TECHNICAL UNIVERSITY OF CIVIL ENGINEERING BUCHAREST

DOCTORAL SCHOOL

DEPARTMENT OF REINFORCED CONCRETE STRUCTURES

Research Report 1

Overview of the seismic hazard associated with the City of Craiova

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1. Introduction

This scientific research report assesses the seismic hazard at the level of the city of Craiova. Based on the available bibliographic references, it briefly presents elements related to the seismicity of Romania, the attenuation relationships used to evaluate ground motion amplitudes, as well as the seismic motions recorded in Craiova during the Vrancea earthquakes of August 1986 and May 1990. It also presents the site conditions in the Craiova area based on data from the literature and from boreholes located in various areas of the city, as well as in neighboring areas. The seismic hazard assessment for Craiova is carried out using both the deterministic method and the results of the probabilistic analyses performed within the BIGSEES research project. Comparisons are also made between the macroseismic intensity values observed in Craiova and those estimated using a model developed for the Vrancea intermediate-depth seismic source. In addition, an analysis of the liquefaction susceptibility of the soil is carried out based on data from 3 boreholes in the city of Craiova.

2. Seismicity Analysis

Seismicity is defined by the distributions in time, space and magnitude of earthquakes. A hypothesis frequently used in characterizing seismicity and in probabilistic seismic hazard studies is the Poisson hypothesis regarding the independence of earthquakes in time and space. Under this hypothesis, the time of occurrence, size and focus location of an earthquake are independent of the time of occurrence, size and focus location of any preceding or future earthquake (Pavel and Văcăreanu, 2017).

Figure 2.1 shows the seismic sources that can affect the territory of Romania, as defined by INFP within the BIGSEES research project (Pavel and Văcăreanu, 2017). In total, 13 crustal seismic sources and the Vrancea intermediate-depth seismic source contribute to the seismic hazard of Romania. The Vrancea intermediate-depth seismic source also influences the seismic hazard of neighboring countries, such as Bulgaria, Serbia, the Republic of Moldova and Ukraine.

Table 2.1 lists, for each seismic source considered in the seismic hazard analysis for the territory of Romania, the year from which the catalog is considered complete, the number of seismic events in the catalog, as well as the minimum magnitude (completeness magnitude) and the maximum magnitude considered (Pavel and Văcăreanu, 2017).

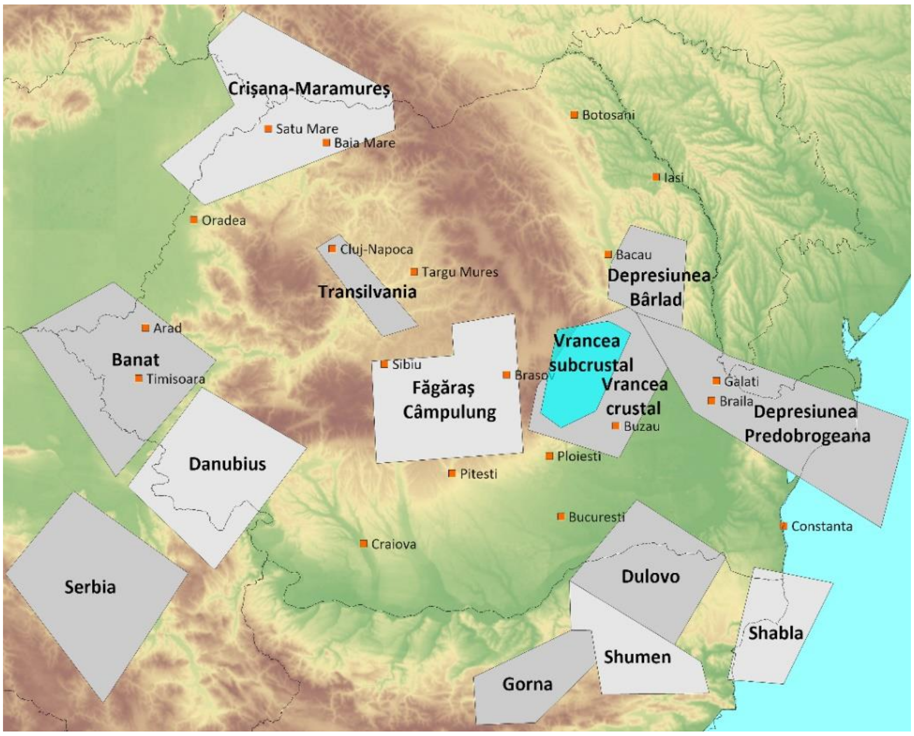

Figure 2.1 Seismic sources that can affect the territory of Romania (defined within the BIGSEES research project) (Pavel and Văcăreanu, 2017)

Table 2.1 Completeness year, number of seismic events, minimum and maximum magnitude for the catalogs of seismic sources that can affect the territory of Romania (Pavel and Văcăreanu, 2017)

Seismic source	Completeness year	No. of seismic events	Completeness magnitude, M_C	Maximum magnitude considered, M_{max}
Banat	1843	57	3,8	6,4
Bârlad Depression	1894	40	3,2	5,8
Crișana	1823	57	3,5	6,6
Danubius	1879	54	3,2	6,0
Făgăraș	1826	31	3,5	6,8
Pre-Dobrogean Depression	1900	54	3,1	5,7
Serbia	1901	122	4,2	6,6
Transylvania	1523	11	4,5	6,2
Vrancea crustal	1893	40	3,8	6,2
Vrancea intermediate	1802	97	5,7	8,2
Dulovo	1892	21	3,2	7,1
Shabla	1900	17	4,5	7,8

Gorna	1900	46	4,1	7,4
Shumen	1850	19	4,5	6,7

Crustal seismicity of the southeastern part of Romania considering earthquakes with $M_W > 2.5$, as well as the various faults in this area, are shown in Figure 2.2 (Diaconescu, 2017). It can be noted that crustal seismic activity in the area of the city of Craiova is very low. The faults identified in the western part of the Moesian Platform are illustrated in Figure 2.3. It can thus be observed that the Jiu Fault passes near the city of Craiova, which generated 2 earthquakes in 2014 in the Corabia-Turnu Măgurele area with magnitude $M_L > 4.0$.

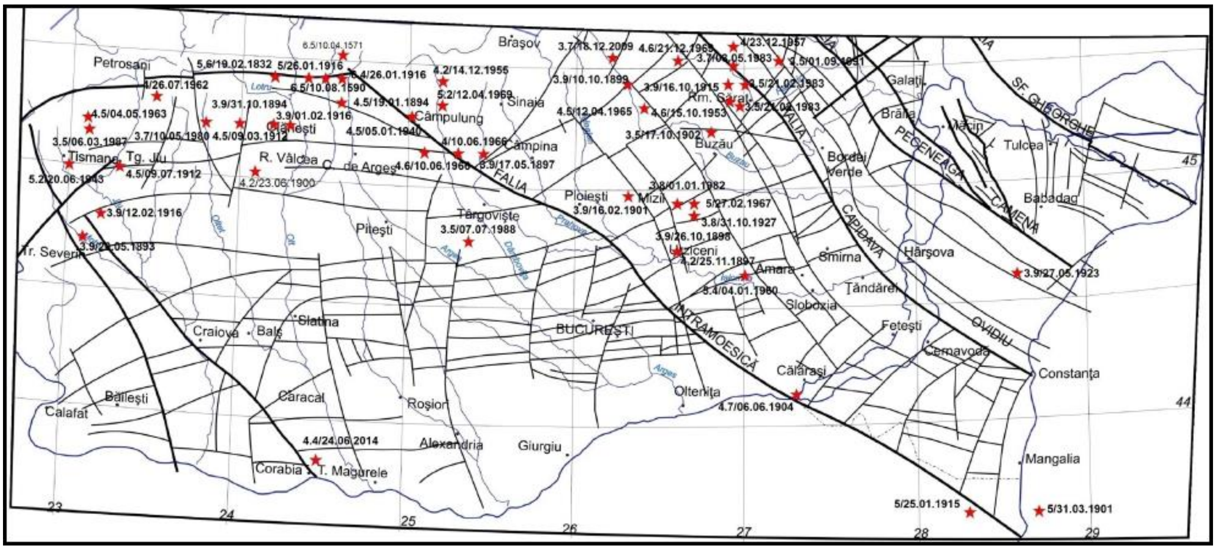

Figure 2.2 Crustal seismicity of the southeastern area of Romania for earthquakes with $M_W > 3.5$ (Diaconescu, 2017)

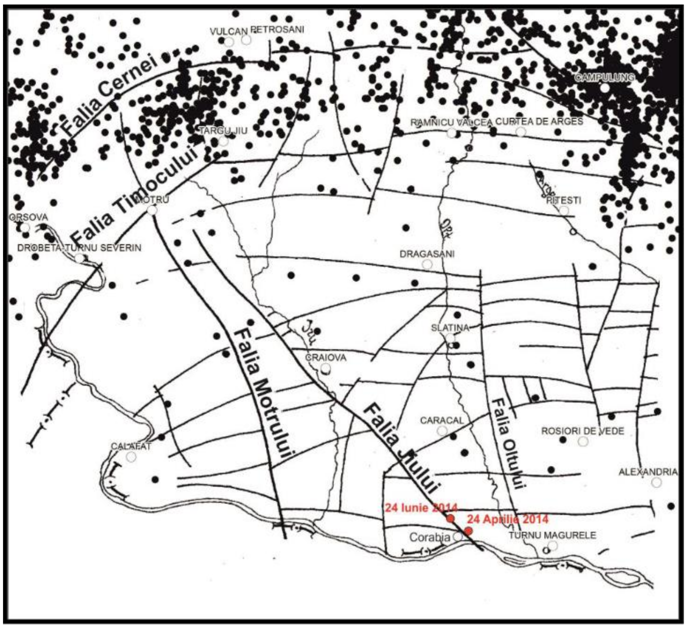

Figure 2.3 Faults located in the western part of the Moesian Platform (Diaconescu, 2017)

The earthquake magnitude recurrence relationship was first proposed by Gutenberg and Richter in the 1940s. They organized the data on California earthquakes according to the number of earthquakes exceeding a given magnitude m, N_m within a time interval, t. Based on these data, Gutenberg and Richter (1944) determined the magnitude recurrence relationship in the form:

$$lg(\lambda_m) = a - b \cdot m \quad (2.1)$$

where a and b are numerical coefficients that depend on the data set, m is the earthquake magnitude and $\lambda_m=N_m/t$ is the mean annual rate of exceedance of magnitude m and is equal to the number of earthquakes with magnitude greater than m divided by the length of the time interval considered in the analysis. Coefficient a describes the overall seismicity of the seismic source (its productivity), while coefficient b is the slope of the recurrence line and describes the relative likelihood of occurrence of earthquakes with large versus small magnitude (Văcăreanu et al. 2015a).

The magnitude recurrence relationship can also be written in the following form (Văcăreanu et al. 2015a):

$$\lambda_m = exp(a \cdot ln(10) - b \cdot ln(10) \cdot m) = exp(\alpha - \beta \cdot m) \quad (2.2)$$

where α and β are the coefficients of the exponential recurrence relationship.

The coefficients a and b (or α and β) can be obtained by regression or by the maximum likelihood method, using a data set describing the seismicity of the source analyzed. Records in the data set (origin time, hypocenter position, magnitude) relating to dependent seismic events (foreshocks and aftershocks) are removed, since only independent events are considered in the probabilistic seismic hazard analysis.

If an upper threshold magnitude, m_{max}, is considered in the earthquake recurrence analysis (in order to account for the maximum credible magnitude of a seismic source or magnitude saturation), together with a lower threshold magnitude (completeness magnitude), m_{min}, the resulting magnitude distribution function is truncated at the lower and upper bounds for $m_{min} \le m \le m_{max}$ (McGuire, 2004):

$$\lambda_m = e^{\alpha-\beta m} \cdot \frac{1-e^{-\beta(m_{max}-m)}}{1-e^{-\beta(m_{max}-m_{min})}} \quad (2.3)$$

The parameters of the magnitude recurrence relationship were calculated for all the seismic sources that can affect the territory of Romania within the BIGSEES research project (Pavel et al. 2016). In the above-mentioned study, the Vrancea intermediate-depth seismic source was divided into 4 depth layers, with the parameters a, b, m_{min} and m_{max}.

3. Local Site Conditions

In the Romanian seismic design code P100-1/2013 (MDRAP, 2013), local site conditions are described in a simplified manner through the values of the control (corner) period T_C for the area of the site considered. These values of T_C synthetically characterize the frequency content of seismic motions and were calculated according to relationships for accelerograms recorded during moderate and strong earthquakes occurring in Romania. The control (corner) period T_C represents the boundary between the zone (plateau) of maximum values in the absolute acceleration spectrum and the zone (plateau) of maximum values in the relative velocity spectrum.

The classification of site conditions in Eurocode 8 (CEN, 2004a) comprises seven ground types (CEN, 2004). The description of the ground types is given from a qualitative and quantitative point of view in Table 6.2, with each ground type being associated with a normalized elastic spectrum.

Table 3.1. Ground types in Eurocode 8 (CEN, 2004a)

Ground type	Description of the stratigraphic profile	$V_{S,30}$ (m/s)	N_{SPT} (no./30 cm)	C_U (kPa)
A	Rock or other rock-like geological formation, including at most 5 m of weaker material at the surface	> 800	-	-
B	Deposits of very dense sand, gravel, or very stiff clay, at least several tens of metres in thickness, with a gradual increase in mechanical properties with depth	360 - 800	> 50	> 250
C	Deep deposits of dense or medium-dense sand, gravel, or stiff clay with thicknesses from several tens to several hundred metres	180 – 360	15 - 50	70 – 250
D	Deposits of loose-to-medium cohesionless soil (with or without some soft cohesive layers) or of predominantly soft-to-firm cohesive soil	< 180	< 15	< 70
E	A soil profile consisting of a surface alluvium layer with $V_{S,30}$ values of class C or D and a thickness varying between about 5 and 20 m, underlain by stiffer material with $V_{S,30}$ > 800 m/s			
S_1	Deposits consisting of, or containing, a layer at least 10 m thick of soft clay/silt with a high plasticity index (*PI* > 40) and high water content	< 100	-	10 – 20
S_2	Deposits of liquefiable soils, sensitive clays, or any other soil profile not included in types A-E or S_1			

In Table 3.1, $V_{S,30}$ is the average shear wave velocity in the top 30 m of soil below the ground surface (CEN, 2004a), evaluated with equation (4.1):

$$V_{s,30} = \frac{30}{\sum_{i=1}^{N} \frac{h_i}{V_i}} \qquad (3.1)$$

N_{SPT} represents the number of blows per 30 cm obtained from the standard penetration test (SPT), while CU is the undrained shear strength.

From a geological point of view (Figure 3.1), the geological structure of the natural soil includes deposits attributed to the Upper Holocene (qh_2), belonging to the Jiu River floodplain, classified as Dune Deposits. The Dune Deposits consist of gravel, boulders and sand, with thicknesses varying between 10 and 15 m.

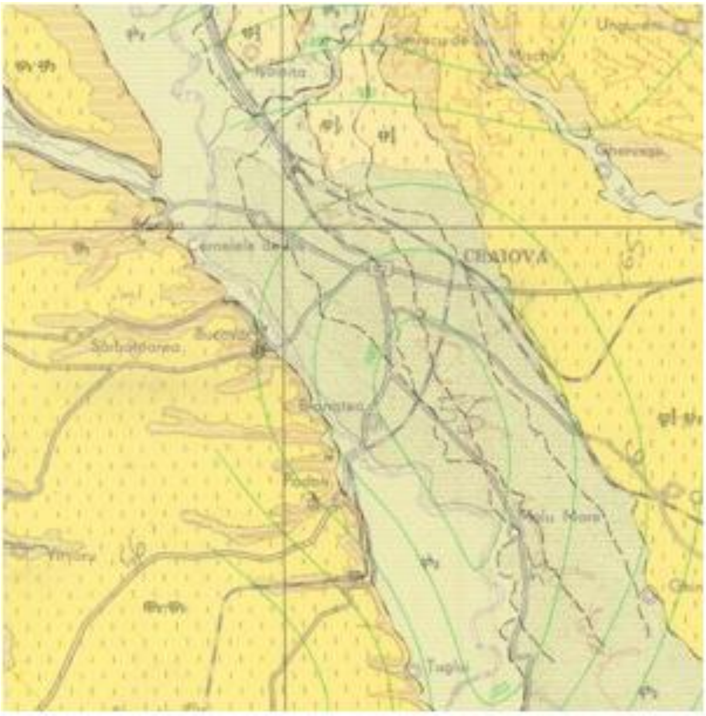

Figure 3.1 Geology of the city of Craiova (Geological Map of Romania, scale 1:200,000)

For the area of the city of Craiova, a value of the parameter $V_{S,30}$ estimated using the topographic slope method proposed by Wald and Allen (2007), is approximately 250–370 m/s (Figure 3.2), which corresponds to a class C ground type according to Eurocode 8 (CEN, 2004a).

The thickness of the sediment packages in the analyzed area (Figure 3.3), as estimated by Pelletier et al. (2016), exceeds 50 m.

A series of geological profiles for three localities near the city of Craiova (Figure 3.5) are illustrated in Figure 3.6 (Bandrabur, 1971). In all 3 cases, it can be noted that beneath the surface layer there are the Frătești layer (consisting of sands and gravels) and the Cândești layer (alternating clays and sands).

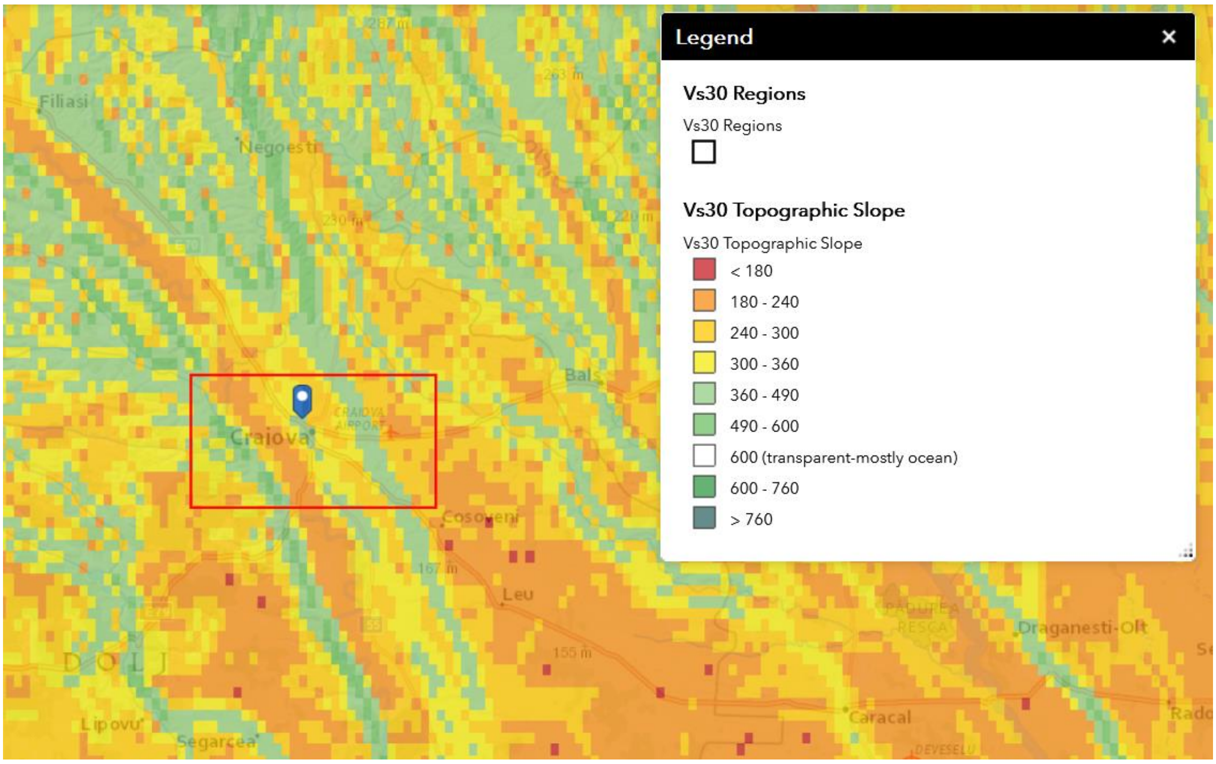

Figure 3.2 Estimated values of the parameter $V_{S,30}$ in the Craiova area based on the methodology of Wald and Allen (2007) (https://usgs.maps.arcgis.com/apps/webappviewer/index.html?id=8ac19bc334f747e486550f32837578e1)

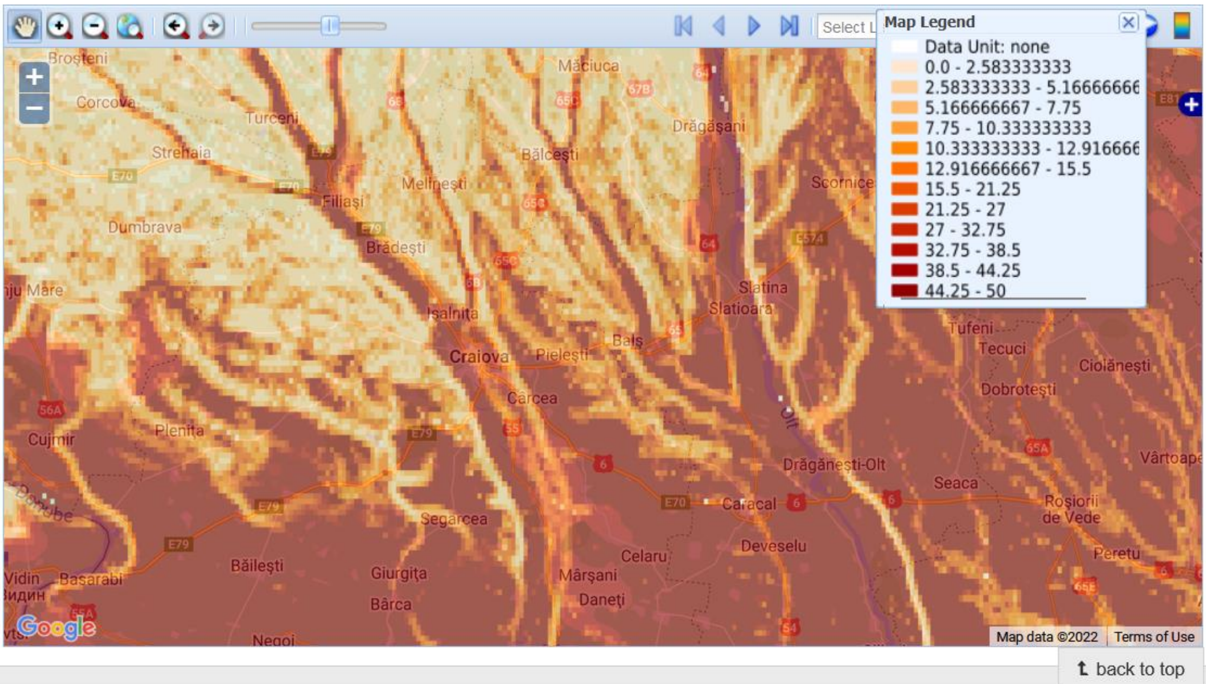

Figure 3.3 Estimated thicknesses of the sedimentary layer package in the Craiova area (https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1304)

In the study by Manea et al. (2020), the depth to bedrock is evaluated based on the analysis of records available at various seismic stations (using the horizontal-to-vertical spectral ratio method), as well as geological and geophysical data. In the above-mentioned study (Figure 3.4), a depth of approximately 900 m to bedrock is estimated for the area of the city of Craiova. This value is similar to that given in the geological map of Romania for the depth to the base of the Cretaceous in that area.

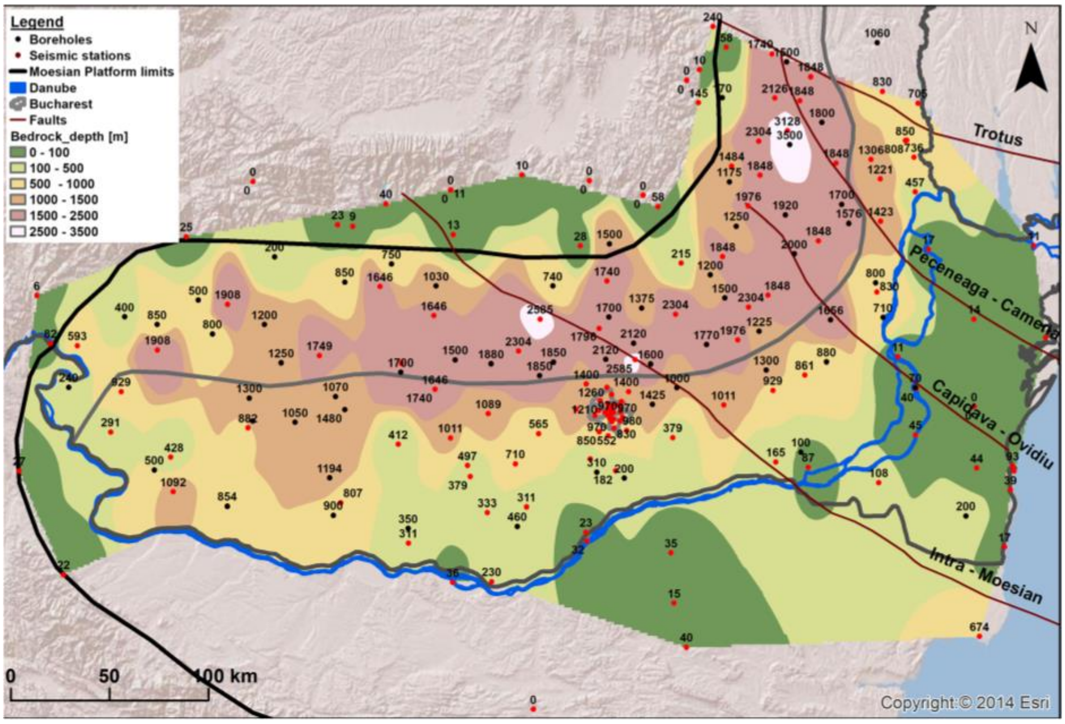

Figure 3.4 Depth to bedrock in the area of the Moesian Platform (Manea et al. 2020)

Figure 3.5 Locations of the 3 geological profiles near the city of Craiova

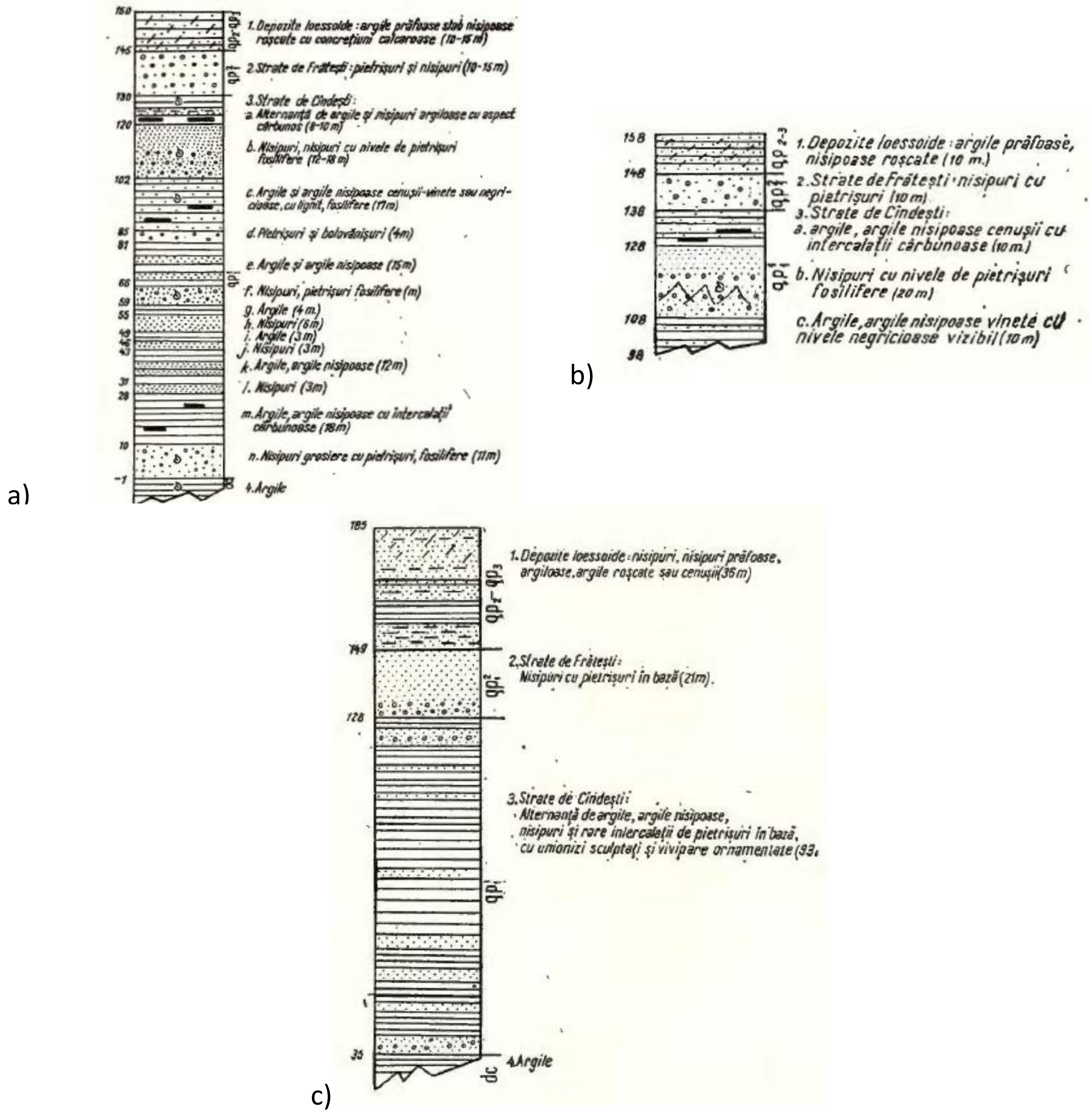

Figure 3.6 Geological profiles at: (a) Bucovăț; (b) Podari; c) Cârcea (Bandrabur, 1971)

Next, Tables 3.2–3.5 present the lithological profiles for three boreholes with SPT measurements located in different areas of the city of Craiova. The studies were carried out by SC Saidel Engineering, SC Consulting Soil Engineering SRL and SC Geoconstruct SRL between 2014 and 2020. The locations of the 3 lithological profiles are shown in Figure 3.7. Table 3.6 also presents the shear wave velocities for another borehole located near the Ion Oblemenco Stadium in Craiova. It can be noted that the shear wave velocity values, as well as the number of SPT blow counts, are fairly low in the top 10 m of soil.

Based on the available data, the $V_{S,30}$ values in the Craiova area correspond to ground type C in Eurocode 8; the depth to bedrock is approximately 900 m, with values similar to those in the Bucharest area.

Figure 3.7 Locations of the 3 lithological profiles in the city of Craiova

Table 3.2. Lithological profile, Craiova Airport Platform borehole

Depth	Soil Layers	γ (kN/m3)	I_p	c (kPa)	ϕ (°)	No. of SPT blows
0 - 0.60 m	fill	-	-	-	-	-
0.60 – 1.80 m	brown sandy clay	18.8	21.9	15	21	14
1.80 – 4.70 m	sandy clay – yellowish brown clayey sand	19.1	18	20	19	15
4.70 – 7.50 m	yellowish brown silty sand	19.4	-	27	5	16
7.50 – 10.00 m	brown sandy clay	20.1	21.2	22	27	18

Table 3.3. Lithological profile, Ion Oblemenco Stadium borehole

Depth	Soil Layers	γ (kN/m3)	I_p	c (kPa)	ϕ (°)	No. of SPT blows
0 - 1.90 m	fill	-	-	-	-	-
1.90 – 8.50 m	fine-to-medium sand	20.7	19.7	-	-	13
8.50 – 10.30 m	fine-to-medium sand with gravel	20.2	28	-	-	12
10.30 – 14.95 m	bluish gray silty clay	20.7	14.9	58	28	-
14.95 – 17.40 m	bluish gray sandy silty clay	19.7	24	8	31	-
17.40 – 20.00 m	gray clay with calcareous concretions	19.4	49.7	135	20	-

Table 3.4. Lithological profile, Calea București 113 borehole

Depth	Soil Layers	γ (kN/m3)	I_p	c (kPa)	ϕ (°)	No. of SPT blows
0 - 0.60 m	fill	-	-	-	-	-
0.60 – 3.40 m	brown clayey sand					8
3.40 – 4.70 m	yellow fine sand					-
4.70 – 7.50 m	brown sandy clay	20.4		30	24	27
7.50 – 10.40 m	medium sand – coarse sand					34
10.40 – 11.10 m	gray fine sand			46	25	-
11.10 – 12.50 m	grayish yellow clayey sand		14			-
12.50 – 13.00 m	brown clay					-
13.00 – 13.90 m	yellowish brown fine sand					-
13.90 – 15.10 m	reddish brown clayey sand					33
15.10 – 15.60 m	brown sandy clay					-
15.60 – 16.60 m	brown clay					-
16.60 – 17.70 m	gray clay	20.2	31	55	25	-
17.70 – 20.00 m	coarse sand					38

Table 3.5. Shear wave velocity profile, Ion Oblemenco Stadium borehole

Depth	Strat	γ (kN/m3)	$V_{s.30}$ (m/s)
0 - 1.00 m	fill	-	-
1.00 – 4.20 m	sandy silt	19.6	146
4.30 – 5.30 m	silty clay	19.1	119
5.30 – 6.30 m	clayey silt	19.1	212
6.30 – 7.30 m	sandy silt	19.6	223
7.30 – 8.30 m	silty sand	18.6	219
8.30 – 9.30 m	nisip	19.1	232
9.30 – 10.30 m	praf	19.1	267
10.30 – 11.30 m	clayey silt	20.6	304
11.30 – 13.50 m	sandy silt	20.4	347

4. Evaluation of Ground Motion Amplitudes

Attenuation relationships are the main tool both for (i) estimating the characteristic parameters of a seismic motion at a given site, and (ii) as an essential component of seismic hazard studies — through the seismic hazard curves and the corresponding hazard maps ultimately required for determining seismic forces in standard design, as well as in the design of special structures (which exceed the applicability of the code) — and further, in seismic risk studies and seismic maps for different areas and categories of structures.

Ground motion prediction models (or attenuation relationships) describe the amplitude of a seismic motion parameter (both as a median value and as a standard deviation) as a function of magnitude, source-to-site distance, focal depth, site conditions and other relevant parameters (Văcăreanu et al. 2015c). An attenuation relationship has the following general form (the logarithm may be natural, as in equation (4.1), or base 10)

$$ln\,Y = \overline{ln\,Y}\,(M, R, P_i) + \sigma(M, R, P_i) \cdot \varepsilon \qquad (4.1)$$

where Y is the amplitude of the seismic motion (e.g., peak ground acceleration, spectral acceleration, peak ground velocity, significant duration of the motion), M is the magnitude of the seismic event (usually the moment magnitude is used), R is the source-to-site distance (e.g., epicentral distance, hypocentral distance, Joyner-Boore distance), and P_i accounts for other parameters related to the seismic source, to seismic wave propagation, or to local site conditions. The random variable lnY is modeled with a normal probability distribution (i.e., the random variable Y has a lognormal probability distribution) characterized by its mean and standard deviation. The variable ε is the standard normal variable (or reduced variable); positive values of ε lead to values of lnY greater than the mean, while negative values of ε lead to values of lnY smaller than the mean.

The attenuation relationship proposed by Văcăreanu et al. (2015a) was obtained using a database containing 704 records from 38 earthquakes that occurred at intermediate depths (60 km < h < 173 km). Of the 38 earthquakes, nine occurred in the Vrancea intermediate-depth seismic zone in Romania, while the rest occurred in other countries: Japan, Chile, New Zealand, Mexico, India, Martinique or Peru. The magnitude range of the earthquakes is 5.2 ≤ M_W ≤ 8.0. Approximately 50% of the records (344 out of the total of 704) come from Vrancea earthquakes that occurred between 1977 and 2013.

The functional form of the attenuation model proposed by Văcăreanu et al. (2015) is presented in equation (4.2):

$$\begin{aligned} ln\,y_{ij}\,(T) &= c_1(T) + c_2(T)(M_{w,i} - 6) + c_3(T)(M_{w,i} - 6)^2 + c_4(T)\,ln\,R_{ij} + \\ &+ c_5(T)(1 - ARC_j)R_{ij} + c_6(T)ARC_jR_{ij} + c_7(T)h_i + c_8(T)Sb_j + \\ &+ c_9(T)Sc_j + c_{10}(T)Ss_j + \eta_i + \varepsilon_{ij} \end{aligned} \qquad (4.2)$$

where i and j are the indices of the earthquake and of the seismic station, respectively, y_{ij} is the geometric mean of the two perpendicular horizontal components of the ground acceleration amplitude or of the spectral acceleration (in cm/s^2), M_W is the moment magnitude of the earthquake, R is the hypocentral distance (in km), ARC = 0 for sites located inside the Carpathian arc (Transylvania) and ARC = 1 for sites outside the Carpathian arc (Moldavia and Wallachia), h is the focal depth of the earthquake (in km), S_b = 1 for class B ground types (according to Eurocode 8) and S_b = 0 otherwise, S_c = 1 for class C ground types (according to Eurocode 8) and S_c = 0 otherwise, S_s = 1 for average ground conditions and S_s = 0 otherwise, while c_1 - c_{10} are coefficients obtained by the maximum likelihood method. η_i and ε_i represent the inter-event (between seismic events) and intra-event (within a seismic event) residuals, respectively, which are characterized by a mean of 0 and standard deviations τ and σ. The total standard deviation of the attenuation relationship is calculated using equation (4.3):

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \tag{4.3}$$

The macroseismic intensity attenuation law of Văcăreanu et al. (2015b) was developed based on the Kronrod et al. (2013) data catalog, consisting of 9822 records (site-MSK intensity pairs), compiled from data provided by various institutions and authors from Romania and neighboring countries. The Vrancea intermediate-depth earthquakes considered are: 10 November 1940 (M_W=7.7), 4 March 1977 (Mw=7.4), 30 August 1986 (Mw=7.1), 30 May 1990 (Mw=6.9), 31 May 1990 (Mw=6.4) and 27 October 2004 (Mw=6.0).

The model is described by the following relationship:

$$\begin{aligned} I_{ij} = c_1 + c_2 M_{w,i} + c_5 ARC_j \left(\sqrt{{d_{ij}}^2 + {h_i}^2} - h_i \right) + \eta_i + \varepsilon_{ij} + c_3 ln \sqrt{\frac{{d_{ij}}^2 + {h_i}^2}{{h_i}^2}} \\ + c_4 (1 - ARC_j) \left(\sqrt{{d_{ij}}^2 + {h_i}^2} - h_i \right) + \end{aligned} \tag{4.4}$$

where i represents the index of the event, j is the index of the site, I is the MSK macroseismic intensity. M_w is the moment magnitude, d is the epicentral distance (in km). The ARC term introduces the position of the site relative to the Carpathian arc (ARC = 0 inside the arc and ARC = 1 outside the arc), h is the focal depth (in km), and c_k (k = 1 to 5) are coefficients determined by the maximum likelihood method.

Figures 4.1 and 4.2 show the time variations of the accelerations, velocities and displacements recorded on the 3 components at Craiova during the Vrancea earthquakes of 30 August 1986 and 30 May 1990 (Borcia, 2004). The records were obtained in the basement of a building with a basement, ground floor and 7 upper floors (B+GF+7S) in Craiova. The maximum values of the accelerations, velocities and displacements recorded for the 2 Vrancea earthquakes are presented in Table 4.1. A spectral analysis of the characteristics of these seismic records was not possible, since the records are not available.

Table 4.1 Maximum values of the accelerations, velocities and displacements recorded on the 2 horizontal components during the Vrancea earthquakes of August 1986 and May 1990 (Borcia, 2004)

Earthquake	PGA (g)		PGV (cm/s)		PGD (cm)	
	Long.	Transv.	Long.	Transv.	Long.	Transv.
1986	0.11	0.14	12.4	12.4	2.5	1.9
1990	0.05	0.06	3.7	5.0	0.5	0.6

A comparison between the median values of the class C peak ground acceleration (geometric means) recorded and those evaluated using the attenuation relationship for the Vrancea intermediate-depth seismic source proposed by Văcăreanu et al. (2015a) is presented in Table 4.2.

Table 4.2 Comparison between the peak ground acceleration values recorded at Craiova during the Vrancea earthquakes of August 1986 and May 1990 and the values calculated using the attenuation relationship developed by Văcăreanu et al. (2015a)

Earthquake	Moment magnitude M_W	Focal depth (km)	PGA (g) – geometric mean	
			Recorded	Calculated
1986	7.1	131	0.128	0.056
1990	6.9	91	0.056	0.039

The median peak ground acceleration calculated for the March 1977 earthquake using the attenuation relationship proposed by Văcăreanu et al. (2015a) is 0.10 g. In the study by Stojkovic et al. (1980), based on the seismic response of rigid bodies, lower and upper bound values of the peak ground acceleration in Craiova during the 1977 earthquake are proposed, of 0.20 g and 0.32 g, respectively.

Another useful comparison is between the median values of the macroseismic intensities observed in the city of Craiova during the Vrancea intermediate-depth earthquakes of November 1940, March 1977, August 1986, May 1990 and October 2004, based on the data from the study by Kronrod et al. (2013), and the values estimated using the attenuation relationship developed by Văcăreanu et al. (2015b). This comparison is presented in Table 4.3. The magnitude and focal depth values corresponding to each seismic event were taken from the ROMPLUS catalog (http://www.infp.ro/data/romplus.txt).

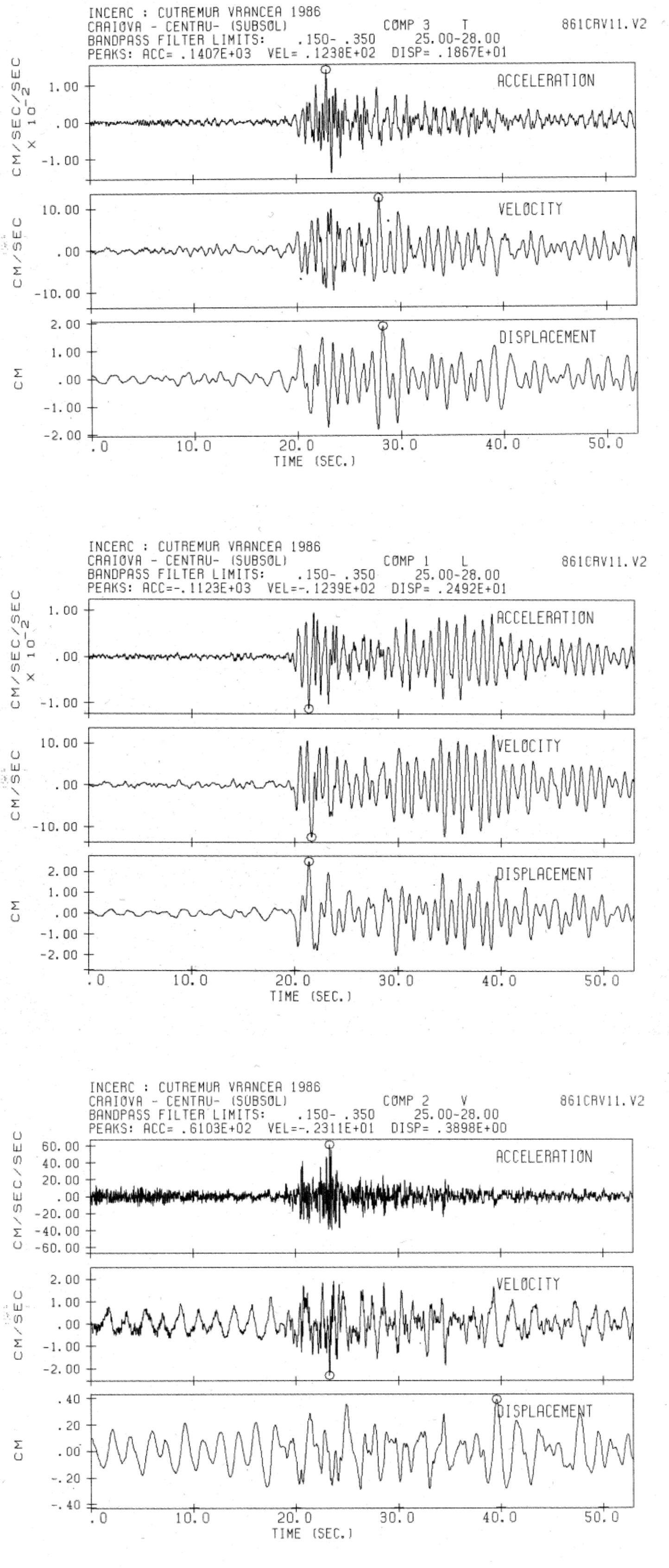

Figura 4.1 Time variation of the accelerations, velocities and displacements for the three components recorded at Craiova during the Vrancea earthquake of 30 August 1986 (Borcia, 2004)

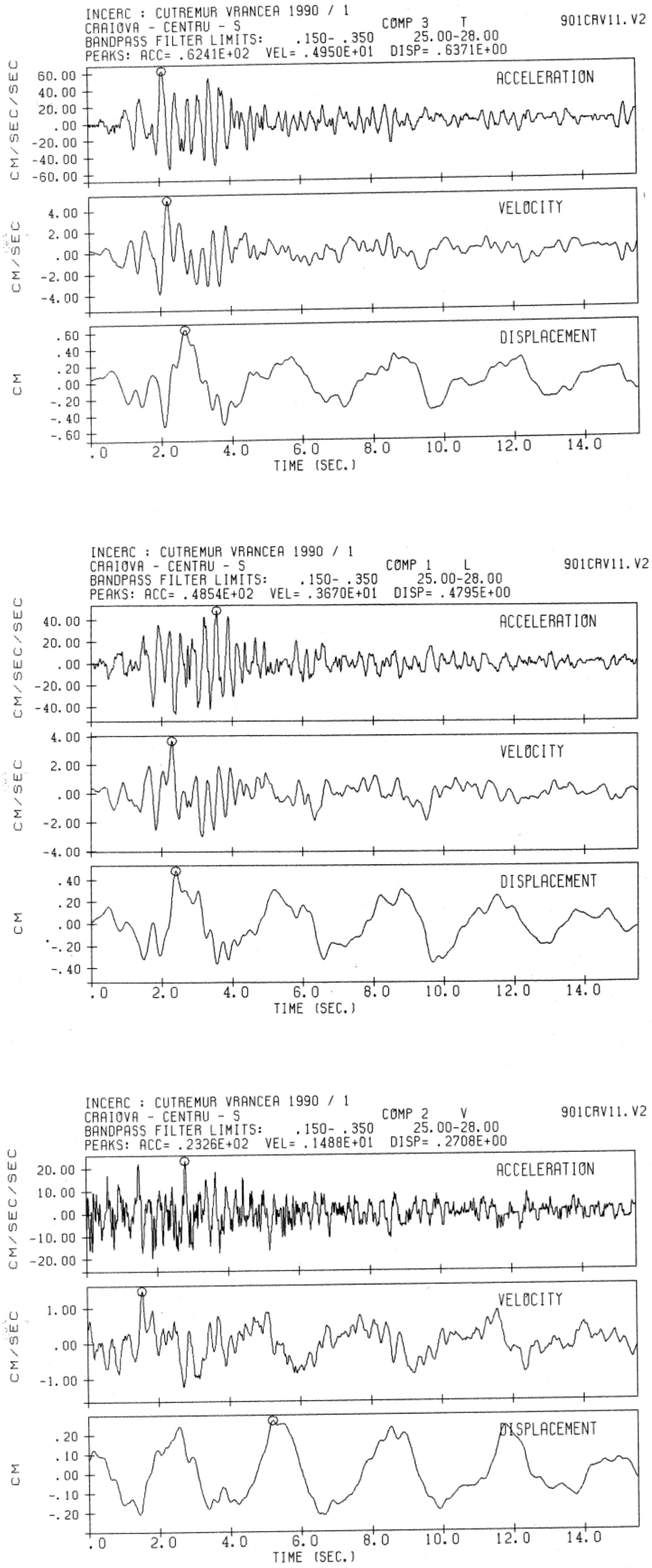

Figura 4.1 Time variation of the accelerations, velocities and displacements for the three components recorded at Craiova during the Vrancea earthquake of 30 May 1990 (Borcia, 2004)

Table 4.3 Comparison between the macroseismic intensities observed at Craiova during the Vrancea intermediate-depth earthquakes of November 1940, March 1977, August 1986, May 1990 and October 2004, and the values calculated using the attenuation relationship developed by Văcăreanu et al. (2015b)

Earthquake	Moment magnitude M_W	Focal depth (km)	Macroseismic intensity	
			Observed (Kronrod et al. 2013)	Calculated
1940	7.7	150	7	6.5
1977	7.4	94	8	5.9
1986	7.1	131	6	5.8
1990 – 1	6.9	91	6	4.9
1990 - 2	6.4	87	5	4.2
2004	6.0	105	4	4.1

5. Seismic Zoning of the City of Craiova

From a seismic zoning point of view, before the March 1977 Vrancea earthquake, Craiova was included in macroseismic intensity zone VI. The design peak ground acceleration values, as well as the corner period T_C values for Craiova given in the seismic codes applied after 1977 are presented in Table 5.1.

Table 5.1 Design peak ground acceleration values, as well as the corner period T_C values for Craiova given in the seismic codes applied after 1977

Seismic code	Design peak ground acceleration a_g (g)	Corner period T_C (s)
P100-81	0.16	1.5
P100-92	0.16	1.5
P100-1/2006	0.16	1.0
P100-1/2013	0.20	1.0

The corner period T_C for Craiova, evaluated according to Eurocode 8 (CEN, 2004a), is 0.6 s, a value much lower than that given in the Romanian seismic codes. A comparison of the design acceleration and displacement spectra calculated according to P100-1/2013 (MDRAP, 2013) and according to Eurocode 8 (CEN, 2004a) is presented in Figure 5.1.

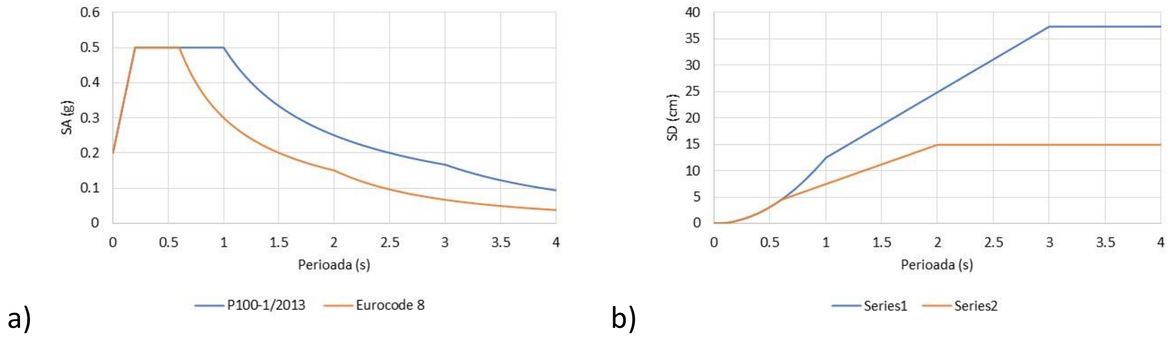

Figure 5.1 a) Comparison between the design acceleration spectra for Craiova calculated according to P100-1/2013 (MDRAP, 2013) and Eurocode 8 (CEN, 2004a); b) Comparison between the design displacement spectra for Craiova calculated according to P100-1/2013 (MDRAP, 2013) and Eurocode 8 (CEN, 2004a)

6. Deterministic Seismic Hazard Analysis for Craiova

The deterministic seismic hazard analysis develops a particular earthquake scenario used to evaluate the amplitude of a ground motion parameter at a site, and is carried out in the following steps, described in Figure 6.1 (Văcăreanu et al. 2015c), after (Kramer 1996):

1. Identification and characterization of the seismic sources that can affect the site – for each seismic source, the position, geometry and maximum credible magnitude, M_{max} thereof are determined;
2. Selection of the minimum source-to-site distance R (hypocentral, epicentral, Joyner-Boore, etc.) for each seismic source identified in the previous step;
3. Selection of the earthquake that produces the largest value of a ground motion parameter at the site, Y; this amplitude may be the peak ground acceleration in the horizontal direction (PGA) , the peak ground velocity in the horizontal direction (PGV) , or the spectral acceleration for a given vibration period, T (SA(T)), etc.; the amplitude of the ground motion parameter at the site is determined using attenuation relationships appropriate to the seismo-tectonic context analyzed.

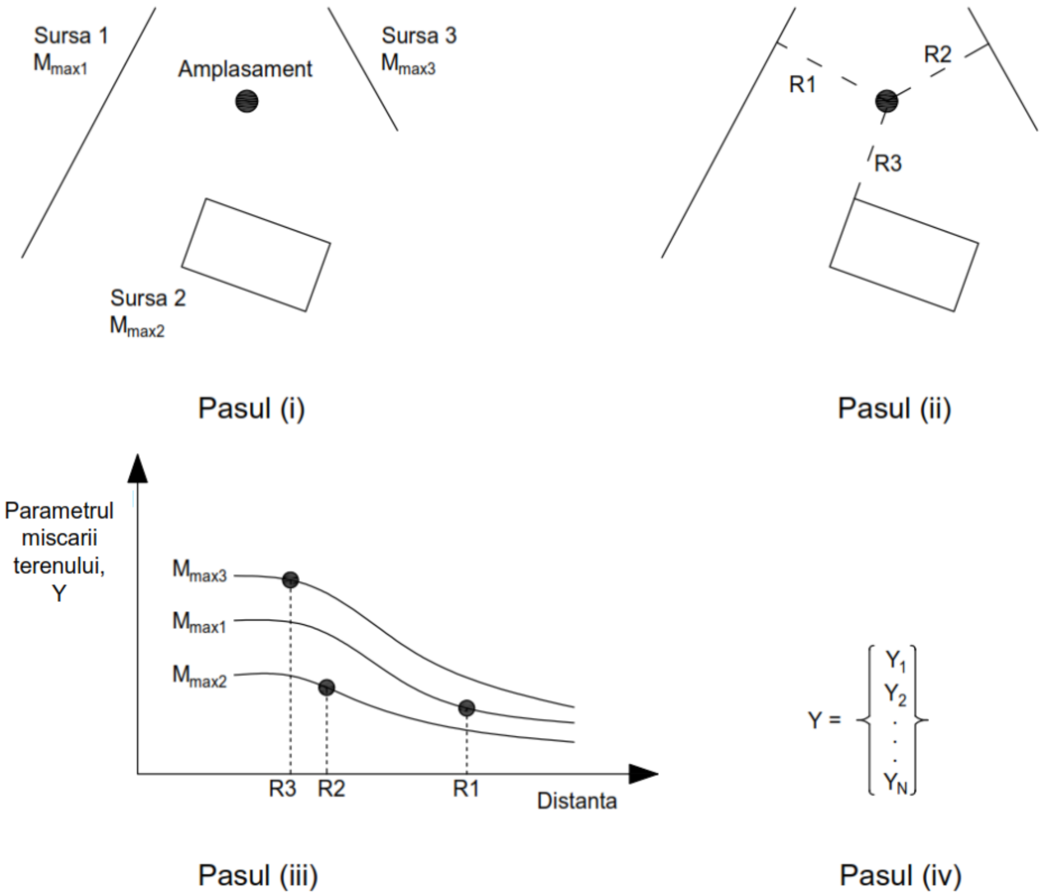

Figure 6.1 Steps of the deterministic seismic hazard analysis adapted from Kramer (1996) (Văcăreanu, 2011)

For the city of Craiova, the deterministic seismic hazard analysis for the peak ground acceleration is carried out considering the three closest crustal seismic sources – Danubius, Făgăraș-Câmpulung and Gorna – as well as the Vrancea intermediate-depth seismic source. The minimum distances between each seismic source and the city of Craiova, as well as the maximum magnitudes from Table 2.1, are considered. For the Vrancea intermediate-depth seismic source, the attenuation relationship proposed by Văcăreanu et al. (2015c) is used, while for the three crustal sources, the attenuation relationship developed by Akkar and Bommer (2010) is used. The results of the deterministic seismic hazard analysis are summarized in Table 6.1.

Table 6.1 Results of the deterministic seismic hazard analysis for the city of Craiova

Seismic source	M_{max}	d_{min} (km)	h (km)	R_{min} (km)	PGA (g)	
					median	median + σ
Danubius	6,0	120	10	120,4	0,02	0,03
Făgăraș-Câmpulung	6,8	75	10	75,7	0,06	0,11

Gorna	7,4	150	10	150,3	0,05	0,09
Vrancea intermediate	8,2	200	90	219,3	0,24	0,49

It can be noted that the highest peak ground acceleration values are those obtained for the earthquake scenario occurring in the Vrancea intermediate-depth source.

7. Probabilistic Seismic Hazard Analysis for Craiova

The probabilistic seismic hazard analysis for a site is carried out by considering all ground motions arising from earthquakes that may occur in the identified seismic sources, of any possible magnitude and/or at any source-to-site distance, together with their associated uncertainties. The probabilistic seismic hazard analysis has the advantage of fully integrating all the random uncertainties arising from the seismicity analysis and from the expected ground motion parameters of a future earthquake at a given site. The probabilistic seismic hazard analysis is carried out in the following steps, described in Figure 7.1 (Văcăreanu et al. 2015c), after (Kramer 1996):

1. Identification and characterization of the seismic sources that can affect the site – for each seismic source, the probability distribution of the source-to-site distances is determined. Seismic sources can be modeled as point sources, fault-type sources (linear sources), area-type sources, or volume-type sources, for which the seismicity distribution varies with focal depth;
2. Determination of the Gutenberg-Richter earthquake magnitude recurrence relationships – for each seismic source, the recurrence relationships giving the mean annual rates of occurrence of earthquakes with a magnitude greater than a given value are determined;
3. Calculation of the median values of the amplitude(s) of the ground motion parameter(s) at the site using attenuation relationships; it is considered that the ground motion may be produced by an earthquake of any magnitude that may occur at any point of any seismic source identified in step (1); the PSHA takes into account the standard deviations (uncertainties) specified by the attenuation relationships;
4. Determination of the mean annual rates/probabilities of exceedance of the amplitude of the ground motion parameter(s) at the site using the total probability theorem.

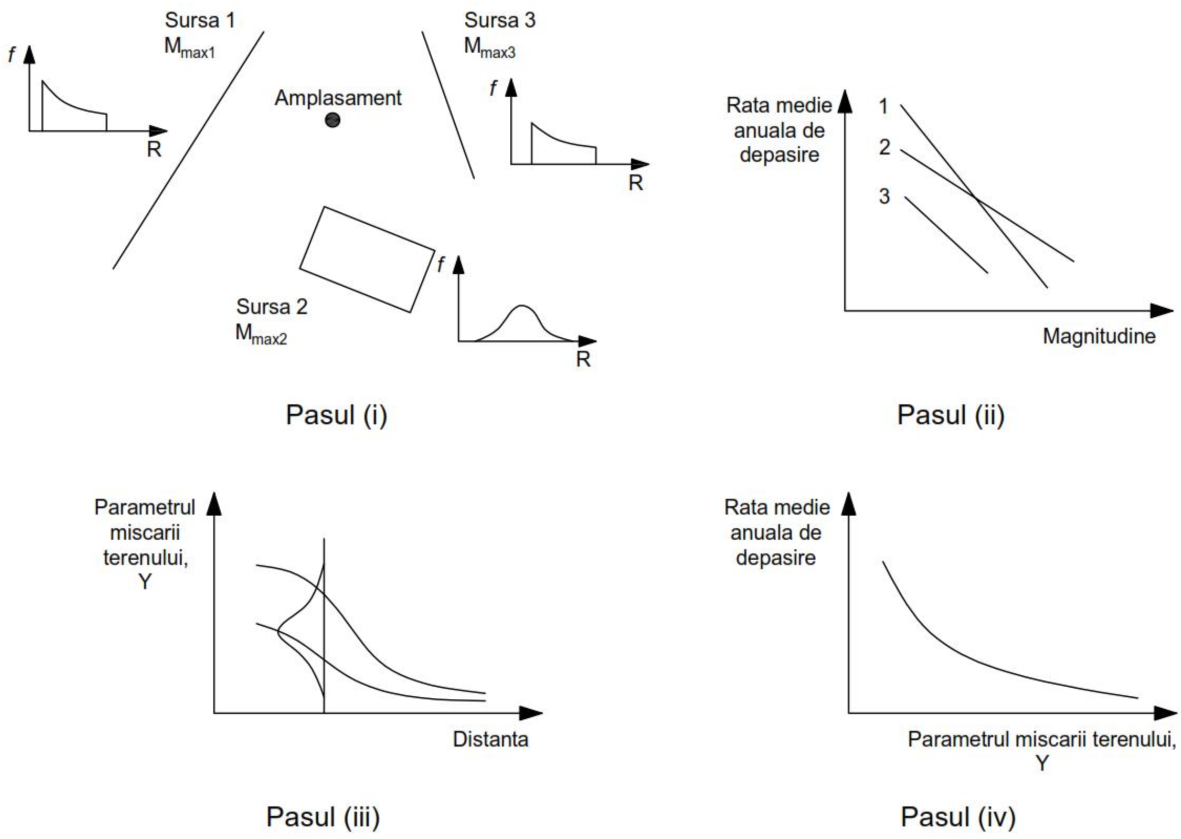

Figure 7.1 Steps of the probabilistic seismic hazard analysis adapted from Kramer (1996) (Văcăreanu, 2011)

The hazard curve for the peak ground acceleration for Craiova, calculated within the BIGSEES project (Pavel et al. 2016), is illustrated in Figure 7.2. The hazard curve was obtained considering a class C ground type according to Eurocode 8 (CEN, 2004a).

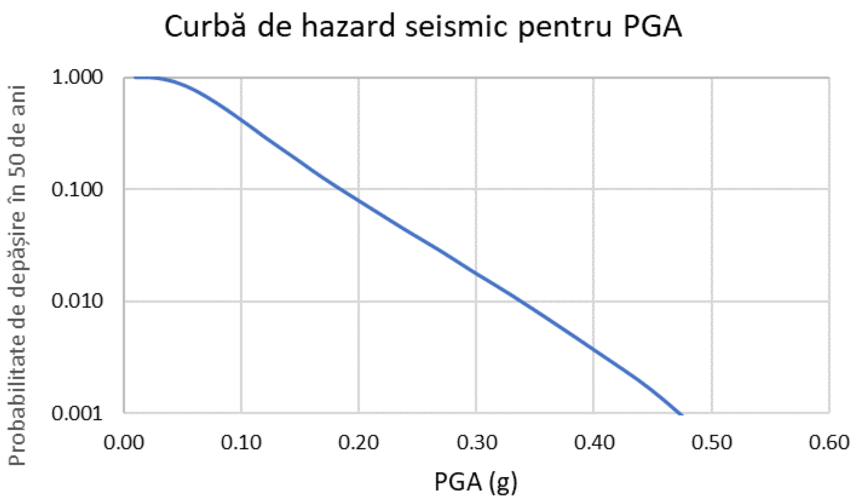

Figure 7.2 Seismic hazard curve for the peak ground acceleration for Craiova, calculated within the BIGSEES project (Pavel et al. 2016)

The peak ground acceleration values associated with different mean return periods, calculated based on the hazard curve in Figure 7.2, are presented in Table 7.1.

Table 7.1 Peak ground accelerations corresponding to different mean return periods for Craiova

Mean return period (years)	Probability of exceedance in 50 years	PGA (g)
20	92%	0.04
50	63%	0.07
100	39%	0.10
225	20%	0.14
475	10%	0.19
975	5%	0.23

The hazard results for Craiova evaluated within the SHARE and ESHM2020 research projects are available on the EFEHR platform (http://www.hazard.efehr.org/en/hazard-data-access/hazard-curves/). The two hazard curves for the peak ground acceleration (rock site conditions) are illustrated in Figure 7.3.

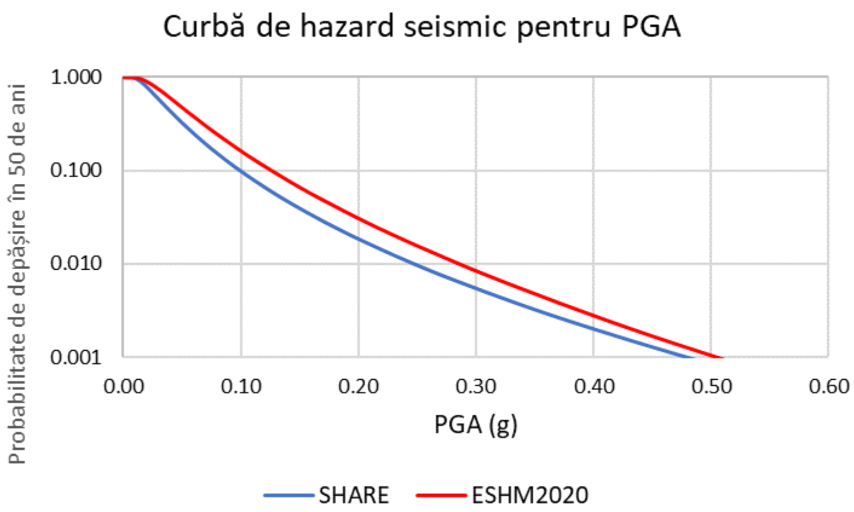

Figure 7.3 Seismic hazard curves for the peak ground acceleration for Craiova, evaluated within the SHARE and ESHM2020 research projects (http://www.hazard.efehr.org/en/hazard-data-access/hazard-curves/)

The peak ground acceleration values associated with different mean return periods, calculated based on the hazard curves in Figure 7.3, are presented in Table 7.2. It can be observed that there are significant differences between the hazard curve for Craiova obtained within the BIGSEES project (Pavel et al. 2016) and those resulting from the SHARE and ESHM2020 research projects, due to different site conditions and different seismic source models.

Table 7.1 Peak ground accelerations corresponding to different mean return periods for Craiova

Mean return period (years)	Probability of exceedance in 50 years	PGA (g)	
		SHARE	ESHM2020
20	92%	0.01	0.02
50	63%	0.03	0.04
100	39%	0.04	0.06
225	20%	0.07	0.09
475	10%	0.10	0.13
975	5%	0.14	0.17

The seismic hazard disaggregation for the peak ground acceleration corresponding to a mean return period of 475 years, showing the contribution of different magnitude and source-to-site distance intervals, is presented for Craiova in Figure 7.4, based on the results of the BIGSEES project (Pavel et al. 2016).

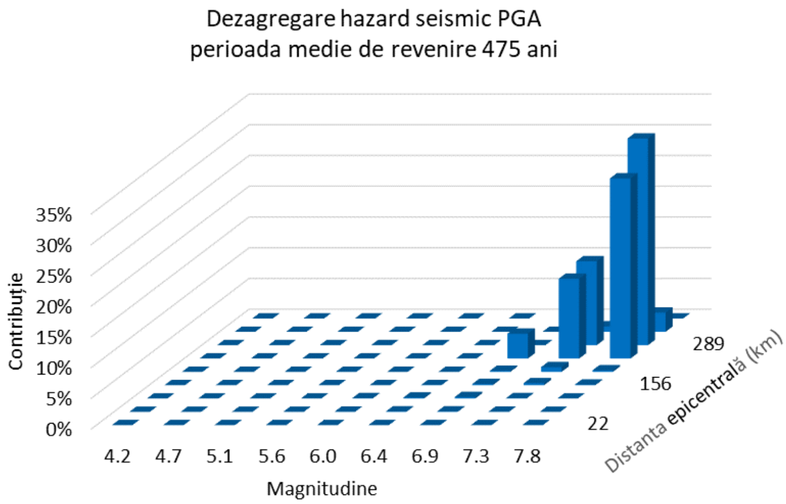

Figure 7.4 Seismic hazard disaggregation for the peak ground acceleration with a mean return period of 475 years for Craiova, calculated within the BIGSEES project (Pavel et al. 2016)

8. Conclusions

Following the seismic hazard assessment for the city of Craiova, carried out based on the available data and information, the following observations can be drawn:

1. Based on the available data, the $V_{S,30}$ values in the Craiova area correspond to ground type C in Eurocode 8;
2. The Vrancea intermediate-depth seismic source has the greatest influence on the seismic hazard in the area of the city of Craiova, as shown by both the deterministic

and the probabilistic seismic hazard analysis. Surface (crustal) seismic activity in the analyzed area is very low;

3. There are significant differences between the peak ground acceleration values recorded in Craiova during the Vrancea earthquakes of August 1986 and May 1990 and the values estimated from attenuation relationships. Significant differences are also observed between the observed macroseismic intensities and those estimated empirically for large-magnitude Vrancea earthquakes;
4. The median peak ground acceleration calculated for the March 1977 Vrancea intermediate-depth earthquake using the attenuation relationship proposed by Văcăreanu et al. (2015a) is 0.10 g. In the study by Stojkovic et al. (1980), based on the seismic response of rigid bodies, lower and upper bound values of the peak ground acceleration in Craiova during the 1977 earthquake are proposed, of 0.20 g and 0.32 g, respectively;
5. Significant differences were observed between the hazard curve for Craiova obtained within the BIGSEES project (Pavel et al. 2016) and those resulting from the SHARE and ESHM2020 research projects, due to different site conditions and different seismic source models.

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