Seismic Hazard: Recurrence and Attenuation of Subcrustal (60-170km) Earthquakes

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ABSTRACT: The hazard analysis for the Vrancea subcrustal earthquakes in Carpathian Mountains, Romania, include relationships for the recurrence of magnitude and directional attenuation functions for the ground acceleration. Sensivity of results to the maximum credible magnitude of the source and to the maximum recorded ground acceleration is discussed.

1 *Recurrence - magnitude relationships*

The major contribution to seismic hazard in Romania comes from Vrancea seismogenic zone, located where the Carpathian Mountains arc bends.

The both historical and instrumental Catalogues of Vrancea events use, the Gutenberg-Richter magnitude, M (Gutenberg - Richter, 1954).

As a systematization requirement, the Global Seismic Hazard Assessment Program in Europe (GSHAP, 1993) promoted at the GeoForschungsZentrum, Potsdam, Germany, recommends the use of the moment magnitude M_w.

For the subcrustal Vrancea earthquakes, the following magnitude conversion relationship may be obtained from the linear regression of available records during the 60yr.:

$$M_w = 1.09\ M - 0.36 \tag{1}$$

where: M is the Gutenberg-Richter magnitude and M_w is the moment magnitude.

The Gutenberg-Richter law for the recurrence of earthquakes with magnitude equal to and greater than M is determined from the Radu's catalogue of Vrancea intermediate depth magnitudes (M≥5.0) occurred during this century (1901-1994). It contains 103 seismic events.

The average number per year of Vrancea earthquakes with magnitude ≥ M, as resulting also from Fig.1, is (Lungu et al, 1995):

$$\log n(\geq M) = 3.49 - 0.72\ M \tag{2}$$

The Hwang and Huo (1994) modification of the Gutenberg-Richter relationship:

$$n(\geq M) = e^{\alpha-\beta M}\ \frac{1 - e^{-\beta(Mmax-M)}}{1 - e^{-\beta(Mmax-Mo)}} \tag{3}$$

was determined for the Vrancea source as (Elnashai, Lungu, 1995):

$$n(\geq M) = e^{8.036-1.658M}\ \frac{1 - e^{-1.658\ (7.8\ -\ M)}}{1 - e^{-1.658\ (7.8\ -\ 6)}} \tag{4}$$

where the threshold magnitude was selected as M_0=6.0,. the maximum credible magnitude of the source was selected as M_{max}=7.8, and 8.036 = 3.489 ln10 and 1.658 = 0.720 ln10. The magnitude recurrence relationship depend on the magnitude intervals it refers, such as, the threshold magnitude calibrates the coefficients of recurrence expression (2).

Although an exact estimation of the maximum credible magnitude of the source can not be done, even an approximate estimation of it has very important numerical consequences on the prediction of magnitude having large recurrence intervals. The maximum credible magnitude of the Vrancea source was estimated in the past to be at most M=8.0 and at least M=7.5.

Marza, Kijko and Mäntyniemi (1991) estimate as "reasonable and stable" a maximum magnitude of the source M_{max} = 7.8, (standard deviation) of 0.2. According to the same authors, the strongest experienced Vrancea earthquake is the 1802 event with a magnitude of M = 7.7 ± 0.3.

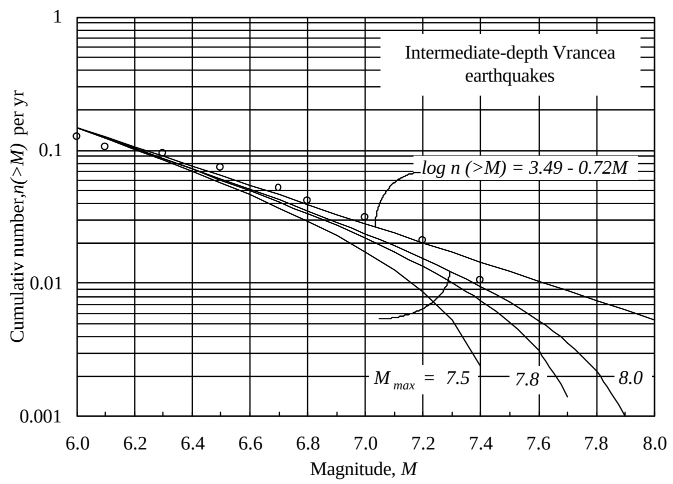

Fig.1 Magnitude-recurrence relation for the subcrustal Vrancea source ($M \geq 6.0$)

The strong correlation (r=0.84-0.96) between the source magnitude and the rupture parameters, given by regression equations developed (from a databank of 244 events in the period 1857-1993) by Wells and Coppersmith (1994), are used to establish confidently the maximum credible magnitude of the Vrancea source.

Firstly, the results obtained from Wells and Coppersmith equations are compared with the past experience of strongest Vrancea earthquakes duringthe last 60 years, Table 1.

Secondly, the validation of Wells and Coppersmith equations by the past experience of Vrancea events recommends the use of equations for the prediction of the rupture parameters for the maximum magnitude in the Vrancea region:

$\log RA=-3.49+0.91M_w$ $s=0.24$ $4.8<M_w<7.9$ (5)

$\log SRL=-3.22+0.69M_w$ $s=0.22$ $5.2<M_w<8.1$ (6)

The local geology combined with the mean and the mean plus one standard deviation values of rupture area (RA) and surface rupture length (SRL) from Wells and Coppersmith equations suggest as the (most probable) maximum credible Vrancea magnitude: M_w=8.1 (M=7.8).

Rupture parameters in Table 1 were excerpted from [1)]Tavera (1991) and [2)]Enescu (1985).

The sensitivity to M_{max} of the mean recurrence interval of the Vrancea magnitudes is presented in Table 2 and as well as in Fig.1.

The statistical counting procedure applied to Radu's historical catalogue of observed epicentral intensity during a millennium (threshold MSK intensity I_0=6.0; aftershocks not included; 182 events) yields the following intensity recurrence relation for subcrustal Vrancea events, (Lungu, Cornea, Coman, 1996):

$$\log n(\geq I_0) = 1.99 - 0.46\, I_0 \quad (7)$$

where n ($\geq I_0$) is the average number of events per year with an epicentral intensity $\geq I_0$.

Based on the epicentral intensity-magnitude conversion relationship recommended by Radu (1974), for intermediate depth Vrancea earthquakes:

$$M = 0.56\, I_0 + 2.18 \quad (8)$$

Eq.(7) combined with Eq.(8) lead to :

$$\log n(\geq M) = 3.78 - 0.82\, M \quad (9)$$

Table 1 Application of the Wells and Coppersmith regression equations (1994) to the Vrancea source

Gutenberg-Richter magnitude M	Moment magnitude M_w	Event	Observed rupture area, km^2	Wells and Coppersmith equations			
				Eq.(5) RA, km^2		Eq.(6) SRL, km	
				mean	mean+1 st.dev.	mean	mean+1 st.dev.
6.7	7.0	May 30, 1990	1100[1)]	646	1318	41	68
7.0	7.2	Aug.30, 1986	1400[1)]	1153	2005	56	93
7.2	7.5	Mar.4, 1977	63x37=2331[2)]	2163	3760	91	150
7.4	7.7	Nov. 10, 1940	-	3290	5715	124	206
7.8	8.1	Max. credible	-	4055	7046	145	240
8.0	8.3	Min. incredible	-	6165	10715	200	331

The recurrence-magnitude relations determined for Radu's historical (984-1900) and XX century (1901-1994) catalogues of Vrancea events are compared in Fig.2.

Table 2 Mean recurrence interval of Vrancea magnitude, T(≥M) as function of the maximum credible magnitude of the source, in years

Gutenberg-Richter magnitude, M	From Eq.(4), for maximum credible magnitude, M_{max}=		From Eq.(2)
	7.8	8.0	
8.0	-	-	187
7.9	-	996	158
7.8	-	457	134
7.7	704	279	114
7.6	323	191	96
7.5	197	139	81
Nov.10,1940 7.4	135	105	69
7.3	98	82	58
Mar. 4, 1977 7.2	75	65	50
7.1	58	52	42
Aug 30, 1986 7.0	46	42	36
6.9	37	35	30
6.8	30	28	26
May 30, 1990 6.7	24	24	22
6.6	20	20	18
6.2	10	10	9

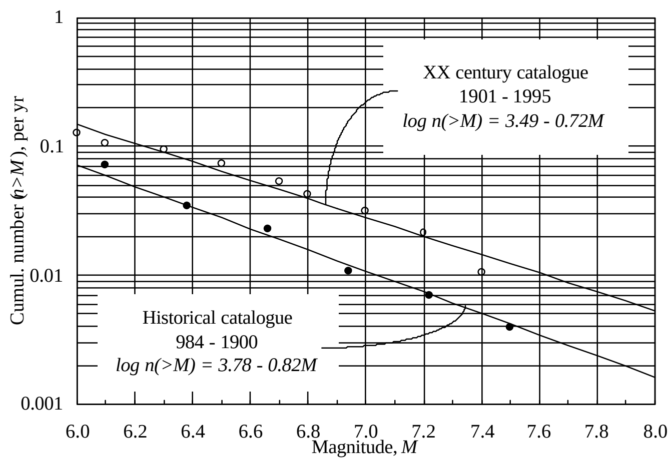

Fig.2 Comparison of magnitude-recurrence relations computed with the data from historical and instrumental catalogues of events

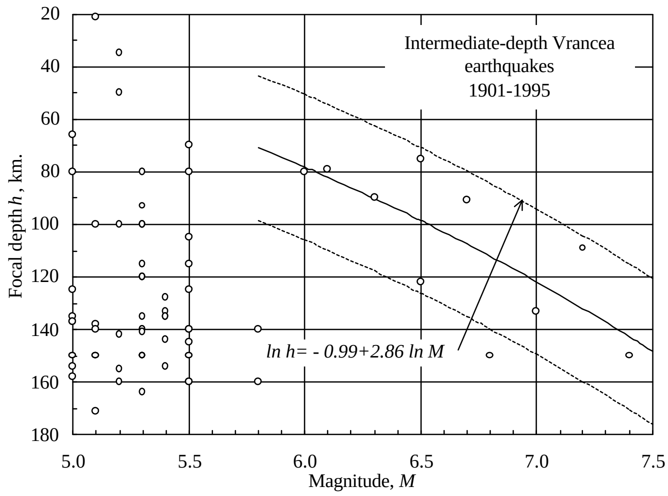

Fig.3 Vrancea source: magnitude (M≥6.0) versus focal depth

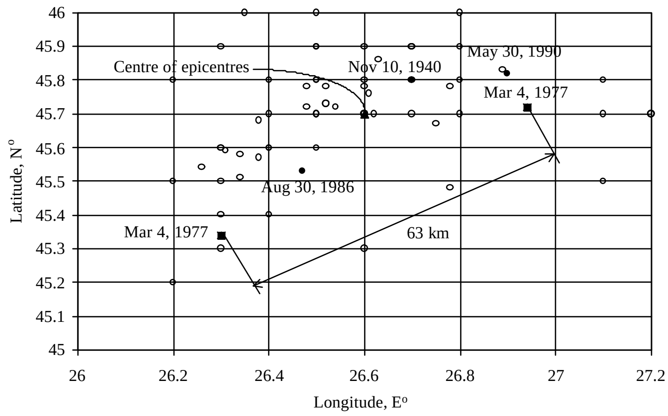

Fig.4 Vrancea source: location of epicentres in the period 1901-1995

As generally is expected, the data collected during XX century are more severe than the historical data collected over a millennium. This is the result of the inherent inaccuracies of the historical catalogue data caused by many reasons such as: subjective interpretation of the damages done by the past seismic motions, general non-homogeneity of the macroseismic observations, etc.

2 *Location of Vrancea focus*

The recurrence interval of the intensity of the damage of a Vrancea earthquake is not the same as the recurrence interval of the corresponding magnitude.

The damage intensity of subcrustal Vrancea earthquakes is the combined result of: (i) magnitude and (ii) location of the focus inside the earth.

The focus depth and the position of the

epicentre on the surface had a great influence on the experienced intensity of the past earthquakes.

Investigating the possible relationship between the magnitude of a destructive earthquake ($M \geq 6.0$) and the corresponding focal depth, the following dependence was found, Fig.3:

$$\ln h = - 0.77 + 2.86 \ln M - 0.18 P \quad (10)$$

where P is a binary variable: P=0 for the mean relationship and P=1.0 for mean minus one standard deviation relationship.

The mean minus one standard deviation curve in Fig.4 should be used as the pessimistic correlation of Vrancea magnitude with focus depth in the PSHA. The correlation coefficient ρ=0.78 implies a moderate joint linear tendency between h and M. The earthquakes of a magnitude smaller than 6.0 display non-correlation between h and M.

A conventional Vrancea epicentre may be approximately located at 45.7° Lat. N and 26.6° Long. E, Fig.3. In reality, various Vrancea earthquakes have proved an extreme mobility of their epicentre: the 1940 and 1990 epicentres were located towards NE (Moldavia) i.e.: 45.8° Lat. N and ≈ 26.8 Lat. E, the 1986 epicentre was located towards SW (Bucharest) i.e.: 45.5 Lat. N and 26.5 Long. E, etc. Moreover, during the same (multishock) Mar. 4, 1977 event the epicentre moved about 61 km along the fracture line, from NE to SW.

The mobility of the epicentre toward Moldavia is more dangerous to Moldavian sites (Nov.10, 1940) and the mobility toward Bucharest induces more damage in Bucharest (Mar.4,1977).

3 *Attenuation of the peak parameters of the ground motion*

A Joyner and Boore model was selected for the analysis of the attenuation phenomenon:

$$\ln PGA = c_1 + c_2 M + c_3 \ln R + c_4 h + \varepsilon \quad (11)$$

where:

PGA is the maximum peak ground acceleration at the site
M- magnitude
R - hypocentral distance to the site
h - focal depth
c_1, c_2, c_3, c_4 - data dependent coefficients.

ε is modeled as a random variable with zero mean and the standard deviation $\sigma_\varepsilon = \sigma_{\ln PGA}$ (standard deviation of ln PGA variable). From second order moment formats in the case of small coefficients of variation: $\sigma_{\ln PGA} \cong V_{PGA}$

If decimal logarithms are used instead of natural ones in Eq.(11) then:

$$\sigma_{\log PGA} = 0.434\, \sigma_{\ln PGA} \quad (12)$$

Taking into account :

(a) The deep fracture structure in the Vrancea zone where three tectonic units come into contact;

(b) The stability of the angles characterizing the fault surface and the motion on this surface;

(c) The ellipse-shape of the macroseismic field produced by the Vrancea source;

the attenuation analysis was performed on two orthogonal directions corresponding to the average direction of the strike of the Vrancea fault plan (ϕ° = 225°) and to the normal to this direction.

As a result 3 circular sectors (of 90° each) centred on these directions were established :

(a) The first sector contains stations in Bucharest area and in central Walachia, on the “young, thin and warm” (Oncescu, 1993) Moesian Platform;

(b) The second sector contains stations in Moldova, on “older, thicker and colder” (Oncescu, 1993) East European Platform;

(c) The third sector contains stations in Eastern part of Walachia and in Dobrogea, including Cernavoda Nuclear Power Plant site as well as the contact line between the East European and Moesian platforms.

During the 1986 and 1990 Vrancea events, about 85% of the KINEMETRICS SMA-1 accelerographs of Romania have been operational.

In the city of Bucharest the Mar 4, 1977, Aug.30, 1986, May 30, 1990 and May 31, 1990 Vrancea events were recorded, respectively, by 1, 10 and 11 instruments.

The data base used for the analysis of the Vrancea strong ground motion attenuation comprises available digitized records from:

Romania:

(i) 1 station for the Mar 4, 1977 earthquake (this event was recorded in Romania by only one SMAC-B accelerograph located in the soft soil condition of Bucharest;
(ii) 44 stations for the Aug 30, 1986 event;
(ii) 46 stations for the May 30, 1990 event;

Republic of Moldova:

(i) 2 stations for the Aug 30, 1986 event;

(ii) 4 stations for the May 30, 1990 event and

Bulgaria:

(i) 6 stations for the May 30, 1990 event.

The stations with available records from Romania belong to three seismic networks: INFP (National Institute for Earth Physics) - 10, INCERC (Building Research Institute of Bucharest) - 44, Bucharest, GEOTEC (Institute for Geophysical and Geotechnical Studies, Bucharest) - 3.

The INFP and GEOTEC seismic stations, as well as, 34 from 44 stations with records from INCERC seismic network are located in approximately "free field" conditions (basement and ground floor in one or max. two-stories buildings).

Other available records comes from the basement of 6, 8 or 10 stories buildings. They were not included in the present attenuation analysis.

The distribution on events and sectors of the maximum PGA at a station is given in Table 3. The recorded PGA field during the August 30, 1906 event is mapped with the ARCVIEW spatial analyst software of ESRI, Inc., USA.

The highest peak ground acceleration ever recorded in Romania was 297.1 cm/s^2 at the Focsani, INFP seismic station in the epicentral area during Aug 30, 1986 event.

The highest peak ground acceleration recorded in Bucharest was 207.6 cm/s^2 during the Mar 4, 1977 event at INCERC seismic station.

Mean and mean plus one standard deviation attenuation functions appropriate for the Vrancea subcrustal source were established through nonlinear multi-regression of the available sets of peak ground accelerations, as function of magnitude, hypocentral distance, focal depth and azimuth.

The data-dependent coefficients $c_1 \div c_4$ as well as the corresponding standard deviation of the lnPGA attenuation functions are found as given in Table 4. These attenuation functions can be used to predict 50 and 84 percentile of PGA, produced by a magnitude having a specified recurrence interval and a corresponding focal depth.

Table 3 Distribution of the free-field data set on events and sectors [2)]

	Earthquake			All events
	Mar41 977	Aug 30, 1980	May 30, 1990	
Epicentral area [2)]	-	(4) 4	(4) 4	(8) 8
Bucharest sector	(1)	(16) 21	(18) 24	(35) 46
Moldova sector	-	(8) 11	(11) 13	(19) 24
Cernavoda sector	-	(6) 10	(10) 15	(16) 25
Complete data set	(1)	(34) 46	(43) 56	(78)103

[1)] The numbers in parenthesis represents the free-field accelerograms used in the attenuation analysis

[2)] Included in the data set for each sector

Table 4 Coefficients of the attenuation function for Vrancea subcrustal earthquakes, Eq.(11)

Coeff.	Complete data set	Bucharest sector	Cernavoda and Bucharest sectors	Moldova and Bucharest sectors
c_1	5.128	7.249	8.886	4.601
c_2	1.063	0.904	0.905	0.929
c_3	-1.297	-1.492	-1.786	-1.030
c_4	-0.009	-0.0081	-0.0096	-0.008
$\sigma_{\ln PGA}$	0.449	0.358	0.349	0.465

The influence of the data obtained for the largest ever recorded Vrancea event in Romania (Mar 4, 1977) is extremely strong resented in the multi-regression procedure, though these data come from a single station in Bucharest.

The regression results from Table 4, as well as the simple regression results for individual 1986 and 1990 events (Lungu et al, 1995) reveal the attenuation characteristics for the recorded PGA:

(i) The azimuthal dependence of the attenuation pattern i.e.:

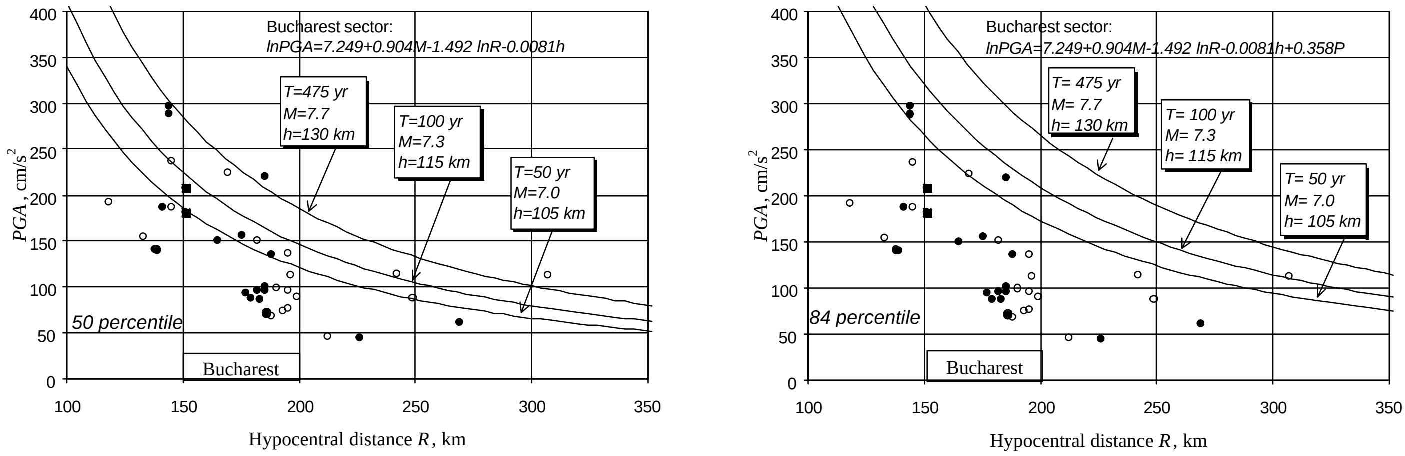

Fig.5 Bucharest sector: Attenuation found from three Vrancea events:
Mar 4, 1977 (M=7.2), • Aug 30, 1986 (M=7.0), o May 30 1990 (M=6.7)

- A slower attenuation along the direction of the fault plane (N45^{0}E) compared to the attenuation normal to this direction (E45^{0}S);
- A slower attenuation along the Bucharest sector compared to Cernavoda (NPP) sector;
- A slower attenuation along Moldova sector compared to the Bucharest sector;

(ii) A faster attenuation for greater magnitude and deeper focus (i.e. for the 1986 event compared to the 1990 event);

(iii) A relatively constant (0.35 ÷ 0.45) coefficient of variation of the attenuation function of the peak ground acceleration.

Table 5 Prediction of the peak ground acceleration in Bucharest

D=135 km: *Mean PGA*, m/s^2

M / *h*, km	*7*	*7.1*	*7.2*	*7.3* T=100yr	*7.4*	*7.5*	*7.6* T=475 yr.	*7.7*	*7.8*
80									
90									**4.0**
100	**x**			**2.5**				**3.5**	
110			**x**						
120					**x**				
130				**2.0**			**x**	**3.0**	
140		**1.5**							
150									

D=135 km: *Mean + 1 standard deviation PGA*, m/s^2

M / *h*, km	*7*	*7.1*	*7.2*	*7.3* T=100yr	*7.4*	*7.5*	*7.6* T=475 yr.	*7.7*	*7.8*
80									
90									
100	**x**							**5.0**	
110			**x**		**3.5**		**4.5**		
120				**3.0**	**x**				
130			**2.5**				**x**	**4.0**	
140	**2.0**								
150									

The conclusion (iii) simply indicates that the mean plus one standard deviation attenuation for the PGA ordinates can be obtained by multiplying the mean attenuation relation by a factor of about 1.4.

For the Bucharest sector, the use of Eq.(11) is illustrated in Fig.5. The prediction of the PGA for the city of Bucharest is illustrated in Table 5.

The most unfavorable focus depth (h) corresponding to a specified magnitude (M) was estimated from Eq.(10) with P=1, indicated by *x* in table 5.

The epicentral distance for Bucharest is approximately Δ=135±35 km; of course, it depends on the location of the site within the city and on the location of the epicentre. Experienced epicentral distances for the city of Bucharest were about: 105km in 1977, 130 km in 1986, 170 km in 1990.

The results in Table 5 are for Δ=135km; for Δ=(135 - 35) km, the PGA values in Table 5 increase with 0.4 m/s^2 (mean values) and 0.6 m/s^2 (mean plus one standard deviation values).

The damage intensity of subcrustal earthquakes is the combined result of magnitude and location of the focus inside the earth. Since the marginal recurrence interval for magnitude $T(M)=1/n(\geq M)$ has less significance for subcrustal earthquakes than for shallow earthquakes, the bivariate extremes theory can be used to estimate the recurrence intervals of Vrancea events in terms of both magnitude and focus depth:

$$T(M,h)=1/(1-F(M,h))$$

where F(M,h) is the bivariate CDF. A forthcoming paper is uncer preparation with more details on a bivariate Weibull-Weibull distribution.

Conclusions

Technical conclusions obtained from seismic hazard analysis for the Vrancea intermediate depth events are:

1. The maximum credible magnitude of the source strongly calibrates the magnitude-recurrence relation in the domain of large magnitudes;

2. The coefficients of the magnitude-recurrence relation are sensitive to threshold magnitude;

3. The XX century (partially-instrumental) catalog of Vrancea earthquakes is clearly more severe than the historical catalogue (see also Van Gelder and Lungu, 1997).

4. The attenuation pattern of PGA from Vrancea subcrustal source is slower along the direction of the fault plan (Bucharest and Moldova), compared to the attenuation normal to this direction (Cernavoda NPP).

5. The Mar 4, 1977 data (M=7.2) strongly calibrates the PGA attenuation function.

6. The mean plus one standard deviation attenuation function can be obtained as 1.4 times the mean attenuation.

7. In the case of subcrustal earthquakes, the influence on PGA of the combination of focus depth and epicenter location seems to be more important than the influence of magnitude.

8. The differences between the random PGA field recorded in real events and resulted from the attenuation analysis seems to be quite unexpected. Te site (soil) effects might partly explain the differences.

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