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EARTH PHYSICS

NEW APPROACH ON SEISMIC HAZARD ISOSEISMAL MAP FOR ROMANIA

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Abstract. The seismicity of Romania comes from the energy that is released by *crustal* earthquakes, which have a depth not more than 40 km, and by the *intermediate* earthquakes coming from Vrancea region (unique case in Europe) with a depth between 60 and 200 km. The authors developed the concept of "control earthquake"and equations to obtain the *banana* shape of the attenuations curves of the macroseimic intensity I (along the directions defined by azimuth Az), in the case of an Vrancea earthquake at a depth $80 < x < 160$ km. There were used deterministic and probabilistic approaches, linear and nonlinear ones. The final map is in MMI intensity (isoseismal map) for maximum possible Vrancea earthquake with Richter magnitude, $M_{GR} = 7.5$. This will avoid any drawbacks to civil structural designers and to insurance companies which are paying all damages and life loses in function of earthquake intensity.

Key words: seismic events, isoseimal map, control earthquake, intermediate earthquakes.

1. INTRODUCTION

The seismicity of Romania comes from the energy that is released by **crustal** earthquakes, which have a depth not more than 40 km, and by the **intermediate** earthquakes coming from Vrancea region (unique case in Europe) with a depth between 60 and 200 km. The crustal earthquakes are clusterd in several epicenter areas: Vrancea, Făgăraş Mountains and Câmpulung, Oradea, Crişana and Maramureş, South and North Dobrogea; to this list we must mention the local earthquake areas like: Jibou, Târnave in Transilvania, North and Western Oltenia, North Moldavia, Romanian Plain, Bârlad depression, intramoesic fault. At international level the knowledge concerning this field of work, resumes more, to normal earthquakes (crustal ones), which are the most relevant and numerous at global scale, including Europe. For our country, the most important are the *Vrancea intermediate depth earthquakes* that have a severe influence on the extracarpathic territory and even parts of neighbouring countries (Bulgaria, Republic of Moldavia and Ukraine).

2. EXISTING STAGE

The last zonation seismic map, existing since 1993, has areas where seismic intensities are sub-evaluated (*e.g.* Dobrogea, Banat etc.), and other areas are over-evaluated. Intensities I = IX on Mercalli scale, at which corresponds a 0.4 g level of acceleration, and 0.8 g at rupture/yielding, make Vrancea county to become an unsustainable development area for the future. A special situation is represented by the Banat area where the last recorded earthquakes from Banloc, Voitec requires a change in the seismic intensities of this area. On the other hand, the chapter regarding „Seismic action" from „Norms for construction building – 2004", in experimental stage, proposed by MTCT and *unaccepted* by National Institute for Earth Physics, proposes design acceleration values far from credible ones. The maximum design acceleration level for Focșani is 0.32 g. At the 30.08.1986 Vrancea earthquake, $M_{GR} = 7.0$ (actually 6.95), the peak ground recorded acceleration recorded in Focșani was 0.304 g. The maximum magnitude for a Vrancea earthquake is $M = 7.5$ on Richter scale. The peak ground acceleration for a 475 years recurrence period and for maximum possible earthquake ($M_{GR} = 7.5$) will be significantly greater than 0.34 g. Also, the maximum peak ground acceleration of 0.36 g for Bucharest can not be justified. The fundamental unacceptable point of view is that this design code is in peak ground accelerations which generates a lot of drawbacks to civil structural designers and to insurance companies which are paying all damages and life loses in function of earthquake intensity.

3. THE INTENSITY MAP FOR STRONG VRANCEA INTERMEDIATE DEPTH EARTHQUAKES

The concept of seismic intensity (or severity of earthquake ground motion) is at present a common concept for seismologists, structural engineers and other specialists, or even non-specialists. Persons working with this concept are recognizing at the same time its importance and some current shortcomings of it. The most important shortcomings that must be emphasized at this place consist of the imperfect definition of the concept, of the fact that the main criteria for intensity estimate are based on vulnerability characteristics which, at their turn, are defined conditionally upon the intensity (building thus a source of bias and tautology), of the lack of satisfactory correlation between the macroseimic intensity on one hand and the instrumental criteria on the other hand [Sandi, 1987].

An interesting particularity is the intensity deforming Vrancea zone, shows a quite enigmatic seismic pattern. In plan view, the earthquakes are localized to a restricted area in the bending zone between the Eastern and Southern Carpathians at least three units in contact: the East European plate, Intra-Alpine and Moesian sub-plates. The Eastern Carpathians have a very thick crustal root of 55–60 km thickness, which is probably bounded by faults and the Transylvanian basin has normal thickness (30–33 km).

Earthquakes in the Carpathian-Pannonian region are confined to the crust, except the Vrancea zone, where earthquakes with focal depth down to 200 km occur. For example, the ruptured area migrated from 150 km to 180 km (November 10, 1940 Vrancea earthquake, $M_w = 7.7$), from 90 to 110 km (March 4, 1977 earthquake, $M_w = 7.4$), from 130 to 150 km (August 30, 1986, $M_w = 7.1$) and from 70 to 90 km (May 30, 1990, $M_w = 6.9$) depth. The depth interval between **110** km and **130** km remains not ruptured since 1802, October 26, when it was the strongest earthquake occurred in this part of Central Europe. The magnitude is assumed to be $M_w = 7.9$–8.0 and this depth interval is a natural candidate for the next strong Vrancea event.

The maximum intensity for strong deep Vrancea earthquakes is quite distant from the actual epicenter and greater than the epicenter intensity. In 1977 strong earthquake ($M_w = 7.4$) at its epicenter, in the Vrancea region, the estimated intensity was only VI (MMI scale), while some 170 km away in the capital city of Bucharest, the estimated maximum intensity was IX–IX½ (MMI).The intensely deforming Vrancea zone shows a quite enigmatic seismic pattern (peak ground accelerations/intensity one, characteristic response spectra with large periods of 1.5 seconds, no significant attenuations on Romanian territory, large amplifications away etc.).

The complexity of the geology of the extra-Carpathian region is obvious (Figs. 1 and 2). The geology of main cities from this area, like Iași, Bacău, Buzău and Craiova is complex. The basement of Iași is constituted of the structural elements of the Moldavian Platform, composed of: (i) folded basement of gneissic, migmatitic granite-gneissic mesometamorphic formations and (ii) sedimentary cover (quartzitic sandstones, black schists, siliceous sandstones, calcareous sandstones, limestones, glauconitic sandstones, silex, sandstones and marls, clays, sands with intercalations of sandstones, quaternary gravels and sands). Bacău city is located on the sedimentary filling of the external avantfosse, built by normal stratigraphic succession: marls and sandstones formations, clayey-sandy deposits, sands, clays and sandstones, gravels, sands and clays, quaternary gravels and sands with loessic intercalations. Buzău is situated in the external avantfosse of the Eastern Carpathians, to East of the flexure separating the internal and external zones. The avantfosse represents the younger structural element from the external border of the Carpathic area. The sedimentary filling of the external avantfosse is represented by a thick pile of deposits, over 3000 m thickness, constituted of clays and marls, sands and clays, sandstones and sands, marls and sands, sands and coaly clays, clays and sands, gravels and sands, gravels, sands and loessic deposits. The

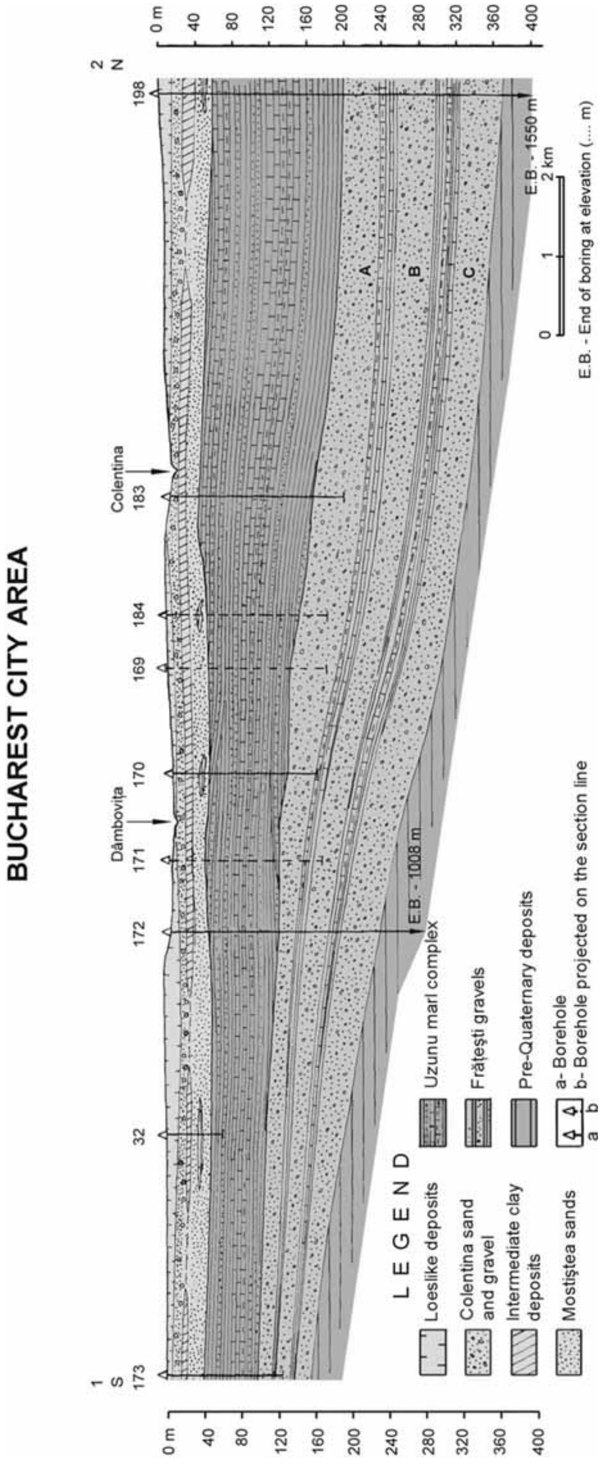

Fig. 1 – Isobaths are generally oriented from east to west, with a slope of about 8‰ dipping from south to north. In the same direction we can notice that the layers become thicker and thicker.

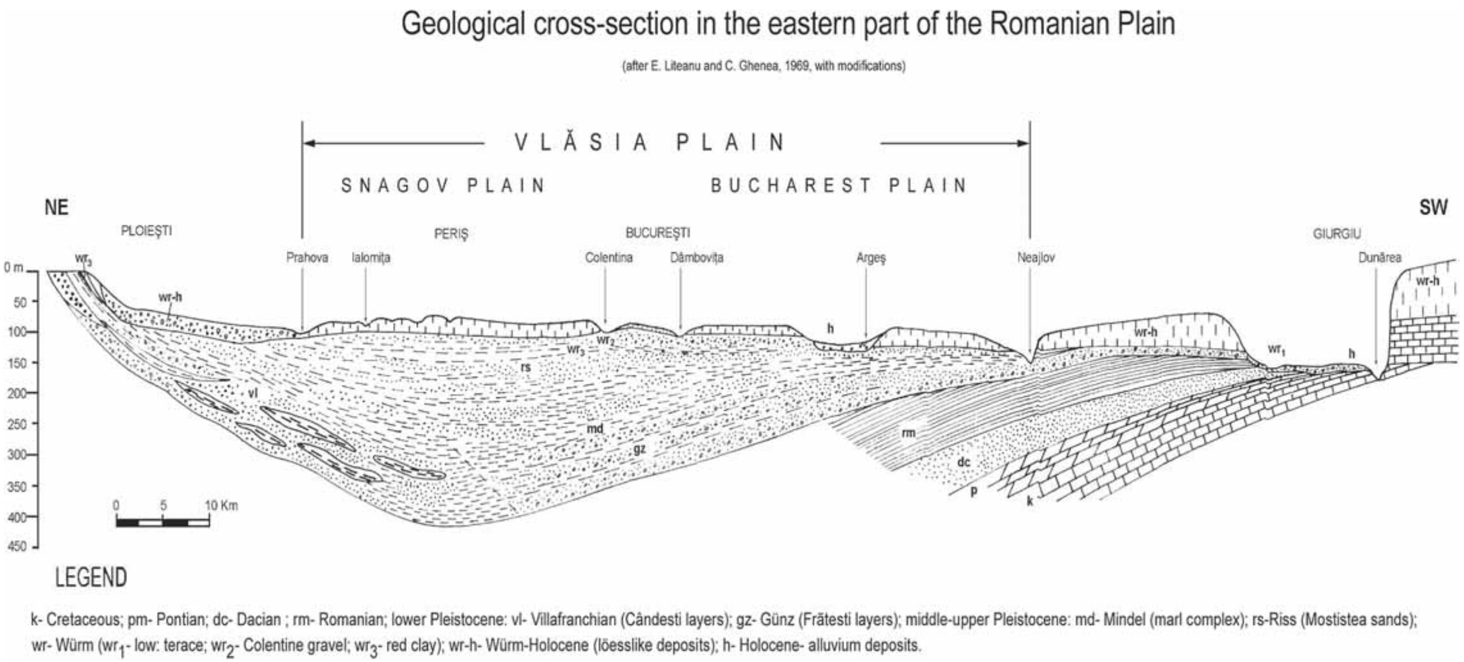

Fig. 2 – Geological section through Quaternary layers from Ploiești to Giurgiu and Danube river.

basement of Craiova is represented by the Oltean threshold or the raised area Craiova-Balș-Optași, from the Walach sector of the structural unit Moesic Platform. This sector is constituted of metamorphic rocks (Moesic basement), sedimentary cycles (cover in fact) and detritic sedimentary rocks (Tertiary post-tectonic cover). Both the basement and the cover of the platform are affected by two systems of fractures: (i) a principal system oriented East-West, which produced a separation in blocks that descend in successive steps North-South and, (ii) more secondary systems.

The scientific problems regarding the waves propagation on source-cristalin fundament-free soil path taking into account the nonlinear behavior are the most recent researches conducted the NIEP in this domain. This was important especially for the city of Buzău where sedimentary layers thickness is up to 5.0 km and constitutive laws concerning shear and strain dependence are viscoelastic nonlinear. Almost similar case is the city of Iaşi where we were dealing with very different sites topography, consisting in hills and plane areas. In Figs. 1 and 2 are given the Bucahrest City area isobaths and, respectively, the geological section through Quaternary layers from Ploiești to Giurgiu and Danube river (Marmureanu *et al.*, 2005).

Many attempts have been made to correlate intensity (I) with recorded ground motion parameters (so called "**instrumental intensity map**"), as well as the hazard assessment for future events, which require a regression relationship between intensity and strong-ground-motion parameters. The correlation of intensity with peak amplitudes (*e.g.*, Trifunac and Brady 1975, Murphy and O'Brien 1977, Krinitzsky and Marcuson 1983, Sandi 1987, Wang 1995 etc.) shows typically larger scater. At present there is no doubt that seismic intensity is an expression of amplitude, duration and frequency content of ground motion, Recently, Sokolov 2002 presented a revised method for estimating the seismic intensity (MMI or MSK scale) by using Fourier amplitude spectra of ground acceleration. If $A(f)$ is the Fourier acceleration spectra calculated in the frequency range 0.2–17 Hz for the most significant portion of the horizontal components of the records and have been equally spaced in intervals, then

$$\log_{10} A(f) = 0.49\, I - 2.0, \tag{1}$$

where the values of $\log_{10}A(f)$ in this correlation are calculated at the "representative" frequencies f_R , which depend on the intensity, and decrease with increasing intensity level (Sokolov 2002).

3.1. THE "ETALON (REFERENCE)" EARTHQUAKE

Enescu *et al.* 2001, 2004 and 2007 continued the elaboration of an estimation method of the seismic hazard generated of strong and deep Vrancea earthquakes by considering only the strong earthquakes ($M_{GR} > 6.5$) produced in Vrancea area after 1940 (Table 1). It was observed that all epicenters are on the same line NE-SV (direction AB) and also for maxim macroseimic intensity I_0-direction A′B′ (Fig. 3) which is parallel to epicenter line AB.

Table 1

Nr.	Date	Time	φ° N	λ° E	*h* [km]	M_{GR}	M_W	I_0
1	November 10,1940	01:39:07	45.8	26.70	**150**	**7.4**	**7.7**	**IX½**
2	March 4,1977	19:22:15	45.34	26.30	**109**	**7.2**	**7.5**	**IX**
3	August 30,1986	21:28:37	45.53	26.47	**135**	**7.0**	**7.1**	**VIII½**
4	May 30,1990	10:40:06	45.82	26.90	**90**	**6.7**	**6.9**	**VIII**

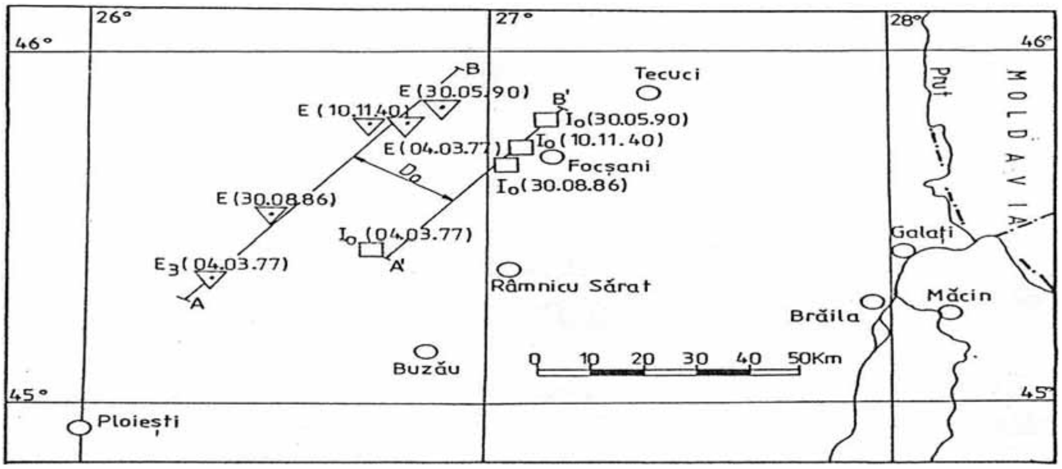

Fig. 3 – Epicentres *E* and I_0 points corresponding to the four strong and major earthquakes ($M_{GR} \geq 6.7$) occurred in the last 68 years: November 10, 1940 ($M_{GR} = 7.4$); March 4, 1977 ($M_{GR} = 7.2$); August 30, 1986 ($M_{GR} = 7.0$) and May 30, 1990 ($M_{GR} = 6.7$) (after D. Enescu, Gh. Marmureanu, B. D. Enescu, 2001).

The peak ground accelerations (a_{max}) and resultant one ($a_{max.res.}$) for Vrancea earthquake on August 30, 1986 ($M_{GR} = 7.0$) recorded by SMA-1 instruments from 32 seismic stations from NIEP and INCERC are given in Table 2 (Gavril Danci – 1979. Ph.D.Thesis, Library of the Bucharest University).

The earthquake on August 30, 1986 is used by us as “control earthquake” in all next studies as it fulfils the following states: (i) it was strong ($M_{GR} = 7.0$); (i) it was recorded in a lot of seismic station on Romanian territory; (iii) the fall plan solutions are very closed (almost identically) to other Vrancea stronger earthquakes (November 10, 1940; $M_{GR} = 7.4$ and March 4, 1977; $M_{GR} = 7.2$) and with majority of earthquakes with moderate magnitudes ($6.5 < M_{GR} < 7.0$); (iv) the depth of oh hypocenter ($h \approx 135$ km) is very close to medium value of all strong Vrancea earthquakes.

Table 2

PGA recorded at seismic stations on Romanian territory on August 30, 1986 earthquake

Nr.	Seismic station	a_{max} [cm/s^2]	$a_{max.res.}$ [cm/s^2]	Nr.	Seismic station	a_{max} [cm/s^2]	$a_{max.res.}$ [cm/s^2]
1	Arges (ARR)	24	26	19	Giurgiu (GRG)	60	64
2	Bacău (BAC)	89	110	20	Iași (IAS)	100	108
3	Baia (BAA)	34	36	21	Istrița (ISR)	109	111
4	Bârlad (BIR)	164	175	22	Lotru (LOT)	14	15
5	Bolintin (BLV)	88	93	23	Muntele Roșu (MLR)	79	80
6	Botoșani (BTS)	23	25	24	Onești (ONS)	158	168
7	Brăila (BRL)	110	117	25	Otopeni (OTP)	215	228
8	Brănești (BRN)	92	98	26	Piatra Neamț (PTT)	11	12
9	București (BUC)	71–161	75–171	27	Ploiești (PLS)	218	232
10	Câmpulung (CMP)	77	82	28	Râmnicu Sărat (RMS)	153	163
11	Cernavodă (CVD)	63	64	29	Roznov (RZN)	19	21
12	Carcaliu (CFR)	90	96	30	Surduc (SDR)	70	75
13	Constanța (CNT)	34	36	31	Tulcea (TLC)	68	72
14	Craiova (CVR)	81	86	32	Turnu Măgurele (TRM)	60	64
15	Deva (DEV)	8	9	33	Vaslui (VSL)	202	215
16	Dochia (DCH)	51	51	34	Văleni Munte (VLM)	193	205
17	Focșani (FOC)	297	312	35	Vrâncioaia (VRI)	141	144
18	Galați (GLT)	120	128				

Using the peak ground accelerations (PGA), recorded during strong Vrancea earthquakes on March 4, 1977 (M_{GR} = 7.2), August 30, 1986 (M_{GR} = 7.0), May 30, 1990 (M_{GR} = 6.7) and May 31, 1990 (M_{GR} = 6.1) and the corresponding macroseimic intensities, there are the following relations (Enescu, 1997):

$$\log a_{max}\ [\mathrm{cm/s^2}] = 0.2712\, I + 0.1814, \tag{2}$$

$$\log a_{max.res.}\ [\mathrm{cm/s^2}] = 0.2714\, I + 0.2085 \quad \text{for} \quad \mathrm{V} = \mathrm{I} = \mathrm{IX}, \tag{3}$$

and the corresponding isoseismal map of the "etalon" earthquake is in Fig. 4. The family of attenuation laws, developed in last time by NIEP [1, 2], determined for the azimuths of Bucharest and all cities from extra-Carpathian area are given by the family of curves for so called "etalon earthquake" or "reference earthquake" (August 1986, M_{GR} = 7.), has the following equations:

$$\log(I_e / I_{0e})\mathrm{Az} = a(\mathrm{Az}) - b(\mathrm{az})\log(R_e / f(h_e)) \tag{4}$$

or

$$\log(I_e / I_{0e})\mathrm{Az} = a'(\mathrm{az}) - b(\mathrm{Az})\log f(h_e) \tag{5}$$

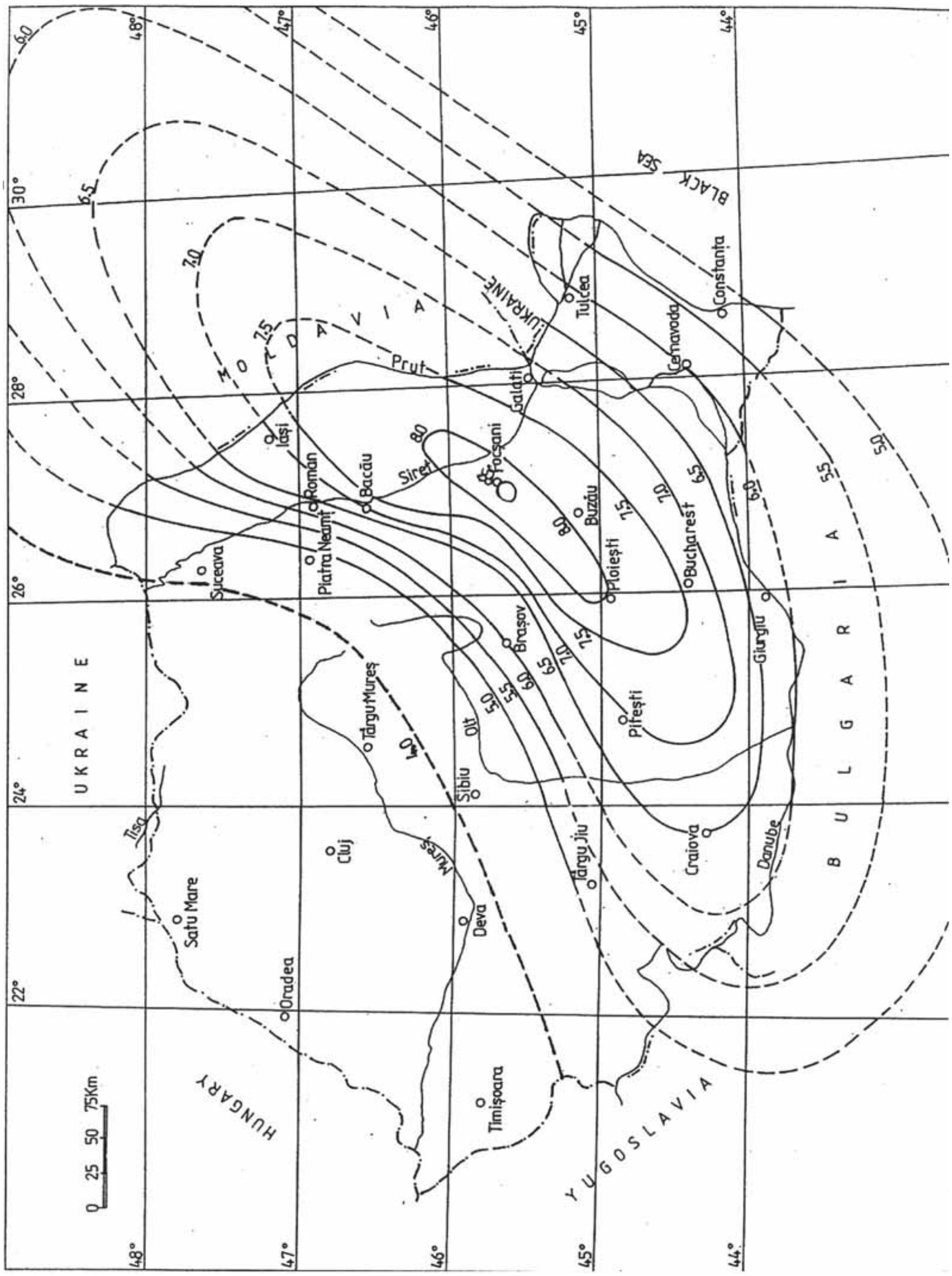

Fig. 4 – Isoseismal map of the *etalon* earthquake (after D. Enescu, Gh. Marmureanu, B. D. Enescu, 2001).

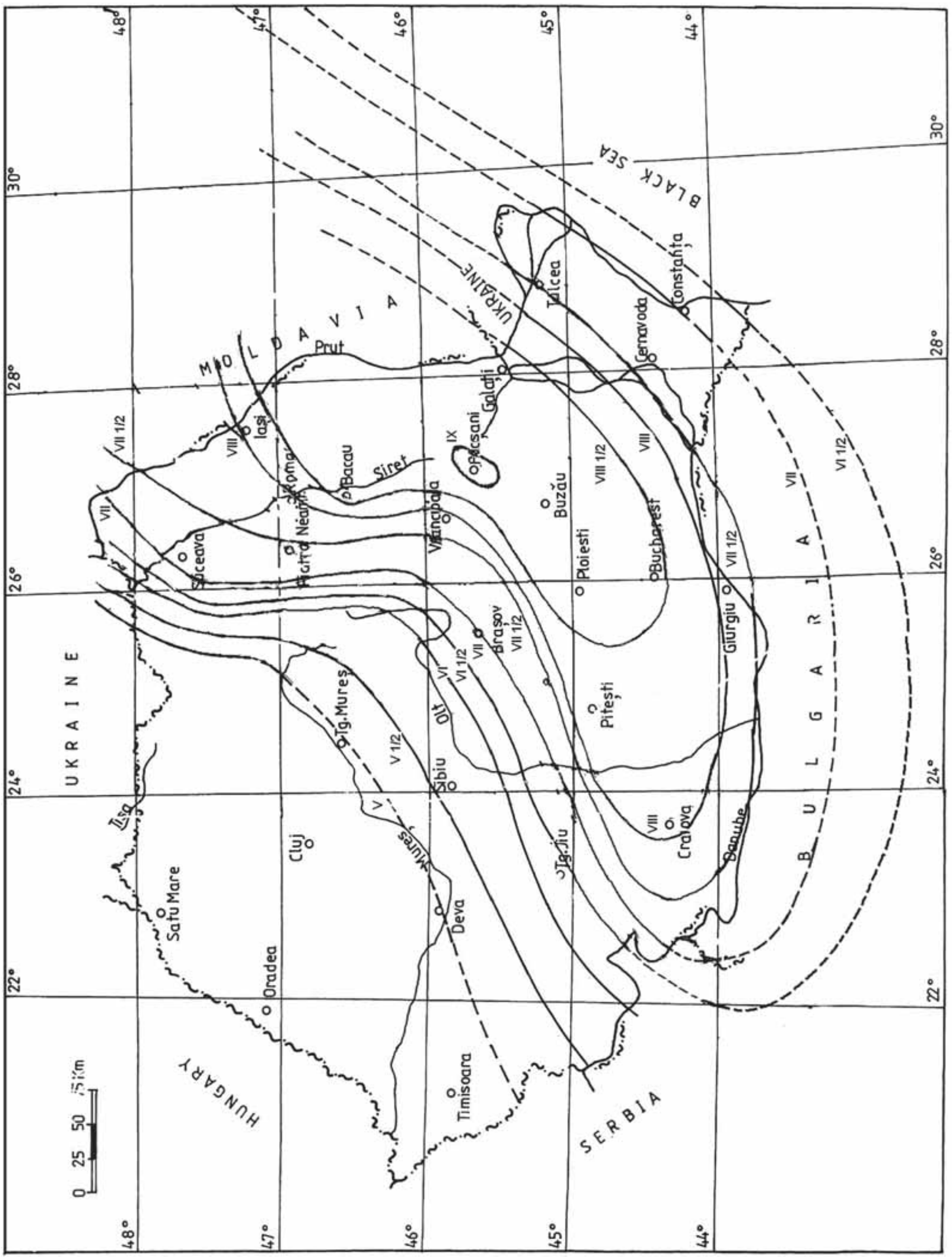

Fig. 5 – The isoseismal map of the maximum possible Vrancea earthquake (M_{GR} =7.5).

where: I_{0e} is the maximum intensity of the "etalon" earthquake; I_e is the intensity of the "etalon" earthquake at a hypocentral distance R_e (along the direction defined by azimuth Az);

$$a'(\mathrm{Az}) = a(\mathrm{Az}) + b(\mathrm{az}) \log f(h_e); \qquad (6)$$

a and b are constant coefficients for a given Az; h_e is the focal depth of the "etalon" earthquake. The coefficients $a'(\mathrm{Az})$ and $b(\mathrm{Az})$ of the attenuation curve family for the etalon earthquake (Table 3) are computed by means of the least square method; C_d from Table 3 is the coefficient of correlation. The values 0.900–0.992 of coefficient C_d (Table 3) prove that the equation (5) represents well the attenuation curves of the "etalon" earthquake (Enescu *et al.*, III).

On the other hand, to obtain the *banana* shape of the attenuations curves of the macroseimic intensity I (along the directions defined by azimuth Az), in the case of an Vrancea earthquake at a depth $80 < x < 160$ km, we developed the following equation [2]:

$$\log I_{x,\mathrm{Az}} = \log I_{0x} + \log[I_e / I_{0e}]_{\mathrm{Az}} + b(\mathrm{Az}) \log[R_e / f(h_e) / R_x / f(x)]_{\mathrm{Az}} + [c \log\delta]_{\mathrm{Az}} \qquad (7)$$

where: I_{0x} is the maximum intensity of an earthquake at a depth $h = x$; δ is the directivity factor of the rupture propagation in the focus [1]; c is the way how the directivity factor may influence the directivity of the seismic source [1];

Table 3

The coefficients $a'(\mathrm{Az})$ and $b(\mathrm{Az})$ from Equation 6

$(\mathrm{Az})^0$	a	b	C_d	$(\mathrm{Az})^0$	a	b	C_d
0	1.22702	0.58127	0.986	210	0.87691	0.43273	0.973
15	0.90014	0.42463	0.978	225	0.92337	0.40448	0.961
30	0.63058	0.29683	0.959	230	0.83521	0.38613	0.957
38	0.51591	0.24538	0.970	240	0.72277	0.34322	0.962
45	0.49790	0.23864	0.977	245	0.71403	0.34445	0.969
60	0.61111	0.29668	0.967	255	0.83510	0.41327	0.909
75	0.98228	0.47142	0.977	258	1.05631	0.51857	0.900
90	1.28924	0.61734	0.986	263	1.12968	0.55801	0.913
105	1.47779	0.70709	0.987	270	1.52947	0.74511	0.931
120	1.57776	0.75503	0.986	285	2.11722	1.02170	0.943
135	1.53155	0.73335	0.985	300	2.64049	1.26767	0.950
150	1.39169	0.66706	0.988	315	2.93848	1.40508	0.966
165	1.23445	0.59187	0.990	330	2.59805	1.24096	0.970
180	1.11992	0.53515	0.990	345	1.97714	0.94255	0.980
195	1.00167	0.47567	0.988	353	1.49197	0.71086	0.992

$R_e = (D^2 + h_e^2)^{1/2}$; $R_x = (D^2 + x^2)^{1/2}$; D is the distance between the observation point of maximum macroseismic intensity.

4. CONCLUSIONS

The seismicity of Romania comes from the energy that is released by *crustal* earthquakes, which have a depth not more than 40 km, and by the *intermediate* earthquakes coming from Vrancea region (unique case in Europe) with a depth between 60 and 200 km.

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The authors developed the concept of *control* earthquake. The earthquake on August 30, 1986 is used by us as *"control" earthquake* in all next studies as it fulfils the following states: (i) it was strong ($M_{GR} = 7.0$); (ii) it was recorded in a lot of seismic station on Romanian territory; (iii) the fall plan solutions are very closed (almost identically) to other Vrancea stronger earthquakes (November 10, 1940; $M_{GR} = 7.4$ and March 4, 1977; $M_{GR} = 7.2$) and with majority of earthquakes with moderate magnitudes ($6.5 < M_{GR} < 7.0$); (iv) the depth of hypocenter ($h \approx 135$ km) is very close to medium value of all strong Vrancea earthquakes.

The maximum possible Vrancea earthquake has the Richter magnitude, $M_{GR} = 7.5$ and this is the magnitude used by us for our Cernavodă Nuclear Plant. The isoseismal map of the maximum possible Vrancea earthquake is given in Fig. 4. Next researches made by us using deterministic approach will give the possibility to complete this isoseismal map with crustal earthquakes from Banat, South of Dobrogea, Moldova and Maramures.

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