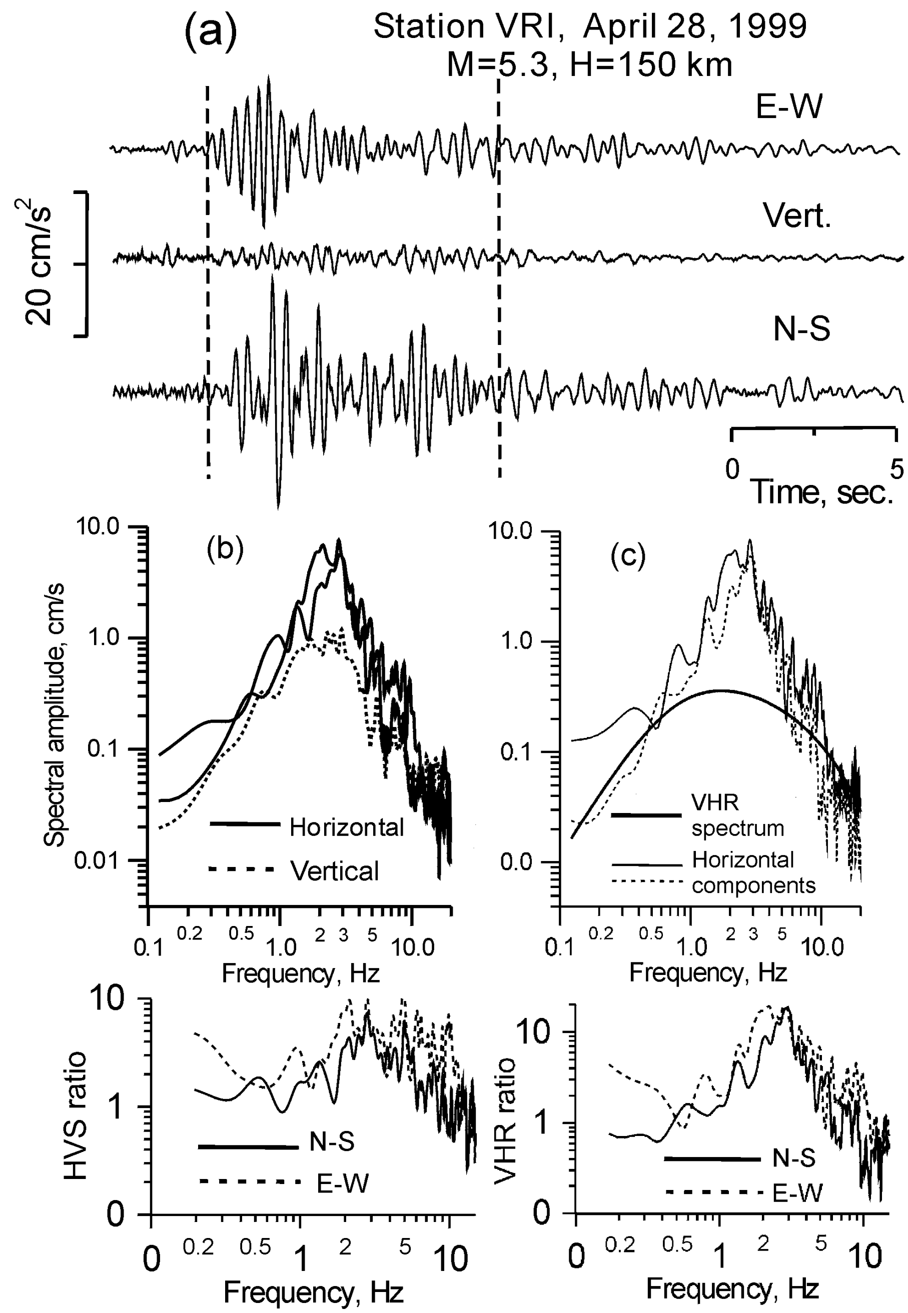

Figure 3. Techniques of analysis. (a) three-component acceleration record, dashed lines mark signal window. (b) Horizontal-to-vertical (HVS) spectral ratio: comparison of Fourier amplitude spectra, HVS ratios. (c). Very hard rock (VHR) spectral ratio: comparison of observed Fourier amplitude spectra (horizontal components) and spectrum modeled for hypothetical very hard rock condition; VHR ratios.

The function $D(R, f)$ accounts for frequency-dependent attenuation that modifies the spectral shape. It depends on the hypocentral distance R, regional upper mantle and crustal material properties, and the frequency-dependent regional quality factor Q that represents anelastic attenuation. These effects are represented by

$$D(R, f) = \exp[-\pi f R / Q(f)\beta] P(f, f_{\max}) \tag{5}$$

where $P(f, f_{max})$ is the high-cut filter. In the studied region for hypothetical very hard rock (VHR) sites [ρ = 2.8 gm/cm^3, β = 3.8 km/sec, $I(f)$ =1], we use the simple spectral model determined by equations 3-5. For the considered earthquakes, the moment magnitude values were taken from ROMPLUS (Romanian earthquakes) catalogue provided by National Institute for Earth Physic (see http://www.infp.ro/Labs/catal.html). The well-known relation between moment magnitude M_W and seismic moment M_0 (Hanks [18]) was used, namely:

$$M_W = 2/3 \log_{10} M_0 - 10.7 \tag{6}$$

For the largest events, if it was possible, values of the seismic moment were taken from the Harvard catalogue (http://www.seismology.harvard.edu). It has been found by fitting the observed and modeled spectra that the magnitude-dependent values of $\Delta\sigma$, increasing from 30 bars for M 3.0-3.5 up to 200-250 bars for M 5.0-5.5, and 500-400 bars for M 7.2-6.9 (Oncescu [19], show good agreement between observed and modeled data.

High-frequency amplitudes are reduced, through the kappa (κ) operator (Anderson [20]), by multiplying the spectrum by the factor $P(f)$

$$P(f) = exp\ (-\pi\, \kappa f) \tag{7}$$

where κ is a region-dependent parameter. The kappa-filter is introduced to consider near-surface (upper crust) attenuation of seismic waves, and the value of kappa exhibit both a region- and a site-dependent character. It has been shown recently (Atkinson [21]) that the parameter should be considered as a magnitude-dependent quantity, as the result of nonlinear behavior of the surface rock. In the considered case (Romania, Vrancea earthquakes, hard rock) we used $\kappa = 0.04$ for small and intermediate earthquakes and $\kappa = 0.07$ for large earthquakes. The generalized three-layers Q-model (Radulian [22]) is applied as $Q(f) = 150 f^{0.8}$ for depth from 200 km to 100 km; $Q(f) = 400 f^{0.9}$ for depth from 100 km to 40 km, and $Q(f) = 100 f^{0.8}$ for depth less than 40 km

The VHR model validation

The applicability of VHR spectral model may be tested by comparison of spectra of real recordings and modeled spectra. The modeled spectra for the site class A (hard rock) should match the averaged observed spectra in a broad frequency range. An example of the comparison is shown in Figure 4a. Station VOI (Voina) is located on crystalline rock (Figure 1) and it may be considered as site class A station. As expected, the ratios between the observed and modeled spectra are close to unity up to frequencies 6-7 Hz. However, there was a problem with the station. The records obtained at the initial location show influence of a high transmission tower near the station - intensive high-frequency vibration. Only three earthquakes of M 5.3, 4.0 and 3.9, which occurred in 1999, were registered with proper signal-noise relation in this location. When the station has been moved to a new location, only records from four earthquakes of M 4.0, 4.1, 4.3, and 4.6, which occurred in 2000, satisfy the signal-noise requirements and can be used in our study. At this location, small amplitude (up to 2.0) amplification was revealed at frequencies 3 - 8 Hz

For stations classified as rock (class B) sites, the modeled VHR spectra should fit the observed ones at low frequencies (less than 0.5-1.0 Hz). This is a general statement for validation of the VHR spectral model in the case of class B station. As it follows from results obtained by Boore [23], Klimis [24], and Chen [10], the amplitude of amplification functions for generalized site classes increases with frequency up to a value that, together with the frequency of the maximum, depends on the soil class and regional crustal properties. The amplitudes decrease rapidly for the higher frequencies. The amplification for site class B (rock) is characterized by the lowest maximum amplitude (1.4-1.5) and the highest frequency of the maximum (3-4 Hz). Thus, when comparing with the class-B observed spectra, the intermediate-frequency amplitudes of VHR modeled spectra should be less than the observed ones at frequencies up to 7-10 Hz.

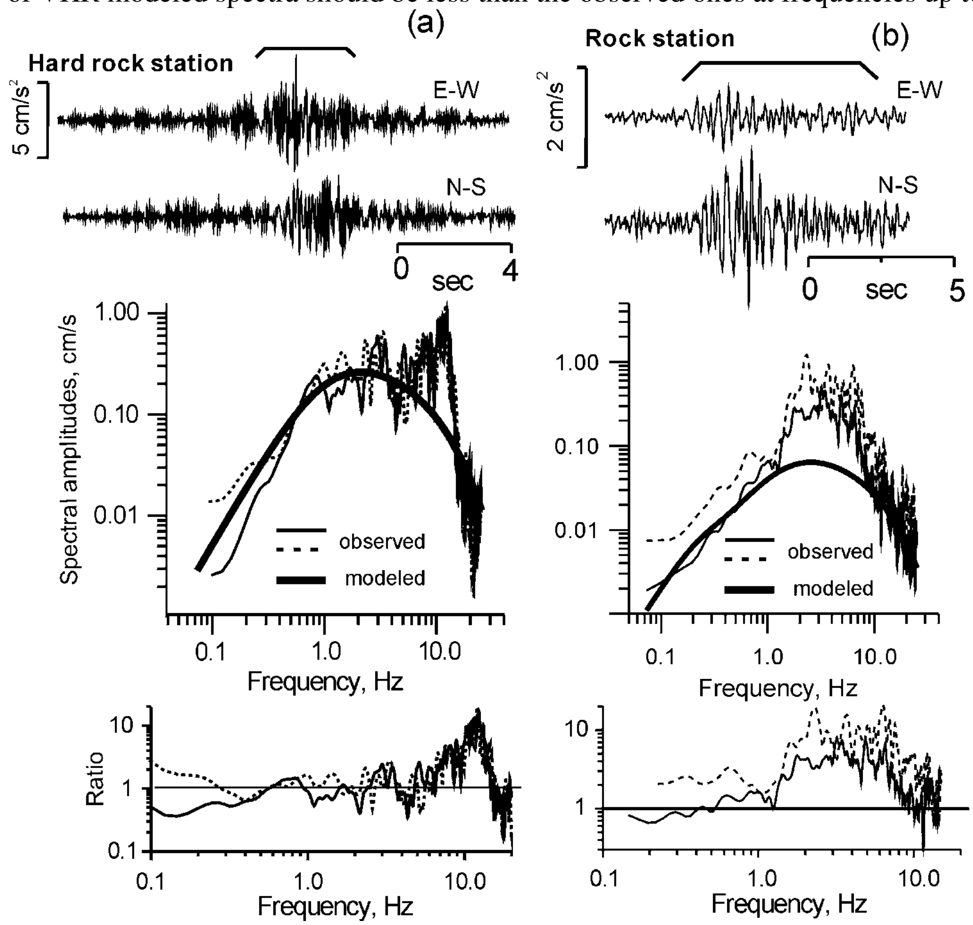

Figure 4. Validation of the VHR spectral model: (observed records; comparison of observed and modeled spectra; VHR ratios). (a) Hard rock, station VOI, earthquake of M 5.3, April 28, 1999, depth 150 km, source-to-site distance about 170 km. (b) Rock, station VRI, earthquake of M 4.5, November 18, 1997, depth and source-to-site distance about 130 km.

RESULTS AND ANALYSIS

Ideally, for the case of linear soil response on earthquake motion, the site amplification functions or ratios between observed and modeled spectra should not depend on magnitude. On the other hand, the site effect should be independent of the source model applied. Therefore, if the proper spectral models are used for various magnitudes, the characteristics (averaged amplitudes and shape) of ratios between observed and modeled spectra should be approximately the same for different earthquakes, at least for those of similar distance and azimuth.

Hard rock and Rock sites

Small and intermediate-size earthquakes
In the case of hard rock sites (no site effect), the HVSR values should be approximately equal to unity within a broad frequency range. If we use the proper VHR spectral model (source scaling and attenuation) the averaged ratio between observed and VHR spectra should be also near unity. Figure 5 shows characteristics of HVSR and VHR functions for hard rock station VOI (new location). There is a good agreement of the HVSR and VHR ratios that demonstrate the validity of the VHR spectral (source scaling and attenuation) model.

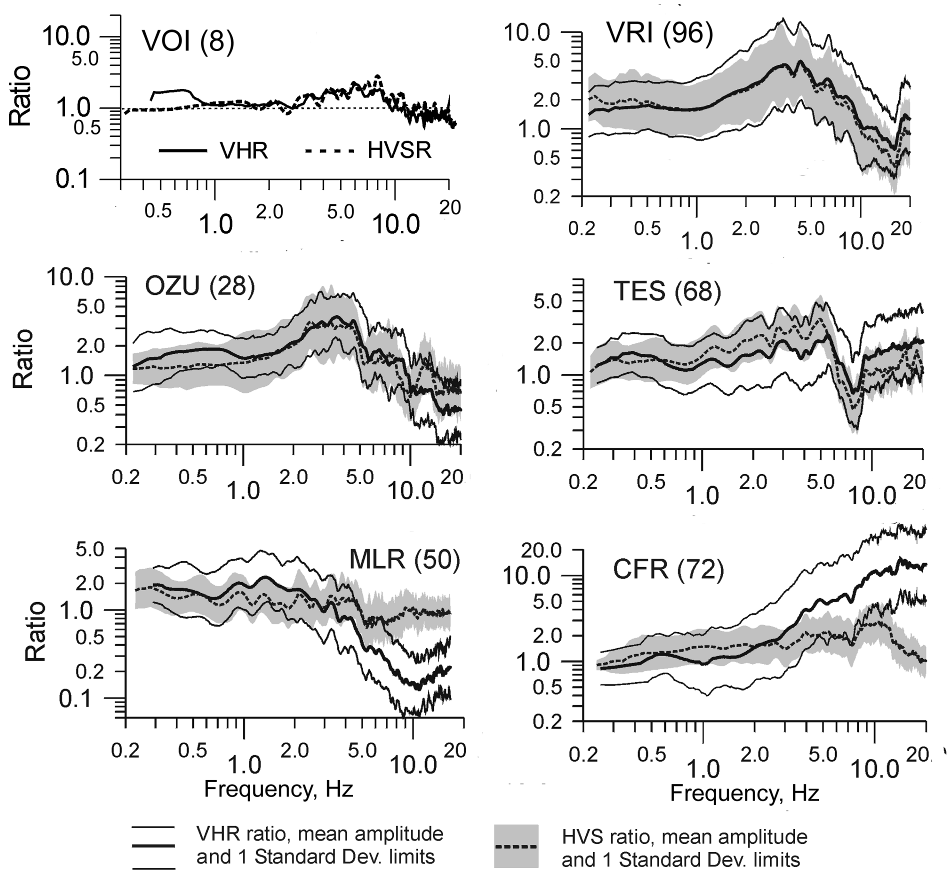

Figure 5. Comparison of characteristics of horizontal-to-vertical (HVSR) and very hard rock (VHR) spectral ratios for various rock stations. Numbers in parentheses show numbers of used records.

Let us consider rock site (class B) station VRI (Vrincioaia), which is in operation since November 1995. The station is located in immediate proximity to the epicentral zone of all Vrancea earthquakes (Figure 1). In this case, the influence of the propagation path is the smallest as compare to the other stations. The database for the station contains 48 small (M 3.2 - 5.3, depth 80-150 km) earthquakes. Characteristics of HVSR and VHR functions obtained from all considered earthquakes are shown in Figure 5. Both used techniques gave similar results regarding the mean values of amplification. The scatter characteristic (standard deviation) is somewhat smaller for the case of the HVS ratio that that for the VHR ratio. Again, if we assume that the results of HVSR technique adequately reflect the real site response for this case, the good agreement of the HVSR and VHR data may be considered as one more confirmation of validity of the VHR spectral model.

When analyzing the HVS and VHR ratios for other class-B stations of the K2 network (Figure 5), we can outline the following features. In the most cases, the HVS and VHR ratios almost identical for frequencies up to 5 Hz. Several stations (e.g. VRI and OZU) reveal the agreement up to 10 Hz. At the higher frequencies, the VHR technique resulted in higher amplitudes of ratios than the HVSR technique. There are stations (e.g. CFR) the overlap of VHR amplitudes over HVSR amplitudes starts from 2-4 Hz. For some stations (e.g. MLR) there is an opposite situation at high frequencies: HVSR level is higher than VHR level.

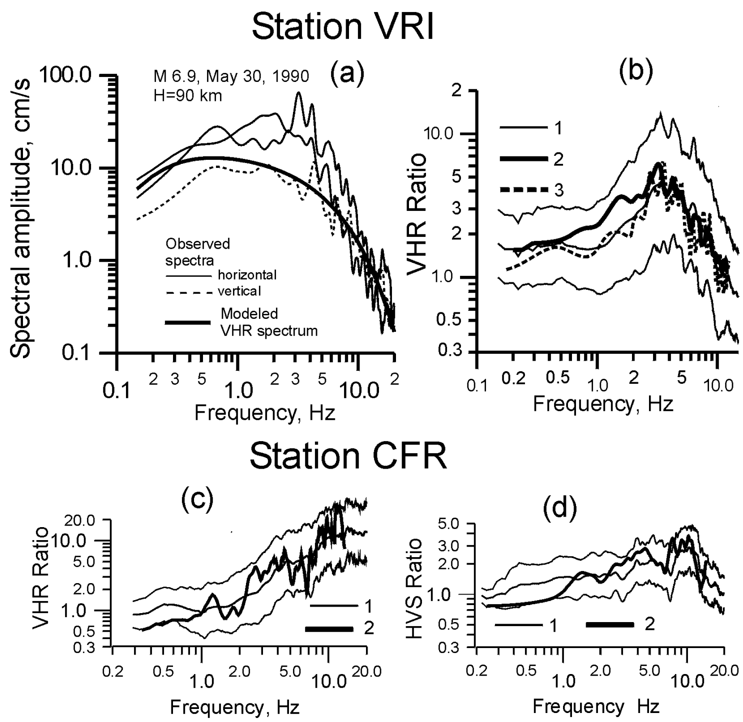

Figure 6. Large earthquakes, rock sites. (a) Comparison of observed Fourier amplitude spectra (horizontal and vertical components) and modeled VHR spectra. (b) Characteristics of very hard rock ratios evaluated from records of small and intermediate-size earthquakes (curves 1, mean amplitude values and ± 1 standard deviation) and ratios (mean amplitude values) calculated from records of large earthquakes (curve 2 - VHR ratio, curve 3 – HVS ratio). (c, d) Comparison of very hard rock (VHR) and horizontal-to-vertical (HVS) spectral ratios evaluated from records of small and intermediate-size earthquakes (curves 1, mean amplitude values and ± 1 standard deviation) and ratios (mean amplitude values) calculated from records of large earthquakes (curves 2).

Large earthquakes

Three large earthquakes, which were registered by strong-motion KINEMETRICS SMA-1 instruments, occurred in the Vrancea zone, namely: M 7.2, August 30, 1986, depth 130 km; M 6.9, May 30, 1990, depth 90 km; M 6.3, May 31, 1990, depth 80 km. Two instruments were located at the same rock sites as the stations of the K2 network (CFR and VRI). We calculated HVSR and VHR functions for the events and compared them with those from small earthquakes. When calculating VHR spectra for the case of large earthquakes, we also used single-corner-frequency model described in the previous section. In other words we consider the source of large earthquake in the Vrancea region as a point source. The assumption seems to be reliable bearing in mind large source-to-site distance and relatively small area of earthquake sources (e.g. Oncescu [4, 19]). Values of seismic moments for 1990 events were taken from Harvard catalogue (http://www.seismology.harvard.edu). Parameters of the 1986 earthquake were taken from Oncescu [19].

Comparison between the data, which were obtained from small and intermediate earthquakes, and those from large earthquakes is shown in Figure 6. The HVSR and VHR functions calculated from small and large earthquakes tend to converge, both in shape and amplitude. This allow concluding that the seismic radiation (within frequency range from 0.2-0.3 to 12-15 Hz) during the large earthquakes in Vrancea zone may be described by simple omega-square single-corner-frequency spectral model (Equations 1-7). Of course, we realize that the conclusion has been made on the basis of only three large earthquakes and two stations. However, bearing in mind the lack of strong-motion data in the territory of Romania, this, even insufficiently confirmed by empirical data, statement allows evaluating models for radiation from future strong earthquakes in the region.

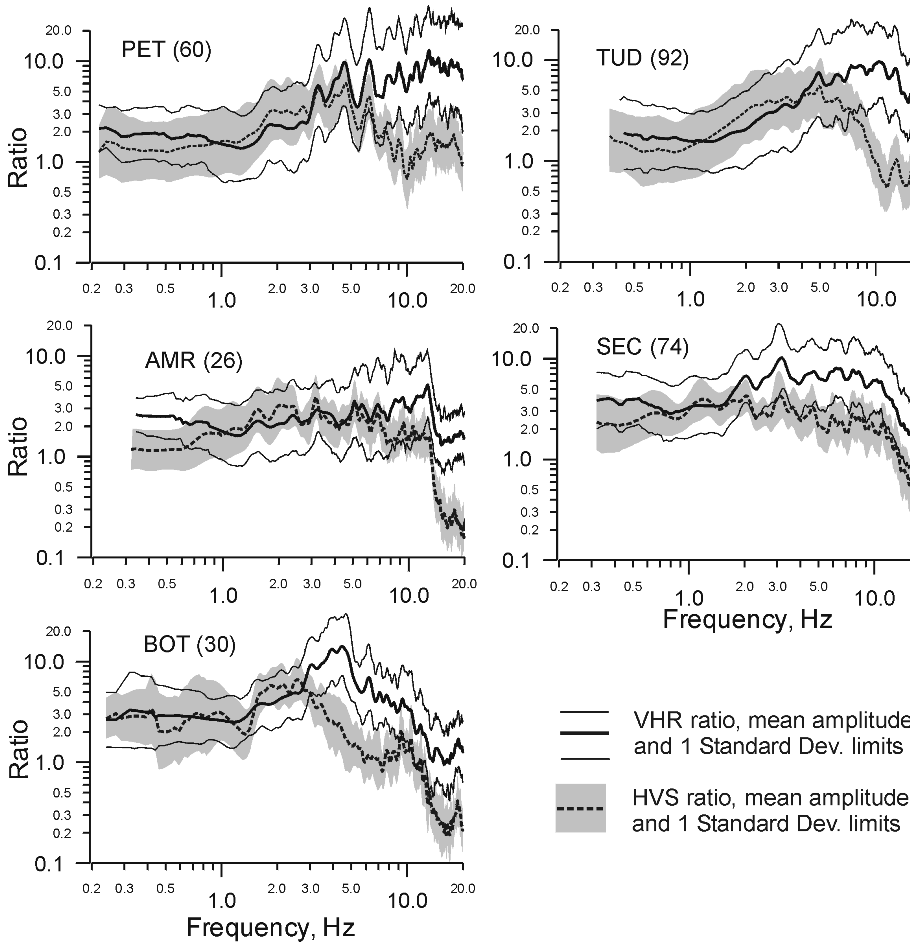

Figure 7. Comparison of characteristics of horizontal-to-vertical (HVSR) and very hard rock (VHR) spectral ratios for various sediment and soft rock stations. Numbers in parentheses show numbers of used records

Sediments and soft soil sites

In this section we show data from various stations, which can not be considered as rock sites. Thickness of sediments may vary from several hundred (GRE, TUD) to several tens of meters and some stations are located on water-saturated deposits (PET, AMR, SUL). Detailed information about local geological condition is not available for the most of the stations. Only for the case of Bucharest area (thick sediments and soft soil, stations INC, BOT, BUC) it is possible to find such information (e.g. Lungu [3], Bonjer [6]. Wirth [7], Mandrescu [25], Lungu [26]).

Figure 7 compares characteristics of HVSR and VHR functions for several soft soil sites. In this case the HVS and VHR, ratios showing a good agreement for frequencies up to 2-5 Hz, reveal stable discrepancy for the higher frequencies: the VHR technique resulted in higher amplitudes of ratios than the HVSR technique. Before analyzing of the reasons of the discrepancy, we need to answer the question: *do the HVSR and VHR curves reflect real site response*? For the purpose, we used a simple 1-D technique that allowed us calculating theoretical spectral amplification of a multi-layered soil column overlying a rigid half-space for SH- and SV-waves approaching the bottom of the soil with arbitrary angles of incidence. Records obtained at station INC (Bucharest) were analyzed. The layered structure of deposits under the site was described using two 1-D velocity-density models obtained from different sources, namely: Model 1 (Lungu [3]), and Model 2 (Bonjer, personal communication). Table 1 presents properties of the soil layers.

Table 1. Velocity-density model for the INC site

Vp km/sec	Vs, km/sec	Density	Quality factor	Thickness, km	Depth, km
Soil Model 1, after Lungu [3]					
0.68	0.1	1.9	10	0.004	0.004
1.66	0.33	2.0	100	0.01	0.014
0.72	0.24	2.0	60	0.02	0.034
2.1	0.35	2.1	100	0.034	0.068
2.1	0.45	2.0	200	0.05	0.118
2.15	1.15	2.3	300	0.43*	0.518
5.4	3,12	2.6		-	-
Soil Model 2					
0.68	0.1	1.9	10	0.008	0.008
1.45	0.37	2.0	50	0.01	0.018
1.8	0.46	2.1	100	0.008	0.026
1.6	0.40	2.05	100	0.014	0.04
1.8	0.42	2.1	100	0.02	0.06
1.9	0.5	2.1	200	0.06	0.066
1.64	0.43	2.05	100	0.06	0.072
1.85	0.47	2.1	200	0.012	0.084
1.9	0.93	2.2	300	0.052	0.136
2.15**	1.15	2.3	300	0.43	0.18
5.4**	3,12	2.6		-	-

* - The thickness of the layer was taken arbitrary
** - two bottom layers were added from the Model 1.

Figure 8a shows spectral amplification curve (horizontal component), which was obtained using the models as average amplification of the cases of SH and SV-waves calculated for three angles of incidence (20^0, 25^0 and 30^0). Of course, it is not possible to expect a perfect fit between the theoretical and empirical amplification functions. However, the both models, and the second model in the larger extent, provide a reasonable agreement with the VHR data. Therefore, we can conclude that the VHR ratio seems to reflect properly the overall site amplification. We also compared results of application of HVSR method and theoretical modelling (Figure 8b). In this case we used model 1 as the basic model and consider response of four models removing several soil layers from the top. After analysis of results of comparison, it is possible to conclude that HVSR method reflects properly the first (fundamental) frequency of site response.

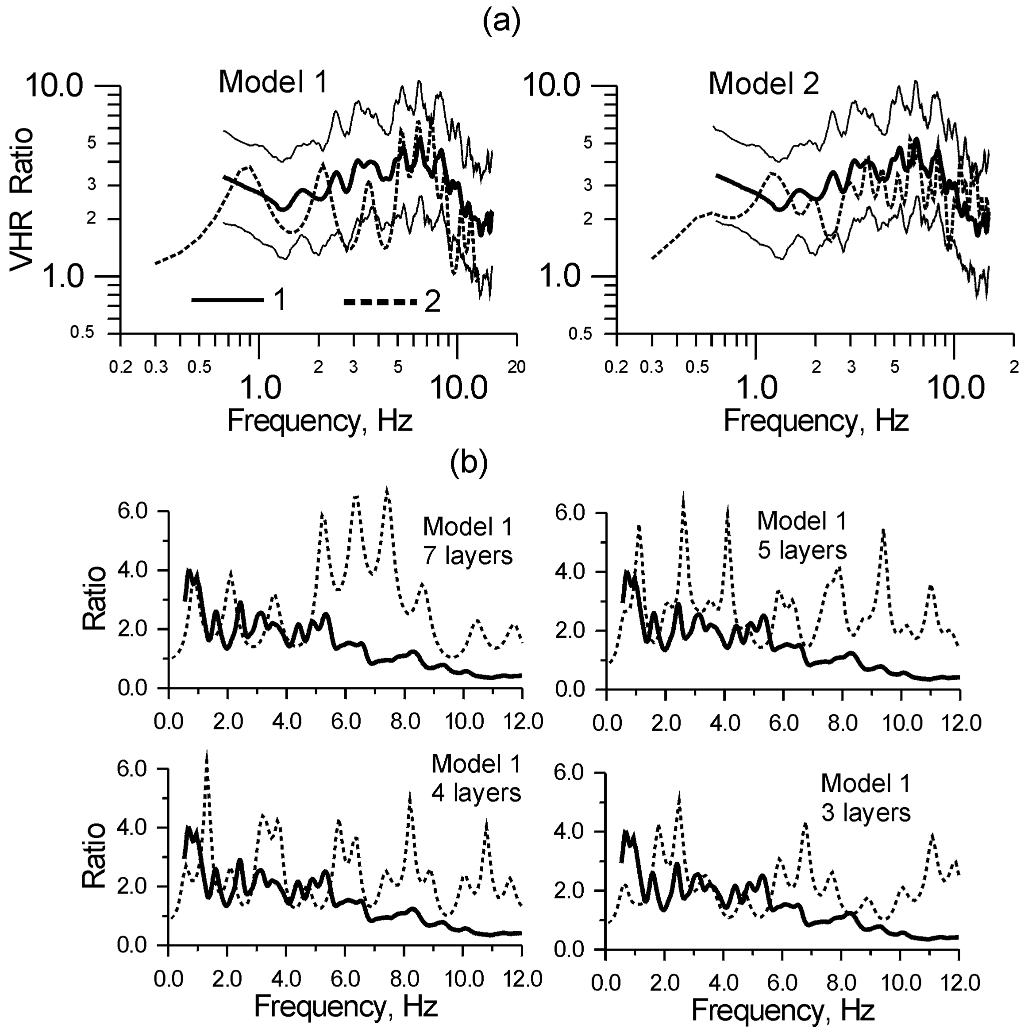

Figure 8. Station INC, Bucharest. (a) Comparison of characteristics of very hard rock (VHR) spectral ratios (curves 1, mean amplitude values and ± 1 standard deviation) and theoretical amplification (curves 2) calculated using different soil models (Table 1). (b) Comparison of horizontal-to-vertical spectral ratio (mean amplitude, solid lines) and theoretical amplification (dashed lines) calculated using variations of the Model 1.

DISCUSSION

The VHR ratio reflects the difference between idealized source scaling and attenuation models and real recordings. Besides local site response, the spectral ratios include effects of source rupture peculiarities and inhomogeneous propagation path. The reverse faulting with principal *T* axis nearly vertical and *P* axis nearly horizontal characterizes all the major events and more than 90% small and intermediate size earthquakes in the Vrancea zone, regardless their magnitude (e.g. Radulian [22]). For the considered case, all analyzed earthquakes are concentrated within an almost vertical narrow volume in depths between 80 and 150 km. Influence of propagation path for every station is the same for all earthquakes, at least for those concentrated below and above 100 km (layers of different Q-model). Therefore, we can suppose that the discrepancy between horizontal-to-vertical spectral ratios and very-hard-rock ratios are caused by local and subsurface factors, which are not considered in the VHR model, but which do influence on vertical component of ground motion.

Beresnev [27] showed that shear waves dominate the vertical motions at frequencies up to approximately 10 Hz. At the higher frequencies the contribution of compressional deformation is about as strong or greater. The VHR spectral model, by definition, does not include P-wave radiation. Thus, when P-wave dominate the vertical component, VHR ratio would be characterized by the higher amplitudes than the horizontal-to-vertical spectral ratio. When analyzing earthquake records obtained in deep borehole array, Takashi [28] concluded that the vertical components observed in the surface layers are mostly P waves converted from the SV waves at the boundaries of the layers above the base rock. It has been also shown by Loukachev [29] that shear waves in granular materials induce longitudinal dilatancy waves with approximately double frequency. This would result in the increase of amplitudes at vertical component.

We have also shown by numerical modeling that phenomenon of mutual overlapping of relatively rigid and soft layers could produce high amplification at horizontal component by compressional wave, and shear wave significantly contributes to vertical motions. The highest amplitudes of amplification are observed at high frequencies. As far as the VHR model does not consider effects of sufficient SV-wave contribution to vertical component and contribution of compressional deformation, we observe large discrepancy between VHR and HVSR amplitudes for this case.

Thus, as it has been already noted by Riepl [30], the horizontal-to-vertical spectral ratio is sensitive, especially for high frequencies, to the presence of local heterogeneities and to a complex 2D or 3D subsurface geometry. Therefore, the HVSR technique could provide satisfactory results mostly in the case of simple geology, which can be modeled using just one horizontal and non-compressible layer.

CONCLUSION

Two “non-reference site” methods of site response evaluation - horizontal-to-vertical spectral ratio (HVSR) and very hard rock spectral ratio (VHR) - were applied for the case of rock sites in Romania and intermediate depth Vrancea (Romania) earthquakes. Analysis of results allows the authors to make the following conclusions.

When considering the methodological aspect, we have to note that there is a good agreement between the HVSR and VHR data within frequency range from 0.3 Hz to 10 Hz for hard rock or rock sites with uncomplicated geology. For frequencies larger than 10 Hz additional influence of P-wave should be considered. The horizontal-to-vertical spectra ratio seems to underestimate amplitudes of site amplification at high frequencies (more than 3-5 Hz) for inhomogeneous medium. However, in the case of extremely high weathering (or/and fracturing) which leads to strong attenuation of high-frequency radiation, the HVSR technique may conversely overestimate amplification. The peculiarities should be taken into account when using generalized regional HVSR data for ground motion prediction.

The VHR technique could provide reliable results in various geological conditions, however, the approach requires correspondent spectral models. At the same time, in order to average effects of source rupture peculiarities and inhomogeneous propagation path, sufficient number of earthquakes (records) should be analyzed. We also have to note that the VHR analysis results in larger scatter of ratio values for complex geological condition than that for the HVSR technique.

The following conclusions may be drawn, when considering regional aspects. Analysis of regional earthquake ground-motion database allows concluding that seismic radiation (within the frequency range from 0.2-0.3 to 15-20 Hz) during the earthquakes of various magnitudes in the Vrancea zone may be described, for rock sites and simple geological condition, by the omega-square single-corner-frequency spectral model and a correspondent *Q*-model.

We realize that the comprehensive analysis of the techniques requires joint analysis of empirical data and results of numerical modeling of site responses. In future we are going to perform a similar study using data collected by other networks (e.g. CALIXTO, see http://www-sfb461.physik.uni-karlsruhe.de/pub/A2/Calixto/calixto99_en.html), which cover the larger territory. The detailed velocity-density models will be analyzed that, as expected, will increase reliability of the techniques comparison.

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REFERENCES

1 Sandi H. “Obstacles to earthquake risk reduction encountered in Romania”. Lungu D and Saito T, Editors, Earthquake hazard and countermeasures for existing fragile buildings 2001: 261-66.
2. Gusev A, Radulian M, Rizescu M, Panza GF. “Source scaling of intermediate-depth Vrancea earthquakes”. Geophys. J. Int. 2002; 151: 879-89.
3. Lungu D, Cornea T, Nedelcu C. “Hazard assessment and site dependent response for Vrancea earthquakes”. Wenzel F, Lungu D, Novak O., Editors, Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, Kluwer Academic Publishers, Dordrecht 1999: 251-67.
4. Oncescu MC, Bonjer KP, Rizescu M. “Weak and strong ground motion of intermediate depth earthquakes from the Vrancea region”. Wenzel F, Lungu D, Novak O., Editors, Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, Kluwer Academic Publishers, Dordrecht 1999: 27-42.
5 Moldovan IA, Enescu BD, Ionescu C. “Predicting peak ground horizontal acceleration for Vrancea large earthquakes using attenuation relations for moderate shocks”. Romanian Journal of Physics 2000; 45 (9-10): 785-800.
6. Bonjer KP, Oncescu MC, Driad L., Rizescu M. “A note on empirical site responses in Bucharest, Romania”. Wenzel F, Lungu D, Novak O., Editors, Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, Kluwer Academic Publishers, Dordrecht 1999: 149-62.
7. Wirth W, Wenzel F, Sokolov V, Bonjer KP. “A uniform approach to urban seismic effect analysis”. Soil Dynamics and Earthquake Engineering 2003; 23: 737-58.
8. Bard PY. “Effects of surface geology on ground motion: recent results and remaining issues” Proc. Tenth European Conf. on Earthq. Eng. Balkema: Rotterdam 1995: 305-23.
9. Lermo J, Chavez-Garcia FJ. “Site effect evaluation using spectral ratios with only one station”. Bull. Seis. Soc. Am. 1993; 83: 1574-94.

10. Chen SZ, Atkinson GM. “Global comparisons of earthquake source spectra”. Bull. Seis. Soc. Am. 2002; 92: 885-95.
11. Bonilla LF, Steidl JH, Lindley GT, Tumarkin AG, Archuleta RJ. “Site amplification in the San Fernando valley, California: variability of site-effect estimation using the S-wave, coda and H/V methods”. Bull. Seis. Soc. Am. 1997; 87: 710-30.
12. Field EH, Jacob KH. “A comparison and test of various site-response estimation techniques including three that are not reference-site dependent”. Bull. Seis. Soc. Am. 1995; 85: 1127-43.
13. Sokolov VY. “Rough estimation of site response using earthquake ground motion records”. Proc. of Second Int. Symp. on the Effects of Surface Geology on Seismic Motion (ESG 1998*),* Yokohama, Japan, Dec. 1-3, 1998: 517-22.
14. Sokolov VY, Loh CH, Wen KL. “Empirical study of sediment-filled basin response: a case of Taipei city”. Earthquake Spectra 2000; 16: 681-707.
15. Sokolov VY, Loh CH, Wen KL .”Evaluation of hard rock spectral models for the Taiwan region on the basis of the 1999 Chi-Chi earthquake data”. Soil Dynamics and Earthquake Engineering 2003; 23: 715-35.
16. Bath M. “Spectral analysis in geophysics”. Elsevier: Amsterdam 1974.
17. Brune JN. “Tectonic stress and the spectra of seismic shear waves from earthquakes”. J. Geophys. Res. 1970; 75: 4997-5009.
18. Hanks TC, Kanamori HA. “A moment magnitude scale”, J. of Geophys. Res. 1979; 84, 2348-50.
19. Oncescu MC. “Investigation of a high stress drop earthquake on August 30, 1986 in the Vrancea region”. Tectonophysics 1989; 163, 35-43.
20. Anderson J, Hough S. “A model for the shape of the Fourier amplitude spectrum of acceleration at high frequencies”. Bull. Seism. Soc. Am. 1984; 74: 1969-93.
21. Atkinson GM, Silva W. “An empirical study of earthquake source spectra for California earthquakes”. Bull. Seism. Soc. Am. 1997; 87: 97-113.
22. Radulian M, Vaccari F, Mandrescu N, Panza GF, Moldoveanu CL. “Seismic hazard of Romania: deterministic approach”. PAGEOPH 2000; 157: 221-47.
23. Boore DM, Joyner WB. “Site amplification for generic rock sites”. Bull. Seism. Soc. Am. 1997; 87: 327-41.
24. Klimis NS, Margaris BN, Koliopoulos PK. “Site-dependent amplification functions and response spectra in Greece”. J. Earthquake Engineering 1999; 3: 237-70.
25. Mandrescu N, Radulian M. “Seismic microzoning of Bucharest (Romania): a critical review”. Wenzel F, Lungu D, Novak O., Editors, Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, Kluwer Academic Publishers, Dordrecht 1999: 109-21.
26. Lungu D, Aldea A, Moldoveanu T, Ciugudean V, Stefanica M. “Near-surface geology abd dynamic properties of soil layers in Bucharest”. Wenzel F, Lungu D, Novak O., Editors, Vrancea Earthquakes: Tectonics, Hazard and Risk Mitigation, Kluwer Academic Publishers, Dordrecht 1999: 136-62.
27. Beresnev IA, Nightengale AM, Silva WJ. “Properties of vertical ground motions”. Bull. Seis. Soc. Am. 2002; 92: 3152-64.
28. Takahashi K, Ohno S., Takemura M, Ohta T, Hatori T, Sugawara Y, Omote S. “Observation of earthquake strong-motion with deep borehole. Generation of vertical motion propagating in surface layers after S wave arrival”. Proc. Tenth European Conf. on Earthq. Eng. Balkema: Rotterdam 1995: 1245-50.
29. Loukachev I, Pralle N, Gudehus G. “Dilatancy-induced P waves as evidence for nonlinear soil behavior”. Bull. Seism. Soc. Am. 2002; 92: 854-62.
30. Riepl J, Bard PY, Hatzfeld D, Papaioannou C, Nechtschein S. “Detailed evaluation of site-response estimation methods across and along the sedimentary valley of Volvi (EURO-SEISTEST)”. Bull. Seis. Soc. Am. 1998; 88: 448-502.