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EVALUATION OF THE PREDOMINANT FREQUENCY OF SEDIMENTARY LAYERS RESONANCE USING VRANCEA CRUSTAL EVENT OF NOVEMBER 22, 2014

E. F. Manea[1], A. Coman[1, 2], C. O. Cioflan[1]

[1] National Institute for Earth Physics, Calugareni, 12, 077125 Bucharest-Magurele, Ilfov, Romania
[2] University of Bucharest, Faculty of Physics, 077125, Magurele, Ilfov, Romania
Corresponding author: *coman@infp.ro*

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Abstract. In this study, the predominant frequency of resonance was identified, interpreted and mapped along the National Seismic Networks of Romania, Republic of Bulgaria and Republic of Moldova, for the November 22, 2014, M_L = 5.7 crustal event generated at 40 km depth in the Vrancea seismogenic area. The horizontal-to-vertical spectral ratio technique was applied on the three-component single station measurements to investigate the local variability at each site. The observed predominant peaks are matching the fundamental frequency of resonance at some sites located on a superficial sedimentary cover and reach higher frequencies for the ones on deep sedimentary basins.

Key words: predominant frequency of resonance, local site effects, Vrancea crustal seismic area, H/V ratio.

1. INTRODUCTION

Seismic site effects evaluation has a substantial impact on the assessment of seismic hazard and risk and it is a crucial step for the mitigation of potentially high seismic risk in densely populated urban regions.

Two thirds of the Romanian territory are mainly affected by the seismicity generated in the Vrancea seismogenic area, where 2 to 3 destructive events with magnitude over 7 occur each century at intermediate depth [1, 2]. This region is located at the junction of three tectonic plates: the East-European plate and the Intra-Alpine and Moesian subplates (*e.g.* [3]). While the seismic activity is quite active at intermediate-depths, the overlying crust seismicity is significantly lower in terms of frequency and moment release (M_{max} < 6.0) [4]. Recently, an earthquake with local magnitude M_L = 5.7 occurred in this region on November 22, 2014, at 21:14:17 local time (19:14:17 GMT) in the lower crust (40 km depth). It was felt up in the Eastern Europe, at distances up to 600 km from the epicenter (Romania, Republic of Bulgaria, Republic of Moldova) and the observed maximum seismic intensity was VI MSK [4]. It was the largest crustal event occurred during the

digitized era and it is of highest interest to understand the seismic features observed for future microzonation purposes.

There exist many techniques for estimating seismic effects in local/superficial geological structure generated by the propagation of the seismic waves, based on experimental methods and instrumental data (macroseismic intensities, noise, weak to strong motion recordings), or numerical modeling as well (*e.g.* finite differences, finite element). In these methods the propagating medium is linearly elastic, equivalent linear, infinite, or partially finite (half-space) (*e.g.* [5–7]). Frequently, uncertainties are encountered in characterizing the spectral features of the relative amplitudes, due to the specific local conditions, source characteristics, wavefield path. Spectral characteristics of the micro-vibrations could bring some information about local conditions for a certain area. The Horizontal-to-Vertical Spectral Ratios (HVSR, *e.g.* [8–11]) technique is used as a reliable tool for estimating the seismic response at a given site. According to these authors, this ratio gives us not only information about resonance period and frequency but also on the corresponding amplification. On the other side, some authors found that the retrieved amplification factor using H/V technique are not expressing completely the local amplification as the study of [12] which notice a tendency of underestimation as compared with classical reference station methods.

In this study, the predominant frequency of resonance was identified and mapped along the regions covered by the National Seismic Networks of Romania, Republic of Bulgaria and Republic of Moldova, aiming to understand the seismic wavefield generated by the 5.7 M_L seismic event generated in the Vrancea crustal zone. For this reason, the Horizontal-to-Vertical Ratios of earthquake records (further denoted EHVR) technique was primarily applied in the frequency range of 0.1–15 Hz, in order to retrieve the predominant frequency (f_{pred}) of resonance along the study area.

In this study the EHVR ratio was computed for the S-waves part of the seismic record in order to approximate the response of the near surface geology. Spectral ratios of the seismic records were computed for 72 online seismic stations from the National Seismic Network of Romania, Republic of Bulgaria and Republic of Moldova.

Using the earthquake records, only a few studies were done to assess the predominant period along this area only for low magnitude events occurred at intermediate depth in the Vrancea area (*e.g.* [13–15] and references therein).

The computed EHVR was compared with the HVR extracted from ambient vibration at each station as provided by studies [16–18]. In order to understand the complexity of seismic wavefield along the interest area, the SH transfer function was retrieved for only the S-waves part.

This study is a step forward in understanding the impact of the local geological structure on ground motion generated in the crustal domain by Vrancea

source and can bring significant improvement in the evaluation of seismic hazard and risk.

2. DATA AND METHODS

The data analysed in this study consist of three-component recordings of 5.7 M_L crustal event, November 22, 2014, from 78 online seismic stations within the National Seismic Networks of Romania, Republic of Bulgaria and Republic of Moldova (Fig. 2).

The Romanian Seismic Network (RSN, https://doi.org/10.7914/SN/RO), operated by the National Institute for Earth Physics, recorded this event by 72 seismic stations. The National Seismological Network of Bulgaria (BS, https://doi.org/10.7914/SN/BS) is operated by the National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy of Sciences (NIGGG – BAS) and consists in 41 stations. The Moldova Digital Seismic Network is operated by the Geological and Seismological Institute of Republic of Moldova (MD, https://doi.org/10.7914/SN/MD) and consists in 3 stations. In this study, we use only free field records of 72 RSN stations, 5 stations of BS and 1 of MD (Fig. 2).

The data were pre-processed following standard time-series analysis procedures [19]: any offset and linear trend (which typically affects broadband recordings) were removed, then filtered from 0.01 to 15 Hz with a fourth-order Butterworth filter and after rotated with respect of the back-azimuth angle to extract the transverse (T) and radial (R) components.

The Horizontal-to-Vertical Fourier Spectral Ratios of earthquake records (EHVR) were computed using the methodology proposed by [9, 10]. The EHVR is usually investigated as the ellipticity of the surface waves under various boundary conditions (*e.g.* [20–22]). The classical theory of Love waves, which assumes a layer super-imposed over a half-space offers the possibility to look for resonance with a wavelength related to the layer thickness. The elastic waves excited on the plane surface of an isotropic half-space were computed [23] in connection to resonance phenomenon, and the dominant soil frequencies were highlighted. To understand the complexity of seismic wavefield present in the H/V spectral ratio, the Transversal-to-Vertical Spectral Ratio (TVSR) was computed as the ratio between the Fourier spectra of the transverse component (T) and Fourier spectra of the vertical (V).

To estimate the EHVR and TVSR, the signals were split in sub-windows of 100 s length for almost all the seismic stations using the entire time series and of 20 –100 s length for coda waves. Each sub-window was tapered with a 5% cosine taper before performing the spectral ratios. The Fourier spectra computed for each component were subsequently smoothed using the Konno and Ohmachi algorithm [8] with a bandwidth of 60. Finally, we compute the EHVR ratio between the

horizontal (geometric mean of the two components) and vertical Fourier spectra of the recordings and TVSR between the transversal and vertical Fourier spectra of the recordings.

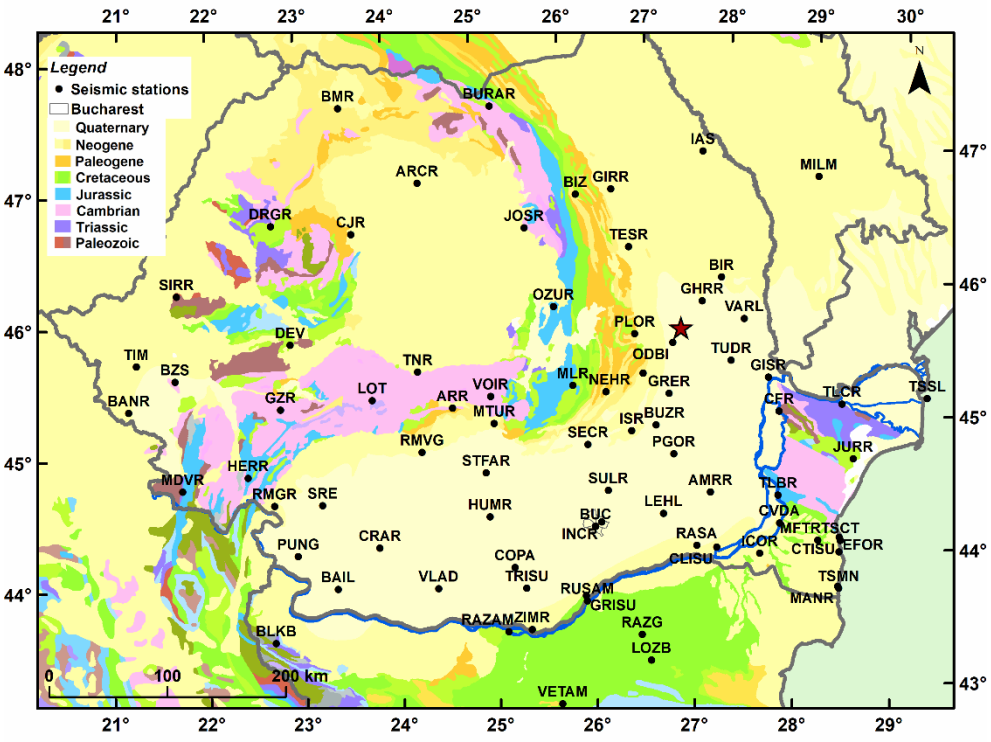

Fig. 1 – Location of the 2014, 5.7 M_L Vrancea crustal event (red star) and of the seismic stations (black dots) on a geological sketch map. See [24] for a detailed legend of the geological map.

3. RESULTS

The Earthquake Horizontal-to-Vertical (EHVR) and the Transversal-to-Vertical Spectral Ratios (TVSR) were computed on 78 single station three-component earthquake records in order to assess the variability of the predominant frequency of resonance and to understand features of the seismic wavefield for 2014, 5.7 M_L Vrancea crustal event. These resulted ratios/curves were compared with the HVR ones retrieved from ambient vibration analysis – HVRA [15–18] to identify the signature of local structure on seismic ground motion generated by the event.

The computed EHVR using seismic input shows similar features with the ones retrieved using ambient noise (Figs. 2 and 3). The EHVR and TVSR are similar and their major peaks follow the ones on HVRA. The similarity between

the two computed curves was actually expected as the EHVR is computed using the geometric mean of the two horizontal components.

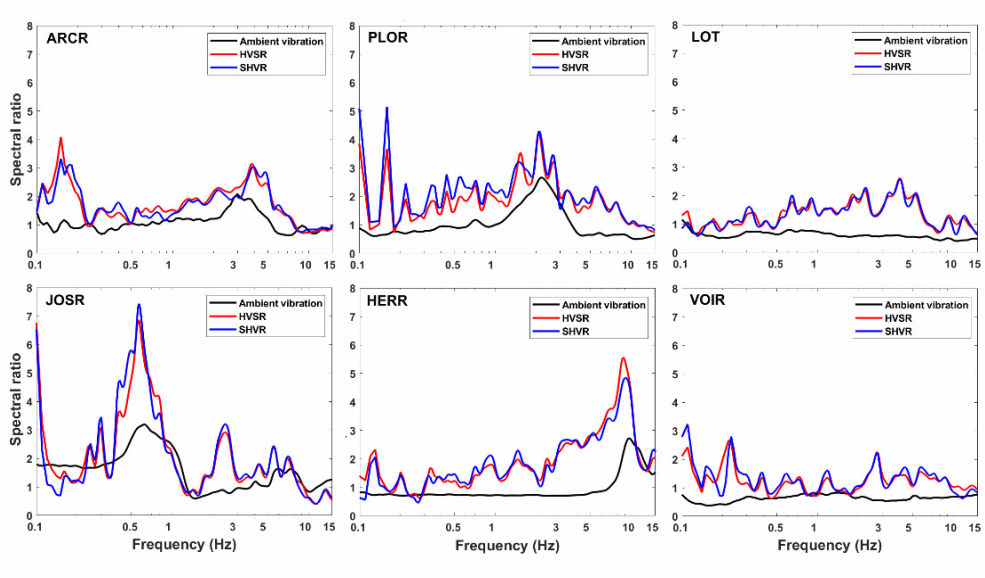

Fig. 2 – The Horizontal-to-Vertical Spectral Ratios computed for signals recorded at the seismic stations located in the intra-Carpathian area and along Carpathian Mountains. The black line represents the HVRA curve obtained using the ambient vibrations [16, 18] and the colored ones are the obtained EHVR and TVSR for the 5.7 M_L crustal event occurred in the Vrancea region.

For the stations located on intra-Carpathian region (*e.g.* ARCR, JOSR) and on the Carpathian Mountains (*e.g.* PLOR, HERR) the shape of the EHVR can be seen in Fig. 2. Two significant peaks are observed: one related to the fundamental frequency of resonance from HVRA (inferred from [18]) and another one at low frequencies (or a group of peaks) related to the local strata excited by the source characteristics. In terms of amplitude of the spectral ratios, a significant attenuation (by a factor of 2) with epicentral distance can be observed from JOSR to ARCR station, considering that both stations have similar local structure. The EHVR shows a migration of f_{pred} from high frequency (0.6Hz at JOSR to 0.15 at ARCR) mostly due to the specific back-arc attenuation of the seismic waves observed by [25, 26] and evidenced by [27].

For stations placed on rock, where no fundamental frequency was observed previously by [17], the EHVR is amplified by a factor of up to 2 relative to the HVRA at low frequencies in the case of VOIR station and within 3–5Hz interval at LOT station (see Fig. 2).

The variation of EHVR and TVSR are compared with the spectral ratio curves computed on ambient vibration (HVRA) reported by [16, 17] to see the

impact of the local structure on the complex seismic wavefield. These are presented in Fig. 3, for different stations located along the extra-Carpathian area.

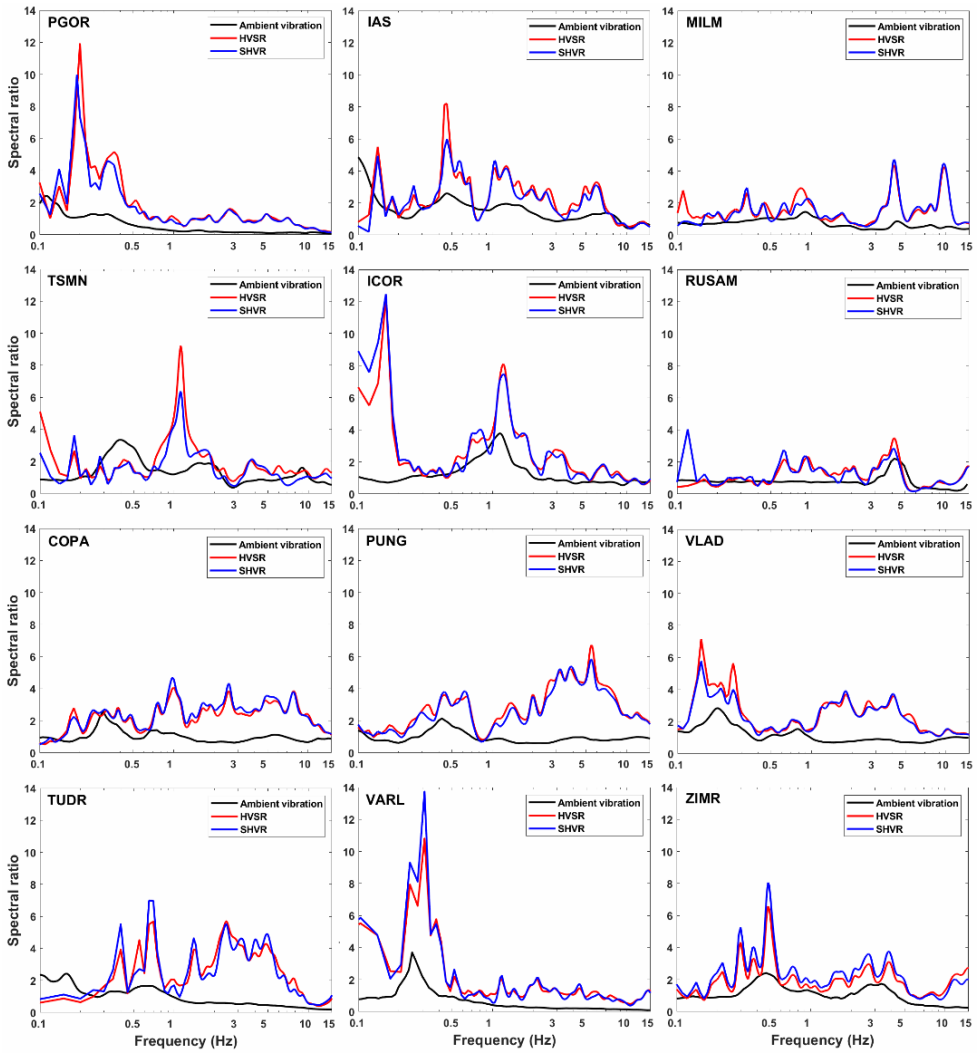

Fig. 3 – The Horizontal-to-Vertical Spectral Ratios computed for signals recorded at the seismic stations located in the extra-Carpathian area. The black line represents the HVRA curve obtained using the ambient vibrations [16, 17] and the colored ones are the obtained EHVR and TVSR for the 5.7 M_L crustal event occurred in the Vrancea region.

For the stations located in the Moesian Platform (*e.g.* PGOR, COPA, PUNG, VLAD, TUDR, ZIMR; see Fig. 3), the EHVR and TVSR show complex features compared to HVRA. Higher modes are excited by the earthquake energy and become predominant at different seismic stations located on the sedimentary structures.

At station PGOR, the first and second higher modes are excited; the first one, identified as f_{pred}, is related to the Pliocene/Miocene interface [16], while the second one (at 0.3 Hz) which was not observed in the HVRA is related with the response of near-surface geology. At station IAS, the f_{pred} is matching the f_0 and the complexity of the geological structure can be observed in the complex pattern of the EHVR (Fig. 3). In Republic of Moldova, at station MILM, two peaks were observed with similar amplitudes at high frequency (5 and 10 Hz) these being related to the very shallow geological structure of the site. At stations such as TUDR, COPA, PUNG and VLAD, a complex feature of the wavefield is observed at frequencies higher than 0.75 Hz. This significant scattering might correspond to the 3-D effects of the Moesian Platform and to the contribution of different seismic surface waves, such as the ones produced at the edges of this large sedimentary basin or multipath interference waves (*e.g.* Airy phases of Love waves) on ground motion [28].

At stations located in Dobrogea and Republic of Bulgaria, the EHVR and SHVR shows simple features, with the f_{pred} identified as f_0 (TSMN, RUSAM). At station ICOR (Fig. 3), the f_{pred} is much lower than the f_0 and this sharp peak might be related to the Crystalline/Cretaceous interface below the recording site.

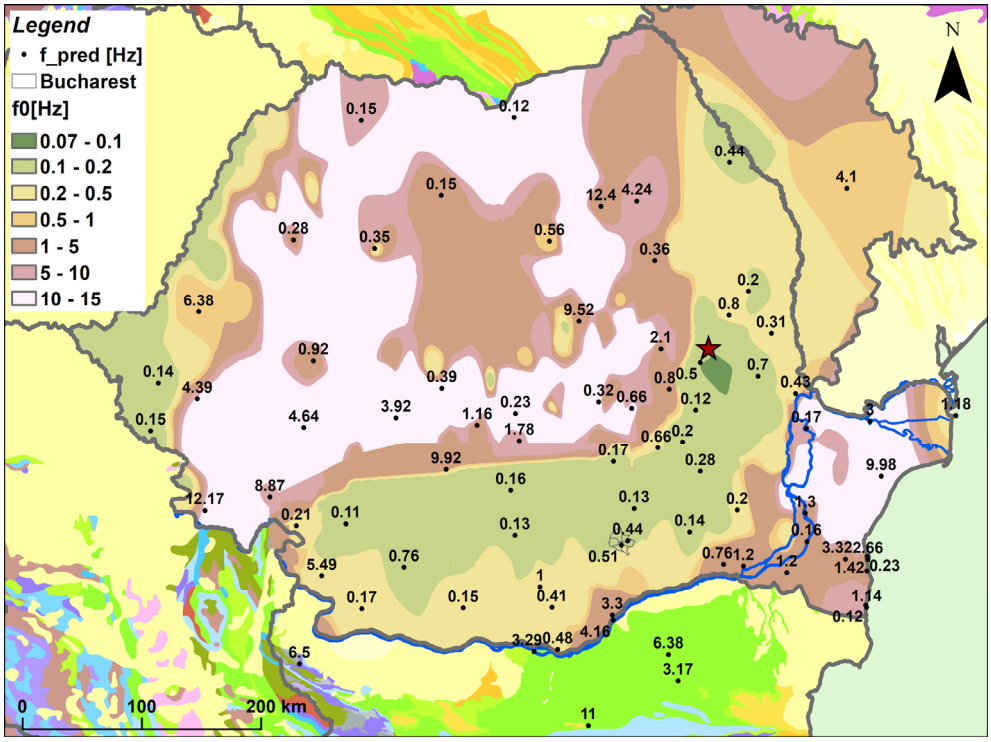

Fig. 4 – Variation of predominant frequency of resonance (f_{pred}) along the study area for the November 22, 2014, 5.7 M_L Vrancea event (its location is shown by the star symbol). The basemap colors is the variation of fundamental frequency of resonance (interpolated after [15–18]).

The predominant peak (f_{pred}) was identified at all the seismic stations that recorded this event in the region and its variability is presented on a basemap containing the interpolated fundamental frequencies of resonance from ambient noise, obtained combining the data of recent studies [15–18]. The f_0 map was generated using a geographic information system (ArcGis tool, www.arcgis.com), the data are spatially interpolated by Natural Neighbor method (http://pro.arcgis.com/en/pro-app/tool-reference/spatial-analyst/natural-neighbor.htm).

In the intra-Carpathian area and along Carpathian Mountains, the f_{pred} matches consistently the f_0 extracted from HVRA by [16–18]. In the extra-Carpathian area, the f_{pred} is marching on of the higher modes observed sometimes in the HVRA or the f_0. For the stations located in the northern part of Danube river, the f_{pred} is close to the second higher peak observed in the HVRA. It was observed that this peak becomes predominant in case of large Vrancea intermediate – depth events ($h > 60$ km; *e.g.* [15]) but was never observed as being predominant on crustal events. This peak was correlated with the seismic response of the complex geological structure under the action of complex surface (a mixture of Love and Rayleigh) waves by [28]. In the southern and eastern part of the Danube river (Republic of Bulgaria and Dobrogea), the f_{pred} matches the f_0 suggesting a homogenous geological structure.

4. CONCLUSIONS

In this study, we performed a step forward in the understanding of the seismic wavefield and ground motion amplification for the November 22, 2014, 5.7 M_L crustal event generated at 40 km depth in the Vrancea seismogenic area.

The predominant frequency of resonance was identified and mapped along the study area for this event by computing the EHSR and SHVR on S-wave.

The EHSR and SHVR show complex features compared with the spectral ratios computed from ambient vibration. In case of the stations located along the Carpathian arc and in the intra-Carpathian area, the predominant frequencies f_{pred} are identified at almost all the stations as the fundamental frequency of resonance from ambient vibration f_0. In case of the stations located in the extra-Carpathian area, in the northern side of Danube river, the predominant frequency is matching the second peak or has a higher frequency indicating a complex seismic response of the Moesian Platform geological structure. A complex feature of the wavefield is observed at higher frequencies (> 0.75 Hz) and can be explained by the significant scattering induced by 3-D effects of the Moesian Platform. A significant attenuation can be observed for the sites located outside of this area (*i.e.* Northern Bulgaria and Dobrogea), where the predominant frequency matches the fundamental one, the seismic energy generated by the crustal event is not able to excite superior vibration modes in the local structures.

These new results increase our understanding of ground motion propagation by emphasizing the ground motion peculiarities in this area for Vrancea crustal events.

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