Romanian Reports in Physics **74**, 708 (2022)

SPECTRAL CHARACTERISTICS OF THE SEISMIC RESPONSE FROM LOCAL RECORDINGS. APPLICATION TO URBAN AREAS

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Received May 5, 2022

Abstract. The seismic response recorded at two sites is analyzed, as it results from strong motion generated by Vrancea intermediate-depth seismic source. Three strongest seismic events generated by the Vrancea intermediate-depth seismic zone in the last five decades are chosen for this purpose. The evaluation is made for two areas of interest, as revealed by the spectral features influenced by the geological deposits under seismic excitation. The results are shown as response spectra at Bucharest-INCERC and Cernavoda downtown seismic stations for three strong earthquakes and other three weaker, collocated as pairs. The manner in which the seismic response for a broader range of magnitudes is affected by the specificity of each site is investigated. The shift of the predominant period is large at INCERC station, where high values are encountered, disposed of on a broader range. At this site, spectral ratios for each of the three pairs of seismic response spectra are performed, in order to showe the seismic source influence on local effects. The observed local amplification in correspondence to the site characteristics is highlighted.

Key words: spectral seismic response, predominant period, local effects, site evaluation.

1. INTRODUCTION

The seismic activity of the Vrancea region source, the most active and dangerous focal area over the country territory, places Romania among the European countries with severe hazard characteristics. The earthquakes originating in this epicentral region are well known as the main risk source of natural disasters. The aim of this work is to contribute to evaluating the local site response for certain areas of interest, as revealed by the spectral features influenced by the site deposits under seismic excitation. More precisely, the accomplishment of such a goal is based on the characterization of the seismic response at the surface, affected by the specificity of the local soils features. The correct foreseeing of the dynamical features of soils is of high importance for an efficient anti-seismic protection of the buildings and for controlling the effective seismic risk to which they are exposed. The ultimate goal is, of course, to limit the seismic risk at an "acceptable" level from a social and economic point of view. In this context, the prediction of the spectral content of the site response during strong earthquakes is relevant.

From the recordings offered by the last strong Vrancea earthquakes (1977.03.04, $M_w = 7.4$; 1986.08.30, $M_w = 7.1$; 1990.05.30, $M_w = 6.9$; 1990.05.31, $M_w = 6.7$) some important features can be noticed: for the same epicentral area there exist important differences in the characteristics of the strong motion at different sites throughout the country territory, and/or for different seismic events. These observations highlight the ground motion level and particularly the local soil conditions as the main factor which affects the seismic shaking characteristics.

Vrancea subcrustal earthquakes, the focal area our studies are restricted to herein, exhibit some particular features, such as the spatial asymmetry of the seismic radiation and notably high peak ground motion values at large epicentral distances [1–5]. The typical directivity of these seismic sources towards N-E and S-W directions, including the Romanian Plain among other areas, makes a lot of cities, or other important industrial objectives, highly exposed.

Therefore the seismic risk assessment for the most populated city, Bucharest, located at ~ 130–160 km average epicentral distance, in the Moesian Platform, or for the Cernavoda Nuclear Power Plant (NPP) site area, at ~ 180–190 km, should be addressed at a proper level. The reason for choosing these two sites in our approach is not only for their apparent social, economic or strategic importance, but also for local site specificity. Though both belong to the same major geological unit *i.e.*, Moesian Platform, their upper soils content is very different. The Nuclear Power Plant is located on the South-Eastern edge of the Moesian Platform (South Dobrogea Platform), on an overthrust tectonic compartment near the city of Cernavoda. Its epicentral distance from the Vrancea focal area is generally larger as for Bucharest, with corresponding hypocenters localization which is, for the earthquakes considered herein, between 209–222 km, while for Bucharest these distances are 180–188 km. Though the Cernavoda NPP is exposed to seismic hazard originating in at least two other focal area (Shabla area, at the Black Sea, near the Bulgarian border, and North Dobrogea crustal areas), we shall discuss herein only the recordings originating from the most dangerous-subcrustal Vrancea-seismic zone.

The evaluation of the ground motion at sites of interest should involve the identification of potentially active sources in the region, the evaluation of the seismicity associated with individual sources, the estimation of travel-path influences on the seismic wave characteristics as they propagate from the source to the particular rock site and the computation of the dynamic response of soil deposits. Some of these issues, closely related to geophysical processes, are treated in many state-of-the-art studies, carried out for the Romanian territory [1, 6–9]. These studies are based on approaches regarding soil behavior under seismic excitation, for local site conditions, and local effects, especially for the soft soils content, developed in [10–15].

Field and laboratory investigations should be oriented, but not limited, to defining soil deposit stratigraphy, soils index properties, static and dynamic stress-strain soil behavior etc. The latter issue is tackled in papers [16–19] with regards to highly populated areas in the Romanian territory and constructed medium (areas), nonlinearities included. The former issues are largely treated in [20–22].

In this paper we limit ourselves to approaching site spectral response as it results from strong motion generated by Vrancea intermediate-seismic source. We consider three strong earthquakes belonging to this focal area and their recordings at INCERC site in Bucharest city and Cernavoda downtown. In fact for the first site there exist recordings for three earthquakes (1977.03.04, $M_w = 7.4$; 1986.08.30, $M_w = 7.1$; 1990.05.30, $M_w = 6.9$), while for the latter site recordings of just two less strong ones are available.

In order to characterize the behavior of soil for seismic purposes, absolute seismic accelerations elastic response spectra are used. The recorded data are gathered from the National Seismic Network and earthquakes' parameters are provided by Romplus Catalogue (www.infp.ro/romplus) [23]. The strongest three seismic events generated by the Vrancea-intermediate seismic zone are chosen for this purpose. Also, for each strong earthquake a less stronger one is selected that shares the same mechanism type and a very close focal localization. These pairs of earthquakes are used to analyze differences in response of certain sites at different magnitudes generated in almost the same focal restricted volume experiencing the same propagation path. The characteristics of the collocated earthquakes are presented in Table 1.

Table 1

Characteristics of the collocated earthquakes. The considered pairs are in successive columns

Station and source characteristics	Earthquakes and their parameters					
Bucharest INCERC (INC)	**1977**	**2016**	**1986**	**2010**	**1990**	**2013**
Moment magnitude M_w	7.4	5.6	7.1	3.9	6.9	4.1
Source Lat. (°)	45.77	45.71	45.52	45.56	45.83	45.78
Source Long. (°)	26.76	26.6	26.49	26.49	26.89	26.71
Focal depth h (km)	94	96.9	131.4	128.8	90.9	91.2
Hypocentral distance *R* (km)	181.41	174.67	179.83	180.97	188.2	197.91
Cernavoda downtown (CVD)	**1977**	**2016**	**1986**	**2010**	**1990**	**2013**
Moment magnitude M_w	–	–	7.1	3.9	6.9	4.1
Source Lat. (°)	–	–	45.52	45.56	45.83	45.78
Source Long. (°)	–	–	26.49	26.49	26.89	26.71
Focal depth h (km)	–	–	131.4	128.8	90.9	91.2
Hypocentral distance *R* (km)	–	–	223.18	224.3	210.19	214.47

2. GEOPHYSICAL AND SEISMOLOGICAL SETTINGS

Many research studies and geophysical descriptive works have been performed along the time, regarding Bucharest subsoil content characteristics [24–29], concerning hazard and microzonation estimations. Local effects have been evaluated using seismic recordings, synthetic seismograms generation, geotechnical data processing, with the consideration of the rocks nonlinear behavior effects. The seismic waves propagation is one of the most important subjects which have continuously pursued and undergone many refinements [30–35]. These studies have a thorough and exhaustive character, comprising detailed information about sedimentary layers below the Bucharest area. Briefly, Bucharest is located in the central part of the Moesian Platform at an average epicentral distance of ~ 150 km from the Vrancea region. The subsoil of the Bucharest area is represented by Quaternary deposits with sedimentary thicknesses that vary from north to south, with an extent deep to 200–300 m [26] (Table 2). These characteristics are generally assumed to induce amplifications in soil shaking, but in a non-uniformly manner throughout the city area, in close dependence to several factors, that are earthquakes magnitude or particularities of the layers content beneath each observational point, including their thickness, variations in the wave velocities and the impedance contrast, or even earthquakes focal depth (which for Vrancea subcrustal focal area are on a large range, between ~ 90–200 km). All these features affect, in different manner or weight, the spectral content of the recorded waveform.

Table 2

Bucharest soil profile (compiled after [26, 27])

Layer compounds	Depth [m]	Thickness [m]	Shear waves velocity v_S [m/s]	Longitudinal waves velocity v_P [m/s]
Loesslike deposits	4	4	104	280
Sands and Gravels	32	28	174	470
Dusty clays	47	15	367	990
Sands	67	20	444	1200
Marly clays, sands with gravels	262	195	694	1700
Clays, marls and sands, marls	732	470	933	1940
Sandy marls and compacted marls	1162	430	1150	2150
Limestones and marls with limestones			3400	5400

Moderate-size earthquakes ($M \leq 7.0$) are considered to stimulate mostly the upper soil deposits, located above the marl complex (Upper Pleistocene-Holocene) and the peaks of soil shaking intensity are in the short period domain. For strong earthquakes ($M > 7.0$) all the cohesionless Quaternary deposits (including the marl complex) behave unitarily in an enhanced vibrating motion, causing amplifications with much longer periods [24].

For the Cernavoda area a simpler geophysical setting is encountered, in the sense that its generic stratigraphy consists in a relatively hard, mostly superficial part (few meters thick), followed by a few layers with different consistency, then an underneath marl complex. The stratigraphy is, in fact, slightly different over the area of the city. For example, at the City Hall site, there are two limestone superior layers (around the first 15 meters) followed by a marl deposit (after Marmureanu *et al.* 2017, [36]). A more detailed profile could be attributed to the NPP site (after Niculescu 2018, [37]), where thinner upper quaternary deposits exist, then continental deposits, below which we encounter a few structural complexes distinguished by a high velocity impedance contrast (Table 3).

Table 3

Cernavoda soil profile (compiled after [36, 37, 50])

Layer compounds	Depth [m]	Thickness [m]	Shear waves velocity v_S [m/s]
Gravel and limestones	9	9	200
Silty clays	25	16	~ 300
Quartzose sands and gravel	32	7	–
Limestones	50	18	900
Marls and marly limestones	100	50	1350
Limestones	200		~ 2000

It is generally admitted that superficial strata could induce a dynamical amplification, depending on the specificity of the area. An important feature in this context is the depth to which these strata are considered to have a determinant influence in producing notable effects on the surface. Of course, the proper choice is to consider the crystalline limit of the deep rocks. The sedimentary stack of layers below Bucharest city extends down to 1000–1500 m depth. The question is whether this feature influences the surface local effects and imprints the spectral content and shapes of the recordings and response spectra as a main factor, for a given magnitude level. However, this important unit expands beneath the entire Moesian Platform with a descending inclination towards the Focsani basin (Vrancea epicentral area), where it attains roughly around 22 km thickness [27].

Therefore the so-called "seismic depth" (or geophysical depth) has to be defined for each area at which the computation is carried out. The correct choice of this parameter assures a very useful information in the development of the national or regional antiseismic design codes. The information about the Bucharest subsoil are available due to several experiments and works, and geophysical prospection, receiver function studies or crustal refraction seismic studies, that allow us to use a seismic depth around 600 m (even 1000 m) [21, 27, 38, 39]. The Cretaceous/ Tertiary (or Cretaceous/Neogen) limit, which attains a depth from 500 m to 1600 m (with a general descending tendency from South to North) is usually considered in computer simulations; at this interface clear differences are encountered in physical or geophysical parameters.

3. SOIL CONDITIONS AND GEOTECHNICAL DESCRIPTION OF THE SITES

3.1. SOIL CONDITIONS

According to the existing soil classification from Romanian seismic design code P100-1/2013 (2013) [40], Bucharest city is described as having the soil conditions of type C, while for Cernavoda area type B is assigned. The Romanian seismic code in force evaluates soil conditions by an approach based on the control period T_C [41, 42]. This parameter is computed using a relationship given by Lungu *et al.* 1997, [43] based on strong motion database offered by the recordings of intermediate Vrancea earthquakes at that time (March 1977 ($M_w = 7.4$, focal depth $h = 94$ km), August 1986 ($M_w = 7.1$, focal depth $h = 131$ km), and May 1990 ($M_w = 6.9$, focal depth $h = 91$ km). A rather different technique is used in the Eurocode 8 [44] classifying soils as a function of the average shear wave velocity for the upper 30 m of soil layer v_{S30}.

Nonetheless, the national code recommends the using of data regarding shear wave velocities as a weighted average value v_s in relation to the thickness of the involved layers, density etc. However, the values of the control periods T_B, T_C and T_D for each of the five soil classes have to be defined by each country according to the characteristics of the earthquakes that are encountered.

The assigned distinction in the foundation soil type is due to a significant difference in the soil profile for the two areas under consideration, which implies different values for the shear wave velocity. Therefore the spectral shape is influenced by these features. These assertions are supported by a detailed discussion in the next section.

Therefore, the design spectra specifications should comprise soil condition classification considering characteristics of the soil formations until a proper depth. As it was discussed above, the geophysical soil characteristics in the Bucharest city area need to be taken into consideration towards a depth of at least 600 m [9, 28, 29], even around 1000 m. This range is justified by large predominant periods (over 1 s) encountered during last destructive seismic events that hit Bucharest city area in the last century [8, 33]. Also between these interfaces there exist variations in shear wave velocities, *i.e.* from ~ 700 to ~ 1340 m/s between those depths, and towards ~ 2040 m/s beyond [26].

A very important database regarding velocity values and thickness (for the crustal and uppermost mantle structure), and physical properties for the sedimentary basins of the Moesian Platform emerged as a result of seismic refraction and tomography experiments (VRANCEA1999, VRANCEA2001, CALIXTO1999) [45, 46] carried out at NIEP in partnership with international institutions. Also important information on v_S and v_P could be found in [47, 48], regarding the same area. A recent work [49] evidences the so-called geophysical depth, a very useful tool in estimating the site amplification induced by Vrancea-intermediate earthquakes, over the Extra-Carpathian areas. The procedure for bedrock depth retrieval uses the computation of the Rayleigh wave ellipticity curve. The models involved obtained v_P and v_S gradient velocity profiles of the sedimentary cover. Using standard non-invasive methods, as *H*/*V* spectral ratio on ambient vibrations a fundamental resonance frequency is obtained for almost the entire Moesian Platform. The higher values for this parameter are found in the south-eastern area, *i.e.* South Dobrogea zone (where Cernavoda NPP is situated). However, the observed high predominant oscillating periods (beyond ~ 1 s) that accompany strong seismic shaking for deeper sedimentary basins suggest the need for knowledge of the deeper soil structure (*i.e.* ~ 800–1000 m for Bucharest city [26, 29]).

For example, Bala *et al.* 2011 [21] assign for the Fratesti layers (average depth around 140–150 m) an average shear wave value v_S = 350–400 m/s, while the parameters v_{S30}~ 220–320 m/s and v_{S50}~ 270–340 m/s are valid throughout the Bucharest area. A lot of drillings are spread over the city area, providing useful data comprising geophysical and geotechnical parameters. The data obtained from these performances were processed and used as input for wavefield simulations in order to obtain surface amplifications or for spectral analyses.

3.2. GEOTECHNICAL DESCRIPTION

Measurements of velocities in the soil layers for Bucharest city area intercepted in these drillings have put forward values for v_S (max. ~ 600 m/s and v_P (max. ~ 2800 m/s). The results are presented in Table 2. When depths larger than 60 m are considered, the layers package velocities do not increase too much with the alluvial sedimentary depth, probably as a consequence of their variability in succession of the content and inhomogeneity, a situation which is encountered even at more profound depths. Consequently an "attenuation" (uniformization) for the averaging value of shear wave velocity appears to take place. However, for a good correlation between the soil fundamental oscillating period, obtained on shear velocity computation basis, and recorded spectral characteristics, an increasing depth has to be adopted as reference.

The available geotechnical information about Cernavoda comes from few boreholes that are drilled in the city area, including one at the City Hall, and those in the Nuclear Power Plant area, which attain a depth of 700 m. Therefore for the city area a simpler geotechnical profile should be used. The stratigraphy encountered at Cernavoda-NPP drilling [37] is presented in Table 3. The superior layer consists of quaternary deposits of limestones and gravel until 8–9 m depth, followed by silty clays to 25 m depth. Then, continental deposits are encountered until 32 m depth composed by quartzose sands and gravels. They are underlain by deposits of limestones and marls.

However, the very strong jump in shear wave velocity after ~ 30 m depth discontinuity was observed almost at each of the drilled points that have been studied. The increase of about 3 times for this parameter towards the depth of ~ 50 m is thought to be decisive in the role played by local soil condition on seismic site response [51].

4. SPECTRAL CHARACTERISTICS OF THE SITE SHAKING – RESULTS

The spectral characteristics of the movement at the surface are mainly described on account of the processed recordings for the absolute recorded accelerations at the site of interest, Bucharest-INCERC and Cernavoda downtown, where the sensor is placed. The results are shown as response spectra at each seismic station for three strong earthquakes and other weaker three collocated as pairs, respectively (see Figs. 1–7). As already specified the strongest event was recorded at only one station, INCERC site, therefore there exist only two common strong seismic events with the corresponding response spectra for the two sites.

For each station, the time histories were manually processed following a standard time history processing technique: mean removal, bandpass filtering (0.3–20 Hz) and baseline correction. The geophysical characteristics of each site as they could be inferred from the shear wave velocity impedance contrast are summarized as follow:

– for the Bucharest-INCERC area – a general trend of increasing the shear wave velocity down to around 600 m depth [1, 26, 29, 52, 53], followed by a gradual increase from ~ 600–700 m/s to 1350 m/s at 1000 m depth. However one could consider a much rapid increase in shear wave velocity below 600 m, and a second significant contrast consisting in a strong jump towards high velocity values of this parameter at ~ 2000 m (v_S~ 2000 m/s);

– for Cernavoda (downtown) area – the existence of a much simpler thin superficial and relatively hard stratigraphy, overlying a much harder deposit, generating a strong contrast for the shear wave velocity at (upper-)high depth [36, 50].

The elastic response spectra, normalized to the corresponding *PGA* value, with 5% damping were computed for each earthquake at both sites. The aim was to see the general trend in spectral characteristics for different magnitude classes of events. For each strong earthquake another small-to-moderate earthquake was chosen, as a corresponding partner with almost the same localization (depth, hypocentral distance), in order to minimize the propagation path effects. The aim is to investigate the way in which the seismic response for a wider range of magnitudes is affected by the specificity of each site. Where the case, the local amplification in correspondence to the site characteristics is highlighted.

The shift of the predominant period, as shown by the processed records (*i.e.* the period corresponding to the maximum response in spectral acceleration or to the highest peak), towards higher values is highlighted in the case of the stronger events. As it can be seen from Figs. 1–7 this phenomenon is much more developed at INCERC station, where higher values of the predominant periods are encountered, disposed of on a broader range. Therefore, at this site spectral ratios for each of the three pairs of elastic response spectra were performed, in order to correlate this behavior to the local effects as influenced by the seismic source strength. Also, potentially higher amplifications are pointed out, induced during low magnitude earthquakes as compared with the high magnitude ones. The upper panels of Figs. 1–3, 5, 6 contain the representation of the stronger event together with the lower magnitude collocated one.

Site response of Bucharest-INCERC (INC) station, recorded during the strong (M_w = 7.4) event of March 4, 1977 (thick line) compared with the one of M_w = 5.6 in December, 2016 (thin line) is shown in Fig. 1. Response spectra computed with 5% damping are normalized to *PGA* of each component (upper panel). For these seismic events, the maximum amplitude corresponds to ~ 0.85–1.22 s for the strongest earthquake, for the horizontal components, while the weak earthquake has the corresponding maximum amplitude around 0.1–0.2 s, and in the same range for all its components. One interesting observation can be made by noticing that the amplitude of the amplification induced by the weaker earthquake (from Fig. 1, upper panel) clearly overpasses that for the stronger earthquake. This behavior can be attributed to nonlinear effects of the local structure. The amplification for the stronger earthquake is clearly attenuated when the elastic waves pass through sedimentary stratification of the Bucharest city area (more exactly at INCERC site).

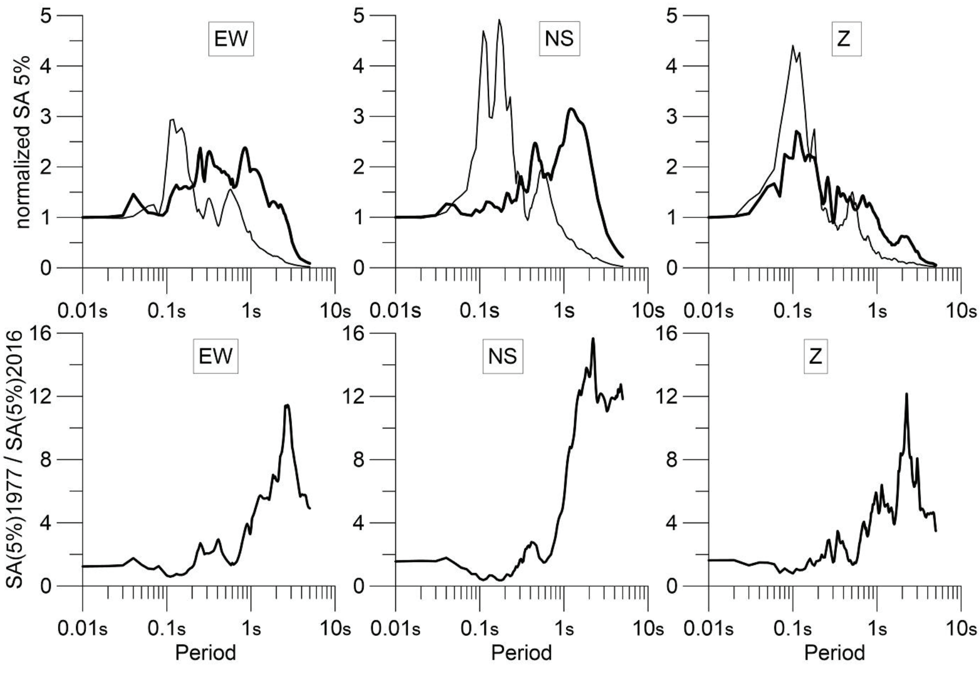

Fig. 1 – Station INC, Bucharest – comparison of the response spectra for 1977.03.04 (M_w = 7.4) and 2016.12.27 (M_w = 5.6); upper panel – spectral response with 5% damping normalized to its first value for each component, thick line 1977 event, thin line 2016 event; lower panel – spectral ratios from normalized spectra to their first values (VR77 / VR2016) for each component.

Plotting the ratios of the response spectra for each component (VR77 / VR2016, lower panel) one can observe that spectral response induced in the local structure by the stronger event is tens of times significantly higher at periods >1s proving its capability to excite deeper strata (responding in long periods >1s), than the source of 5.6 M_w located at similar depth (94 and 96.7 km, respectively). The difference in the hypocentral distance of the recordings 6.74 km, is less than the events location errors. Having a similar focal mechanism the energy distribution in each component is similar for both these earthquakes.

For the 1986 and 2010 seismic events at Bucharest-INCERC the maximum amplitude corresponds to the predominant period interval ~ 0.5–0.7 s for the stronger earthquake (Fig. 2, thick line), while the weak earthquake has the maximum amplitude between 0.1–0.2 s (Fig. 2, thin line), for all components. Therefore one could infer the same tendency as for the previous earthquakes pair, meaning the high values of the predominant period for the stronger earthquake, and almost stationary (low) values for the weak one. This can be considered as the effect of both source magnitude (*i.e.*, energy) and of the local structure, since predominant period of the spectra (corresponding to the peak of response) can be directly correlated with the thickness of the stack of layers excited by earthquake.

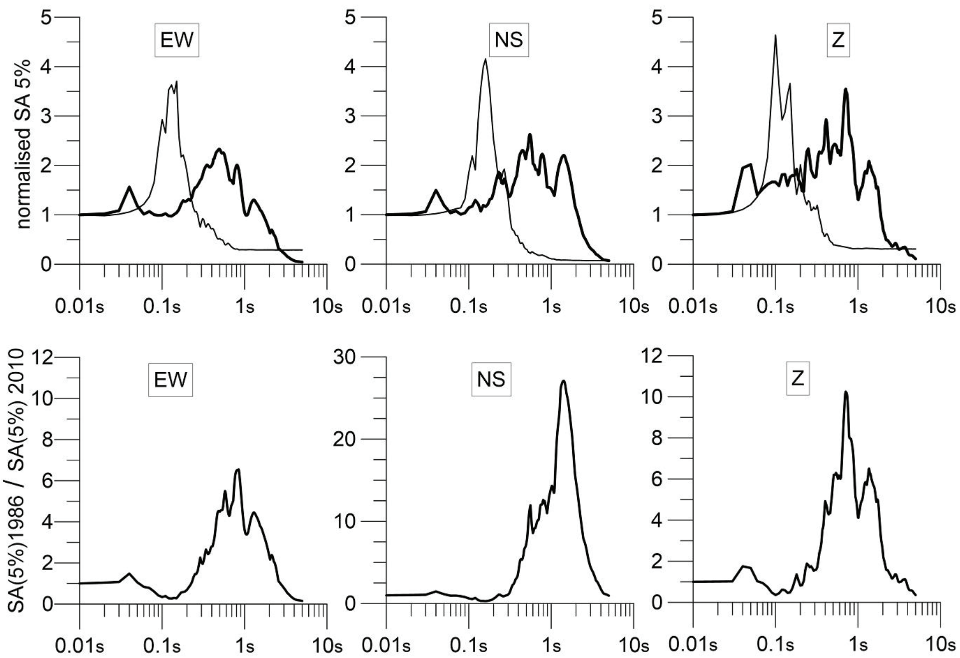

Fig. 2 – Station INC, Bucharest – comparison of the response spectra for 1986.08.30 (M_w = 7.1) and 2010.06.05 (M_w = 3.9); upper panel – spectral response with 5% damping normalized to its first value for each component; lower panel – spectral ratios from normalized spectra to their first values (VR86 / VR2010) for each component. Thick line 1986 event; thin line 2010 event.

Also, for this pair we can observe a higher ordinate amplitudes (amplification) for the weak seismic event in comparison to the stronger event (Fig. 2, upper panel), perhaps due to local nonlinear effects, acting for the stronger event, *i.e.* an increasing damping with the magnitude, or the corresponding level of stress. The signature of the local structure also is more visible when analyzing the ratios of the response spectra for each component VR86 / VR2010 (Fig. 2, lower panel); one can see the capability of the source $M_w = 7.1$ to excite deeper strata (responding in long periods >1s) than the source of 3.9 M_w located at approximately the same depth (~ 131 km and 129 km respectively, the difference being much less than the location errors of the stronger event, Table 1).

For the 1990 and 2013 seismic events at Bucharest-INCERC the maximum amplitudes do not shift anymore beyond the corresponding period of ~ 0.3 s for none of the earthquake components considered in this pair (Fig. 3, upper panel). Though a secondary peak exists on the EW component for the stronger one at ~ 0.65 s, one can consider the seismic response acting more effectively in the quite narrow spectral range for both earthquakes (~ 0.1–0.2 s for weaker one, ~ 0.3 s for stronger). A higher amplification can still be seen for the weak seismic event (Fig. 3, upper panel), although the magnitude for the stronger event is the lowest of the two previously discussed. The source influence starts to become less appreciable for the stronger earthquake, but possible nonlinear effects can be inflicted in the site behavior.

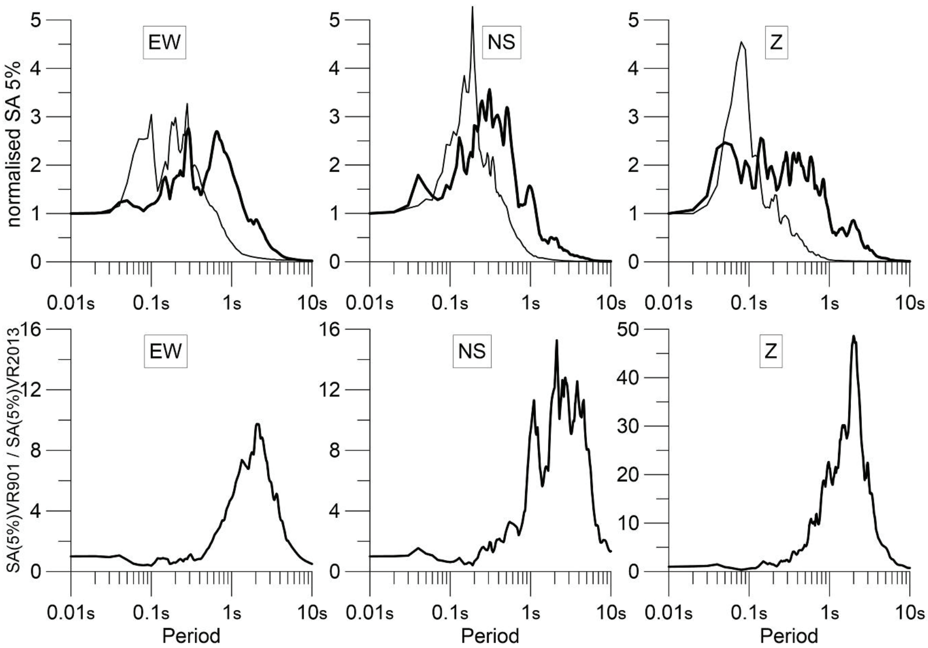

Fig. 3 – Station INC, Bucharest – comparison of the response spectra for 1990.05.30 ($M_w = 6.9$) and 2013.08.11 ($M_w = 4.1$); upper panel – spectral response with 5% damping normalized to its first value for each component; lower panel – spectral ratios from normalized spectra to their first values (VR90 / VR2013) for each component. Thick line 1986 event; thin line 2013 event.

The local effects are retrieved in the spectral ratios which have maximum amplification in long periods, over 1 s (VR90 / VR2013, Fig. 3, lower panel). The differences in the hypocentral distance of the records is 8.2 km, still less than the location errors for both events.

For the INCERC site one can observe a clear displacement of the peak response towards long periods when magnitude increases. In Fig. 4 the response spectra are shown, with 5% damping computed for the NS component and normalized to the maxima of the respective records for the strongest four earthquakes. The predominant period varies from 0.17 s for the smallest event to 1.22 s for the stronger one. We consider this feature as an effect of the source on soil response due to the absence of a sharp bedrock, or a clear interface with high velocity contrast in the local structure. The respective events have the same mechanism (reverse faulting) and similar fault plane solutions.

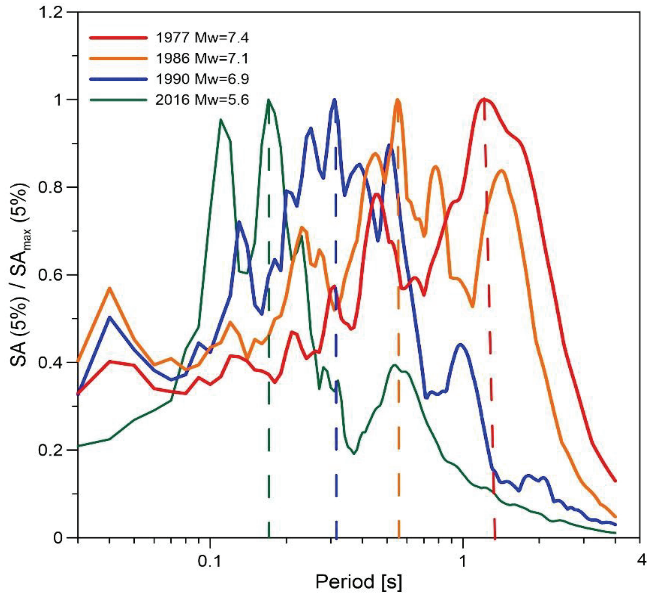

Fig. 4 – Response spectra with 5% damping normalized to *PGA* at INCERC site, NS component, for the stronger four earthquakes recordings.

Site response of Cernavoda (CVD) station recorded during August 30, 1986, $M_w = 7.1$ event (thick line) compared with the one of May 6, 2010, $M_w = 3.9$ event (thin line) can be seen in Fig. 5.

The maximum amplitude values are in a rather lower predominant period range for both earthquakes (0.18–0.38 s stronger, 0.06–0.23 s weaker). This is seen on all three components for both earthquakes. The highest amplification is observed for the stronger event ($M_w = 7.1$), this time in the vertical component which also displays the bigger shift of the peak response towards longer periods. It is negligible on both horizontal components. This may be interpreted as an absent nonlinear feature in this location. The difference in the hypocentral distance of the records is 1.12 km *i.e.*, much less than the location errors.

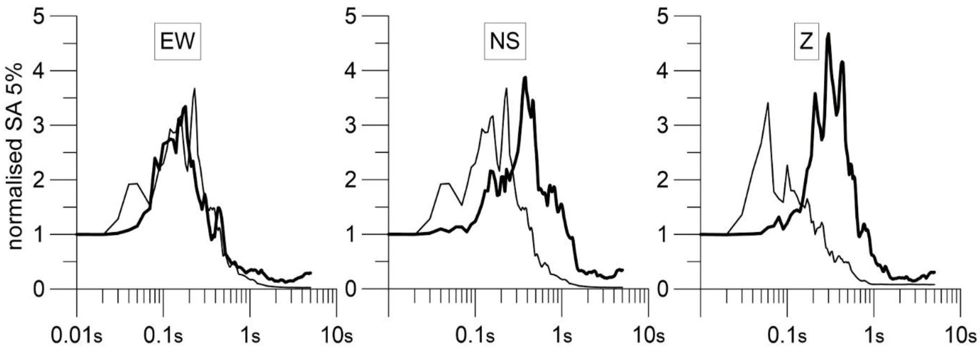

Fig. 5 – Station CVD, Cernavoda – comparison of the response spectra for 1986.08.30, $M_w = 7.1$ (thick line) and 2010.06.05, $M_w = 3.9$ (thin line) with 5% damping normalized to its first value for each component.

For the 1990 and 2013 seismic events at Cernavoda the maximum amplitudes are in the range ~ 0.34–0.5 s for the horizontal components of the stronger earthquake (Fig. 6, thick line), while, for the weaker event, all amplitudes correspond to ~ 0.2 s (Fig. 6, thin line), similar to the vertical component for the stronger. The difference in the hypocentral distance of the records is 3.12 km *i.e.*, much less than the location errors of the stronger event. The highest amplification is observed for the 1990 event (M_w= 6.9) in the EW component, therefore the strata in this area act in a more elastic manner when excited by this level of solicitation, though the local response changes in terms of predominant period shifting to higher magnitude, as can be seen on both horizontal components.

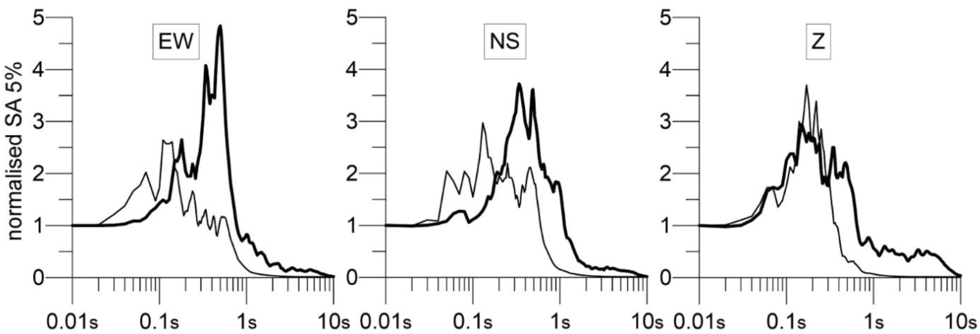

Fig. 6 – Station CVD, Cernavoda – comparison of the response spectra for 1990.05.30, $M_w = 6.9$ (thick line) and 2013.08.11, $M_w = 4.1$ (thin line) with 5% damping normalized to its first value for each component.

A more stable response can be observed in Fig. 7 where the period corresponding to the maximum response of the NS component can be found in the 0.13–0.4 s interval for all the four earthquakes recorded at this site.

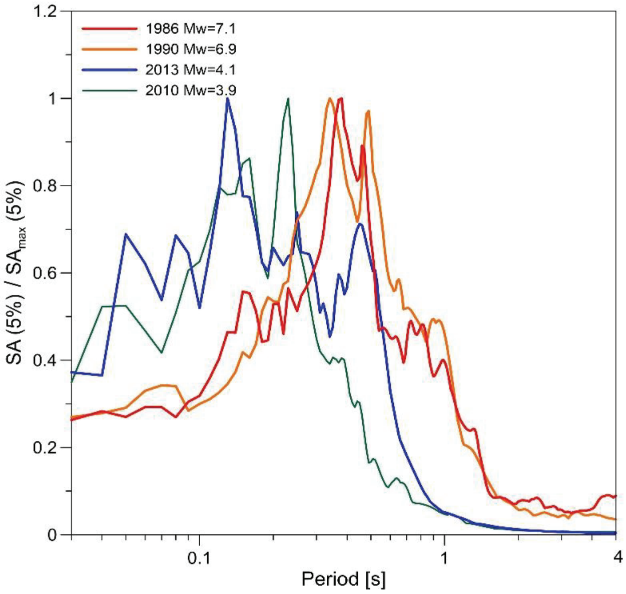

Fig. 7 – Response spectra with 5% damping normalized to the maximum value at CVD site, computed from the NS component.

For INCERC site, as the magnitude increases, the local response is influenced by the seismic source strength/energy which determines the local structure acting differently, implying predominant period shift toward higher values (Fig. 4). For the medium or/and small earthquakes the response is observed at low predominant periods, and is stable.

For the CVD site the local response does not change too much in terms of predominant period shifting. The local site effects are predominant, irrespective of the earthquake magnitude.

From the spectral response shown in these figures one can conclude that there exists the possibility to evaluate, though at a qualitative level, the characteristic parameters for the future (strong) seismic movements at Cernavoda site. On the contrary, for the Bucharest area (at least for the INCERC site) this aim remains out of reach, or at a low level, most intuitive in a qualitative manner. As regards the moderate or weak earthquakes, for the Cernavoda site, the spectral parameters and maximum values are more confined or limited in ranges, offering some stability in appreciation, therefore, they may express the specificity of the seismic response of the site at lower seismic excitation.

5. DISCUSSION AND CONCLUSIONS

The seismological features, geophysical and geotechnical characteristics influence ground deposits response and contribute to the local site effects variability. In this respect the elastic vibration characteristics of the soil deposits and impedance contrast between the bedrock and overlying soil materials affect the local soils behavior considerably.

The main purpose of this study is to evaluate local seismic response at two different sites by using spectral characteristics of strong earthquakes.

The differences in seismic site response from one magnitude level to another, and from one site to another are highlighted and discussed in terms of their causes, namely the source strength and local conditions. We infer that for these two sites there are differences in the latter feature.

The spectral characteristics exhibited by the strong seismic recordings are highlighted through typical local conditions in two areas (cities of Bucharest and Cernavoda): (a) the presence of a clear velocity "jump" for the shear waves at small depth for the latter spot; (b) a slowly increasing tendency in the shear waves velocity towards the bedrock for the former area. Two features are discussed in this respect, as they are shown from the spectral response. One is related to the predominant period shift, as can be seen from the elastic response spectra, the other is the spectral amplification of the weaker earthquakes compared to the collocated stronger ones. Both phenomena are encountered at a higher level and are active for the INCERC site (Bucharest). The former is also present at Cernavoda site, though in a low and more restricted range, whereas the latter is reversed, that is the higher amplification is for the stronger earthquake, as a general behavior, a phenomenon due to the local structure characteristics, which respond in a more or less elastic manner to the seismic input. As a consequence, one can infer a nonlinear behavior of the soils, which is more developed at the Bucharest-INCERC site. The displacement of the predominant period is due to the strength of the seismic source, although in connection to the site specificity, being more developed at the INCERC site.

The conclusion that can be drawn is: as the magnitude increases the seismic source influence on the spectral response consists in a predominant period shift toward higher values, while for the medium or/and small earthquakes the seismic (local) response is seen at low predominant periods.

For each recorded seismic event the *PGA*-normalized acceleration response spectra are used, computed for three components (two horizontal and one vertical) with damping 5%. The main difference observed from the spectral composition for the two sites is related to the stability in the shape of the spectra in terms of predominant period ranges or amplification level. This could be attributed to the local effects induced by the geophysical characteristics of the uppermost geological layers (*i.e.* their type, succession, and impedance contrast).

The sites considered in this study are representatively chosen for their spectral composition, and for different local soil conditions as well. The Bucharest-INCERC site presents a non-uniform behavior in terms of spectral features, at different strong seismic events, whereas for the Cernavoda site a much stable spectral composition is observed. Moreover, for the latter area the site formations are characterized by the presence, at upper depth (~ 30 m), of a clear, very high jump in shear wave velocity, whereas for the former area there is a continuously tendency in shear waves velocity to increase with the depth down to a much profound level (around 600 m, at least). This could imply the high importance of the local conditions, though relatively high spectral accelerations are encountered for the seismic events of May 30, 1990 at Cernavoda area. Particularly interesting for this site is the very high amplification in terms of spectral acceleration for the less strong event ($M_w = 6.9$, May 30, 1990), which clearly overpasses the corresponding value of the much stronger event ($M_w = 7.1$, August 30, 1986), and even those for all the three stronger seismic events at Bucharest-INCERC site. In this respect one must specify the upper focal depth for this event comparative to the stronger one (91 km *vs* 131 km) and differences of the hypocentral distance at each site, besides a much stronger attenuation for the INCERC site and a different azimuthal angle.

From Figs. 1–4 (upper panels) one can observe the well-known characteristics of the strong-intermediate Vrancea earthquake, *i.e.* long predominant period encountered in the city of Bucharest (INCERC), the only site for which all three strong recordings are available. There is a clear shift of the maximum amplitudes, especially for the horizontal components, in comparison to the weaker earthquakes. The same situation is encountered for the Cernavoda site, but to a much lesser extent, in the sense that predominant period are in a much more confined range (their maximum values are ~ 0.4–0.5 s), sometimes with values very close to those belonging to the weaker earthquakes (Figs. 5–7, upper panels). This behavior at INCERC site can be due to the seismic source effect, although one cannot eliminate the other two contributions, *i.e.* the path propagation and the local effects. As for Cernavoda site, the seismic source influence is considered to be less effective, an important role being played by the local site effects.

The higher amplification for the weaker earthquakes (on almost all components) for all three pairs, at INCERC site, as it can see from Figs. 1, 2, 3 (upper panels), can be due to the softer soils which strongly attenuate the seismic waves generated by high magnitudes. This behavior implies an elastic reaction from the upper most geological layers at this site (INCERC) under small seismic action, while in much deeper soft sedimentary layers the energy of the strong earthquakes is much more dissipated and the site behaves in a less elastic manner, probably producing nonlinear effects. The local site contribution does not affect the seismic response at low magnitudes much, whereas as the magnitude increases and the energy is much more dissipated, the site response has lower spectral amplitudes. For the weaker earthquakes, though low in quantity, the energy is transferred to the surface response to a higher extent, with consequences in the spectral amplitudes level.

At Cernavoda site a completely different behavior is encountered, the amplification being generally higher for the stronger earthquake (Figs. 5, 6). Moreover, the maximum amplification at this site overpasses the amplitudes at INCERC site and may sustain the nonlinear behavior for the soil in Bucharest city when exposed to strong earthquakes, as well as its lesser presence at Cernavoda site, where site effects may dominate, in spite of the source influence or nonlinear effects.

These observations are drawn out from the elastic acceleration response spectra corresponding to the recordings of the last three strongest earthquakes triggered in the Vrancea-intermediate seismic area. For the Bucharest-INCERC seismic station the acceleration response spectra representations show either many peaks with close amplitude, or rather a general variability tendency of the spectral content. We infer that this feature is the specific manner in which the local effects there are affected by the earthquakes magnitude.

As there are many secondary peaks in the spectral response corresponding to the (unfortunately) single recording of the 1977.03.04 strong event, they generally correspond to the peaks of the same spectral range of the other two less strong earthquakes, for which there exist many recordings; one could suggest that the main peak, highlighted during the strong Vrancea earthquake, 1977.03.04, around the high value 1.22 s, according to the single recording that was achieved (INCERC site), may be extrapolated to other sites across city area.

It seems that the dynamical behavior of the package of layers excited by various seismic energy levels acts as filtering the spectral composition of the seismic waves that are passing through. Therefore the influence of the local conditions is viewed in connection with the increase in magnitude, in the sense that, in Bucharest, where higher magnitude probably sets in motion thicker package layers, an increase in the soil predominant period values may be encountered.

Though rather speculative, it could be suggested that the higher fundamental period around 1.22 s is the seismic source imprint, as the smaller periods corresponding to the amplitude peaks could be attributed to the local conditions features.

For the Cernavoda area such a clear dependence cannot be inferred. There, the oscillating period corresponding to the peak spectral amplitude is rather stable with the increase in magnitude. The main factors responsible for these features are the local site conditions given by the specific rocks content and layering and impedance contrast in the shear waves velocity. The stabilization tendency for the spectral content offers the possibility to predict these values for the future strong seismic events in this area.

As regards the weaker earthquakes, their amplitudes are confined to a much narrow range of predominant period, in the low values spectral zone. This is encountered at both sites, encouraging us to infer that this is the manifestation of the local effects in the site response in low magnitudes domain.

Acknowledgments. This paper was partially carried out within NUCLEU Program MULTIRISC, supported by Ministry of Research, Innovation and Digitization, project no. PN19080102.

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