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AN ASSESSMENT OF LOCAL SEISMIC EFFECTS IN SITES LOCATED FROM THE NORTH OF DOBROGEA TO THE EASTERN CARPATHIANS BEND

V. RĂILEANU, A. BĂLĂ, B. GRECU

National Institute for Earth Physics, Bucharest-Măgurele, P.O. Box MG-2, România
raivic@infp.infp.ro

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Abstract: An analysis of the spectral ratios derived from seismic records in eleven sites located from east of Tulcea to the Vrancea seismic region shows two distinct cases: (1) a major peak with high amplitudes (1.7–2.5 units) within the range of frequencies from 1 to 5 Hz (0.2–1 s period) for the Dunavățul de Jos, Măcin, Măxineni and partly for Cataloi sites; here one or a few shallow thin layers (tens of meters thickness) comprising soft rocks overlie a very thick layer of hard rocks; (2) a peak area within the 0.1–2.5 Hz (0.4–10 s) window with amplitudes of 1.2–1.4 units for the Brăila, Gulianca, Mihălceni, Bogza, Bordești, Dumitrești and Vintileasca sites where a thick pile of sediments (hundreds of meter thick) comprising soft and hard rocks generates those low resonance frequencies.

Key words: seismic records, spectral ratio, resonant frequency, local seismic effects.

1. INTRODUCTION

This paper continues the studies of assessment of seismic effects in sites using the spectral ratios derived from three component seismic records along Vrancea 2001 – a seismic refraction line which runs from east of Tulcea town in Dobrogea, through the Vrancea region, to Aiud town in Transylvania.

In the two previous papers [1, 2] the spectral ratios were derived from the seismic records collected on the Vrancea 99 refraction seismic line which runs from south of Bacău town to south of Bucharest city. Seismic records along the deep seismic lines comprise information, not only about the source and wave crustal path peculiarities, but also on the local conditions of the receiver sites. We attempted to see which is the influence of the source and of the local geological and geophysical conditions on the seismic effects in the studied sites.

Observational and experimental data proved that the local geological and geophysical conditions are the factors which strongly influence the magnitude and distribution of earthquake damages. In any place where one or more instrumental recordings of the seismic events (pre-, main- or after shocks) are available, an analysis can identify the frequencies where the soil amplification occurred. For a pertinent analysis seismic instruments over the studied region are required over a large populated area densely distributed. The time occurrence of an earthquake cannot be predicted and therefore it is of no practical use to expect for an event to be instrumentally recorded in order to estimate the local site effects [3].

An empirical alternative solution to the instrumental data for the estimation of the local effects of earthquakes could be the analysis of microtremors. A reason supporting it is that the microtremor and aftershock studies use generally the same methods to seek for the spectral peaks which are considered to stand for the resonant frequencies in the response of a site. Even if not all seismologists accept as enough reliable the microtremor method in the assessment of the seismic response of a site [4, 5], some of them consider that the microtremors provide a rough approximation of the earthquake site amplifications [6, 7]. As long as a more reliable method which allows a prediction of the local seismic effects in a site is not available, the microtremor method was and is being experienced and applied in different countries such as Japan, Mexico [8], USA [9] and others. A combination of microtremor and earthquake data has been used in Romania for the study of the site response in Bucharest [10], followed by a study of site response due to some large Vrancea earthquakes [11].

Nakamura's or the microtremor method [7] uses a single three component station analysis of microtremors and compares the spectral amplitudes of the horizontal and vertical records. It was applied in different seismic areas and showed some agreement with other results obtained using the spectral analyses of aftershocks or S- and coda waves of the main earthquakes. Nakamura's microtremor single station method provides closer results to earthquake data than the soil/rock station pair microtremor method. A good overlapping of the spectral peaks is observed at least for the fundamental periods, while the spectral amplitudes are different from each other [4].

2. PHYSICAL BACKGROUND

Observational data collected in different areas proved that the amplification of microtremor and coda amplitudes in a site is the result of the trapped seismic energy in sedimentary layers [12]. As local effects are observed for a pair of seismic stations – one on rock and other on soil –, the amplification of energy from a site to the other is due to the effect of wave propagation in soil. What happens if a single station on soil is used and the general result is the same? Nakamura showed that the effects of the Rayleigh waves are removed using the ratio of the horizontal/vertical spectrum components. Other authors [6, 13] stated that, on the contrary, the Rayleigh waves assure the success of Nakamura's method. The peak of the fundamental period is produced by the vertical component of the Rayleigh wave going towards zero.

In this paper a practical method to compute the spectral ratios of the horizontal spectral component (H)/vertical component (V) was used. It consists of the following steps [14]:

– computation of the amplitude spectrum for each component: horizontal and vertical;

– as in the horizontal plane there are two components, N-S and E-W, a global horizontal spectral component is computed as a complex signal:

$\mathrm{CH} = \mathrm{NS} + i * \mathrm{EW}$ complex horizontal component,

$i = \sqrt{-1}$,

$\mathrm{CHS} = \mathrm{CFT}\,[\mathrm{CH}]$ complex Fourier transform,

$\mathrm{HS} = \left(1/\sqrt{2}\right) * |\mathrm{CHS}|$ horizontal spectrum

– HS/V ratio is computed for the whole frequency band used for analysis.

3. SEISMIC DATA PREPARATION FOR SPECTRAL ANALYSIS

The Vrancea 2001 seismic refraction line follows an alignment WNW-ESE of ~ 450 km length, from east of the Tulcea town in Dobrogea, through the Vrancea region, to Aiud town in Transylvania, (Fig. 1). The seismic experiment was a result of the co-operation inside a consortium of universities and research institutes from Germany, Holland, United States and Romania. The objective of the seismic line was to decipher the structure of the crust and the upper mantle based on seismic velocities [15]. 10 big shots (300–1500 kg charge) generated the seismic energy for deep crustal investigations. The 10 shot locations covered the whole line with a mean spacing of 40 km. From easternmost end of line to Aiud town some 150 digital portable instruments with three component receivers (Mark Products, L-4-3D), 1 Hz resonant frequency and with a 3 km mean spacing were deployed. All seismic stations were installed within the locality areas for security reasons. The final seismic records have 100 s length and consist of a useful seismic signal in the first tens of seconds and of the ambient noise in the rest. Such a seismic record represents a complex signal emerged from the deep crustal levels and modulated by the shallow local geology. Influence of the local geology can be extracted using some techniques such as Nakamura's method.

A dedicated computing program under UNIX known as Seismic Handler [16] was applied to prepare data and compute the Fourier spectra. In addition some own software was written specially for this task and used for data processing and preparation for plotting on graphs.

This paper analyzes the seismic records generated by four shots in 11 sites from the eastern margin of the Carpathians to the eastern end of the line Vintileasca (site 1218, Vrancea county-VR), Dumitrești (site 1199, VR), Bordești (site 1188, VR), Bogza (site 1175, VR), Mihălceni (site 1163, VR), Gulianca (site, 1145, Brăila county-BR), Măxineni (site 1135, BR), Brăila (site 1106), Măcin (site 1092, Tulcea county-TL), Cataloi (site 1042, TL), Dunavățul de Jos (site 1002, TL), (Table 1 and Fig. 1). Geologically speaking all sites are placed on Quaternary, Neogene or older sedimentary cover of the North Dobrogea Orogen, the Moesian Platform / Focșani Depression and the Moldavidian Nappes of the Eastern Carpathians.

4. DATA PROCESSING

Basic data consisted of collections of digital records of four shot groups located along the eastern segment of the Vrancea 2001 seismic refraction line (Table 1, Fig. 1). From the original digital records (100 samples per second) only the studied site records are selected and saved in new record files. Such a file comprises a record on three components in a site for a shot. This process resulted in 3 components × 11 sites × 4 shots = 132 digital seismograms. Each new record comprises, besides the first arrivals with high energy generated by explosion, some later arrivals as well as the coda waves and ambient noise for the most part of the seismogram until 40 s. A spectral analysis of each component belonging to a seismic record is made using a Fast Fourier Transform procedure. The first 40 s of the seismic record are analyzed. No instrument correction is applied as the frequency responses of the three geophone components are practically the same. The output signal of the spectral analyses is computed within 0.1–20 Hz, the range having 200 samples.

In the next stage spectral ratios are computed using the formula suggested by [14]:

$$SR = (SH/SV) \quad \text{and} \quad SH = (0.5)^{1/2} * (S^2n + S^2e)^{1/2}$$

where: SR = spectral ratio, SH = the amplitude spectrum of the horizontal component, SV = the amplitude spectrum of the vertical component, Sn = the amplitude spectrum of the north-south component, Se = the amplitude spectrum of the east-west component.

The analyzed seismic signal comprises the influence from the seismic sources (explosion and ambient noise), propagation paths and local geology of the site. Comparing different spectral ratio curves for the same site but for different shots, they show both common and particular features. The latter are very probably related to the seismic sources and propagation paths, while the former are caused preponderantly by local geology. If we add several spectral ratio curves for the same site but for different shot points, then the common features will be enhanced

Table 1

Seismic records used in spectral ratio analyses. X marks shot points which produced records for a certain site. Charge for each shot is marked in kg

No	Site	County	Site no.	Shot O 1500 kg	Shot P 1000 kg	Shot R 600 kg	Shot S 300 kg	Shot T 1000 kg	Shot U 1000 kg	Shot W 300 kg
1	Dunavățul de Jos	Tulcea	1002	x	x	x	x			
2	Cataloi	Tulcea	1042	x	x	x	x			
3	Măcin	Tulcea	1092	x	x	x	x			
4	Brăila	Brăila	1106	x	x	x	x			
5	Măxineni	Brăila	1135	x	x	x	x			
6	Gulianca	Brăila	1145	x	x	x	x			
7	Mihălceni	Vrancea	1163	x	x	x	x			
8	Bogza	Vrancea	1175	x	x	x	x			
9	Bordești	Vrancea	1188			x	x	x	x	
10	Dumitrești	Vrancea	1199			x	x	x	x	
11	Vintileasca	Vrancea	1218				x	x	x	x

and the others will be diminished. This last procedure helps us to point out the spectral peculiarities of the site geology and it was applied for our studied sites.

5. RESULTS

Finally 44 curves of the spectral ratios are derived from the seismic records collected from four shots for each out of the eleven sites. In order to distinguish among the common and the uncommon features of the spectral ratio curves belonging to the same site but to different shots, we analyze three sites which display three different cases: Măcin, Brăila and Vintileasca (Fig. 2). Then in a second part, an averaged curve of the four single curves and a plus/minus a standard deviation curve of the spectral ratios for each site (Fig. 3) are analyzed and commented.

Măcin site – located between shots P and R, (Figs. 1 and 2):

– the four spectral ratio curves for the O, P, R and S shots show as a common peculiarity a high peak at 1.5–2.0 Hz with amplitudes of the spectral ratios of 2.5–3.0 units;

– for the closer shots P (1000 kg charge) and R (600 kg) the spectral ratios for frequencies > 3 Hz show some secondary peaks exceeding 1.5 units while for the farther shots O (1500 kg) and S (300 kg) the spectral ratio amplitudes are on the average smaller and oscillate around 1.0 unit; this suggests that source proximity seems to have more influence than the charge of the shot.

Brăila site – located ca 20 km south-east of shot R (Figs. 1 and 2):

– A common peak of the spectral ratios is remarked for all shots around 1 Hz; other common peaks are noticed for each pair of shots placed to east (O and P shots) and west (R and S) of the site. Amplitudes are less than 1.5 units and oscillate around 1.0.

– Spectral ratio curves of shots R and S show some similar shapes having common peaks at frequencies of 1 Hz, 5–6 Hz, 7 Hz and 10–11 Hz. As a remark, all amplitudes are under 1.5 units.

– The spectral ratio curves for shots P (1000 kg) and O (1500 kg) display some similar shapes but with amplitudes a bit larger than for the closer shots R and S. Some common peaks are at 1 Hz, 4 Hz and 10 Hz.

– As a conclusion, all shots give a common peak at 1 Hz; beyond 2–3 Hz some differences appear for the shot groups located on each side of site probably due to the different geology to the east and west of the site.

Vintileasca site – located at about 1 km distance of shot T (Figs. 1 and 2):

– The spectral ratio curves show low amplitudes on the average < 1, except shot T where amplitudes are higher and oscillate between 1.5–2.5 units.

– The farther shots (S, U and W) show some small peaks at 3 and 5 Hz.

– The spectral ratio curve for shot T shows a high peak around 1 Hz; the next peaks 6 Hz, 8 Hz and 10 Hz have amplitudes around 2 units.

– This case underlines the importance of the epicentral distance on the local effects: besides the 1 Hz peak generated by thicker and deeper layers, other local shallow and thinner layers generate high peaks at 6, 8 and 10 Hz.

In the following the average curves of the spectral ratios for each site are analyzed and commented (Figs. 1 and 3). We try as well to make some estimation on the physical parameters of the geology which generate the main resonance periods as they are noticed on the spectral ratio diagrams. Based on the well known relationship between thickness (h) and shear wave velocity (Vs) in a layer on the one hand and the resonance period of that layer on the other hand, that is Ts = 4h / Vs, an assessment of the thickness can be derived if we suppose a value for Vs as a function of the known lithology in the studied area.

Site Dunavățul de Jos is located in the North Dobrogea Orogen at the eastern end of the Vrancea 2001 seismic line. It overlies a thin and soft sedimentary layer (loess and clay) which has at the base a hard sedimentary Triassic age rock. The spectral ratio curve (Fig. 3) displays an extended peak at 3.2–3.7 Hz (or 0.27–0.31 s period) that reaches an amplitude of 2.5 units and a secondary peak at 5.1 Hz (0.20 s) with 1.7 units. These short periods (0.20–0.31 s) suggest that amplification is generated by some thin and shallow sedimentary layers about 10–20 m thick.

Cataloi site is located to the south of Tulcea town within the North Dobrogea orogen area. A soft sedimentary layer covers an older hard Triassic age rock. Although the amplitude of the spectral ratio does not exceed 1.7 units some peaks are displayed for the following frequencies: 1.8 Hz (0.55 s), 4.0 Hz (0.25 s), 8.2 Hz

(0.12s) and 9.7 Hz (0.10 s). The succession of the spectral ratio peaks suggests a layered geological structure. The first sedimentary layers that generate amplifications within the 1–10 Hz range could reach up to 30–40 m thickness. This fact confirms that soft sedimentary layers with 0.10–0.55 s resonance periods cover a hard rock.

Măcin site is located in the western part of North Dobrogea Orogen near the Danube river. The geological structure is like that of the first two sites: a soft and thin sediment layer (loess, clay, sand, etc.) over an older and harder rock. A single high amplitude peak of 1.6 Hz (0.63 s) dominates the whole spectral ratio curve having about 2.5 units. This single peak suggests a shallow and relatively homogeneous layer 30–50 m thick that overlies a very thick and hard rock layer.

Brăila site is settled on the eastern margin of the Moesian Platform. A Neogene sediment cover with relatively soft rocks and thickness of a few hundred meters overlies the Mezo- and Palaeozoic stack with hard rocks. The spectral ratio curve shows a peak extended over the 0.1–1.2 Hz (0.83–10 s) range which reaches 1.4 units amplitude. The peaks for low frequencies (< 1.2 Hz) suggest that the geological structure has a seismic behavior like a relatively homogeneous layer with a thickness of a few hundred meters. This layer could correspond to the Neogene pile. From 2 Hz to 10 Hz a diminution of energy seems to occur in respect of the incident seismic energy because the spectral ratio amplitudes reach less than 1 unit.

Măxineni site is placed on the Moesian Platform near the western margin of the Focșani Depression. The Neogene pile reaches several hundred meter thickness and comprises a mixture of shallow soft rocks which hardens with depth. Underneath there is a Mesozoic stack with hard rocks. A prominent peak at 1.2–1.8 Hz (0.55–0.83 s) dominates the whole spectral ratio diagram. The next secondary peaks beyond 2 Hz have amplitudes < 1 pointing out a decreasing of the seismic energy for that spectral range. The main peaks of 1.2–1.8 Hz (0.55–0.83 s) with amplitudes of 1.7 units suggest as a possible cause a shallow layer stack about 40–60 m thick.

Gulianca site is situated in the Focșani Depression area characterized by a very thick sedimentary pile. The amplitudes of the spectral ratio diagram do not exceed 1.4 units for the two main peaks. The first peak comprises low frequencies of 0.1–1.3 Hz (0.77–10 s) probably generated by a stack of sediments with thicknesses from a few tens meters to several hundred meters or more. The second peak is around 6.4 Hz (0.16 s). It is a result of the thin layer of a few meters thickness. In between the two peaks and up to 10 Hz the spectral ratio amplitude oscillates around 1.

Mihălceni and *Bogza sites* have many common features. Both of them are located within the Focșani Depression. A very thick pile of sediments exceeds several kilometers of thickness. Except frequencies less than 2.5 Hz (0.4 s), all amplitudes of the spectral ratio curves are < 1, which means that the seismic energy at the surface is diminished in respect of the incident energy emerging from the deep levels. A weak peak at 1.8–2.4 Hz (0.42–0.55 s) with only 1.2 amplitude units is obtained for the Mihălceni site and it is the seismic response of a shallow layer with a few tens of meters of thickness. For the Bogza site a weak peak area from 0.1 to 1.6 Hz (0.66–10 s) is noticed. The peak is generated by a thicker pile of sediments with thickness from several tens to several hundreds of meters or more.

Bordești site is located within the internal sector of the Carpathian Foredeep and about within the maximum sinking region of the Focșani Depression. The tertiary pile is extended down to 8–10 km depth and comprises a mixture soft rocks (clay, sand, marl) at the shallow levels and harder rocks in the depth (limestone, sandstone and conglomerate). The spectral ratio curve shows small amplitude (1.2 units) at 0.1–1.4 Hz (0.71–10 s). For higher frequencies (1.4–10 Hz) the amplitudes are < 1, indicating a decrease of the seismic energy in respect of the incident energy. The peak with the amplitude of 1.2 units at low frequency can be due to the same thick pile of sediments with thickness from several tens to several hundreds of meters, like for Bogza site.

Dumitrești site has the same rough geological structure as the Bordești site. Once again the spectral ratio diagram displays an amplitude peak of 1.2 units over the frequencies range 0.1–1.7 Hz (0.50–10 s) and the amplitude becomes < 1 for the upper frequencies. The same cause as in the last two sites can generate the low resonance frequencies.

Vintileasca site is settled at the eastern margin of the Carpathians Nappes (Moldavides) on a rock mixture from relatively soft (clays and marls) to harder rocks (shale, sandstones, limestone, evaporite, etc.). The eastern front of nappes overlies the Tertiary foredeep sediments which extend down to 8–10 km depth. The spectral ratio curve displays a peak of 1.3 units within 0.1–1.0 Hz (1–10 s) then from 2 to 10 Hz there are some small oscillations around the unitary amplitude. The small peaks are probably due to a thin layer with thickness from a few meters to 10–20 meters. The peaks for the low frequencies can have the same cause as for the adjacent sites.

6. CONCLUSIONS

Based on a large amount of field data provided by the Vrancea 2001 seismic experiment we extract new information on the local geological and geophysical conditions of the receiver sites along of the eastern segment of the refraction seismic line from east of Tulcea (Dunavățul de Jos site) to the Vrancea seismic region (Vintileasca site).

This study analyses the seismic data collected in eleven sites located from the North Dobrogea Orogen (Dunavățul de Jos, Cataloi, Măcin), through the Moesian Platform and the Carpathian Foredeep (Brăila, Măxineni, Gulianca, Mihălceni, Bogza, Bordești, Dumitrești) to the Carpathian Orogen (Vintileasca). The seismic records generated by four shots for each site are analyzed. The spectral ratios for each site and shot are obtained by a multistep processing of the field data. An average of the four spectral ratio curves for each site is done and one standard deviation from mean is computed.

The results point out that the amplitude and frequency of the spectral ratios are function not only of the epicentral distance from source to site and of the energy released by the seismic source, but also of the local geological and geophysical conditions. Nevertheless it is noticed that mainly the frequency windows with high spectral ratios are about the same, regardless of the position and magnitude of the source, which suggests a strong influence of the local conditions.

Analyses of the spectral ratios show two distinct cases:

– A major peak with high amplitudes (1.7–2.5 units) within the range of frequencies from 1to 5 Hz (0.2–1 s) for the Dunavăţul de Jos, Măcin, Măxineni and partly Cataloi sites; here one or a few shallow thin layers (tens of meters thick) comprising soft rocks overlie a very thick layer with hard rocks; a secondary peak suggests a thinner layer belonging to the shallow geology; beyond 5 Hz (0.2 s) the amplitudes oscillate around one unit;

– A peak area within the 0.1–2.5 Hz (0.4–10 s) window with amplitudes of 1.2–1.4 units followed by some insignificant peaks with amplitudes ≤ 1; this is the case for the Brăila, Gulianca, Mihălceni, Bogza, Bordeşti, Dumitreşti and Vintileasca sites where a thick pile of sediments (hundreds of meters thick) comprising soft and hard rocks generates those low resonance frequencies.

The spectral ratio analysis applied on the seismic records from the explosions proved that the local geology plays a major role in determining the resonance frequency and the amplification at a site. As a shallow, thin and soft sedimentary layer overlies a thicker and hard layer, then a high and distinct peak of the spectral ratio occurs for frequencies > 1 Hz. If a thick and mixed soft and hard sediment pile dominates the upper section beneath a site, then we can expect some low resonance frequencies < 2–3 Hz.

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