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SEISMIC RESPONSE ANALYSIS FOR ROMANIAN EXTRA-CARPATHIAN SEDIMENTARY AREAS*

ANÁLISE DA RESPOSTA SÍSMICA EM ÁREAS SEDIMENTÁRIAS EXTRA-CARPATIAS ROMENAS

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ABSTRACT

The seismic response of the ground motion is analysed using processed recordings and related spectral characteristics. The analysis is carried out for few representative different sites, with different geological local conditions. Data used are recordings from the last strongest seismic events (1986, August 30, M_w = 7.1, 1990, May 30, M_w = 6.9 and 1990, May 31, M_w=6.4). The approach used herein to assess the particular features of the seismic effects could open a new perspective in microzoning and risk studies. In the context of Vrancea-intermediate depth seismicity, whose effects are encountered at long epicentral distances, the choice of these sites is fully justified. Therefore the paper intends to focus on the particularities in the site effects that occur due to the sedimentary deposits' oscillation under strong seismic ground motion for different areas. The spectral amplification factors are introduced in order to have a quantitative representation with respect to the variability of site effects.

Keywords: Seismic response, ground motion recordings, spectral amplification factors.

RESUMO

O movimento do solo é analisado, em termos de resposta sísmica, usando gravações processadas e características espectrais relacionadas. A análise é realizada para alguns locais representativos, com diferentes condições geológicas locais. Os dados usados consistem em registros dos últimos eventos sísmicos mais fortes (30 de agosto de 1986, M_w = 7.1, 30 de maio de 1990, M_w = 6.9 e 31 de maio de 1990, M_w = 6.4). A abordagem usada para avaliar as características particulares dos efeitos sísmicos pode abrir uma nova perspectiva no microzoneamento e estudo do risco. No contexto da sismicidade de profundidade intermédia de Vrancea, a escolha destes locais é perfeitamente justificada, dado que os seus efeitos podem ser encontrados até longas distâncias epicentrais. Deste modo, o estudo pretende destacar as particularidades que ocorrem devido à oscilação dos depósitos sedimentares, devido ao forte movimento sísmico do solo em diferentes áreas. Foram introduzidos fatores de amplificação espectral para se ter uma representação quantitativa, da variabilidade resultante dos efeitos locais.

Palavras-chave: Resposta sísmica, registos de movimentos do solo, fatores de amplificação espectral.

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Introduction

The seismic response and local seismic effects are analysed herein in terms of spectral accelerations (S_a) and maximum ground acceleration (a_{max}) for city of Bucharest, capital of Romania and other cities from the outside of the Carpathian Arc Bend (including Cernavoda city, where is situated a Nuclear Power Plant). The available seismic recordings for the last strong Vrancea earthquakes (M_w>6.3) are analysed and processed in order to highlight some spectral characteristics which may have influence on hazard assessment. For the last destructive Vrancea earthquake, 1977, March 4, M_w=7.4 there was but just one recording, at INCERC site (INC) in South-Eastern part of Bucharest, by which it could be noticed the peak acceleration value of 0.21g. Starting from this single waveform one could manage to obtain the elastic response spectrum which reveals the long predominant period corresponding to the maximum spectral acceleration from the elastic response spectra. For the next (three) strong earthquakes (M_w>6.3) the surveillance capacity in our country was much more developed, therefore the available recordings offer new possibilities for the evaluation of the seismic effects almost all over the country territory.

The intermediate depth earthquakes originating in Vrancea seismic source are characterized by very specific features. Apart from their long range-focal depth (focal depths between 70 and 200 km) and outstretched (extended) affected areas they depict quite challenging surface effects. The recordings of the last strong seismic events show not only large ground motion amplification in remote areas, but rather higher, comparative to the epicenter ones. Moreover, the available acceleration recordings for the strong 1986 (M_w=7.1) earthquake are generally lower than the next less strong seismic event of 1990 (M_w=6.9). As regards the predominant periods from the elastic response spectra it is worth noticing the tendency to encounter long fundamental oscillating periods (sometimes exceeding 1 s) at seismic stations in the Bucharest area, as well as in some other spots over Extra-Carpathian territory, especially for very strong seismic events. Yet another feature was observed especially for the capital city area, which is the decreasing values of the predominant period of soil, with the decreasing of the earthquake magnitude. Hence, the necessity of defining a fundamental period-value range corresponding to seismic movements for each site, by comparing some terrain characteristics induced by strong events (acceleration, amplitudes from response spectra, oscillating period of the superficial soil deposit) and their changes related to the magnitude of the earthquake.

In response to the dynamical solicitations produced by major earthquakes, the particular geological features may induce various effects in the Romanian capital Bucharest and largely over the country territory (Cioflan *et al.*, 2004, p.1149), Moldoveanu and Panza, 1999a, p.85, Moldoveanu and Panza, 1999b, p.1, Mandrescu and Radulian, 1999, p.109, Lungu *et al.*, 2001, p. 43). The spectral characteristics of the strong seismic recordings in a certain area, in terms of spectral amplification factors could give information about type of local soil response for future earthquakes (Marmureanu *et al.*, 2004, p. 47). The influence of the local geological conditions on the characteristics of the strong ground motion in sedimentary areas was thoroughly addressed in many papers (see, for example, Aki, 1993, p.93). The importance of the characteristic soil frequency in relation to the depth of the sedimentary layers was put forward in recent papers concerning the areas considered in this work (Manea *et al.*, 2019, p.709), including a distribution of this parameter based on geophysical estimation (Manea *et. al.*, 2020, p. 4829).

The observational data, especially for strong earthquakes, show no tendency of lineal descending ground motion values from the epicenter to the remote areas. Seismic hazard assessment and risk mitigation studies based on so-called probabilistic or deterministic seismic “scenarios” have succeeded to take into account this specificity of the Vrancea-intermediate depth seismicity, that proved a strong variability especially on the peak ground acceleration values (Ardeleanu *et al.*, 2005, p. 679, Leydecker *et al.*, 2008, p. 1431, Lungu *et al.*, 1999, p. 251, Mantyniemi *et al.*, 2003, p. 371, Marmureanu *et al.*, 2011, p. 226, Moldovan *et al.*, 2008, p. 575, Pavel *et al.*, 2015, p. 1881, Radulian *et al.*, 2000, p. 221, Sokolov *et al.*, 2004, p. 927). It was suggested that, besides magnitude and hypocentral distance, the local site characteristics, through their possibility to induce amplification are primarily factors responsible for the seismic hazard over Romanian territory. In this regard the approach used herein, involving appropriate tools such as spectral amplification factors (SAF), intends to add new outcomes regarding seismic site response characterization.

As regards the Bucharest city area the spatial variations of site conditions may be caused by both geological and topographic features. The variations in the ground motion noticed within the city area have been modelled by approaches that have led to integrate different types of data sets and information (see, for example, Wirth *et al.*, 2003, p.737) which indicate the importance of the local site effects.

Some of these features are encountered in other regions around the world, which share some common characteristics, such as those located on sedimentary basins, or areas with deep unconsolidated structure (Seed *et al.*, 1976, p. 1323, Seed *et al.*, 1973, p. 99, Seed and Schnabell, 1970, p. 61, Chopra and Choudhury, 2011, p. 1551, Celebi *et al.*, 2018, p. 3289, Fah *et al.*, 1993, p. 131).

An example is the case of the 1985 Mexico City earthquake (M_w=8.0) where the ground motion recorded on the sedimentary area was almost 5 times larger than the one recorded on bedrock area (Anderson *et al.*, 1986, p. 1043, Rukos, 1988, p. 771) The amplification of ground motion is caused by the impedance between bedrock and sediments. The 1989 Loma Prieta earthquake, with effects on soft soil in Bay Area, is also important because of adding empirical data (O'Rourke and Holzer, 1992, 320 p.). The importance of site effects in risk studies have been observed as well throughout several other earthquakes, such as the 1994 Northridge earthquake (Beresnev *et al.*, 1998, p. 1079), the 1995 Kobe earthquake, with ground motion recorded in sediments modified compared to the one in bedrock (Hartzell *et al.*, 1997, p.1377, Kavase, 1996, p.25).

The aim of this paper is to highlight the influence of the local effects generated by uppermost geological layers on the seismic response at certain sites. The characteristics of the elastic response spectra for last strong Vrancea-intermediate earthquakes are discussed by starting from earthquakes recordings. The processing of the records was made in the same condition by using CALTECH and Kinemetrics methodologies. We emphasize that all seismic events discussed herein are located in the same focal area, called Vrancea-intermediate seismic source, which is responsible for the strongest seismic events that hit the country territory, and controls seismic hazard especially in Extra-Carpathian areas (fig. 1).

The analysis is focused on Bucharest Metropolis and other cities, placed from the SW to NE of the Vrancea seismic source, where buildings or important objectives exist, including Cernavoda Nuclear Power Plant. The regions of the South-West, South and North-East of Romania are much affected by the Vrancea strong earthquakes, generated at the South-Eastern Carpathians Arc bend at intermediate focal depth. Other regions belonging to our country, such Transylvanian Basin with neighbourhood areas, are also affected by these seisms, but at a lower level (Marmureanu 2016, p. 330, Radulian *et al.*, 2000, p. 221).

Geotectonics and seismicity

Romania is a seismic country, with a rather moderate seismic activity, subjected both to shallow and deep earthquakes. The seismic hazard of the country is mainly caused by Vrancea-intermediate depth earthquakes, with focal depth between ~70 and ~200 km which affect especially the Extra-Carpathian areas. The hypocenters are positioned in confined volume of a parallelipiped, belonging to a lithospheric slab, now decoupled from the crust (Ismail-Zadeh *et al.*, 2012, p. 50), in Vrancea region, a rather complex tectonic area, where three tectonic units are in contact and separable on Romanian territory: (i)-East-European; (ii)-Inter-Alpine and (iii)-Moesia Plates. Macroseismic intensities field through its specific shape affects large areas of the country territory and the

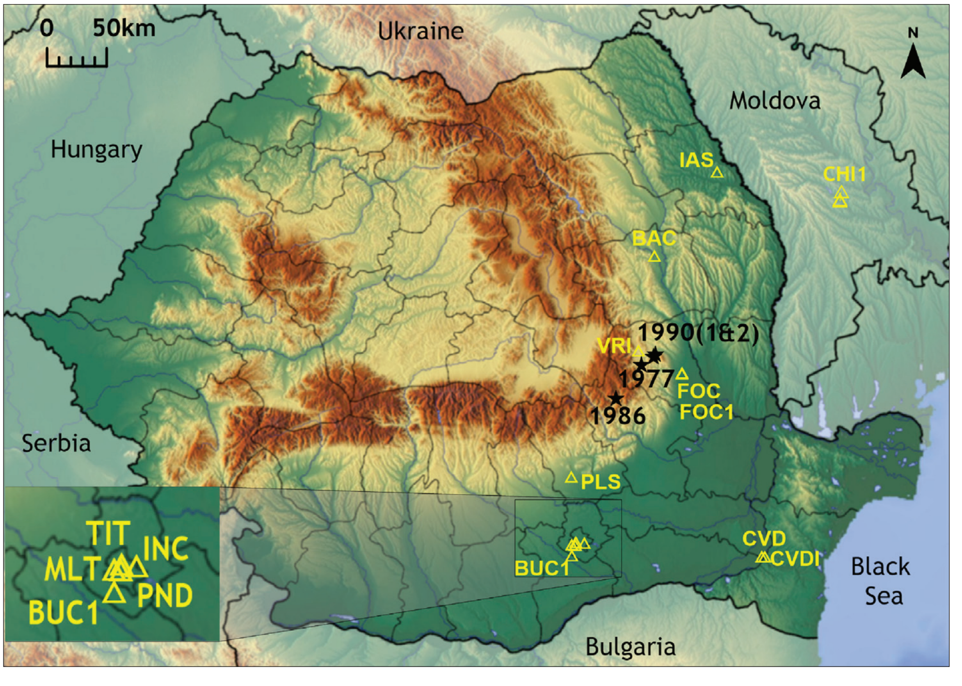

Fig. 1 - Epicenters (black) and the seismic stations location (yellow) considered in the analysis for the last four strong earthquakes at Vrancea.

Fig.1 - *Epicentros (preto) e localização das estações sísmicas (amarelo) considerada na análise dos quatro últimos fortes terremotos em Vrancea.*

neighborhoods countries as well. The simulation made for the maximum possible earthquake (Marmureanu *et al.*, 2011, p. 226) reveal intensities of IX½ on MMI scale in epicenter area (Focsani and surroundings) and Bucharest.

This seismic source triggered in the XXth century five major (M_w>6.9) earthquakes: 1908, October 6, M_w=7.1, 1940, November 10 with moment magnitude M_w=7.5, followed by 1977, March 4, M_w=7.4, 1986, August 30, M_w=7.1 and 1990, May 30, M_w=6.9 (Oncescu *et al.*, 1999, p. 43). Unfortunately only after the last destructive earthquake (1977), whose only recording is at INCERC site (Bucharest), the necessity for having as many realistic recordings has become a real achievement.

One of the main concerns of the "National Institute for Research and Development for Earth Physics", Magurele, Romania, is the monitoring of seismic activity on the territory of Romania, with the help of seismic stations within the "National Seismic Network". Currently, this network is made up of over 150 seismometers and accelerometers located all over places in Romania, transmitting real-time data (Neagoe *et al.*, 2011, p. 9).

The majority of the strong M_w>6.5 Vrancea-intermediate seismic events is characterized by a reverse faulting mechanism regardless of their magnitude, with a nearly vertical the T-axis and a nearly horizontal P-axis (Oncescu and Trifu, 1987, p.149). The fault plane orientations are divided in two classes: one along the NE-SW direction, with the P (compressional) axis perpendicular to the Carpathian mountain arc and another on the opposite NW-SE direction with the P axis parallel to the Carpathian mountain arc.

From this point of view, the lesser strong seismic event of 1990 had the latter fault plane orientation, while the previous stronger ones of 1990 and 1986 had the former-corresponding fault plane orientation. However the focal depth for the stronger earthquake was deepest (131 km) of all the seismic events considered herein (Table I).

Extra-Carpathian area geology presents deep soil deposits, of various thickness. The sedimentary part of the Moesian Platform consists in relatively thick deposits (6,000 m average), with depths which can attain 15-20 km in the Depression of Focsani - Odobești, to 1.5 km under Bucharest city area, or tens of meters around Cernavoda area, at south-eastern part of the Moesian Platform. The soft geological deposits in the basement of the Bucharest are from: (i)- loësslike deposits, (ii)- Colentina gravels and sands; (iii)-Clay deposits; (iv)- Mostistea sands; (v) -Marl lacustrian complex, (vi)- Fratesti layers of sand and gravel with intercalations of clayey rocks etc., which attains depth up to ~ 400 m. (Mandrescu *et al.*, 2008, 136 p., Mandrescu *et al.*, 2007, p. 367).

Seismological settings

The seismic phenomena, involved three general elements: source mechanism, seismic waves propagation to the surface of the earth, and their effects on surface. Almost all techniques of ground motion estimation depend on two parameters, earthquake magnitude (M) and distance to epicenter. The situation encountered for the last recorded strong-intermediate Vrancea earthquakes (August 30, 1986, 1atitude 45.53N, longitude 26.47E, M_w=7.1, focal depth h=131.4 km; May 30, 1990, 1atitude 45.82N, longitude 26.90E, M_w=6.9, focal depth h=90.9 km; May 31, 1990, 1atitude 45.83N, longitude 26.89E, M_w=6.4, focal depth h=86.9 km) consists in peak ground accelerations recordings with values larger than the epicenter ones, at many seismic stations in all extra-Carpathian areas. Consequently, classic seismic hazard analyses are not applicable to all strong and deep Vrancea earthquakes.

For the sites located inside or at the edge of the Focsani Depression, a basin formed in the Carpathian foreland, consisting in unconsolidated sediments, of the Badenian-Quaternary, with depths of ~13 km, the large values for recorded peak accelerations could be justified by taking into account the geological specificity of this area. This tendency seems to be maintained for the recorded values at much larger distances, from North-East to South-West of the epicentral area, also located on sediments though are of shallow depths. Therefore the necessity appears to use an approach capable to evaluate this specific behavior, with a general applicability.

Table I - Vrancea intermediate-depth earthquakes with M_w> 6.5 from the twentieth century (after Oncescu *et al.*, 1999, updated).

***Tabela I** - Terremotos de profundidade intermediária de Vrancea com M_w> 6,5 do século XX (após Oncescu et al., 1999, atualizado).*

Date	Depth [km]	Moment magnitude M_w
1904.02.06	75	6.6
1908.10.06	125	7.1
1912.05.25	90	6.7
1934.03.29	90	6.6
1940.11.10	150	7.5
1945.09.07	80	6.8
1977.03.04	94	7.4
1986.08.30	131	7.1
1990.05.30	91	6.9

The spectral amplification factors (SAF), which may give a hint about seismic response at strong seismic loadings, could be employed with relevance on seismic hazard and local site effects.

These data about soil deposits behaviour could be used as input data for seismic risk mitigation. They provide an important contribution, in a very effective way, to getting solutions toward a safer seismic design.

Data processing and results analysis

Spectral amplification factors (SAF) can be used to make a connection between local site effects and the response of the soil deposit (Cioflan *et al.*, 2009, p. 951). When applied to areas with thick sediments, as the great part of the Moesian Platform, this approach may offer a measure for local site response, at strong magnitudes.

Spectral amplification factors (Marmureanu *et al.*, 2004, p. 47) are defined as the ratio of the maximum spectral values of absolute acceleration (S_a), relative velocity (S_v) and displacement (S_d) from response spectra for a fraction of critical damping (b %) at fundamental period to maximum values of acceleration (a_{max}), velocity (v_{max}) and displacement (d_{max}), respectively, from processed strong motion recordings, that are:

$$(SAF)_a = S^a_{max}/a_{max};\ (SAF)_v = S^v_{max}/v_{max};\ (SAF)_d = S^d_{max}d/_{dmax}.$$

To illustrate this we shall consider some stations from the Bucharest metropolitan area (INC, BUC1, PND, MET, TIT) and other sites at different locations (fig. 1 and Table II), spread over Moesian and Moldavian Platforms areas: Vrancioaia (VRI), located in the epicentral zone, Focsani (FOC), at the edge of the deep sedimentary basin, Cernavoda city area (CVDI), Cernavoda City Centre (CVD), Bacau (BAC), Iasi (IAS), Ploiesti (PLS), Chisinau (CHI1) where the above mentioned factors exist for the last four major seismic events (1977, one recording at INCERC station, 1986, and 1990 May 30, 31) (ROMPLUS, 2019). The choice of these stations was not made necessarily on the criteria regarding the ground recordings tendency described in the previous section, but rather for the highly populated cities with a more detailed knowledge about local geology. As regards the soil conditions for the sites, they fall into two categories, i.e. B type and C type, according to the classification from EUROCODE 8 (EN 1998-1/2003) (Table II). The epicentral distances for each station corresponding to the last three strong earthquakes for which there exist many recordings can be seen in Table II, together with the soil conditions characteristics as given by topographic slope method (Wald and Allen, 2007, p.1379). However, upon the criteria considering the $V_{S,30}$ parameter there are large variations in the values of this parameter. For the sites of B-type, the $V_{S,30}$ parameter is covering almost all the assigned range (~360-800 m/s) with highest values in the most remote site, i.e. Chisinau city (~800 m/s) (Table II). In the Bucharest city area all sites are assigned with C-type soil conditions, situation encountered also for another cities in the Moesian Platform (e.g., Ploiesti city). One should be mentioned that the criteria adopted for design purposes in the Romanian seismic design code (P 100-1/2013, 2013) are based on the corner period T_c. This choice is justified by the variation of this parameter extracted from the response spectra with magnitude, especially for strong earthquakes. Hence, for this parameter different values for different areas are considered, irrespective of the epicentral distance or tectonic units on which the sites are located.

The spectral amplification factors for absolute accelerations at 5% fraction of critical damping (b=5%) are computed at several seismic stations (Tables III-XV). Out of them, five are in Bucharest metropolitan area, two in Cernavoda (one in city area, one in the centre of the city) and one in Chisinau (Republic of Moldova). Another five seismic stations cover the most affected areas of the country territory, with location in the risk exposed

Table II - Approximate epicentral distances and soil conditions for the considered stations.
Tabela II - *Distâncias epicentrais aproximadas e condições do solo para as estações consideradas.*

Seismic station	Epicentral distances / earthquakes			$V_{S,30}$ (m/s) using the topographic slope method Wald and Allen (2007)	Soil conditions classification according to EN 1998-1/2003
	August 30, 1986 M_W=7.1	May 30, 1990 M_W=6.9	May 31, 1990 M_W=6.4		
Vrancioaia (VRI)	42.6	13.23	14.28	368	B (360-800m/s)
Focsani (FOC)	57.37	26	27.63	249	C (180-360m/s)
Ploiesti (PLS)	75	96	93	241	C (180-360m/s)
Iasi (IAS)	204	160	157	705	B (360-800m/s)
Bacau (BAC)	121	82	80	283	C (180-360m/s)
Chisinau (CHI1)	245	198	195	800	B (360-800m/s)
Bucharest (INC)	135	155	152	269	C (180-360m/s)
Cernavoda (CVDI)	190	205	203	363-400	B (360-800m/s)

city, including epicentral area. The upper geological stratigraphy for some of these site is: Bucharest-INCERC - soft soils, quaternary layers with a total thickness of 700 m; Bucharest-Magurele (sand, loess – thickness 350 m); Cernavoda (marl, loess, limestone – thickness 270 m), Bacau (gravel, loess – 20 m), Iasi (loess, sand, clay, gravel – with thickness between 20 and 60 m), etc. (Mandrescu *et al*., 2008, 136 p., Marmureanu, 2016, 330p.) For the Bucharest city the Quaternary (200-300 m depth) deposits with an inclined depth (from South down to the North) consist in a succession of many layers with different consistency. They are especially formed from soft rocks with varying wave velocity, which though not attains high value even at lower depth.

Table III - Bucharest - INCERC (INC) Seismic Station.
***Tabela III** - Bucareste - Estação sísmica INCERC (INC).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
March 4, 1977, M_W=7.4	207	650	3.14	1.33
August 30, 1986, M_W=7.1	97	255	2.63	1.59
May 30, 1990, M_W=6.9	66	275	4.17	1.000

Table IV - Bucharest - Magurele (BUC1) Seismic Station.
***Tabela IV** - Bucareste - Estação Sísmica Magurele.*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	114	307	2.70	1.33
May 30, 1990, M_W=6.9	90.25	324	3.59	1.00
May 31, 1990, M_W=6.4	-	-	-	-

Table V - Bucharest - Panduri (PND) Seismic Station.
***Tabela V** - Bucareste - Estação Sísmica Panduri (PND).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	89.4	295	3.30	1.47
May 30, 1990, M_W=6.9	131.3	590	4.50	1.08
May 31, 1990, M_W=6.4	33.0	160	4.85	1.00

Table VI - Bucharest - Metalurgiei (MET) Seismic Station.
***Tabela VI** - Bucareste - Estação Sísmica Metalurgiei (MET).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	71.07	220	3.10	1.47
May 30, 1990, M_W=6.9	55.40	220	3.98	1.15
May 31, 1990, M_W=6.4	12.10	55	4.55	1.00

Table VII - Bucharest – Titulescu (TIT) Seismic Station.
***Tabela VII** - Bucareste - Estação Sismica Titulescu (TIT).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	87.5	355	4.07	1.37
May 30, 1990, M_W=6.9	56.8	250	4.41	1.26
May 31, 1990, M_W=6.4	7.2	40	5.56	1.00

Table VIII - Cernavoda (CVDI) Seismic Station.
***Tabela VIII** - Estação Sísmica de Cernavoda (CVDI).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	62	290	4.68	1.33
May 30, 1990, M_W=6.9	100	485	4.84	1.59
May 31, 1990, M_W=6.4	37	200	5.41	1.000

Table IX - Cernavoda Center Seismic Station (CVD).
***Tabela IX** - Estação Sísmica Central de Cernavoda (CVD).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	54.3	212	3.91	1.33
May 30, 1990, M_W=6.9	92.6	400	4.32	1.59
May 31, 1990, M_W=6.4	31.7	180	5.68	1.000

Table X - Focsani (FOC) Seismic Station.
***Tabela X** - Estação Sísmica de Focsani (FOC).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	161.8	425	2.63	1.55
May 30, 1990, M_W=6.9	117.9	405	3.44	1.18
May 31, 1990, M_W=6.4	46.8	190	4.06	1.00

Table XI - Iasi (IAS) Seismic Station.
***Tabela XI** - Estação Sísmica de Iasi (IAS).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	68	225	3.31	1.29
May 30, 1990, M_W=6.9	97	365	3.77	1.14
May 31, 1990, M_W=6.4	49.44	211	4.27	1.00

Table XII - Bacau (BAC) Seismic Station.
***Tabela XII** - Estação Sísmica de Bacau (BAC).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	72	292	4.06	1.46
May 30, 1990, M_W=6.9	132	684	5.19	1.14
May 31, 1990, M_W=6.4	63.00	372	5.91	1.00

Table XIII - Ploiesti (PLS) Seismic Station.
***Tabela XIII** - Estação Sísmica de Ploiesti (PLS).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	219.3	685	3.13	1.17
May 30, 1990, M_W=6.9	72.6	235	3.24	1.13
May 31, 1990, M_W=6.4	16.4	60	3.66	1.00

Table XIV - Chisinau (CHI) Seismic Station.
***Tabela XIV** - Estação Sísmica de Chisinau (CHI).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	187	569	3.05	1.54
May 30, 1990, M_W=6.9	173	700	4.05	1.16
May 31, 1990, M_W=6.4	61	285	4.68	1.00

Table XV - Vrancioaia (VRI) Seismic Station.
***Tabela XV** - Estação Sísmica de Vrancioaia (VRI).*

Earthquake	a_{max} [cm/s^2] recorded	S^a_{max} [cm/s^2] b=5%	$(SAF)_a$	c
August 30, 1986, M_W=7.1	82.3	290	3.53	1.54
May 30, 1990, M_W=6.9	119.6	481	4.03	1.16
May 31, 1990, M_W=6.4	43.7	195	4.47	1.00

In Tables III-XV, a_{max} is the maximum recorded acceleration, is the corresponding spectral acceleration, and $(SAF)_a$ is the acceleration spectral amplification factor. The coefficient *c* is introduced as a measure of comparison for the response of the sites. It represents the ratio of SAF for the smallest magnitude, to SAF for the stronger earthquake. Therefore these smallest values for magnitude were taken to stand for a reference behavior in the elastic range. It was considered that these are the cases of the less strong events, May 31 or even May 30, 1990 (depending on the available recordings), and their corresponding site's response could be considered as being linear. The simple linear response could be inferred by multiplying the coefficient *c* (over unity) to the values of the corresponding parameters. The higher is its value, the attenuation is considered higher. On the other hand all these SAF values are generally higher than those recommended by Regulatory Guide 1.60 of the U. S. Atomic Energy Commission (U.S. Atomic Energy Commission 1973, p.1.60), and accepted by IAEA Vienna, and the values used by AECL-Canada in 1978. For example at Cernavoda (CVDI, in the area where is located the Nuclear Power Plant) the SAF values computed above from response spectra are 4.68, 4.84, 5.41, as those given by Regulatory Guide are 3.13, 3.63, 4.16. One should mention that a calculated response spectrum is not the same as a specified standard/design spectrum. Design response spectra are obtained by analyzing, evaluating and statistically combining a number of individual response spectra derived from the significant past earthquakes or from a ground acceleration process generation. This standard response spectrum is then scaled up to the value of ground acceleration, velocity and displacement specific to each site by using spectral amplification factors.

The sites for which we have presented the recordings and computed SAF are situated on different local geological settings, though they consist in sediments. The differences consist in depth of the sedimentary layers, their stratigraphy, thickness, $V_{S,30}$ parameter, geometry, geological content, more or less consolidated, and in general the specificity of the corresponding tectonic units, i.e. Moldavian Platform, Moesian Platform (including South Dobrogea unit).

As it can be seen from Tables III-XV there is a general trend of decreasing for the SAF values as the magnitude increases. A similar situation holds for the recordings belonging to the epicentral area (Vrancioaia station, VRI). In this respect, one may suggest that spectral amplification factors may have a certain nonlinear dependence on the seismic magnitude.

This tendency is maintained irrespective of the maximum recorded acceleration (a_{max}), or maximum spectral acceleration (S_a) values e.g., the seismic event of 1986, August 30 M_w=7.1 displays lower recordings as the corresponding magnitude are higher. An example is Cernavoda (CVDI), where for the stronger event of 1986 the a_{max} value was lowest (62 cm/s^2) in comparison to other sites, as for the less strong event, M_w=6.9, at this station the a_{max} value was quite high (100 cm/s^2). However these values are not overpassed by the epicentral ones. Also, for Bacau city the stronger event generated lower motion value, as for the next less powerful events the acceleration values were higher and even overpassed epicentral ones. Hence, there is a large variability of the peak ground acceleration values, at some stations with a clear tendency for increasing with the epicentral distance, irrespective on earthquake magnitude (ROMPLUS 2019, Romanian earthquake catalogue, www.infp.ro/romplus). There exist stations where the recordings were higher than in epicenter (considered Vrancioaia station), with locations either in the Moldavian Platform (North-East from epicenter), or in Moesian Platform (South-West or South from epicenter). Also there are stations where the earthquake of 1990, May 30 generated higher ground motion values than the stronger 1986 one (e.g. Iasi, Bacau, Cernavoda, Vrancioaia, Paduri-Bucharest), aleatory spread. From these values we can see the high variability in the Vrancea-intermediate source seismic effects over the highly exposed areas (fig. 2).

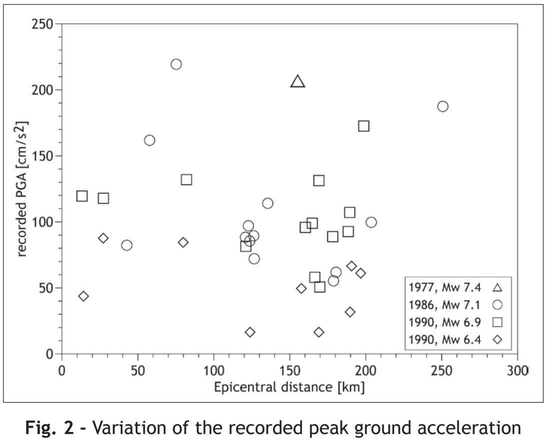

Fig. 2 - Variation of the recorded peak ground acceleration values (PGA) with the epicentral distance.

Fig. 2 - *Variação dos valores do pico de aceleração do solo (PGA) registados em função da distância epicentral.*

Discussion

The last Vrancea strong earthquakes on August 30, 1986 (M_w=7.1), on May 30, 1990 (M_w=6.9) and on May 31,1990 (M_w =6.3) were recorded at seismic station covering the almost entire country territory and Bucharest city as well. Also, the earthquake on March 4, 1977 (M_w=7.4) recorded at INCERC seismic station by SMAC-B apparatus. The processing of the records was made by using CALTECH and Kinematics procedures and the results are given in

Tables III-XV where we can find the peak values of a_{max}. Also, in Tables III-XV are given the spectral amplification factors for fraction of critical damping b=5%.

Examining the feature of these strong earthquakes we can notice that the magnitude is in direct relation to spectral amplification factors. At least for large sedimentary basins and for soft soils sedimentary areas, the spectral amplification factors (SAF) are generally decreasing with increasing magnitude for strong Vrancea earthquakes. This can be interpreted as an attenuation tendency and stabilization of the strong motion as the magnitude increases. The spectral amplification factors for last three strong and deep Vrancea earthquakes for Cernavoda (CVD and CVDI) sites are larger than the values given by Regulatory Guide 1.60 of the U. S. Atomic Energy Commission, and accepted by IAEA Vienna, and the values used by AECL-Canada in 1978. However, their higher values and clear tendency to decrease as the magnitude increases suggest the attenuation tendency for stronger earthquakes and departure from linear response which contributes at sites specificity.

This complex state of facts is due to a rather complex geological and seismological reality encountered over Romania country' territory. As the presented data and processing outline, there is a high variability of the seismic parameters in the area subjected to obvious manifestation of the seismic effects. At the general geological situation given by the tectonic sub-units sedimentary characteristics (Moesian Platform, Moldavian Platform, etc.) the very local specificity for each site add. It cannot be inferred a dependence between the weight factors values or increasing tendency of the SAF and $V_{S,30}$ parameter at no site (see Table II and Tables III-XV). Also, neither between the level of shaking or spectral amplitudes and the values or ranges of the same parameter $V_{S,30}$ at a certain site (see Table II and fig. 2).

It is worth to mention the specificity of the intermediate-Vrancea earthquakes, such as the extended directivity effects for the strong earthquakes, and, not in the last, the possibility for occurrence, at magnitude-dependent extent, of the nonlinear behavior of the soil compounds. The attenuation pattern of the peak ground acceleration generated by Vrancea subcrustal source is lesser enhanced along the direction of the fault plane (Bucharest and Moldova), compared to the attenuation normal to this direction (Cernavoda). Moreover, the site effects should be considered in a proper manner as an important weight in areas where local geology consisting in soft soils or deep sedimentary deposits are exposed to very strong seismic movement.

Considering that this phenomenon can have its explanation in the specificity of each area, at regional geological level, but especially at local level, it is necessary a method that is generally valid and to describe quantitatively the implications at the level of local hazard. In these circumstances, the spectral amplification factors are the only constantly evidence for the local site effects. They are capable to evaluate, in a quantitative manner the site response, as the effects of the propagation of the seismic waves, generated by strong seismic movement, through complex layered (soft) sedimentary soils.

Conclusions

We point to the necessity of devising a specific procedure for estimating the local site effects as regards the strong and deep Vrancea earthquakes. Such a procedure should include both the specificity of the geological conditions and data about soil deposits, obtained mostly by empirical investigations. This information provides an important contribution to getting solutions towards a safer seismic design. The spectral amplification factors (SAF), which may give a hint about seismic response at strong seismic loadings, could be employed with relevance on seismic hazard and local site effects. We highlighted stronger ground motions at distances longer than the epicentral distances for Vrancea earthquakes.

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