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Microzonation of Bucharest: State-of-the-Art

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Abstract—The 1940 ($M_w = 7.7$) and 1977 ($M_w = 7.4$) Vrancea earthquakes (Romania) inflicted heavy damage and casualties in Bucharest and the statistics indicate a recurrence interval of 25 years for $M_w \geq 7.0$ events. Under these circumstances, the seismic microzonation represents important information for detailed urban planning that establishes an appropriate level of preparedness to the earthquake threat. This paper reviews the main studies concerning the seismicity of the Vrancea region, the site conditions of the city, the characterization of the building stock, and the codes of practice that regulate the antiseismic design. The first-order microzonation of Bucharest was performed starting from the existing database of structural and geotechnical parameters. New insights originating from direct instrumental observation and interpretation of the local effects as well as realistic numerical modeling that update and improve the input data necessary for a detailed microzoning map of the city are also discussed.

Key words: Bucharest, Vrancea earthquake, damage, microzonation, antiseismic code.

1. Introduction

The strong intermediate-depth earthquakes of the Vrancea region have caused a high toll of casualties and extensive damage over the last several centuries in the Romanian territory. The occurrence of these earthquakes is irregular, but they are not infrequent. Statistics based on historical records (Oncescu *et al.*, 1999) indicate that about three destructive subcrustal earthquakes per century occur in Vrancea. They can produce peak ground displacement of about 30 cm and peak acceleration on the order of about 30% of the gravity acceleration, 0.3 g (Radulian *et al.*, 2000a).

Bucharest is the most populated and most important city of Romania (Fig. 1), the principal political, administrative, economic, financial, banking, educational,

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Figure 1
Geographical map of Romania. Topography, main rivers, provinces and some towns for reference are shown.

scientific and cultural center of the country. The city is located in S-SE Romania, at an altitude of 60–90 m, at 44°25′50″ latitude north and 26°06′50″ longitude west.

Romania's capital is the major city in the Balcanic area exposed to the significant hazard produced by strong Vrancea earthquakes. The metropolitan area is characterized by the presence of 2 million inhabitants (on 01.01.1998), accounting for 9% of the total population of the country and for 15% of the urban total. In terms of population size, Bucharest ranks third in the region after Athens and Istanbul. The downtown area is about 230 km^2 and among its main features are the presence of a considerable number of high-risk structures and infrastructures, and geological settings consisting of deep sedimentary deposits.

Historical data show that during past centuries Bucharest suffered repeatedly important damage due to strong Vrancea earthquakes (RADU, 1979; PURCARU, 1979). Within the last 28 years the city was threatened by two events with moment magnitudes $M_w > 7.0$ (1977 and 1986). The strongest one, recorded in 1977 ($M_w = 7.4$), claimed more than 1,500 lives, the majority of them in the capital where the inflicted destruction was the heaviest observed in modern times. The studies published to date indicate that the alluvium/sedimentary layer in Bucharest amplifies, to a varying extent, the site response to seismic waves in the period range 0.1 to 1.2 s, a critical period range for many elements of the built environment (e.g., LUNGU *et al.*, 1994). Under these circumstances it is urgent that the decision-makers (e.g., city planners, civil engineers, and civil defense) should establish an appropriate level of preparedness for the earthquake threat. To accomplish this complex target, the information regarding the local seismic hazard evaluation of the Bucharest area represents a key element to be taken into account. The modifications of the ground motion parameters, due to the influence of the near-surface layers (seismic microzonation), must be integrated with the design parameters for the soil-structure interaction (aseismic design). The first seismic microzonation of Bucharest was performed after the strong 1940 Vrancea event ($M_w = 7.7$) by GHICA (1953), and since then this problem has become a permanent topic of geological and engineering investigations, through various approaches and methods. Due to the complex character of the subject, on one hand, and to the new numerical/modeling methods and computational/information progress, on the other hand, the study of the seismic site effects in Bucharest develops and improves continuously.

This paper presents the state-of-the-art of the microzonation study of Bucharest together with the seismicity of the Vrancea region and the legislation addressing antiseismic codes.

2. Vrancea Region Seismicity

The seismic regime of the national territory is characterized by a moderate to high earthquake activity with both shallow and intermediate-depth events (Fig. 2). The Romanian catalogue covers a relatively extended time interval and its completeness thresholds are: from 1411 to 1800 for $M_w \geq 7.0$, from 1801 to 1900 for $M_w \geq 6.5$, from 1901 to 1935 for $M_w \geq 5.5$, from 1936 to 1977 for $M_w \geq 4.5$, and from 1978 up to the present for $M_w \geq 3.0$ (ONCESCU *et al.*, 1999). Vrancea is the main seismogenic zone of Romania and exhibits the following remarkable features:

(a) highly restricted hypocentral area within 45°–46°N latitude and 26°–27°E longitude, at the SE corner of the strongly bent Carpathian arc;
(b) shallow seismic activity — located mainly in the lower crust ($h > 15$ km) with small to moderate magnitudes; $M_L = 5.3$ (1914) is the strongest crustal event ever recorded;
(c) subcrustal seismicity, very well clustered in a focal volume confined between 60 and 180 km of depth, represents the major feature of Vrancea region; the persistent rate of occurrence amounts to 12–15 events monthly ($M_L \geq 3$); the corresponding epicentral area is limited to a rectangle of about 30 × 70 km^2 NE-SW oriented that partly overlaps the epicentral area of the crustal events (RADULIAN *et al.*, 2000b); maximum ground displacements up to 30 cm and peak

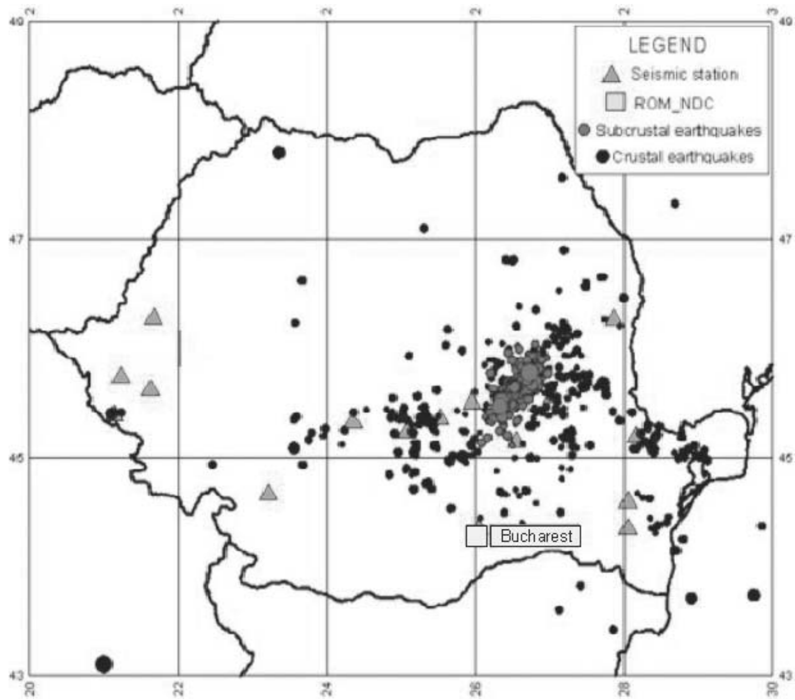

Figure 2
Romanian seismicity map. Crustal and subcrustal earthquakes are shown for the time interval 1995–2000.

accelerations on the order of 0.3 g were recorded in the area situated eastward and southward of the Carpathians arc (RADULIAN *et al.*, 2000a);

(d) the recurrence times estimated from the available catalogues are: 10 years for $M_w \geq 6.5$, 25 years for $M_w \geq 7.0$ and 50 years for $M_w \geq 7.4$ (WENZEL *et al.*, 1999);

(e) the large earthquakes (instrumentally recorded) show a remarkably similar fault plane solution that typically has strike SW-NE (220°), dip 60° to 70° to the NW, and slip roughly 80° to 90° (RADULIAN *et al.*, 2000b, WENZEL *et al.*, 1999); the stress regime is clearly compressive; despite the similarity of the fault plane solutions, significant variations of the radiation pattern are noticeable, which reflect the dynamics of the rupture process (ONCESCU and BONJER, 1997);

(f) the total seismic moment released by the last four strong events (1940, 1977, 1986 and 1990) is similar to a maximum possible Vrancea source of magnitude $M_w = 8.0$ which means an average amount of seismic moment released of 8×10^{20} Nm/yr (WENZEL *et al.*, 1999); according to ONCESCU and BONJER (1997) the sum amounts to 7.5×10^{20} Nm for a period of about 100 years;

(g) the depth interval between 110 and 130 km is considered to be a candidate for the next strong Vrancea event since this remained unruptured during at least the last 150 years (ONCESCU and BONJER, 1997).

Several geophysical models based either on subduction processes or on slide break-off and necking have been proposed to explain the amazingly confined Vrancea subcrustal seismicity (e.g., FUCHS *et al.*, 1978; ONCESCU, 1984; TAVERA, 1991; GIRBACEA, and FRISH, 1998). Additional physical insight originates from estimates of the deformation rate in the source volume, recent tomographic results and models of stress distribution within a passive slab (WENZEL *et al.*, 1999).

3. Bucharest Local Site Conditions

The synthesis of the geological data available was first presented by LITEANU (1951) and then by others, e.g., MANDRESCU and RADULIAN (1999), LUNGU *et al.* (1999a).

Bucharest city (Fig. 3) is situated in the Romanian Plain, along the roughly parallel valleys of the Dambovita and Colentina rivers. Structurally the downtown is located in the central part of the Moesian Platform, at an average epicentral distance of 160 km from the Vrancea region. Topographically the city is built on a plane slightly dipping southeast, following the direction of the Dambovita and Colentina rivers, which divide the city into several morphological units: Bucharest Plain (Dambovita – Colentina interstream), Baneasa-Pantelimon Plain, Cotroceni-Vacaresti Plain, and the meadows along the abovementioned rivers. The hydrostatic level ranges between 1 and 5 m in Dambovita and Colentina meadows, between 5 and 10 m in the Dambovita – Colentina interstream, and below 10 m in the Cotroceni – Vacaresti and Baneasa – Pantelimon plains.

The foundation ground in Bucharest is represented exclusively by Quaternary deposits. The large amount of geological, geotechnical and hydrological data (the geotechnical bore-holes alone exceed 10,000) provided by Proiect Bucuresti Institute, the S.C. Prospectiuni S.A., Metrou S.A., and others, allow us to separate different Quaternary deposits according to their genesis and lithological composition. In this framework more than 2,000 boreholes were analyzed, and the seismic wave velocity was measured by seismic refraction in about 200 points. These data have been synthesized by MANDRESCU and RADULIAN (1999) and are shown in Figure 4. Four main classes of deposits are identified:

(1) *alluvial-proluvial deposits* (*loesslike deposits*) which contain clay and sandy yellow dust, with loess dolls; the structure of these deposits is macroporous and very compressible in a saturated state and their thickness ranges between 10 to 16 m in the Cotroceni-Vacaresti Plain and between 3 to 6 m in the Dambovita — Colentina interstream, respectively;

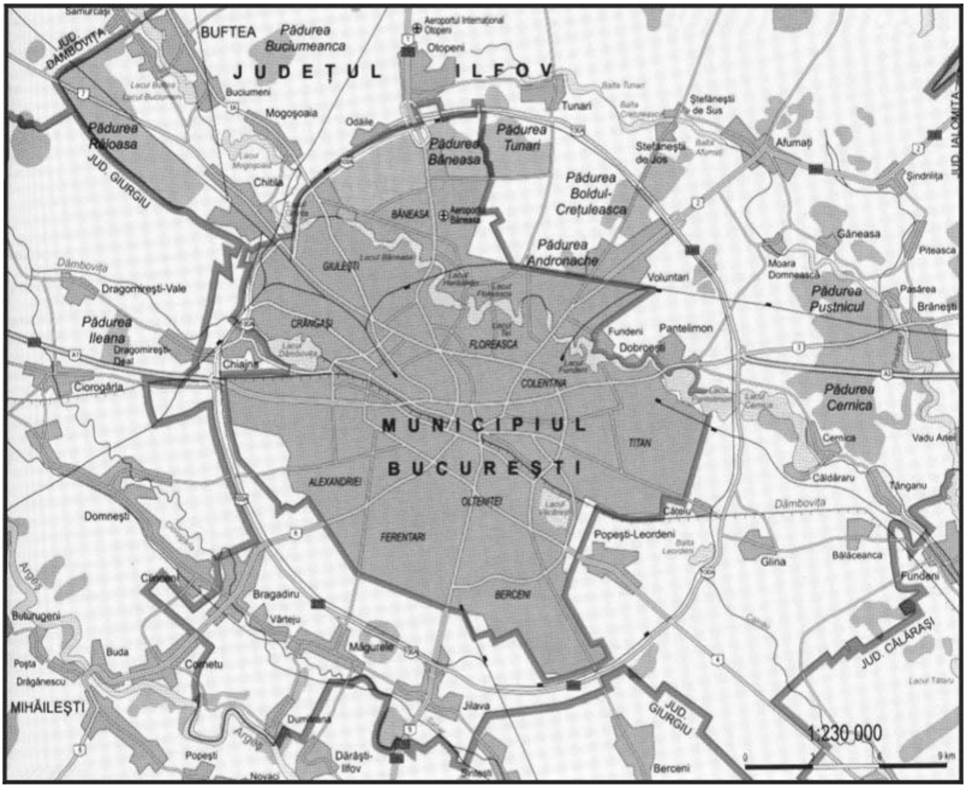

Figure 3
Bucharest city (Municipiul Bucuresti) map.

(2) *diluvial deposits* represented by loesslike and clay deposits with slightly macroporous structure; they overlay a most of the Dambovita terraces; an increase of the clay content is noticed as compared with the loesslike deposits in the plains;
(3) *alluvial deposits* consisting of clays, dusty and sandy clays and mud; the predominant clay character at surface changes in depth, the clay content diminishes in comparison with sand; these deposits are found in Dambovita and Colentina meadows;
(4) *artificial fills* that largely stand in the Dambovita – Colentina interstream.

4. Seismic Damage Inflicted on Bucharest by Strong Vrancea Earthquakes

The city dates from the 14th century and is recorded for the first time in 1459 as the residence of Prince Vlad Tepes. It was the capital of Wallachia in the 17–19th centuries, subsequently of Romania since 1862. The effects of the strong Vrancea

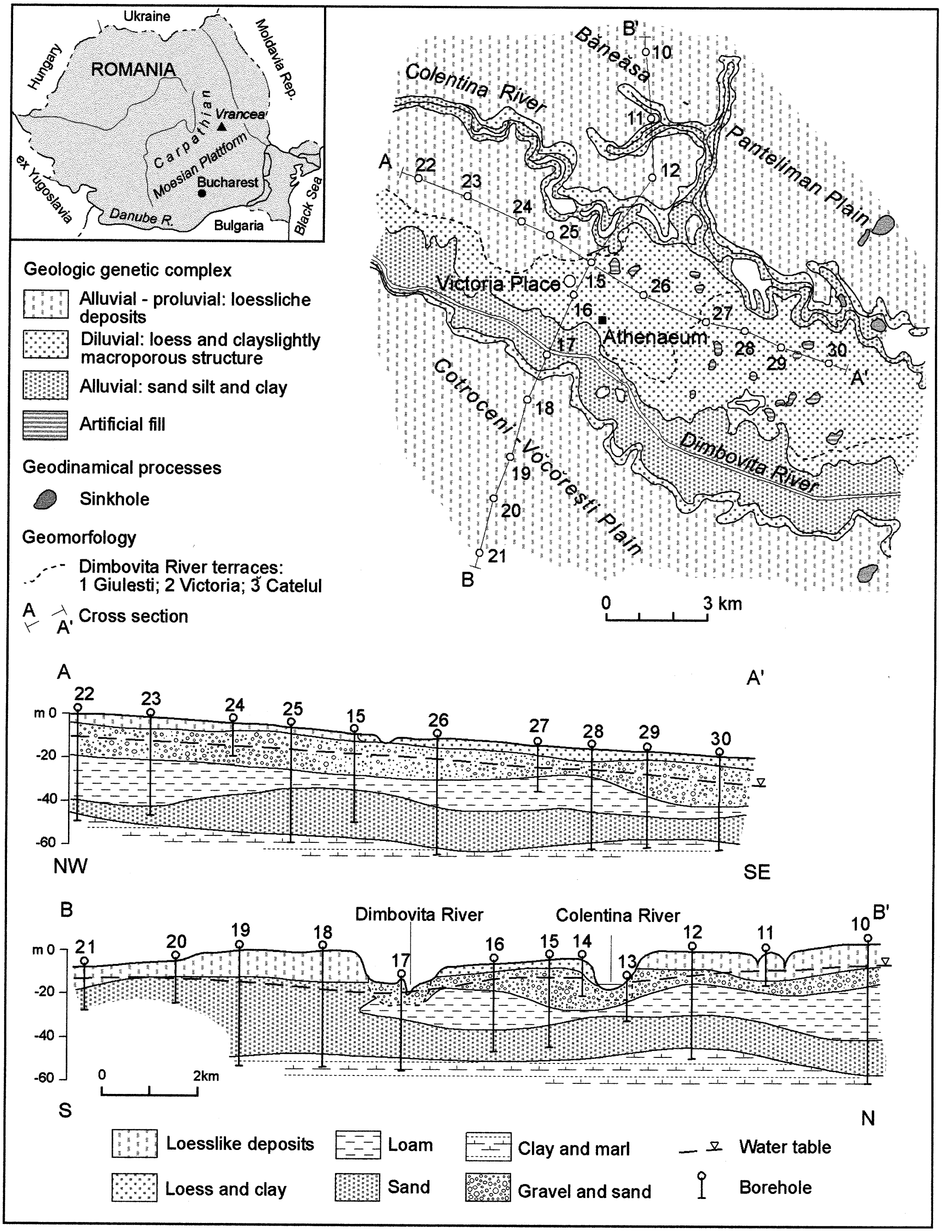

Figure 4
Engineering geological map of Bucharest (MANDRESCU and RADULIAN, 1999).

earthquakes in Bucharest were first documented in the 17th century. The first report describes the $M_w = 7.1$ Vrancea event that occurred on August 19, 1681 (STEFANESCU, 1901). According to the contemporary account, "the Earth shook so strongly that nobody had ever related.'' The next strong event hit the town on June 11, 1738 ($M_w = 7.7$) and destroyed the walls and the tower of the Prince's Court in Bucharest; many houses and churches were damaged, and a ''deep fracture'' opened near the town. The strongest historically recorded event ($M_w = 7.9$) occurred on October 26, 1802, and accordingly was described by contemporaries as the ''big earthquake''. During this earthquake all the church towers in Bucharest cawed in, and many churches and houses collapsed. Another major earthquake occurred on January 11, 1838 ($M_w = 7.5$) and caused the collapse of five churches and extensive damage to fifty other churches and several hundred houses.

During the last century the city was affected by two highly destructive earthquakes: November 10, 1940 ($M_w = 7.7$, $h = 150$ km), and March 4, 1977 ($M_w = 7.4$, $h = 94$ km). The seismic effects inflicted on Bucharest by the 1940 earthquake are summarized as follows: 167 people lost their lives; many buildings, some of them with reinforced-concrete frames, suffered severe damage; a new 13-storey reinforced concrete structure (Carlton Hotel), sited in the central zone of the city, collapsed. The damage was scattered both in terms of district distribution and damage degree (MANDRESCU and RADULIAN, 1999). Consequently, the Romanian authorities decided for the first time to introduce rules for antiseismic building design. These recommendations were mostly ignored and buildings were cosmetically repaired. The consequences were catastrophic during the next major earthquake in 1977, which produced the most destructive effects ever recorded in modern times in Bucharest. 1,424 people were killed, 32 buildings of 8-12 storeys collapsed, 150 long-standing buildings of 6-9 storeys were heavily damaged (many of them were subsequently demolished). These buildings were located in the central part of the city and had old, flexible, reinforced concrete frame structures. Their fundamental period ranged from 0.7 to 1.6 s. This range corresponds to the maximum in the acceleration response spectrum obtained for the only reliable accelerogram recorded in Bucharest during that earthquake (AMBRASEYS, 1977; MANDRESCU, 1978). The rigid structures of similar height (e.g., large panel precast concrete structures, cast-in-place reinforced concrete shear wall structures, as well as masonry dwellings of 1–3 storeys) have fundamental periods from 0.2 to 0.7 s, and therefore suffered relatively slight seismic damage. The evaluation of the damage distribution in Bucharest was performed by analyzing the status of the building stock. By direct inspection 2,429 buildings were grouped into three classes: A — 1,293 masonry buildings, B — 739 reinforced concrete frame structures, and C — 397 large panel precast concrete structures and cast-in-place reinforced concrete shear-wall structures (MANDRESCU, 1978). The building response to the seismic input was evaluated in a scale from 0 to 5. Figure 5 presents the territorial damage distribution for the buildings of A and B classes, expressed in terms of MSK-64 intensity (MANDRESCU and RADULIAN, 1999). The largest values of the damage degree were concentrated in the central zone of the city. The C class buildings, mainly sited in the new residential districts, did not suffer significant damage. The damage degree of a sample of about 18,000 buildings was

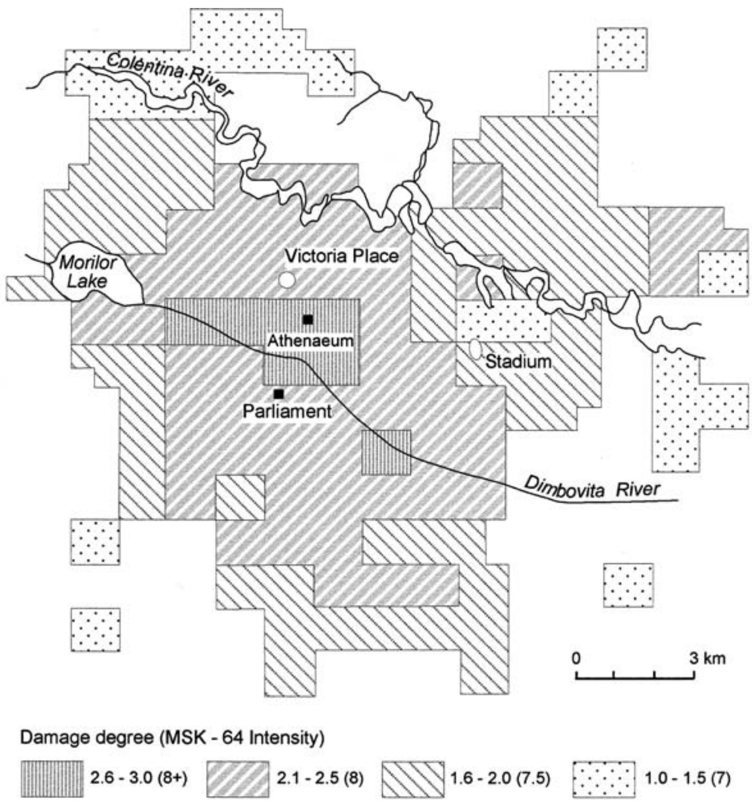

Figure 5
The 1977 earthquake: damage distribution in Bucharest corresponding to masonry buildings and reinforced concrete frame structures (Mandrescu and Radulian, 1999).

evaluated in terms of MSK-64 intensity. According to their fundamental period (empirically estimated) these structures can be grouped into three classes: 0.00–0.15 s, 0.15–0.25 s, and 0.70–1.00 s. The results are shown in Figure 6 (Mandrescu and Radulian, 1999), and reveal the concentration of the maximum effects in the central part of the city and the tendency of the damage degree to increase with the increase of the fundamental period of the structure (Sandi and Pelea, 1982).

5. Dominant Periods of the Site Effects in Bucharest from Noise Measurements

The spectral method demonstrates a clear peak in the H/V- ratios (horizontal and vertical amplitudes of the seismic recordings) that correlates with the fundamental resonance period of the site, in particular in a soft soil environment (e.g., Bard, 1995). The thickness of the alluvial sediments in Bucharest supposedly varies between

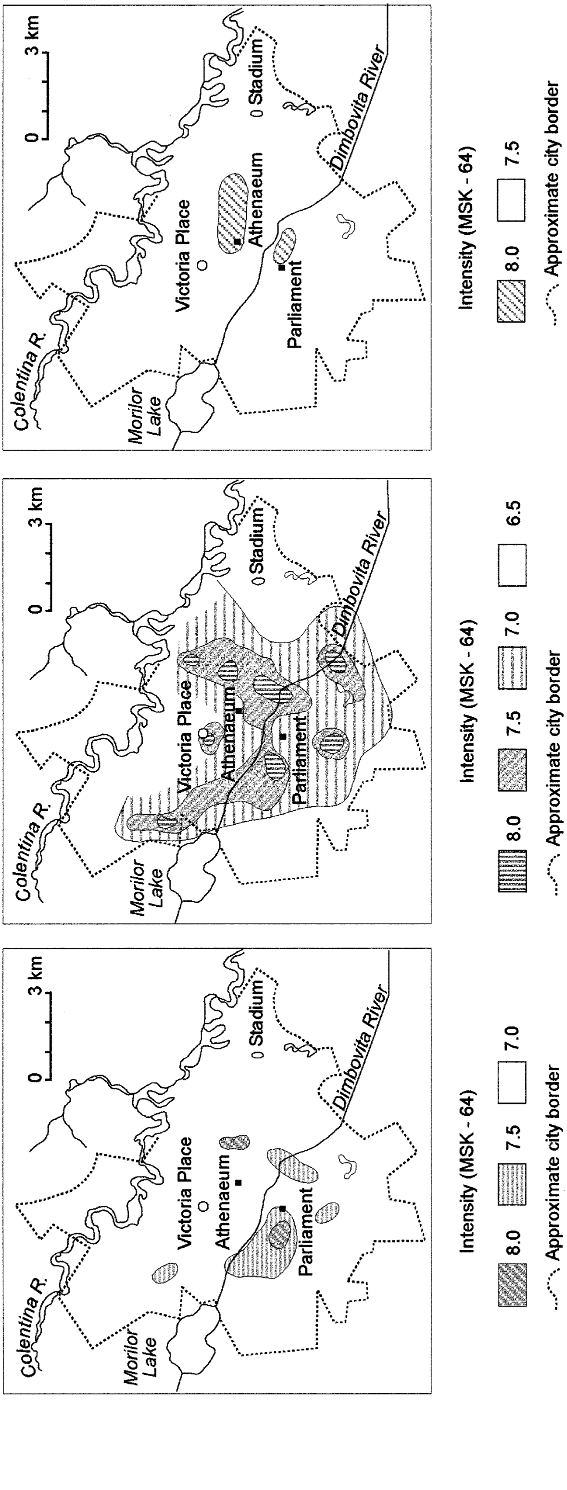

Figure 6

The macro-intensity MSK-64 distribution in Bucharest for the March 4, 1977 earthquake for the following different period ranges: (a) 0.00–0.15 s, (b) 0.15–0.25 s, 0.25–1.00 s (MANDRESCU and RADULIAN, 1999).

100 and 200 m. In order to examine the local soil resonance several experimental studies were carried out in the Romanian capital.

SANDI and PELEA (1982) performed the first systematic measurements of ambient seismic noise in the central part of Bucharest, on a local profile EW-oriented. In the sampled area the spectral amplification factor is almost constant for periods below 0.15 s, and it increases by about 35% for periods from 0.35 to 0.7 s, mostly in the western sites of the city, close to the Dambovita River.

Another site response experiment was performed by BONJER *et al.* (1999) using the noise ambient measurements as well as the records of small earthquakes. The ambient noise ratios were determined along two profiles that cross each other in downtown Bucharest (a wide city area). This experiment documented the existence of a broad and stable soil resonance in the range of 1 to 2 seconds. The resonance peaks around 1.4 s would correspond to a 120-m thick layer of unconsolidated sediments, with a shear-wave velocity $Vs = 0.35$ km/s (simple horizontal layer resonance interpretation). This is a very important observation since flexible reinforced-concrete frame 6–12-storey buildings are expected to experience a shift of their fundamental resonance towards the range of the strongest site resonance (e.g., AMBRASEYS, 1977; ROJAHN, 1984). This observation is also valid for those buildings that already have been weakened by the 1940 and 1977 earthquakes, as well as by the bombing during World War II, and might have been further weakened by the 1986 and 1990 earthquakes. Under these circumstances, an earthquake similar to the one of 1977, with the same spectral content, would be an enormous threat to the Romanian capital (BONJER *et al.*, 1999).

6. *Seismic Microzonation Maps of Bucharest*

The first seismic zonation of Romanian territory was performed in 1941 (one year after the devastating $Mw = 7.7$ earthquake). Practically no map was prepared, however the country was divided into two regions: a seismic one was represented by the provinces of Moldova (eastern part of the country), Walachia (southern part of the country), and Brasov area (southeastern part of the Transylvania province, inside the Carpathian arc), and a non-seismic one, represented by the rest of the national territory. The evolution of the macroseismic zonation maps of Romania may be inferred from the following documents: (1) *STAS 2923-52* and *STAS 2923-63*, macrozonation of the territory of R.S. Romania, *State Office for Standardization*, *OSS*, Bucharest, 1952 and 1963, (2) *Decree 66/1977*, Romanian Government, 1977, (3) *STAS 11100/1-77*, macrozonation of the territory of R.S. Romania, *Romanian Institute for Standardization*, *IRS*, Bucharest, 1978, (4) *STAS 11100/1-91 and SR 11100/1-93* Macrozonation of the territory of Romania, *Romanian Institute for*

Standardization, *IRS*, Bucharest, 1991 and 1994. The main features of these maps can be summarized as follows (LUNGU *et al.*, 1999b):

(1) absence of the 9th degree intensity zone (Mercalli-Cancani scale) in the epicentral Vrancea region; the 8th degree intensity in Bucharest is surrounded by a 7th degree intensity zone; low seismicity (i.e., the 6th degree intensity) in southeastern Romania (including Cernavoda and half of Dobrogea province, between the Danube River and the Black Sea) (1952 map);
(2) a very small 9th degree intensity zone is identified in the epicentral region; the 8th and 7th degree intensity zones have the same borders like as in the 1952 map; a 7th degree intensity is assigned to the provinces of Transylvania and Dobrogea (1963 map);
(3) the 7th degree intensity zone from the 1963 zonation map is extended towards the SW of Romania (Craiova); inside the 7th degree intensity zone some cities are settled at higher local intensity as follows: Bucharest – 8.0, Iasi – 7.5, Zimnicea – 7.5, Craiova – 7.5; the northeastern part of the Dobrogea province receives the 6th degree intensity (1977 map);
(4) Iasi city is assigned to an 8th degree intensity; the Dobrogea province and the southeastern of the Transylvania province are declared zones of 7th degree intensity (1991 and 1993 maps).

We can observe that all these seismic zoning maps assign to Bucharest city an 8th degree seismic intensity that, on the MSK-64 scale, corresponds to a peak ground acceleration (PGA) of 0.20–0.25 g (LUNGU *et al.*, 1999b).

The seismic microzonation studies of the Romanian capital can be separated into two groups: before and after the strong 1977 Vrancea earthquake. The first studies were carried out by GHICA (1953), CIOCIRDEL *et al.* (1964), and MANDRESCU (1972, 1978). The seismic microzoning maps of Bucharest elaborated before 1977 were based on MEDVEDEV'S method (1962) which considers the influence of the surficial soil and water table level on the building behavior. The city area was divided into three microzones following the main geomorphological units. Even if not identical, these microzones are similar for all the authors. The associated macroseismic intensities were: the 8th degree for Dambovita and Colentina meadows, the 7th – 8th degree for the central part of the city, and the 7th degree for the plains of Cotroceni–Vacaresti, Baneasa–Pantelimon and the largest part of the Dambovita–Colentina interstream. The damage distribution inflicted by the 1977 earthquake is in disagreement with the microzoning maps of Bucharest existing at that time. The criteria based on the acoustic impedance of the foundation ground proved inadequate. This might be because: (a) MEDVEDEV'S method (1962) is defined for source and local conditions (small epicentral distances, shallow earthquakes and thin sedimentary deposits) very different from those that characterize Vrancea events and the Bucharest site (large epicentral distances, intermediate-depth events, and thick sedimentary deposits), (b) the 1977 earthquake had peculiar spectral characteristics, and (c) the vulnerability of the building stock cannot be ignored when drawing the microzoning maps (MANDRESCU and RADULIAN, 1999).

In 1977, after evaluating the earthquake effects, the NCST (Commission for the seismic microzonation of Bucharest) proposed a preliminary microzoning map of Bucharest (Fig. 7). The distribution of the maximum acceleration is concentric with the maximum expected values (0.4 g) in the central part of the city. This pattern is not sustained either by the surficial soil distribution, or by the subsurface geological conditions, and does not fit the PGA values and spectral content of the records in Bucharest and in its environs for the 1986 and 1990 earthquakes (MANDRESCU and RADULIAN, 1999).

The urbanization process in the central part of the city took place mainly in two periods: at the beginning of the last century and between the two World Wars. Simultaneously the number of inhabitants nearly trebled. The buildings constructed in these periods had no earthquake design provisions, and suffered damage during

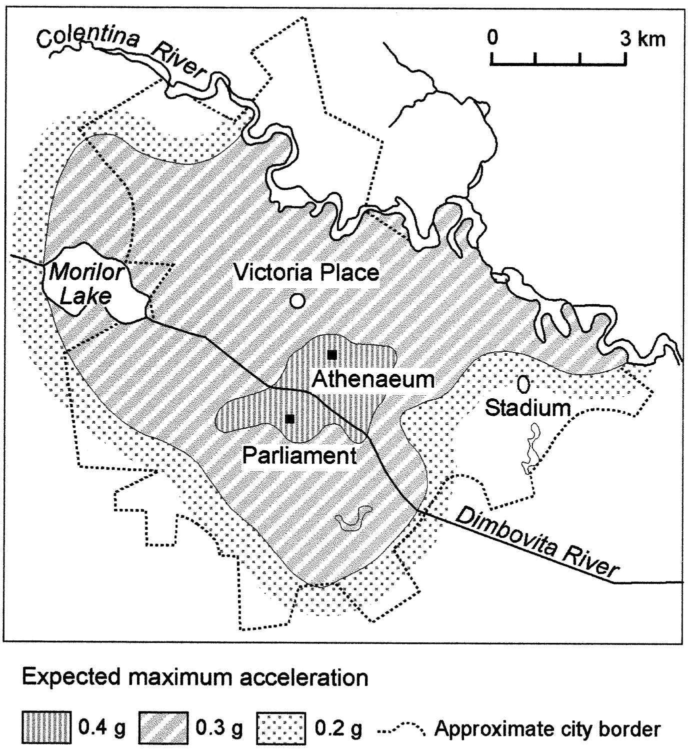

Figure 7
Preliminary seismic microzoning map of Bucharest (NCST REPORT, 1977). The distribution of the maximum acceleration is concentric, with the maximum expected value (0.4 g) in the central part of the city.

the 1940 earthquake and World War II. Moreover, part of these civil constructions successively changed their vocation, which imposed important structural alterations that ignored the original design. For these reasons, MANDRESCU and RADULIAN (1999) stress the importance of mapping the vulnerability distribution for each type of building. Only by comparing these maps with the seismic microzonation and the damage distribution maps, can we better understand the real cause of the earthquake effect pattern.

7. Ground Motion Modeling

In microzoning studies, the mapping of the strong ground motion can rely on either recorded or theoretically computed seismic signals, or both. To use recorded data requires a dense set of instruments to be triggered when a strong earthquake occurs. The preparation of a sufficiently large database of recorded strong motion signals represents a difficult, if not practically impossible task in the near future. While waiting for the increment of the strong ground motion data set, the theoretical computation of the seismic signals (by exploiting the available information concerning the tectonic and geological/geotechnical properties of the propagation medium, the theoretical knowledge of the physics of the source and of the wave propagation) represents a very useful approach to perform immediate mapping of the seismic ground motion for microzonation purposes. Obviously, whenever possible modeling has to be calibrated with the available recordings.

Strong motion recorded accelerograms for the Bucharest area are very scarce and correspond to the last three strong Vrancea events (1977, 1986 and 1990). Nonetheless they represent a database that, integrated by modeling, may permit a realistic estimate of the seismic input, for a given set of earthquake scenarios.

The first studies devoted to the mapping of the seismic ground motion in Bucharest due to the strong Vrancea earthquakes by means of synthetic signals have been carried out by MOLDOVEANU and PANZA (1999, 2001) and MOLDOVEANU *et al.* (2000). The numerical method implied is a complex hybrid waveform modeling (FÄH *et al.*, 1994; PANZA *et al.*, 2001) that combines modal summation (PANZA, 1985; VACCARI *et al.*, 1989; FLORSCH *et al.*, 1991; ROMANELLI *et al.*, 1996) with finite-difference techniques (ALTERMAN and KARAL, 1968; BOORE, 1972; KELLY *et al.*, 1976), and allows us easy parametric tests. The input information necessary for the modeling consists of the source mechanism, the average regional structural model, and the laterally heterogeneous anelastic local structure.

MOLDOVEANU and PANZA (1999) and MOLDOVEANU *et al.* (2000) succeeded in modeling the ground motion in Bucharest for the May 30, 1990, Vrancea event with good accuracy for microzonation purposes. The frequency window considered in the computations extends up to 1 Hz and allows us the modeling of the seismic input appropriate for 10-storey and higher buildings. This is in agreement with the observed predominant period, 1.0–1.5 s, of the ground motion induced by the major Vrancea subcrustal earthquakes in Bucharest. Even if a relatively simple local structure and seismic source have been considered, the matching between records and the computed signals is at a satisfactory level for seismic engineering. The comparison observed-synthetic signals accounts for the shape, peak ground acceleration (PGA), duration, frequency content, and response spectra (Sa) (computed with 5% and 10% of critical damping). By considering the two dominant scenario earthquakes for Vrancea, MOLDOVEANU and PANZA (2001) analyzed the source influence on the local response in order to define generally valid ground motion parameters to be used in the seismic hazard estimations. This was done along an array of equally spaced sites on a profile, NE-SW oriented, which crosses the central part of the city. The source has its own (detectable) contribution to 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 effects affect the T component, both observed and synthetic, a complete determination of the seismic input for the built environment requires the knowledge of all three components of motion (R, V, T).

The numerical modeling performed to date demonstrates that standard convolutive approaches are not reliable and that detailed numerical schemes are required to obtain realistic estimates of the seismic amplification/response due to site effects. These kinds of computations applied for the Bucharest site supply synthetic results consistent with the observations (e.g., MOLDOVEANU *et al.*, 2000; MOLDOVEANU and PANZA, 2001; CIOFLAN *et al.*, this issue).

8. Characterization of Bucharest Building Stock

The evolution of the building stock (construction rate) in Bucharest and in Romania can be divided into three time intervals that are correlated to the economic and political changes at the national level: (a) before 1970 (moderate), (b) from 1970 to 1990 (very high), and (c) after 1990 (low, both for civil and industrial purposes). The building stock in Bucharest was constructed according to the Romanian ruling seismic code that was subjected to modifications (updated) in 1941, 1964, 1971, 1978, 1992 and 1996. Obviously, the seismic risk of a structure strongly depends on its height, design and site location. Table 1 presents the distribution of the tall buildings in Bucharest by period of construction and number of stories, as defined by the data supplied by the 1992 census (LUNGU *et al.*, 1999b).

The dynamic response of a structure is characterized by its fundamental period of vibration. During recent decades the building construction in Romania was generally based on standard projects. Table 2 presents the fixed-base period (i.e., the period of the structure without the fill-in walls) of the various types of standard structures in

Table 1

Distribution of tall buildings censored in 1992 in Bucharest, grouped by period of construction and number of stories (LUNGU et al., 1999)

Stories	< 1945	1945 – 1963	1964 – 1970	1971 – 1977	1978 – 1990	1990 – 1992
9	89	104	45	88	1550	21
10	17	77	137	51	177	4
11	63	70	447	830	1063	5
> 11	9	34	7	87	72	1
Total	486	434	657	1091	2970	36

Table 2

Fixed-base period (structure without in-fill walls) and the relative frequency of various building structures in Bucharest reported by the Typified Building Design Institute (IPCT) (LUNGU and CORNEA, 1988)

IPB-code of the structure	Number of stories	Structure type (1)	Period T, s		Estimated number of:	
			Transverse	Longitudinal	Staircases	Apartments
D3g	5	Shear-wall	0.17	0.23	30	600
D3f	5		0.19	0.31	5	100
P4m	5	Prefabricated	0.14	0.16	106	2120
P4r	5	shear-wall	0.14	0.15	18	360
P4o	5		0.13	0.15	78	1560
P6b	9		0.30	0.39	225	7000
P11f	9	Shear-wall	0.36	0.44	66	2400
P11e	9		0.44	0.50	99	3200
D13b	9		0.51	0.60	22	800
D13b	11		0.65	0.83	27	1200
D11d	11		0.37	0.58	21	660
G	9	Shear-wall	0.36		–	4000

[1] Including the ground floor Total: 24000 apt.

Bucharest, according to the data of the Romanian Institute for Building Design (IPCT) (LUNGU and CORNEA, 1988). The fixed-base period is larger than the actual period of the building and the post-earthquake period exceed the pre-earthquake period.

The main structural types of buildings used in Romania are designed for a peak ground acceleration (PGA) that corresponds to the 7^{th} or the 8^{th} degree on the MSK-64 macroseismic intensity scale. Table 3 presents the fundamental period, both longitudinal and transversal, of the main structural types used in Romania, constructed before 1990. The maximum MSK design intensity considered and the number of structure storeys are also indicated. The buildings are grouped according to the IPCT code of the structure (LUNGU and CORNEA, 1988).

Table 3

Fundamental period (longitudinal and transversal) of the main structural types used in Romania, according to the data of the Typified Building Design Institute (IPCT). The maximum MSK intensity considered, the number of stories and the IPCT code of the structure are also reported. (Lungu and Cornea, 1988)

IPCT – code of structure	MSK seismic Intensity	Number of stories (1)	Type of structure	Period T, s	
				Longit.	Transv.
No. 770	7	5	Prefabricated shear-wall	0.13	0.15
No. 1402	8	9	(dense walls)	0.38	0.33
				0.44	0.37
				0.44	0.30
No.1340	7	5	Prefabricated shear-wall (rare walls)	0.15	0.15
No.1403	7	5	Shear-wall,	0.22	0.20
			With prefabricated slabs	0.19	0.20
No.1406	7	9		0.67	0.62
No.1421	7	5	Dual structure	0.26	0.23
No.1422	8	5	(frame and shear-wall)	0.21	0.21
No.1426	8	9		0.56	0.38
No.1377/a	8	5	Frame	0.54	0.46
				0.53	0.47
				0.50	0.49
No.1410	7	9	Frame	0.90	0.82
No.1378/a	7	9	Frame	0.86	0.75
				0.92	0.90
				0.90	0.88
No. –	7.5	5	Frame,	0.47	0.45
			With shear-walled columns	0.45	0.45
				0.44	0.43
				0.42	0.46
No. –	7.5	9	Frame,	0.68	0.70
			With shear-wall columns	0.72	0.70
				0.70	0.69
				0.65	0.63
No.1376	7	3	Columns and	0.57	0.55
No.1376	7	4	flat slabs	0.47	0.48

[1] Including ground floor.

9. *Romanian Code of Practice and Eurocode*

The national code for the antiseismic design of the buildings is represented by the Romanian Code of Practice (P100). This code was revised in 1992 and 1996 and it includes the latest experience and concepts in seismic design. The European prestandard in the field is represented by Eurocode 8 (EC8) which was published in 1998. Both P100 and EC8 are based on the capacity design procedure. They provide the rules for the modification of seismic action effects in order to direct the potential plastic hinge at the base of the walls and to avoid brittle fracture in shear. The elastic response spectra considered in the framework of the two distinctive codes are presented in Figure 8.

The regulations of the codes EC8 and P100 are similar, still in practice they imply different design requirements for the same structure. For illustrating them, PASCU and MUNTEANU (1999a) considered the case of a regular multistory frame structure and accomplished a comparison of the structural design and detailing provisions included in EC8 and P100, respectively. The major differences between the two structures are: (1) the base shear force value is 20% larger in P100 than in EC8; (2) the interstorey drift limit is 230% more restrictive for the P100 designed frames in comparison to those of the EC8; (3) the more severe interstorey drift limitation and the larger base shear force value require the cross-sectional area of the members of the P100 structure to be up to 200% larger than the homologue EC8-designed; (4) the P100-designed beams require larger (by about 10–25%) flexural reinforcing ratios than EC8-designed ones; (5) the EC8 shear reinforcing ratios are larger by 10–30% than those of the P100; (6) the EC8-designed columns have larger (by 20–40%) reinforcing ratios than the homologue P100-designed; (7) the EC8 shear reinforcement ratios of the columns become up to 300% larger than those of the corresponding P100.

According to the regulations from *STAS 11100/1-91* and *SR 11100/1-93*, the present zonation map of the Romanian territory assigns to Bucharest area an 8th degree of intensity (MSK). The past seismic design practice required the increase by at least one degree of intensity for any essential facility in the city, i.e., buildings and

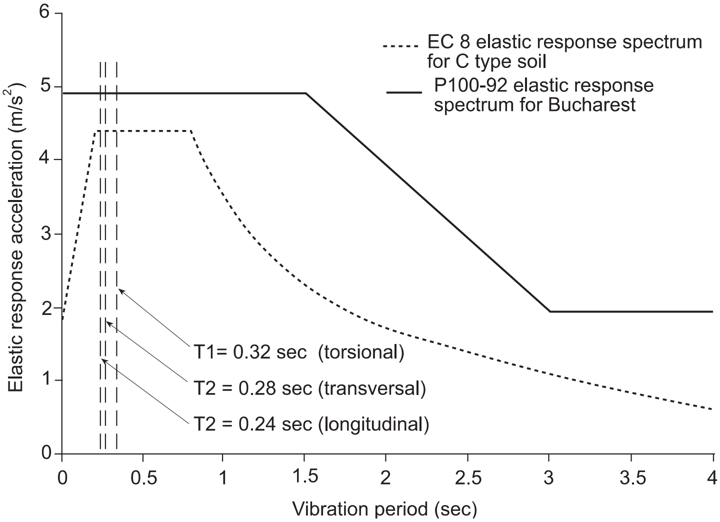

Figure 8
Elastic design spectra considered by EC8 and P100.

structures that are intended to remain operational in case of an extreme intensity earthquake (LUNGU *et al.*, 1999b). The requirement of a 9th degree intensity in Bucharest corresponds to a PGA of 0.32 g (MSK-64 macroseismic intensity converted into PGA).

10. Conclusion

The important destruction and the large number of victims experienced in Bucharest during the extreme 1940 and 1977 Vrancea earthquakes require vigorous investigations to reduce life and economic losses. The assessment and mitigation of earthquake risk are particularly important in the Romanian capital since major investments and vital lifeline systems are concentrated in this seismically dangerous area. Therefore, the next large Vrancea earthquake will inflict serious economic and social consequences, unless comprehensive action is timely taken.

The earthquake effects on the ground surface are defined by the seismic zoning and microzoning, and by the antiseismic design parameters, respectively. Generally speaking, a detailed urban planning rests on the proper knowledge of: (1) regional geology and tectonics, (2) regional seismicity and earthquake catalogues, (3) seismic ground motion and zoning, (4) faulting and permanent ground deformations, and (5) engineering aspects of disastrous earthquakes. The investigations of the major previous events supply the information regarding (a) the damage distribution on different structural types, and (b) the social and economic implications of earthquakes in the region. This allows us the evaluation of the adequacy between the existing building codes and regulations, on one side, and the geological regional and local site conditions, on the other side.

The seismic zonation of Romania and a first-order microzonation of Bucharest have been performed using the existing database on structural and geotechnical parameters. The available information is still not satisfactory for a detailed assessment of the site effects in the entire Romanian territory. The new studies concerning direct instrumental observation and interpretation of the local effects on the soft soil environment in the city, on one hand, and the realistic numerical modeling which considers the contribution of the source, travel path and local site condition, tested against the recorded seismograms, on the other hand, update and improve the database necessary for a detailed microzoning map of Bucharest. The microzoning map proposed by NCST after the evaluation of the effects inflicted on Bucharest by the March 4, 1977 ($M_w = 7.4$) Vrancea event, and expressed in terms of expected accelerations, displays a concentric distribution with the maximum value of 0.4 g localized in the central part of the metropolitan area (Fig. 7). The geological subsoil condition and the instrumental observations of the 1986 ($M_w = 7.2$) and 1990 ($M_w = 6.9$) Vrancea earthquakes do not correlate with this distribution. CIOFLAN *et al.* (this issue) propose an improvement of the microzoning map of the capital. The city area is divided into five zones (Fig. 9) on the basis of: (a) the local lithological data, (b) the epicentral distance variations not larger than 3 km, and (c) the recorded seismograms available for both 1986 and 1990 events. No zone is indicated for the northwestern part of the city since no instrumental recorded signals are available here. The numerical simulations (in the frequency range 0.05–1.0 Hz) have been extended to all regions of the city where similar geological structures are present. Each zone is assigned the representative response spectra that, together with the recorded and/or simulated seismograms, give a more adequate evaluation of the seismic site response than those expressed exclusively in terms of expected PGA. Even if the NCST (1977) and the Cioflan *et al.* (this issue) maps are expressed in terms of different parameters used by civil engineering, the main observation is that the concentric distribution of

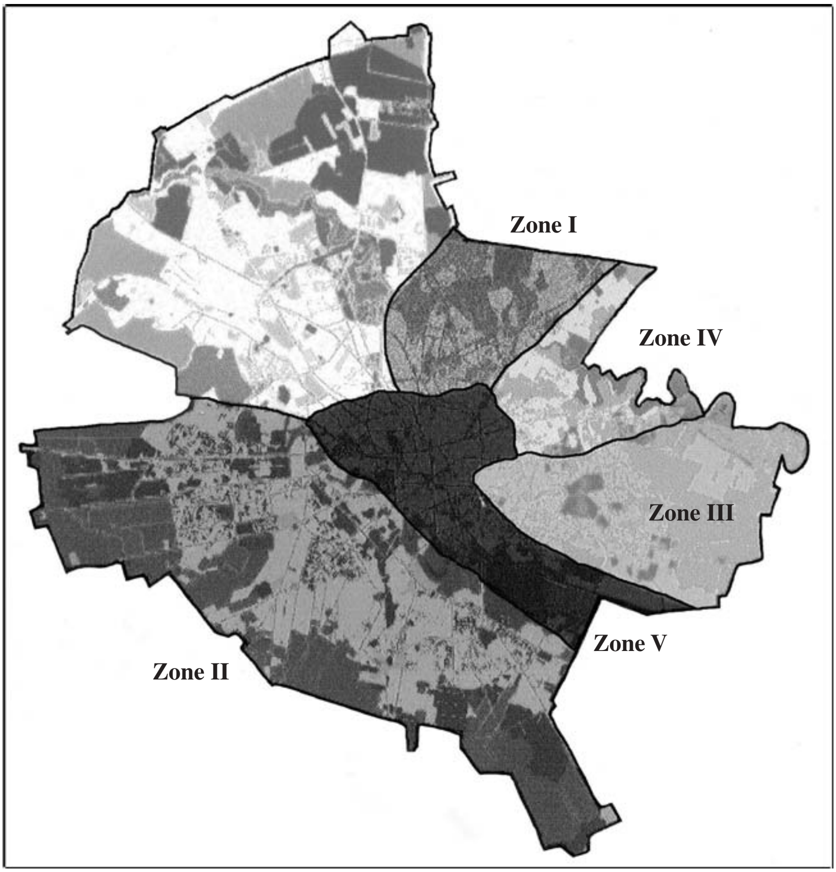

Figure 9
Preliminary zoning map of Bucharest (Cioflan *et al.*, this issue). The five zones have been defined on the basis of: (a) the local lithological data, (b) the epicentral distance variations no larger than 3 km, and (c) the recorded seismograms available for both the 1986 and 1990 events.

the expected local effects visible in the NCST (1977) map and not consistent with the available observations is not present on the map shown in Figure 9.

The Romanian P100 seismic code includes the latest experience and concepts in seismic design and its regulations have important similarities to the EC8. Damage to the built environment caused by earthquakes is known to depend both on the ground motion characteristics (amplitude, frequency distribution and shaking duration) and on the characteristics of engineering structures (resonance period of the structures in relation to subsoil local transfer function). Of course, the existing building infrastructure must be retrofitted with advanced knowledge, materials, and technologies related to the peculiarities of the Romanian building stock.

Future efforts in Romania, as elsewhere, must be focused on developing increasingly reliable microzonation maps for earthquake ground shaking in all urban areas where the seismic risk is moderate and high. These studies should be focused on: (a) the compilation of the available topographical, geological, geotechnical data in the form of maps (1:10,000 – 1:25,000 scale) and a GIS database, (b) the collection of seismic records (e.g., strong motion and seismic noise) using a dense network of instruments deployed in the target area, (c) the application of the numerical techniques for the modeling of the seismic ground motion, and (d) the evaluation of the building stock vulnerability taking into account the advanced knowledge, materials, technologies and peculiarities of the Romanian conditions.

The optimal exploitation of the realistic estimation of the site effects, based on the scenario-like modeling approaches used to predict the seismic strong motion and limited to technical problems is certainly not a simple task. In fact, the results of the microzoning are used by end users, such as local authorities, city planners, land-use specialists and civil engineers, whose background is very different and for whom the recommendations must be clear and sound.

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References

Alterman, Z. S. and Karal, F. C. (1968), *Propagation of Elastic Waves in Layered Media by Finite Difference Methods*, Bull. Seismol. Soc. Am. *58*, 367–398.

AMBRASEYS, N. N. (1977), *Long-period Effects in the Romanian Earthquake of March 1977*, Nature *268*, 324–325.

BARD, P. Y., *Effects of Surface Geology on Ground Motion: Recent Results and Remaining Issues*. In *Proc. 10th European Conf. Earthquake Engineering* (ed. Duma, G.) (A.A.Balkema, Rotterdam 1995) pp. 305–323.

BONJER, K-P., ONCESCU, M.-C., DRIAD, L., and RIZESCU, M., *A Note on Empirical Site Response in Bucharest, Romania*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation*, (eds. Wenzel, F., Lungu, D., and Novak, O.) (Kluwer Academic Publ. 1999) pp. 149–162.

BOORE, D. M., *Finite-difference Methods for Seismic Waves Propagation in Heterogeneous Materials*. In *Methods in Computational Physics*, Vol. 11 (ed. Bolt, B.A.) (New York, Academic Press 1972) pp. 1–37.

CIOCIRDEL, R., TITARU, E., and CISMIGIU, A. (1964), *Seismic Microzoning of Bucharest City*, Arh. IGP, Bucharest (in Romanian).

CIOFLAN, C. O., APOSTOL, B., MOLDOVEANU, C. L., PANZA, G. F., and MARMUREANU, G. (2004), *Deterministic Approach for the Seismic Microzonation of Bucharest*, Pure Appl. Geophys. 161, Nos. 5/6, 2004.

FÄH, D., SUHADOLC, P., MUELLER, St., and PANZA, G. F. (1994), *A Hybrid Method for the Estimation of the Ground Motion in Sedimentary Basins: Quantitative Modelling for Mexico City*, Bull. Seismol. Soc. Am. *84* (2), 383–399.

FLORSCH, N., FÄH, D., SUHADOLC, P., and Panza, G. F. (1991), *Complete Synthetic Seismograms for High-frequency Multimode SH Waves*, Pure Appl. Geophys. *136*, 529–560.

FUCHS, K., BONJER, K. P., BOCK, G., RADU, C., ENESCU, D., JIANU, D., NOURESCU, A., MERKLER, G., MOLDOVEANU, T., and Tudorache, G. (1978), *The Romanian Earthquake of March 4, 1977. II. Aftershocks and Migration of Seismic Activity*, Tectonophysics *53*, 225–247.

GHICA, S. (1953), *Geologic Microzonation of Bucharest City*, Arh. Deo. Geol., MMPG, Bucharest (in Romanian).

GIRBACEA, R. and FRISH, W. (1998), *Slab in the Wrong Place: Lower Lithospheric Mantle Delamination in the Last Stage of the Eastern Carpathian Subduction Retreat*, Geology *26*, 611–614.

KELLY, K. R., WARD, R. W., TREITEL, S., and ALFORD, R. M., (1976), *Synthetic Seismograms: A Finite-difference Approach*, Geophysics *41*, 2–27.

LITEANU, G. (1951), *Geology of the City of Bucharest*, Technical Studies, Serie E, Hydrogeology *1* (in Romanian).

LUNGU, D. and CORNEA, T. (1988), *Ground Motion Parameters for the Design of Earthquake Resistent Structures in the City of Bucharest*, Institute Proiect-Bucharest (in Romanian).

LUNGU, D. M., SCHERER, R. J., ZSOHAR, M., and COMAN, O. (1994) *On the Phenomenon of Long Periods of Ground Vibration During the 1990, 1986 and 1977 Earthquake Records from Vrancea Source*. In *Earthquake Resistance Construction and Design* 1 (eds. Savidis, S. A., Balkema, A. A.) (Rotterdam 1994) pp. 51–59.

LUNGU, D., ALDEA, A., MOLDOVEANU, T.,CIUGUDEAN, V., and STEFANICA, M. (1999a), *Near-surface Geology and Dynamic Properties of Soil Layers in Bucharest*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999a) pp. 137–148.

LUNGU, D., DEMETRIU, S., and ARION, C. (1999b), *Seismic Vulnerability of Buildings Exposed to Vrancea Earthquakes in Romania*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999) pp. 215–224.

MANDRESCU, N. (1972), *Experimental Researchs on Seismic Microzoning*, St. Cerc. Geol. Geogr. Geofiz. *10*(2), 103–116 (in Romanian).

MANDRESCU, N. (1978), *The Vrancea Earthquake of March 4, 1977 and the Seismic Microzoning of Bucharest*. In *Proc. Int. Conf. Microzonation*, vol. 1 (San Francisco 1978), pp. 339–411.

MANDRESCU, N., and RADULIAN, M. (1999), *Seismic Microzoning of Bucharest (Romania): A Critical Review*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999) pp. 109–122.

MEDVEDEV, S. V. (1962), *Seismic Engineering*, Moscow.

MOLDOVEANU, C. L. and PANZA, G. F. (1999), *Modelling for Microzonation Purposes of the Seismic Ground Motion in Bucharest, Due to the Vrancea Earthquake of May 30, 1990*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999) pp. 85–97.

Moldoveanu, C. L., and Marmureanu, G., Panza, G. F., and Vaccari, F. (2000), *Estimation of Site Effects in Bucharest Caused by the May 30–31, 1990, Vrancea seismic Events*, Pure Appl. Geophys. *157*, 249–267.

Moldoveanu, C. L., and Panza, G. F. (2001), *Vrancea Source Influence on Local Seismic Response in Bucharest*, Pure Appl. Geophys. *158*, 2407–2429.

Oncescu, M. C. (1984), *Deep Structure of Vrancea Region, Romania, Inferred from the Simultaneous Inversion for Hypocenters and 3-D Velocity Structure*, Ann. Geophys. *2*, 23–28.

Oncescu, M. C. and Bonjer, K. P. (1997), *A Note on the Depth Recurrence and Strain Release of Large Vrancea Earthquakes*, Tectonophysics *272*, 291–302.

Oncescu, M. C., Marza, V. I., Rizescu, M., and Popa, M. (1999), *The Romanian Earthquake Catalogue Between 984–1996*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999) pp. 43–48.

Panza, G. F. (1985), *Synthetic Seismograms: The Rayleigh Waves Modal Summation*, J. Geophys. *58*, 125–145.

Panza, G. F., Romanelli, F., and Vaccari, F. (2001). *Seismic Wave Propagation in Laterally Heterogeneous Anelastic Eedia: Theory and Applications to Seismic Zonation*, Advanced in Geophysics *43*, 1–95.

Pascu, P. and Munteanu, M. (1999a), *Eurocode versus Romanian Seismic Practice. Case Study of an Eight-storey RC Frame Building*, In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999) pp. 233–240.

Purcaru, G. (1979), *The Vrancea, Romania, Earthquake of March 4, 1977 – A Quite Successful Prediction*, Phys. Earth. Planet. Inter. *18*, 274–287.

Radu, C. (1979), *Catalogul cutremurelor puternice produse pe teritoriul Romaniei. Partea I: inainte de 1901; Partea II – 1901 – 1979*, In *Cercetari Seismologice aspra Cutremurului din 4 Martie 1977* (eds. Cornea, I., Radu, C.) (CSEN Centrul de Fisica Pamantului si Seismologie, Bucuresti) pp. 723–752 (in Romanian).

Radulian, M., Vaccari, F., Mandrescu, N., Panza, G. F., and Moldoveanu, C. L. (2000a), *Seismic Hazard for Romania: Deterministic Approach*, Pure Appl. Geophys. *157*, 221–247.

Radulian, M., Mandrescu, N., Panza, G. F., Popescu, E, and Utale, A. (2000b), *Characterization of Seismogenic Zones of Romania*, Pure Appl. Geophys. *157*, 57–77.

Rojahn, N. N. (1984), *The Interrelationship Between the Ground Motion Spectra, Building Period, Number of Storeys and Maximum Interstory Drift: A Basis for Evaluating Earthquake Damage Potential*, In *Critical Aspects of Earthquake Ground Motion and Building Damage Potential* (eds. Rojahn, C., Sharpe, R. L.) (Redwood City 1984) pp. 89–94.

Romanelli, F., Bing, Z., Vaccari, F., and Panza, G. F., (1996), *Analytical Computations of Reflection and Transmission Coupling Coefficients for Love Waves*, Geophys. J. Int. *125*, 132–138.

Sandi, H., and Pelea, V. (1982), *Engineering Study on Ground Motion*, In *Romanian Earthquake of March 4, 1977* (ed. Balan, St.) (Acad. Publ. Houses Bucharest) pp. 137–221 (in Romanian).

Stefanescu, G. (1901), *Earthquakes in Romania in 1391 Time Interval, from 455 until 1878*, An. Acad. Rom. *II*, XXIV (in Romanian).

Tavera, I. (1991), *Etude des mecanismes focaux de gros seismes at seismicite' dans la region de Vrancea-Romania* (*Raport stage DEA de geophysique interne*) (Institut de Physique du Globe, Universite' de Paris).

Vaccari, F., Gregersen, S., Furlan, M., and Panza, G. F. (1989), *Synthetics Seismograms in Laterally Heterogeneous, Aanelastic Media by Modal Summation of the P-SV Waves*, Geophys. J. Int. *99*, 285–295.

Wenzel, F., Lorenz, F. P., Sperner, B., and Oncescu, M. C. (1999) *Seismotectonics of the Romanian Vrancea area*. In *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation* (eds. Wenzel, F., Lungu, D., Novak, O.) (Kluwer Academic Publ. 1999) pp. 15–25.

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