EARTHQUAKE HAZARD AND RISK IN ROMANIA

D. Lungu, R. Vacareanu, A. Aldea, C. Arion

ABSTRACT

The paper presents the evolution of seismic zonation and seismic design codes, focusing the probabilistic seismic hazard map and design spectra in new Romanian seismic design code P100-1/2006 following Eurocode 8 format. The paper target is historical earthquake damage and learned lessons and strengthening of tall RC fragile buildings in central Bucharest including conservation of heritage buildings. Intervention strategies of public authorities on pre WWII RC buildings are included.

INTRODUCTION

The Vrancea region, located where the Carpathians Mountains Arch bends, at about 135km epicentral dis-tance from Bucharest, is a source of subcrustal seismic activity, which affects more than 2/3 of the territory of Romania and an important part of the territories of Republic of Moldova, Bulgaria and Ukraine. The Vrancea source induces a high seismic risk in the densely built zones of the South-East of Romania.

VRANCEA EARTHQUAKES CATALOGUES

The catalogues of earthquakes occurred on the territory of Romania were compiled by Radu (1970, 1974, 1980 and 1994 manuscripts published by Lungu et al., 1997) and Constantinescu and Marza (1980, 1995). In 1997 Romplus – a version of Constantinescu and Marza catalogue was presented at First International Seminar on Vrancea earthquakes, updated daily on the web site (www.infp.ro) by National Institute of Earth Physics, INFP, Magurele. A graphical representation of Romplus Catalogue and of seismic areas affecting Romania is given in Figure 1. The most complete Vrancea historical catalogue is Radu Catalogue, even the significant events are also included in Constantinescu and Marza Catalogue. A selection of Radu Catalogue is presented in Table 1. In Table 2 is presented an comparison of earthquakes parameters given by different authors.

The magnitude in the Radu catalogue is the Gutenberg-Richter magnitude, *M*. From existing catalogues, one may note: during the time interval 984-1900, one event/century with epicentral intensity $I_0 \geq 9.0$ and during the period 1901-2000, two events per century with intensity $I_0 \geq 9.0$ (or magnitude $M \geq 7.2$).

The most powerful Vrancea earthquake is generally accepted to be the 26th of October 1802 event ($M_{G-R} \geq 7.5$). It was felt on a surface over 2 000 000 km^2 (Popescu, 1941). Strong earthquakes followed on 26th of Nov 1829 and on 23rd of Jan 1838 (maximum seismic intensity 8 ÷ 9).

The Vrancea earthquake with the highest magnitude during 20th century is the Nov 10th, 1940 event ($M_{G-R}=7.4$).

The most destructive Vrancea earthquake during 20th century was the March 4, 1977 ($M_{G-R}=7.2$, moment magnitude $M_w=7.5$) earthquake. On this occasion was obtained the first strong ground motion in Romania (on SMAC B Japanese instrument at INCERC, National Institute for Building Research, seismic station, Eastern Bucharest).

Technical University of Civil Engineering, Bucharest (UTCB)

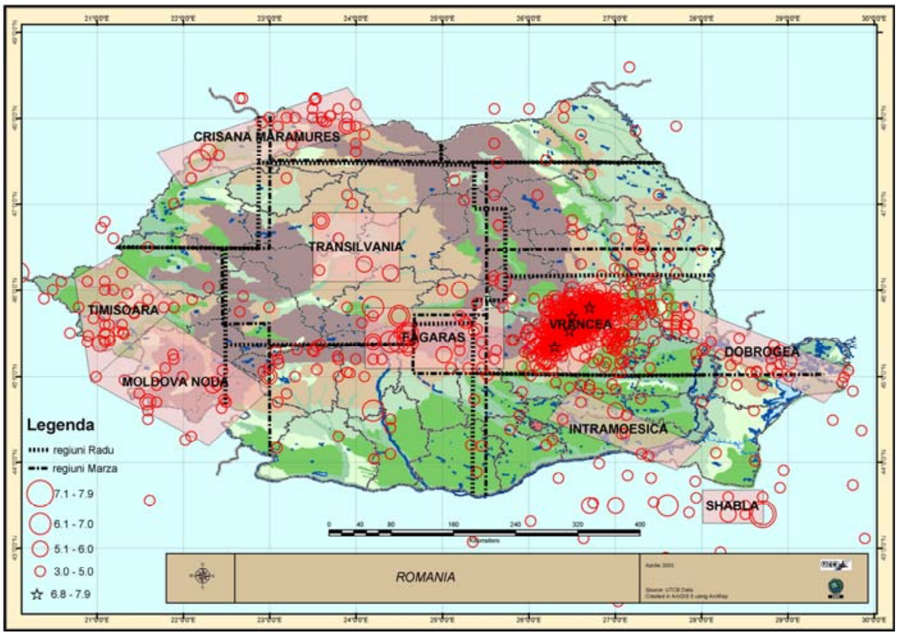


Fig. 1 Romania: Location of the epicenters from 984 to 2003 and seismic regions (Arion 2003)

Table 1. Radu's historical catalogue of major Vrancea subcrustal earthquake, $I_0 \geq 9$ (Radu manuscripts, 1994 published Lungu *et al*., 1997, [1), 2), 3)]

No.	Date		Max MSK Intensity, I_o		Magnitude M_{G-R}		Magnitude M_s	Radu's source
			Radu	Others	Radu	Others		
1	1196	Feb 13	(8) 8-9	9/CM	(6.7) 7.2	7.0/KS	7.3/CM	RT, R
2	1230	May 10	(8-9) 9+	8.5/CM	(6.9) 7.4	7.1/KS	7.1/CM	RT, R, N
3	1446	Oct 10	8	8.5/CM, 8-9RT	6.7	7.3/KS	7.3/CM	RT, R
4	1471	Aug 29	(8) 9	9/CM, 8-9 KS	(6.9) 7.4	7.1/KS	7.3/CM	RT, R
5	1516	Nov 8	9	9/CM, 8/KS	7.2		6.8/KS	RT, R
6	1620	Nov 8	(8-9) 9	9/CM, 8/KS	(6.9) 7.2	6.5/KS	7.3/CM	RT
7	1679	Ian29?/Aug 9	(8) 6	9/CM	(6.7) 5.5	6.8/KS	7.3/CM	RT
8	1681	Aug 18	9	8/CM	(6.7) 7.4	6.8/KS	6.8/CM	RT
9	1738	May 31/ Jun 11	(8-9) 9	9.5/CM	(6.9) 7.4	7.0/KS	7.5/CM	RT, R
10	1802	Oct 26	9	10/CM	7.5	7.4/KS	7.7/CM	R
11	1838	Jan 23	8	9/CM	6.7	6.9/KS	7.3/CM	R

1) Source abbreviations: R - Radu, C., 1971, 1974 catalogues; RT - Radu, C., Torro, E., 1986 catalogue; N - Nikonov catalogues; CM - Constantinescu and Marza, 1980 catalogue; KS - Kondorskaya N. V., Shebalin N.V., 1977 catalogue; SKH - Shebalin, N. V., Karnic V., Hadzievski, D., 1974 catalogue;

2) Focus depth h is considered as intermediate depth: $60 \leq h \leq 170$km;

3) The intensity in parenthesis indicates the previous estimations made by Radu (1980).

Past strong earthquakes

1802 and 1838 earthquakes

The 26 Oct 1802 (M_S = *7.4 – 7.7*) earthquake is considered to be the strongest Vrancea subcrustal event; there are no precise information on causalities but some information on damages. The earthquake was felt in Ukraine, Russia, Poland, Bulgaria and Turkey. The event was felt on a total estimated area of more than 2 millions square kilometers.

Table 2. 20th century strong Vrancea earthquakes, $M_{G\text{-}R}$ *or* $M_s \geq 6.0$ (Lungu *et al.*, 2000)

No.	Date	Lat. N°	Long. E°	Focus depth *h* km			Magnitude[3)]			
							M_s	M_w	$M_{G\text{-}R}$	M_w
				Radu	Marza	infp.ro	Marza	infp.ro	Radu	[1)]
1	*1903* Sep 13	45.7	26.6	*>60*	70	70	5.7	6.3	*6.3*	6.6
2	*1904* Feb 6	45.7	26.6	*>60*	75	75	6.3	6.6	*5.7*	-
3	*1908* Oct 6	45.7	26.5	*150*	125	125	6.8	7.1	*6.8*	7.1
4	*1912* Mai 25	45.7	27.2	*80*	90	90	6.4	6.7	*6.0*	6.3
5	*1934* Mar 29	45.8	26.5	*90*	90	90	6.3	6.6	*6.3*	6.6
6	*1939* Sep 5	45.9	26.7	*115*	120	120	6.1	6.2	*5.3*	-
7	*1940* Oct 22	45.8	26.4	*122*	125	125	6.2	6.5	*6.5*	6.8
8	*1940* Nov 10	45.8	26.7	*133*[2)]	135[2)]	150	7.4	7.7	*7.4*	7.7
9	*1945* Sep 7	45.9	26.5	*75*	80	80	6.5	6.8	*6.5*	6.8
10	*1945* Dec 9	45.7	26.8	*80*	80	80	6.2	6.5	*6.0*	6.3
11	*1948* Mai 29	45.8	26.5	*140*	130	130	6.0	6.3	*5.8*	-
12	*1977* Mar 4	45.34	26.30	*109*	-	94	7.2	7.4	*7.2*	7.5
13	*1986* Aug 30	45.53	26.47	*133*	-	131	-	7.1	*7.0*	7.3
14	*1990* Mai 30	45.82	26.90	*91*	-	91	-	6.9	*6.7*	7.0
15	*1990* Mai 31	45.83	26.89	*79*	-	87	-	6.4	*6.1*	6.4

Notes: 1) $M_w \cong M_{G\text{-}R} + 0.3$ for $6.0 \leq M_{G\text{-}R} \leq 7.4$ (Lungu, 1999)

2) In present the value accepted for focus depth for Nov.10, 1940 event is *h*=140km

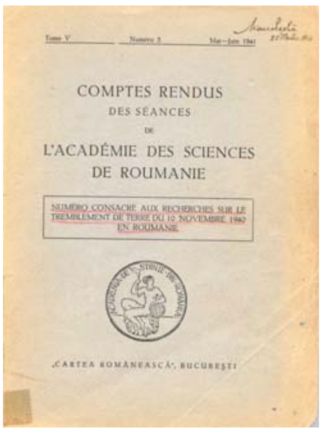
3) Magnitudes: $M_{G\text{-}R}$ - Gutenberg-Richter Magnitude, M_S – surface waves magnitude, M_W - moment magnitude.

The 23 Jan 1838 ($M_S = 6.9 - 7.3$) earthquake was felt on an extended area in Europe: Ukraine, Poland, Bulgaria, up to Constantinople and to NE of Italy. The following description of the effects of 1838 earthquake effects in Bucharest is given in the book "Voyage dans la Russie Méridionale et la Crimée par la Hongrie, la Valachie et la Moldavie", par M. A. de Démidoff, Illustré par Raffet, E. Bourdin, éditeur Paris. 1841 & 1854, page 144.

1940 earthquake

"The November 10, 1940 earthquake put damages all around Romania and throw the people in mourning", Comptes Rendus des Séances de l'Académie des Sciences de Roumanie, 1941. "Numéro consacré aux recher-ches sur le tremblement de terre du 10 Novembre 1940 en Roumanie", Tome V, numéro 3, mai-juin, Cartea Romaneasca, Bucuresti, p. 177-288, Fig.2.

In Bucharest the most significant loss from the Nov. 10, 1940 earthquake ($M_{G\text{-}R}$ = 7.4) was the complete collapse of Carlton building (Fig. 3), the highest RC building (47m, 12 storeys) in Romania at that moment.


COMPTES RENDUS
DES SÉANCES
DE
L'ACADÉMIE DES SCIENCES
DE ROUMANIE

NUMÉRO CONSACRÉ AUX RECHERCHES SUR LE TREMBLEMENT DE TERRE DU 10 NOVEMBRE 1940 EN ROUMANIE

„CARTEA ROMÂNEASCĂ", BUCUREŞTI

Fig. 2 Comptes Rendus des Séances de l'Academie des Sciences de Roumanie, 1941

Fig. 3 Carlton building in Bucharest, collapsed during 1940 earthquake (postcard)

The earthquake was felt on about 2 millions square kilometers: from East (Odessa, Cracovia, Moscow were the estimated intensity was V-VI) to north up to Leningrad, to West up to Tissa river and in South in Yugoslavia and all Bulgaria up to Istanbul.

In Romania were identified two zones of maximum intensity: one is in the area of Panciu and Focsani and the second one in Campina to Bucharest. In those areas the seismic intensity was over VIII on Mercalli-Sieberg scale i.e. close to IX in Campina, Focsani, Tecuci, Beresti, and about X in Panciu.

No realistic estimation of the number of deaths was reported. Some authors indicated the following numbers: >1000 (Beles, Ifrim, 1962; Coburn & Spence 1992), 980 (EM-DAT: The OFDA /CRED International Disaster Database.

1977 earthquake

The March 4, 1977 (M_{G-R} = 7.2) was the most destructive earthquake in the history of Romania. International experts dispatched in Romania in the aftermath of the earthquake reported as follows.

"The unusual nature of the ground motion and the extent and distribution of the structural damage have important bearing on earthquake engineering efforts in the United States." Jennings & Blume foreword in Berg et al 1980.

"It mostly affected the densely populated and rapidly developing centres of Craiova, Pitesti, Zimnicea, Bucharest, Ploiesti, Focsani, Barlad" Ambraseys, N.N., 1977. "Long-period effects in the Romanian earthquake of March 1977", Nature, Vol.268, July, p.324-325.

The March 4, 1977 earthquake killed 1,578 people including 1,424 in Bucharest and injured 11,221 people including 7,598 in Bucharest. According to the World Bank Report 16.P-2240-RO, 1978) the total losses in Romania worth 2.05 billion (1977!!) USD.

SEISMIC RECORDS

The first strong ground motion recorded in Romania was the 1977 record in Eastern Bucharest, at seismic station of INCERC on a Japanese SMAC - B instrument. The ground motion was digitized and analysed by Building Research Institute, Ministry of Construction, Japan, 1978 and was published "Digitized data of strong-motion earthquake accelerograms in Romania (March 4, 1977)" by Observational Committee of Strong Motion Earthquake in Kenchiku Kenkyu Shiro No.20.

The unusual 1977 record, characterized by a long predominant period of ground vibration, $T_p \cong 1.6s$, has been used for calibrating design response spectra in Romanian seismic code for the period 1977-1992 when almost 40% in Bucharest buildings stock has been built. After the 1977 earthquake a significant ground motion database of more than 40 records was collected in Bucharest during the 1986 and 1990 earthquakes.

The envelope of the peak ground acceleration recorded in Romania during the last 3 strongest Vrancea events in Romania are interpolated in Figure 4 and shows the NE-SW directivity of the subcrustal Vrancea source, as it has been firstly observed by Montessus de Ballore, 1906.

The database of Vrancea strong ground motions contains records from 47 free-field stations in Romania distributed on networks and events. The "free field" accelerograms were obtained at the ground level or the basement of 1 - 2 storey buildings. The distribution of the recorded accelerograms is given in Table 3.

Table 3. Distribution of the free field accelerograms used in the attenuation analysis

Seismic network	Romania			Rep Moldova	Bulgaria	Total
Earthquake	*INCERC*	*INFP*	*GEOTEC*[1)]	*IGG*[2)]		
March 4, 1977	1	-	-	-	-	1
Aug. 30, 1986	24	8	3	2	-	37
May 30, 1990	23	10	2	2	5	42
Total	48	18	5	4	5	80

1)GEOTEC, Institute for Geotechnical and Geophysical Studies, Bucharest

2)IGG, Institute of Geophysics and Geology, Moldavian Academy of Science, Chisinau

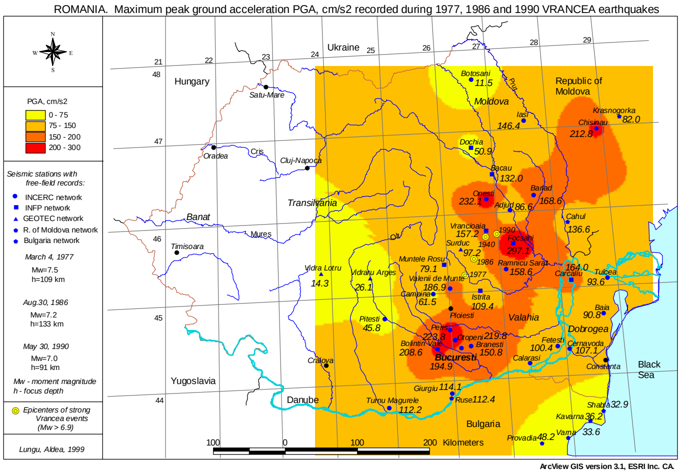


Fig. 4 Maximum recorded peak ground acceleration during the last Vrancea strong events

Based on the very important conclusions from 1977, 1986 and 1990 earthquakes, the seismic instrumentation of Bucharest has been recently extended and improved by various national and international efforts. Presently Romania has more than 100 digital K2 & ETNA, Kinemetrics instruments, about half in Bucharest, distributed in three seismic networks: INCERC, INFP and NCSRR (National Center for Seismic Risk Reduction).

The maximum of the two horizontal components of the ground motions was considered for *PGA* attenuation. The following attenuation model was selected for the attenuation analysis:

$$ln\ PGA = c_0 + c_1\ M_w + c_2\ lnR + c_3 R + c_4\ h + \varepsilon \qquad (1)$$

where: *PGA* is peak ground acceleration at the site, M_w- moment magnitude, R - hypocentral distance to the site $R = \sqrt{h^2 + \Delta^2}$, h - focal depth, c_0, c_1, c_2, c_3, c_4 - data dependent coefficients and ε - random variable with zero mean and standard deviation $\sigma_\varepsilon = \sigma_{ln\ PGA}$. The coefficients obtained from the regression are as follows [Lungu, Demetriu *et al.*, 1999]: c_0 = 3.098, c_1 = 1.053, c_2= -1.000, c_3=-0.0005, c_4=-0.006, σ_{lnPGA} =0.502.

The seismic hazard assessment for Vrancea subcrustal source took into consideration the magnitude recurrence. The classical recurrence relationship was modified into the truncated Gutenberg-Richter relationship that for Vrancea source gives [Elnashai & Lungu, 1995]:

$$n(\geq M_w) = e^{8.654 - 1.687 M_w} \frac{1 - e^{-1.687(8.1 - M_w)}}{1 - e^{-1.687(8.1 - 6.3)}} \qquad (2)$$

In *Eq.(2),* the threshold lower magnitude is $M_w=6.3$, the maximum credible magnitude is $M_{w,max}=8.1$, and $\alpha = 3.76\ ln10 = 8.654,\ \beta = 0.73\ ln10 = 1.687$.

The relationship between the magnitude of a potentially destructive Vrancea earthquake ($M_w \geq 6.3$) and the corresponding focal depth shows that higher the magnitude, deeper the focus [Lungu et al., 1997]:

$$ln\ h = -\ 0.866 + 2.846\ lnM_w - 0.18\ P \qquad (3)$$

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

ZONATION STANDARDS AND CODES FOR EARTHQUAKE RESISTANCE OF STRUCTURES IN ROMANIA

The first seismic zonation of Romania was done after the 1940 Vrancea earthquake. The 1941 zonation map contains two areas: one seismic area (Moldova, Valachia and Brasov area) and a second one considered as being not seismic (the remaining part of Romania).Two Romanian engineers wrote the first modern Romanian code for seismic design of buildings in 1954, but the first official regulation appeared only in 1963. Table 4 presents the evolution of the seismic zonation and seismic design codes for buildings in Romania during the last 50 years. The P100-1/2006 Code for earthquake-resistant design of buildings - Part 1 (244p), was approved by Ministry of Transportation and Constructions order No.1711/19.09.2006 and it was enforced on Jan 1, 2007.

Table 4. Classification of codes for design of earthquake resistant buildings and of standards for seismic zonation of Romania (1940-2008)

Period		Code for earthquake resistant buildings	Seismic zonation standard
Pre-code, before 1963	Prior to the 1940 earthquake and Prior to the 1963 code	*P.I. - 1941* *I - 1945*	*P.I. – 1941* *I – 1945* *STAS 2923 - 52*
Low-code, 1963-1977	Inspired by the Russian seismic practice	*P 13 - 63* *P 13 - 70*	*STAS 2923 - 63*
Moderate-code, 1977–1990	After the great 1977 earthquake	*P 100 - 78* *P 100 - 81*	*STAS 11100/1 - 77*
Moderate-code to High-code, after 1990	After the 1986 and the 1990 earthquakes	*P 100 - 90* *P 100 - 92*	*STAS 11100/1 - 91* *SR 11100/1 - 93*
High code, after 2006	Inspired by Eurocode 8	*P100 –1/2006*	*In P100 –1/2006 code*

After the 1977 event, ductility rules for RC structures were imported into Romanian codes from American Concrete Institute ACI code of practice. Those ductility rules were improved and enlarged in 1990 according to the EUROCODE 8 requirements.

The evolution of normalised acceleration response spectra in the listed codes is indicated in Fig. 5.

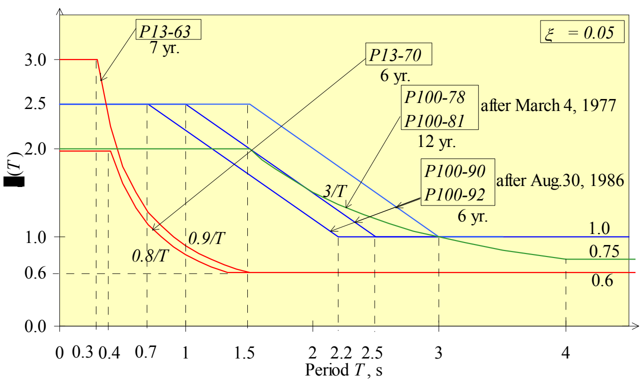


Fig. 5 Normalized acceleration elastic response spectra in Bucharest, 1963 – 2000

NEW ROMANIAN SEISMIC DESIGN CODE

Based on the results of probabilistic seismic hazard assessment from Vrancea source and taking into account the macroseismic fields from the crustal seismic sources in Romania, in Fig. 6 is presented the seismic hazard map from P100-1/2006 earthquake resistant design code, enforced from January 1st,

2007. The map presents the design ground acceleration (*PGA*) for an event with mean recurrence interval *MRI*=100 years. The *MRI*=100 yr represents a transition MRI towards the *MRI*=475years recommended by Eurocode 8 & ASCE7. Certainly the next version of *P100* code, after 2010, will definitely introduce 475yr-PGA for design in Romania. For Bucharest the *PGA* having 475 yr recurrence interval is about 0.36g.

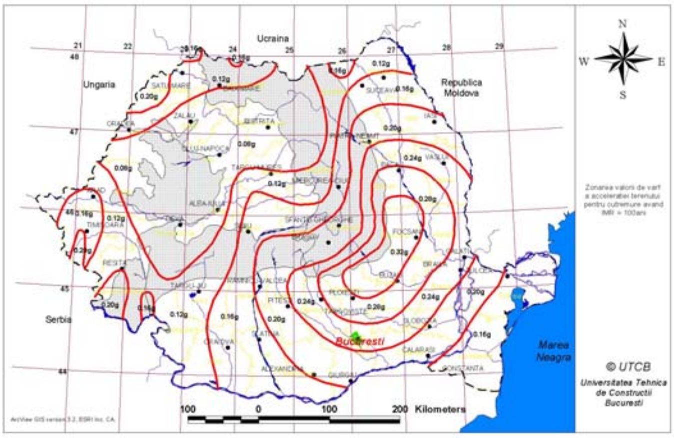


Fig. 6 P100–1/2006 design ground acceleration a_g, for an event with *MRI*=100 yr.

In the P100-1/2006, the ground conditions are characterized by the control period of response spectra T_C. The T_C macrozonation in the P100-1/2006 is based on processed ground motion from 1977, 1986 and 1990 events records. The studies made on the complete database of strong motion accelerograms of Romania [Lungu et.al., 2000] showed that the control period of response spectra T_C is the most reliable and stable indicator for characterizing the frequency content of ground motions. Microzonation maps for control period of response spectra T_C for 1986 earthquake is presented in Fig. 7.

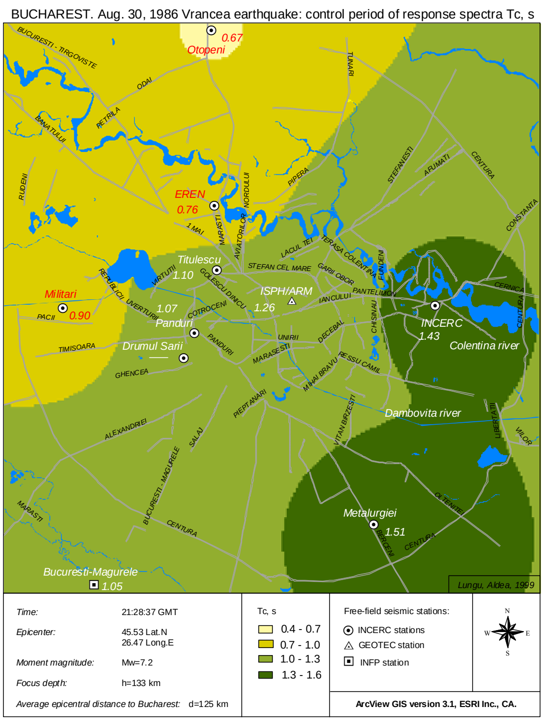


Fig. 7 Bucharest - Aug.30, 1986 earthquake: microzonation of T_C

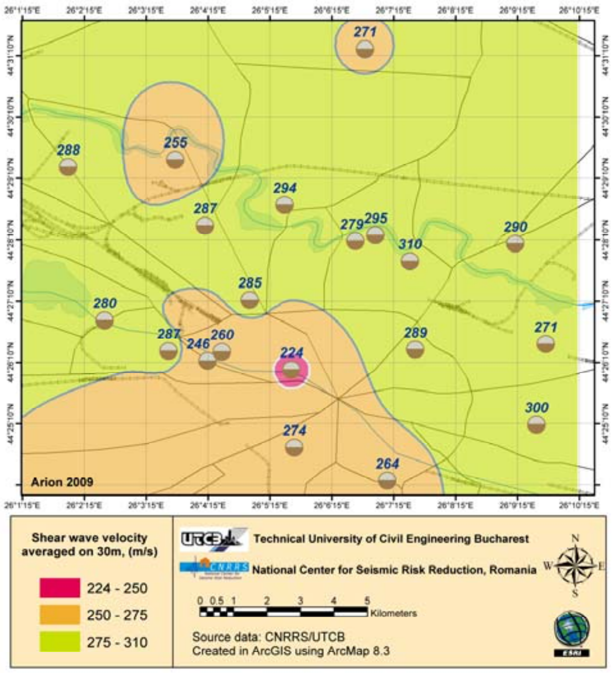


Fig. 8 Bucharest. Microzonation map for shear wave velocity (m/s) averaged on 30m

A direct characterization/classification of ground conditions based on soil data (soil profile and shear velocities profile) is not yet possible due to the lack of significant soil data correlated with recorded strong ground motions. The few cases where such information exists (i.e., soil data and earthquake records) showed that imported criteria and corresponding design spectra from other countries are not valid in the area under the influence of Vrancea source [Aldea, 2002]. Using recent PS logging results (from NCSRR) the average shear wave velocities in the top 30 meters of soil, are presented in Fig. 8 for Bucharest.

For each area zones with same T_C, a normalised acceleration elastic response spectrum is recommended according to the EC8 format, Fig. 9. The seismic action in the P100-1/2006 design spectra is to be used at ultimate limit state design, in connection with 3 other new Romanian codes: Basis of design, Wind action and Snow action. The new set of codes has been prepared in 2005 at Technical University of Civil Engineering Bucharest following the EC0 and EC1 format and contents. The Ministry of Development, Public Works and Housing in 2007 enforced them.

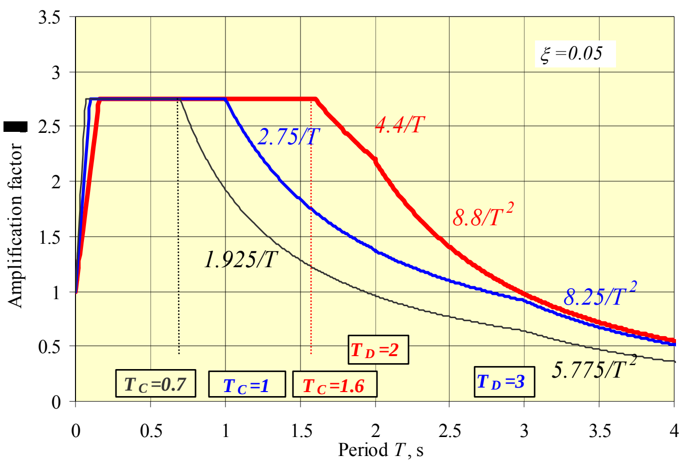


Fig. 9 P100-1/2006 - Normalized acceleration response spectra for horizontal ground motion

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