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Deterministic Approach for the Seismic Microzonation of 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 modeling method which combines the modal summation technique, valid for laterally homogeneous anelastic media, with finite-differences technique, and optimizes the advantages of both methods. For recent earthquakes, it is possible to validate the modeling by comparing the synthetic seismograms with the records. We consider for our computations the frequency range from 0.05 to 1.0 Hz and control the synthetic signals against the accelerograms of the Magurele station, low-pass filtered with a cut-off frequency of 1.0 Hz of the 3 last major strong ($M_w > 6$) Vrancea earthquakes. Using the hybrid method with a double-couple seismic source approximation, scaled for the source dimensions and relatively simple regional (bedrock) and local structure models, we succeeded in reproducing the recorded ground motion in Bucharest at a satisfactory level for seismic engineering. Extending the modeling to the entire territory of the Bucharest area, we construct a new seismic microzonation map, where five different zones are identified by their characteristic response spectra.

Key words: Microzonation, synthetic seismograms, Bucharest, Vrancea.

1. Introduction

The historical seismic activity of the Romanian territory is known since the Roman times (the 1st century b.c.). All major events originate at intermediate depth in the Vrancea region which is localized at the arched bending of the Carpathian Mountains. In Romania, the first instrumental records became available after 1934 when the first seismographic stations started to operate in the country. Bucharest City is located on a relatively stable platform with a single minor fault (Tg. Fierbinti-Urziceni) at about 40 km N from Bucharest. The seismicity of the region is relatively

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low: about 50 events in the last century, with a medium magnitude $M_w \approx 2.7$. For the event with maximum magnitude in the area ($M_w = 5.0$, depth of the source ≈ 42 km (Romplus catalog) there is no damage reported. Bucharest is the largest cultural and economic center of Romania exposed to seismic risk due to the strong Vrancea earthquakes. It has an urbanized area of 228 km^2 and 2.53 millions inhabitants that represent about 10% of the country's population. During the last century the City was affected by three Vrancea earthquakes with moment magnitude $M_w > 7$ which occurred in 1940, 1977 and 1986. The most severe effects on the national territory were inflicted by the March 4, 1977 event, $M_w = 7.4$. Victims of this event totalled 1,574, out of which 1,424 were registered in Bucharest, where 32 tall buildings collapsed. The World Bank's loss estimation due to the 1977 earthquake (Report No.P.-2240-RO, 1978) indicates a total loss of 2.05 Billion US dollars of which more than 2/3 were in Bucharest, where half of the total loss was accumulated from building damage. The most controversial question in the definition of the standards to be used in the evaluation of the regional or local seismic hazard regards the criteria and methods to be employed should they be of a probabilistic or deterministic method? For solving this dilemma studies carried out for some of the most recent strong earthquakes (e.g. the 1977 Vrancea and 1985 Mihoacan earthquakes) have proved to be important sources of basic knowledge and have acted as a catalyst in the use of zoning in seismic risk management. The post-earthquakes studies (e.g., PANZA *et al.*, 1996) have shown that earthquake destruction is the result of the interaction of three complex systems: 1) the solid earth system made up of a) the seismic source, b) the propagation of the seismic waves, c) the geometry and physical conditions of the local geology; 2) the anthropised system, whose most important feature in this context is the quality of construction (buildings, bridges, dams, pipelines etc.); 3) the social, economic and political system which governs the use and development of a settlement before it is struck by an earthquake.

The seismic hazard at regional and local scale for Bucharest has been the object of many studies, based mainly on probabilistic and/or traditional deterministic methods that make use of the large quantity of macroseismic information available, since the strong motion records are rather scarce. This study is a deterministic approach based on the computation of realistic synthetic seismograms using the hybrid method (FÄH *et al.*, 1990, 1993; FÄH, 1992). The method allows us to estimate the parameters of the seismic motion at any site of interest for given seismic sources and geological/geotechnical properties of the propagation media.

2. Characteristics of Vrancea Region

Bucharest City is exposed to the seismic hazard generated by the intermediate-depth events originating in the Vrancea region which is located at the intersection of four tectonic structures: East-European Plate, Moesian, Black Sea and Intra-Alpine

(Pannonian-Carpathian) subplates (SOLOVIEV *et al.*, 2000). The statistics show that in this seismic region up to five shocks with $M_w \geq 6.5$ occur each century (RADULIAN *et al.*, 2000 B). Their effects are felt over a large territory, from Central Europe to Moscow and from Greece to Scandinavia.

The focal volume in which the intermediate-depth events occur is restricted to a parallelepiped 100-km long, 40-km wide, with a vertical extension from 70 km to 180 km depth (MOLDOVEANU *et al.*, 2000). The crustal events are also present in the Vrancea region and the epicentral depths do not exceed 40 km. The seismic activity is concentrated within an epicentral area of about 3000 km^2, NE-SW oriented and delimited by the rectangle of coordinates: 45.5°–45.9° N, and 26.4°–26.9° E.

Several models have been proposed to explain the main tectonic aspects in Vrancea that consider a paleo- (MCKENZIE 1972; ONCESCU and TRIFU, 1987) or an active subduction (ENESCU and ENESCU 1993), a pure shear faulting or tensile faulting, etc. (ISMAIL-ZADEH *et al.*, 2000).

The strong earthquakes originating in the Vrancea region during the last century caused important economic damage and loss of human lives in Romania and in the neighboring countries. These events are: November 10, 1940 ($M_w = 7.7$; $M_0 = 5.1 \cdot 10^{20}$ Nm); March 4, 1977 ($M_w = 7.4$; $M_0 = 1.5 \cdot 10^{20}$ Nm) August 30, 1986 ($M_w = 7.1$; $M_0 = 6 \cdot 10^{19}$ Nm); May 30 and 31 ($M_w = 6.9$; $M_0 = 3.8 \cdot 10^{19}$ Nm, respectively $M_w = 6.4$; $M_0 = 3.8 \cdot 10^{18}$ Nm).

The typical focal mechanism of strong Vrancea earthquakes ($M_w > 6$) is a reverse faulting, with principal T axes almost vertical and P axes horizontal (RADULIAN *et al.*, 2000a). The fault plane orientation can be grouped in two main types:

— fault plane NE-SW oriented and P axes perpendicular to the mountain arc (class A);
— fault plane NW-SE oriented with P axes parallel to the mountain arc (class B).

3. Soil Characteristics in the Bucharest Area

Bucharest City is located in the central part of the Moesian subplate (age: Precambrian and Paleozoic) in the Romanian Plain. After a Cretaceous and a Miocene deposit (with the top at roundly 1000 m of depth) a Pliocene shallow water deposit ($\sim$ 700-m thick) was settled. The surface geology consists mainly of Quaternary alluvial deposits. Later loess covered these deposits, and rivers carved the present landscape. From the surface: —seven lithological formations are identified (MANDRESCU, 1972): (i)—Backfill (thickness h up to 3 m); (ii)—Sandy-clay superior deposits (loess and sand, $h = 3$–16 m) from Holocene, and the others from Pleistocene; (iii)—"Colentina" gravel (gravel and sand, $h = 2$–20 m); (iv)—Intermediate cohesive deposits of lacustral origin (80% clay and some sand, $h = 0$–25 m); (v)—"Mostistea" banks of sands (mainly sand, sometimes lenses of clay included, $h = 10$–15 m); (vi)—Lacustral deposits from clay and sands ($h = 10$–

60 m) and (vii)—''Fratesti'' gravel (gravel and sands separated by clay, $h = 100$–180 m).

Strong lateral variations in depth and thickness of these 7 layers can be observed throughout Bucharest. A considerable number of geotechnical drillings are available for the central part of the city. The majority of these holes penetrate the upper 30–40 m, and some of them extend to depths between 70 m and 180 m (WENZEL *et al.*, 2000). An important role in the evaluation of the site effects in Bucharest must be associated with the numerous aquifers underground in the city. There are three main aquifer systems: (i) ''Colentina'' located about 8 m deep, (ii) ''Mostistea'' situated at about 25–30 m depth, and (iii) ''Fratesti''—the deepest aquifer consisting of three layers located between 120 and 200 m deep.

The available soil data indicate that the surface geology on the eastern side of Bucharest comprises a succession of clay and sand layers. The corresponding average shear-wave velocity has values lower than 380 m/s in the uppermost 200 m of depth. Due to this velocity structure dangerous amplifications in the long-period range could be expected in this city area in case of strong Vrancea earthquakes.

The eastern, southern, and center of the city are covered by predominantly clayey soil profiles and exhibit large control periods of the response spectra, with the corner period T_c ranging from 1.1–1.5 s. The northern part of Bucharest is covered by predominantly sandy soil profiles. Here the medium control period of the response spectra spans the interval $T_c = 0.6$–1.0 s. The geometry, NE-SW oriented, of the T_c isolines corresponding to the 1986 and 1990 Vrancea earthquakes is quite similar, even if the T_c values for 1986 Vrancea event, $M_w = 7.1$ are about 1.5 times larger than the T_c values for the 1990 Vrancea event, $M_w = 6.9$ (LUNGU *et al.*, 2000).

4. Deterministic Seismic Microzonation of Bucharest

The simulation of the seismic strong motion is performed using a hybrid method that combines the modal summation technique (PANZA, 1985, 1993; VACCARI *et al.*; 1989; ROMANELLI *et al.*, 1996; PANZA *et al.*, 2001) and the finite-difference technique (VIRIEUX, 1984, 1986). The modal summation allows a description of the seismic waves propagation through an anelastic, horizontally-layered structure containing the seismic source and the path Vrancea-Bucharest (bedrock structure). Further, the finite-difference technique is used to describe the seismic ground motion of Bucharest sedimentary cover, described as a stack of anelastic layers with lateral heterogeneities (local structure). The input data are the earthquake scenario and the geological structures through which the seismic waves propagate from the source to the sites of interest. The earthquake scenario is described as a point double-couple source and the relevant fault plane solution is taken from CMT catalogue (Harvard University and/or ROMPLUS catalogue). The source parameters we consider in the modeling are given in Table 1.

Table 1

Seismic source parameters used for the numerical simulations

Quake	Hypocenters			Mechanism solutions			M_w	M_0
M/D/Y	Lat.	Long.	Depth	Strike	Dip	Rake		
5/30/90	26.89	45.83	74 km	236	63	101	6.9	$3.0 \cdot 10^{19}$ Nm
5/31/90	26.91	45.85	87 km	308	71	97	6.4	$3.8 \cdot 10^{18}$ Nm
8/30/86	26.49	45.52	131 km	227	65	104	7.1	$6.0 \cdot 10^{19}$ Nm

The bedrock structure represents an averaged regional model, modified from RADULIAN *et al.* (2000-b) to take into account recent tomographic results (MARTIN *et al.*, 2002). Figure 1 displays the variations with depth of density, phase velocities and quality factors for *P* and *S* waves in the upper 300 km of the bedrock model, below this depth an average continental model is used. The local structures considered are representative of the profiles whose position is shown in Figure 2.

The S_1 and S_2 cross sections are modeled with horizontal layers of sediments; the minimum shear-wave velocities are 367 m/s for S_1, 420 m/s for S_2 while the corresponding quality factor is 30. The S_1 structure has a low velocity channel (for both *P* and *S* waves) between 1.75 km and 3.25 km of depth. The structure S_2 has two channels (for both *P* and *S* waves) in the depth intervals 1.82–2.02 km and 2.2–2.6 km. For the S_3 cross section a more detailed structural model is used. Nine tilted (by about 4%) layers form it. Inside the first three, water–bearing layers of sediments and the velocity varies laterally within the limits given in Figure 3. The smallest shear-wave velocity in this model is 163 m/s and Q_s is 11. The unconsolidated sediments consist of loess-like deposits, dusty clays, sand with gravel (Mostistea sands, Colentina gravel), sand, clayey marls, gravel and sands with thin lignite lenses

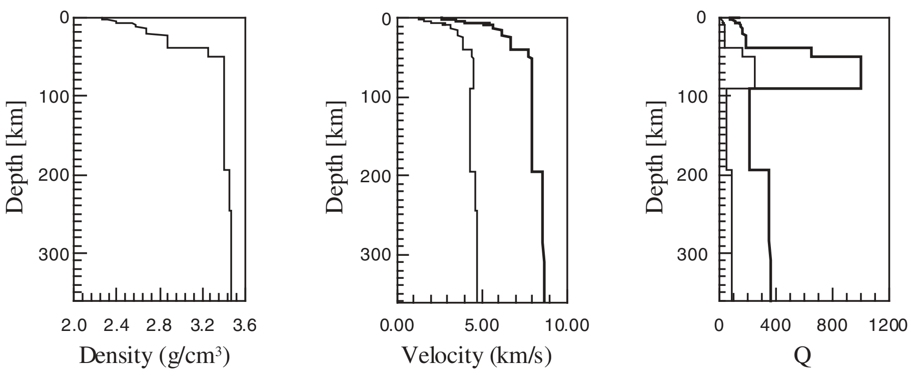

Figure 1
The bedrock structure: variation with depth of the density, V_s and V_p and the corresponding quality factors.

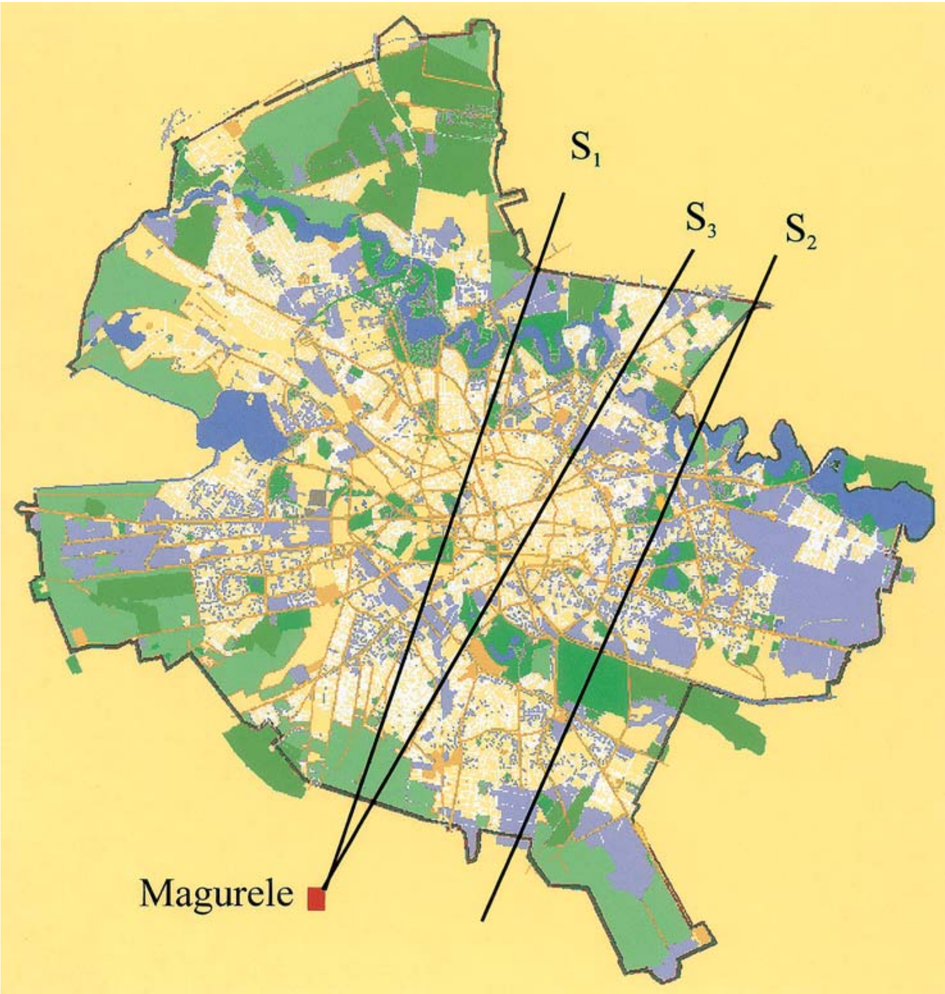

Figure 2
City sketch with the location of the profiles used in the numerical simulations; S_1 and S_2 are parallel and are about 3.5 km apart.

interbedded. The seismic wave velocities have been measured by seismic refraction (MANDRESCU, 1972) and Q_P and Q_S values are evaluated from empirical correlation with the geology.

In the case of the May 30, 1990 earthquake the epicentral distance for all the cross sections ranges from 165 to 185 km.

With these input data, complete signals (displacement, velocity and acceleration) have been computed by using the hybrid method. The frequency range considered in the simulations is the interval 0.05–1.0 Hz, appropriate for 10-story or higher buildings. The real seismic signal considered for the validation of the synthetic

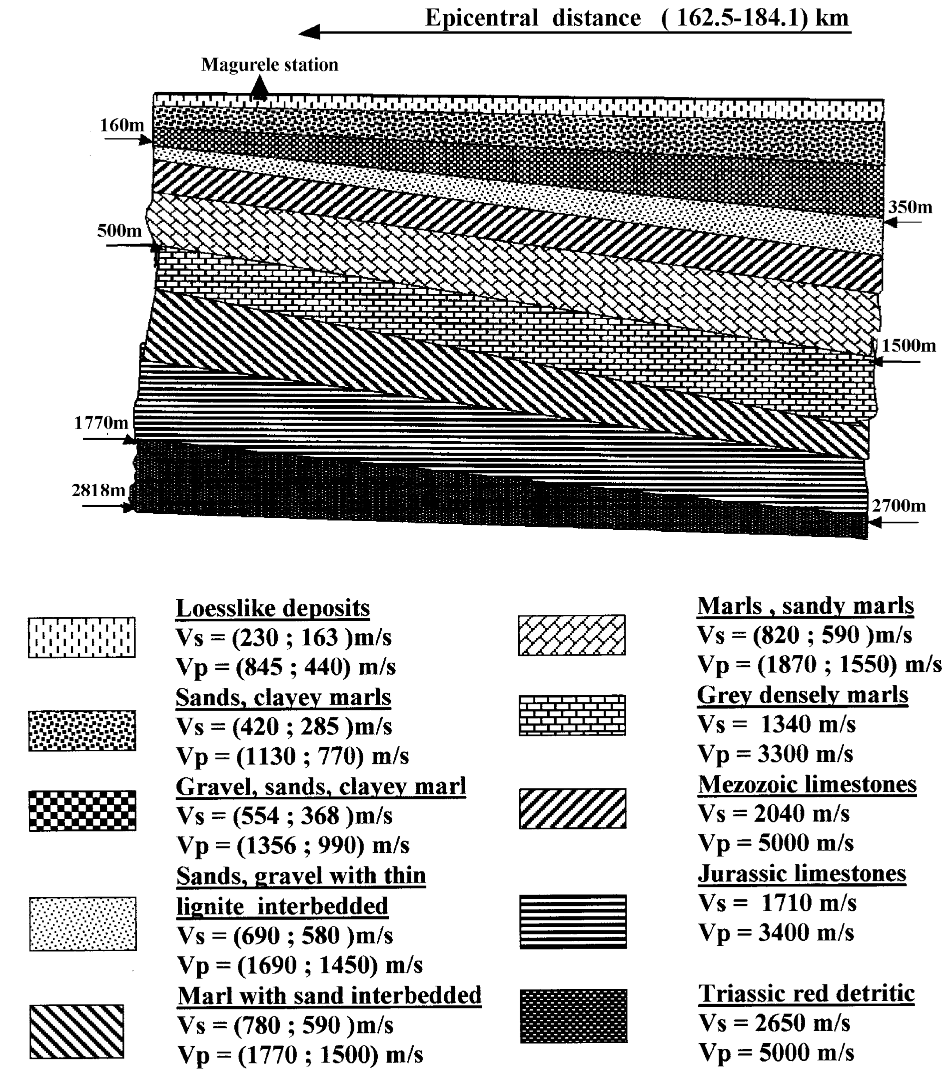

Figure 3
Local structure S_3 used for the ground motion modelling induced in Bucharest by the May 30, 1990, Vrancea earthquake.

seismograms is represented by the three-component record at Magurele seismic station, located at the southwestern part of the city, which was triggered by the May 30, 1990 Vrancea earthquake. The recorded signals, band-pass Butterworth filtered from 0.1 Hz to 1 Hz, are presented in Figure 4. The corresponding synthetic seismograms are shown in Figure 5. The synthetic seismograms reproduce well the shape of the recorded ones and the amplitudes for the vertical (VER) and the transverse (TRA) components (the origin time in Figs. 4 and 5 is not the same).

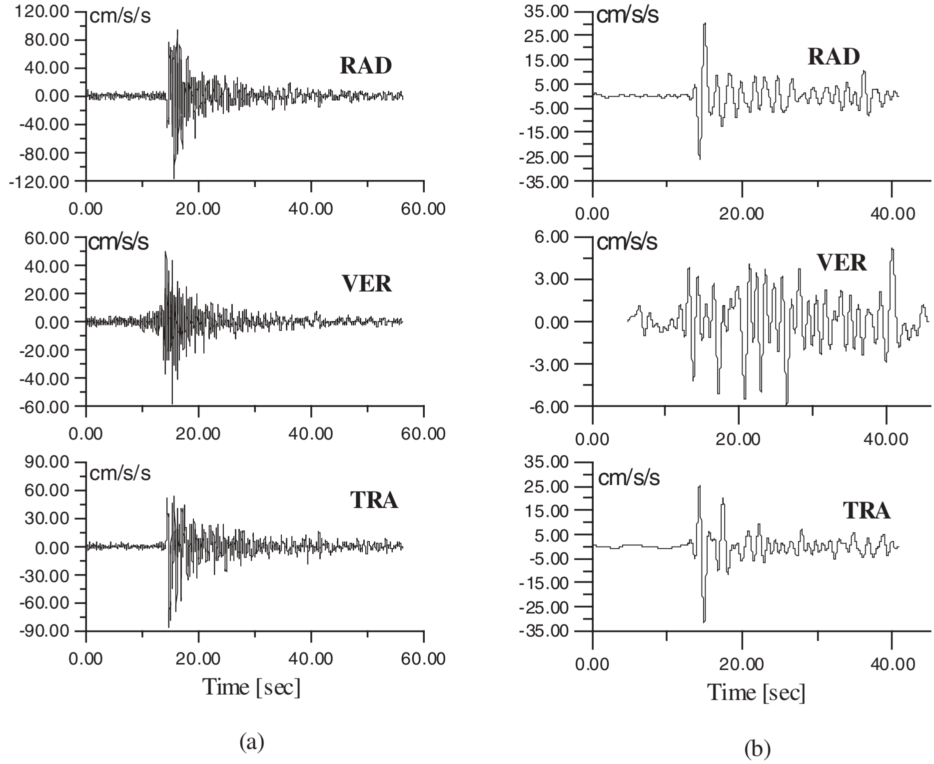

Figure 4
The three-component accelerogram recorded at Magurele seismic station during the May 30, 1990 Vrancea earthquake (a), and the low-pass filtered (0.05–1 Hz) one (b).

Obviously our synthetic time series computed for both bedrock (1-D) and local structure (2-D) can be processed in the same way as the real seismograms in order to obtain the response spectra and the spectral ratio. These quantities, together with PGA (the maximum value of the synthetic accelerograms) are of main importance for seismic engineering purposes.

Figure 6 displays the distribution of the peak ground acceleration (PGA) values along each studied profile, simulated for the case of the May 30, 1990 earthquake. Both the shape and the amplitudes of the spatial distribution of the synthetic PGA are quite similar along S_1 and S_2 profiles, while they are remarkably different along S_3. This is due to the specific geometry and to the lateral variations of the seismic waves velocity in the tilted layers of profile S_3.

To discuss the site effects it is convenient to consider the spatial distribution of the relative peak ground acceleration PGA (2-D)/PGA(1-D), where 2-D indicates the computations for the laterally varying model and 1-D indicates the computations for the bedrock model. Figure 7 shows the relative PGA vs. epicentral distance along the

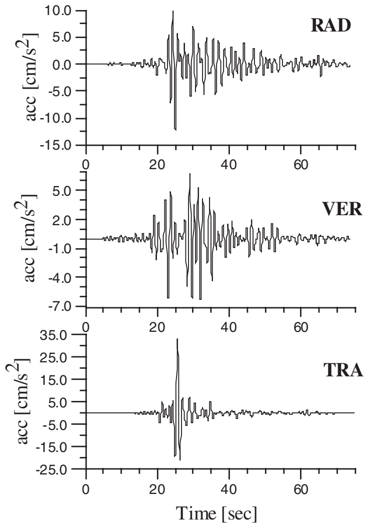

Figure 5
The synthetic seismogram simulated for the Magurele site in the case of the May 30, 1990 earthquake.

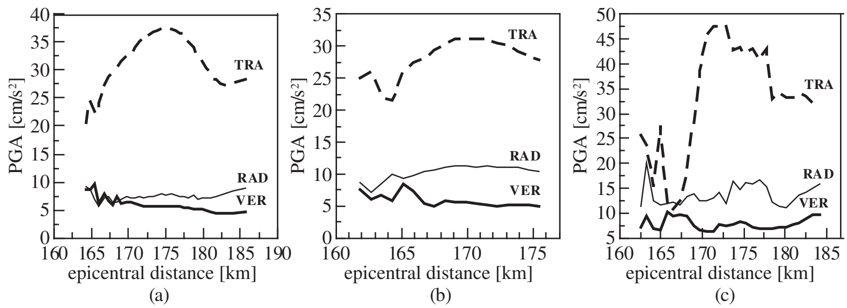

Figure 6
The spatial distribution of the synthetic peak ground acceleration (radial component RAD—thin line, vertical component VER—thick line and the transverse one TRA—dashed line) along profile S_1 (a), S_2 (b) and S_3 (c) for the case of the May 30, 1990 earthquake.

S_1 and S_2 profiles as regards the Aug. 30, 1986 (a,b) and May 31, 1990 (c,d) earthquakes.

The synthetic signals computed using the hybrid method along the local profiles show that the local effects, in terms of PGA, affect mainly the vertical (VER) and the transverse (TRA) components. For these components the local amplification of PGA ranges from 1.2 to 2.9. The radial (RAD) component is less affected, the maximum amplification being 2 .The relative PGA shows different site effects along S_1 and S_2 (Fig. 7). The strong amplification of the TRA and RAD components along the S_1 profile can be due to the differences in the thickness of the same

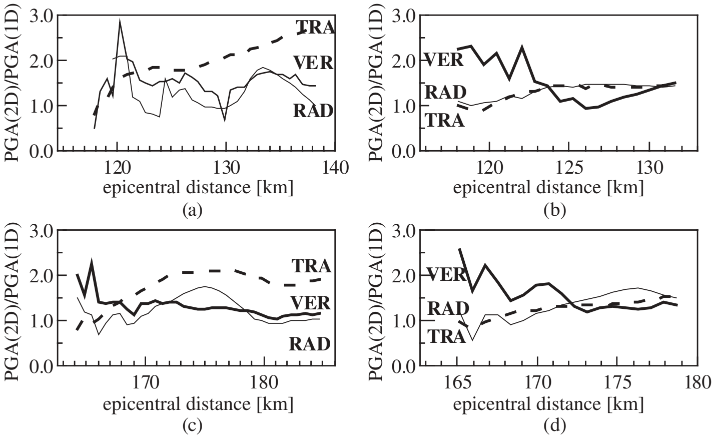

Figure 7
The spatial distribution of relative peak ground accelerations (radial component RAD—thin line, vertical component VER—thick line and the transverse one TRA—dashed line) along profiles S_1 and S_2 in the case of the August 31, 1986 (a and c) and May 31, 1990 (b, d) events.

sedimentary layers and to the presence of a 127-m thick layer, composed of weak consolidated Quaternary sediments. This layer extends to 400 m of depth and has a shear-wave velocity of about 800 m/s and a corresponding quality factor $Q_s = 30$.

The synthetic response spectra ratios (RSR), i.e., the ratio between the response spectra for the laterally varying model, Sa(2-D), and the one for the bedrock model, Sa(1-D), computed with 5% critical damping, are shown in Figures 8–10. Figure 8 shows a different response of the local structures S_1 and S_2 in the case of the May 30, 1990 event (class A event, $M_w = 6.9$). Figure 9 represents the Sa (2-D)/ Sa (1-D) along profile S_3 computed for 2 variants: (a) with horizontal layers, and (b) with 4% tilt layers to mimic the geological local structure. We see that the tilting of the layers induces an amplification of the seismic response, especially for the RAD and TRA components. Important site effects are induced in a confined area located at about 170–178 km epicentral distance, which corresponds to the central part of the city. This effect of the seismic waves propagation explains the abnormal high intensity, VIII+ degree MSK-76, reported in the center of Bucharest after the March 4, 1977 earthquake $M_w = 7.4$ (Mandrescu and Radulian, 2000).

In Figure 10, the peak response in the RAD component along S_2 in the case of August 30, 1986 event (class A event, $M_w = 7.1$) is 1.8 at about 0.3–0.4 Hz. This peak can correspond to the first 360 m of weak Quaternary and Tertiary deposits. The same peak is again present in the case of the May 31, 1990 (class B, $M_w = 6.4$) event, but the maximum RSR (2.2) in the RAD component along S_2, appears at about 0.8–0.9 Hz. For the VER component the maximum RSR (4) along S_2 corresponds to the

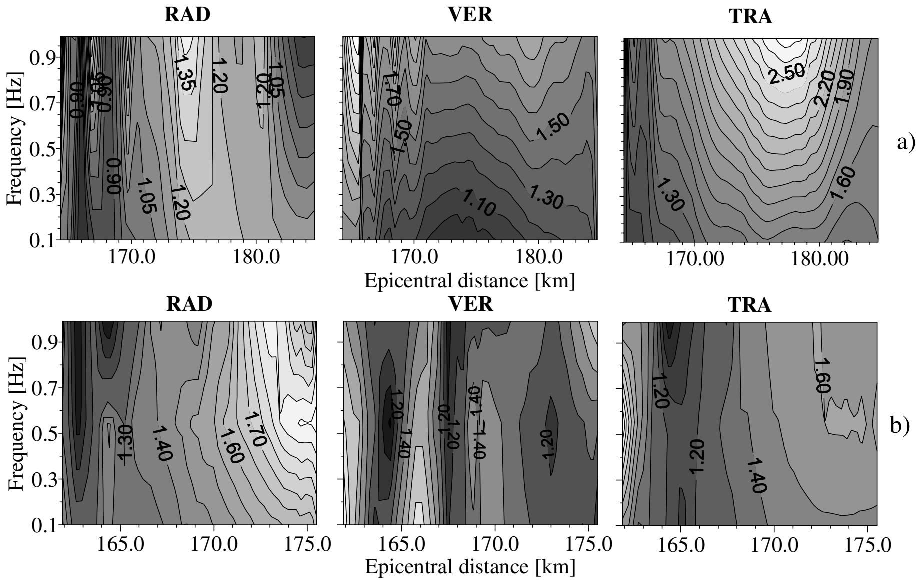

Figure 8
The Relative Spectra Response (RSR), i.e., Sa(2D)/Sa(1D), versus frequency and epicentral distance for S_1 and S_2 profiles (a, b) in the case of the May 30, 1990 earthquake displayed separately for the radial component (RAD), for the vertical component (VER) and the transverse one (TRA).

frequency interval 0.6–0.65 Hz in the case of the August 30, 1986 earthquake. For the May 31, 1990 event the RSR value in the 0.6–0.65 Hz interval is just 2.2, and the maximum value (3.5) is reached at about 0.85–0.9 Hz, i.e., at the uppermost frequency limit used in our modeling. The RAD and VER components are very sensitive to the change of the focal mechanism from class A to class B, while the site effects in the TRA component are relatively stable as shown also by the parametric tests performed by MOLDOVEANU and PANZA (2001). The shift of the maximum RSR values from 0.4 to 0.9 Hz (RAD) or from 0.6 to 0.9 Hz (VER) shows that the frequency content of the seismic ground motion changes with earthquake magnitude. From the modeling one may expect that in Bucharest the large magnitude Vrancea earthquakes induce seismic ground motion that peaks in the low frequency band (<1 Hz), since they are able to significantly excite soil layers with low modal frequency. On the other side, the $M_w < 7$ intermediate-depth events have no such capability and therefore induce seismic ground motion that maximizes in a higher frequency band (>1 Hz). Observations of past strong earthquakes (1977, 1986 and both 1990 events) indicate that the modeling is in agreement within the considered frequency limits, with the real soil response in Bucharest. The dominant recorded period decreases from 1.7 seconds for the strongest event (March 4, 1977, $M_w = 7.4$) to about 1 second (the absolute maximum is actually reached at about 0.4 seconds,

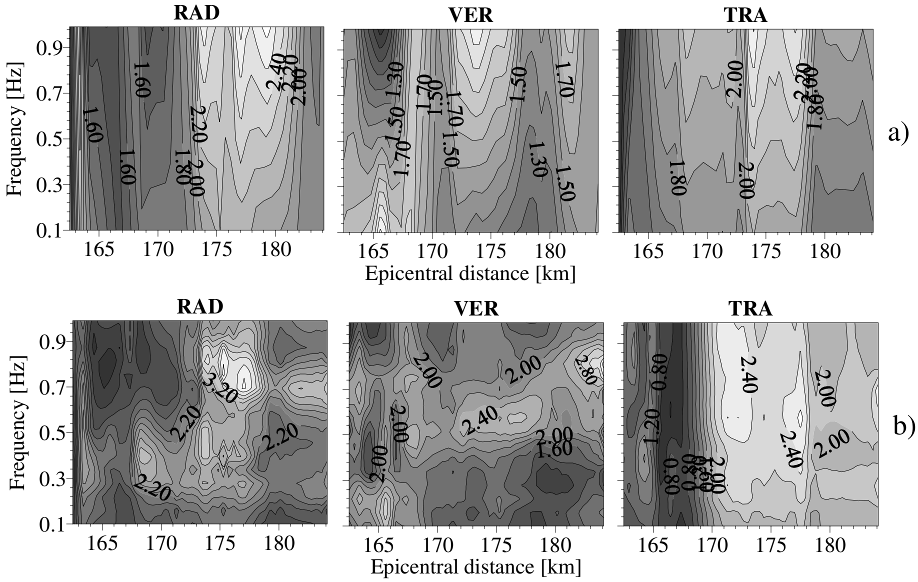

Figure 9
The RSR along S_3 vs. frequency and epicentral distance simulated for the May 30, 1990 earthquake in the case of a structure with horizontal layers (a) and the case of the more realistic structure with tilted layers (b).

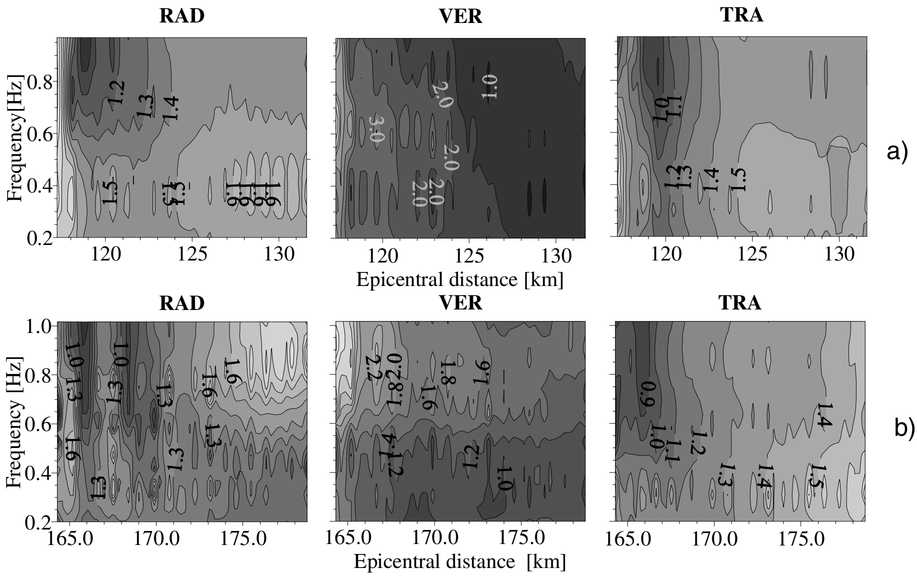

Figure 10
The RSR along S_2, simulated for the August 30, 1986 (a) and May 31, 1990 (b) events.

i.e., outside our modeling frequency band) for the smallest one (May 31, 1990, $M_w = 6.4$).

5. Conclusions

The hybrid technique that we have used makes possible the study of the local soil effects even at long distances from the source, as in the case of Bucharest, taking into account the characteristics of the seismic source, and the effects of the seismic waves propagation. Applied in microzonation studies, this technique provides realistic estimates of spectral amplifications and can supply, when necessary, the lack of strong motion recordings for the "target" site.

The synthetic time series computed by the hybrid method using S_1 and S_1 profiles have been successfully compared with the damage distribution caused in Bucharest by the March 4, 1977 earthquake (MOLDOVEANU and PANZA, 1999).

From the RSR of the synthetic seismograms, computed for the 1986 and 1990 Vrancea earthquakes in the 0.05–1.0 Hz frequency range, it can be concluded that the thickness of the Quaternary and Tertiary sediments strongly affects the seismic ground motion in Bucharest.

On the basis of the results reached and considering the high seismic hazard, it is reasonable for preparedness purposes to extend the results of the numerical simulations to all city zones where the geological conditions are similar to those represented in the studied profiles. The regionalization following these criteria is shown in Figure 11. The variation of the epicentral distances for these regions is less than 3 km. To each of the five zones we assign a representative site, chosen along the virtual arrays used in the numerical simulations. The corresponding response spectra computed for 0% and 5% critical damping are shown in Figure 12, for the case of the May 30, 1990 Vrancea event.

Further computations regarding the simulation of the seismic ground motion excited by other strong Vrancea events (such as the March 4, 1977, $M_w = 7.4$ or November 10, 1940, $M_w = 7.7$ events), and for the "maximum expected earthquake" will substantially improve the reliability of this first deterministic zonation for Bucharest. The ongoing activity regards the extension of the frequency interval of the simulations in order to include the resonance of the masonry buildings.

The numerical simulations of Vrancea strong earthquakes performed by means of the used method makes it possible to obtain at low cost and exploiting large quantities of existing data (e.g. geotechnical parameters, surface geology data, seismological data), the definition of the realistic seismic input to build structures of interest. The synthetic data set, including those corresponding to the "maximum expected" Vrancea event, tighter with the recorded ones can be fruitfully used by civil engineers in design of new seismo-resistant constructions and in the reinforcement of the existing ones.

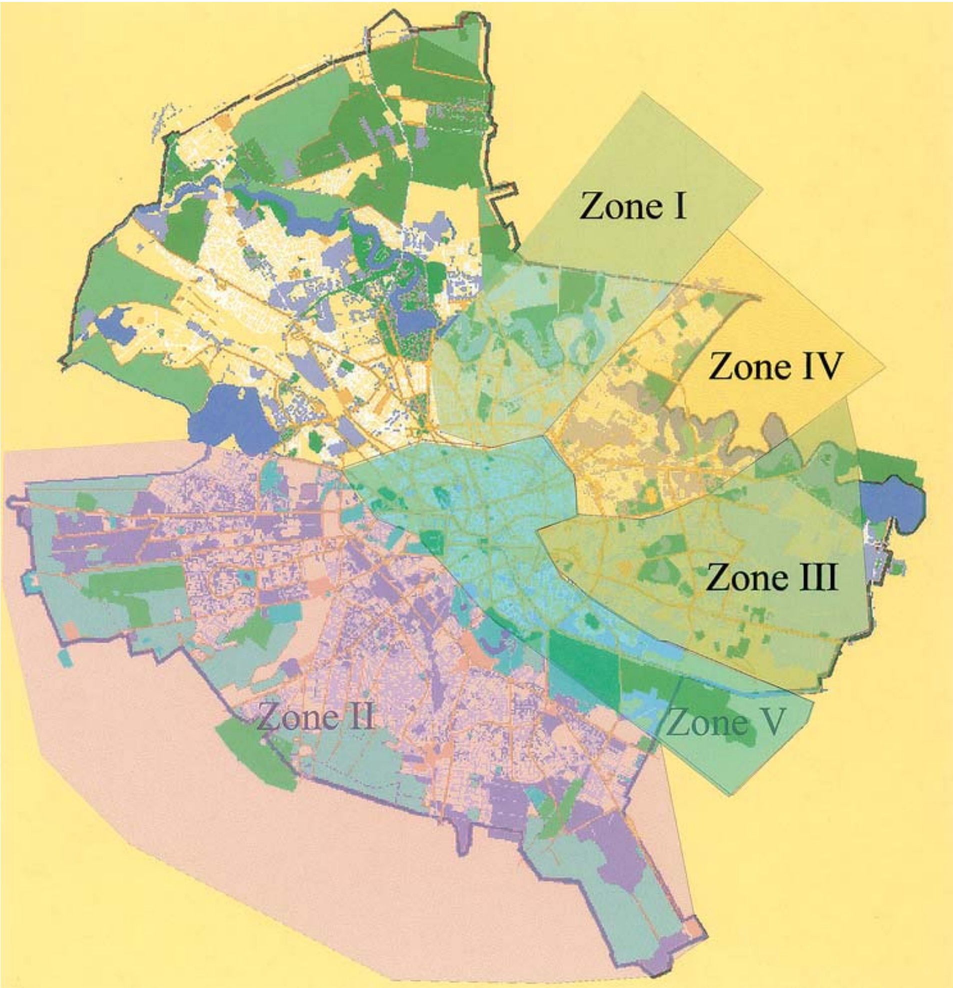

Figure 11
Preliminary seismic zonation map of the city.

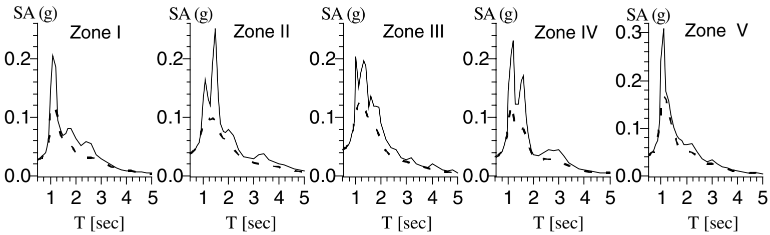

Figure 12
Acceleration response spectra (0% damping—solid line; 5% damping—dashed line) representative of the five zones shown in Figure 11.

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