LARGE VRANCEA INTERMEDIATE DEPTH EARTHQUAKES AND SEISMIC MICROZONATION OF BUCHAREST URBAN AREA

LES GRAND SÉISMES DU VRANCEA DE PROFONDEUR INTERMÉDIAIRE ET LE MICROZONATION D'AIRE URBAINE DE BUCAREST

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Le grand séisme qui a eu lieu dans la région de Vrancea, le 4 Mars 1977, a produit l'écroulement de 32 haut bâtiments dans la parte centrale de Bucarest et une autre dizaine de haut bâtiments ont été gravement avariés. On a généralement supposé que la cause principale de cette destruction a été la proximité de la période d'oscillation du bâtiment vis-à-vis de la période fondamentale de résonance spécifique pour les conditions géologique au-dessous de la ville. Le but principal de cette étude est l'analyse de l'influence des conditions locales sur la réponse de sol dans Bucarest, pendant les grands tremblements de terre de Vrancea ($M > 7$) de profondeur intermédiaire. Pour accomplir ce but nous avons utilisé deux sets de dates: (1) dates géologiques, géotechniques et géophysiques, comprenant les mesurages in situ des ondes transversales, et (2) les enregistrements d'accélération des séismes du Vrancea de profondeur intermédiaire, produit entre 1977 et 2004. Les résultats de notre étude concernant l'évaluation de la réponse locale, en utilisant les contrastes d'impédance et facteurs d'amplification, mettent en évidence deux caractéristiques majeurs de haut signifiance pour l'ingénieurs: (1) le discordance pour le cas de la ville de Bucarest de la procédure standard qui limite la profondeur d'investigation à 30 m pour établir les caractéristiques dynamiques du sol; la réponse locale pendant les grands tremblements de terre de Vrancea est contrôlée par les dépôts sédimentaires Quaternaires entières qui sont significativement plus grosses que 30 m au-dessous Bucarest; (2) la difficulté de définir des zones avec des réponses différentes. Ainsi, pour la zone urbaine de Bucarest et pour les tremblements de terre de Vrancea de profondeur intermédiaire on peut parler plutôt des effets régionales que 'locales'.

1. VRANCEA INTERMEDIATE DEPTH EARTHQUAKES – THE MAIN SOURCE OF SEISMIC HAZARD FOR BUCHAREST URBAN AREA

The Bucharest is among the most vulnerable European capitals to earthquake, due to the seismic activity in the Vrancea region. That region, in which earthquakes are located in a confined, isolated focal volume, beneath the Eastern

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Carpathians Arc bend, at intermediate depths (60–180 km), is characterized by a persistent seismicity rate with an unusually high frequency of strong shocks (2–3 shocks with Mw > 7.0 per century) relative to such a small source active volume. The focal mechanism for the largest Vrancea shocks are typically of reverse faulting type with the T axis almost vertical and P axis almost horizontal (*e.g.*, Radulian *et al.*, 2000).

Among the former earthquakes those of 1471, 1620, 1681, 1738, 1802, 1829, 1838, 1893, 1894 stand out in terms of their effects. These events certainly caused great damage, but information about them is scarce, mainly because there was not a permanent observation network and also because of the relatively reduced density of the population.

The first document referring to the effects of a Vrancea earthquake in Bucharest dates from August 19, 1681 (Mw = 7.1), in the reign of Șerban Cantacuzino (Ștefănescu, 1901). According to the contemporary account "the Earth shook so strongly as nobody had ever related". The earthquake of June 11, 1738 (Mw = 7.7), destroyed the walls and tower of the Prince's Court in Bucharest. Many houses and churches were damaged and a "deep fracture" was open near the town. A very strong earthquake occurred on October 26, 1802, (Mw = 7.9), known by the contemporaries and lasting in the memory of the subsequent generations as the "big earthquake". The earthquake was felt over a huge area, from Saint Petersburg to Greek islands and from Moscow to Belgrade. During the earthquake all the church towers in Bucharest felt down, and many churches and houses collapsed. The next Vrancea major earthquake occurred on January 11, 1838, mentioned in several documents and in the newspaper "Romania", that started to be issued that time in Bucharest. A well-documented description of the earthquake effects was reported by Gustav Schüller (1882) immediately after the earthquake. Many of houses, especially of stone, were destroyed (much less damage was reported for wooden houses) and the royal palace was significantly damaged. Some documents indicated around 600 casualties and roughly the same number of injured people. Other significant earthquakes in 19 century occurred on November 13 1864 and March 4 1894.

Last century two destroying earthquakes hit the city, in November 10, 1940 (Mw = 7.7) and March 4,1977 (Mw = 7.4). The more recent events of August 30, 1986; May 30 and 31, 1990 were recorded by a relatively large number of instruments, providing this way important information on the Vrancea earthquake characteristics.

The November 10, 1940 earthquake severely damaged many buildings and the new 13-storey reinforced-concrete Carlton Hotel, sited in the central zone of the city, collapsed, killing 267 people. Since other tall buildings with reinforced-concrete frame suffered heavy damage, the authorities decided for the first time in Romania to introduce rules for antiseismic building design. In a work issued immediately after the earthquake, Beleş (1941) identified numerous buildings in the central part of the city, mainly of 6–8 storied, which needed urgent work of consolidation. The ignorance of these recommendations and the superficiality of the repairs had catastrophic consequences when the next major earthquake hit the city on March 4, 1977. The author also mentioned: "for the same material and execution, the buildings will behave worse as the tallness is higher" and, "as concerns the dislocations of the foundation, we have almost nothing to notify in Bucharest, and except a few isolated cases, the building basements were not affected".

The March 4, 1977 earthquake was the most destructive seismic shock that hit the city in modern times. A number of 32 buildings of 8–12 storey collapsed in the central part of city, while about 150 old buildings of 4–6 storey high were strongly damaged. Almost all the collapsed buildings had been built between 1920 and 1940 without earthquake resistant design. These buildings suffered greater or smaller damages during the November 10, 1940 earthquake and during the second World war. Moreover, some of the buildings had been submitted to important structural alteration, required by successive changes in their vocation, while the initial design was ignored. The most of victims were reported in Bucharest (1391 deaths and over 7576 injuries). The total value of damage exceeded 2 billion US dollars, of which about 2/3 recorded in Bucharest. The earthquake was recorded on the Romanian territory by a single station, in Bucharest, by a SMAC-B type analog accelerometer and a Wilmot WS-1 seismoscope. The earthquake produced no permanent deformation, no slides or collapses along the Colentina and Dâmbovița river sides.

2. SEISMIC MICROZONATION OF THE BUCHAREST URBAN AREA

In earthquake prone areas the protection of buildings is mainly achieved by certain paraseismic design norms and standards depending on the degree of seismic hazard involved in the area under consideration, and on the type and function of the building themselves. The *seismic zoning* maps have been elaborated, generally on the basis of data collected on previous earthquakes and of geological and seismotectonic research activities. These maps usually show the expected seismic intensity; they cover the country's entire territory and give the general seismic characteristics, but they prove insufficient for a detailed planning.

In order to choose seismically safe zones for sitting most important or most vulnerable component of urban and industrial development a detail investigation and study of *seismic microzoning* is imperative. The seismic microzoning methods currently employed developed by studying the impact of local geological conditions upon the construction behavior during an earthquake. This activity, promoted as a measure of antiseismic protection of constructions stimulated the elaboration and improvement of design codes and standards for constructions located in seismic regions.

2.1. SHORT HISTORY

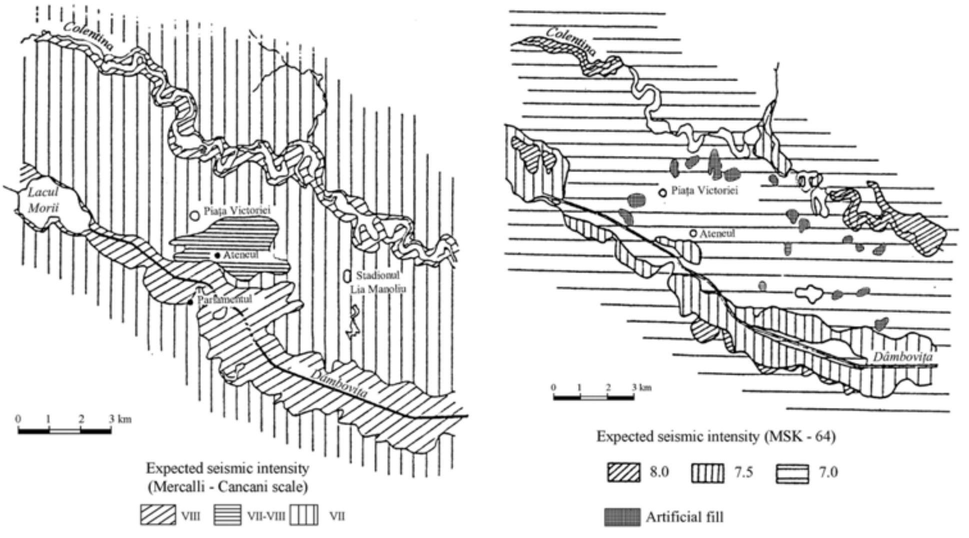
The seismic microzonation studies started in Romania more than 50 years ago. Two important stages can be distinguished in the development of these studies. The first one started in 1953 with the study by Ghica (1953) and was followed by the works of Ciocârdel *et al.* (1964) and Mândrescu (1972). This stage ends with the record of the first accelerogram of the strong Vrancea earthquake of 4th March, 1977 which marks the beginning of the second stage that continues up to the present day.

2.1.1. 1953–1977 interval

The seismic microzonation studies of the first stage were based on the experience gained through evaluation of the effects of the crustal earthquakes that took place in various seismic regions on traditional buildings, generally one or two-floored and built of wood, brick, stone or adobe. Starting from the assumption that foundation ground is very important for the behavior of the buildings, the geological, geophysical, geotechnical and hydrogeological particularities of some urban areas were thoroughly studied.

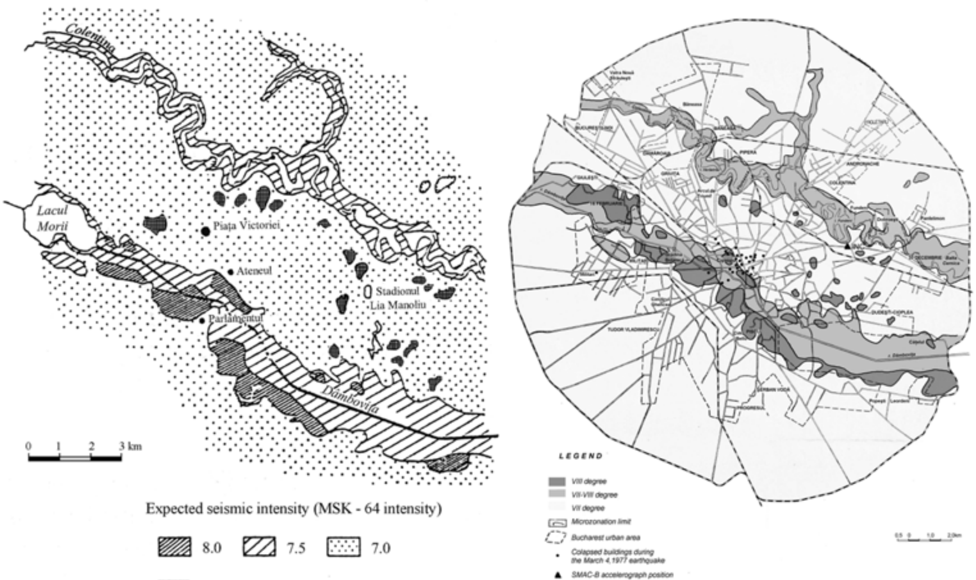
The first study on seismic microzonation in Bucharest was carried out by Ghica (1953) at the Geological Department of the former Geological Committee. The microzonation map (Fig. 1A) was drawn on the basis of the analogy between the seismo-geological characteristics of the city of Bucharest and those of other cities from other seismic areas and the theoretical evaluations related to the response of the different types of rocks to seismic stress (Sieberg, 1937). According to official regulation (STAS 2923/52), that time Bucharest belonged to the area of VIIIth seismic degree. The author kept the seismic intensity provided by the above mentioned standard for the meadows of Dâmboviţa and Colentina rivers and reduced the intensity on the Băneasa-Pantelimon plain, Cotroceni-Văcăreşti plain and Dâmboviţa-Colentina interstream by one degree. He separated a transitional area (VII–VIII) in the center of the city on the reason that the phreatic water between the loesslike deposits and the Colentina gravels could cause settlements of the foundation ground, threatening the stability of the buildings. A major contribution of the work is the recommendation to the designer engineers to avoid location buildings with a period of oscillation between 1.0–1.5s, as this is the fundamental period characteristic for the Bucharest city area.

The study carried out at the "Project Bucharest" Institute (Ciocârdel *et al.*, 1964) was based on a huge amount of geological, geotechnical and hydrogeological data. At that time the standard in force (STAS 2923/63) placed Bucharest in the VIIth degree of intensity area. The authors established, for each important geomorphologic unity, a synthetic lithological column for the first 40 m from the



A. Geologic-seismic microzoning map of Bucharest (Ghica, 1953)

B. Seismic microzoning map of Bucharest (Ciocârdel et al., 1964)



C. Seismic microzoning map of Bucharest (Mândrescu, 1972)

D. Seismic microzonation map of Bucharest, STAS 8879/6-73

Fig. 1 – The seismic microzonation maps of Bucharest urban area.

surface. Among these, a “reference” lithological column was chosen, which was representative for the geotechnical particularities of most of the city area. This was associated to the VIIth degree of seismic intensity stated by the above mentioned standard. The criterion for the separation of the microzones was the seismic rigidity of the foundation ground and the influence of water table level, according to Medvedev’s method (1960). The information regarding the seismic waves velocity was taken from literature. As one can notice (Fig. 1B), the authors preserved for most of the city the VIIth degree of seismic intensity and increased by half, respectively one degree in certain areas from Dâmbovița and Colentina river meadows. On this map there are also marked the artificial fill areas, with the recommendation to be avoided as building sites.

The Bucharest Geological Prospecting Company organized during 1970–1972 geological research and geophysical measurement of the seismic wave velocity in the Quaternary deposits, in order to establish the seismic rigidity of the foundation soils. Records were made in more than 200 points all over the city; there were collected and analyzed data regarding the lithological structure and the geotechnical characteristics of the Quaternary deposits in over 2000 geological, geotechnical and hydrogeological boreholes (Popescu *et al.*, 1964; Mândrescu, Soare, 1970). At the time of the study there was also in force the standard from 1963 (STAS 2923/63), according to which Bucharest belonged to the VIIth degree seismic area.

The seismic microzoning map carried out by Mândrescu (Fig. 1C), represented the key element in elaboration of the first seismic microzonation standard (STAS, 8879/6-73) for Bucharest city area (Fig. 1D).

The analysis of the first three microzonation maps (Fig. 1A, B and C) reveals two common features as follows:

– Seismic microzonation represents by definition the separation of an area characterized by a certain degree of seismic intensity, into microzones of different degrees. Each time, one starts from the reference level of intensity established through official standards or norms for the respective city or area. But, as showed before, the seismic zonation map can undergo changes in time, as a result of either the knowledge level of the seismic phenomenon and its impact on the built environment, or due to the seismic protection level which society can afford at one time. For example, at the moment of the first seismic microzonation study (1953), the city was considered to belong to the VIIIth degree macrozone (STAS 2923/52) while at following the researches of 1964 and 1972 to the VIIth degree macrozone (STAS 2923/63). At present, according to the Romanian standard of seismic zonation (SR 11100/1-93), elaborated after the 1977 earthquake, the city belongs again to the VIIIth degree macrozone;

– The separation into microzones leads to changes in the parameters for the earthquake resistant design of the buildings, with effects on costs and of course on responsibilities. Taking into account the fact that the microzonation map reflects the influence of the geological conditions at local scale (“local response”), the boundaries of the microzones are, generally speaking, natural ones. They are either changes in topographic aspect (the upper part of the terraces, the base of the slopes, the limit of the plaines etc.) or differences between the lithological structures of the deposits. But, obviously, the geological conditions change abruptly very rarely. As a rule, the lithological properties of the subsoil change in a continuous manner with distance. Under these circumstances, the boundaries of the microzones will be settled after the interpolation of the correction values or of the points where the parameters have been recorded; the number of these observation points must be high enough, so as their density on the surface unit should endow the separate microzones with justification and credibility.

2.1.2. 1977–2006 interval

The evaluation of the 1977 earthquake effects in Bucharest proved that the old tall buildings, with a reinforced concrete frame structure, situated in the center of the city, were the most damaged. On the contrary, the rigid buildings of the same height, the large-panel precast concrete structures and cast-in-place reinforced concrete shear wall structures, as well as the brick houses with 1–2 floors, were the least affected. The location of the 32 blocks of flats that collapsed during the earthquake are represented in Fig. 1D.

As one can see, most of the collapsed blocks were in the centre of the city, both in the VIIth degree microzone and in the VII–VIIIth and VIIIth degree of seismic intensity areas. Except for the blocks in Militari, Lizeanu and the building of the Computed Centre of the Ministry of Transport and Telecommunication – which were new, all the other collapsed buildings had been built in the 1920–1940 period, without any seismic protection precautions. After the earthquake a team working for the National Council for Science and Technology (CNST), proposed a new seismic microzonation map of the city (Fig. 2). The separation of the microzones was made by converting the seismic intensity (established as a result of the behavior analysis of a large number of buildings during the earthquake) in acceleration, using, slightly modified, Shebalin’s suggestions (Shebalin, 1975). The overestimated values of the acceleration, as well as the concentric distribution of the microzones, do not correspond to the geological particularities of the city. Moreover, the instrumental records of the 1986 and 1990 earthquakes in Bucharest refuted this delimitation of the microzones. Taking into account all these, we think that this map shows essentially the distribution of the effects of the earthquake on buildings rather than the local site effects (Mândrescu and Radulian, 1999).

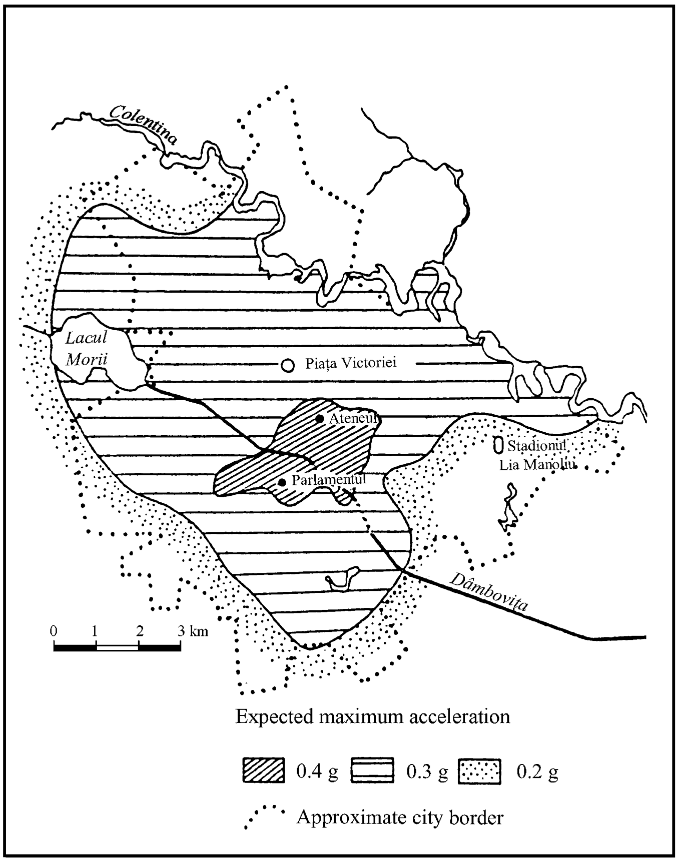


Fig. 2 – The seismic microzonation map proposed by the NCST Report, 1977.

3. CRITERIA USED FOR SEISMIC MICROZONING MAPPING OF BUCHAREST

Two types of information have been used for new seismic microzoning of Bucharest city: a) physical properties of the local setting and b) spectral analysis of the strong-motion records of the Vrancea subcrustal earthquakes occurred between 1977–2004.

a) The information about the regional and local natural conditions was provided mainly by the geological, geotechnical and hydrogeological boreholes, and by in situ geophysical measurements done on seismic profiles and in boreholes, measuring the seismic wave velocity (Fig. 3). This data set allowed us to elaborate some important maps showing geographical distribution of site response. The predominant period (Fig. 4), seismic intensity correction (Fig. 5) and amplification factor (Figs. 6 and 7) were computed taking into consideration the acoustic impedance contrast of the city subsurface strata (Mândrescu *et al.*,

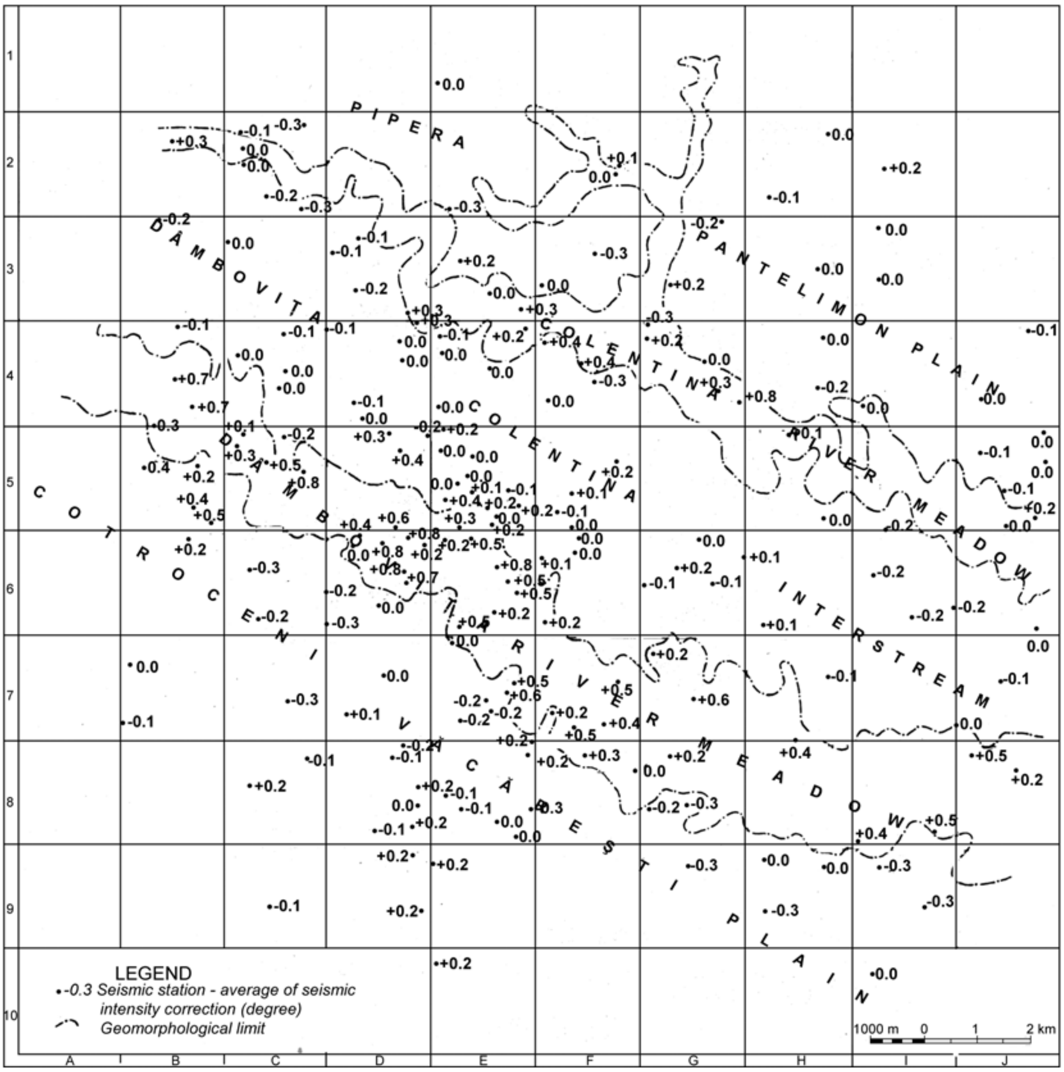


Fig. 5 – Average seismic intensity correction (Medvedev's method).

2006). The slight differences between the values of the above mentioned parameters render evident the *difficulty of separating microzones of different seismic intensities or local amplifications.*

b) Both in Bucharest and in the surrounding area, the bedrock does not come to the Earth surface, so we have no direct information regarding the characteristics of the seismic movement at bedrock level. The lack of some "reference" records on the one hand, and the large extension of weakly consolidated sedimentary deposits on the other hand, determined us to evaluate the influence of the local conditions on the seismic movement by comparative analysis of all the records of each earthquake. First, we evaluate the average response spectra of acceleration for each earthquake, taking into account all the records available at all the stations in the city (Fig. 8). This spectrum is considered to be characteristic for the average local conditions. It makes sense to compute an average spectrum having in mind the similarity among the spectra for every event at each station. Then, the individual acceleration response spectra are represented relative to the average response spectrum for each earthquake. The deviations from the average response spectrum are insignificant for 1986 event (Fig. 9A), 1990 event (Fig. 9B) and 2004 event (Fig. 10A).

The Vrancea moderate-size earthquakes ($4.0 < M_w < 5.3$), were recorded at 9 seismic stations (Bonjer, Rizescu, 1999). The number of recorded seismic events differs from one station to other. Thus, 4 earthquakes were recorded at CA, COS, CV and TIT stations, 6 at GB station, 7 at FOR station, 8 at INC and FGG stations, and 11 at MG station. On each graph (Fig. 10B) the average spectrum, calculated on the basis of the records of the 15 events is represented in comparison with the average spectrum calculated on the basis of the earthquake records at each station. The maximum amplification of the average spectrum of the 15 events is found at 0.23 s or, if we take into account the shape of this spectrum, the maximum amplification takes place between 0.23 s and 0.4 s. Some differences, otherwise insignificant, are observed when comparing the average spectrum computed on the basis of all the seismic events and the average spectrum at each station, which can be explained by the variable number of events per station, each with its own magnitude, azimuthally orientation, depth and different spectral characteristics.

Two important issues come out from our analysis: (1) the spectral similarity among different stations for a given earthquake, and (2) the local deviations occur each time at different stations (at EREN for 1986 event, PND for 1990 event, GB for the moderate-size earthquakes). The spectral analysis of the records obtained at the stations in Bucharest reveals the *difficulty of separating microzones with different spectral amplifications*.

4. THE NEW SEISMIC MICROZONING MAP OF BUCHAREST

The microzonation of any target area, including that of a city, requires integration of that location into the seismic area established by an official document in force. According to the seismic zoning map of the Romanian territory (SR 11100/1–93) the city of Bucharest belongs to the 8th seismic degree area (MSK-scale). This map (see inset from Fig. 11) shows, in terms of intensity, the distribution of the seismic hazard all over the country. It relates to the average ground conditions, defined as “a shallow superficial geological package, with the velocity of S waves between 300–500 m/s”.

For the seismic microzoning map of Bucharest we choose as support the topographic map presented and described in a previous work (Mândrescu *et al.*, 2004). The map preserves certain elements from the original variant, such as the elevation contour lines that point out the flat relief of Bucharest Plain, the location of the now drained swamps and the former flow of the Bucureştioara river. There are also shown the recent filling areas, sinkholes, and the erosion witnesses. On this map there are represented a series of new elements, such as the isolines that mark the fundamental period characteristic for the city area, and the limits of the area in Dâmboviţa river meadow that is exposed to floods in case the dam at the Morii Lake broke at a very large Vrancea subcrustal earthquake ($M > 7.0$).

Considering the geographic distribution of the points where the corrections of the seismic intensity and the dynamic amplification factors were computed, as well as the locations of the stations where the considered earthquakes were recorded, we come to the conclusion that on the city area there cannot be defined microzones with seismic intensities different from the intensity established through seismic zonation. Sandi and Borcia (2000) and Borcia (2006), come to a similar conclusion after analyzing the acceleration spectra of the large Vrancea earthquakes. We obviously mean by microzones those that can have a real practical significance, requiring the change from a certain level of seismic protection, which is the 8th degree, established through seismic zonation (STAS 11100/1-93), to other levels, by dividing into halves (for 7th degree) or, by doubling the acceleration (for 9th degree) to be taken into account for the earthquake resistant design of the buildings, with the due responsibilities and costs.

5. DISCUSSION AND CONCLUSIONS

Before drawing the conclusions we would like to add some comments related to microzoning in general and to the seismic microzonation of Bucharest city in particular. We first to point out that microzoning should be seen as a mean to take measures that will allow to avoid or at least to diminish the damage and the number of casualties in earthquake prone areas. The microzonation map is the result of a detailed research of the natural environment of an area for which the level of the seismic hazard endanger has been established by the seismic zoning map. A map showing the distribution of PGA (or other parameter of the ground motion recorded during the earthquakes), cannot be considered as a microzonation map, having in mind the very large variability of these parameters. In order to accomplish this, the microzonation map must show the distribution of the soil response to the action of the maximum possible seismic event for that area. To develop into safety an urban area sited in earthquake prone areas call above all for accommodate building activity to environmental conditions. Studies and seismic microzoning maps, elaborate taking into consideration the natural conditions, will of large interest for the present-day evolution and especially for the future evolution of the urban area analyzed.

It is known that urban planning should not disregard the interaction between two complex systems: the manmade system (the city itself) and the natural system consisting of the geologic factors and processes that cause or accompany a large earthquake. The causality connection between these two systems call for a good co-operation between architects, designers, civil engineers and local administration factors on the one hand, geologists, seismologists and other geoscientists on the other hand. Unfortunately, the recommendations or warnings given by geologists or seismologists are mentioned in technical accounts or in scientific papers, but are not heeded by the ones they address to. Serious consequences were in many cases brought about by ignorance or incomprehension of geological information. Among the many examples of this kind, we quote the Anchorage (USA), Yungay and Ranrahirca (Peru) zones and Bucharest city (Romania).

The Anchorage zone was geologically investigated long before the 1964 Alaska earthquake. The undertaken investigations emphasized the presence of clays locally called the "Bootlegger Cove clay". The distribution area and its characteristics were described in a geological report in which the activation conditions of slides were also rated (Miller and Dobrovolny, 1959). Although some administrative departments had this report and even used part of the data included, the information were not taken into consideration and the hazard implied by these deposits was ignored when the general fast developing systematization of Anchorage was undertaken. The huge landslides and settlements of the loose granular deposits triggered by the 1964 Alaska earthquake ($8.3 < M < 8.6$) caused about 60% of the total losses.

Another example is supplied by the Yungay and Ranrahirca localities, in zones threatened by avalanches. Geological investigations pointed out numerous avalanches and landslides that had occurred not long before in the area. Yungay itself was sited on such a stabilized avalanche. Had these conditions been known and had adequate measures been taken before the 1970 earthquake ($M = 7.5$) the calamity that struck the two localities and in which 18.000 casualties occurred could have been prevented (Cluff, 1971).

In the first seismic microzonation study made in Romania in 1953, Ghica recommended to take care when constructing tall buildings in Bucharest with fundamental periods in the range of 1.0 s and 1.5 s. His advice was disregarded by designers and civil engineers until the 4th March 1977 earthquake. Thus for many high buildings built between 1953–1977 the values of basic design parameters were four times lower than normal, if they had taken into account the real natural conditions (See Table 1). The tall blocks of flats built in that period are highly vulnerable and this could prove fatal in case of the next strong Vrancea earthquake ($M > 7.0$).

Table 1

Values of basic design parameters (k_s, β, T_c, ψ)

Regulation	k_s coefficient				β	T_c	Ψ
	VI	VII	VII	IX			
I-42 and I-45	0,005				1,0		1,0
P. 13-63		0,025	0,05	0,10	0,60–3,0	0,3	1,00–1,50
P. 13-70		0,03	0,05	0,08	0,60–2,0	0,4	1,00–2,00
P.100-78	0,07	0,12	0,20	0,32	0,75–2,0	1,5	0,15–0,35
P.100-81	0,07	0,12	0,20	0,32	0,75–2,0	1,5	0,15–0,35
P.100-91 and P.100-92	0,8	0,12	0,20	0,32	1,00–2,5	1,5 1,0 0,7	0,15–0,65

k_s = basic design coefficient represents the ratio of design ground acceleration (PGA or EPA) to gravity acceleration, g;

β = dynamic amplification factor, defined for average ground conditions, depends on natural period of structure T and on corner period, T_c;

ψ = reduction coefficient which depends on structure ductility, redistribution capacity of stresses, attenuation effects, etc.

Another example is given by the strong earthquake of 1986. This event was recorded by 7 seismic stations in Bucharest. Since the record at the seismic station EREN is different from the others, one assumed that this record is typical for the northern Bucharest area, covered by “predominantly sandy soil profiles” (Lungu *et al.*, 2000). The other six sites are presumably characteristic for the eastern, central and southern parts of the city, covered by “predominantly clayed soil profiles”.

However, there are numerous and sound arguments (Liteanu, 1952; Ciocârdel *et al.*, 1964; Mândrescu, 1972; Radulian *et al.*, 2000; Mândrescu *et al.*, 2004) to query the credibility of the accelerogram of 1986 event recorded at EREN and the subsequent separation of the city area in two different regions. We draw attention on the dramatic effects that can come out through considering erroneous conclusions infered on false premises. This example, as well as the preceding ones, argues for a continuous and constructive collaboration between specialists from geosciences, design and civil engineering.

The seismic microzonation maps have a predictive character, but this refers to the ground response to the future large seismic event, and not to the response of the built environment. That is why one cannot speak of “validating”, “confirming” or “matching” the seismic microzonation maps with/to those showing the distribution of the damage done by an earthquake or another. We draw attention on this aspect because after the 1977 earthquake, the finding that “the most damage in Bucharest corresponded to the safest area” (Berg, 1977), was interpreted by some specialists in a wrong way, blaming the natural conditions (local effects) for damages and disregarding the real cause, that is the vulnerability of the built environment and the proximity of the building fundamental period (T) and the characteristic period of the geological deposit response beneath the city (Ts). It is known that none of the buildings that crushed down in the centre of the city had been designed according to the microzonation standard in force at that time (STAS 8879/6-73). We have to reiterate some of our previous statements (Mândrescu, 1978, 1982; Mândrescu, Radulian, 1999; Mândrescu, Zugrăvescu, 2000) – that, as long as in the cities coexist old, traditional buildings, built with or without seismic precautionary measures, and new buildings, made of new materials, with new technologies and designed according to the provisions from official standards and regulations, we cannot expect the seismic microzonation maps "match" the damage distribution maps. Of course, the comparison of both types of maps could be relevant provided the buildings whose response to the earthquake are analyzed were *located*, *designed* and *built* in accordance with the requirements of the respective microzonation map.

There are some things to be added in respect to the allegation that the damage done by the 1977 earthquake was caused by "the focalization of the seismic waves as a result of the deep geological structure" or by "the fault in the Neogene layer" (NCST Report, 1977). Deep borehole information which we used for the maps and geological sections in one of our previous works (Mândrescu *et al.*, 2004), pointed out the quasi-horizontal position of the strata that form the sedimentary package of the Moesian Platform, which questions the possibility of a focalization of the seismic waves. But, even in the case of a hypothetical focalization of the seismic waves at 3–4 km depths, according to the allegations in the above-mentioned report, it is difficult to explain the selective character of the damage. As known, many blocks of flats, very close to those that collapsed, met no serious damage.

Regarding the faults identified in the basement of the Moesian Platform through boreholes and outside city seismic survey, they could be traced only in pre-Neogene formations, and not in the Miocene so much the less in the Pliocene ones. These are older faults, reactivated several times in connection with the orogene movements that led to the building up of the Carpathians. The most recent movements are considered to take place after Upper Meotian (about 3.5 Ma ago) when, according to some authors (Paraschiv, 1979) the gas and petroleum accumulations were formed in the surroundings of the city of Bucharest.

Regarding the fault slip, we would like to add that an "active" or "capable" fault must have at least one of the following characteristics (CFR, Appendix A, 1980): a) the proof of a surface slip or of a slip close to the surface of the ground at least once in the last 35,000 years or repeated slips in the last 500,000 years;

b) the existence of a micro seismic activity instrumentally determined precise enough to prove a connection to the fault; c) the existence of a structural connection with a capable fault, as defined at (a) and (b), such as the movement of either of them could trigger the movement of the other as well. If we take into account these characteristics, we will acknowledge that the fault considered by some people to be responsible for the collapse of blocks OD-16 and Lizeanu and of the Computer Centre of the MTTC does not meet the requirements of an active fault. On the other hand, even if it were regarded as active, it is hard to accept its simultaneous movement with the 1977 seismic event. As difficult as that is, we must accept the idea that among the faults at the Moesian Platform basement this was the only one to move at the 1977 earthquake and that the effect of the slip was the fall of three blocks out of the several hundreds situated on its hypothetical trace.

*

The seismic hazard for Bucharest urban area comes from the Vrancea seismogenic region, where 2–3 large earthquakes ($M > 7.0$) occur per century. According to the seismic zoning map of Romanian territory (SR 11100/1-93) Bucharest city belongs to the 8th macrozone degree (MSK-scale).

The main result of the seismic microzonation study for Bucharest city emphasizes seemingly in a paradoxically way the impossibility of delimiting certain microzones with different "response" to the strong subcrustal Vrancea earthquakes. The slight differences between the values of the computed parameters are confirmed by the similarities in the acceleration response spectra of each earthquake recorded by the different seismic stations in Bucharest. The good correlation between the result obtained by using these two data sets are mainly due to the quasi-uniform geological peculiarities over the entire city area, with almost horizontal strata and insignificant lateral inhomogeneity; there is no strong enough lithological differences (acoustic impedance contrast) to be reflected in different site response.

Based on our analysis we conclude that the seismic source, travel path and site effects will result in similar response over the entire city area in case of strong Vrancea intermediate-depth earthquakes; thus, for Bucharest urban area and strong subcrustal Vrancea earthquakes ($M > 7.0$), one can refer rather to "regional" than "local" effects.

The differences are determined by the increasing thickness of the resonant layer from south to north and by the increase in the fundamental period characteristic in the same direction, from 1.0 s in the southern part of city, to about 2.0 s in north (Figs. 4 and 11).

The power spectrum densities of 1977, 1986 and 1990 earthquakes, point out a maximum dynamic amplification around 2.2 s period which could become a serious threat for the tall buildings in Bucharest, in case of a large Vrancea intermediate-depth earthquake ($M > 7.0$).

Finally, we want to draw attention on two crucial conclusions as concerns the microzonation analysis for Bucharest city: 1. It is completely inadequate to apply the usual procedure which limits the investigation of dynamic characteristics of soil at 30 m depth in order to establish the local response (Borcherdt, 1994; EUROCODE 8 CEN,1994; Wirth *et al.*, 2003); 2. The unstationary of the dynamic amplification process shows that the information provided by the study of the weak and moderate-size earthquakes cannot be extrapolated to anticipate the local response in case of strong subcrustal Vrancea earthquakes.

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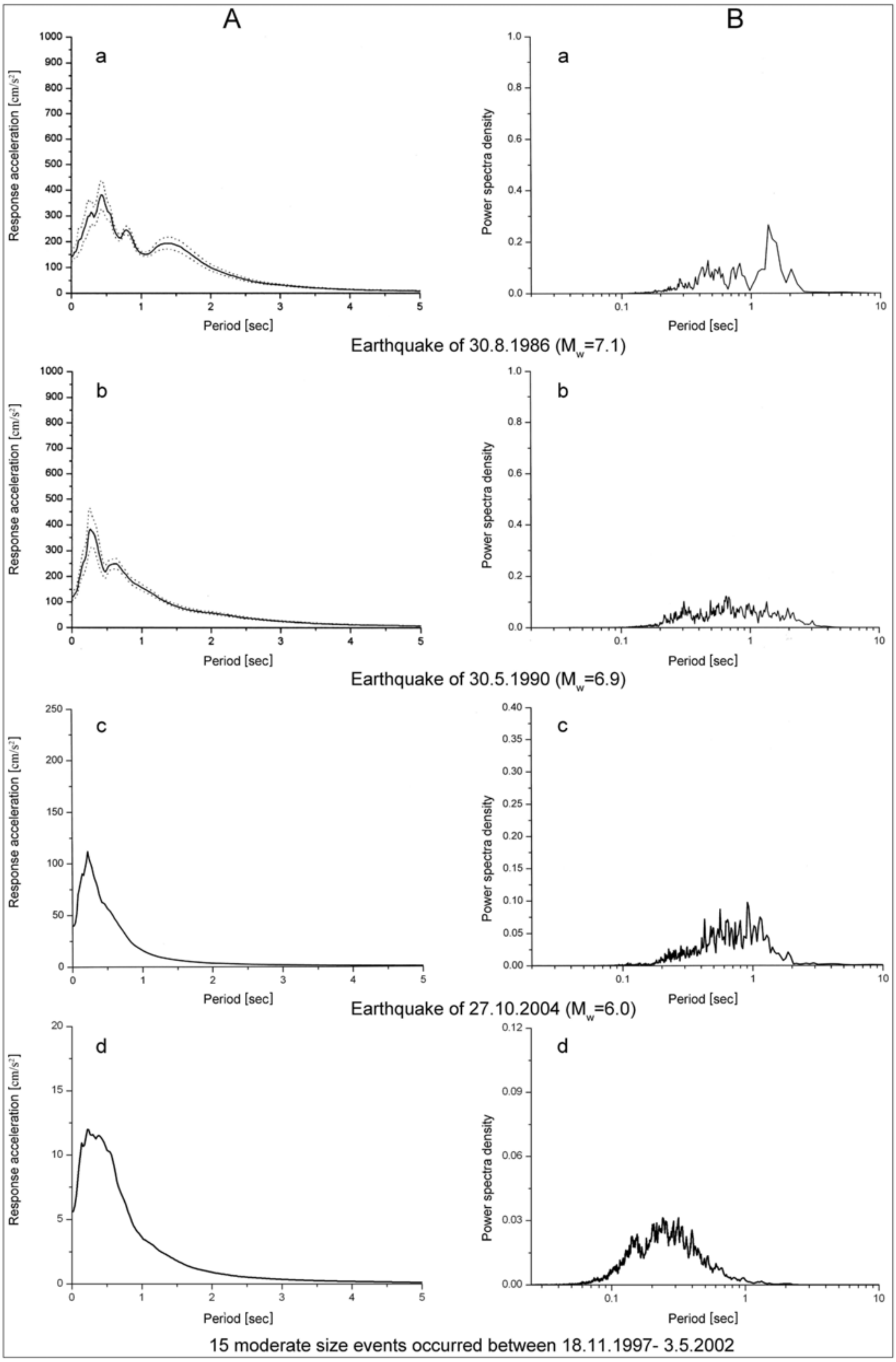

Fig. 8 – Average acceleration response spectra (A) and average power spectra density (B), for the analyzed earthquakes.

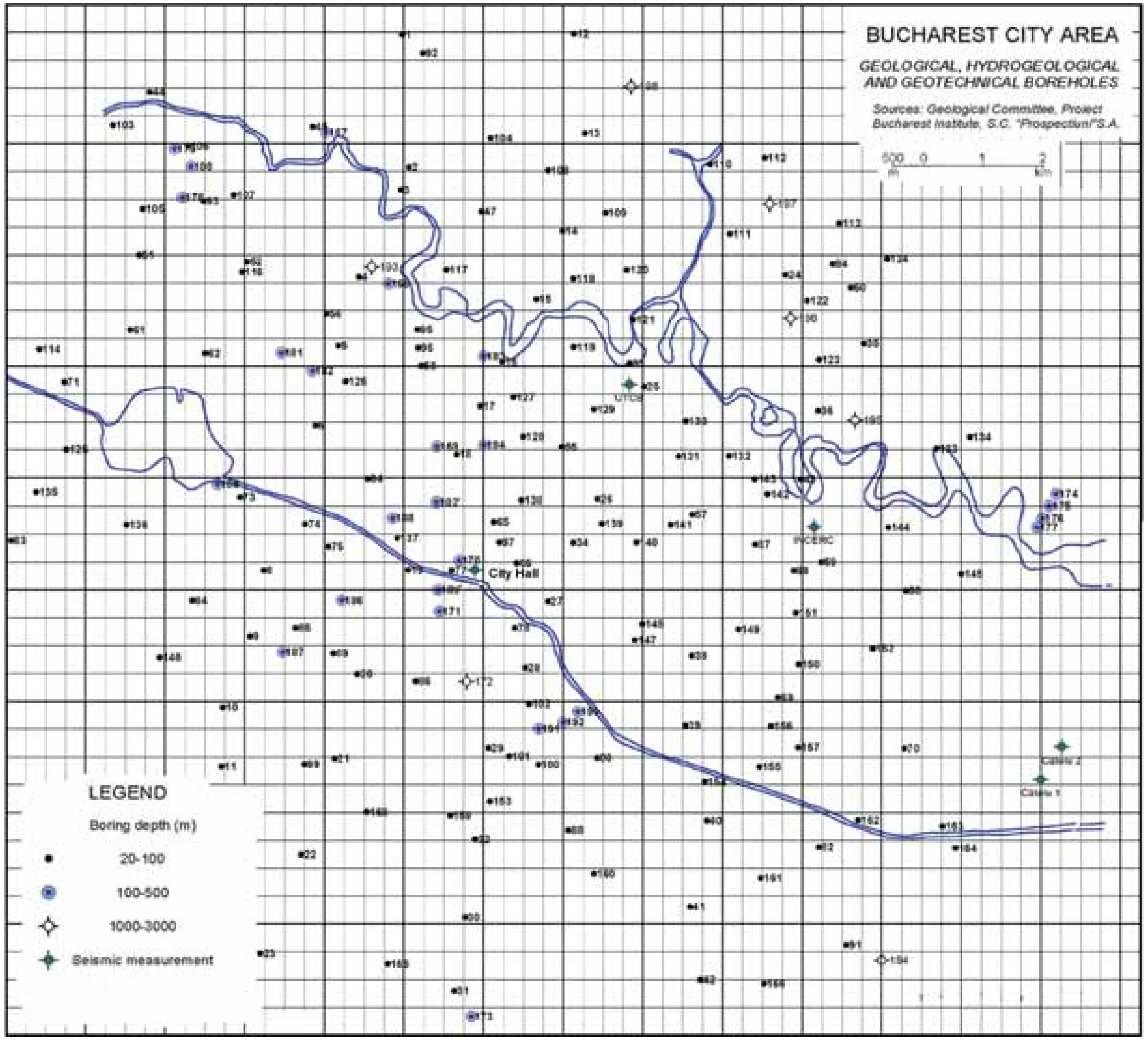

Fig. 3 – Location of boreholes used in this study.

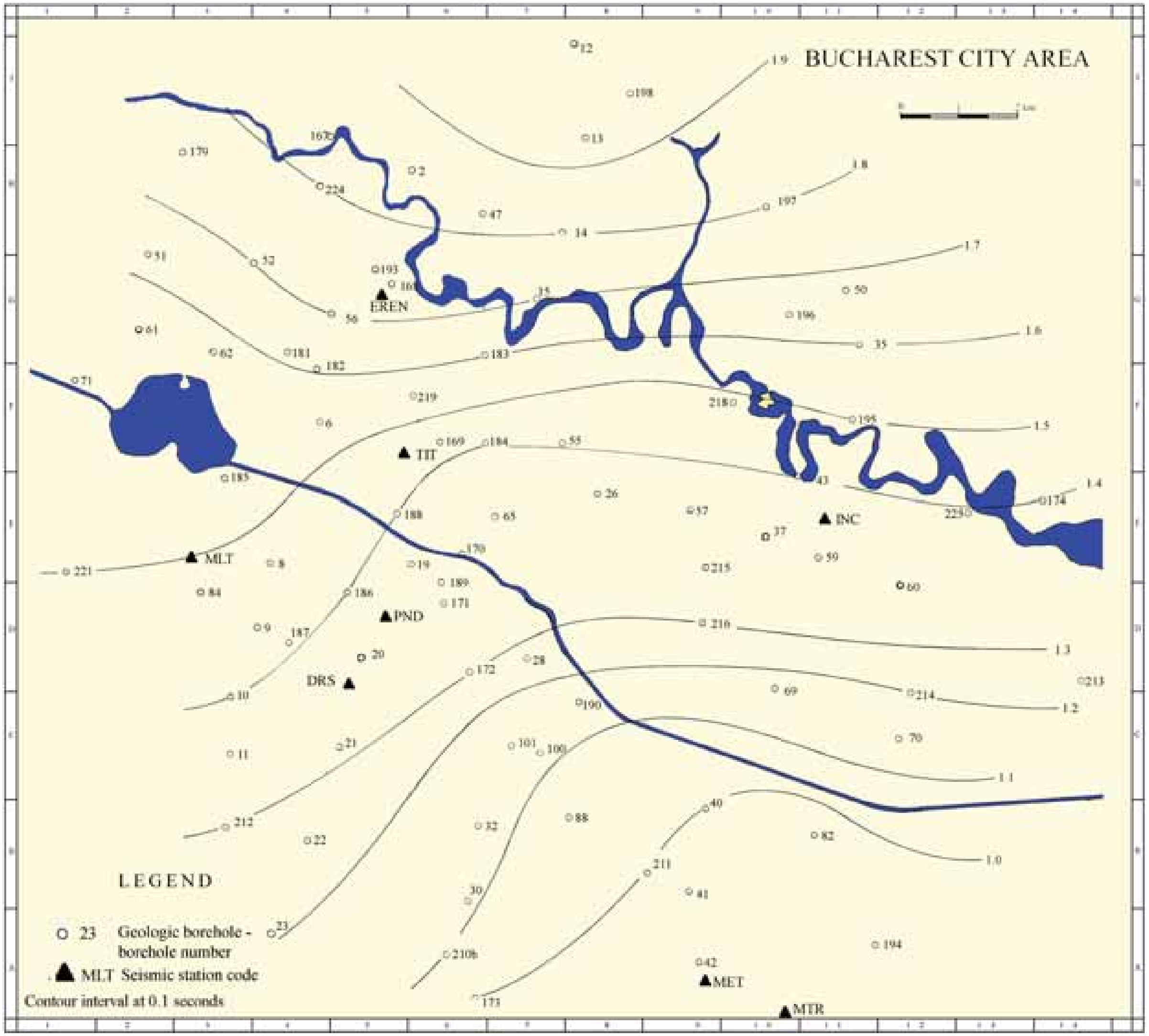

Fig. 4 – Distribution of the predominant period.

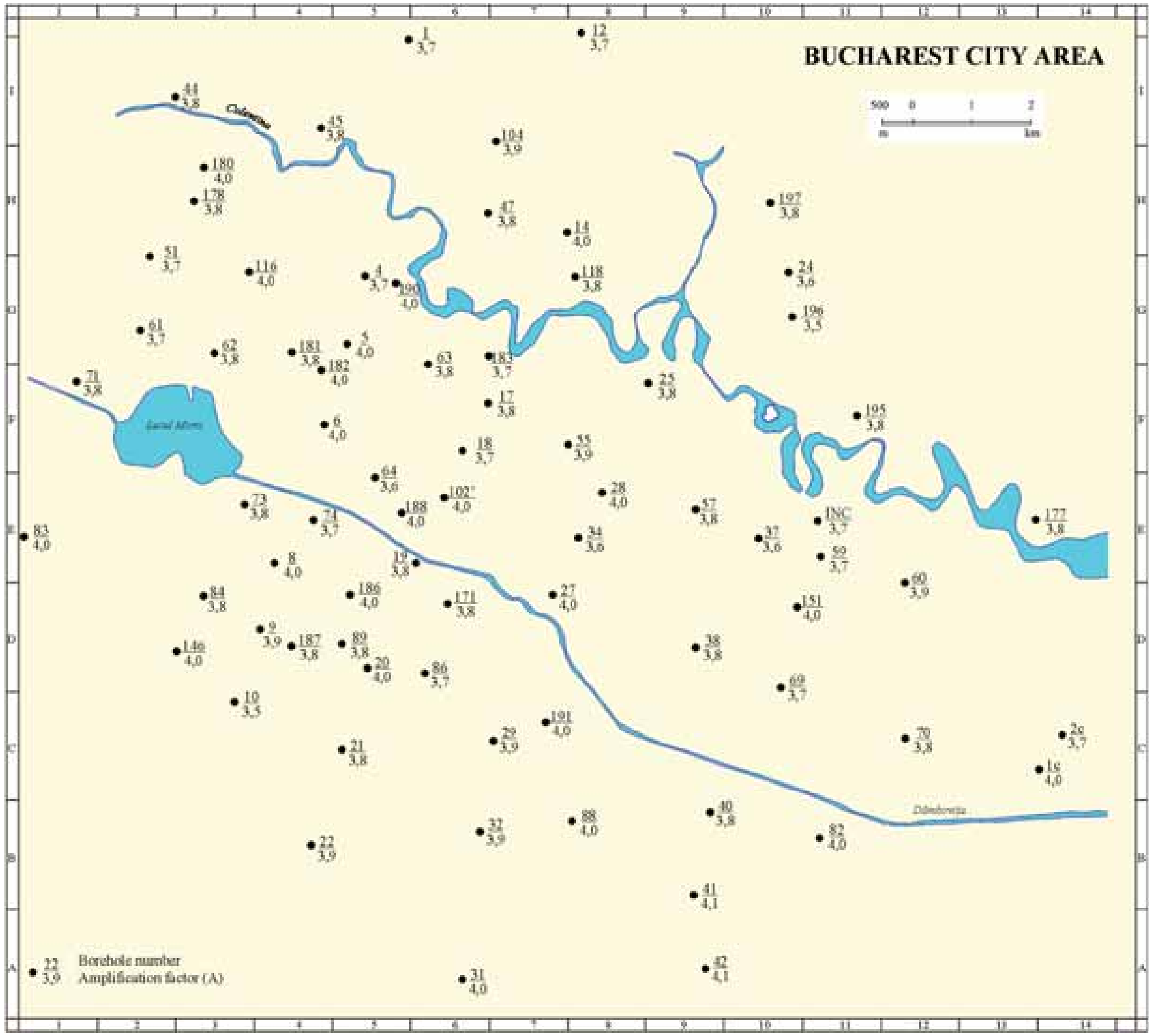

Fig. 6 – Ground motion amplification factor (After Okamoto, 1973).

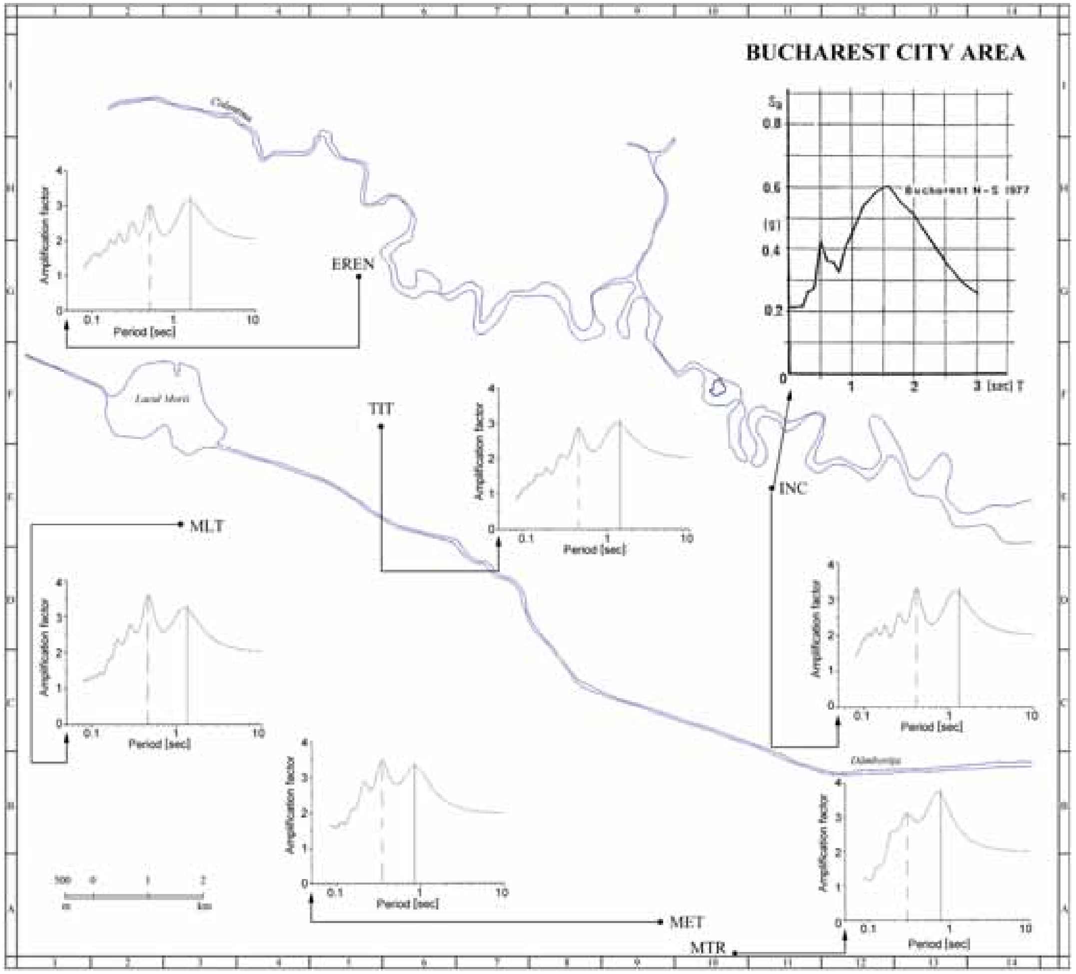

Fig. 7 – Amplification factor computed for 1-D structure modelling for six seismic stations in Bucharest area. The solid vertical line represents the fundamental period predicted by the quarter wavelength law for the geological deposit above the Frătești gravel/marl complex interface (see the map in Fig. 4); the dashed line represents the fundamental period predicted for the layers above the Upper Pleistocene-Holocene/marl complex interface. The acceleration response spectrum of the 1977 Vrancea earthquake (Mw = 7.4) recorded at the INC seismic station is shown in the upper right corner of the figure.

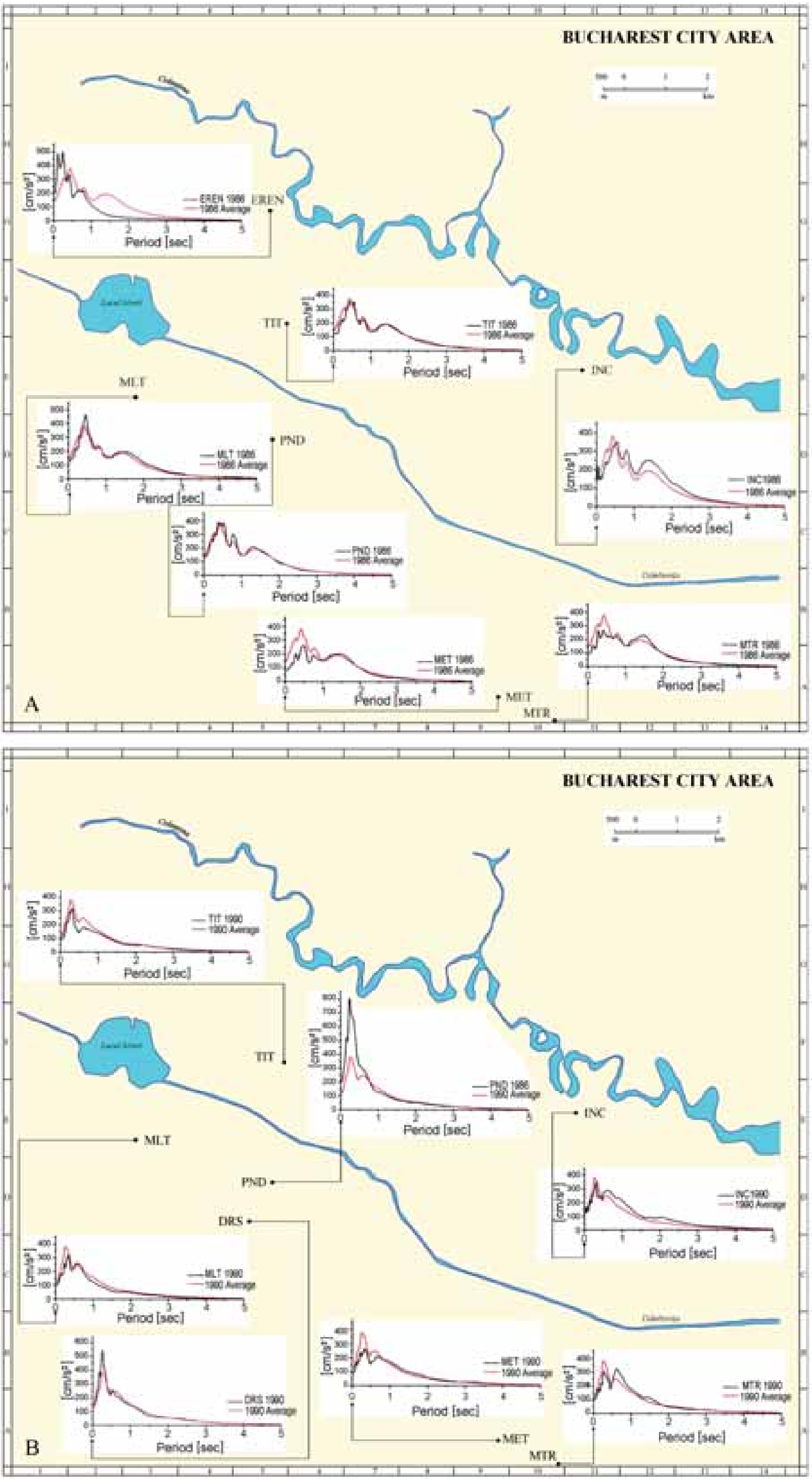

Fig. 9 – Acceleration response spectra of the 1986 event (A) and 1990 event (B), compared with the corresponding average reference spectra.

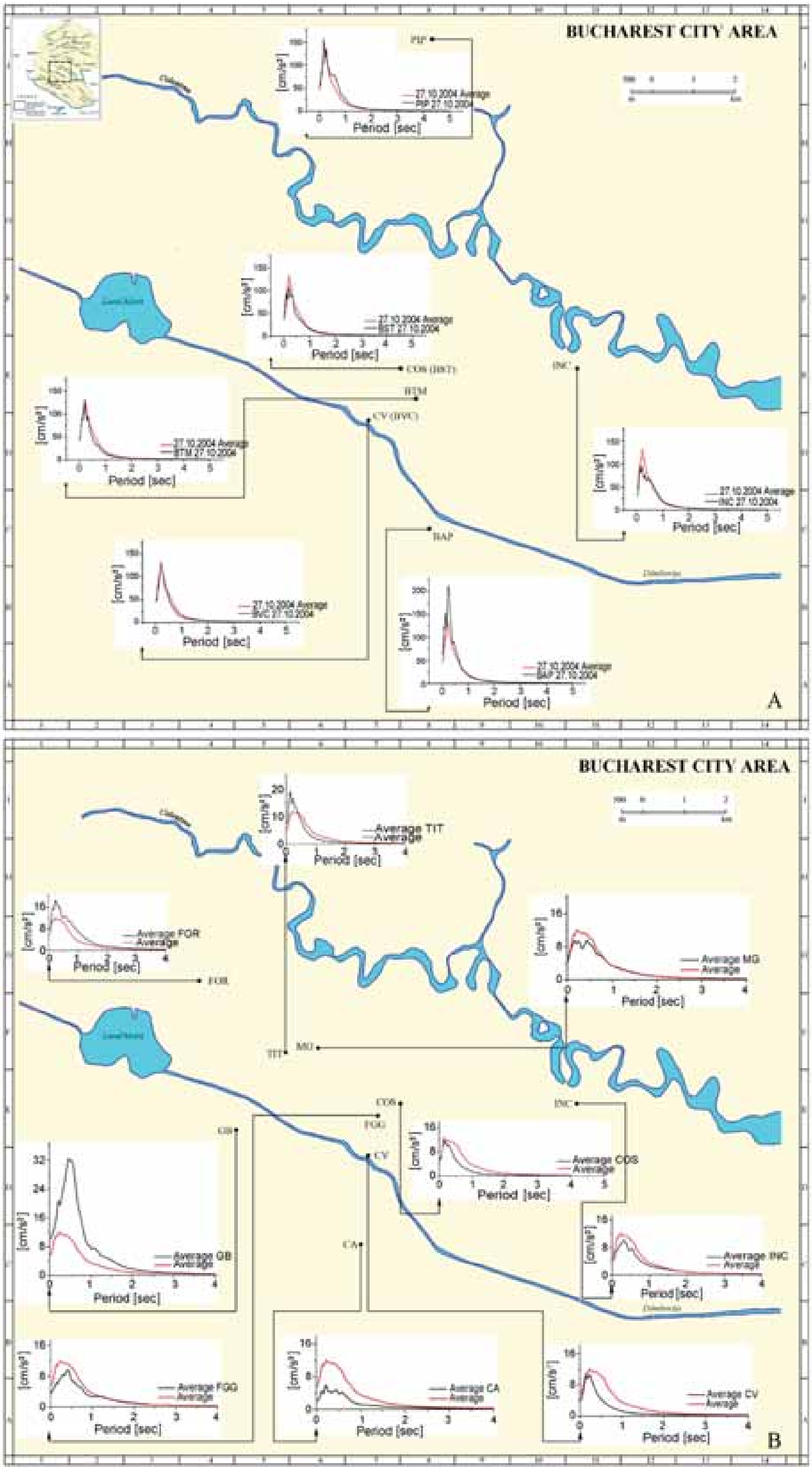

Fig. 10 – Acceleration response spectra of the 2004 event (A) and of the moderate-size events occurred between 19972002 (B), compared with the corresponding average reference spectra.

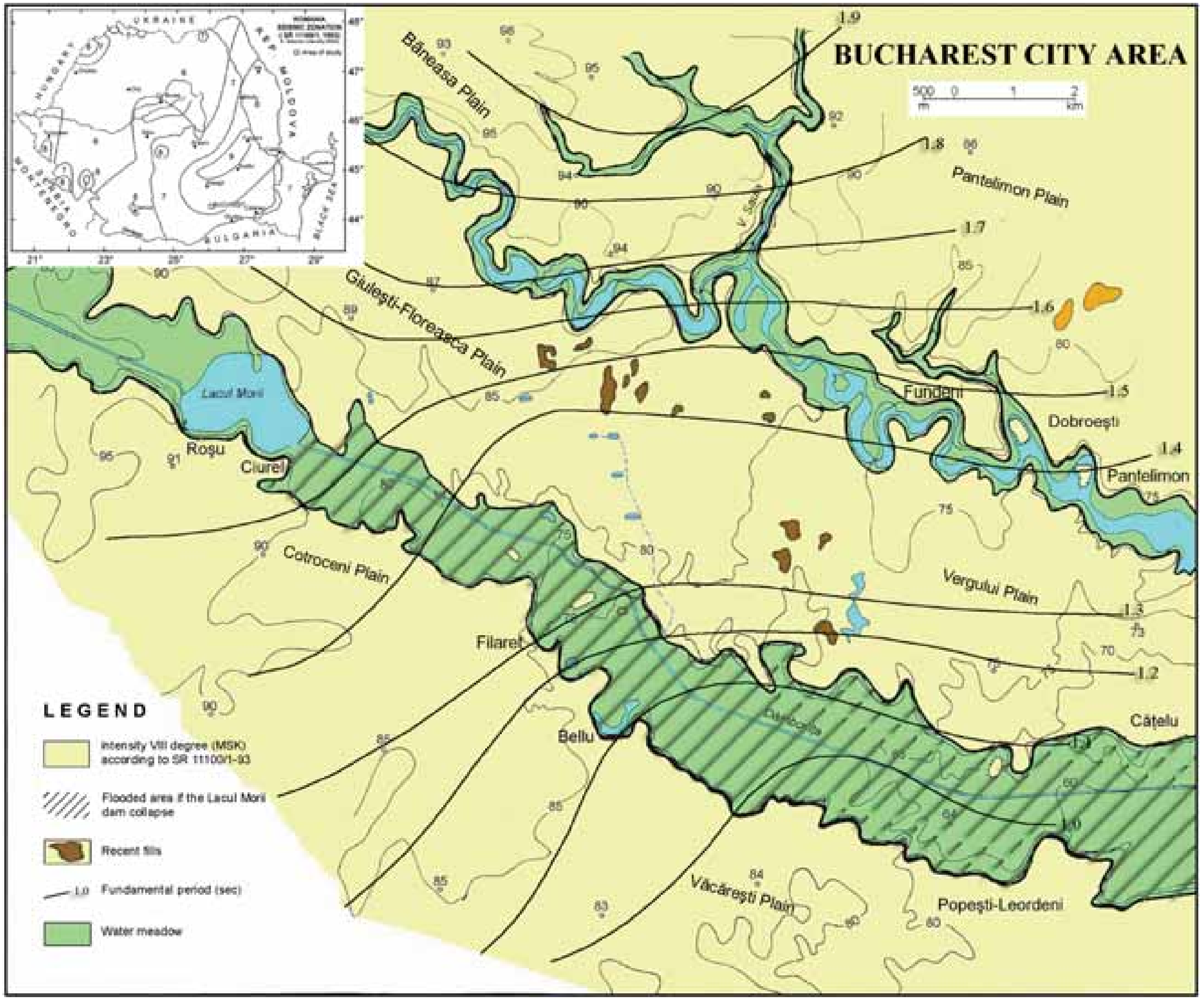

Fig. 11 – Seismic microzonation map of the Bucharest urban area as proposed in this study. The map of the seismic zonation of the Romanian territory (SR,11100/1-93) is shown in the upper left corner of the figure.