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IC/2004/25

United Nations Educational Scientific and Cultural Organization
and
International Atomic Energy Agency

THE ABDUS SALAM INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS

ESTIMATION OF SITE EFFECTS IN TERMS OF A NEW MICROZONATION MAP OF BUCHAREST

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MIRAMARE – TRIESTE

May 2004

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Abstract

Bucharest city represents the largest urban center (about 2 million inhabitants and 230 km^2 constructed area) located in the Balcanic area periodically subjected to strong subcrustal seismicity conditions originating in the Vrancea region (60-200 km depth), Romania. The statistics indicate a recurrence interval of 25 years for $M_w \geq 7.0$ Vrancea events and a significant earthquake hazard for the city location with a 50% chance for an event of $M_w > 7.6$ every 50 years. The strongest Vrancea events of the last century occurred in 1908 ($M_w=7.1$), 1940 ($M_w=7.7$), 1977 ($M_w=7.4$) and 1986 ($M_w=7.1$) and inflicted heavy damage and casualties in Bucharest. Under these circumstances, the ground motion evaluation for the city area represents an essential step toward the mitigation of the local seismic risk. This paper presents new insights coming 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 Romanian capital. Our results show that the synthetic local hazard distribution we obtain with the deterministic approach supplies a realistic estimation of the seismic input, highly sensitive not only to the local conditions, but also to the source and the path structure parameters. The complex hybrid method we use offers the chance to merge the different specific accumulated information in reasonably well constrained scenarios for a level C realistic microzonation of Bucharest area to be used to mitigate the effects of future strong events originating in the Vrancea region.

1. Introduction

Bucharest is the most populated and most important town of Romania. It is the principal political, administrative, economic, financial, banking, educational, 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.

The Romanian capital, is periodically subjected to the strong subcrustal seismicity originating in the Vrancea region (about 60-180 km depth, epicentral distance some 140-160 km) that is located at the sharp bend of the Southeast Carpathians. Historical data show that during the past centuries Bucharest suffered repeatedly important damage due to these strong earthquakes (e.g. Radu, 1979). The large number of victims and the severe damage experienced by the city during the 1908 (M_w=7.1), 1940 (M_w=7.7, h=150 km) and 1977 (M_w=7.4, h=94 km) Vrancea earthquakes require vigorous investigations to reduce future life and economy losses. The earthquake hazard is significant, with a 50% chance for an event of M_w>7.6 every 50 years (Radulian et al., 2000).

The first order microzonation of the city has been performed using the existing database on structural and geotechnical parameters. The microzoning map proposed by NCST (Commission for the seismic microzonation of Bucharest) 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 0.4g expected in the central part of the metropolitan area. 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. This pattern is neither sustained by the surficial soil distribution, nor by the subsurface geological conditions, and does not fit the PGA values and spectral content of the records in Bucharest and in its neighborhood for the 1986 and 1990 earthquakes (Mandrescu and Radulian, 1999).

This paper presents new insights coming 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 C level microzoning map of the Romanian capital to be used to mitigate the effects of future strong events originating in the Vrancea region.

2. Geological Setting

Bucharest city is located in the central part of the Moesian Subplate (age: Precambrian and Paleozoic) in the Romanian Plain, along the roughly parallel valleys of Dambovita and

Colentina rivers. From a tectonic point of view, the region is relatively stable even if a minor fault (Tg.fierbinti-Urziceni) is crossing the region at about 40km North from Bucharest. The seismic activity of the region is relatively low: about 50 events/century with a medium magnitude $M_w \approx 2.7$, among which a single event of $M_w = 5$ (1967, depth of source ≈42km). The deep geological structure consists of a sequence of Cretaceous and Miocene deposits having the top at about 1000 m of depth and followed by a Pliocene shallow water deposit (~700m thick). The surface geology consists mainly of Quaternary alluvial deposits. Later loess covered these deposits, and rivers carved the present landscape. Seven lithological formations are identified from the surface (Mandrescu,1972): (1) backfill (thickness h up to 3 m); (2) sandy-clay superior deposits (loess and sand, h=3-16 m) from Holocene, and the others from Pleistocene; (3) "Colentina" gravel (gravel and sand, h=2-20 m); (4) intermediate cohesive deposits of lacustral origin (80% clay and some sand, h=0-25 m); (5) "Mostistea" banks of sands (mainly sand, sometimes lenses of clay included, h=10-15m); (6) lacustral deposits from clay and sands (h=10-60 m), and (7) "Fratesti" gravel (gravel and sands separated by clay, h=100-180m).

Strong lateral variations in depth and thickness of these 7 layers can be observed everywhere in 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).

The numerous aquifers present in the underground of the city play an important role in the evaluation of the site effects in Bucharest. There are three main aquifer systems: (1) "Colentina" located about 8 m deep, (2) "Mostistea" situated at about 25-30 m depth, and (3) "Fratesti", the deepest aquifer, consisting of three layers located between 120 and 200 m of depth.

The available soil data indicate that the surface geology in the East side of Bucharest is composed by 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 downtown areas are covered by predominantly clayey soil profiles and exhibit large control periods of the response spectra, with the corner period Tc in the range from 1.1-1.5 s. The Northern part of the city is covered by predominantly sandy soil profiles and exhibits a medium control period of the response spectra that spans the interval Tc = 0.6-1.0 s (Lungu et al., 2000).

3. 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 but 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 (south-eastern part of 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. 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., 1999).

The March 4, 1977, Vrancea earthquake (M_w=7.4, M_o=1.5x10^{20} Nm) represents the most destructive seismic event ever experienced in Bucharest. The seismic microzonation studies of the Romanian capital performed before the strong 1977 earthquake 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) that 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 greatest 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 did prove not adequate. This might be because: (a) the 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 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).

The preliminary microzoning map of Bucharest proposed in 1977 by the NCST Commission after evaluating the earthquake effects displays a maximum acceleration distribution in a concentric pattern with the peak expected values (0.4 g) located in the central part of the city. This pattern is not sustained neither by the surficial soil distribution, nor by the subsurface geological conditions, and does not fit the PGA values and spectral content of the records in Bucharest and in its neighborhood 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 the inhabitants nearly trebled. The buildings constructed in these periods had no earthquake design provisions, and suffered damages during the 1940 earthquake and the 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, we shall be able to better understand the real cause of the earthquake effect pattern.

4. 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 that a dense set of instruments is 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 the 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 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), Moldoveanu et al. (2000), and Cioflan et al. (2003). The numerical method implied is a complex hybrid waveform modeling (Faeh et al., 1994; Panza et al., 2001) that combines modal summation (e.g. Panza, 1985; Vaccari et al., 1989; Romanelli et al., 1996) with finite differences techniques (e.g. Alterman and Karal, 1968; Kelly et al., 1976). The method, that allows us to take into account the source, path and local geological properties, permits to generate very realistic synthetic seismograms and is particularly suitable to perform parametric tests. The input information necessary for the modeling consists of the source mechanism, the average regional structural model (bedrock model), where the source is located, and the laterally heterogeneous anelastic local structure. The modal summation method is adopted in the bedrock model, while the finite difference scheme is used to describe the wave propagation in the local structure.

The realistic synthetic seismograms, tested against the recorded signals, are used in the estimation of the local site amplifications, and form a relevant part of the database necessary for a detailed microzoning of the city.

5. Deterministic Modeling for Seismic Microzonation of Bucharest

The presence of unconsolidated sediments (deep soft soils) with irregular geotechnical characteristics and distribution in space has been detected by different civil construction enterprises (e.g. “Proiect Bucureşti” Institute, S.C. “Prospecțiuni” S.A., “Metrou” S.A.), which have made available a substantial set of geological, geotechnical and hydrogeological data. The synthesis of these data, performed by Mandrescu and Radulian (1999), was used as the basis for the compilation of three cross-sections, all of them NE-SW oriented, in the downtown of Bucharest.

Using these local models Moldoveanu and Panza (1999) and Moldoveanu et al. (2000) reproduced the ground motion in Bucharest for the May 30, 1990, Vrancea event, with a good accuracy for microzonation purposes. The comparison observed-synthetic signals accounts for the shape, peak ground acceleration (PGA), duration, frequency content, and the response spectra (Sa) (computed with 5% and 10% of critical damping). 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, the frequency window considered in the computations is up to 1 Hz. This choice allows us the modeling of the seismic input appropriate for 10-storey and higher buildings, a kind of building particularly common in Bucharest. The source has its own detectable contribution on the ground motion and its effects on the local response in Bucharest are quite stable on the transversal component (T), while the radial (R) and vertical (V) components are sensitive to the scenario earthquake. Although the strongest local 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 the three components of motion (R, V, T).

Cioflan et al. (2003) extended the studies of deterministic computations of the seismic response in Bucharest by considering three new representative local profiles. Two of these cross sections are modeled with horizontal layers of sediments and one, respectively two, low velocity channels for both P- and S-waves. The third cross section uses a more detailed structural model with nine tilted (by about 4%) layers and laterally variations of the velocity due to the presence of water-bearing sediments. The synthetic signals computed using the hybrid method along these local profiles show that the local effects, in terms of PGA, affect mainly the vertical (V) and the transverse (T) components.

For these components the local amplification of PGA ranges from 1.2 to 2.9. The radial (R) component is less affected, the maximum amplification being 2 .

The synthetic signals (analysed against the recorded one for the May 30, 1990 Vrancea earthquake) computed using the hybrid method along these local profiles show that the local effects, in terms of PGA, affect mainly the vertical (V) and the transverse (T) components. For these components the local amplification of PGA ranges from 1.2 to 2.9. The radial (R) component is less affected, the maximum amplification being 2 . The 4% tilt layers model that mimic the geological local structure induces an amplification of the seismic response, especially for the R and T components, with important site effects confined in an area 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 Mw=7.4 (Mandrescu and Radulian, 1999). From the response spectra of the synthetic seismograms, computed for the 1986 and 1990 Vrancea earthquakes in the frequency range up to 1 Hz, it can be concluded that the thickness of the Quaternary and Tertiary sediments strongly affects the seismic ground motion in Bucharest.

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 excite significantly soil layers with low modal frequency. On the other side, the M_w<7 intermediate-depth events do not have such a capability and therefore induce seismic ground motion that maximizes in a higher frequency band (> 1Hz). 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, Mw=7.4), to about 1 second (the absolute maximum is actually reached at about 0.4 seconds, i.e. outside our modeling frequency band) for the smallest one (May 31, 1990, Mw=6.4).

6. Conclusions

The hybrid technique that we have used makes the study of the local soil effects possible even at large distances from the source, like 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 data set, including those corresponding to the "maximum expected" Vrancea event, tighter with the recorded ones can be fruitfully used by civil engineers in the design of new seismo-resistant constructions and in the reinforcement of the existing ones.

On the base of the reached results and considering the high seismic hazard, it is reasonable, for preparedness purposes, to extend the results of the numerical simulations to all zones of the city where the geological conditions are similar to the ones represented in the studied profiles. The regionalization made following these criteria is shown in Fig. 1. 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 Fig. 1, in the case of May 30, 1990 Vrancea earthquake.

The numerical modeling performed by Moldoveanu and Panza (1999), Moldoveanu et al. (2000), Moldoveanu and Panza (2001) and Cioflan et al. (2003) is at the base of the new microzoning map of Bucharest given in Fig. 1, and shows that standard convolutive approaches are not reliable. Detailed numerical schemes are required to obtain realistic estimates of the seismic risk.

Future efforts in Romania, 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 have to 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 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, (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, is certainly not a simple task, and is limited to technical problems. In fact, the results of the microzoning are used by end users, like 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.

Acknowledgments. The authors have been supported by the UNESCO-IUGS-IGCP project 414 "Realistic Modelling of Seismic Input for Megacities and Large Urban Areas" and NATO Science for Peace Project 972266 "Impact of Vrancea earthquakes on the security of Bucharest and other adjacent urban areas" (Ground motion modeling and intermediate-term prediction)". With the contribution of the Italian Ministry of Foreign Affairs (MAE), Directorate General for Cultural Promotion and Cooperation.

References

Alterman, Z.S., Karal, F.C.(1968), Propagation of elastic waves in layered media by finite difference methods, Bull. Seism. Soc. Am., ***58***, 367-398.

Ciocirdel, R., Titaru, E., Cismigiu, A. (1964), Seismic microzoning of Bucharest city, *Arh. IGP*, Bucharest (in Romanian).

Cioflan, C.O., Apostol, B., Moldoveanu, C.L., Panza, G.F., Marmureanu, G. (2003), Deterministic approach for the seismic microzonation of Bucharest, Pure and Appl. Geophys., in press.

Faeh, D., Suhadolc, P., Mueller, St., 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.

Ghica, S. (1953), Geologic microzonation of Bucharest city, *Arh. Deo. Geol., MMPG, Bucharest* (in Romanian).

Kelly, K.R., Ward, R.W., Treitel, S., Alford, R.M., (1976), Synthetic seismograms: A finite difference approach, Geophysics, ***41***, 2-27.

Lungu, D., Demetriu, S., Arion, C. (1999), Seismic vulnerability of buildings exposed to Vrancea earthquakes in Romania, *Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation*, Editors: Wenzel, F., Lungu, D., Kluwer Academic Publishers, 215-224.

Lungu, D., Arion, C., Aldea , A., Cornea, T. (2000), City of Bucharest Seismic Profile: From Hazard Estimation to Risk Mitigation, Earthquake Hazard and Countermeasures for Existing Fragile Buildings, Editors: Lungu D., Saito T., 43-67.

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, *Proc. Int. Conf. Microzonation*, San Francisco, **1**, 339-411.

Mandrescu, N., Radulian, M. (1999), Seismic microzoning of Bucharest (Romania): a critical review, Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation, Editors: Wenzel, F., Lungu, D., Kluwer Academic Publishers, 109-122.

Medvedev. S.V. (1962), Seismic engineering, Moscow.

Moldoveanu, C.L., Panza, G.F. (1999), Modelling, for microzonation purposes, of the ground motion in Bucharest, due to the Vrancea earthquake of May 30, 1990, Vrancea Earthquakes: Tectonics, Hazard, and Risk Mitigation, Editors: Wenzel, F., Lungu, D., Kluwer Academic Publishers, 85-97.

Moldoveanu, C.L., Marmureanu, G., Panza, G. F., 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., Panza, G.F. (2001), Vrancea source influence on local seismic response in Bucharest, Pure and Appl. Geophys., ***158***, 2407-2429.

Panza, G.F. (1985), Synthetic seismograms: the Rayleigh waves modal summation, J.Geophys., ***58***, 125-145.

Panza, G.F., Romanelli, F., Vaccari, F. (2001). Seismic wave propagation in laterally heterogeneous anelastic media: Theory and applications to seismic zonation. Advanced in Geophysics, ***43***, 1-95.

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

Radulian, M., Vaccari, F., Mandrescu, N., Panza, G.F., Moldoveanu, C.L. (2000), Seismic hazard for Romania: deterministic approach, Pure appl. geophys., ***157***, 221-247.

Romanelli, F., Bing, Z., Vaccari, F., Panza, G.F., (1996), Analytical computations of reflection and transmission coupling coefficients for Love waves, Geophys. J.Int., **125**, 132-138.

Vaccari, F., Gregersen, S., Furlan, M., Panza, G.F. (1989), Synthetics seismograms in laterally heterogeneous, anelastic media by modal summation of the P-SV waves, Geophys.J.Int., **99**, 285-295.

Wenzel,F., Ciugudean, V., Wirth, W., Kienzle, A., Hannich, D., Bonjer, K.-P., Moldoveanu, T., Sokolov, V. (2000), Options for rapid ground motion assessment in Bucharest, Earthquake Hazard and Countermeasures for Existing Fragile Buildings, Editors: Lungu D., Saito T., 81-91.

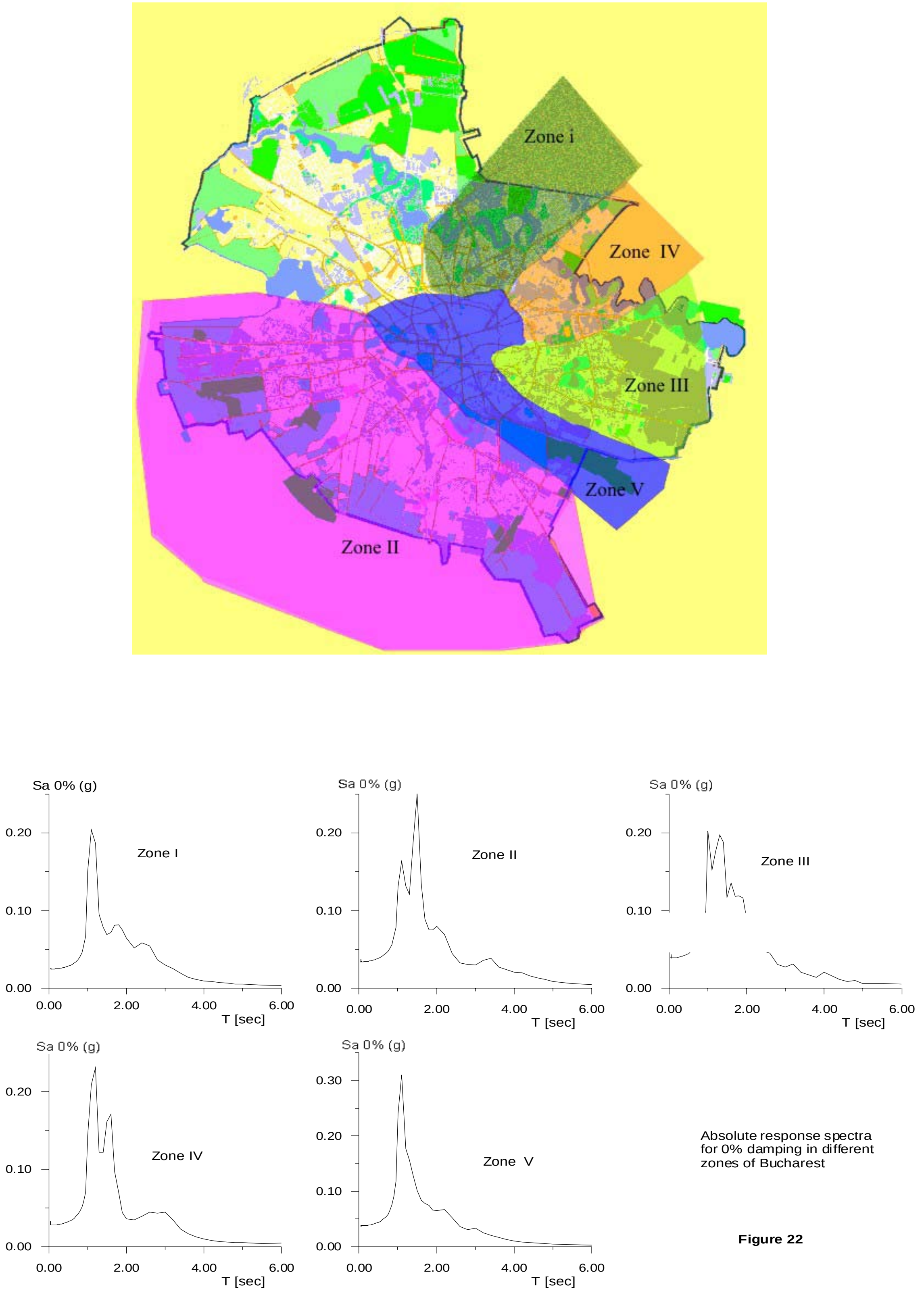

Figure 1. Preliminary seismic microzoning map of Bucharest: five representative zones are individuated. Acceleration response spectra (0% damping) representative of the five zones shown.