Earthquakes and Structures, *Vol. 6, No. 2 (2014) 141-161*
DOI: http://dx.doi.org/10.12989/eas.2014.6.2.141

Empirical ground motion model for Vrancea intermediate-depth seismic source

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(Received August 1, 2013, Revised October 12, 2013, Accepted October 22, 2013)

Abstract. This article presents a new generation of empirical ground motion models for the prediction of response spectral accelerations in soil conditions, specifically developed for the Vrancea intermediate-depth seismic source. The strong ground motion database from which the ground motion prediction model is derived consists of over 800 horizontal components of acceleration recorded from nine Vrancea intermediate-depth seismic events as well as from other seventeen intermediate-depth earthquakes produced in other seismically active regions in the world. Among the main features of the new ground motion model are the prediction of spectral ordinates values (besides the prediction of the peak ground acceleration), the extension of the magnitudes range applicability, the use of consistent metrics (epicentral distance) for this type of seismic source, the extension of the distance range applicability to 300 km, the partition of total standard deviation in intra- and inter-event standard deviations and the use of a national strong ground motion database more than two times larger than in the previous studies. The results suggest that this model is an improvement of the previous generation of ground motion prediction models and can be properly employed in the analysis of the seismic hazard of Romania.

Keywords: ground motion prediction equation; strong ground motion database; seismic hazard; acceleration response spectra; peak ground acceleration

1. Introduction

A comprehensive description regarding the characteristics (focal depth range, area of seismic source, magnitude range, etc.) of the Vrancea subcrustal seismic source can be found in the papers of (Lungu *et al.* 2000), (Marmureanu *et al.* 2010) and (Ismail-Zadeh *et al.* 2012). A more complex shape of this seismic source was defined by the National Institute for Earth Physics for the SHARE project (Vacareanu *et al.* 2013a). On average, this seismic source produced 3 to 5 earthquakes of $M_W > 6.5$ each century (Ismail-Zadeh *et al.* 2012). In the 20th century earthquakes with magnitudes $M_W > 6.7$, occurred in October 1908 ($M_W = 7.1$, $h = 125$ km), November 1940 ($M_W = 7.7$, $h = 150$ km), March 1977 ($M_W = 7.4$, $h = 94$ km), August 1986 ($M_W = 7.1$, $h = 131$ km)

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http://www.techno-press.org/?journal=eas&subpage=7 ISSN: 2092-7614 (Print), 2092-7622 (Online)

and May 1990 (M_W = 6.9, h = 91 km), respectively. Several possible geodynamic models for the Vrancea subcrustal seismic source are presented in Radulian *et al.* (2000), Sperner *et al.* (2001), Milsom (2005), Mocanu (2010), Müller *et al.* (2010) or Ismail-Zadeh *et al.* (2012).

The first studies regarding ground motion models for the prediction of the peak ground acceleration of intermediate-depth Vrancea subcrustal seismic events were performed by Lungu *et al.* (1994) and Radu *et al.* (1994). The functional form of the azimuth-dependent attenuation model is the following:

$$\ln PGA = c_0 + c_1 M + c_2 \ln R + c_3 R + c_4 h + \varepsilon \quad (1)$$

where: *PGA* is peak ground acceleration at the site, *M* - magnitude (surface- wave magnitude or moment magnitude), *R* - hypocentral distance to the site, *h* - focal depth, c_0, c_1, c_2, c_3, c_4 - data dependent regression coefficients and ε - random variable with zero mean and standard deviation $\sigma_\varepsilon = \sigma_{\ln PGA}$. The same functional form was also used by Lungu *et al.* (2000) for the development of a ground motion prediction equation that is not azimuth-dependent (using all available recorded data, regardless of their geographic location). Some additional (azimuth-dependent) ground motion prediction equations for the Vrancea subcrustal seismic source and for *PGA* were also developed in the papers of Stamatovska and Petrovski (1996) and Musson (1999). In the work of Sokolov *et al.* (2008) a set of azimuth-dependent ground motion prediction equations specifically derived for the Vrancea subcrustal seismic for peak ground acceleration (*PGA*), peak ground velocity (*PGV*), pseudo-spectral acceleration (*PSA*) and MSK scale seismic intensity is given. Considering the fact that the parameters of this ground motion prediction model (Sokolov *et al.* 2008) are not readily available, this GMPE is not considered in the analysis.

The characteristics of the four above-mentioned *GMPE*s developed for the Vrancea subcrustal seismic source are given in Table 1 using also data from the work of Douglas (2012).

Table 1 Characteristics of the datasets for the considered ground motion prediction models

GMPE	Database	No. of horizontal components	No. of earthquakes	Magnitude range	Source-to-site distance range	Focal depth range	No. of soil classes
Lungu *et al.* (1994)	Vrancea	160	3	6.9 - 7.4	10 - 310	91 - 131	1
Stamatovska and Petrovski (1996)	Vrancea	190	4	6.4 - 7.4	10 - 310	87 - 131	1
Musson (1999)	Vrancea	-	3	6.9 - 7.4	10 - 310	91 - 131	1
Sokolov *et al.* (2008)	Vrancea	178	4	6.4 - 7.4	10 - 310	87 - 131	1

The main focus of this article is the development of a new ground motion prediction equation *GMPE* for Vrancea subcrustal seismic source. The performance of this new model, which is based on an increased strong ground motion database is evaluated using several goodness-of-fit measures presented in the work of Scherbaum *et al.* (2004, 2009) and Delavaud *et al.* (2012). The analysis of the inter-event and intra-event residuals (Stafford *et al.* 2008, Scassera *et al.* 2009, Shoja-Taheri *et al.* 2010) is also performed for the available dataset of strong ground motions. Other *GMPE*s are recommended for the Vrancea intermediate-depth seismic source in the paper of Delavaud *et al.* (2012) which deals with attenuation models for the probabilistic seismic hazard assessment in Europe. The four recommended ground motion prediction equations for Vrancea are: Youngs *et al.* (1997), Zhao *et al.* (2006), Atkinson and Boore (2003) and Lin and Lee (2008). An evaluation of some of these models is shown in the papers of Vacareanu *et al.* (2013b, 2013c). In the final part of this paper the impact of the use of the new proposed GMPE on the seismic hazard levels for several cities in Romania is also assessed.

2. Strong ground motion database for regression analysis

The proposed ground motion model for the prediction of spectral accelerations is derived from a national database (strong ground motion records from Vrancea subcrustal earthquakes) and an international database consisting altogether of 431 strong ground motions (861 horizontal components) recorded from 26 intermediate-depth seismic events with moment magnitudes in the range $5.2 \leq M_W \leq 7.8$. The strong ground motions from Vrancea earthquakes were recorded in Romania, Republic of Moldova, Bulgaria and Serbia. The international strong ground motions were recorded in intermediate-depth earthquakes in Japan (K-net and Kik-net data), New Zealand, Mexico, Chile and India. The range of the focal depth of all earthquakes is in between 69 km to 173 km. This depth range is typical for seismic events produced in the Vrancea region, which are the main focus of this attenuation model.

The main characteristics of the database used for the derivation of the ground motion prediction model are given in Table 2. All the analyzed strong ground motions were collected for the BIGSEES national research project from the seismic networks of INFP (National Institute for Earth Physics), INCERC (Building Research Institute), GEOTEC (Institute for Geotechnical and Geophysical Studies) and NCSRR (National Centre for Seismic Risk Reduction). For each seismic event, the date of occurrence, the magnitude, the position of the epicentre, the focal depth and the number of strong ground motions are presented in Table 3.

Table 2 Characteristics of the database of strong ground motions

GMPE	Database	No. of horizontal components	No. of earthquakes	Magnitude range, M_W	Epicentral distance range, km	Focal depth range, km
Proposed model	Vrancea + International	465 + 396	9 + 17	5.2 - 7.8	2 - 647	69 - 173

The distribution of the soil conditions for the seismic stations which have recorded the strong ground motions in the database with respect to the earthquake magnitude is shown in Fig. 1. The soil conditions are defined according to Eurocode 8 (EN 1998-1) and are assigned according to Trendafilovski *et al.* (2009). The vast majority of the strong ground motions were recorded in soil conditions (classes B, C or D), the exception being some strong ground motions from Vrancea earthquakes recorded in the epicentral region in soil class A. These strong ground motions were also kept in the database due to the lack of strong ground motions recorded in soil conditions from the epicentral region of Vrancea intermediate-depth earthquakes. Although the proposed ground motion prediction model is derived only for soil conditions, it is the authors' opinion that the use of the strong ground motions recorded on harder soil conditions (only in the epicentral region) does not affect the results for larger epicentral distances. In the case of some seismic station the exact soil classification could not be retrieved from the existing database. Nevertheless, the conditions for these stations were assigned as soil, so these data were also used in the regressions (these stations are defined as not classified hereinafter).

Table 3 Characteristics of the considered seismic events

Event no.	Country	Date	Lat.	Long.	M_W	*h* (km)	No. of strong ground motions
1	Romania	04.03.1977	45.34	26.30	7.4	94	3
2		30.08.1986	45.52	26.49	7.1	131	38
3		30.05.1990	45.83	26.89	6.9	91	46
4		31.05.1990	45.85	26.91	6.4	87	25
5		28.04.1999	45.49	26.27	5.3	151	11
6		27.10.2004	45.84	26.63	6.0	105	50
7		14.05.2005	45.64	26.53	5.5	149	15
8		18.06.2005	45.72	26.66	5.2	154	18
9		25.04.2009	45.68	26.62	5.4	110	27
10	Japan	2.12.2001	39.40	141.26	6.4	122	6
11		26.05.2003	38.81	141.68	7.0	71	26
12		21.09.2005	43.71	146.40	6.0	103	8
13		12.06.2006	33.13	131.41	6.2	146	7
14		24.07.2008	39.73	141.63	6.8	108	21
15		2.02.2013	42.70	143.30	6.4	120	20
16	Mexico	28.08.1973	18.29	-96.45	7.0	84	4
17		24.10.1980	18.03	-98.29	7.0	70	8
18		21.10.1995	16.92	-93.62	7.2	98	5
19		15.06.1999	18.18	-00.51	7.0	69	15
20	New Zealand	5.01.1973	-39.04	175.26	6.6	173	7
21		8.09.1991	-40.24	157.17	5.6	94	8
22		22.03.1995	-41.05	174.18	5.8	90	12
23	India-Myanmar	6.08.1988	25.15	95.13	6.8	90	17
24		9.01.1990	24.75	95.24	6.1	119	10
25		6.05.1995	24.99	95.29	6.4	117	5
26	Chile	13.06.2005	-20.01	-69.24	7.8	108	19

The histograms in Fig. 1 and Fig. 2 reveal a concentration of the strong ground motions recorded at epicentral distances in the range 100 - 200 km.

The distribution of the earthquake magnitude versus the focal depth for the 26 analyzed seismic events is shown in Fig. 3.

In Fig. 4 and Fig. 5 the distributions of the peak ground acceleration (defined as the geometric mean of the two horizontal components) with respect to the earthquake moment magnitude and epicentral distance of the recording seismic station are given.

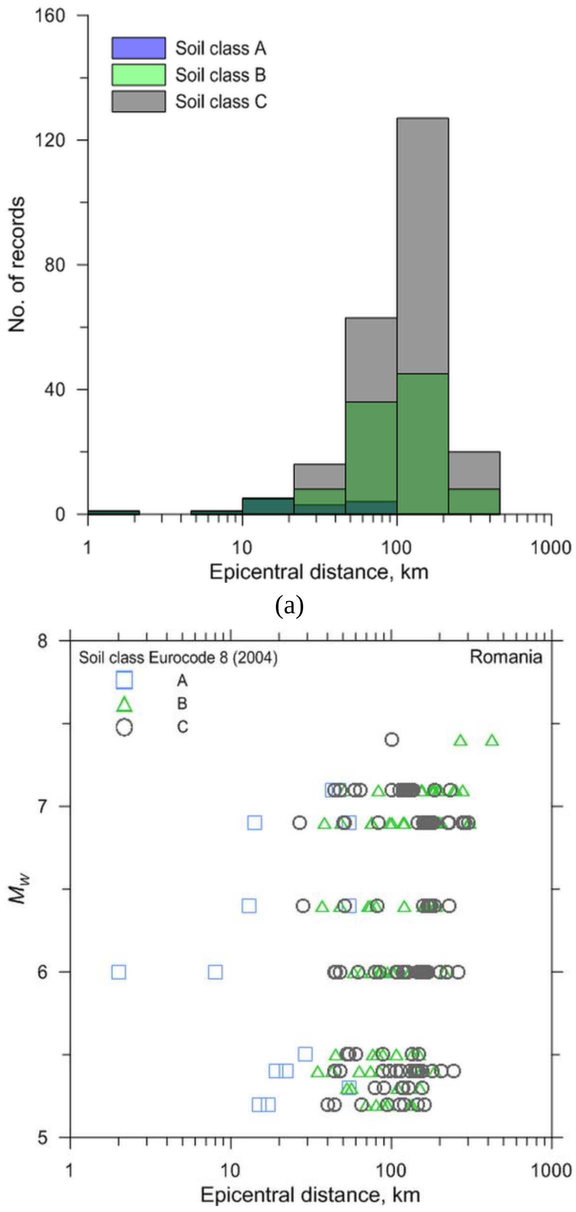


Fig. 1 Distribution of the earthquake magnitude M_W with the epicentral distance for Vrancea, Romanian strong ground motions

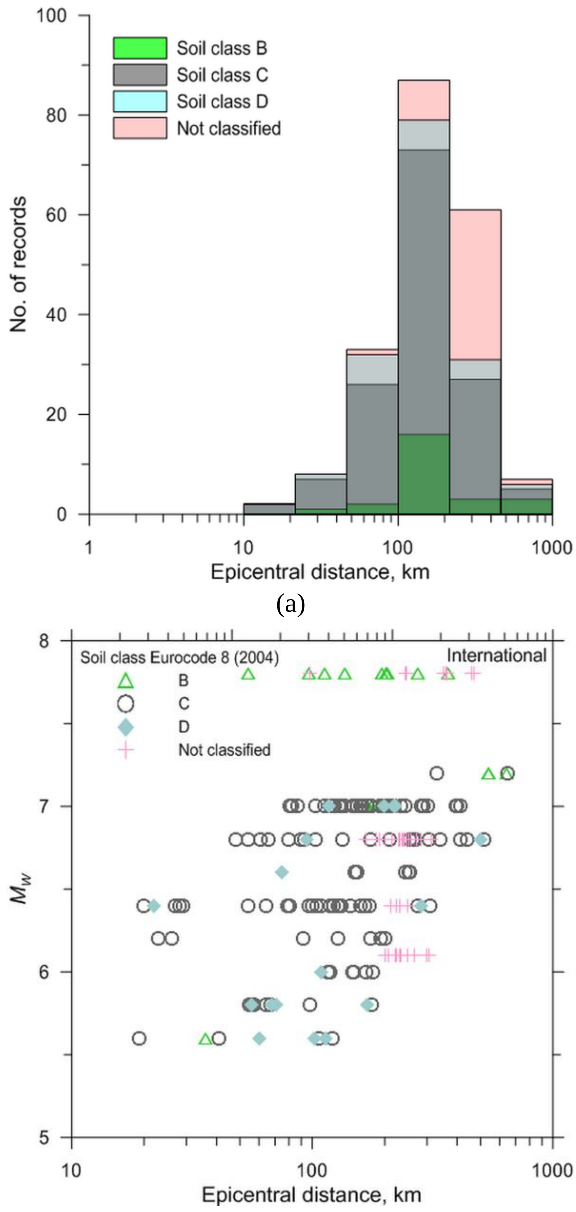


Fig. 2 Distribution of the earthquake magnitude M_W with the epicentral distance for international strong ground motions

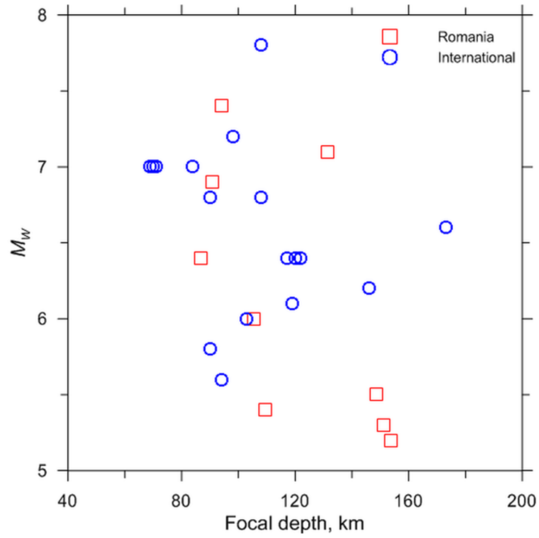


Fig. 3 Distribution of the earthquake magnitude M_W with the event focal depth h

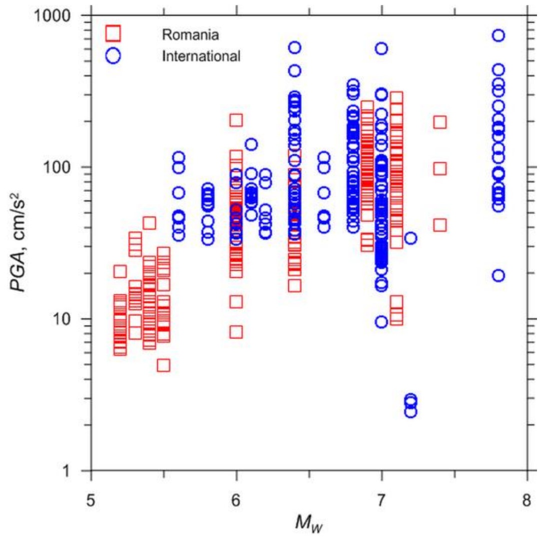


Fig. 4 Distribution of the peak ground acceleration (*PGA*) with the earthquake magnitude M_W

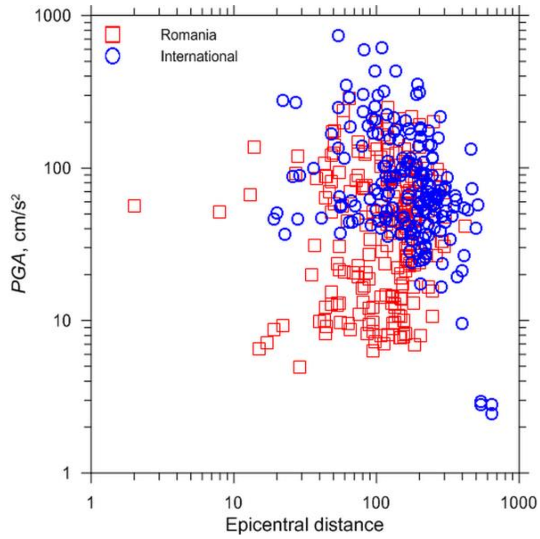


Fig. 5 Distribution of the peak ground acceleration (*PGA*) with the epicentral distance of the recording seismic station

3. Functional form and regression model

In the present study the following functional form of the *GMPE* is selected:

$$\ln y_{ij}(T) = c_1(T) + c_2(T)\left(M_{w,i} - 6\right) + c_3(T)\left(M_{w,i} - 6\right)^2 + c_4(T)\ln R_{ij} + c_5(T)R_{ij} + c_6(T)h_i + \eta_i + \varepsilon_{ij} \quad (2)$$

where i is the earthquake index, j is the recording station's index, y_{ij} is the geometrical mean of the two horizontal components of either *PGA* (in cm/s^2) or 5% damped response spectral acceleration (in cm/s^2) for a spectral period *T*, M_w is the moment magnitude (use M_w = 7.6 for events of M_w > 7.6 for spectral periods up to 1.0 s and use M_w = 8.0 for events of M_w > 8.0 for spectral periods in excess of 1.0 s), *R* is the source to site (hypocentral) distance in kilometers, *h* is the focal depth in kilometers and c_k (k = 1 to 6) are coefficients determined from the data set by regression analysis at each spectral period. The independent normally distributed variates η_i and ε_{ij} are the inter-event residuals (error that represents earthquake to earthquake variability of ground motions) with zero mean and a standard deviation of τ and respectively, the intra-event residuals (error that represents within earthquake variability of ground motions) with zero mean and a standard deviation of σ. Both intra- and inter-event standard deviations σ and τ are period dependent, but are assumed independent of magnitude. The total standard deviation of the model's prediction is defined by:

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \qquad (3)$$

The regression coefficients and the residual terms are obtained with the maximum likelihood method (Joyner and Boore 1993, 1994). The magnitude effect on the predicted values of ground motion parameters is considered through c_1 to c_3 coefficients. The influences of the geometrical spreading and of the anelastic attenuation are accounted for in relation (2) through c_4 and c_5 coefficients. The depth effect is given by the coefficient c_6. The coefficients c_1 to c_6 as well as the standard deviations are shown in Table 4. One can notice from Table 4 the range of the total standard deviation from 0.71 to 0.92 and the rather balanced contribution of intra- and inter-event standard deviations to the total variability of the model.

Table 4 Regression coefficients and standard deviations of the proposed *GMPE*

T, s	c_1	c_2	c_3	c_4	c_5	c_6	σ_T	τ	σ
0.0	8.5851	1.4863	-0.4758	-1.000	-0.00138	0.00484	0.738	0.550	0.491
0.1	9.1790	1.2914	-0.3798	-1.000	-0.00095	0.00447	0.923	0.692	0.611
0.2	9.5719	1.5016	-0.5250	-1.000	-0.00193	0.00474	0.874	0.658	0.575
0.3	9.4383	1.7468	-0.6167	-1.000	-0.00267	0.00571	0.818	0.617	0.536
0.4	9.2379	1.9355	-0.6987	-1.000	-0.00269	0.00561	0.823	0.592	0.572
0.5	9.0571	2.0346	-0.7008	-1.000	-0.00289	0.00518	0.790	0.513	0.601
0.6	8.9340	2.0695	-0.6845	-1.000	-0.00276	0.00381	0.793	0.502	0.614
0.7	8.7733	2.1370	-0.7029	-1.000	-0.00271	0.00308	0.773	0.488	0.599
0.8	8.6120	2.1907	-0.6726	-1.000	-0.00275	0.00273	0.755	0.461	0.597
0.9	8.4383	2.2422	-0.6653	-1.000	-0.00271	0.00242	0.729	0.414	0.600
1.0	8.3839	2.2537	-0.6684	-1.000	-0.00247	0.00097	0.729	0.414	0.600
1.2	8.1855	2.3182	-0.6193	-1.000	-0.00287	0.00036	0.719	0.377	0.612
1.4	7.8850	2.3958	-0.5977	-1.000	-0.00312	0.00073	0.711	0.366	0.610
1.6	7.7061	2.4470	-0.5812	-1.000	-0.00329	0.00039	0.728	0.401	0.608
1.8	7.5257	2.4958	-0.5865	-1.000	-0.00329	-0.00002	0.732	0.410	0.607
2.0	7.4295	2.5124	-0.5638	-1.000	-0.00324	-0.00115	0.730	0.410	0.605
2.5	7.0493	2.6036	-0.5870	-1.000	-0.00312	-0.00175	0.735	0.402	0.615
3.0	6.6822	2.6306	-0.6053	-1.000	-0.00275	-0.00218	0.750	0.433	0.613
3.5	6.4087	2.6152	-0.6290	-1.000	-0.00236	-0.00290	0.751	0.436	0.612
4.0	6.1352	2.6116	-0.6607	-1.000	-0.00198	-0.00313	0.752	0.463	0.593

4. Evaluation of proposed *GMPE*

The evaluation and validation of the proposed *GMPE* is performed in several steps. The first step consists of several comparisons of the proposed ground motion model with the observed data from the most instrumented seismic events produced by the Vrancea subcrustal seismic source. In Figure 6 the proposed model is compared with the spectral accelerations at T = 0.0 s, 0.3 s and 1.0 s obtained from the data recorded during the Vrancea earthquakes of August 1986 (M_W = 7.1), May 1990 (M_W = 6.9) and October 2004 (M_W = 6.0).

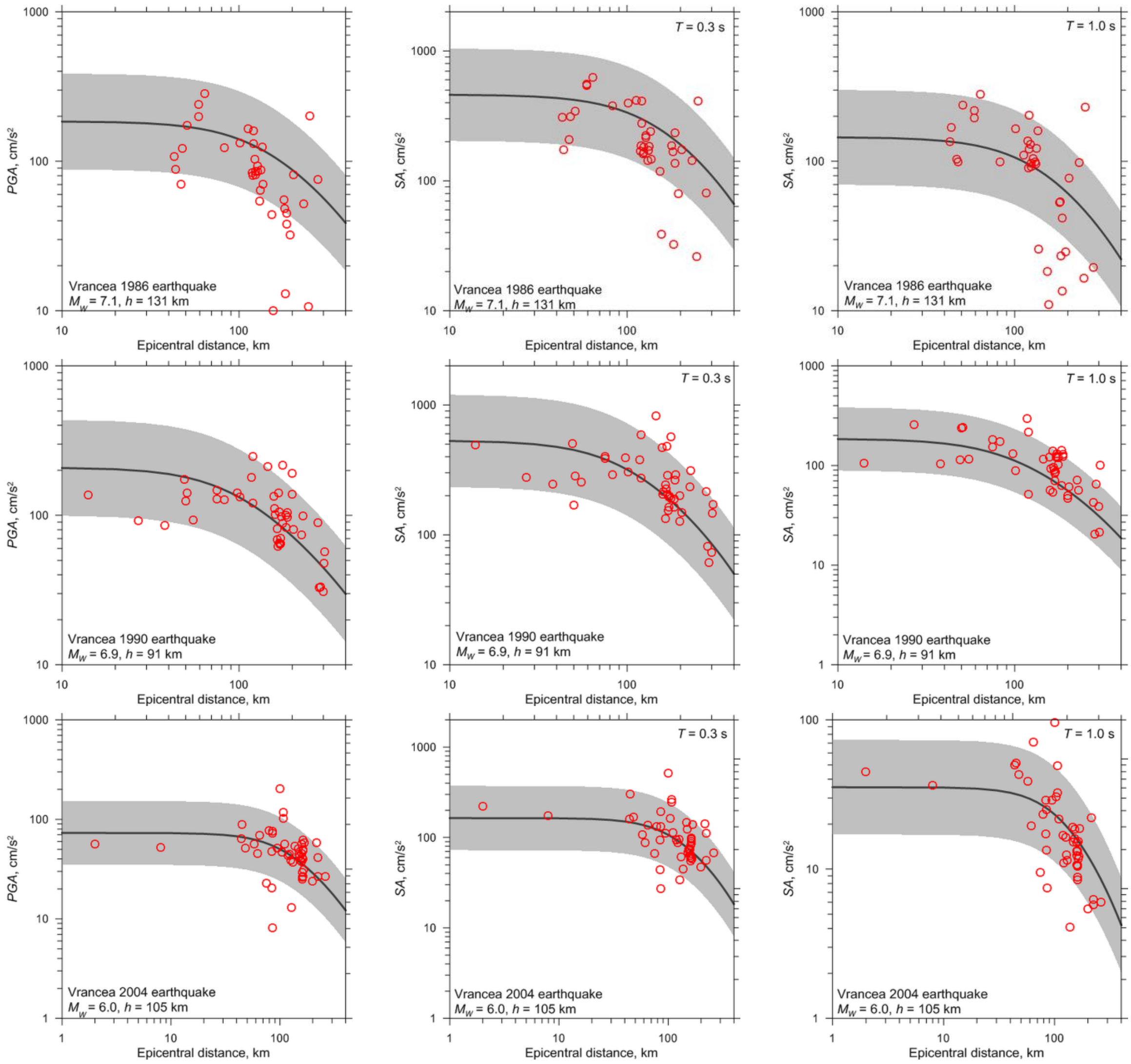


Fig. 6 Comparison of observed and predicted spectral accelerations using the proposed *GMPE* for three spectral periods (T = 0.0 s, T = 0.3 s and T = 1.0 s) and for three subcrustal Vrancea seismic events. Red circles correspond to observed values, solid lines correspond to predicted median values and shaded areas correspond to the region between the 16th and 84th percentile predicted values

It is noticeable from Fig. 6 that most of the observed data for all three periods are distributed between the median plus/minus one standard deviation.

Fig. 7 shows the distribution of the normalized residuals *NRES* (Scherbaum *et al.* 2004) versus earthquake magnitude, focal depth and epicentral distance. In the second and third rows of plots the earthquakes are separated into three bins according to their magnitude: events with $5.2 \leq M_W < 6.0$; events with $6.0 \leq M_W < 7.0$ and events with $7.0 \leq M_W < 7.8$.

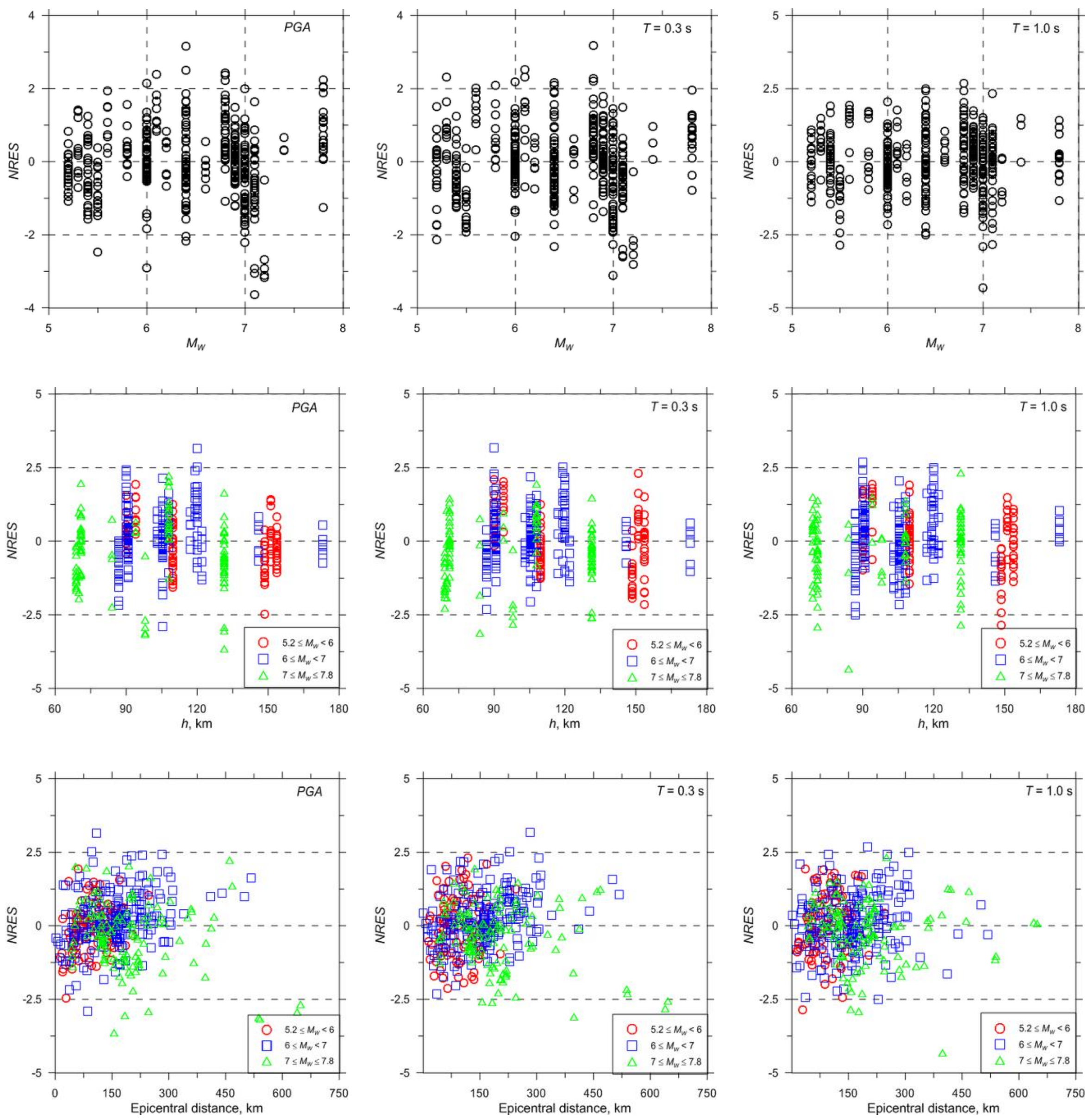


Fig. 7 Distribution of normalized residuals *NRES* with the magnitude of the seismic event, focal depth and epicentral distance of the recording station for three spectral periods ($T = 0.0$s, $T = 0.3$s and $T = 1.0$s)

No significant bias in the distribution of the residuals can be observed from Fig. 7. However, the plots reveal a large amount of variability in the dataset.

The histogram of normalized residuals *NRES* and of the likelihoods *LH* (Scherbaum *et al.* 2004) for all the spectral periods is given in Fig. 8. It is visible that the distribution of the normalized residuals fits closely the standard normal probability distribution, while the *LH* distribution closely matches the uniform probability distribution.

Fig. 9 displays the histograms of inter-event and intra-event normalised residuals (Stafford *et al.* 2008), (Scassera *et al.* 2009), (Shoja-Taheri *et al.* 2010) computed for all the spectral periods. One can easily notice that the distribution of the normalised residuals follows the standard normal distribution.

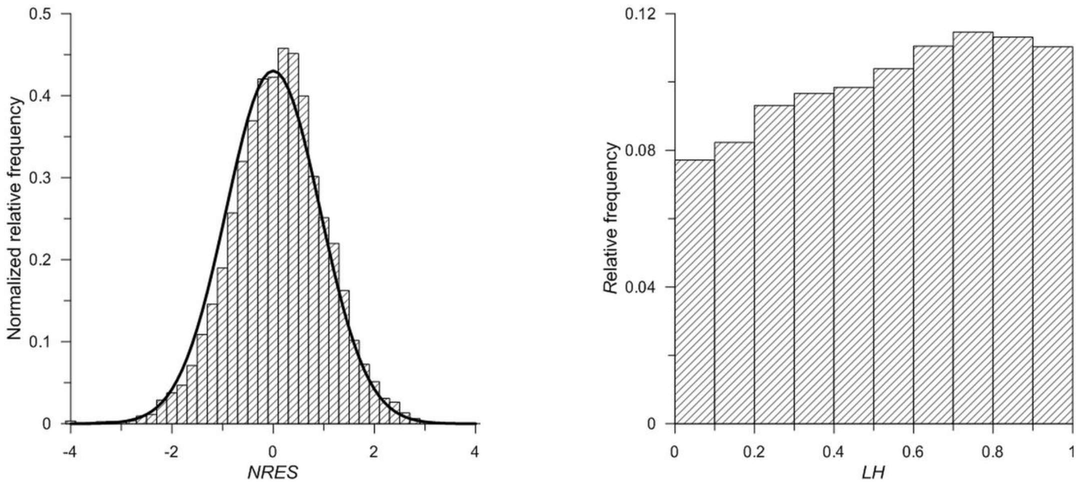


Fig. 8 Histograms of normalized residuals *NRES* (*left*) and likelihoods *LH* (*right*) for all the spectral periods. The standard normal probability distribution is superimposed on the histogram of normalized residuals on the left

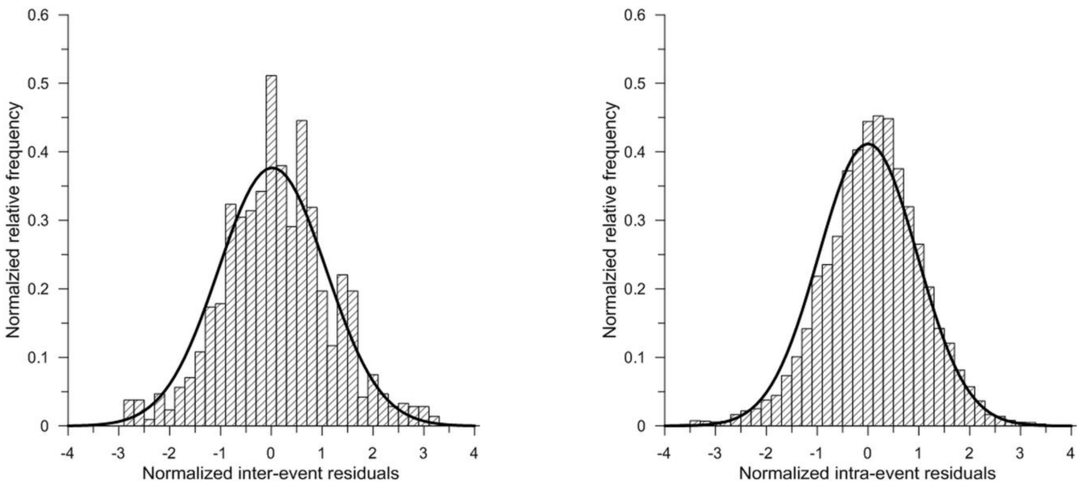


Fig. 9 Histograms of normalized inter-event residuals (*left*) and normalized intra-event residuals (*right*). The standard normal probability distribution is superimposed on the histograms of normalized residuals

The use of magnitude independent standard deviations is confirmed in Fig. 10 in which the distribution of the inter-event residuals for four spectral periods is displayed. One can notice from Fig. 10 that the distribution of the residuals has no trend nor bias, being thus magnitude independent.

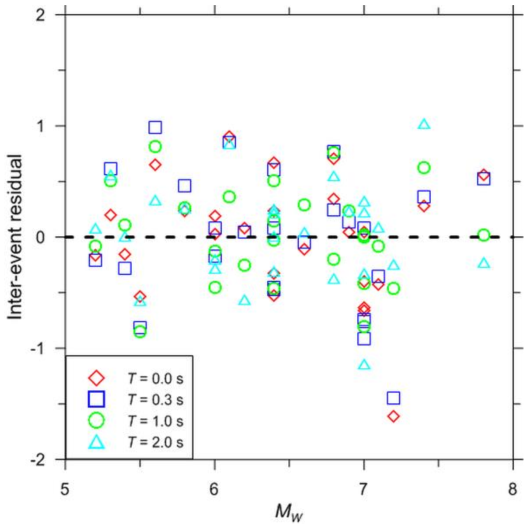


Fig. 10 Distribution of the inter-event residuals with the earthquake magnitude for four selected spectral periods (T = 0.0 s, T = 0.3 s, T = 1.0 s and T = 2.0 s)

The mean, median and standard deviation of the normalised residuals calculated for the subset of Vrancea strong ground motions are, respectively *MEANNRES* = -0.06, *MEDNRES* = -0.03 and *STDNRES* = 0.82. The sampling errors (Wu 1986) of the previously mentioned indicators are less than 1%. If one considers only the ground motions recorded in Vrancea intermediate depth earthquakes, the total standard deviation of the model's prediction decreases overall with 18%. Moreover, the bias introduced by the reduced sampling is very low, thus providing a high degree of confidence in using the proposed *GMPE* for Vrancea intermediate depth seismic events.

5. Comparison with other *GMPE*s

The proposed ground motion prediction model is compared for three reference earthquakes with other *GMPE*s from literature in Fig. 11. The reference earthquakes used for comparison have magnitudes M_W = 6.5, M_W = 7.0 and M_W = 7.5 and are produced at a depth of 100 km. The comparisons are performed for three spectral periods T = 0.0 s, 0.2 s and 1.0 s. Our model is assessed against the Lungu *et al.* (2000) model (LEA00) and the four *GMPE*s proposed within the SHARE project (Delavaud *et al.* 2012): Youngs *et al.* (1997) for soil conditions - YEA97, Atkinson and Boore (2003) for soil class D - AB03, Zhao *et al.* (2006) for soil class III - ZEA06 and Lin and Lee for soil conditions (2008) - LL08. The comparisons with the LEA00 model are performed only for T = 0.0 s.

The first obvious conclusion which can be drawn from Fig. 11 is the relatively large scatter in the median predictions. Moreover, one can notice the low attenuation with the epicentral distance of the LEA00 GMPE. The proposed model gives higher ground motion amplitudes for T = 0.2 s and T = 1.0 s for earthquakes with $M_W \leq 7.0$.

It is also worth mentioning the fact that in most of the analyzed cases, the proposed *GMPE* has similar median predictions as the Youngs *et al.* (1997) model denoted as YEA97. One can notice from Fig. 11 the very similar predictions of the median amplitudes of spectral acceleration at the natural period T = 1.0 s given by both the YEA97 and proposed *GMPE*s. The previous remark shows that the spectral response is less sensitive to local conditions and, consequently better

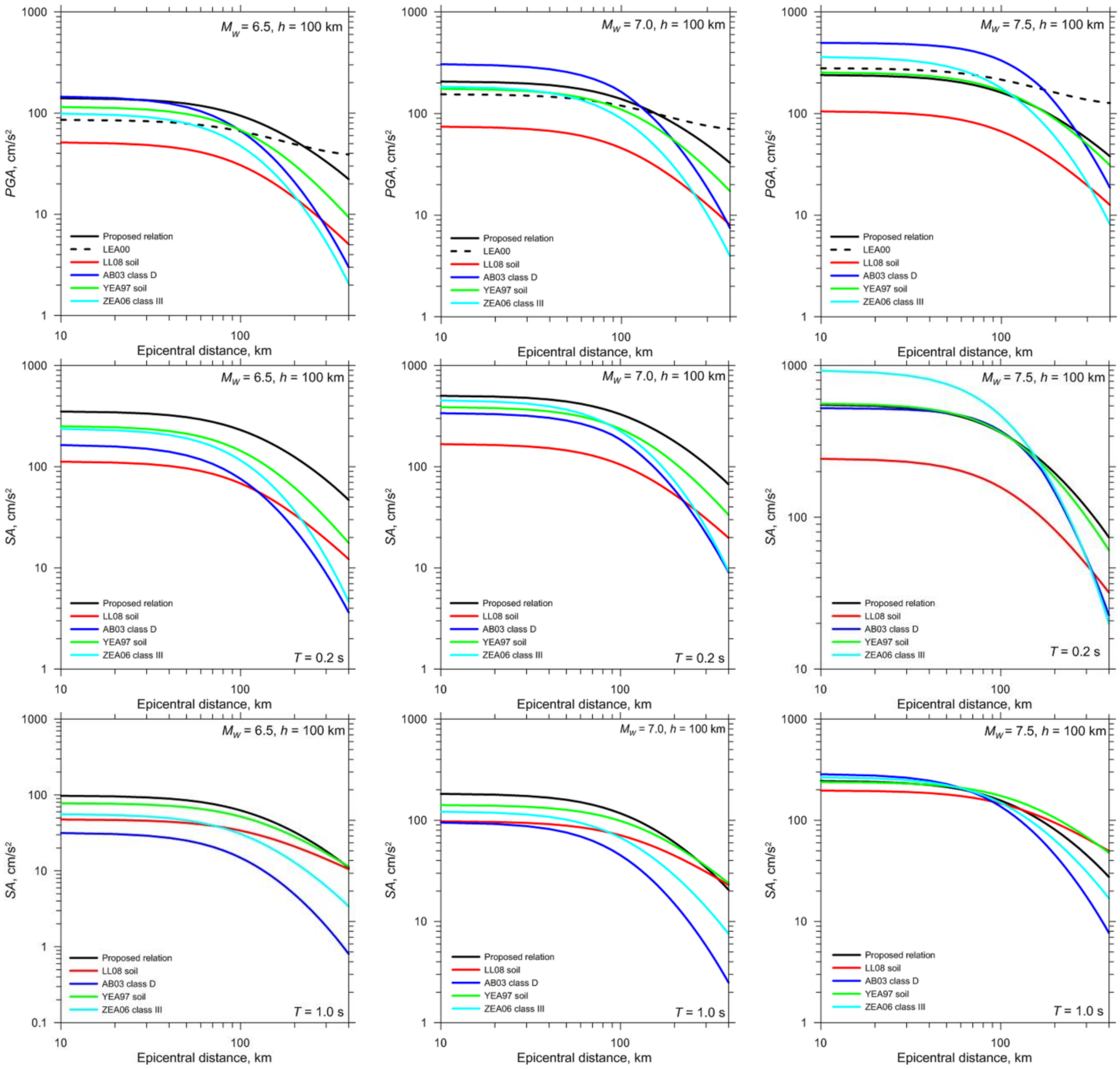


Fig. 11 Median amplitudes for three spectral periods (T = 0.0 s, T = 0.2 s and T = 1.0 s) and for seismic events characterized by three magnitudes (M_W = 6.5, M_W = 7.0 and M_W = 7.5) with a focal depth of 100 km. The curves correspond to the proposed model and to 5 additional models: LEA00, YEA97, AB03, ZEA06 and LL08

constrained at higher natural periods. The attenuation rate with the epicentral distance of the proposed GMPE is smaller than that of the models developed for subduction earthquakes (YEA97, AB03, ZEA06, LL08) and larger than that of the model developed using only strong ground motions from Vrancea intermediate-depth earthquakes (LEA00).

In Fig. 12 the total standard deviation of the proposed *GMPE* is compared with the standard deviations of four other *GMPE*s: Youngs *et al.* (1997) - YEA97, Atkinson and Boore (2003) - AB03, Zhao *et al.* (2006) ZEA06 and Lin and Lee (2008) - LL08. The standard deviation in the case of the YEA97 model is computed for a $M_W = 7.0$ earthquake.

One can notice from Fig. 12 that the total standard deviation of the proposed model is the largest in the period range up to $T = 0.7$ s. However, for spectral periods in excess of 0.7 s the total standard deviation of the proposed model is smaller than that of the other considered ground motion prediction models, except the AB03 model.

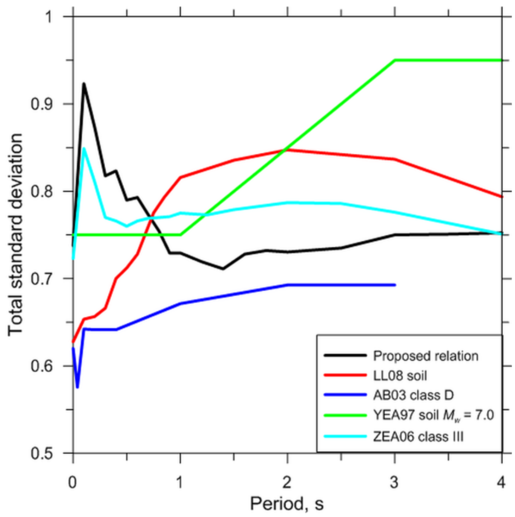
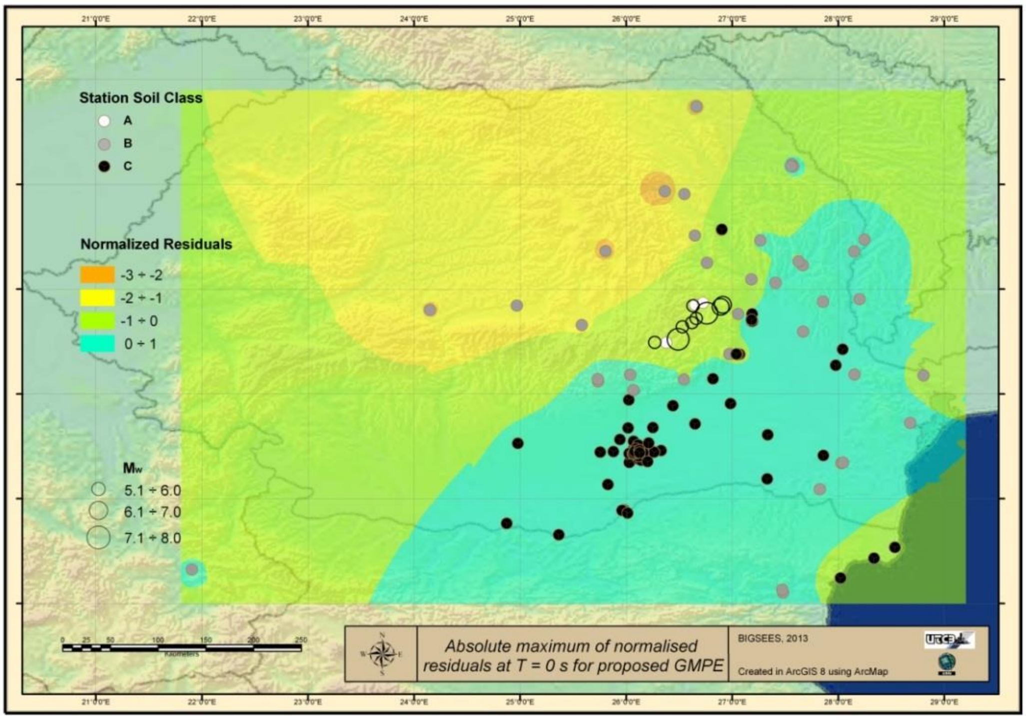
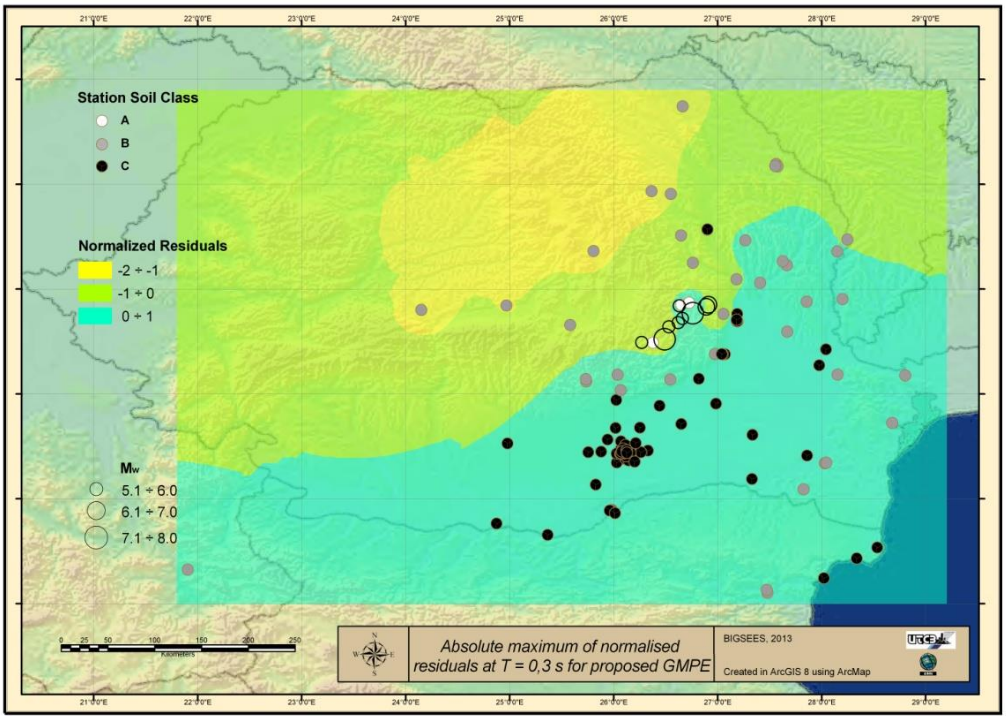


Fig. 12 Comparison of total standard deviation for the analyzed *GMPE*s

6. Discussion

Previous *GMPE*s developed for Vrancea subcrustal source by Lungu *et al.* (1994), Radu *et al.* (1994), Stamatovska and Petrovski (1996) or Musson (1999) are azimuth-dependent. Since the new *GMPE* proposed in this paper is based on a much larger database with both domestic and international earthquakes, the further need for azimuth dependency is investigated. In this respect, the normalised residuals between the observed and the predicted ground motion parameters is obtained for each of the 233 values in the subset of the seismic records generated by Vrancea intermediate-depth source and the pattern distribution of the residuals is investigated. The normalized residuals in each seismic station and for all Vrancea earthquake are represented on the map and the spatial distribution of the residuals is investigated. After careful investigation of the maps one can conclude that there is no need for further modification of *GMPE* in order to make it azimuth-dependent. In Fig. 13 the absolute values of maximum normalised residuals at spectral periods T = 0 s, T = 0.3 s and T = 1.0 s for the proposed *GMPE* are represented and one


Station Soil Class
A
B
C
Normalized Residuals
-3 ÷ -2
-2 ÷ -1
-1 ÷ 0
0 ÷ 1
Mw
5.1 ÷ 6.0
6.1 ÷ 7.0
7.1 ÷ 8.0
Absolute maximum of normalised residuals at T = 0 s for proposed GMPE
BIGSEES, 2013
Created in ArcGIS 8 using ArcMap


Station Soil Class
A
B
C
Normalized Residuals
-2 ÷ -1
-1 ÷ 0
0 ÷ 1
Mw
5.1 ÷ 6.0
6.1 ÷ 7.0
7.1 ÷ 8.0
Absolute maximum of normalised residuals at T = 0,3 s for proposed GMPE
BIGSEES, 2013
Created in ArcGIS 8 using ArcMap

Continued

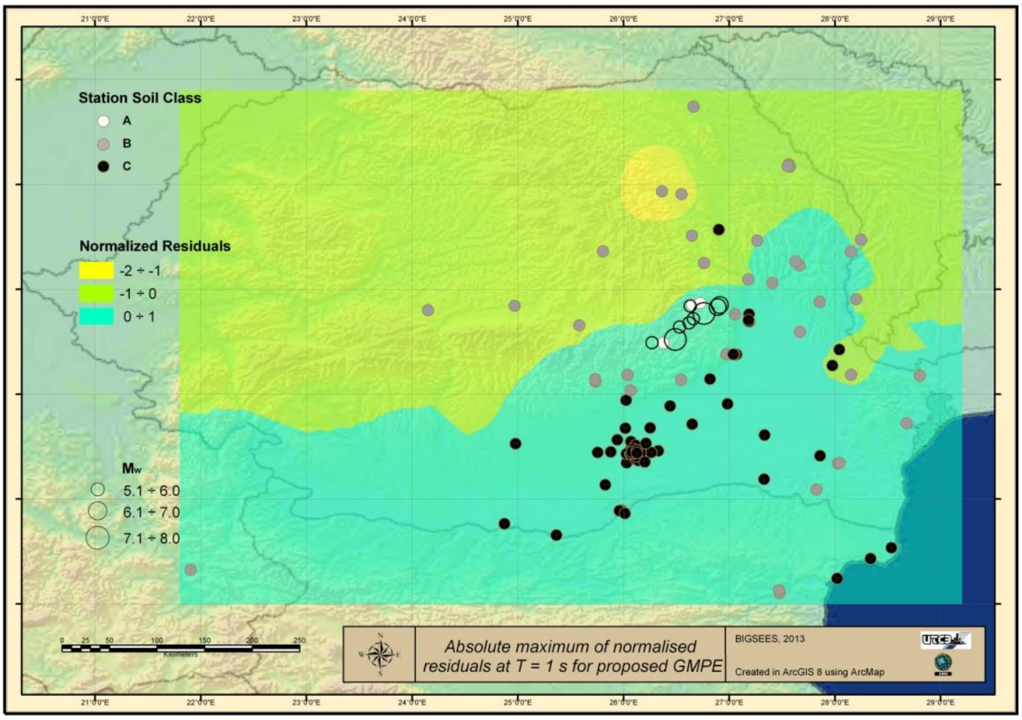


Fig. 13 Distribution of absolute values of maximum normalised residuals at $T = 0$ s (top), $T = 0.3$ s (middle) and $T = 1.0$ s (bottom) for the proposed *GMPE*

can notice that there is no significant azimuth dependency of the residuals. Nevertheless, there is a pattern of the spatial distribution of the values of the normalized residuals: there is a slight underestimation of the observed values in the regions in the front of the Carpathians Mountains (fore-arc region), an overestimation of the observed values in the regions in the back of the Carpathians Mountains (back-arc region) and a transition region in between fore-arc and back-arc.

We are currently investigating this pattern in an ongoing research project and a *GMPE* valid for both fore-arc and back-arc regions is under development. Also, in Fig. 13 the soil conditions at the seismic stations are represented as soil classes defined in EN 1998-1 (2004). Fig. 13 reveals the rather uniform spatial distribution of the residuals and the apparent lack of correlation between the soil conditions and the residuals' values.

Another issue to be discussed is the behaviour of the proposed *GMPE* for values of moment magnitude M_W at the higher end of the scale. For example, in Fig. 14 the observed values of *PGA* in a distance range of 85 km to 115 km along with the predicted median values for an earthquake with a focal depth of 100 km and an epicentral distance of 100 km are represented. One can notice a saturation of the values of *PGA* along with a trend of predicted values to slightly decrease for $M_W > 7.6$. The decrease of the predicted values occurs irrespective of the epicentral distance and is produced by the quadratic term in magnitude; the same decrease is reported in the paper of Atkinson and Boore (2003). From Fig. 14, one can notice that the *GMPE* requires the capping of the maximum magnitude at $M_{W,cap} = 7.6$ for prediction of *PGA* values. Thus estimates of *PGA* values for seismic events of $M_W > 7.6$ should be made using $M_{W,cap} = 7.6$. This saturation effect does not imply that a maximum moment magnitude of 7.6 should be assigned in the probabilistic seismic hazard analysis. Rather, the *PGA* values for seismic events of $M_W > 7.6$ should be calculated using the value of $M_{W,cap} = 7.6$ in the *GMPE*. More generally, a capping magnitude can be derived for any spectral period by differentiating relation (2) with respect to M_W and equating the result with zero. The analysis reveals that the capping magnitude is $M_{W,cap} = 7.6$ for spectral periods up to 1.0 s and $M_{W,cap} = 8.0$ for spectral periods in excess of 1.0 s. Nevertheless, from our analyses, the differences that arise in a probabilistic seismic hazard analysis performed with and without magnitude capping amounts 2% at the most for ground motion amplitudes with mean return periods larger than 1000 years in the case of $M_{W,cap} = 7.6$ and vanish for $M_{W,cap} = 8.0$. Actually, the capping moment magnitude $M_{W,cap} = 8.0$ corresponds to the higher end of the scale considered to provide reliable results in using the proposed *GMPE*.

The decrease of the predicted values can be avoided if the quadratic source terms in the *GMPE* are refit to a linear form, i.e. $c_1'+c_2'(M_W-6)$. For example, at $T = 0$ s, $c_1'=8.2996$, $c_2'=1.0105$ and the predicted median values are presented in Fig. 14. Nevertheless, the need for such a recalibration is not necessary since the quadratic source terms provide a better fit than the linear magnitude scaling, especially at short epicentral distances, and the maximum value of moment magnitude $M_{W,\,cap}$ is imposed.

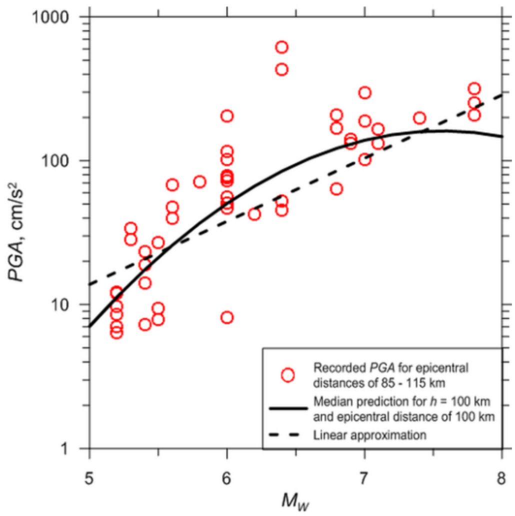


Fig. 14 Scaling of *PGA* with moment magnitude in the distance range from 85 to 115 km; assumed event depth is 100 km

The last issue to be discussed is the impact of the proposed *GMPE* on the results of probabilistic seismic hazard analysis, *PSHA* and the comparison of the *PSHA* results obtained using other *GMPE*s as well. In this section, the proposed *GMPE*, applicable to intermediate depth Vrancea earthquakes, is used to perform probabilistic seismic hazard analyses for some Romanian cities. The analyses are performed using the proposed *GMPE* and two other *GMPE*s applicable for Vrancea intermediate-depth earthquakes, namely (i) LEA00 (Lungu *et al.* 2000) - used for the peak ground acceleration and (ii) YEA97 (Youngs *et al.* 1997) for soil conditions - used for the peak ground acceleration and response spectral acceleration values as well.

The input data on seismicity of Vrancea intermediate-depth source are given in (Vacareanu *et al.* 2013a). Considering the seismic events of the 20th century with the lower-bound magnitude $M_{W,min}$ = 5.0 and the upper bound magnitude $M_{W,max}$ = 8.1, the seismicity parameters are α = 10.3164 and β = 1.9589. The Vrancea intermediate-depth seismic source is covered with a grid of uniformly distributed points at 0.1 degrees of latitude and longitude, respectively. The computations are performed based on the *PSHA* methodology given in (Kramer 1996) and (McGuire 1999, 2004) using developed MATLAB-based routines. The computations are performed using $-3 \leq \varepsilon \leq 3$, where ε is the number of logarithmic standard deviations by which the logarithm of the ground motion amplitude deviates from the mean value of the logarithm of the ground motion amplitude (McGuire 1999).

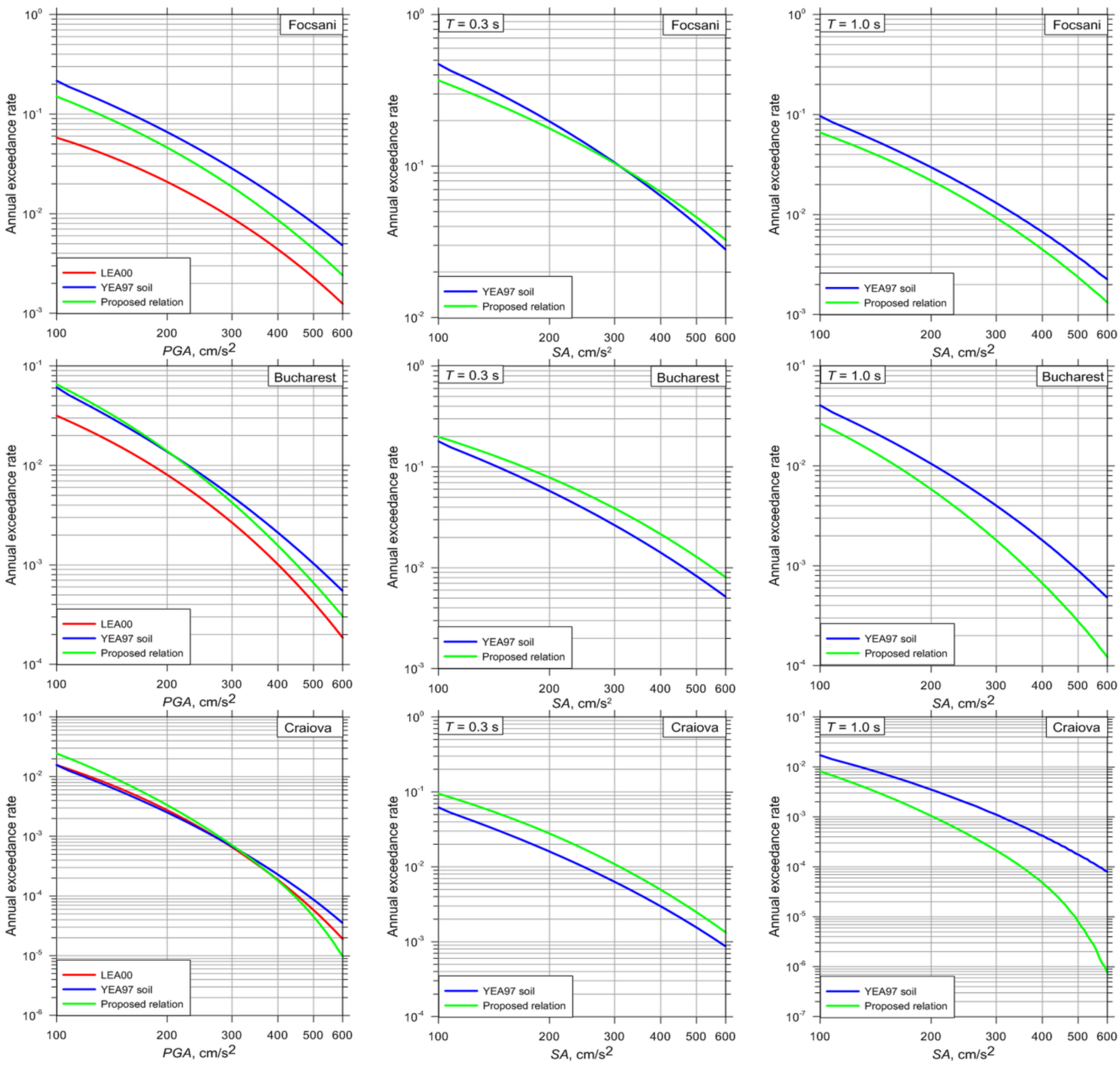


Fig. 15 Hazard curves obtained with the proposed *GMPE* and LEA00 & YEA97 *GMPE*s for Focsani (top), Bucharest (middle) and Craiova (bottom)

The results of the *PSHA*, given in terms of hazard curves for peak ground accelerations and pseudo-spectral accelerations at spectral periods of T = 0.3 s and T = 1.0 s are presented in Figure 15 for 3 selected cities in Romania, namely Bucharest, Focsani, and Craiova. The shortest mean epicentral distance is for Focsani (60 km) and the longest one is for Craiova (260 km). For Bucharest the mean epicentral distance is 160 km. One can notice from Figure 15 that at short (in Focsani) and medium (in Bucharest) epicentral distances LEA00 provides the lowest hazard values for *PGA*, while YEA97 for soil conditions provides the highest values, the proposed *GMPE* lying in between. At long epicentral distances the three *GMPE*s provides very close results, the proposed relation pointing to lower hazard values at very large mean return periods (>10000 years). For mean return periods of 500 to 1000 years and at large epicentral distances the *PGA* values obtained with all three *GMPE*s are almost the same. Regarding the values of the response spectral accelerations at periods of T = 0.3 s and T = 1.0 s, one can notice from Fig. 15 that YEA97 provides lower hazard values at T = 0.3 s and higher hazard values at T = 1.0 s. This trend is not noticed for short epicentral distances at T = 0.3 s (where the two *GMPE*s produce almost the same hazard values) and is very intense for large epicentral distances at T = 1.0 s where YEA97 provides hazard values much larger than the proposed *GMPE* for mean return periods in excess of 100 years.

7. Conclusions

A new ground motion prediction model for Vrancea intermediate-depth seismic source is developed in this study. The database used in the regression analysis is by far the largest used for Vrancea. The extension of the database consists in including all the instrumented Vrancea earthquakes with moment magnitudes larger than 5.0 and an additional seventeen foreign intermediate-depth earthquakes. The use of international earthquake data is a temporary solution for filling the gaps in the national database. Nevertheless, as more strong ground motions recorded in Vrancea intermediate-depth earthquakes become available, we will revisit this analysis. The current extension of the database increased both the ranges of magnitudes and of the source-to-site distances. We consider that the proposed ground motion prediction model provides reliable results for a magnitude range $M_W = 5.0 \div 8.0$, an epicentral distance range from 10 km to 300 km and a focal depth range from 60 km to 200 km. We acknowledge that there is some uncertainty related to the upper bound of the moment magnitude scale, which is poorly constrained by the data (extending to $M_W = 7.8$). The epicentral distance and the focal depth ranges may be extrapolated beyond the previously mentioned limits with some caution. We believe that this new *GMPE* might supersede the previous GMPEs derived for Vrancea intermediate-depth seismic source and address the limits identified in those models. In addition, the proposed *GMPE* covers peak ground accelerations and response spectral accelerations and a much broader range of earthquake magnitudes and source-to-site distances. The regression coefficients of the *GMPE* and the residual terms are obtained with the maximum likelihood method (Joyner and Boore, 1993, 1994). Both intra- and inter-event standard deviations σ and τ are period dependent but are independent of magnitude. The total, inter- and intra-event normalized residuals closely fit a standard normal distribution of probability.

After careful investigation of the residuals one can conclude that there is no need for further modification of *GMPE* in order to make it azimuth-dependent. The spatial distribution of the normalized residuals reveals that there is a slight underestimation of the observed values in the regions in the front of the Carpathians Mountains (fore-arc region), an overestimation of the observed values in the regions in the back of the Carpathians Mountains (back-arc region) and a transition region in between. A *GMPE* valid for both fore-arc and back-arc regions is under development in an ongoing research project. Also, the spatial distribution of the normalized residuals shows an apparent lack of correlation between the soil conditions and the residuals' values. The predicted values of ground motion parameters are applicable for average soil conditions (soil classes B and C in EN 1998-1). The estimates of ground motion parameters for seismic events with $M_W > M_{W,cap}$ should be made using the impose capping magnitude, implying that the ground motion parameters' amplitudes for seismic events of $M_W > M_{W,cap}$ should be calculated using the value of $M_{W,cap}$ in the proposed *GMPE*.

Regarding the results of *PSHA*, for mean return periods of 500 to 1000 years (of interest for the design of regular buildings and structures) the *PGA* values obtained with the proposed *GMPE* and YEA97 at moderate and large epicentral distances are almost similar. As for the values of the pseudo-spectral accelerations at natural vibration periods of T = 0.3 s and T = 1.0 s, the YEA97 *GMPE* provides lower hazard values at T = 0.3 s and higher hazard values at T = 1.0 s as compared to the proposed ground motion model. The last remark is in line with one of the conclusions of Youngs *et al.* (1997) that "the attenuation relationship for *SA* … may be somewhat conservative at longer periods".

The analysis of the design implications in using the proposed attenuation relationship is of interest. Future work will be devoted to the issue and the results will be presented in a future paper.

Acknowledgments

Funding for this research was provided within BIGSEES Project by the Romanian National Authority for Scientific Research (ANCS), CNDI – UEFISCDI under the Grant Number 72/2012. This support is gratefully acknowledged. The authors would also like to thank Dr. Carlos Gutiérrez Martínez and Dr. Leonardo Alcántara from CENAPRED-UNAM for providing the strong ground motions from subcrustal earthquakes recorded in Mexico within the international cooperation enabled by IPRED Platform. The authors would also like to acknowledge the support of Professor Stavros Anagnostopoulos, editor-in-chief of the international journal Earthquakes and Structures and the valuable suggestions of two anonymous reviewers.

References

Atkinson, G. and Boore, D. (2003), "Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions", *Bull. Seismol. Soc. Am.*, **93**(4), 1703-1729.

Bazzurro, P. and Cornell, C.A. (1999), "Disaggregation of seismic hazard", *Bull. Seismol. Soc. Am.*, **89**(2), 501-520.

BIGSEES - Bridging the gap between seismology and earthquake engineering: from the seismicity of Romania towards a refined implementation of seismic action EN 1998-1 in earthquake resistant design of buildings, http://infp.infp.ro/bigsees/default.htm.

Delavaud, E., Cotton, F., Akkar, S., Scherbaum, F., Danciu, L., Beauval, C., Drouet, S., Douglas, J., Basili, R., Sandikkaya, A., Segou, M., Faccioli, E. and Theodoulidis, N. (2012), "Toward a ground-motion logic tree for probabilistic seismic hazard assessment in Europe", *J. Seismol.*, **16**(3), 451-473.

Douglas, J. (2011), "Ground-motion prediction equations 1964-2010", PEER Report 2011/102 Pacific Earthquake Engineering Research Center, College of Engineering, Berkeley, California.

EN 1998-1 (2004), *Design of structures for earthquake resistance – Part 1: General rules, seismic actions and rules for buildings*, European Committee for Standardization.

Ismail-Zadeh, A., Matenco, L., Radulian, M., Cloetingh, S. and Panza, G. (2012), "Geodynamics and intermediate-depth seismicity in Vrancea (the south-eastern Carpathians): current state-of-the art", *Tectonophysics*, **530-531**, 50-79.

Joyner, W. and Boore, D. (1993), "Methods for regression analysis of strong motion data", *Bull. Seism. Soc. Am.* **83**, 469-487.

Joyner, W. and Boore, D. (1994), "Erratum", *Bull. Seism. Soc. Am.*, **84**, 955-956.

Kramer, S. (1996), *Geotechnical earthquake engineering*, Prentice Hall, Upper Saddle River, New Jersey.

Lin, P.S. and Lee, C.T. (2008), "Ground-motion attenuation relationships for subduction-zone earthquakes in Northeastern Taiwan", *Bull. Seismol. Soc. Am.*, **98**(1), 220-240.

Lungu, D., Aldea, A., Arion, C., Demetriu, S. and Cornea, T. (2000), "Microzonage Sismique de la ville de Bucarest – Roumanie", *Cahier Technique de l'Association Française du Génie Parasismique*, **20**, 31-63.

Lungu, D., Demetriu, S., Radu, C. and Coman, O. (1994), "Uniform hazard response spectra for Vrnacea earthquakes in Romania", *Proceedings of the 10th European Conference on Earthquake Engineering*, Balkema, Rotterdam, 365-370.

Lungu, D., Vacareanu, R., Aldea, A. and Arion, C. (2000), *Advanced structural analysis*, Conspress, Bucharest, Romania.

Marmureanu, G., Cioflan, C.O. and Marmureanu, A. (2010), *Research regarding the local seismic hazard (microzonation) of the bucharest metropolitan area*, Tehnopress, Iasi, Romania. (in Romanian)

McGuire, R. (1999), "Probabilistic seismic hazard analysis and design earthquakes: closing the loop", *Bull. Seismol. Soc. Am.*, **85**(5), 1275-1284.

McGuire, R. (2004), *Seismic hazard and risk analysis*, Engineering Reseach Institute MNO-10.

Milsom, J. (2005), "The Vrancea seismic zone and its analogue in the Banda arc, eastern Indonesia", *Tectonophysics*, **410**, 325-336.

Mocanu, V. (2010), "Mantle flow in the Carpathian bend zone? Integration of GPS and geophysical investigations", *Tectonic Crossroads: Evolving Orogens of Eurasia-Africa-Arabia, Geological Society of America International Meeting*, Ankara, Turkey.

Müller, B., Heidbach, O., Negut, M., Sperner, B. and Buchmann, T. (2010), "Attached or not attached - evidence from crustal stress observations for a weak coupling of the Vrancea slab in Romania", *Tectonophysics*, **482**(1-4), 139-149.

Musson, R. (1999), "Probabilistic seismic hazard maps for the North Balkan region", *Ann. di Geof.*, **42**(6), 1109-1124.

NEHRP (1994), *Recommended provisions for seismic regulations for new buildings, FEMA 222A/223A*, Federal Emergency Management Agency, Washington.

Radu, C., Lungu, D., Demetriu, S. and Coman, O. (1994), "Recurrence, attenuation and dynamic amplification for intermediate depth Vrancea earthquakes", *Proceedings of the XXIV General Assembly of the ESC*, vol. III, 1736-1745.

Radulian, M., Mandrescu, N., Popescu, E., Utale, A. and Panza, G. (2000), "Characterization of Romanian seismic zones", *Pure Appl. Geophys.*, **157**, 57-77.

Rodriguez-Marek, A., Montalva, G.A., Cotton, F. and Bonilla, F. (2011), "Analysis of single-station standard deviation using the KiK-net data", *Bull. Seismol. Soc. Am.*, **101**(2), 1242-1258.

Scassera, G., Stewart, J., Bazzurro, P., Lanzo, G. and Mollaioli, F. (2009), "A comparison of NGA ground-motion prediction equations to Italian data", *Bull. Seismol. Soc. Am.*, **99**(5), 2961-2008.

Scherbaum, F., Cotton, F. and Smit, P. (2004), "On the use of response spectral-reference data for the selection and ranking of ground-motion models for seismic-hazard analysis in regions of moderate seismicity: the case of rock motion", *Bull. Seismol. Soc. Am.*, **94**(6), 2164-2185.

Scherbaum, F., Delavaud, E. and Riggelsen, E. (2009), "Model selection in seismic hazard analysis: an information-theoretic perspective", *Bull. Seismol. Soc. Am.*, **99**(6), 3234-3247.

Shoja-Taheri, J., Naserieh, S. and Hadi, G. (2010), "A test of the applicability of NGA models to the strong ground-motion data in the Iranian plateau", *J. Earthq. Eng.*, **14**, 278-292.

Sokolov, V., Bonjer, K.P., Wenzel, F., Grecu, B. and Radulian, M. (2008), "Ground-motion prediction equations for the intermediate depth Vrancea (Romania) earthquakes", *Bull. Earthq. Eng.*, **6**(3), 367-388.

Sperner, B., Lorenz, F., Bonjer, K.P., Hettel, S., Muller, B. and Wenzel, F. (2001), "Slab break-off - abrupt cut or gradual detachment? New insights from the Vrancea region (SE Carpathians, Romania)", *Terra Nova*, **13**, 172-179.

Stafford, P., Strasser, F. and Bommer, J. (2008), "An evaluation of the applicability of the NGA models to ground-motion prediction in the Euro-Mediterranean region", *Bull. Earthq. Eng.*, **6**(2), 149-177.

Stamatovska, S. and Petrovski, D. (1996), "Empirical attenuation acceleration laws for Vrancea intermediate earthquakes", *Proceedings of the 11th World Conference on Earthquake Engineering*, Acapulco, Mexico, paper no 146.

Trendafilovski, G., Wyss, M., Rosset, P. and Marmureanu, G. (2009), "Constructing city models to estimate losses due to earthquakes worldwide: application to Bucharest, Romania", *Earthq. Spec.*, **25**(3), 665-685.

Vacareanu, R., Lungu, D., Marmureanu, G., Cioflan, C., Aldea, A., Arion, C., Neagu, C., Demetriu, S. and Pavel, F. (2013a), "Statistics of seismicity for Vrancea subcrustal source", *Proceedings of the International Conference on Earthquake Engineering SE-50 EEE*, Skopje, Macedonia, paper no. 138.

Vacareanu, R., Pavel, F., Lungu, D., Iancovici, M., Demetriu, S., Aldea, A., Arion, C. and Neagu, C. (2013b), "Uniform hazard spectra for cities in Romania", *Proceedings of the International Conference on Earthquake Engineering SE-50 EEE*, Skopje, Macedonia, paper no. 164.

Vacareanu, R., Pavel, F. and Aldea, A. (2013c), "On the selection of GMPEs for Vrancea subcrustal seismic source", *Bull. Earthq. Eng.*, **11**(6), 1867-1884.

Wu, C.F. (1986), "Jackknife, bootstrap and other resampling methods in regression analysis", *Ann. Math. Statist.*, **14**, 1261-1295.

Youngs, R.R., Chiou, S.J., Silva, W.J. and Humphrey, J.R. (1900), "Strong ground motion attenuation relationships for subduction zone earthquakes", *Seism. Res. Lett.*, **68**(1), 58-73.

Zhao, J., Zhang, J., Asano, A., Ohno, Y., Oouchi, T., Takahashi, T., Ogawa, H., Irikura, K., Thio, H., Somerville, P., Fukushima, Y. and Fukushima, Y. (2006), "Attenuation relations of strong ground motion in Japan using site classification based on predominant period", *Bull. Seismol. Soc. Am.*, **96**(3), 898-913.

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