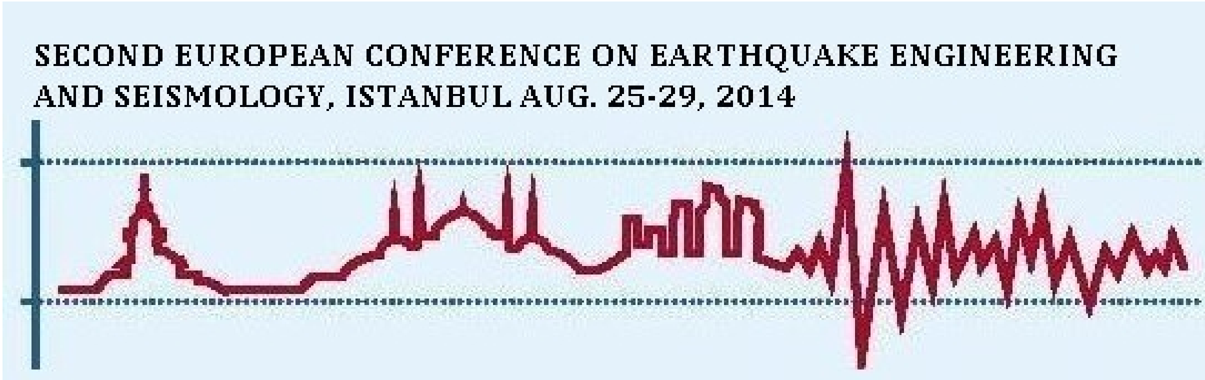

FORE-ARC AND BACK-ARC GROUND MOTION PREDICTION MODEL FOR VRANCEA INTERMEDIATE-DEPTH SEISMIC SOURCE

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ABSTRACT

A next generation ground motion model for the prediction of spectral accelerations both in the fore-arc and back-arc regions of the Carpathians Mountains is developed for the Vrancea intermediate depth seismic source in Romania. This ground motion prediction equation is an updated version of the model given in Vacareanu et al. (2013b) and is applicable in both the fore-arc and the back-arc regions. The strong ground motion database used in this study consists of over 700 triaxial accelerograms from Vrancea subcrustal seismic events, as well as from other intermediate-depth earthquakes produced in other seismically active regions in the world. The applicability of this ground motion prediction model in both the fore-arc and the back-arc region is tested using the analysis of residuals. Moreover, the appropriateness of this ground motion prediction equation *GMPE* for soil classes B and C defined in EN 1998-1, as well as for average soil conditions is investigated. All the results suggest that this model is an improvement of the previous versions of ground motion prediction equations for Vrancea intermediate-depth seismic source and its use in both the fore-arc and the back-arc regions make it a reliable candidate for more accurate seismic hazard studies of Romania.

INTRODUCTION

It is well-known that the volcanic structures in the crust and mantle may affect the attenuation in the active subduction zones owing to the strong lateral heterogeneity between the fore-arc (FA) and back-arc (BA) regions. The mantle wedge in the BA regions has low seismic velocity and a low quality factor (Q), where Q is the inverse of anelastic attenuation. This wedge filters out the high-frequency content of motions propagating from deep-focus in-slab events that traverse the wedge (Morikawa et al., 2006; Kanno et al., 2006; Zhao et al., 2006). As typical examples for FA/BA attenuation contrast, we can mention: Japan (Kanno et al., 2006; Zhao et al., 2006; Takanami et al., 2000; Nakamura and Uetake, 2000; Yoshimoto et al., 2006; Ghofrani and Atkinson, 2013); Hellenic Arc (Papazachos and Comninakis,

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1971; Spakman et al., 1988; Papazachos and Nolet, 1997; Boore et al., 2009); Casacadia region (Atkinson and Boore, 2003; Crouse, 1991; Gregor et al., 2002).

In addition to the active subduction regions characterized by well-defined and clearly inclined earthquake zone, like Tonga - Fiji, Japan, South America, a stronger attenuation in the BA versus FA direction was noticed as well for continent-continent collision zones with intermediate-depth seismicity, such as Hindu Kush in Afghanistan and Vrancea in Romania. The Vrancea seismogenic zone in Romania is one of the few examples of prominent localized intermediate-depth seismicity situated far from active plate boundaries.

The goal of the present study is to obtain a next generation of empirical ground motion model, specifically developed for the Vrancea subcrustal source that explicitly considers the back-arc versus fore-arc difference in attenuation of the seismic waves.

The Vrancea intermediate-depth earthquakes are felt over large areas, unusually extended along NE-SW direction (intensity MMI = V reported as far as 2000 km epicentral distance in this direction). The strong ground motion distribution at the surface is significantly asymmetric as well, in agreement with the strong lateral variation in the mantle across the Vrancea region. The anisotropic distribution poses challenges in setting GMPEs for the Vrancea region. To take into account these effects, several azimuth-dependent ground motion prediction equations were proposed (Lungu et al., 1994; Radu et al., 1994; Stamatovska and Petrovski, 1996; Musson et al., 1999). Alternatively, GMPEs have been determined for various characteristic regions (Sokolov et al., 2010) or introducing over an isotropic relationship anisotropic regional correction (Sørensen et al., 2010).

In Delavaud et al. (2012) four ground motion models are recommended for the Vrancea intermediate-depth seismic source. An evaluation of these models for strong ground motions recorded in Vrancea seismic events is given in (Vacareanu et al., 2013a; Pavel et al., 2013).

The new approach we propose in this paper aims at improving the previous results by (Vacareanu et al., 2013c):

- enlarging significantly the database for regression (new data cover a broader magnitude range and source-to-site distance by including all the instrumental data available for Vrancea earthquakes of M_W larger than 5 and an extra set of strong ground motion data collected from intermediate-depth earthquakes occurred worldwide);
- adopting a simple functional form which takes into account the differences in attenuation between fore-arc and back-arc regions through a dummy variable *ARC* that is set to 1 for fore-arc and 0 for back-arc stations. In this way, the coefficients measuring attenuation for fore- and back-arc simply enter into play, depending on the binary (yes/no) value of the dummy variable into a single functional form;
- considering the soil conditions in the regression analysis through dummy variables S_b, S_c and S_s set to 1 for soil classes B, C and respectively average soil conditions and set to 0 otherwise;
- performing extensive analysis of both inter-event and intra-event residuals for the available dataset of observed strong ground motions.

STRONG GROUND MOTION DATABASE

The ground motion model for the prediction of spectral accelerations is derived from (i) a national database (strong ground motion records from Vrancea subcrustal earthquakes) and (ii) an international database consisting altogether of 704 strong ground recorded from 38 intermediate-depth seismic events (nine Vrancea earthquakes and twenty-nine international earthquakes) with moment magnitudes in the range $5.1 \leq M_W \leq 8.0$. This large strong ground motion database is an extension of the database used in the previous study of (Vacareanu et al., 2013b). The set of strong ground motions from Vrancea earthquakes was extended from 233 to 344 records. Moreover, the international strong ground motion database was also extended and it contains strong ground motions recorded in intermediate-depth earthquakes in Japan (K-net and Kik-net seismic networks), New Zealand, Mexico, Chile, India, Martinique and Peru. The focal depth range of the earthquakes is 60 - 173 km. This depth range is also typical for seismic events generated from Vrancea intermediate-depth seismic source, which represents the main focus of this study.

The main characteristics of the database used for the regression analysis to derive the ground motion prediction model are given in Table 1. All the strong ground motions were collected within the BIGSEES national research project (http://infp.infp.ro/bigsees/default.htm) from the seismic networks of Romania: INFP (National Institute for Earth Physics), INCERC (Building Research Institute) and CNRRS (former National Centre for Seismic Risk Reduction, currently Research Center for Seismic Risk Assessment). For each seismic event, the date of occurrence, the magnitude, the position of the epicenter, the focal depth and the number of strong ground motions are presented in Table 2.

Table 1 Characteristics of the database of strong ground motions (Vacareanu et al., 2013c)

Database	No. of strong ground motions	No. of earthquakes	Magnitude range, M_W	Epicentral distance range, km	Focal depth range, km
Vrancea + International	344 + 360	9 + 29	5.1 - 8.0	2 - 399	60 - 173

The strong ground motion database used for the fore-arc region (FA) consists of records from all the above-mentioned eight countries, while the strong ground motion database for the back-arc (BA) region consists of records from only two countries, Romania and Japan. A necessary constraint is applied for the strong ground motion database from Japan used for the fore-arc region in the sense that only strong ground motions recorded within 80 km of the epicenter are used. This is due to the fact that the earthquakes in Japan are very-well instrumented and the use of strong ground motions recorded at larger epicentral distances would have lead to a very unbalanced database, more suitable for deriving ground motion prediction models for Japan. Moreover, the Vrancea earthquakes database contains a limited number of strong ground motions recorded in the epicentral distance range up to 80 km and a larger number of records in the range of 100 km to 200 km. Thus, the database becomes more balanced for all the bins of epicentral distances.

Table 2 Characteristics of the considered seismic events (Vacareanu et al., 2013c)

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	109	2
2		30.08.1986	45.52	26.49	7.1	131	40
3		30.05.1990	45.83	26.89	6.9	91	52
4		31.05.1990	45.85	26.91	6.4	87	36
5		28.04.1999	45.49	26.27	5.3	151	25
6		27.10.2004	45.84	26.63	6.0	105	66
7		14.05.2005	45.64	26.53	5.5	149	40
8		18.06.2005	45.72	26.66	5.2	154	37
9		25.04.2009	45.68	26.62	5.4	110	46
10	Japan	13.05.1999	42.95	143.91	6.4	104	9
11		02.12.2001	39.40	141.26	6.4	122	42
12		26.05.2003	38.81	141.68	7.0	71	15
13		21.09.2005	43.71	146.40	6.0	103	1
14		12.06.2006	33.13	131.41	6.2	146	6
15		17.04.2008	39.04	140.22	5.8	166	22
16		08.05.2008	36.23	141.95	6.4	60	20
17		24.07.2008	39.73	141.63	6.8	108	31
18		07.04.2011	38.20	141.92	7.1	66	1

19		02.02.2013	42.70	143.23	6.5	102	20
20	New Zealand	05.01.1973	-39.04	175.26	6.6	173	8
21		08.09.1991	-40.24	157.17	5.6	94	11
22		22.03.1995	-41.05	174.18	5.8	90	16
23		13.03.2005	-40.18	173.67	5.3	138	15
24		13.08.2006	-41.76	172.65	5.2	90	8
25		03.10.2007	-42.16	172.88	5.5	66	13
26		03.12.2011	-41.36	174.31	5.1	63	21
27		07.12.2012	-38.35	176.03	6.3	156	23
28	Mexico	28.08.1973	18.29	-96.45	7.0	84	4
29		24.10.1980	18.03	-98.29	7.0	70	7
30		21.10.1995	16.92	-93.62	7.2	98	1
31		15.06.1999	18.18	-00.51	7.0	69	15
32	Chile	15.10.1997	-31.02	-71.23	7.1	68	3
33		13.06.2005	-20.01	-69.24	7.8	108	17
34	India-Myanmar	6.08.1988	25.15	95.13	6.8	90	17
35		6.05.1995	24.99	95.29	6.4	117	5
36	Peru	31.05.1970	9.25	-78.84	8	73	1
37		05.01.1974	12.36	-76.39	6.6	82	2
38	Martinique	29.11.2007	14.94	-61.24	7.4	148	6

The soil conditions are defined according to EN 1998-1 (CEN, 2004) and in the case of the seismic stations in Romania are assigned according to (Trendafilowski et al., 2009). Most of the strong ground motions were recorded in soil conditions (soil classes B and C). In the case of some seismic stations from Mexico, India or Martinique, the accurate soil classification could not be retrieved from the available information. Nevertheless, the conditions for these stations were assigned implicitly as soil, so these data could be also used in the regression analyses (these stations are defined as "soil" hereinafter). The distribution of the seismic stations from Romania and their corresponding soil classes are given in Figure 1. Moreover, the limit between the fore-arc and back-arc regions is also given in Figure 1.

The distributions of earthquake moment magnitude with respect to the peak ground acceleration (defined as the geometric mean of the two horizontal components) and with respect to the epicentral distance of the recording seismic station are given in Figure 2.

The distribution of the strong ground motion records with respect to the soil class in the recording seismic stations site, for the fore-arc and the back-arc regions is given in the Table 3.

Table 3 Distribution of the strong ground motion records with respect to the soil class of the recording seismic stations site

Epicentral distance bin, km	Fore-arc seismic stations					Back-arc seismic stations		
	Soil Class A	Soil Class B	Soil Class C	Soil Class D	Soil	Soil Class A	Soil Class B	Soil Class C
1-50	0	24	42	9	3	15	0	0
50-100	0	61	74	8	3	4	7	0
100-150	0	32	83	5	6	0	6	6
150-200	1	42	69	3	11	0	9	5
200-250	0	14	20	0	24	0	5	3
250-300	0	9	17	0	6	0	13	3
300-350	0	6	1	0	2	0	14	5
350-400	0	8	7	0	3	0	12	4

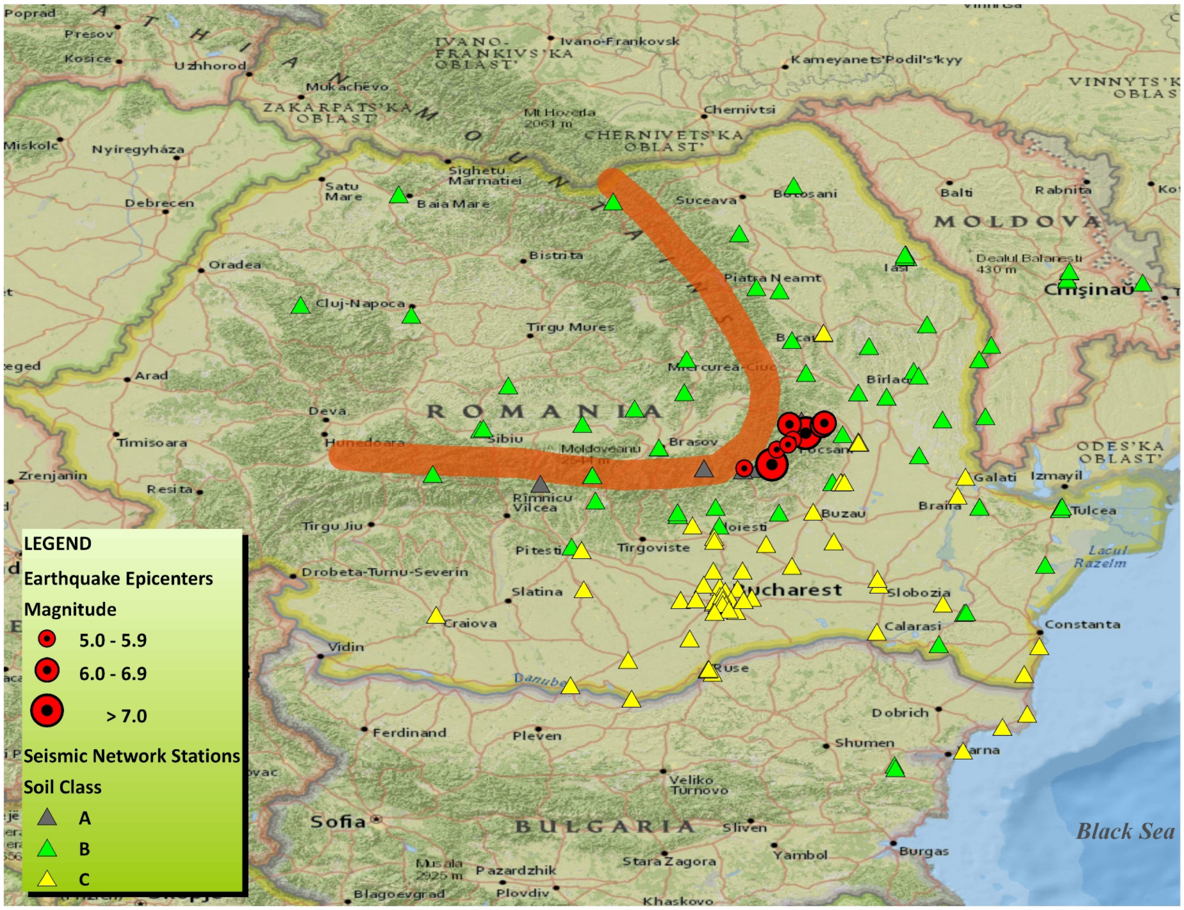


Figure 1. Distribution of earthquake epicentres in Romania and recording seismic stations soil classes; the limit between fore-arc and back-arc regions is also highlighted in orange (courtesy of Mihai Sercaianu - Technical University of Civil Engineering Bucharest)

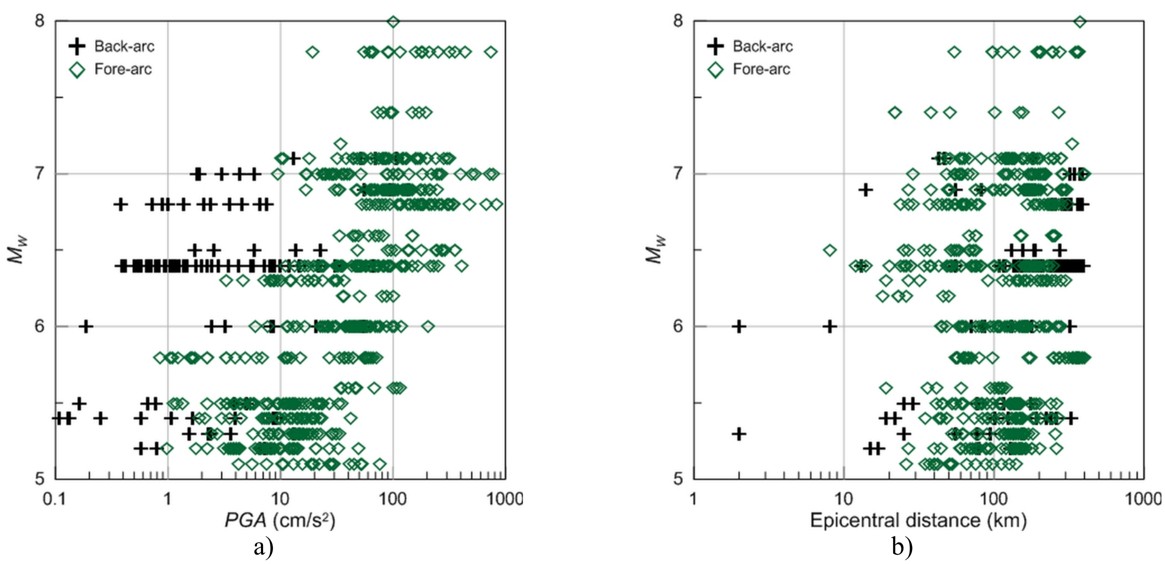


Figure 2. (a) Distribution of earthquake magnitude M_W with the peak ground acceleration (*PGA*) and (b) Distribution of earthquake magnitude M_W with the epicentral distance of seismic stations

REGRESSION ANALYSIS AND EVALUATION OF THE PROPOSED GMPE

The functional form of the GMPE represents an extension of (Vacareanu et al., 2013b) model, able to consider, in addition, the different anelastic attenuation in the fore-arc and back-arc regions and the soil conditions. Both intra-event σ and inter-event τ standard deviations are considered spectral period dependent, but are assumed to be independent of magnitude. The following functional form of the *GMPE* is selected (Vacareanu et al., 2013c):

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

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* (expressed in cm/s^2) or 5% damped response spectral acceleration (expressed in cm/s^2) for a given spectral period T, M_w is the moment magnitude, R is the source to site (hypocentral) distance (in kilometers). The *ARC* term introduces the recording site location with respect to the mountain arc (*ARC = 0* for back-arc sites and *ARC = 1* for fore-arc sites), h is the focal depth (in kilometers) and c_k (k = 1 to 10) are coefficients determined from the data set by regression analysis at each spectral period T. In the equation (1), Sb = 1- for soil class B and Sb = 0 - otherwise, Sc = 1 - for soil class C and Sc = 0 - otherwise, Ss = 1- for average soil condition and Ss = 0 - otherwise.

The functional form given in Eq. (1) is slighty modified for the prediction of the geometrical mean of the two horizontal components of *PGV*

$$\ln y_{ij}=c_1+c_2(M_{w,i}-6)+c_3(M_{w,i}-6)^2+c_4\ln R_{ij}+c_5(1-ARC_j)R_{ij}+c_6 ARC_j R_{ij}+c_7 h_i+c_8 Sr_j+c_9 Ss_j+\eta_i+\varepsilon_{ij} \tag{2}$$

where i, j, M_w, R, ARC, h, c_k (k = 1 to 9) have the same meaning as in Eq. (1), y_{ij} is the geometrical mean of the two horizontal components of *PGV* (expressed in cm/s), Sr = 1- for rock and Sr = 0 - otherwise, and Ss= 1 - for soil and Ss = 0 - otherwise.

The regression coefficients and the residual terms (given in Table 4) are obtained using the one-stage maximum likelihood algorithm of (Joyner and Boore, 1993). The values of c_4 coefficient reveal that the attenuation generated by the geometrical spreading is larger for short spectral periods and decreases for medium and long period range. The anelastic attenuation is much larger in the back-arc region than in the fore-arc region, as it is shown by the values of c_5 and c_6 coefficients. The total standard deviation ranges from 0.70 to 0.81 and the contribution of intra- and inter-event standard deviations to the total variability of the model for all the spectral periods considered in the analysis is rather balanced.

The variation of the inter-event standard deviation τ and intra-event standard deviation σ with spectral period T is given in Figure 3. The peaks of the standard deviations occur in the short period range (from 0.1 s to 0.4 s) showing that the most variability is encountered in high frequency seismic waves. For all the spectral periods the intra-event variability is larger than the intra-event one; the ratio of the corresponding standard deviations is almost constant for spectral periods larger than 0.5 s.

The appropriateness of the magnitude and distance scaling of the proposed GMPE is proven through a detailed analysis of the inter-event and intra-event residuals, respectively. Figure 4 a) and b) displays the variation of the inter-event residuals with the moment magnitude at two spectral periods T = 0 s; 1.0 s. The appropriateness of magnitude scaling is tested by examining the trends of inter-event residuals versus magnitude. The GMPE's magnitude scaling at all the spectral periods proves to be appropriate. The very low values of the slope and of the offset of the linear equations of the trendlines plotted in Figure 4 a) and b) prove that there is neither trend nor bias in the inter-event residuals. Since the same conclusions are reached for all the investigated spectral periods, it comes out that the homoscedatic hypothesis holds true (Vacareanu et al., 2013c). The variation of the inter-event residuals with spectral period is shown in Figure 4 c) as box-whisker plot.

Table 4 Regression coefficients and standard deviations of the proposed *GMPE* (Vacareanu et al., 2013c)

T, s	c_1	c_2	c_3	c_4	c_5	c_6	c_7	c_8	c_9	c_{10}	σ_T	τ	σ
PGA	9.6231	1.4232	-0.1555	-1.1316	-0.0114	-0.0024	-0.0007	-0.0835	0.1589	0.0488	0.698	0.406	0.568
0.1	9.6981	1.3679	-0.1423	-0.9889	-0.0135	-0.0026	-0.0017	-0.1965	0.1670	0.0020	0.806	0.468	0.656
0.2	10.0090	1.3620	-0.1138	-1.0371	-0.0127	-0.0032	-0.0004	-0.1547	0.2861	0.0860	0.792	0.469	0.638
0.3	10.7033	1.4580	-0.1187	-1.2340	-0.0106	-0.0026	0.0000	-0.1014	0.2659	0.0991	0.783	0.480	0.619
0.4	10.7701	1.5748	-0.1439	-1.3207	-0.0093	-0.0022	0.0005	-0.1076	0.3062	0.1183	0.810	0.519	0.622
0.5	9.2327	1.6739	-0.1664	-1.0022	-0.0100	-0.0041	0.0007	-0.0259	0.2576	0.0722	0.767	0.461	0.613
0.6	8.6445	1.7672	-0.1925	-0.8938	-0.0099	-0.0045	-0.0004	-0.1038	0.2181	0.0179	0.740	0.429	0.603
0.7	8.7134	1.8500	-0.1990	-0.9780	-0.0088	-0.0039	0.0002	-0.1867	0.1564	0.0006	0.735	0.426	0.599
0.8	9.0835	1.9066	-0.2022	-1.1044	-0.0078	-0.0031	0.0005	-0.2901	0.0546	-0.1019	0.726	0.417	0.594
0.9	9.1274	1.9662	-0.2465	-1.1437	-0.0074	-0.0031	0.0001	-0.2804	0.0884	-0.0790	0.719	0.403	0.596
1.0	8.9987	1.9964	-0.2658	-1.1226	-0.0071	-0.0031	-0.0009	-0.2992	0.0739	-0.0955	0.715	0.400	0.592
1.2	8.0465	2.0432	-0.2241	-0.9654	-0.0072	-0.0041	-0.0013	-0.2681	0.1476	-0.0412	0.713	0.392	0.595
1.4	7.0585	2.1148	-0.2167	-0.8011	-0.0078	-0.0049	-0.0013	-0.2566	0.2009	-0.0068	0.714	0.392	0.597
1.6	6.8329	2.1668	-0.2418	-0.8036	-0.0075	-0.0047	-0.0018	-0.2268	0.2272	0.0211	0.732	0.418	0.601
1.8	6.4292	2.1988	-0.2468	-0.7625	-0.0073	-0.0047	-0.0020	-0.2464	0.2200	0.0082	0.745	0.427	0.611
2.0	6.3876	2.2151	-0.2289	-0.8004	-0.0066	-0.0043	-0.0024	-0.2767	0.2134	-0.0091	0.744	0.425	0.611
2.5	4.4248	2.2541	-0.2144	-0.4280	-0.0079	-0.0061	-0.0031	-0.2924	0.2108	-0.0177	0.750	0.420	0.622
3.0	4.5395	2.2812	-0.2256	-0.5340	-0.0072	-0.0054	-0.0034	-0.3066	0.1840	-0.0387	0.765	0.436	0.629
3.5	4.7407	2.2803	-0.2456	-0.6250	-0.0065	-0.0045	-0.0041	-0.3728	0.0918	-0.1192	0.778	0.436	0.645
4.0	4.4928	2.2796	-0.2580	-0.6215	-0.0062	-0.0041	-0.0048	-0.3763	0.0512	-0.1428	0.792	0.443	0.657
PGV	10.2438	1.8264	-0.0522	-3.6280	0.0036	0.0101	0.0017	6.6201	6.9340	-	0.751	0.334	0.672

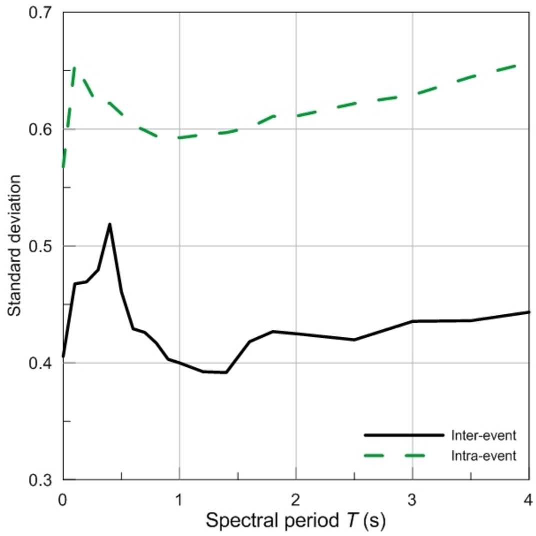
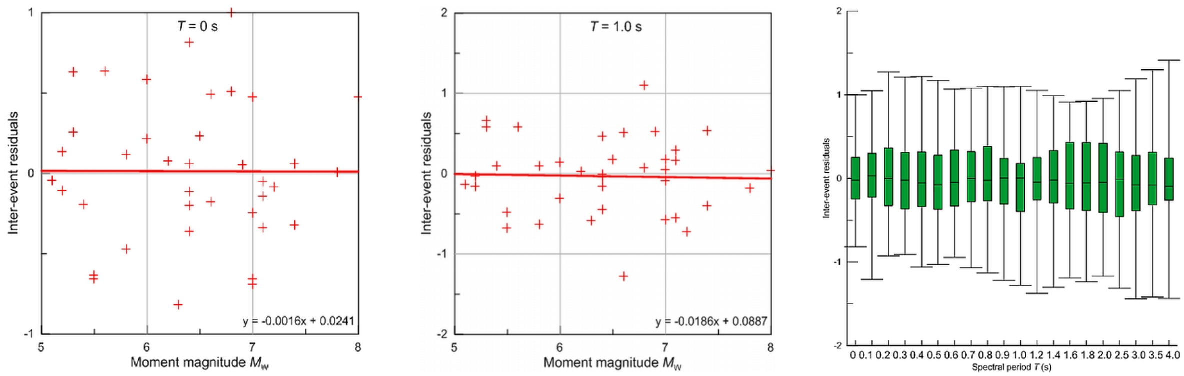


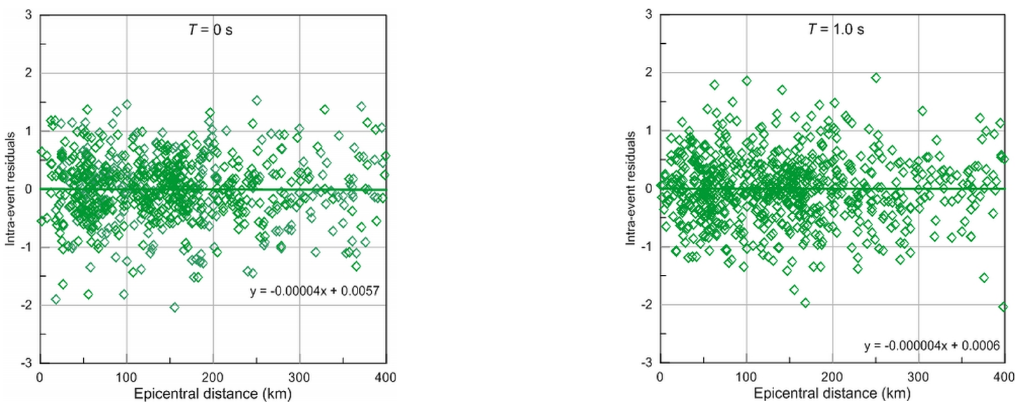
Figure 3. Variation of standard deviation with spectral period.

The appropriateness of distance scaling is tested by examining the trends of intra-event residuals versus distance. The distance scaling of the proposed GMPE is investigated in Figure 5 where the intra-event residuals versus epicentral distances are represented for two spectral periods T, namely 0 s and 1.0 s. The very low values of the slope and of the offset of the linear equations shown in Figure 5 a) and b) prove the correctness of the distance scaling for the proposed GMPE (Vacareanu et al., 2013c).



a) b) c)

Figure 4. Variation of the inter-event residuals with moment magnitude for two spectral periods: 0 s (left) and 1.0 s (middle). The linear trendlines and corresponding equations are also shown. Variation of the inter-event residuals with spectral period (right).



a) b)

Figure 5. Variation of the intra-event residuals with epicentral distance for two spectral periods: 0 s (left) and 1.0 s (right). Linear trendlines and corresponding equations are also shown.

COMPARISON WITH OTHER GMPES

The proposed ground motion prediction model (VEA13) is compared in Figure 6 with Zhao et al. (2006) (ZEA06) and Atkinson and Boore (2003) (AB03) *GMPE*s for two reference earthquakes with moment magnitudes M_W = 6.5 and M_W = 7.5 and a focal depth of 100 km. The comparisons are performed for two spectral periods T = 0.0 s and 1.0 s.

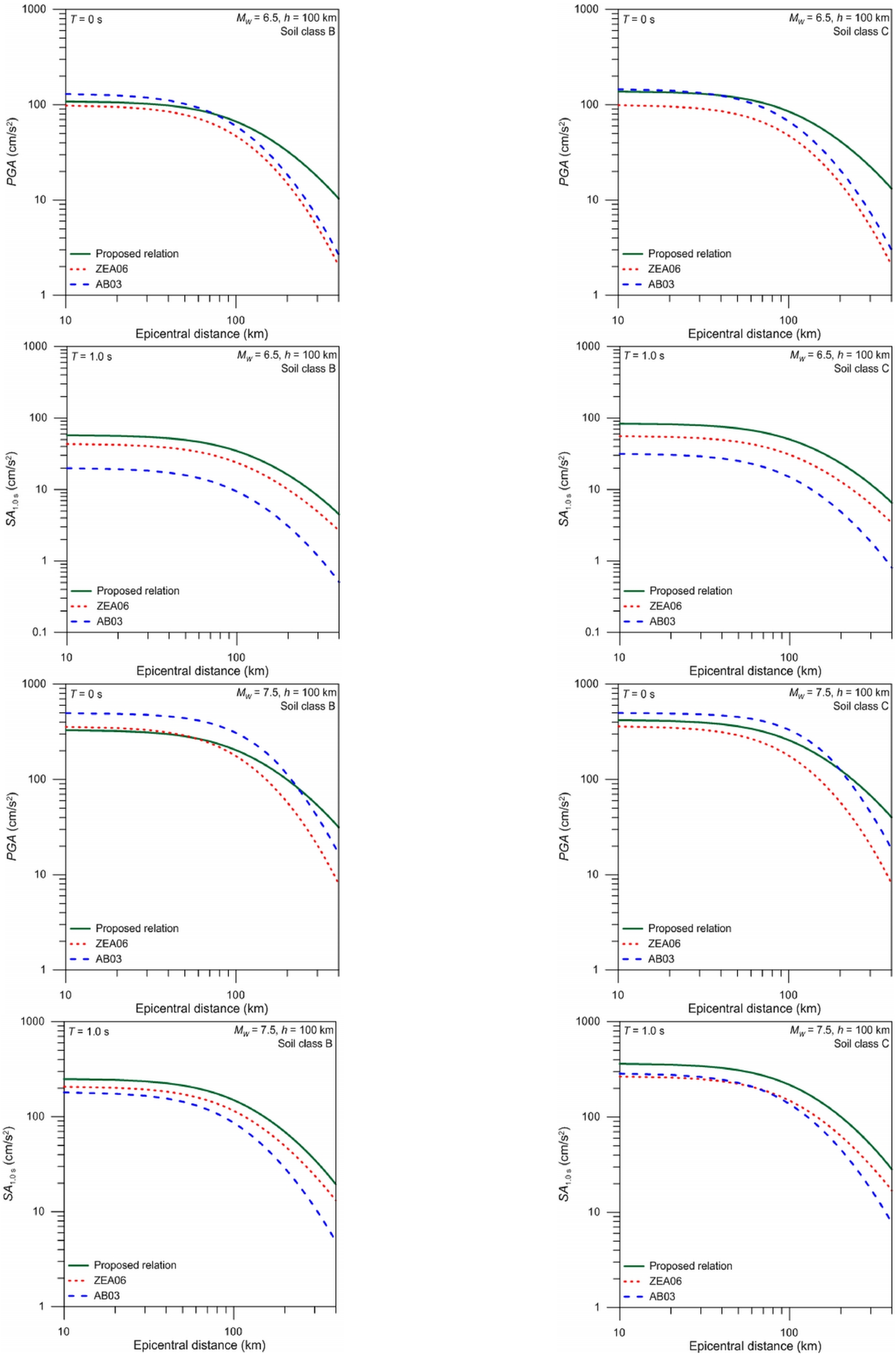


Figure 6. Median amplitudes for two spectral periods (T = 0.0 s and T = 1.0 s) and for seismic events characterized by two magnitudes (M_W = 6.5 and M_W = 7.5) with a focal depth of 100 km.

The first conclusion from Figure 6 is the relatively large scatter in the median predictions of different GMPEs. The scatter of the results is higher for peak ground accelerations and lower for spectral accelerations at $T = 1.0$ s.

The proposed model produces peak ground accelerations in-between ZEA06 and AB03 on soil classes B and C up to an epicentral distance of 100 km for $M_W = 6.5$ and up to an epicentral distance of 200 km for $M_W = 7.5$. The slower attenuation for large epicentral distances might be attributable to the large share of Vrancea subset of strong ground for which the lower rate of attenuation for medium and large epicentral distances was also noticed in (Vacareanu et al., 2013a). The proposed GMPE gives higher ground motion amplitudes for $T = 1.0$ s both on soil class B and C and the attenuation rate with distance is quite similar to the one of ZEA06 and lower than of the AB03 (Vacareanu et al., 2013c).

CONCLUSIONS

The paper presents a next generation ground motion prediction model for the Vrancea intermediate-depth seismic source in Romania. The model is derived from a national and international strong ground motion database of over 700 triaxial accelerograms that represents a significant improvement as compared to the databases used in the previous studies with the same focus. Moreover, this ground motion prediction equation is applicable both in the fore-arc and back-arc region of the Carpathian Mountains. The model has a functional form suitable for soil classes B and C, as defined in EN 1998-1, as well as for average soil conditions. Due to the scarcity of strong ground motion data recorded in soil classes A or D, this model can't be applied for rock or soft soil conditions. The model is evaluated through detailed analyses of the residuals. The comparisons with other ground motion prediction equations suitable for Vrancea intermediate-depth seismic source reveal the fact that this model provided in some cases higher spectral ordinate values, especially in the longer period ranges, due to the influence in the databases of the strong ground motions recorded from Vrancea seismic events.

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