GEOLOGICAL, GEOPHYSICAL AND SEISMOLOGICAL DATA FOR SITE EFFECTS EVALUATION IN THE BUCHAREST URBAN AREA

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Données géologiques, géophysiques et sismologiques pour l'évaluation des effets locaux dans l'aire urbaine de Bucarest. Le grand séisme de profondeur intermédiaire de Vrancea, qui a eu lieu le 4 mars 1977, a provoqué l'écroulement de 32 hauts bâtiments de l'aire centrale de Bucarest et, en même temps, une autre dizaine de hauts 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 géologiques au-dessous de la ville. La recherche sur les effets des conditions locales en Bucarest pendant les grands tremblements de terre a été constamment développée à l'Institut National du Physique de la Terre avec le but final d'établir leurs effets sur le comportement de l'ensemble des habitations. L'information obtenue par les forages géologiques, interprétée dans le système des coordonnées géographiques, nous a permis de dresser de nouvelles cartes, à l'échelle de 1:50.000, comme suit: la carte géostructurelle à la limite Néogène, la carte à la limite des couches de Frăteşti, la carte à la limite du complexe Uzunu, la carte de la distribution de la période prédominante et une série de sections transversales et diagrammes, surtout pour la zone centrale de la ville. L'étude utilise et met en corrélation les résultats obtenus par la recherche géologique, géotechnique et géophysique comprenant le mesurage *in situ* des ondes transversales dans la ville, qui a commencé il y a plus de 50 ans. Les résultats de notre étude mettent en évidence deux caractéristiques principales d'une haute signification pour la pratique de l'ingénierie sismique: *(1)* la discordance pour le cas de la ville de Bucarest de la procédure standard (EUROCODE 8 CEN, 1994) 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 qui sont significativement plus gros 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 on peut parler plutôt d'effets régionaux que locaux.

Mots clés: effets locaux, période prédominante, facteur d'amplification, Bucarest.

1. GEOLOGICAL AND GEOPHYSICAL BACKGROUND

Bucharest city is located in the Romanian Plain, at around 165 km from the epicenter area of Vrancea (Fig.1). The elevation of the Bucharest zone above the sea level lies between 95 m and 60 m, gradually decreasing from NW to SE. The

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elevation contour lines are generally oriented NE–SW, roughly perpendicular to the direction of the main rivers, Dâmbovița and Colentina, going across the city.

From a geological point of view Bucharest city lies on the northern edge of the Moesian Platform, close to the contact between this major structural unit and the external part of the Carpathian foredeep. The Moesian Platform has a basement with two structural stages, a lower one with chloritic and sericitic schists of Precambrian age and an upper one made up of old Paleozoic folded marine formations going back to the Middle Carboniferous age. The sedimentary cover, relatively thick (exceeding 6,000 m), is the result of four major cycles of sedimentation: a) Paleozoic, b) Permian-Triassic, c) Jurassic-Cretaceous and d) Upper Miocene-Quaternary.

The accumulation of geological deposits in the basement of the Bucharest area during the last sedimentary cycle took place first in a marine environment, then lacustrine and litoral-deltaic and finally, in a continental environment (Paraschiv, 1979). The description of the formations from every sedimentary cycle was made in a previous work (Mândrescu *et al.*, 2004). The deep geological boreholes (Fig. 2) provide information down to bottom of the Quaternary deposits, which refers to the following lithological layers (Liteanu, 1952): *(a)* loesslike deposits and the alluvia of the Dâmbovița and Colentina rivers; *(b)* Colentina gravels and sands; *(c)* intermediate-clay deposits; *(d)* Mostiştea sands; *(e)* Marl lacustrine complex (Uzunu complex) and *(f)* Frăteşti layers, represented by three layers of sand and gravel, separated by two intercalations of clayey rocks. Excepting the layer of the intermediate clay, which from place to place becomes thinner, sometimes disappearing completely (see Figs. 3 and 4), the other layers can be found at distances that are over the present limits of the city. The information obtained from a large number of geological boreholes processed in the system of the geographical coordinates, allowed us to draw up some new maps and lithological cross-sections at the scale of 1:50,000, such as: the map at the surface of the Frăteşti layers; the map at the surface of the marl lacustrine complex (Uzunu complex); the lithological north-south cross-section (Fig. 3) and the block diagram for the central part of city (Fig. 4). The isobaths of the Frăteşti layer surface (Fig. 5) are generally oriented from east to west, with a slope of about 7‰ dipping from south to north. In the same direction we can notice that the layers become thicker and thicker. The slowing down of the subsidence process from the Upper Pleistocene and then its complete cessation is underlined by the almost horizontal position of the Uzunu complex surface (Figs. 3 and 6). Obviously, the layers above this, beginning with the Mostiştea sands have a quasi-horizontal position.

The information referring to the seismic characteristics and especially to the distribution of the seismic wave velocity in the geological formations beneath the city area comes from two sources: *a)* seismic measurements made in more than 200 seismic profiles with the portable seismograph FS_3-Huntec, Canada (Mândrescu, 1972); *b)* seismic measurements made in boreholes at INCERC, UTCB, Căţelu and Mayoralty area (Aldea *et al.*, 2000; Moldoveanu, 2000; Bâlă *et al.*, 2004).

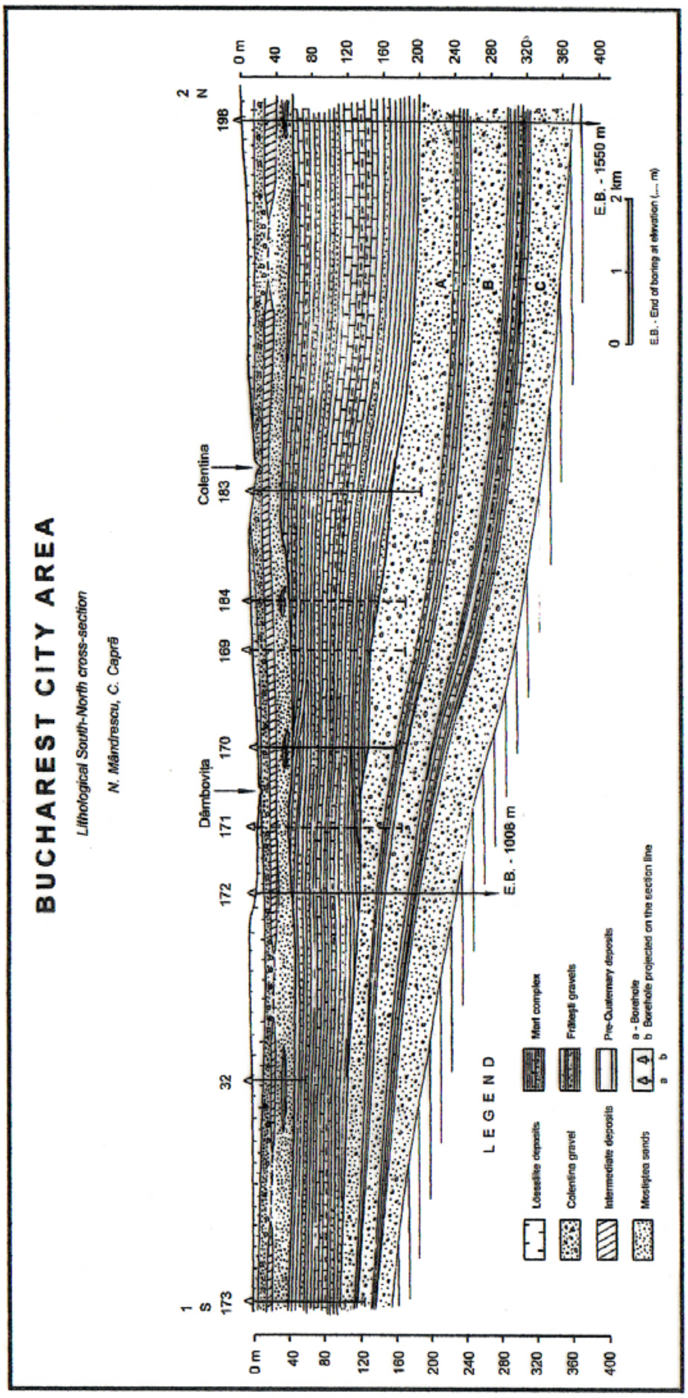

Fig. 3 – Lithological south–north cross-section. Cross-section position is plotted in Fig. 2.

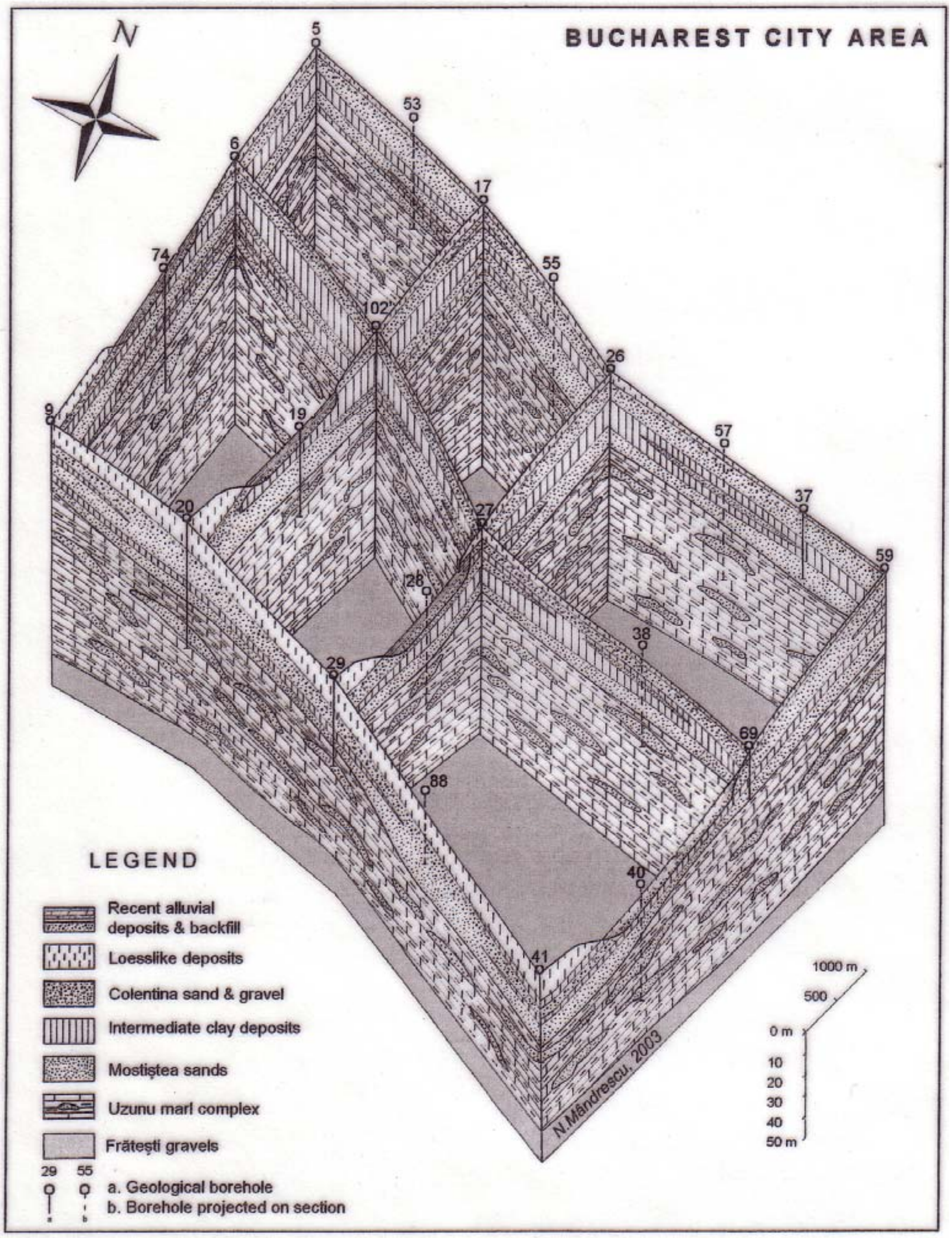

Fig. 4 – Three dimensional representation of stratification extrapolated from boring.
Block diagram position is plotted in Fig. 2.

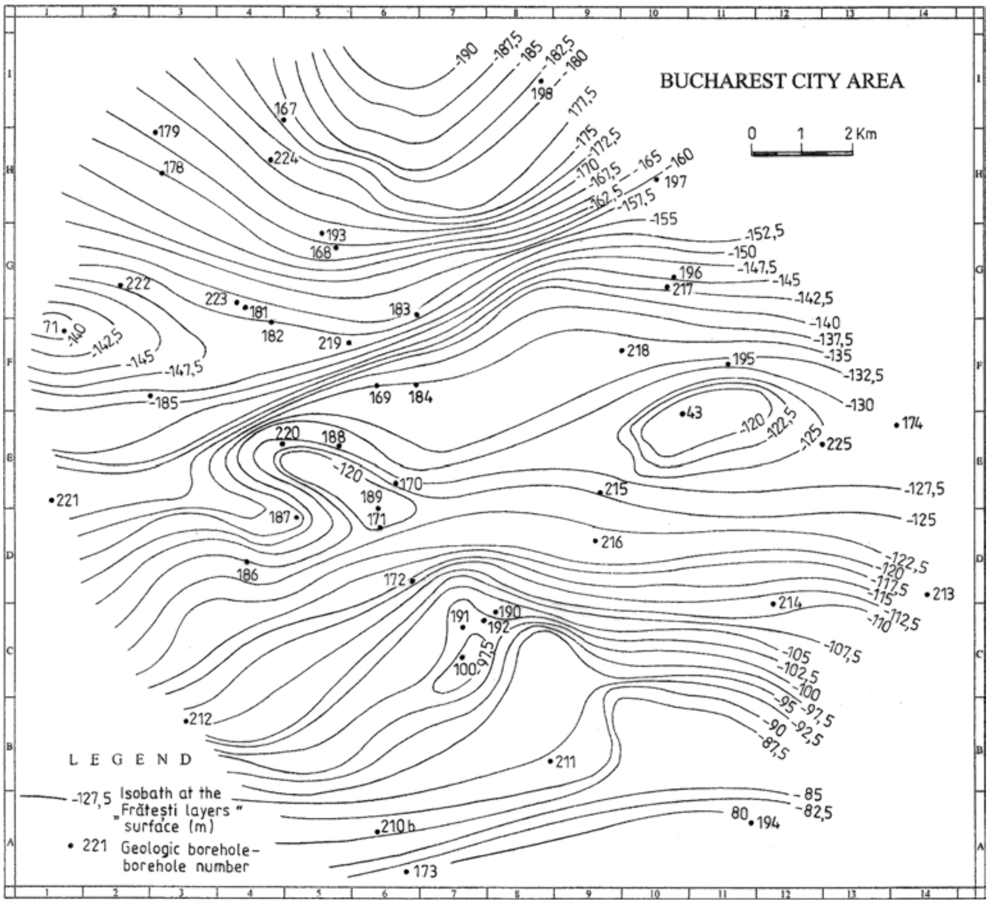

Fig. 5 – Map at the "Frăteşti gravels" surface.

Although the measurements are made in spots, the velocity of the seismic waves are characteristic for the entire layer since the petrographic material has a common source, way of formation and its subsequent evolution has taken place within similar lithofacial conditions. The lithological composition passes from clay to sandy clays or sands, from marl to sandy marl or sand lenses, but these passing have been made gradually and have not modified significantly the seismic behavior of the deposit as a whole. This is also outlined by the narrow interval of the velocity values obtained from seismic measurements (Table 1).

Table 1

Interval velocities of the Vp and Vs waves for the lithological complexes, determinated through seismic profile, up-hole and down-hole seismic measurements

No. Layer	Lithological Complex	Soil type	Thickness (m)	Interval velocity	
				Vp (m/s)	Vs (m/s)
1	Backfill, topsoil	--	0–8	200–400	90–180
2	Loesslike deposits	Silty clay	3–20	485–750	210–320
3	Colentina gravel	Gravel and sand	4–18	1200–1695	300–350
4	Intermediate clay	Clays	0–20	1650–2050	320–450
5	Mostiştea sand	Fine sands	8–20	1200–1900	350–400
6	Marl Complex M	Marl and fine sands	60–140	1660–2000	375–460
7	Frăteşti gravel	Gravel and sand	50–200	1830–2300	600–700

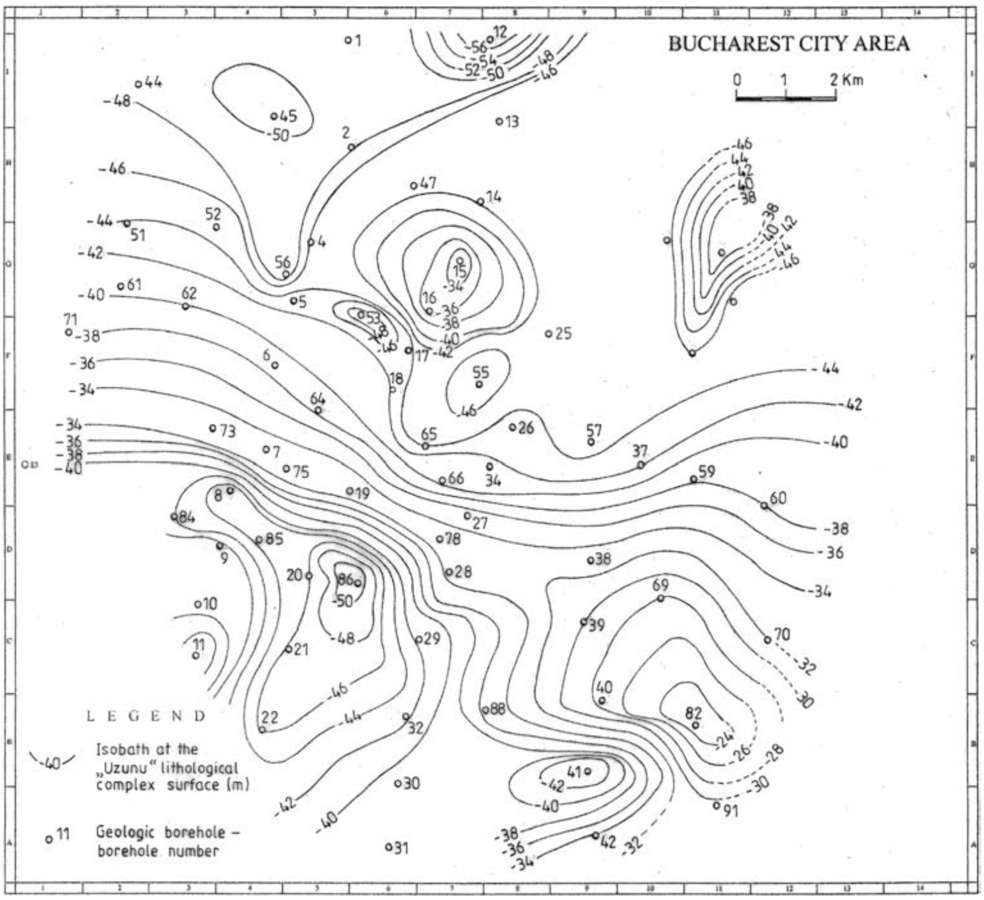

Fig. 6 – Map at the "Uzunu complex" surface.

2. SITE RESPONSE EVALUATION

The inhomogeneous spatial distribution of the damage caused by earthquakes is, above all, due to the influence of the local geological conditions that can amplify or deamplify the amplitude of the seismic motion parameters before they reach the surface of the ground or the foundation of the buildings. The damages produced by the Michoacan (1985), Loma Prieta (1989), Northridge (1994) and Kobe (1995) earthquakes were determined by the effect of the local conditions on the ground response. The amplification of earthquake ground motion by local site effects has important implication for urban planning and development of Bucharest city, built on cohesionless Pleistocene-Holocene deposits. The large Vrancea intermediate-depth earthquake of March 4, 1977 (Mw = 7.4) occurred at a 165 km epicentral distance, excited the ~1.5 s fundamental vibration mode in the Bucharest subsoil layers. Site response over the Bucharest city area has been estimated from: *a)* the physical properties of the local setting revealed by boreholes, seismic profiles, up-hole and down-hole seismic measurements and *b)* recording of the Vrancea intermediate-depth earthquakes occurred between 1977 and 2004.

2.1. SITE RESPONSE EVALUATION USING THE PHYSICAL PROPERTIES OF THE NATURAL ENVIRONMENT

2.1.1. Predominant period computation

Likewise other big cities hit by strong earthquakes (Caracas, Mexico City) (Seed *et al.*, 1970; Girault, 1986; Resendiz and Roesset, 1986; Whitman, 1986) the largest damage was noticed in Bucharest for the tall and flexible buildings (Beleş, 1941; Ambraseys, 1978). Thus, during the 1977 Vrancea strong earthquake 32 tall buildings collapsed in Bucharest city. The principal cause was considered to be the proximity of the building fundamental period (*T*) of the characteristic period of the geological deposit response beneath the city (*Ts*). The period of oscillation characteristic for different sites in the Bucharest area was computed immediately after the earthquakes, resulting values between 0.9 s and 1.6 s (Mândrescu, 1978).

Information concerning the physical properties of the local setting and shear waves velocity allowed us to compute the period of oscillation characteristic for different sites, using the formula: Ts = 4H/Vs, where *Ts* is the period, *H* is the depth, and *Vs* is the shear wave velocity. We considered as bedrock the compact horizon of the Frăteşti gravels, for which a shear wave velocity of 650 m/s was adopted. Since the deposit lying above the bedrock is represented by a sequence of layers of different thickness and shear wave velocity, an average velocity is considered, given by:

$$\overline{V_s} = \frac{\sum_{i=1}^{n} d_i}{\sum_{i=1}^{n} d_i / v_{si}} \tag{1}$$

where d_i = thickness and v_{si} shear wave velocity in the *i* layer.

The computation is made for the site where boreholes reach the surface of the Frăteşti layers. The map of the predominant period (Fig. 7) is drawn by interpolating the values obtained in the locations of 120 deep geological boreholes, almost uniformly distributed over the surface of the city. The predominant period varies between 1.0 s in the southern part of the city and 1.9 s in its northern part. Similar results were obtained by applying the H/V ratio technique for ambient noise and small and moderate earthquakes (Bonjer *et al.*, 1997). The shape of the isolines outlines the increase of the predominant period from south to north in correlation with the constant increase of the thickness of the Quaternary cohesionless deposits in the same direction. Fig. 8A shows an almost linear increase of the predominant period in correlation with the thickness increase of the weak consolidated Quaternary deposits. To verify if there is a correlation between the granulometric composition of the Quaternary deposits from subsoil and the predominant period, we represent in Fig. 8B the ratio (R), between the coarse fraction (psephites, psammites) and the fine one (aleurites, pelites) for the whole lithological column of every borehole *versus* the values of the computed predominant period. The plot refers to all the 120 boreholes for which the predominant period was computed. The large scatter of data shows no correlation between the predominant period and the granulometric composition of the Quaternary deposits from Bucharest's subsoil.

As already showed the geological deposits in the city location were formed in similarly conditions, valid over extended areas that overpass significantly the present limits of the city area. The lateral variations, the increase of the weight of a certain granulation in the sand and gravel deposits mass, the transition from clays to sandy clays or sands, from marl to clays-marls are made gradual and the separation limits are not sharp-cut. The results obtained show only a clear correlation between the thickness of the Quaternary cohesionless deposits and the predominant period, characteristic for the local response and confirm the important role of the Quaternary deposits thickness, in the computations of the predominant period, fact which, otherwise, has been known and demonstrated for a long time (Omote *et al.*, 1956; Kanai, 1962; Seed and Idriss, 1969; Seed *et al.*, 1970; Seed and Schnabel, 1972; Goto *et al.*, 1978; Kudo, 1978).

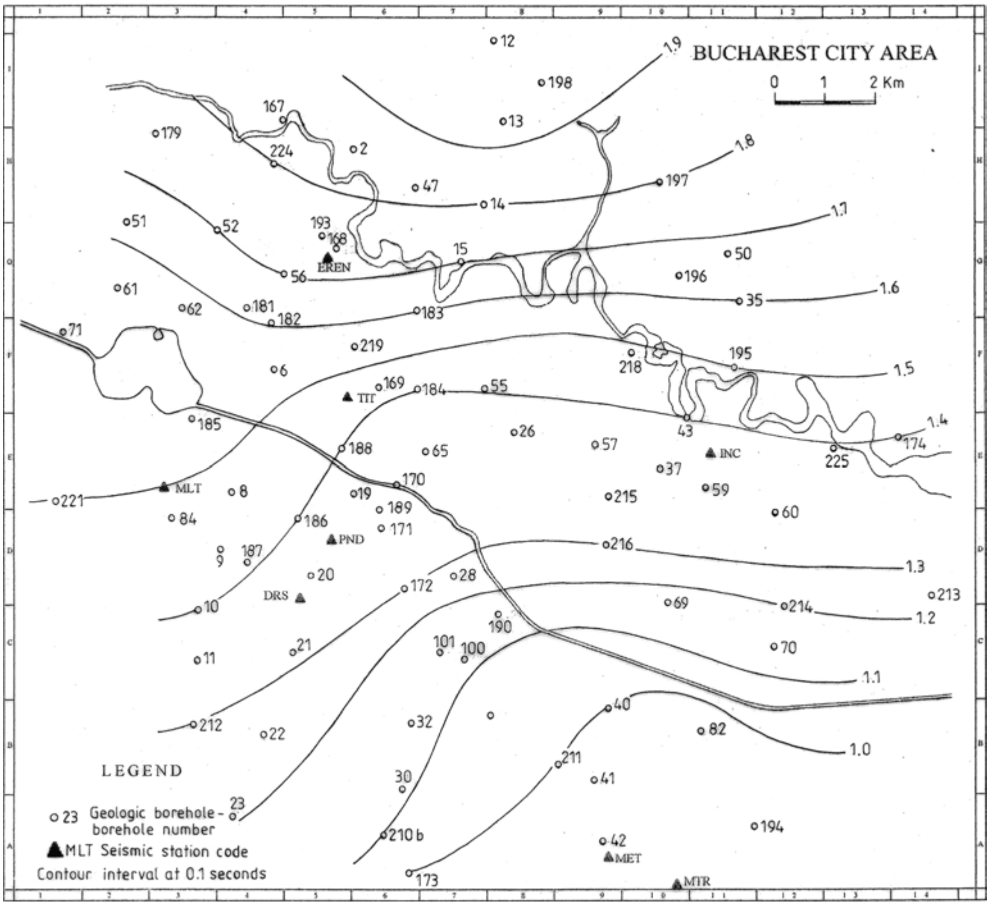

Fig. 7 – Distribution of the computed predominant periods, Ts (sec).

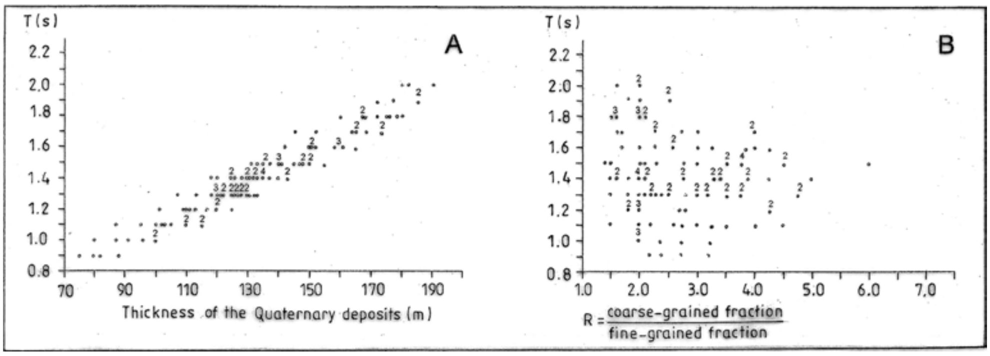

Fig. 8 – Correlation between the computed predominant period (Ts) and thickness of the Quaternary cohesionless deposits (*A*) and grain-size fraction, R (*B*).

2.1.2. Computation of the seismic intensity corrections

Medvedev (1960) proposed a method for the local effect evaluation, starting from the connection between the damage suffered by the buildings, expressed through the seismic intensity and the acoustic impedance ($Vp \times \rho$) of the foundation ground (10–15 m from the surface). It came out that the decrease of rigidity of the foundation ground had as effect the increase of the damage suffered by the buildings.

The empirical formula proposed by Medvedev has two terms, the first one represents the ratio of the acoustic impedance of a pattern rock (generally granite is used) and of the rocks from the studied location. The second term represents the influence of the ground water table. The value of this correction is added to the correction computed taking into consideration the acoustic impedance of the foundation soil.

For Bucharest city area the computations were made in about 200 points (Fig. 9). The corrections computed in such a way are applied to the seismic intensity, settled through zonation, finally obtaining microzones having different seismic intensities. In 164 points, the correction values are between –0.3 and +0.3 degrees. For the area implied, representing about 83% of the whole researched area, the seismic intensity settled through the seismic zonation map (STAS 2923/70), available at that date, respectively the degree VII (MSK), did not change. The exception are the Dâmbovița and Colentina river floodplains in which the influence of the ground water table increases the correction value, allowing increase of the seismic intensity by half or even one degree in certain areas (Mândrescu, 1972).

2.1.3. Computation of the dynamic amplification factor

According to Okamoto (1973) if the bedrock motion is a harmonic wave, with a period equal to the fundamental period of the elastic surface layer ($T = 4H/Vst$), the amplification factor for the motion at the ground surface is:

$$A=2/K \tag{2}$$

where,

– K, the impedance ratio, is $Vst\rho t\,/Vsr\rho r$;

– ρt , ρr the volumetric weight;

– Vst, Vsr – the shear wave velocity, t and r refer to the layer from above (t) and respectively the bedrock from beneath (r).

This relation represents the combined effects of the impedance ratio and input motion-soil layer resonance. The dynamic amplification factor (A) was computed on the basis of the geological data from 75 boreholes distributed on the whole Bucharest city surface (Fig. 10). For the bedrock (the compact horizon of the Frăteşti gravels), the shear wave velocity (Vs = 650 m/s) was considered constant for its whole developing area. The results show a very narrow variation domain of the amplification factor, from 3.5 to 4.1. Of course, now we are not interested in the absolute value of this factor, but in the way in which the values obtained through calculus are distributed over the city surface. The very close values and their geographic distribution make difficult the separation of some areas with different amplifications. These results naturally come from the relative small lateral variability in the lithological composition, layer distribution and their geometry, geotechnical and velocity characteristics, topography of the area and so on.

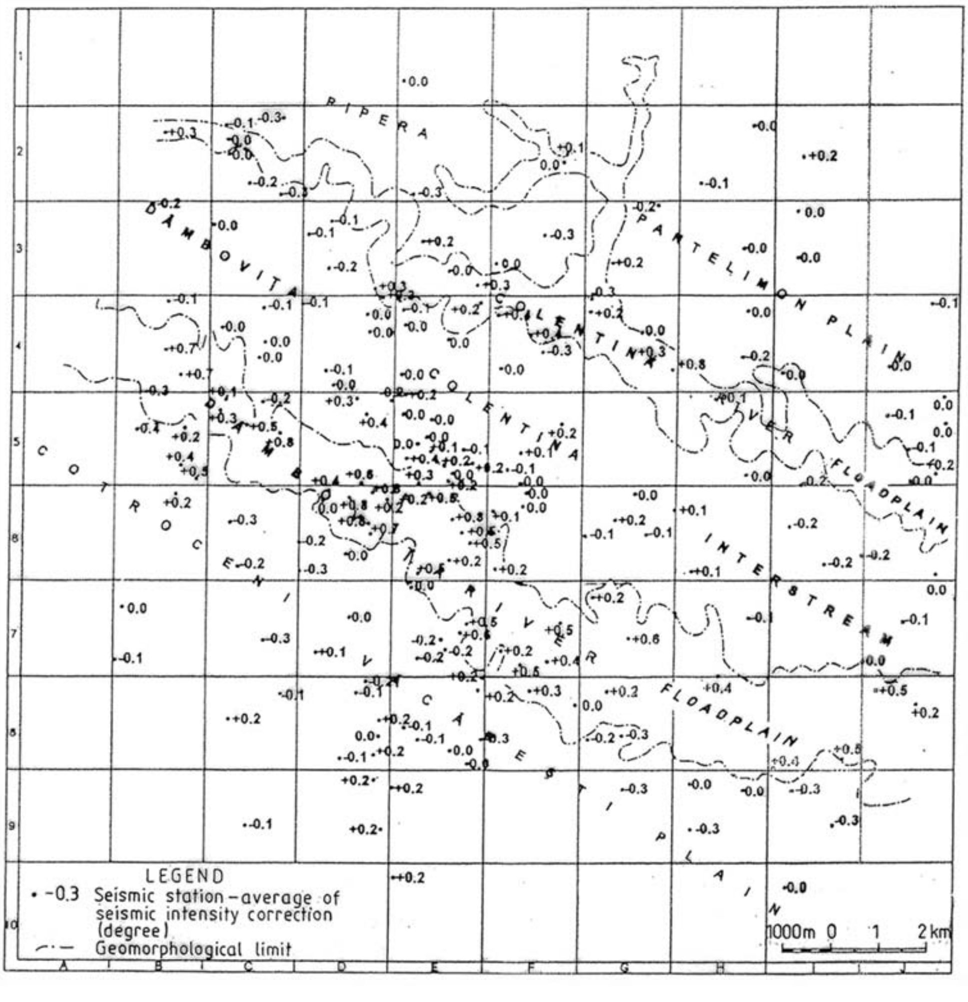

Fig. 9 – Values of the average seismic intensity corrections computed by the Medvedev method (1960).

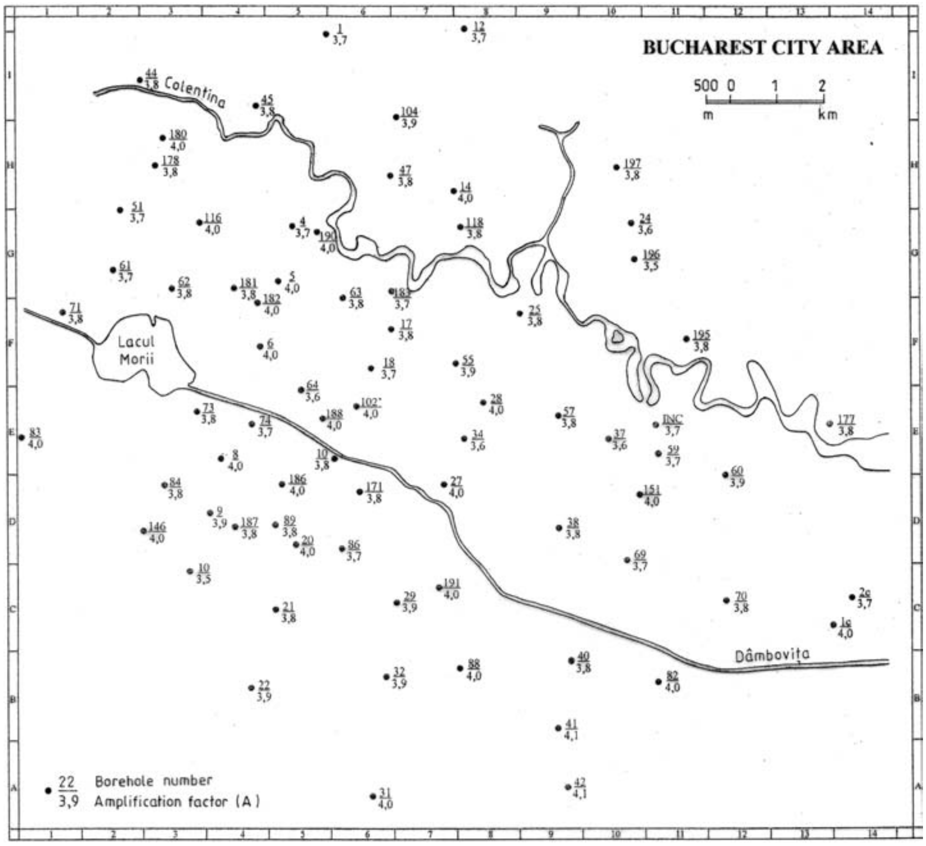

Fig. 10 – Ground motion amplification factor (*A*) using the relation proposed by Okamoto (1973).

2.1.4. 1-D site response analysis

For some seismic stations (EREN, MTR, INC, MET, MLT and TIT) from the Bucharest city area the dynamic amplification factor was computed using 1D geological structure. As one can notice (Fig. 11, Table 1), amplifications occur in two period domains: 0.3 s – 0.5 s, and 0.8 s and 1.6 s, according to the conditions from the station subsoil. The very large amount of boreholes allowed us to separate in the Quaternary deposits, two layer complexes above the Frăteşti gravels (Fig. 3): *a)* a lower complex, represented by the marl, lacustrian deposit, which was formed in the Middle Pleistocene, having the thickness between 47 m and 135 m and *b)* an upper complex, Upper Pleistocene-Holocene, river-lacustrian and continental, represented by the Mostiştea sands, the intermediate clay, the Colentina sands and gravels, the loesslike deposits and river alluvia. The thickness of the latter complex is much lower, between 30 m and 50 m. The spectral peaks for the 0.3 s and 0.5 s periods represent the resonance characteristics of the layers found over the marl complex, and the ones of 0.8 s and 1.6 s represent the response of the whole Quaternary deposits above the Frăteşti layers (see Figs. 3 and 4). In case of a large Vrancea intermediate-depth earthquake (M > 7.0), the deposits behave as a whole, the maximum amplifications being near the intermediate and mid-periods band. The influence of the layers close to the surface becomes insignificant. See the acceleration response spectrum for Vrancea intermediate-depth earthquake of March 4, 1977 (Mw = 7.4) recorded at the INC seismic station (see inset in the upper right corner from Fig. 11).

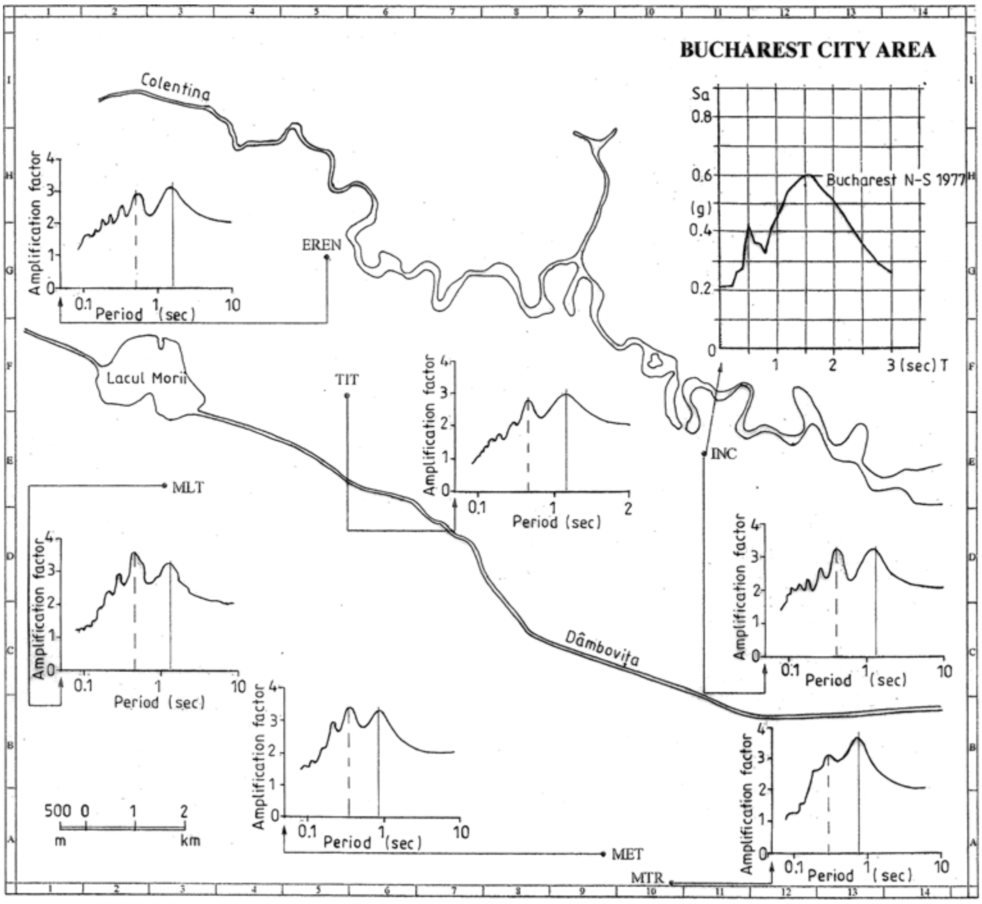

Fig. 11 –1-D ground motion amplification factor for six seismic stations in the Bucharest area. The solid vertical line represents the fundamental period predicted by the quarter wavelength law for the geological deposit above the Frăteşti gravel/marl complex interface (see Fig. 7); the dashed line represents the fundamental period predicted for the geological deposits above the Upper Pleistocene-Holocene/marl complex interface. In the upper right corner of the figure is presented the acceleration response spectrum of the 1977 earthquake (Mw = 7.4) recorded at the INC seismic station (Ambraseys, 1978).

2.2. SITE RESPONSE EVALUATION BASED ON THE STRONG-MOTION RECORDS ANALYSIS

The recent Vrancea intermediate-depth earthquakes were recorded by a relatively large number of instruments, providing in this way important information on the site response characteristics. Fig. 12 shows the epicenters of the 1986, 1990 (May 30), 2004 earthquakes and other 15 moderate-size subcrustal earthquakes occurred between November 1997 and May 2002. The epicenter positions and the focal mechanism for the largest Vrancea shocks (1940 and 1977) are also showed.

The earthquake of August 30, 1986 (Mw = 7.1). Seven stations recorded this earthquake in Bucharest (Fig. 13A). The PGA values are given in Table 2. The table specifies also the seismic station coordinates, instrument type and orientation, local soil type, hypocentral distance. The values of the ground motion parameter come from two sources (Lungu *et al.*, 2000 and INCERC Report, 2001). In our analysis we used data from the latter source. The maximum acceleration (peak ground acceleration) has values between 69.30 cm/s^2 (MTR station, instrument installed at the second level of the subway tunnel) and 161.10 cm/s^2 (EREN station). The latter value suggests the existence of a special site amplification. However, the local geological and geophysical conditions (Mândrescu, 1972, 1978, 1995) do not justify such a variation. Also, the apparent shape of the record is uncommon. As one can notice, on the fragment from the EREN record (Fig. 14A), the normal calibration of the pulses before and after the earthquake is missing. Moreover, the original accelerogram and the digitization of the vertical component are missing, too. The next important seismic event of May 30, 1990 which could have brought some light concerning the ground response in that place, recorded in other 7 stations in Bucharest, was not recorded at EREN (Report INCERC, 2001). Consequently we consider suspect the record obtained at EREN during the earthquake of August 30, 1986 (in fact, the only record obtained in this site).

The earthquake of May 30, 1990 (Mw = 6.9). This earthquake was also recorded by 7 instruments in Bucharest area (with two differences, EREN not operating and a new station available DRS, Fig. 13B). The PGA (Table 3) has values between 67.4 cm/s^2 (TIT station) and 151 cm/s^2 (PND station). Note the obvious similarity among the records at different stations (Fig. 14B).

The Vrancea intermediate-depth earthquake of October 27, 2004 (Mw = 6.0). The earthquake was produced at the depth of 105 km. The stations which recorded this earthquake are shown in Fig. 13C.

Moderate-size Vrancea intermediate-depth earthquakes (4.0 < Mw < 5.3). As we mentioned before, for the local response evaluation we analyzed the records of the moderate-size earthquakes occurred between November 18, 1997 and May 3, 2002 (see Table 4). Only the earthquakes with the moment-magnitude between 4.0 and 5.3 are considered in order to assure a good signal-to-noise ratio. The seismic stations which recorded these events are shown in Fig. 13D. Each station recorded between 4 and 11 seismic events. The source parameters are given by the Romplus catalogue (Oncescu *et al.*, 1999).

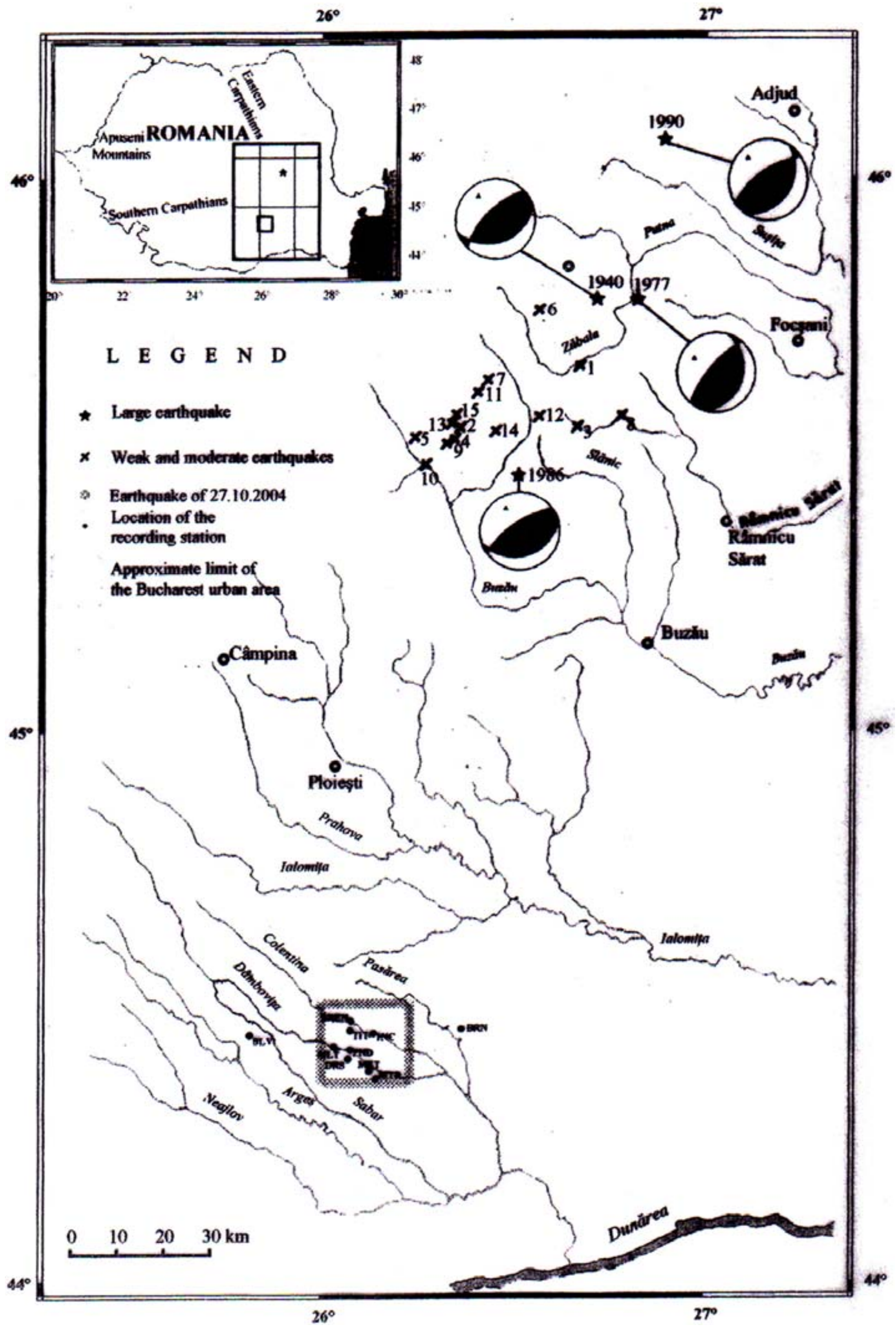

Fig. 12 – Epicenters of the Vrancea intermediate-depth earthquakes used in this study. Fault plane solutions for the largest shocks are also represented.

Table 2

Peaks of strong-motion acceleration, velocity and displacement characteristics of the accelerograms recorded in Bucharest during the Vrancea intermediate-depth earthquake of August 30, 1986

No.	Recording station / Position	Lat (° N)			Long (° E)			Instrument type	Instrument orientation	Soil type[1]	Hypocentre distance[2] (km)	Component	Peak acceleration (cm/s²)		Peak velocity (cm/s)		Peak displacement (cm)	
													a	b	a	b	a	b
1	EREN	44°	27'	40"	26°	04'	40"	SMAC-E	N 10° W	C	160	R	156.00	161.10	15.10	15.10	3.10	3.09
									W 10° S			T	105.80	105.80	14.50	14.40	2.80	2.70
	G.F.											V	42.00	-	-	-	-	-
2	INCERC (INC)	44°	25'	30"	26°	10'	15"	SMAC-B	N - S	C	161	T	88.70	97.00	15.50	15.50	3.70	3.60
									E - W			R	95.30	103.50	10.50	11.30	2.50	2.50
	G.F.											V	28.00	20.60	-	2.70	-	5.80
3	Metalurgiei (MET)	44°	21'	20"	26°	08'	45"	SMA-1	W32° S	C	167	T	71.70	71.70	14.80	14.80	3.10	3.10
									N 37° W			R	40.70	40.70	4.80	4.80	1.00	1.01
	G.F.											V	34.40	34.40	3.20	3.15	0.70	0.70
4	Militari (MLT)	44°	25'	15"	26°	02'	30"	SMA-1	N - S	C	165	R	71.20	72.10	8.40	8.40	2.30	2.20
									E - W			T	100.60	101.00	14.00	14.00	3.40	3.20
	G.F.											V	44.10	41.10	3.30	3.30	0.80	0.70
5	Metrou (MTR)	44°	21'	00"	26°	09'	45"	SMA-1	N 30° W	C	168	T	59.50	59.50	7.10	7.06	1.60	1.50
									N 120° W			R	69.30	69.30	12.80	12.80	2.80	2.80
	2B											V	29.50	29.50	2.40	2.40	0.60	0.60
6	Panduri (PND)	44°	24'	40"	26°	04'	40"	SMA-1	N 131° E	C	165	T	89.40	89.00	8.20	8.10	1.40	1.40
									N 139° W			R	96.20	96.20	15.00	15.00	2.80	2.80
	G.F.											V	64.10	64.10	5.40	5.40	0.80	0.80
7	Titulescu (TIT)	44°	26'	15"	26°	04'	55"	SMA-1	N 145° W	C	162	T	87.50	87.00	15.40	15.40	3.20	3.20
									N 55° W			R	83.80	83.00	7.50	7.50	1.40	1.30
	B											V	52.90	52.00	5.00	5.00	0.90	0.20

[1] After N. Mândrescu: Intermediate-depth earthquakes from 1986 (August 30) and 1990 (May 30 and 31): geological and seismological aspects, St. Cerc. Geophys. 1995, 33, 31–40 (in Romanian)

[2] Based on epicenter location of Lat. 45°5'N, Long. 26°5'E

Position: G.F. – Ground floor; B – Basement; 2B – Second basement

Component: R=Radial; T=Transversal; V=Vertical

Digitized data of the strong-motion come frome the following source:

a – D. Lungu, A. Aldea, C. Arion, S. Demetriu, T. Cornea, Microzonage Sismique de la Ville de Bucarest (Roumanie), Cahier Technique, 20, AFPS, p. 60, 2000

b – Technical Report MENER (INCERC, Seismic data of the Romanian earthquakes. December, 2001)

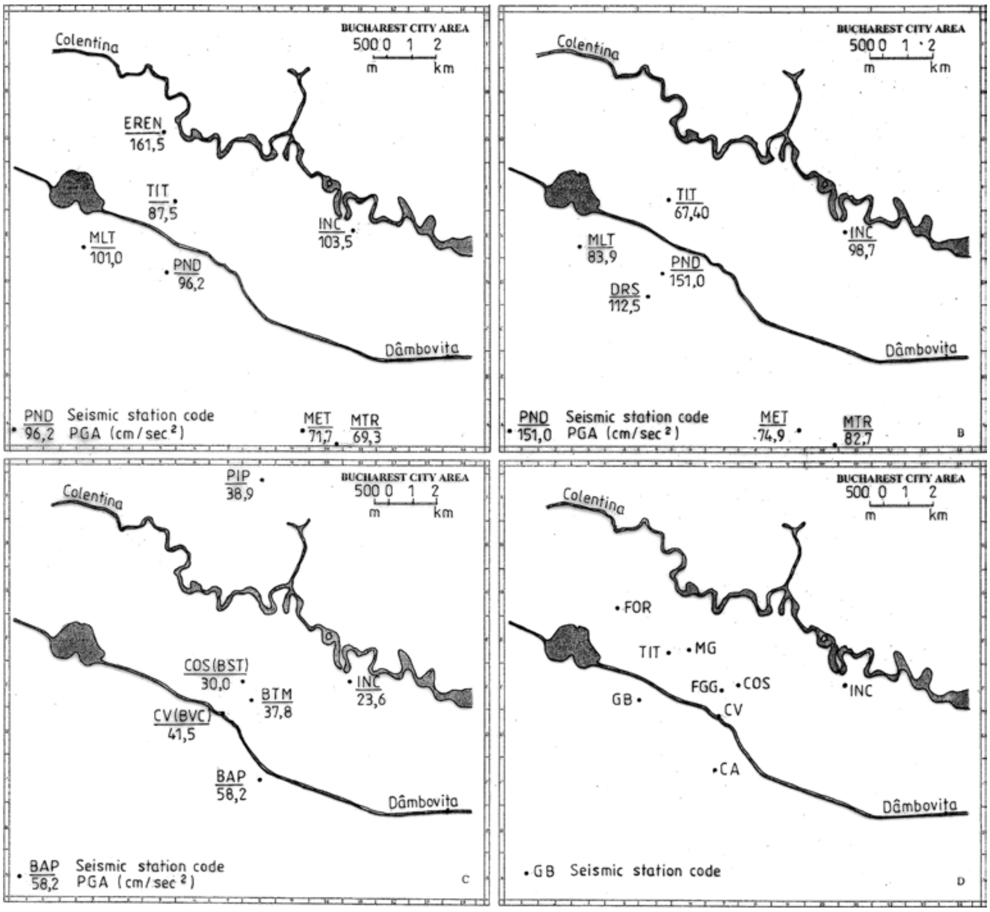

Fig. 13 – Locations of the seismic stations which recorded the August 30, 1986 event (*A*), the May 30, 1990 event (*B*), the October 27, 2004 event (*C*) and the moderate-size events occurred between November 18, 1997 and May 3, 2002 events (*D*).

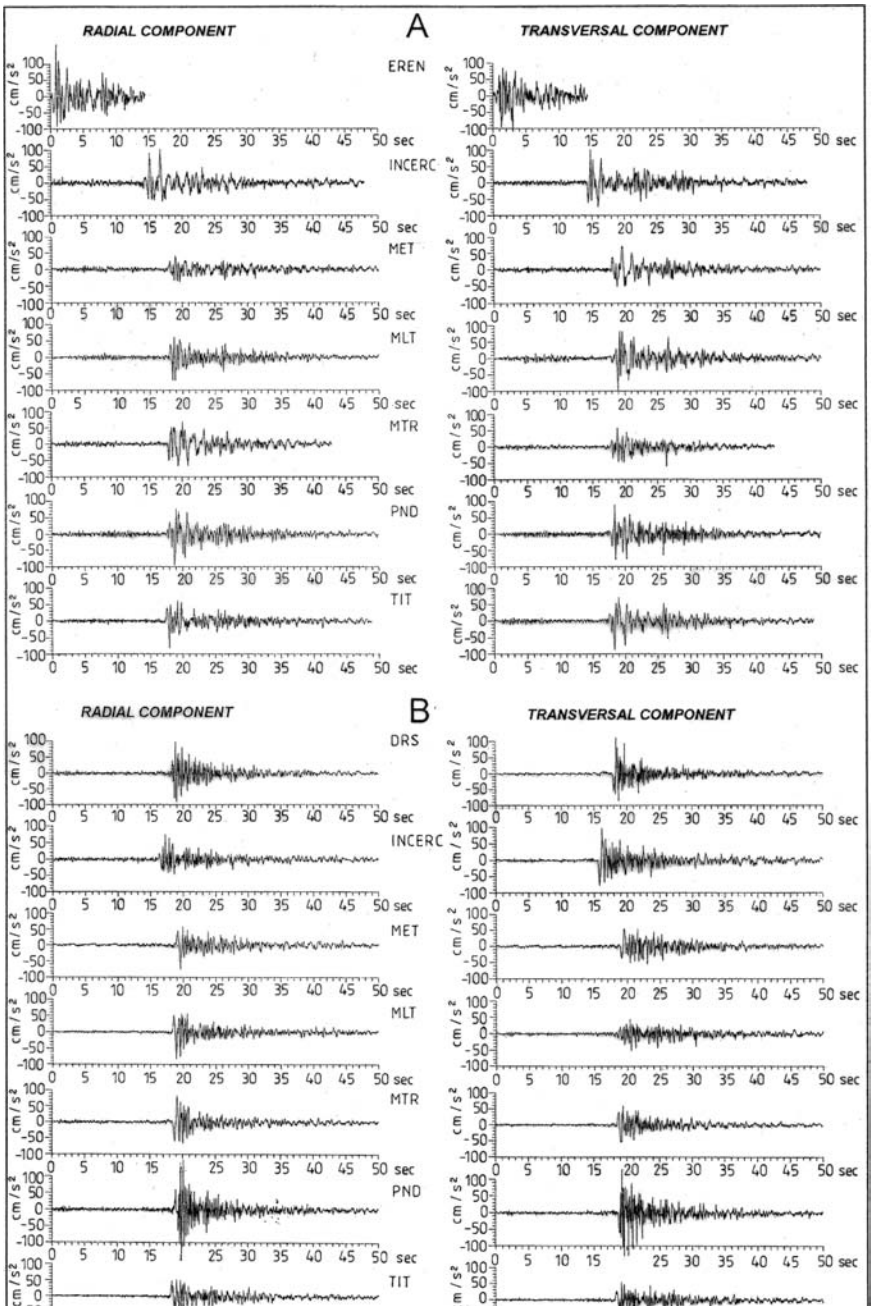

Fig. 14 – Radial and transversal components of acceleration of stations which recorded the 1986 (*A*) and 1990 (*B*) events.

Table 3

Peaks of strong-motion acceleration, velocity and displacement characteristics of the accelerograms recorded in Bucharest during the Vrancea intermediate-depth earthquake on May 30, 1990

No.	Recording station / Position	Lat (° N)			Long (° E)			Instrument type	Instrument orientation	Soil type[1]	Hypocentre distance[2] (km)	Component	Peak acceleration (cm/s²)		Peak velocity (cm/s)		Peak displacement (cm)	
													a	b	a	b	a	b
	Drumul Sării (DRS)								N 84° W			T	112.50	98.00	13.20	5.40	2.00	0.90
1		44°	24'	10"	26°	04'	20"	SMA-1	N 174° W	C	203	R	97.90	87.00	5.40	2.50	1.00	0.50
	G.F.											V	87.70	88.00	2.50	2.50	0.50	0.50
	INCERC (INC)								N - S			R	76.60	66.20	6.20	6.30	1.10	1.00
2		44°	25'	30"	26°	10'	15"	SMAC-B	E - W	C	197	T	98.70	98.90	17.20	17.00	-3.00	2.90
	G.F.											V	-	27.90	-	2.70	-	5.60
	Metalurgiei (MET)								W32° S			T	59.00	55.40	8.20	8.80	1.60	1.60
3		44°	21'	20"	26°	08'	45"	SMA-1	N 37° W	C	205	R	76.30	74.90	9.20	10.20	1.70	2.00
	G.F.											V	43.30	39.60	2.30	2.50	0.50	0.70
	Militari (MLT)								N - S			T	51.10	50.60	3.40	3.80	0.90	1.10
4		44°	25'	15"	26°	02'	30"	SMA-1	E - W	C	203	R	95.30	83.90	11.10	10.10	1.80	1.60
	G.F.											V	43.80	41.10	2.30	2.90	0.50	0.70
	Metrou (MTR)								N 30° W			R	90.80	82.70	10.60	11.40	2.00	2.00
5		44°	21'	00"	26°	09'	45"	SMA-1	N 120° W	C	206	T	60.20	59.90	7.70	8.30	1.10	1.26
	2B											V	50.10	47.30	3.00	2.90	0.40	0.60
	Panduri (PND)								N 131° E			T	127.90	131.00	7.90	9.60	1.30	1.30
6		44°	24'	40"	26°	04'	40"	SMA-1	N 139° W	C	203	R	136.60	151.00	7.70	10.60	1.00	1.30
	G.F.											V	57.90	81.00	2.60	2.90	0.40	0.50
	Titulescu (TIT)								N 145° W			T	56.80	56.80	6.70	6.60	1.30	1.20
7		44°	26'	15"	26°	04'	55"	SMA-1	N 55° W	C	201	R	67.40	67.40	9.60	9.60	1.70	1.60
	B											V	48.70	48.70	4.90	4.80	1.40	1.40

[1] After N. Mândrescu: Intermediate-depth earthquakes from 1986 (August 30) and 1990 (May 30 and 31): geological and seismological aspects, St. Cerc. Geophys. 1995, 33, 31–40 (in Romanian)

[2] Based on epicenter location of Lat. 46° 3' N, Long. 26° 9' E

Position: G.F. – Ground floor; B – Basement

Component: R=Radial; T=Transversal; V=Vertical

Digitized data of the strong-motion come from the following source:

a – D. Lungu, A. Aldea, C. Arion, S. Demetriu, T. Cornea, Microzonage Sismique de la Ville de Bucarest (Roumanie), Cahier Technique, 20, AFPS, p. 60, 2000

b – Technical Report MENER (INCERC, Seismic data of the Romanian earthquakes. December, 2001)

Table 4

Catalog of the selected moderate-size Vrancea intermediate-depth earthquakes occurred between November 18, 1997 and May 3, 2002

No.	Origin time	Lat. ° N	Long. ° E	Depth (km)	M_w	Stations which recorded the earthquakes
1	18.11.1997 11:23	45.53	26.52	123	4.7	CA, FGG, FOR, INC
2	30.12.1997 04:39	45.54	26.32	139	4.6	CA, FGG, INC
3	19.01.1998 00:53	45.64	26.67	105	4.0	CA, MG, GB, FOR
4	13.03.1998 13:14	45.56	26.33	155	4.7	CA, FOR, MG, GB, FGG, INC
5	27.07.1998 15:02	45.67	26.53	135	4.4	FGG, MG, GB, FOR, INC
6	22.03.1999 19:25	45.52	26.31	144	4.4	FGG, MG, GB, FOR, INC
7	28.04.1999 08:47	45.49	26.27	151	5.3	FGG, MG, GB, FOR, INC
8	29.04.1999 18:44	45.62	26.40	148	4.0	FGG, MG, GB,FOR, INC
9	08.11.1999 19:22	45.55	26.35	138	4.6	FGG, INC
10	04.03.2001 15:38	45.51	26.24	154	4.8	TIT, MG, COS, CV
11	28.03.2001 22:07	45.77	26.53	121	4.3	TIT, MG, CV
12	24.05.2001 17:34	45.63	26.42	144	4.9	TIT, MG, COS, CV
13	20.07.2001 05:09	45.75	26.79	132	4.8	TIT, COS, CV
14	16.03.2002 22:39	45.55	26.46	142	4.3	MG, COS
15	03.05.2002 18:32	45.58	26.33	162	4.6	MG

2.2.1. Acceleration response spectra

The acceleration response spectra show directly the effects of the ground acceleration upon a simple, typical structure, including the structure dynamic response, the duration and all the details of the frequency content (Hudson, 1970). The response spectra computed for the resultant of the maximum acceleration for every earthquake in every station are presented on the same figure to make easier the comparative analysis of the local effect (Fig. 15). A simple visual inspection underlines obvious similarities of the spectra for every seismic event, but different from one event to another.

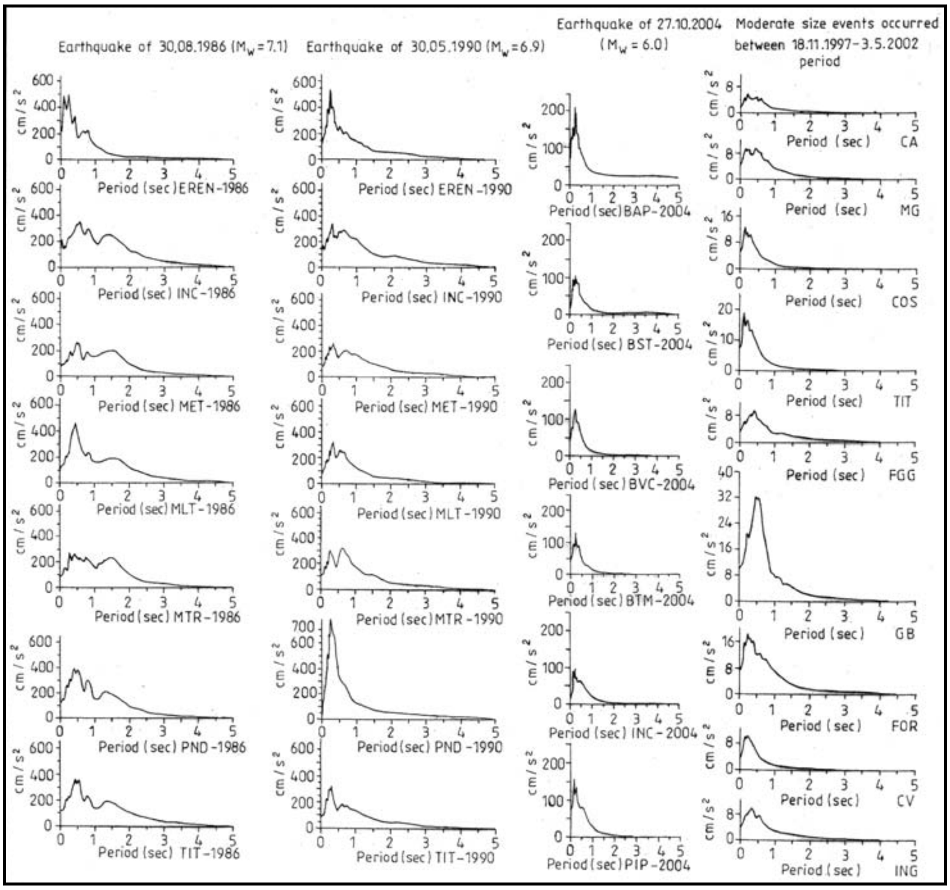

Fig. 15 – The acceleration response spectra of the earthquakes analyzed in this study.

For the earthquake of 1986, except the EREN spectrum (where one can see a maximum amplification around 0.3 s), we remark the existence of a maximum of the dynamic amplification around 0.5 s and two secondary maxima at 0.8 s and respectively at 1.5 s. These maxima are better emphasized in the average response spectra (Fig. 17Aa). At the stations MTR and MET, the amplifications are almost constant between 0.3 and 1.5 s, with less obvious but, anyway, identifiable maxima.

For the earthquake of 1990 (May 30) there are maximum amplifications around the periods 0.3 s and 0.7 s (Fig. 15). The average response spectra (Fig. 17Ab) clearly show the existence of a maximum amplification around 0.3 s and an additional maximum, around 0.7 s.

For the earthquake of 2004, the acceleration response spectra show only one maximum value, around 0.2 and 0.3 s (Fig. 15). The average value of the response spectra is around 0.25 s (Fig.17Ac).

For the moderate-size earthquakes the spectral peaks (Fig. 15) show amplifications around 0.2 and 0.6 s. The average response spectra (Fig. 17Ad) have amplifications around 0.2 and 0.3 s.

Our analysis shows no tendency of dependence of the spectral amplification on site location. This is explained by the relatively uniform geology with the same layers extended over large areas (Mândrescu *et al.*, 2004). To this respect, it is worth mentioning that no systematic distribution of the maximum acceleration values among the stations is observed. The maximum value per event and seismic station differs from one earthquake to another and this variability is comparable with the expected random errors (Bolt, 1983; Abrahamson and Youngs, 1992; Somerville and Moriwaki, 2003).

2.2.2. The power spectral density

The power spectral density defines the spectral domain which corresponds to the maximum power of the seismic signal, therefore to the predominant period. The power spectral density values computed for the records of 1986, 1990, 2004 events and for the moderate-size earthquakes are presented in Fig. 16. The diagram analysis shows, for each event, an obvious similarity, although the relative amplitudes of the maxima are different.

For the 1986 earthquake we can distinguish two domains: one, well individualized, with higher amplitudes, grouped around 1.5 s and another, with lower amplitudes, grouped around 0.5 and 0.8 s. In addition, the power spectral densities at INC, MLT and TIT stations have a clear maximum around 2.2 s. The average power spectral density (Fig. 17Ba), computed on the basis of all the records of 1986 earthquake, has relatively well individualized spectral peaks around the values of 0.5 s, 0.8 s, 1.5 s and 2.2 s.

For the earthquake of 1990, the power spectral density maxima have much wider variation domains, from 0.3 to 2.0 s and the spectral peak amplitude is relatively low. The average power spectral density (Fig. 17Bb) has a flat aspect and covers a wide domain, from 0.3 to 2.0 s, without being able to individualize a certain spectral maximum.

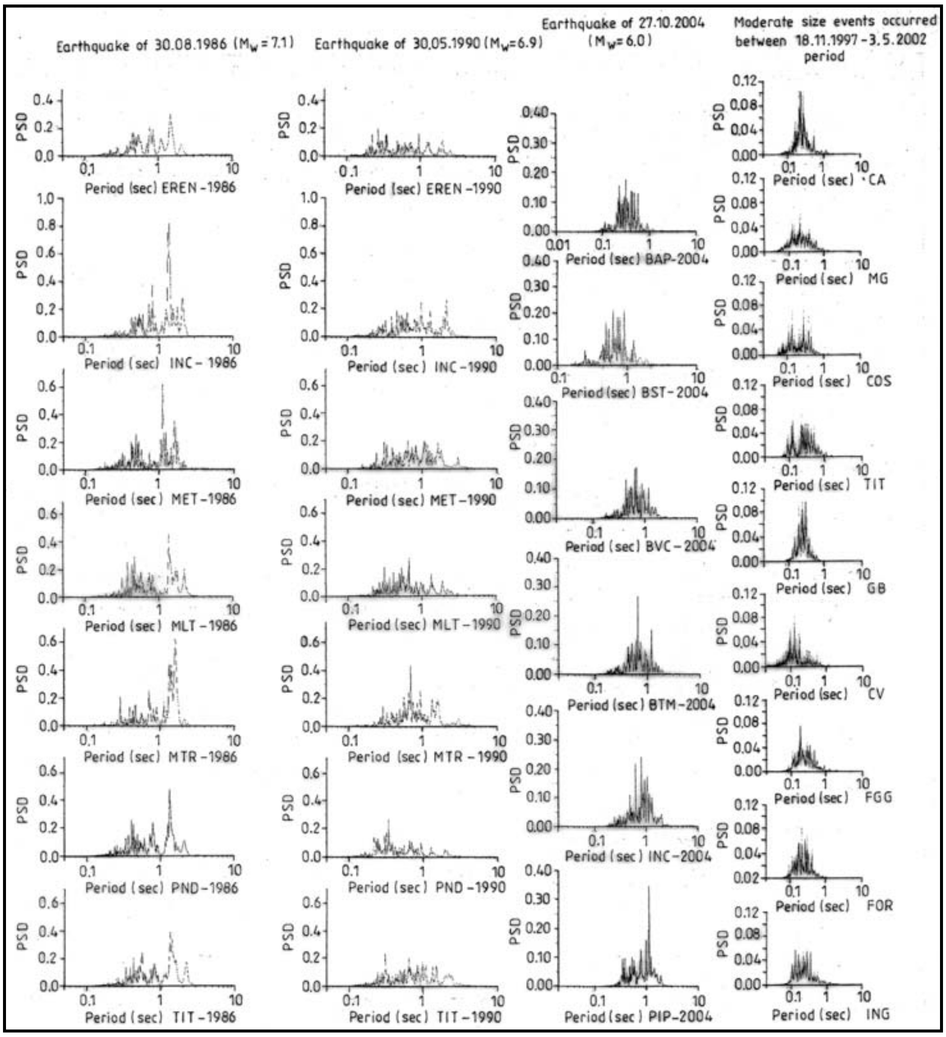

Fig. 16 – The power spectral density of the earthquakes analyzed in this study.

The earthquake of 2004 shows amplifications around 1.0 s at INC and PIP stations; between 0.2 and 0.6 s at the BAP station; at BTM, BST and BVC stations (Fig. 16), the values are 0.4 and 0.8 s. The average values are placed between 0.4 and 1.2 s (Fig. 17Bc).

In the case of the *moderate-size earthquakes*, we can not separate a prominent peak, corresponding to a certain period (Fig. 16). The amplifications, having almost equal values, are distributed over an interval between 0.2 and 0.6 s. The average power spectral density (Fig. 17Bd) shows maximum amplifications for values between 0.2 and 0.4 s and a secondary peak around 0.15 s.

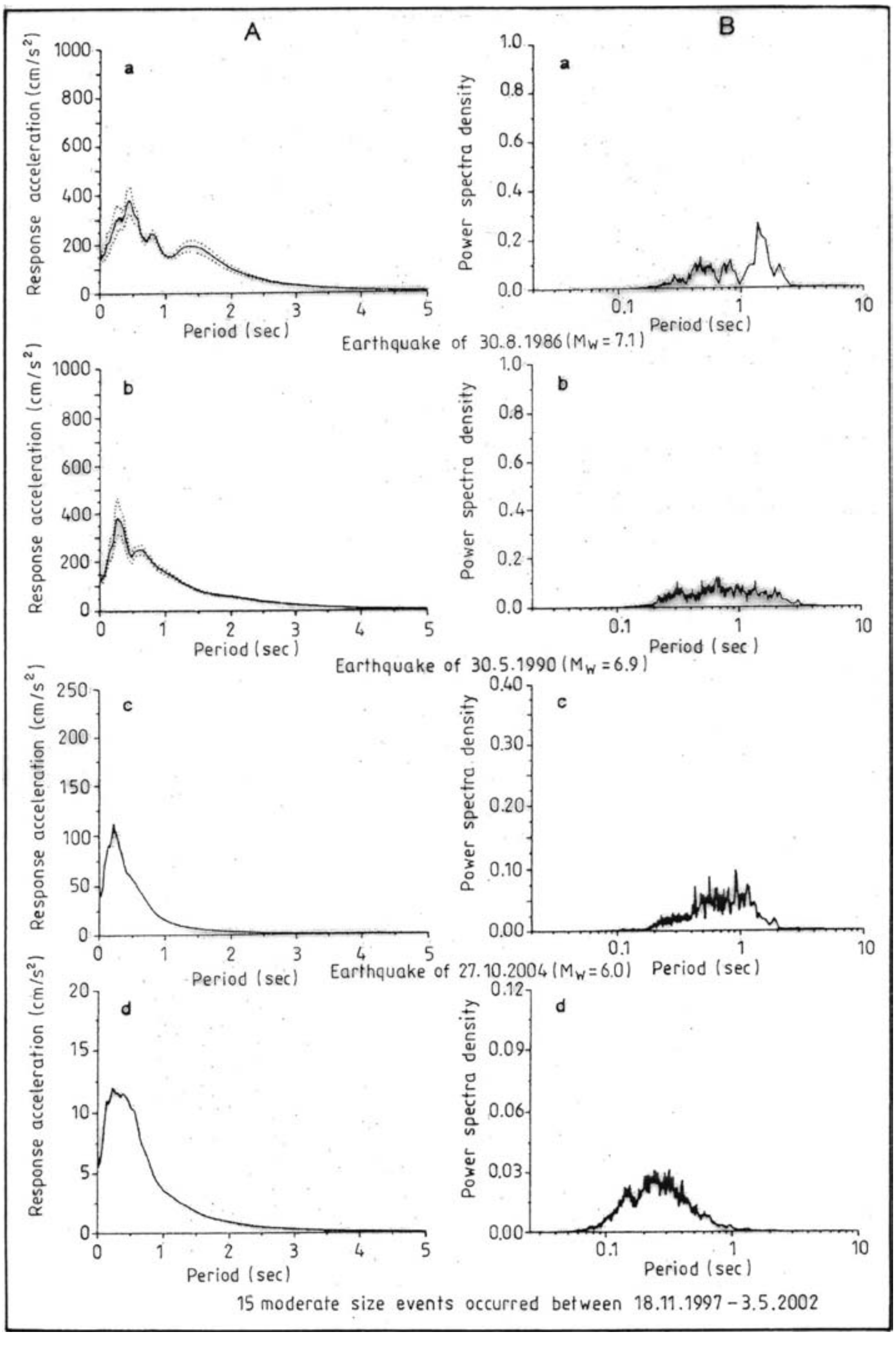

Fig. 17 – Average acceleration response spectra ± 1 standard deviation (*A*) and power spectral density (*B*) for all of the earthquakes used in this study.

2.2.3. Comparative analysis of the acceleration response spectra of the earthquakes records, obtained at the INCERC (INC) seismic station

The INC is the only station that recorded all the significant Vrancea earthquakes, including the large event of March 4, 1977. In order to evaluate the degree of stability of the dynamic amplification process of the ground motion due to Vrancea earthquakes, we made a comparative analysis of the acceleration response spectra and of the power spectra density using the records at INC for the events of 1977, 1986, 1990, 2004 and eight earthquakes of moderate size (Fig. 18).

For the eight moderate-size earthquakes ($4.0 < Mw < 5.3$) the average acceleration response spectra show that the maximum amplifications occur around 0.3 s; the earthquake of October 27, 2004 has amplifications between 0.2 and 0.3 s; the earthquake of 1990 shows maximum spectral amplifications around of 0.3 and 0.7 s; the earthquake of 1986 presents amplifications around 0.6 and 0.8 s and the amplification becomes more clear around 1.4 s, amplification which is enhanced in the case of the earthquake of 1977 (Fig. 18A).

The average power spectra density in the case of the moderate earthquakes, shows amplifications over the domain between 0.1 and 0.4 s. The earthquake of October 27, 2004 shows spectral amplifications around 1 s; the earthquake of 1990 presents spectral peaks around 1.0, 1.5 and 2.2 s; the 1986 earthquake spectrum presents clearly two domains: a main one around 1.4 and the other one around 2.2 s. In the case of the earthquake of 1977, the peaks remain well individualized around the values 1.4 and 2.2 s (Fig. 18B). The similitude among the spectra based on records of the same earthquake done at various stations in Bucharest leads us to the conclusion that the results of the comparative analysis carried out for the INC station are characteristic for the other seismic stations as well, and as a matter of fact for the entire city area.

3. DISCUSSION AND CONCLUSIONS

As our results can be directly used for practical purposes (*e.g.*, to accomplish the seismic microzonation map of Bucharest urban area), it is important to identify the errors sources in the computed parameters. For computation of predominant period, seismic intensity corrections, and amplification factors we made some simplifications, and suppositions which could be all error sources. So, it was assumed that the velocity models decided on the basis of the geophysical measurements are homogeneous over the whole city area. The individual values measured in boreholes are close to real values, but the sites between the boreholes could be characterized by specific subsoil properties causing variations more or less important relatively to the assumed homogeneous model. In the theoretical computation we considered that above the bedrock there is only one elastic,

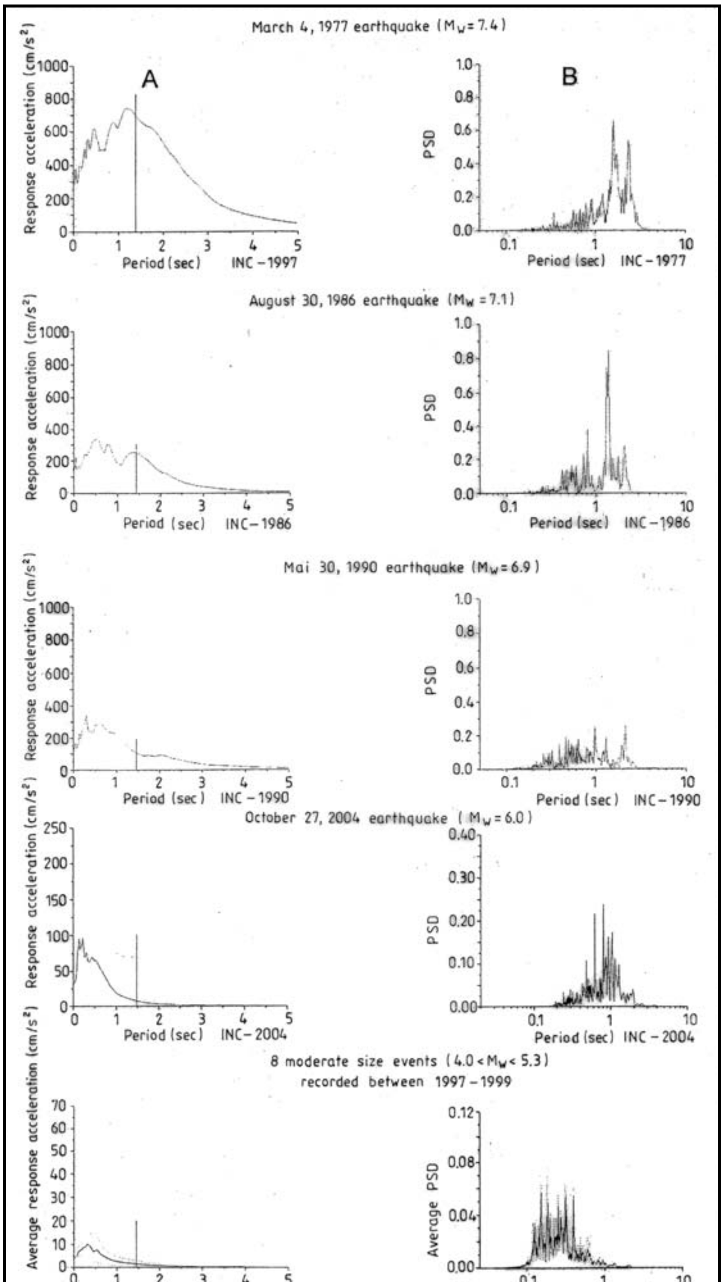

Fig. 18 – The acceleration response spectra (*A*) and the power spectral density (*B*) of the earthquakes recorded at the INC station. The vertical line (on the acceleration response spectra) represents the fundamental period predicted by the quarter wavelength law for the INC station.

homogeneous layer, characteristic for the whole area. In reality, in the subsoil of Bucharest, above the Frăteşti gravels (considered as bedrock) a succession of layers can be found, each one with specific dynamic characteristics and different thicknesses, even if these differences are not so obvious. To compute the predominant period (*Ts*) and dynamic amplification factor (A) we selected only the boreholes which reach the Frăteşti gravels. Because there is a gradual passage from one layer to the other, with no clear contrast, or obvious limit, there can be some errors in measuring the thickness of every layer and, consequently, its influence in the value of the average velocity. There can also be errors in determining the real limits between the Frăteşti gravels and the bottom of the marl complex. Another source of errors could be due to the small number of direct geophysical measurements and also to the technical difficulties related to the correct determination of seismic wave velocity in boreholes, most of all at greater depths. To all these, we can add the possible errors which could be introduced from the initial data, which, at least partially, come from the re-interpretion of the information from other works.

Anyway, we consider that the possible errors can not influence significantly our main results. The lithological structure, the sequence, spatial distribution and dynamic characteristics of the strata from the subsurface of the city are reflected by the small variation of the seismic intensity corrections (Fig. 9) and the dynamic amplification factors (Figs. 10 and 11) and their geographic distribution. Some differences will be determined by the increasing thickness of the resonant layer from south to north of the city, and the increase in the fundamental period in the same direction, from 1.0 s in the south to about 2.0 s in the northern part of the city (Fig. 7).

The acceleration response spectra computed for the earthquakes recorded in Bucharest underlines similarities of the spectra for every seismic event, but different from one event to another (Fig. 15). The comparative analysis of the acceleration response spectra for the earthquakes recorded at the same station shows that the dynamic amplification peaks shift from short periods to intermediate or mid-ones at the same time with the growth of the earthquake magnitude (Fig. 18).

The power spectra density of the 1990, 1986, 1977 earthquakes (Fig. 14B), outlines a dynamic amplification around the 2.2 s period, which could become a serious threat for the tall buildings in Bucharest, in case of a large Vrancea earthquake.

The existence of two main lithological complexes in the Quaternary deposits account for the unstationary of the dynamic amplification process from one earthquake to another. In our opinion, the moderate-size subcrustal earthquakes ($M < 7.0$) stimulate the Upper Pleistocene-Holocene deposits (located above the marl complex) and cause amplifications in the short period domain. In case of strong subcrustal earthquakes ($M > 7.0$) all the cohesionless Quaternary deposits (including the marl complex) are excited and react unitarily, causing amplifications of the intermediate and mid-band period; the influence of the strata close to the surface is greatly diminished, the acceleration response spectrum having practically a single peak (see inset from the upper right corner in Fig. 11). This proves that the information acquired through the study of weak and moderate-size earthquakes cannot be extrapolated to anticipate the ground response in Bucharest during the large Vrancea intermediate-depth earthquakes.

Our study concerning the site response evaluation emphasizes the good correlation between the results coming from the two principal data sets used: *a)* physical characteristics of the natural environment and *b)* observational data, supplied by the acceleration records of the Vrancea intermediate-depth earthquakes occurred between 1977 and 2004.

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