VRANCEA SOURCE INFLUENCE
ON LOCAL SEISMIC RESPONSE IN BUCHAREST

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Abstract

The mapping of the seismic ground motion in Bucharest, due to the strong Vrancea earthquakes, is carried out using a complex hybrid waveform modelling method that allows easy parametric tests. Starting from the actually available strong motion data base, we can make realistic predictions for the possible ground motion. The basic information necessary for the modelling consists of: (a) the representative mechanisms for the strong subcrustal events, (b) the average regional structural model, and (c) the local structure for Bucharest. Two scenario earthquakes are considered and the source influence on the local response is analyzed in order to define generally valid ground motion parameters, to be used in the seismic hazard estimations. The source has its own (detectable) contribution on the ground motion and its effects on the local response in Bucharest are quite stable on the transversal component (T), while the radial (R) and vertical (V) components are sensitive to the scenario earthquake. Although the strongest local effect affects the T component, both observed and synthetic, a complete determination of the seismic input for the built environment requires the knowledge of all the three components of motion (R, V, T). The damage observed in Bucharest for the March 4, 1977 Vrancea event, the strongest earthquake that hit the city in modern time, is in agreement with the synthetic signals and local response.
1. Introduction

Bucharest is a large city of about 2 million inhabitants and a considerable number of high-risk structures and infrastructures are located in its area. The geological setting of the city is characterized by the presence of deep sedimentary deposits. Thus, the information concerning the local seismic hazard of this location is an important aspect to account for by the decision-makers (civil engineers, city planners, and Civil Defense) to establish the appropriate level of preparedness to the earthquake threat. The source that practically controls the entire seismic hazard, not only at the national level (Romania) but also for the neighboring countries, is represented by the Vrancea region located in the rectangle of geographical coordinates: 45°- 46 °N, 26°-27 °E (RADU & POLONIC, 1983; RADULIAN et al., 1998,a). The seismic regime of this region is mainly characterized by earthquakes in the depth range from about 60 to 200 km with the largest magnitudes $M_w$ above 7.0. The statistics based on historical records (ONCESCU et al., 1999) indicate that about 3 to 5 destructive subcrustal earthquakes occur in Vrancea per century, therefore this seismogenic volume has to be considered both for seismic hazard analysis at national and regional level, as well as for microzonation studies of the highly populated cities located in the range of influence of this source. Bucharest is the most important city exposed to the potential damage due to these strong intermediate-depth shocks, the ground motion evaluation of this site being therefore an essential step toward the mitigation of the local seismic risk.

The records concerning the damage effects in Bucharest, due to the Vrancea earthquakes, start with the August 19, 1681 ($M_w$=7.1) event, and continue with the June 11, 1738 ($M_w$=7.7); October 26, 1802 ($M_w$=7.9); November 23 and 26, 1829 ($M_w$=7.3); January 11, 1838 ($M_w$=7.5) events. In this century more detailed information is available for the strong events that occurred on November 10, 1940 ($M_w$=7.7); March 4, 1977 ($M_w$=7.4); August 30, 1986 ($M_w$=7.1), and May 30, 1990 ($M_w$=6.9), and it is briefly summarized in MANDRESCU & RADULIAN (1999,a).
The mapping of the seismic ground motion for microzonation purposes requires: (1) the collection and extended use of the recorded strong motion data, and (2) the use of advanced modelling techniques, that allow us to compensate the lack of strong motion records by computing a realistic seismic input. Whenever possible modelling must be calibrated with the available recordings. Strong motion data for Bucharest area are very scarce and correspond to the last three strong Vrancea events (1977, 1986 and 1990), but they represent a data base that, integrated by modelling, may permit a realistic estimate of the seismic input.

Using a realistic ground motion simulation technique that combines modal summation (PANZA, 1985; VACCARI et al., 1989; FLORSCH et al., 1991; PANZA, 1993; ROMANELLI et al., 1996) and finite differences (FAEH, 1991; FAEH & PANZA, 1994; FAEH et al., 1994), together with the accumulated information about seismic sources, sampled medium and local soil conditions MOLDOVEANU & PANZA (1999) and MOLDOVEANU et al. (1998,a) modelled the ground motion in Bucharest, with an accuracy fully satisfactory for microzonation purposes. For the sedimentary setting of the city they made use of a simplified geotechnical profile (laterally varying local structure), and of a regional structure representative for the propagation path from the source to the local structure. As earthquake scenarios two different focal mechanisms were considered, which are representative of: (a) the May 30, 1990 (Mw=6.9), and (b) the May 31, 1990 (Mw=6.4), Vrancea events. Although relatively simple source and structural models are used, the synthetic accelerograms for the May 30, 1990, earthquake are in good agreement with the records of Măgurele station (44.347°N, 26.030°E) and with the observed local site effects in Bucharest (MOLDOVEANU & PANZA, 1998). In addition, the peak ground acceleration to peak ground velocity ratios, PGA/PGV, both for the synthetic and the observed signals lowpass filtered with the cut-off frequency 1 Hz (average for Măgurele station: 3.5 (s⁻¹) observed, and 3.8 (s⁻¹) synthetic) are in very good agreement with the value determined from globally available strong motion records for deep soft soils - PGA/PGV= 5 ± 2.6 (s⁻¹) - by DECANINI & MOLLAIOLI (personal communication, 1998),
and with the value reported earlier (PGA/PGV < 7.4 (s⁻¹)) by Seed & IDRISS (1982). Perturbing the source parameters of the May 30, 1990, Vrancea event, Moldoveanu et al. (1998,a) analyzed the stability of the local site effects when changing the scenario earthquake. They showed that all the three components of motion are influenced by the presence of the deep alluvial sediments, the strongest local effect being visible in the transversal (T) one, both observed and synthetic. The local effects vary with varying the scenario earthquake, but the maximum values of the quantities considered for their quantification are stable.

In this paper we analyze the differences in the ground motion in Bucharest when considering two seismic sources that mimic the dominant Vrancea scenario earthquakes.

2. Seismicity of Vrancea Region

The seismic regime of the Romanian territory is a moderate one and consists of both shallow and intermediate-depth events. The Vrancea region, localized in the rectangle 45°- 46°N and 26°-27°E, beneath the bending of Eastern Carpathian Arc, is the main source responsible of the seismic flow in the area. The subcrustal seismic activity concentrates within an epicentral area of about 3,000 km², NE-SW oriented, that partly overlaps the epicentral area of the crustal events (Radulian et al., 1996,a; 1998,b; Moldoveanu et al., 1998,b). During this century 12 major intermediate depth events (Mw≥6.4) have been recorded (Table1), and the released seismic energy presents a peak in the last twenty two years. The shallow seismicity of the region, mainly located in the lower crust (h>15km), is generally characterized by small and medium magnitude earthquakes (the strongest crustal event, recorded in 1914, has an Ml=5.3).

Several models have been proposed to describe the tectonic processes in Vrancea, but the driving mechanism of the intermediate-depth seismicity is not yet completely understood. The seismic sources might be localized in a relic slab sinking into the asthenosphere and now overlaid by continental crust (Mckenzie, 1970, 1972). The driving mechanism might be the rapid south-
west motion of the plate containing the Carpathian Arc and the surrounding regions, relative to
the Black Sea plate, or the vertical gravitational sinking of an oceanic slab, detached from the
continental lithosphere, into the asthenosphere (Fuchs et al., 1978). The seismicity is taking
place in a cold relic slab, denser and more rigid than the surrounding mantle that sinks due to the
gravity. The hydrostatic buoyancy forces help the slab to subduct, but the viscous and frictional
forces act as a resistance to its descent. These forces produce an internal stress with the principal
axis directed downward, and intermediate-depth earthquakes occur in response to it (Oncescu &
Trifu, 1987). The strong subcrustal events account for high pressure faulting processes, which
could be facilitated by the stress produced by heterogeneity in volume change, due to basalt-

3. Scenario Earthquakes

The major intermediate-depth Vrancea earthquakes are characterized by a reverse faulting
mechanism with the T-axis almost vertical and the P-axis almost horizontal. This could mean that
the large events in the Vrancea region are governed by the same geodynamical process (Oncescu &
Bonjer, 1997). The same mechanism is observed for more than 70% of the studied events,
regardless of their magnitude (Enescu, 1980; Enescu & Zugrăvescu, 1990; Oncescu & Trifu,
1987). The fault plane orientations can be divided into two main groups oriented on a: (1) NE-SW
direction, with the P-axis perpendicular to the Carpathian mountain arc (e.g. the March 4, 1977, the
August 30, 1986, the May 30, 1990 events); and (2) NW-SE direction, with the P-axis parallel to the
Carpathian mountain arc (e.g. the May 31, 1990 event). The major Vrancea events exhibit: (a) a
source located around 90 km of depth (March 4, 1977 event), and (b) a source located around 150
km of depth (November 10, 1940 event) (Radulian et al., 1998,a). The observed focal mechanisms
of these two events are close to each other, and the average mechanism can be described with the
following parameters of the fault plane: 225° strike, 60° dip, and 80° rake (mechanism 1).
The second class of focal mechanisms corresponds to a smaller hypocentral depth, around 80 km, lower magnitudes, for example the May 31, 1990, and a mechanism having the following average fault plane parameters: 310° strike, 70° dip, and 90° rake (mechanism 2), i.e. reverse faulting, with the nodal planes rotated by about 90° with respect to mechanism 1. From the distribution of macroseismic data MĂNdREScu & RAduLAN (1999,b) assign to this class of mechanisms the events of May 31, 1990, March 4, 1894 (Io=7), May 25, 1912.

4. Geological Setting

The geological input required for the deterministic evaluation of the resultant ground motion in Bucharest by means of the hybrid method (FAEH & PANZA, 1994; FAEH et al., 1994) consists of an averaged regional bedrock anelastic model, representative of the Vrancea-Bucharest path, and a local, laterally varying, anelastic model. MOLDOvEAnu & PANZA (1999) give the bedrock structure compiled on the basis of the information provided by RAduLAN et al. (1996,b).

Bucharest is situated in the central part of the Moesian Platform at an average epicentral distance of about 140-170 km from the Vrancea region. The relief of the city is generally plane, and with a slight dipping towards southeast. The Dâmbovița and Colentina rivers divide the city into several morphological units: Bucharest Plain (Dâmbovița – Colentina interstream), Băneasa-Pantelimon Plain, Cotroceni-Văcărești Plain, and the meadows along the above mentioned rivers. The foundation ground in Bucharest area, represented exclusively by Quaternary deposits, exhibits (for the Middle and Upper Quaternary deposits) the following lithological succession, from bottom to top: sands and gravel; clay marls and sands; fine sands with sandstone and clay insertions; gravel and sands with lenticular clay intercalation; clay and sandy yellow dust (loesslike deposits) and sandy clays with lenticular silt intercalation (alluvial deposits in the meadows of the Dâmbovița and Colentina rivers). The presence of unconsolidated sediments (deep soft soils) with irregular geotechnical characteristics and distribution in space has been detected by
different civil construction enterprises (e.g. “Proiect București” Institute, S.C. “Prospețiuni” S.A., “Metrou” S.A.), that have made available a large amount geological, geotechnical and hydrogeological data (the geotechnical bore-holes alone are more than 10,000). The synthesis of these data made by MĂNGRESCU & RADULJAN (1999,a) defines the following four geologic-geotechnical complexes: (a) alluvial-proluvial deposits (loesslike deposits) containing clay and sandy yellow dusts, with loess dolls; the structure is macroporous and very compressible in the saturated state; (b) diluvial deposits formed by loesslike and clay deposits with slight macroporous structure; they overlay almost completely the Dâmbovița terraces; an increase of the clay content is noticed as compared with the loesslike deposits in the plains; (c) alluvial deposits represented by clays, dusty and sandy clays and mud; the predominant clay character at surface is changing with depth, the clay content diminishing in comparison with the sand; alluvial deposits are found in Dâmbovița and Colentina meadows; (d) artificial fills are largely spread in the Dâmbovița-Colectina interstream.

On the basis of this synthesis, MOLDOVEANU & PANZA (1999) compiled a simplified model (NE-SW oriented cross section of the city) of the laterally varying, anelastic deep sedimentary formation of Bucharest, and use it (together with the bedrock anelastic model) for the simulation of the seismic motion due to the May 30, 1990, Vrancea event.

5. Ground Motion Modelling

The scenario earthquakes we consider in our modelling, both with $M_w=7.4$, are shown in Fig.1 and can be described as follows: (a) epicenter defined by Lat.=45.7°N, Lat.=26.5°E, hypocentral depth 90 km, and mechanism 1 (source V-1 from now on), and (b) epicenter defined by Lat.=45.8°N, Lat.=26.9°E, hypocentral depth 80 km, and mechanism 2 (source V-2 from now on).

Starting from the results obtained by MOLDOVEANU & PANZA (1999) and MOLDOVEANU et al. (1998,a) we extend the analysis of the local response in Bucharest to these two earthquake
scenarios. The modelling is performed by means of the hybrid technique (FAEH, 1991; FAEH & PANZA, 1994; FAEH et al., 1994) that combines the modal summation (PANZA, 1985; VACCARI et al., 1989; FLORSCH et al., 1991; ROMANELLI et al., 1996) and the finite difference techniques (ALTERMAN & KARAL, 1968; BOORE, 1972; KELLY et al., 1976) allowing to calculate synthetic signals, complete in a given frequency-phase velocity window, which take into account the effects of the source, path and local geological conditions. We use the geological structure for the propagation path Vrancea-Bucharest already adopted by MOLDOVEANU & PANZA (1999). The source is modeled as a double couple and the finiteness of the fault is accounted for by scaling the synthetic signals with the empirical source spectra scaling curves (GUSEV, 1983) modified for the Vrancea intermediate-depth events (MOLDOVEANU et al., 1998,c). The frequency range covered by the simulations is 0.005-1.0 Hz that allows us the modelling of the seismic input appropriate for ten storeys and higher buildings.

Using the geological models and the scenario earthquakes V-1 and V-2, we synthesize the time series for an array of 35 equally spaced (at 0.6 km) sites in Bucharest located along the 21 km long local profile indicated by full triangles in Fig.5. In Fig.2 (a,b) we present the three component of acceleration (R, V, and T) corresponding to a subset of 7 sites equally spaced at 3 km. The epicentral distance increases from top to bottom. The signals are scaled for a $M_w=7.4$ ($M_o=1.26\times10^{20}$N-m). Fig. 2a illustrates the waveforms for the scenario earthquake V-1, and Fig. 2b the source V-2.

Popular quantities related to ground motion, mostly used in seismic engineering to characterize the seismic input for the built environment, are the peak ground acceleration (PGA) and the Arias intensity ($W$). Since the simulation technique we make use of considers the complete wavefield, both for SH- and P-SV motion, the synthetic signals can be processed as the observed accelerograms. A convenient set of relative quantities for evaluating the local response are the ratios $A_{2D}/A_{1D}$ and $W_{2D}/W_{1D}$, i.e., the relative PGA and $W$, where 2D stands for the laterally varying
model and 1D stands for the bedrock structure. Along the local profile of Bucharest, the spatial variations of the relative PGA and relative W, evaluated considering the scenario earthquakes V-1 and V-2 are presented in Fig.3 (a,b). From Figs. 2 and 3 it is evident the stability of the transverse component while the other two, mainly the radial, are sensitive to the variation of the scenario earthquake. This fact warrants further considerations.

6. Source Signature in the Local Effects

The analysis of the two sets of accelerograms presented in Fig. 2 (a,b) indicate that the maximum amplitudes of the ground motion components corresponding to source V-1 compared with those for source V-2 are: (a) about 3-4 times larger for R and V, and (b) about 3 times larger for T. When the scenario earthquake varies from V-1 to V-2, the shape of the signals change considerably for the R and V components while for the T component it is rather stable. The total duration of the time series for source V-2 compared with that for the source V-1: (a) increases for the R and V components, while (b) it remains approximately the same for T. Thus, the scenario earthquake has a significant influence only on R and V.

The distribution of the relative PGA (A2D/A1D) and relative W (W2D/W1D) along the local profile presented in Fig.3(a,b) allow us to observe that the strongest amplification effect, with respect to the bedrock model, is present in the T ground motion component: up to 2.0 for both sources, while R and V have average amplification not exceeding 1.5. T is quite stable while R and V are varying with varying the scenario earthquake.

The relative response spectra (SA2D/SA1D), that is the ratio between the undamped response spectra corresponding to the laterally varying structure and the bedrock structure, and the spectral ratio (FT2D/FT1D), i.e., the ratio between the Fourier transform of the signals computed for the laterally varying structure and the bedrock structure, are very useful quantities to study the local effects in the frequency domain. For illustration, in Fig.4 we show the relative response spectra and
the relative spectral ratio computed for a site located in the central part of the city (the circle along the local profile from Fig.5) in the case of the V-1 seismic scenario (mimic of the March 4, 1977 earthquake - Fig.4a) and for the V-2 seismic scenario (mimic of the May 31, 1990 earthquake - Fig.4b). The position of the peaks is different among the components. For example, for source V-1, the largest excitations in the T component can be observed at 0.4 Hz (amplification about 3.0) and at 0.9 Hz (amplification about 5.5). R and V exhibit smaller amplification (not higher than 2.0) in other frequency ranges: (a) 0.25-0.35, 0.55-0.6 and 0.85-0.95 Hz for R, and (b) 0.65-0.8 and 0.99 Hz for V. For the scenario earthquake V-2 and the same receiver (Fig.4b), the strongest local effects are presented in the T component that preserves the peak of 0.4 Hz (amplification about 3.4) and 0.9 Hz (amplification about 2.8), but the second maximum is half in comparison with the case of source V-1. R and V present amplifications not larger than 3.0 in almost the same frequency ranges as for the source V-1: (a) 0.25-0.40 and 0.95-0.99 Hz for R, and (b) 0.65 and 0.78 Hz for V.

The frequency resonance of the sedimentary layers might explain these spectral amplifications at the considered site. For T, the peak around 0.4 Hz can be associated with the resonance of the upper 400 m, and the peak of 0.9 Hz with that of the uppermost 270 m. The other peaks in R and V cannot be explained in such simple terms and they are the result of the complex interaction of the P-SV wavefield, radiated by the source, with the lateral variations.

The position of most of the largest values in the spectral domain is close to the resonance periods (in the range 1.0-1.5 s), of the ground motion induced by the major Vrancea subcrustal earthquakes in Bucharest (MÂNDRESCU & RADULIAN, 1999,a).

Traditionally, for engineering purposes, only the transversal component is considered as seismic input. Although the strongest site effect is observed in T, the R and V are very sensitive to
source mechanism variations, and therefore they should not be neglected for mapping the seismic ground motion and in antiseismic structural design.

7. Local Effects and Damage Distribution

The most destructive seismic shock that hit the city in modern times is the March 4, 1977, Vrancea event (V-1 scenario earthquake). No strong motion records for this event are available for sites in Bucharest along the considered profile, therefore we compare our modelling with the damage that can be summarized as follows: 32 buildings of 8-12 storeys collapsed, while about 150 old buildings of 6-9 storeys high were strongly damaged (many of them were subsequently demolished).

The damage distribution for the masonry buildings and reinforced concrete frame structures expressed in MSK-64 intensity is presented in Fig.5 (from MÄNDRESCU & RADULIAN, 1999,a), where the position of the profile considered in our computations is indicated by triangles. The strongest damage is concentrated in the central part of the profile. This fact is well reproduced by the seismic scenario corresponding to the V-1 source. The relative PGA, as well as the relative W, display an extended peak in the central part of the profile, as can be seen from the T component in Fig.3a. The good agreement between the simulated local effects and the damage distribution in the city, along the considered profile, is clearly visible when considering the normalized quantities presented in Fig.6.

Fig.6 summarizes the results obtained in this study and in the previous ones by MOLDOVEANU & PANZA (1999) and MOLDOVEANU et al. (1998,a), and compares them with the macroseismic intensity, deduced from the damage to the masonry and frame concrete buildings (a1 – thick continuous line) reported by MÄNDRESCU & RADULIAN (1999,a) and the macroseismic intensity in Bucharest (a2 – thick dashed line) reported by MÄNDRESCU (1979). MOLDOVEANU & PANZA (1999) and MOLDOVEANU et al. (1998,a) consider the following scenario events: A - 236° strike, 63° dip, 101° rake (mimic of the May 30, 1990, Vrancea mechanism), and B - 325° strike, 63°
dip, and 101° rake (mimic of the May 31, 1990, Vrancea mechanism), both of them with hypocentral depth $H=60$ km, and epicenter defined by Lat.$=45.92^\circ$N, Lon.$=26.81^\circ$E.

For all the scenario earthquakes (V-1, V-2, A and B) we can observe that the normalized relative PGA ($b_1$, $c_1$, $e_1$, $d_1$) has a smaller space variation than the normalized relative $W$ ($b_2$, $c_2$, $e_2$, $d_2$). This different behavior is due to the fact that the Arias intensity depends on the duration of the signal. The absolute PGA ($b_3$, $c_3$, $d_3$, $e_3$) and relative PGA ($b_1$, $c_1$, $d_1$, $e_1$) are similar for the four considered earthquakes. A particularly good agreement with the observed macroseismic intensity is visible in the absolute PGA in the case of source A. Therefore, the dominant local effects turn out to be reliable and stable with varying the seismic source. Analyzing in pairs the four sets of curves we can identify the source signature on the local response: (1) for V-1 all the extremes are localized to the left side of the local profile ($b_1$, $b_2$, $b_3$), (2) for V-2 the extremes are shifted to the central–right part of it ($c_1$, $c_2$, $c_3$), (3) for A and B the extremes occupy almost the same position, (4) the local minima are systematically smaller for V-1 than for V-2.

The main differences between V-1 and A on one side, and V-2 and B on the other, is the focal depth. Thus, our results seem to indicate that the damaging energy radiated by the Vrancea events comes from depth close to the shallower limit of the hypocentral range. The differences in the local response in Bucharest, summarized in Fig.6, are the signature of the considered source models, and therefore are likely to embrace the possible scenarios along the considered profile.

8. Conclusions

The last decade in seismology represents the third era of seismic risk mitigation when the hallmark is the ability to achieve more quantitative and cost-effective efforts in risk reduction in a broad urban setting, with particular attention to megacities and densely populated industrial complexes (BOLT, 1994). The understanding gained from strong ground motion records from various earthquake source types and sizes, and for various site conditions, together with the
theoretical knowledge and accumulated data on the sources and the sampled medium, now makes it possible, given an active fault source, to predict numerically the radiated seismic waves.

The earthquakes of the Vrancea region dominate the seismic hazard of Romania and of south-eastern Europe, in general, and of Bucharest city, in particular. The heavy destructions experienced in the past, most recently in 1977, certainly indicate that the seismic microzonation in Bucharest is an important goal to achieve. The microzonation of the city can be performed by means of possible seismic scenarios constructed using very realistic synthetic signals. In such a way we can estimate the amplification effects in complex structures, exploiting the available data concerning the dominant Vrancea strong earthquakes, the average regional medium and the geotechnical structure of the local sedimentary settings in Bucharest.

Starting from the work of MOLDOVEANU & PANZA (1999) and MOLDOVEANU et al. (1998,a) we analyze the influence of Vrancea source on the local response in Bucharest. The two dominant fault plane solutions that can be identified in the major subcrustal Vrancea events ($M_w > 6.0$), V-1 and V-2, are used for the investigation. In this study we prove that the source has its own contribution on the resultant ground motion. The source effects on the local response (in Bucharest) indicate a quite stable behavior for the T component, while the R and V components are sensitive to the scenario earthquake. Although the strongest local effect is measured (both observed and synthetic) in the T component, for a complete determination of the seismic input all the three components (R, V, T) should be used. The results are in good agreement, both with the recorded signals in Mâgurele station ($44.347^\circ$N, $26.030^\circ$E) for May 30, 1990 event, and with the reported damage in Bucharest for the March 4, 1977 Vrancea event (source V-1).

For the complete microzonation of Bucharest, the modelling will be extended to a set of representative cross sections that span the entire area of the city.
Acknowledgements

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Table 1.
Vrancea intermediate-depth earthquakes with \( M_w \geq 6.4 \) for the period 1990-1998
(modified from ONCESCU et al., 1998)

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<th>Date</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Depth (km)</th>
<th>( M_w )</th>
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<td>90.</td>
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**Figure captions**

Fig.1: Focal mechanism V-1 and V-2 representative for the Vrancea intermediate-depth events considered as scenario earthquakes for the modelling of the seismic input in Bucharest.

Fig.2(a,b): Acceleration time series (R, V, and T components) at an array of 7 receivers equally spaced at 3 km, along the local, laterally varying, profile of Bucharest setting considered in the simulations. The scenario earthquakes considered are the two dominant Vrancea strong events: (a) for V-1, and (b) for V-2. The signals for both sources are scaled for a \( M_w = 7.4 \) (\( M_o = 1.26 \times 10^{20} \) N·m) using empirical source spectra curves (Gusev, 1983) modified for the deep intermediate-depth Vrancea shocks. Acceleration is given in \( \text{cm/s}^2 \) and time in seconds. Peak values correspond to MSK-64 macroseismic intensity 8.
Fig. 3 (a,b): Spatial distribution of the relative values of PGA (A2D/A1D) - continuous line, and W (W2D/W1D) - dotted line, for the three components of motion (R,V,T) along the local profile of Bucharest setting considered in the seismic simulations; 2D stands for the laterally varying structure, while 1D stands for the bedrock structure. (a) corresponds to source V-1, and (b) corresponds to source V-2.

Fig. 4 (a,b): Relative response spectra SA2D/SA1D for 0% damping - continuous line, and spectral ratio, for 0.025 Hz smoothing, FT2D/FT1D - dotted line, for the three components of the synthetic signal (R,T,V) at the site no.21 (indicated in Fig. 5 by a square) located in the central part of the city. (a) corresponds to source V-1, and (b) corresponds to source V-2.

Fig. 5: The March 4, 1977, Vrancea earthquake (MW=7.4): Intensity (MSK-64) from the damage distribution in Bucharest (masonry buildings and reinforced concrete frame structures), after MĂNDRESCU & RADULIAN (1999,a). The position of the local profile for the analyzed seismic scenarios is indicated by triangles. The northernmost triangle is at an epicentral distance of 140 km from source V-1 and at an epicentral distance of 160 km from the source V-2. The position of the receiver no.21 (referred in Fig 4) is indicated by a circle.

Fig. 6: Normalized T ground motion parameters along the local profile and the observed macroseismic intensity:

a1 - thick continuous line - intensity (MSK-64) as deduced from damage to the masonry buildings and reinforced concrete frame structures (MĂNDRESCU & RADULIAN, 1999a) for March 4, 1977 Vrancea strong event;

a2 - thick dashed line - reported by MĂNDRESCU (1979) for March 4, 1977 Vrancea event;
b1 – thick dotted line - A2D/A1D for source V-1 (mimic of the March 4, 1977 Vrancea event); 
b2 - thick dotted line - W2D/W1D for source V-1; 
b3 – thick dotted line - PGA(2D) for source V-1; 
c1 – thin dashed line - A2D/A1D for source V-2; 
c2 - thin dashed line - W2D/W1D for source V-2; 
c3 - thin dashed line - PGA(2D) for source V-2; 
d1 – thin continuous line - A2D/A1D for source A from MOLDOVEANU & PANZA (1999) 
and MOLDOVEANU et al. (1998,a) (mimic of the May 30, 1990 Vrancea mechanism with 
the hypocentral depth H=60 km; 
d2 - thin continuous line - W2D/W1D for source A; 
d3 - thin continuous line - PGA(2D) for source A; 
e1 -dot-dashed thick line - A2D/A1D for source B from MOLDOVEANU et al. (1998,a) 
(mimic of the May 31, 1990 Vrancea mechanism with the hypocentral depth H=60 km; 
e2 - dot-dashed thick line - W2D/W1D for source B; 
e3 – dot-dashed thick line - PGA(2D) for source B. 

2D stands for the local laterally varying structure, while 1D stands for the bedrock 
structure model. The zero distance corresponds to the northernmost site (triangle) in 
Fig.5.
Fig. 1
Fig. 3 (a,b)
Fig. 4 (a,b)
Fig. 6