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and
International Atomic Energy Agency

THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

STABILITY OF LOCAL SOIL EFFECTS IN BUCHAREST

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Abstract

The Vrancea region seismicity, characterised by focal depths larger than 60 km and strong events with magnitudes $M_w \geq 6.9$, is responsible for the most destructive effects experienced in the Romanian territory and may seriously affect high risk constructions located on a wide area, from Central to Eastern Europe. This seismogenic volume has to be taken into account both for seismic hazard analysis at regional level (southeastern Europe) and national level (Romania and Bulgaria), as well as for microzonation studies of the highly populated cities in the range of influence of this source. Since about four destructive earthquakes occur every century in Vrancea, the microzonation of Bucharest, exposed to the potential damages due to these strong intermediate-depth shocks, is an essential step toward the mitigation of the local seismic risk. Two main approaches can be considered for the evaluation of the local seismic hazard: (a) collection and extended use, for engineering purposes, of the recorded strong motion data, and (b) advanced modelling techniques that allow us the computation of a realistic seismic input, which can compensate the lack of strong motion records, actually available only for a few events which occurred in the last 20-30 years.

Using a ground motion simulation technique that combines modal summation and finite differences, we analyze, along a geologic profile representative of the Bucharest area, the differences in the expected ground motion when two source mechanisms, typical for the Vrancea seismogenic zone, are considered. 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 computed. The details of the local effects vary with varying the earthquake scenario, even if the maximum values of the quantities considered for evaluating the local effects are stable when the two representative Vrancea fault plane solutions are considered.
1. Introduction

Bucharest, the capital of Romania, is strongly affected by the Vrancea strong intermediate-depth events, and the presence of more than 2 million inhabitants, together with a remarkable number of high seismic risk vulnerable buildings and infrastructures, makes the microzonation of the city a goal of main importance. During this century, the major events \( (M_w \geq 6.5) \) originating in Vrancea occurred in: 1904 - \( M_w = 6.6 \), 1908 - \( M_w = 7.1 \), 1912 - \( M_w = 6.7 \), 1940 - \( M_w = 6.5 \), 1940 - \( M_w = 7.7 \), 1945 - \( M_w = 6.8 \), 1945 - \( M_w = 6.5 \), 1977 - \( M_w = 7.4 \), 1986 - \( M_w = 7.1 \), and 1990 - \( M_w = 6.9 \), (ONCESCU et al., 1998).

Two approaches can be followed for the evaluation of the seismic input, for engineering purposes, at a given site: (1) the collection and processing of the strong motion records obtained by means of a dense seismic network, and (2) the use of advanced modelling techniques for the computation of realistic seismic ground motion. The ideal situation is represented by the possibility to follow both ways and to calibrate modelling with the available recordings. In practice, strong motion data are very scarce and correspond to events which occurred in the last 20-30 years. Exploiting the accumulated information about seismic sources, sampled medium and local soil conditions, together with realistic ground motion simulation techniques, it is now possible to estimate for microzonation purposes the local behavior of a given site. Whenever possible, the complementary use of the two approaches should be followed because of (1) the high installation and operation cost of a dense permanent seismic network, and (2) the necessity to calibrate with observations the synthetic signals obtained using the geological and geotechnical knowledge accumulated for the investigated region.

Bucharest area represents a typical case where the complementary use of modelling and data processing may allow us to obtain quite useful predictions of the expected ground motion, since only a few strong motion records of the last 3 strong Vrancea events are available. For microzonation purposes, MOLDOVEANU & PANZA (1998), making use of a simplified geotechnical profile, both for the regional and local structures, compute the seismic ground motion (SH and P-SV waves) along a representative profile in Bucharest, considering as a scenario earthquake the strong Vrancea event of May 30, 1990 (\( M_w = 6.9 \)). They use a hybrid method modelling that successfully combines the 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) in order to describe the propagation of the seismic wavefield generated by a given seismic source in a complex geological structure. Although relative simple source and structural models are considered, the computed
accelerograms are in good agreement with the records of Magurele station (44.347°N, 26.030°E) located on the local profile considered, in the southern part of the city, and with the observed local site effects in Bucharest. In the present paper we analyze the stability of the local site effects when changing the scenario earthquake.

2. Brief description of Vrancea region and of the structural model considered

Vrancea region, localized in the rectangle delimited by latitude 45°-46°N and longitude 26°-27°E, beneath the bending of Eastern Carpathian Arc, is characterized by a very well confined and persistent subcrustal seismic activity. In this seismogenic source originate about 10-15 events per month (2.5<M<5.5), and three to five strong events (M_w~7.0) per century. The volume in which the intermediate-depth earthquakes are localized is a parallelepiped about 100 km long, 40 km wide, with a vertical extension from 50-60 km to 160-170 km depth. The subcrustal seismic activity concentrates within an epicentral area of about 3000 km^2, NE-SW oriented, that partly overlaps the epicentral area of the crustal events (RADULIAN et al., 1996). In the depth range from about 40 km to about 60 km, a gap is observed between the crustal and subcrustal seismic activity. The five major earthquakes (M_o>10^13 N.m, M_w>6.9) that occurred in Vrancea (in 1908, 1940, 1977, 1986 and 1990) during this century (ONCESCU et al., 1998) caused large damage and many casualties, not only in Romania, but also in other parts of Europe. Several models have been proposed to explain the main aspects of the tectonic processes in Vrancea, briefly summarized in KUZNETZOV et al. (1998), but the driving mechanism of the intermediate-depth seismicity of this region is not yet completely understood.

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. The same mechanism is observed for more than 90% 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 mainly oriented on a: (1) NE-SW direction, with the P-axis perpendicular to the Carpathian mountain arc (e.g. the March 4, 1977 event, M_w=7.4, the August 30, 1986 event, M_w=7.1, the May 30, 1990 event, M_w=6.9); and (2) NW-SE direction, with the P-axis parallel to the Carpathian mountain arc (e.g. the May 31, 1990 event, M_w=6.4).

The ground motion in Bucharest area is simulated (MOLDOVEANU & PANZA, 1998) considering an averaged regional bedrock model for Vrancea-Bucharest path, and a local, laterally varying,
anelastic model. The bedrock structure is compiled after RADULIAN et al. (1996) considering: (a) for the crust the velocity model used for the event location with the Romanian telemetered observatories, and (b) for the deeper structure, a low-velocity channel from 90 to 190 km with standard Q values. Below the depth of 250 km, an average continental model is adopted. To investigate the influence of Vs and Q variations within reasonable limits, four variants of the bedrock structure have been considered. Vs changes affect significantly only arrival times of the signals, and Q variations do not produce relevant changes in the simulated waveforms. The laterally varying, anelastic sedimentary formation of Bucharest, consists of alluvium, loess like, gravel, sand, clay and sandy marl, and corresponds to a NE 20° SW oriented cross section of the city. The presence of unconsolidated sediments (deep soft soils) with irregular geotechnical characteristics and distribution in space for the Bucharest area was detected by the Geological Prospecting Enterprise during the prospecting work made for the construction of the Bucharest subway. In this framework, more than 2000 bore-holes were analyzed, and the seismic wave velocity was measured by seismic refraction in more than 200 points. We use the synthesis of these results given by MANDRESCU and RADULIAN (1998). The quality factors, Qp and Qs, are evaluated from empirical correlations with geology, and from similar data published in the literature.

3. Ground Motion Modelling

The local effects are analyzed by considering the ground motion representative parameters: (1) peak ground acceleration (PGA), (2) peak ground velocity (PGV), (3) relative peak ground acceleration (PGA(2D)/PGA(1D)), (4) relative standard Fourier transform (FT(2D)/FT(1D)), (5) relative energy (W(2D)/W(1D)), (6) relative spectral amplification (Sa(2D)/Sa(1D)), and (7) response spectra Sa.

The modelling performed by MOLDOVEANU & PANZA (1998) provides results that are in good agreement with the recorded data and local effect observations. In addition, the peak ground acceleration to peak ground velocity ratios, PGA/PGV, given in Table 1, both for the synthetic and the observed signals (Magurele station, low pass filtered with a cut-off frequency of 1 Hz) are in a 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 by SEED & IDRIS (1982).
Table 1

PGA/PGV ratios corresponding to the three components - radial, vertical and transversal - of the observed and simulated signals for Magurele station (MOLDOVEANU & PANZA, 1998).

For the deep soft soils the globally available data indicate the PGA/PGV=5±2.6 (s^-1).

<table>
<thead>
<tr>
<th></th>
<th>R</th>
<th>V</th>
<th>T</th>
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<tbody>
<tr>
<td>Magurele - observed</td>
<td>3.1</td>
<td>3.9</td>
<td>3.4</td>
</tr>
<tr>
<td>Magurele - synthetic</td>
<td>2.9</td>
<td>4.6</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Starting from the results obtained by MOLDOVEANU & PANZA (1998) and using, along the same path, the bedrock structure and the laterally varying local structure for Bucharest area, already adopted by them, we consider an earthquake scenario (from now on event B) that differs from the one of May 30, 1990 (from now on event A) only in the azimuth of the fault plane, that we choose close to the one of the May 31, 1990 (M_w=6.4) event, as given in the CMT catalogue (DZIEWONSKI et al., 1991).

3.1. Influence of soil conditions on ground motion characteristics

The main characteristics of seismic ground motion, at any site, are the cumulative result of a number of factors including: (1) magnitude of the earthquake, (2) distance of the site from the source of energy release, (3) geologic characteristics of the rocks along the wave transmission path from source to site, (4) source mechanism of the earthquake, (5) finiteness of fault rupturing, and (6) local site conditions. The influence of some of these factors is better understood than others. To provide an adequate degree of safety, at an affordable cost, requires a high level of expertise in earthquake engineering and this, in turn, implies an extensive knowledge about the properties of strong earthquakes, the influence of soil conditions on ground motions, and the dynamics of structures that are moved by ground shaking.

3.2. Seismic input simulations

Considering the two different earthquake scenarios A and B, we simulate both acceleration and velocity time series for an array of 35 equally spaced (at 0.6 km) sites located along the profile of Bucharest, already considered by MOLDOVEANU & PANZA (1998). The ground motion is computed for
a seismic moment $M_o = 3 \cdot 10^{19}$ N·m, in the frequency range from 0.005 to 1.0 Hz. In Figure 1 we show, for a subset of seven sites (the distance between two successive sites is 1.8 km), accelerations (Figure 1 a and b) and velocities (Figure 1 c and d) corresponding to sources A and B, respectively. The epicentral distances of the first and the last site in Figure 1 are 173.5 and 183.5 km, respectively. The sixth trace from the top corresponds to the epicentral distance of 181.7 km and represents the Magurele station location. The comparison of the two sets of signals shows that the radial component (R) is the most sensible component of motion to the source parameter variation, the change from source A to source B strongly affecting the shape of the signal that becomes much longer. The vertical component (V) is relevantly affected by the change of focal mechanism in the maximum amplitudes that increase by a factor of 2 for source B in comparison to source A (PGA and PGV, respectively), while the simulated waveforms do not change significantly. The transversal component (T) is quite stable, both in the peak amplitudes as well in the waveform shape, with the change of the source mechanism.

Typical ground motion related quantities, used in seismic engineering, are the peak ground acceleration (PGA), the peak ground velocity (PGV), and the quantity $W$ defined as:

$$ W = \lim_{\rho \to \infty} \left[ t \int [x(t)dt]^2 dt \right]$$

where $x(t)$ is the time series describing the ground displacement. Since the ground motion modelling technique we use considers the complete wavefield, that contains all the main body- and surface-wave phases, both for SH- and P-SV motion, the synthetic signals can be processed as the observed time series. It is therefore convenient to consider the ratios PGA(2D)/PGA(1D) and W(2D)/W(1D), i.e., the relative PGA and W, where 2D indicates the computations for the laterally varying model, while 1D represents the computations for the bedrock model. The spatial variation along the local profile of Bucharest of the relative values PGA(2D)/PGA(1D) and W(2D)/W(1D) that we obtain considering source A and source B, respectively, are shown in Figure 2 (a, b). The main changes in the spatial distribution of the relative PGA and W are observed in the radial (R) and vertical (V) components of motion, while the transversal (T) component is very stable with varying mechanism.

Similar stability analysis can be performed in the frequency domain considering the 0% damping relative response spectra, i.e., the ratio between the response spectra for the laterally varying model, $S_a(2D)$, and the response spectra for the bedrock model, $S_a(1D)$, and the spectral ratio, i.e., the ratio between the Fourier transform of the signals computed for the laterally varying model, $F_T(2D)$, and for the bedrock, $F_T(1D)$. The Fourier spectra of the signals are smoothed with a frequency window.
of 0.025 Hz, both at the sites in the laterally heterogeneous model and in the reference bedrock model. Figure 3 (a, b) shows these relative quantities corresponding to a site located in the central part of the city, at an epicentral distance of 176.1 km, considering the two scenario earthquakes, A and B. As we could expect from Figure 2, the behavior of the relative response (Sa(2D)/Sa(1D)) and relative Fourier (FT(2D)/FT(1D)) spectra varies significantly for the R and V components, while the T component is quite stable.

The position of the peaks is different for the different components, and changes for the radial (R) and vertical (V) components, with the source parameters considered, A and B. The large excitation of the radial component (2.5 times for source A and 3.8 times for source B) for the frequency around 0.35 Hz, is not seen in the vertical component that, in the case of source A, has mainly four peaks of relative values greater than 2.0 for the frequencies around 0.53, 0.65, 0.75 and 0.95 Hz, and mainly three peaks of relative values greater than 2.0 for the frequencies around 0.5, 0.75 and 0.9 Hz, in the case of source B. The transverse component has two peaks of relative values, around 0.42 and 0.9 Hz, greater than 2.5 for source A, and greater than 2.25 for source B, respectively. The resonance frequency of the sedimentary layers might explain these spectral amplifications at the considered site. For example, the peak around 0.4 Hz can be due to the resonance of the upper 400 m, while the peak of 0.9 Hz can be due to the resonance of the uppermost 270m. The maximum values of the quantities describing the ground motion are given in Table 2, for each of the three components and for both scenario earthquakes.

From a simultaneous analysis of Table 2 and Figures 2 and 3 we can observe that: (1) the local response along the profile is sensible to the seismic source, the most affected being the radial (R) and the vertical (V) components, (2) the maximum values of the relative PGA and PGV change by no more than one unit, as well as the spectral quantities, (3) the computed local effect, expressed as the ratios PGA/PGV, is in very good agreement with the values reported for the deep soft soils (DECANINI & MOLLAIOLI, personal communication, 1998; SEED & IDRIS, 1982).

For engineering purposes, very much used is the response spectrum, Sa, computed for different critical damping values. In Figure 4 (a, b) we show these response spectra for the three components of the motion, computed for the critical damping of 5% and 10%, respectively, and corresponding both to the accelerograms recorded at Magurele station for the May 30, 1990 Vrancea event, as well as for the two different sets of simulated signals (source A and B). Even if a simplified source process (a double-couple model) is considered in the simulations, the synthetic signals reproduce most of the main features of the observations, that is relevant for seismic engineering, as can be seen from Figure 4. The fit between the response spectra of the observed (low-pass filtered with a cut-off frequency of 1.0 Hz) accelerograms (continuous line in Figure 4) and the simulated ones for the May 30, 1990 Vrancea
earthquake scenario – source A (dotted curves in Figure 4).

Table 2

Maximum values obtained along the profile in Bucharest (W, PGA and PGA/PGV), and spectral values (Sa and FT) corresponding to a site located in the center of the city, at an epicentral distance of 176.1km

<table>
<thead>
<tr>
<th>component</th>
<th>R</th>
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<th>V</th>
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<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>W(2D)/W(1D)</td>
<td>2.7</td>
<td>2.5</td>
<td>6.0</td>
<td>7.0</td>
<td>7.9</td>
<td>8.2</td>
</tr>
<tr>
<td>PGA(2D)/PGA(1D)</td>
<td>1.3</td>
<td>1.5</td>
<td>2.3</td>
<td>2.3</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Sa(2D)/Sa(1D)</td>
<td>2.6</td>
<td>3.9</td>
<td>3.5</td>
<td>3.2</td>
<td>5.5</td>
<td>5.3</td>
</tr>
<tr>
<td>FT(2D)/FT(1D)</td>
<td>2.7</td>
<td>4.6</td>
<td>4.2</td>
<td>4.2</td>
<td>5.0</td>
<td>5.5</td>
</tr>
<tr>
<td>PGA/PGV</td>
<td>3.3</td>
<td>3.9</td>
<td>4.8</td>
<td>4.8</td>
<td>4.7</td>
<td>4.7</td>
</tr>
</tbody>
</table>

4. Conclusions

The mapping of the seismic ground motion due to the earthquakes originating in a given seismogenic zone can be made by measuring seismic signals with a dense set of recording instruments when a strong earthquake occurs or/and by computing theoretical signals, using the available information about tectonic and geological/geotechnical properties of the medium, where seismic waves propagate. Strong earthquakes are very rare phenomena and this makes very difficult (practically impossible in the near future) the preparation of a sufficiently large database of recorded strong motion signals that could be analyzed in order to define generally valid ground parameters, to be used in seismic hazard estimations.

While waiting for the increment of the strong motion data set, a very useful approach to perform immediate microzonation is the development and use of modelling tools based, on one hand, on the theoretical knowledge of the physics of the seismic source and of wave propagation and, on the other hand, exploiting the rich database about the geotechnical, geological, tectonic, seismotectonic, historical information already available.
Using a double-couple source approximation and relatively simple path (bedrock) and local structure models, MOLDOVEANU & PANZA (1998) succeeded in reproducing, for periods greater than 1 second, the recorded ground motion in Bucharest, at a very satisfactory level for seismic engineering.

Parametric tests, that represent a major advantage of the numerical simulations, a powerful and economically valid tool for seismic microzonation, have been performed considering the two fault plane solutions representative of the major Vrancea intermediate-depth earthquakes. These tests indicate that the site effects are relatively stable with changing focal mechanism. Although the strongest site effect is observed in the transversal component (T), the radial (R) and vertical (V) components are the most sensible to source mechanism variations of the earthquake scenario.

Acknowledgements

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**Figure captions**

**Figure 1 a.** Acceleration time series computed for a set of 7 successive receivers spaced by 1.8 km; source A; R - radial component, V - vertical component, T - transversal component; seismic moment $M_o=3.0 \times 10^{19}$ N·m; frequency range 0.005-1.0 Hz. The epicentral distances for the first and the last trace are 173.5 and 183.5 km, respectively. The sixth trace from the top corresponds to Magurele station location.

**Figure 1 b.** Acceleration time series computed for a set of 7 successive receivers spaced by 1.8 km; source B; R - radial component, V - vertical component, T - transversal component; seismic moment $M_o=3.0 \times 10^{19}$ N·m; frequency range 0.005-1.0 Hz. The epicentral distances for the first and the last trace are 173.5 and 183.5 km, respectively. The sixth trace from the top corresponds to Magurele station location.

**Figure 1 c.** Velocity time series computed for a set of 7 successive receivers spaced by 1.8 km; source A; R - radial component, V - vertical component, T - transversal component; seismic moment $M_o=3.0 \times 10^{19}$ N·m; frequency range 0.005-1.0 Hz. The epicentral distances for the first and the last trace are 173.5 and 183.5 km, respectively. The sixth trace from the top corresponds to Magurele station location.

**Figure 1 d.** Velocity time series computed for a set of 7 successive receivers spaced by 1.8 km; source A; R - radial component, V - vertical component, T - transversal component; seismic moment $M_o=3.0 \times 10^{19}$ N·m; frequency range 0.005-1.0 Hz. The epicentral distances for the first and the last trace are 173.5 and 183.5 km, respectively. The sixth trace from the top corresponds to Magurele station location.

**Figure 2 a.** Source A - Spatial distribution of the PGA (PGA(2D)/PGA(1D)) - continuous line, and $W$ (W(2D)/W(1D)) - dotted line, relative values for the R, V, T components of motion along the cross-section of Bucharest considered in the computations; 2D stands for the local sedimentary structure, while 1D stands for the bedrock structure.

**Figure 2 b.** Source B - Spatial distribution of the PGA (PGA(2D)/PGA(1D)) - continuous line, and $W$ (W(2D)/W(1D)) - dotted line, relative values for the R, V, T components of motion along...
the cross-section of Bucharest considered in the computations; 2D stands for the local sedimentary structure, while 1D stands for the bedrock structure.

**Figure 3 a.** Source A - Relative response spectra $\frac{S_a(2D)}{S_a(1D)}$ for 0% damping - continuous line, and spectral ratio $\frac{F_T(2D)}{F_T(1D)}$ for 0.025 Hz smoothing - dotted line, obtained for a receiver located in the center of Bucharest, at the epicentral distance 176.1 km; R, V, and T are the components of motion.

**Figure 3 b.** Source B - Relative response spectra $\frac{S_a(2D)}{S_a(1D)}$ for 0% damping - continuous line, and spectral ratio $\frac{F_T(2D)}{F_T(1D)}$ for 0.025 Hz smoothing - dotted line, for a receiver located in the center of Bucharest, at the epicentral distance 176.1 km; R, V, and T are the components of motion.

**Figure 4a.** Response spectra ($S_a$) for 5% damping, corresponding to the epicentral distance of 181.7 km for both May 30, 1990 Vrancea event, accelerograms recorded at Magurele station - continuous line, and for the synthetic signals corresponding to source A - dotted line, and to source B - long dashed line. R, V, and T are the three ground motion components.

**Figure 4b.** Response spectra ($S_a$) for 10% damping, corresponding to the epicentral distance of 181.7 km for both May 30, 1990 Vrancea event, accelerograms recorded at Magurele station - continuous line, and for the synthetic signals corresponding to source A - dotted line, and to source B - long dashed line. R, V, and T are the three ground motion components.
Figure 2 a
Figure 2 b
Figure 3a
Figure 3 b
Figure 4 a
Figure 4 b