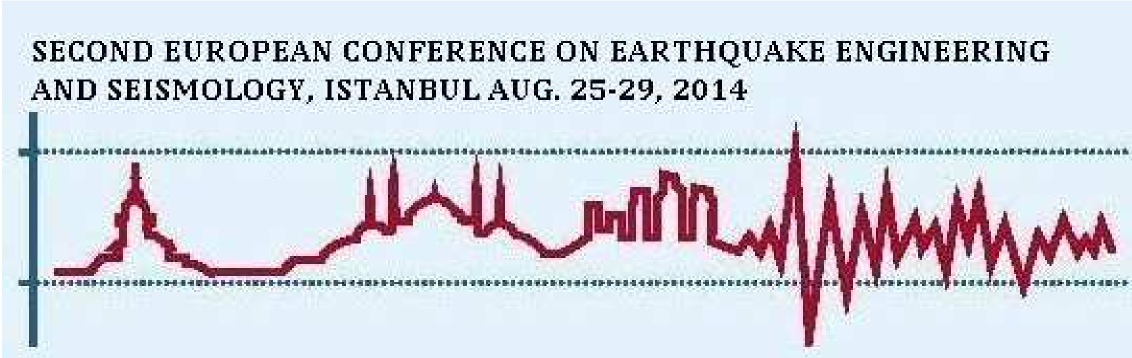

EVALUATION OF GMPES FOR VRANCEA INTERMEDIATE-DEPTH SEISMIC SOURCE

Florin PAVEL[1], Radu VACAREANU[2] and Alexandru ALDEA[3]

ABSTRACT

This study focuses on a new evaluation of the applicability of four ground motion prediction models recommended within the SHARE project (Delavaud et al. 2012) for Vrancea subcrustal seismic source. The investigation is performed on a database which consists of over 300 strong ground motions recorded in Romania, Bulgaria and Moldova during ten Vrancea subcrustal earthquakes. This strong ground motion database was assembled for the BIGSEES national research project (http://infp.infp.ro/bigsees/default.htm). Besides the four GMPEs from the SHARE project, a new state-of-the-art ground motion prediction model (Vacareanu et al. 2014) is also tested. This study is a continuation of a previous one with the same topic (Vacareanu et al. 2013). The testing procedure employed in this study uses several goodness-of-fit measures recommended in several studies (e.g. Scherbaum et al. 2004; Scherbaum et al. 2009; Kale and Akkar 2013). Besides the computation of the goodness-of-fit measures (overall and for each spectral period of the model), the inter-event and intra-event residuals are evaluated (Scassera et al. 2009), as well. The results obtained in this study will be incorporated in the future probabilistic seismic hazard assessment of Romania, leading thus to an improved quantification of the seismic hazard levels.

INTRODUCTION

The Vrancea subcrustal seismic source, located at the bend of the Carpathian Mountains in the Eastern part of Romania, is a region of concentrated intermediate-depth seismicity, far from any active plate boundaries (Ismail-Zadeh et al. 2012). This seismic source is limited to a volume having a horizontal area of about 30 x 70 km^2 (Ismail-Zadeh et al. 2012) and spanning in depth between 60 and 170 km (Marmureanu et al. 2010). Beyond the depth of 170 km the seismicity decreases very abruptly. The Vrancea seismic zone is bounded to the east by an area of shallow seismicity which extends in the Focsani basin (Ismail-Zadeh et al. 2012). The distribution of the epicentres is elongated in the NE-SW direction, bordered to the NE by the Trotus fault and to the SW by the Intramoesic fault (Ismail-Zadeh et al. 2012). A more thorough description of the seismological features of the Vrancea intermediate-depth seismic source is beyond the scope of this article and can be found elsewhere (e.g. Radulian et al. 2000; Ismail-Zadeh et al. 2012).

This study focuses on a more complete evaluation of the four ground motion prediction models proposed within the SHARE project for the Vrancea subcrustal seismic source (Delavaud et al. 2012). These four ground motion prediction equations (GMPEs) are: Youngs et al. (1997) – YEA97, Zhao et al. (2006) – ZEA06, Atkinson and Boore (2003) – AB03 and Lin and Lee (2008) – LL08. A previous testing of the four models was performed in the work of Vacareanu et al. (2013) using a strong ground

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motion database of 109 recordings. The grading of the candidate GMPEs was performed using the goodness-of-fit parameters given by Scherbaum et al. (2004, 2009) and Delavaud et al. (2012). In addition, the distribution of the inter-event and intra-event residuals was also checked using the procedure given by Scassera et al. (2009). The results showed that the Youngs et al. (1997) and Zhao et al. (2006) GMPEs produced a good fit with the available strong ground motion database.

A summary of the main characteristics of the above-mentioned ground motion prediction models is given in Table 1. Some of the data shown in Table 1 were taken also from Douglas (2011).

Table 1. Characteristics of the GMPEs considered in the SHARE project

GMPE	Database	No. of horizontal records	No. of earthquakes	Magnitude range	Source-to-site range, km	Depth range, km	No. of site classes
Youngs et al. (1997)	Global	476	164	5 - 8.2	8.5 - 550.9	10 - 229	2
Atkinson and Boore (2003)	Global	> 1200	43	5.5 - 8.3	11 - 550	< 100	4
Zhao et al. (2006)	Japan + overseas	4518 + 208	249 + 20	5 - 8.3	0 - 300	< 162	5
Lin and Lee (2008)	NE Taiwan + foreign	4244 + 139	44 + 10	4.3 (6) - 7.3 (8.1)	15 - 630	4 (15) - 146 (161)	2
Vacareanu et al. (2014)	Vrancea + foreign	344 + 360	9 + 29	5.1 – 8.0	2 - 399	60 - 173	3

An additional testing of two ground motion prediction models for the Vrancea subcrustal seismic source – Youngs et al. (1997) and Zhao et al. (2006) was also performed in the work of Pavel et al. (2014) using an increased strong ground motion database of 233 recordings. In the paper of Vacareanu et al. (2014) a new ground motion prediction model was developed for the Vrancea subcrustal seismic source using a national and international strong ground motion database. This ground motion model has distinct coefficients for the regions situated to the South and to the East of the Carpathian Mountains (termed fore-arc region) and for the region situated to the North and to the West of the Carpathian Mountains (termed back-arc region).

In this paper, the five ground motion prediction models previously mentioned are tested against a much increased strong ground motion database recorded during ten intermediate-depth Vrancea earthquakes. This strong ground motion database includes also recordings from the last Vrancea seismic event with $M_W > 5.0$ (the seismic event of October 6, 2013). The goodness-of-fit parameters proposed by Scherbaum et al. (2004, 2009) and Delavaud et al. (2012) will be re-evaluated using the new increased strong ground motion database. In addition, the ranking procedure proposed by Kale and Akkar (2013) is also used for the evaluation of the candidate ground motion prediction models.

STRONG GROUND MOTION DATABASE

The strong ground motion database used in this study consists of 431 recordings from ten intermediate-depth Vrancea earthquakes (Table 2).

The main characteristics of the earthquakes and the number of the strong ground motions for each earthquake are given in Table 2. Only seismic events with $M_W > 5.0$ were selected in the database since smaller magnitude events have relatively minor effects. All the analyzed strong ground motions were collected for the BIGSEES national research project and were recorded by three seismic networks: INCERC (Building Research Institute), INFP (National Institute of Earth Physics) and NCSRR (former National Centre for Seismic Risk Reduction, currently Research Centre for Seismic Risk Assessment). The recordings were grouped according to the position of the seismic station with respect to the Vrancea seismic zone into two categories – fore-arc and back-arc and again according to the soil conditions of the recording seismic station. The soil conditions for the recording seismic stations were taken from borehole data assembled within the BIGSEES national research project and from the study of Trendafilovski et al. (2009). The seismic stations were divided into three categories – A, B or C according to the corresponding soil conditions defined as in EN 1998-1 (2004). Since very few recordings (3) are available from soil class A seismic stations in the fore-arc region and from soil class C conditions (2) in the back-arc region, these were removed from the analysed dataset. The final strong ground motion database contains 365 recordings from the fore-arc region (145 from soil class B conditions and 220 from soil class C conditions) and 61 recordings from the back-arc region (36 from soil class A conditions and 25 from soil class B conditions). The database consists of both analogue and digital recordings (the later corresponding to earthquakes after 1999). The raw recordings were available only for the digital data. The processing of all the raw analogue strong ground motion recordings was performed originally with an Ormsby band pass filter having the low-cut frequency of 0.15 - 0.25 Hz and the high-cut frequency of 25 - 28 Hz. The digital recordings were processed according to the procedures given in the literature (Akkar and Bommer, 2006; Boore and Bommer, 2005) and using a band-pass Butterworth filter of 4th order with cut-off frequencies of 0.05 Hz and 50 Hz.

Table 2. Characteristics of the earthquakes and strong ground motion database

Earthquake date	Lat. N	Long. E	M_W	h (km)	No. of strong ground motions
04.03.1977	45.34	26.30	7.4	94	2
30.08.1986	45.52	26.49	7.1	131	40
30.05.1990	45.83	26.89	6.9	91	52
31.05.1990	45.85	26.91	6.4	87	36
28.04.1999	45.49	26.27	5.3	151	25
27.04.2004	45.84	26.63	6.0	105	66
14.05.2005	45.64	26.53	5.5	149	40
18.06.2005	45.72	26.66	5.2	154	37
25.04.2009	45.68	26.62	5.4	110	46
06.10.2013	45.67	26.58	5.2	135	87

The distribution of the epicentral distances of the recording seismic stations with the earthquake magnitude is given in Figure 1. The recording seismic stations are divided according to their position with respect to the epicentral region (either fore-arc or back-arc) and according to the corresponding soil conditions (soil classes A, B or C).

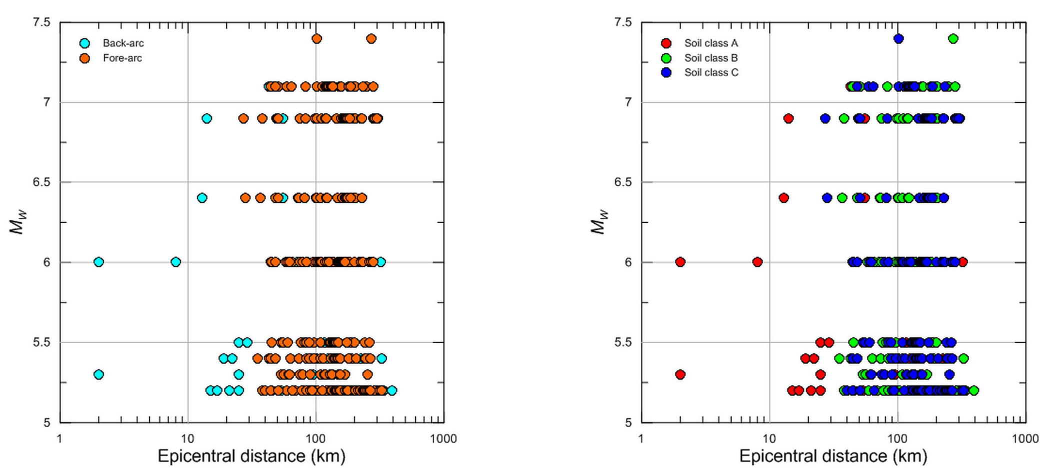

Figure 1. Distribution of the epicentral distances of the recording seismic stations with respect to the earthquake magnitude. The recording seismic stations are divided according to their position relative to the epicentral region and corresponding soil conditions

EVALUATION OF THE GMPES

The study of Vacareanu et al. (2013) grades the four ground motion prediction model recommended within the SHARE research project (Delavaud et al. 2012) using a strong ground motion database of

109 recordings from Vrancea subcrustal earthquakes and using the goodness-of-fit parameters given in Scherbaum et al. (2004, 2009) and Delavaud et al. (2012). The results show that the Youngs et al. (1997) GMPE fits the best with the available strong ground motion database. In addition, in the study of Pavel et al. (2014), two ground motion models - Youngs et al. (1997) and Zhao et al. (2006) are again tested using an increased strong ground motion database of 233 recordings from Vrancea intermediate-depth earthquakes. The results show again that the Youngs et al. (1997) GMPE is graded better than the Zhao et al. (2006) GMPE.

In this study the four GMPEs recommended in SHARE project are re-evaluated and in addition the ground motion prediction model of Vacareanu et al. (2014) VEA14 is also tested. The grading is performed using some of the goodness-of-fit parameters given by Scherbaum et al. (2004, 2009) and Delavaud et al. (2012) and moreover, the testing procedure of Kale and Akkar (2013) is employed, as well. The methodology of Kale and Akkar (2013) is called Euclidean distance-based ranking (*EDR*) and it relies on the Euclidean distance concept (*DE*). This grading procedure considers separately the ground motion variability (standard deviation) and the bias between the median predictions of the model and the observed data. The testing is performed separately for the fore-arc region and for the back-arc region.

In the case of the fore-arc region, the ground motion prediction models are grouped into categories according to the soil conditions considered in the functional form: soil (applicable for all soil classes), soil class B and soil class C. In the case of the Zhao et al. (2006) GMPE, the site classes II and III from are taken as soil classes B and C from EN1998-1 (2004).

For the back-arc region, due to the scarcity of data, the testing is performed using the entire strong ground motion database (61 soil class A and B recordings). Only the functional form of the five GMPEs derived for hard/stiff soil conditions or rock conditions is evaluated.

The average results of the grading process using all the spectral periods for some of the goodness-of-fit parameters given in Scherbaum et al. (2004, 2009) and Delavaud et al. (2012) are shown in Tables 3 and 4, separately for the fore-arc and back-arc region. The parameters are the following: median of the likelihood *LH* - *MEDLH*, the mean *MEANNR*, median *MEDNR* and standard deviation *STDNR* of the normalized residuals and the average sample log-likelihood *LLH*. *LLH* measures the distance between the tested model and the actual data.

Table 3. Values of grading parameters for fore-arc GMPEs - 1

Grading parameter	Ground motion prediction model								
	Soil conditions			Soil class B			Soil class C		
	YEA97	LL08	VEA14	ZEA06	AB03	VEA14	ZEA06	AB03	VEA14
MEANNR	-0.075	0.455	0.317	0.279	1.564	0.444	0.187	1.457	0.171
MEDNR	-0.028	0.510	0.316	0.343	1.603	0.477	0.240	1.467	0.152
STDNR	0.919	1.278	0.995	1.334	1.663	1.082	1.150	1.432	0.919
MEDLH	0.559	0.335	0.508	0.347	0.087	0.438	0.405	0.121	0.559
LLH	1.273	2.260	1.506	2.263	5.140	1.796	1.805	4.293	1.283
Model ranking based on *LLH*	**1**	**3**	**2**	**2**	**3**	**1**	**2**	**3**	**1**

Table 4. Values of grading parameters for back-arc GMPEs - 1

Grading parameter	Ground motion prediction model				
	YEA97	AB03	ZEA06	LL08	VEA14
MEANNR	-1.256	0.005	-1.109	-1.758	0.265
MEDNR	-1.300	0.094	-1.214	-1.663	0.284
STDNR	1.215	2.010	1.525	2.022	1.216
MEDLH	0.180	0.152	0.163	0.077	0.437
LLH	3.351	4.136	3.748	6.617	1.949
Model ranking based on *LLH*	**2**	**4**	**3**	**5**	**1**

The results from Tables 3 and 4 show considerable differences between the selected ground motion prediction models. Besides the VEA 14 GMPE, which is derived from a database that includes most of the analysed strong ground motion recordings, the Youngs et al. (1997) ground motion model provides also a good fit with the observed ground motions in the fore-arc region. In addition, ZEA06 and LL08 models can also be considered as candidate GMPEs for the probabilistic seismic hazard assessment of Romania. In the case of the back-arc region, as expected, the VEA14 model is graded the best.

Tables 5 and 6 show the results of the grading procedure using the methodology of Kale and Akkar (2013). *MDE* parameter takes into account the variability, while κ accounts for the bias between the predicted and the observed values. The overall goodness-of-fit parameter is termed *EDR* (Euclidean distance-based ranking).

Table 5. Values of grading parameters for fore-arc GMPEs - 2

Grading parameter	Ground motion prediction model								
	Soil conditions			Soil class B			Soil class C		
	YEA97	LL08	VEA14	ZEA06	AB03	VEA14	ZEA06	AB03	VEA14
$\sqrt{MDE^2}$	1.04	1.02	0.93	1.08	1.47	1.00	0.96	1.34	0.87
$\sqrt{\kappa}$	1.21	1.37	1.09	1.28	1.28	1.11	1.25	1.28	1.07
EDR	1.27	1.41	1.01	1.38	1.95	1.11	1.19	1.76	0.93
Model ranking based on *EDR*	**2**	**3**	**1**	**2**	**3**	**1**	**2**	**3**	**1**

Table 6. Values of grading parameters for back-arc GMPEs - 2

Grading parameter	Ground motion prediction model				
	YEA97	AB03	ZEA06	LL08	VEA14
$\sqrt{MDE^2}$	1.70	1.31	1.40	1.73	1.04
$\sqrt{\kappa}$	1.70	1.17	1.47	1.89	1.08
EDR	2.90	1.55	2.10	3.28	1.13
Model ranking based on *EDR*	**4**	**2**	**3**	**5**	**1**

The results of the ranking shown in Tables 5 and 6 are somewhat different than the ones shown in Tables 3 and 4 in the case of soil results for the fore-ac region and for the back-arc region, as well. Generally, the analysed models address better the variability, as compared to the model bias. In addition, one can observe that the differences between the analysed GMPEs are smaller when using *EDR*, as compared to *LLH*.

In order to scrutinize in-detail how well the selected ground motion prediction models fit with the available dataset of strong ground motions, the variation of the goodness-of-fit parameters – *MDE*, κ and *EDR* is plotted in Figures 2 and 3.

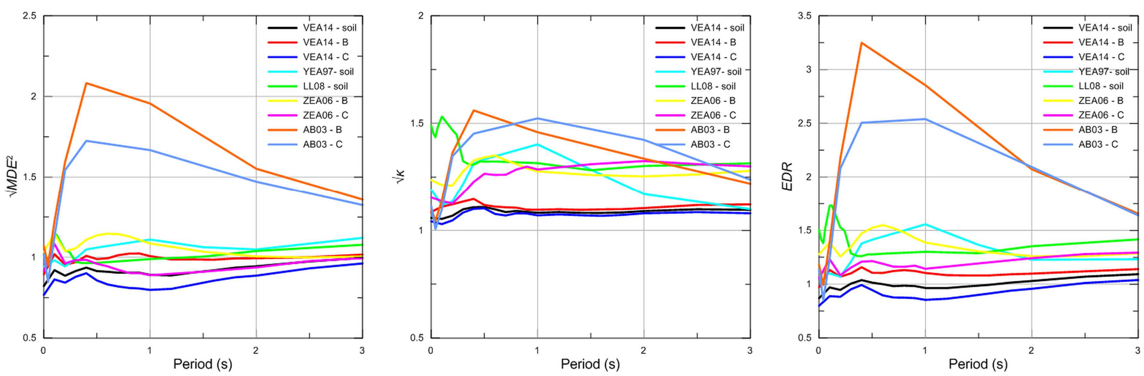

Figure 2. Variation of $\sqrt{MDE^2}$, κ and *EDR* parameters with period for the ground motion prediction models used in the fore-arc region

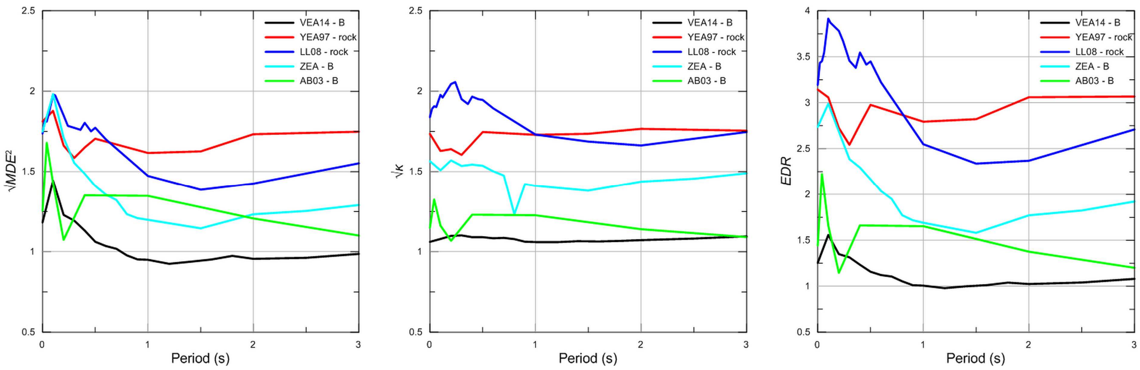

Figure 3. Variation of $\sqrt{MDE^2}$, κ and EDR parameters with period for the ground motion prediction models used in the back-arc region

The plots in Figures 2 and 3 show that in the case of the fore-arc region, several ground motion prediction models can be applied, as both *MDE*, κ and *EDR* parameters do not differ too much, with the exception of the AB03 model. On the contrary, in the back-arc region the differences are more significant and it appears that only two models – VEA14 (for back-arc region) and AB03 – for soil class B provide reliable estimates of the ground motion.

Subsequently, the analysis of the residuals (inter-event and intra-event) is performed with respect to the earthquake magnitude and epicentral distance (Scassera et al. 2009) for three spectral periods T = 0.0 s, T = 0.2 s and T = 1.0 s. The distribution of the inter-event residuals with the earthquake moment magnitude (magnitude scaling) is checked for both fore-arc and back-arc regions in Figures 4 and 5.

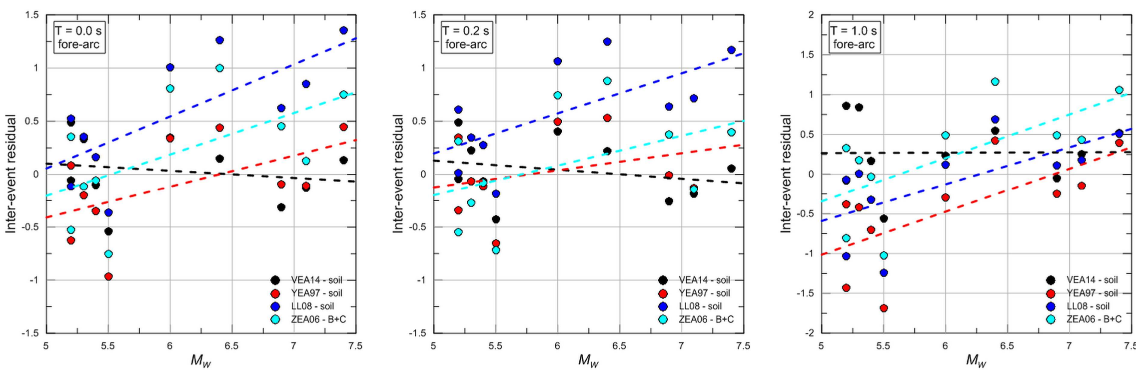

Figure 4. Variation of inter-event residual with the earthquake moment magnitude for the ground motion prediction models used in the fore-arc region (the inter-event trendlines are shown with dotted lines)

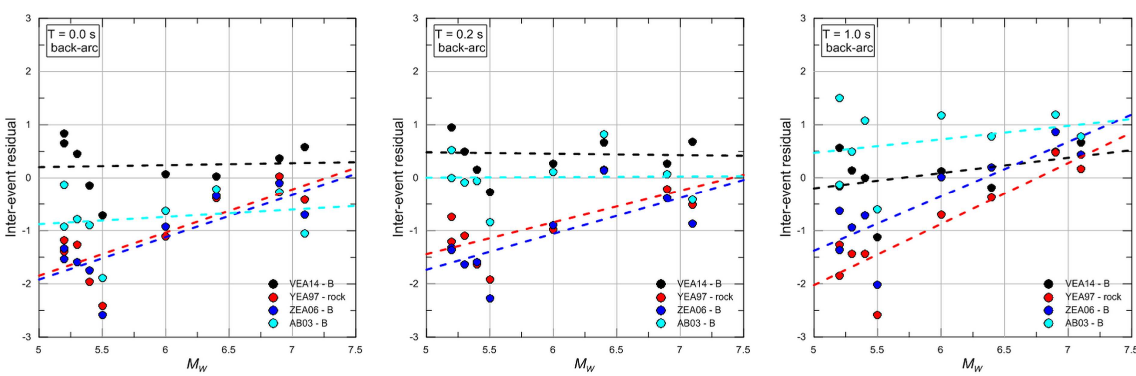

Figure 5. Variation of inter-event residual with the earthquake moment magnitude for the ground motion prediction models used in the back-arc region (the inter-event trendlines are shown with dotted lines)

In the case of the fore-arc region the results for AB03 ground motion prediction model are not shown, while for the back-arc region, the LL08 model is not shown here. The bias in the magnitude scaling is checked through the slopes of the linear trendlines fitted against the computed inter-event residuals One can observe from Figure 4 that the VEA14 ground motion prediction model has the smallest slope of the fitted trendline. In the back-arc region, a small under-estimation of the observed ground motions in noticeable for T = 0.0 s and T = 0.2 s. The LL08 GMPE underestimates the ground motion, especially in the short period range and for large magnitude seismic events. In the case of the YEA97 and ZEA06 the trendlines show over-predictions for smaller magnitude earthquakes and under-predictions for larger magnitude earthquakes. From Figure 5 it is noticeable that the VEA14 model has again the smallest slope of the fitted trendlines. The model slightly underestimates the observed ground motion for T= 0.0 s and T = 0.2 s. The other tested models, with the exception of (perhaps) the AB03 model for soil class B, show large slopes of the fitted trendlines and some large overpredictions, especially in the short period range.

The variation of the intra-event residuals with the epicentral distance of the recording seismic station (distance scaling) is checked in Figures 6 and 7 for the same spectral periods T = 0.0 s, T = 0.2 s and T = 1.0 s. The differences in the slopes of the fitted trendlines are much smaller than in the case of the inter-event residuals. None of the analyzed ground motion prediction models either for the fore-arc or back-arc region does not appear to grossly under-predict or over-predict the observed ground motion. The largest slopes are encountered for the ZEA06 GMPE for soil class B in the fore-arc region and for YEA97 GMPE for rock conditions in the back-arc region. As such, it appears that the magnitude scaling determines whether a particular GMPE can be applied or not for the Vrancea subcrustal seismic source.

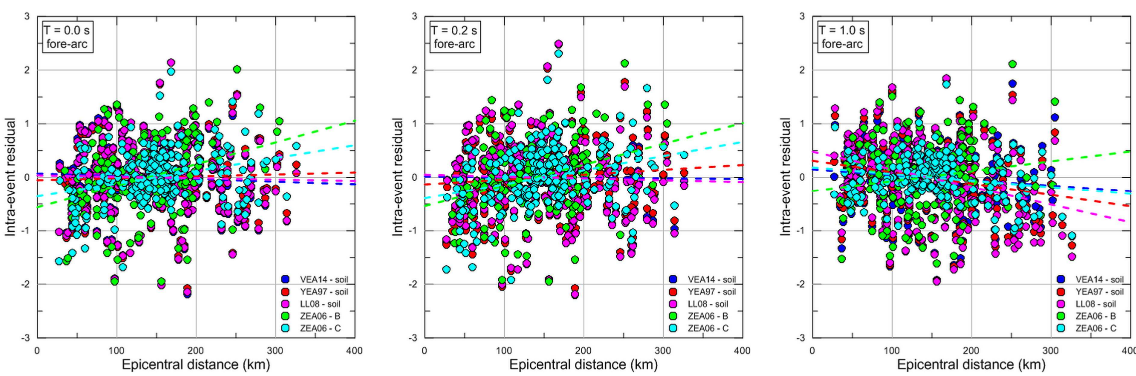

Figure 6. Variation of intra-event residual with the epicentral distance of the recording seismic station for the ground motion prediction models used in the fore-arc region (the intra-event trendlines are shown with dotted lines)

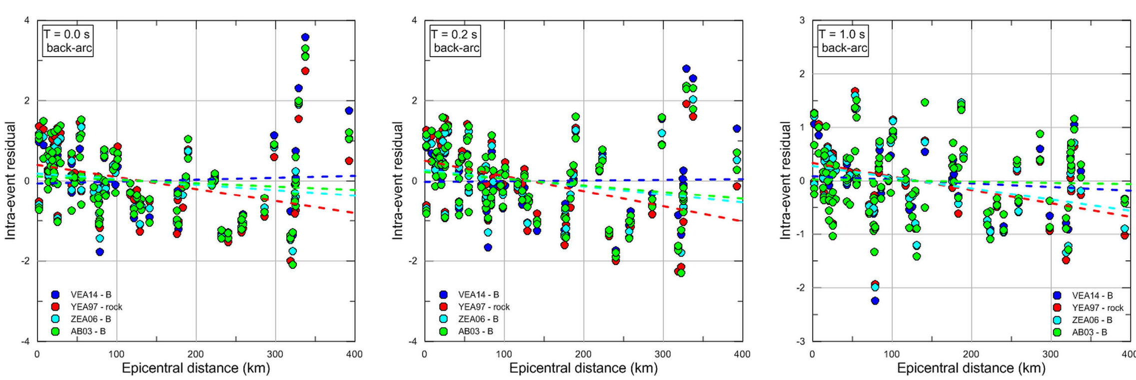

Figure 7. Variation of intra-event residual with the epicentral distance of the recording seismic station for the ground motion prediction models used in the back-arc region (the intra-event trendlines are shown with dotted lines)

Several weighing factors have recently been proposed for the GMPEs selected in the SHARE project for the Vrancea subcrustal seismic source in order to be used for the probabilistic seismic hazard assessment (Delavaud et al. 2012, Vacareanu et al. 2013). The weighing factors shown in the two references are given below in Table 7.

Table 7. Weighing factors for *PSHA* from previous studies

Ground motion prediction model	Weighing schemes		
	Delavaud et al. (2012)		Vacareanu et al. (2013)
	WS 1	WS 2	
ZEA06 – soil class C	0.40	0.25	0.30
AB03 - soil class C	0.20	0.25	0.15
YEA97 - soil	0.20	0.25	0.40
LL08 - soil	0.20	0.25	0.15

In this study, a new weighing scheme involving the tested ground motion prediction equations is proposed. The weighing factors are given separately for the fore-arc and for the back-arc regions in Table 8 and Table 9, respectively.

Table 8. Weighing factors for *PSHA* from this study for fore-arc region

Ground motion prediction model	Weighing factors
ZEA06 – soil class B + C	0.25
YEA97 - soil	0.25
LL08 - soil	0.10
VEA14 - soil	0.40

Table 9. Weighing factors for *PSHA* from this study for back-arc region

Ground motion prediction model	Weighing factors
ZEA06 – soil class B	0.10
YEA97 - rock	0.10
AB03 - soil class B	0.20
VEA14 - soil class B	0.60

The weighing factors are computed based on the values of the goodness-of-fit parameters *LLH* and *EDR* computed previously and on the evaluation of the distribution of inter-event and intra-event residuals.

CONCLUSIONS

This study focuses on the testing of ground motion prediction models for Vrancea intermediate-depth seismic source and is a continuation of the previous studies of Vacareanu et al. (2013) and Pavel et al. (2014). Four GMPEs recommended within the SHARE project (Delavaud et al. 2012) – Youngs et al. (1997), Atkinson and Boore (2003), Zhao et al. (2006) and Lin and Lee (2008), as well as a newly developed GMPE for Vrancea subcrustal seismic source by Vacareanu et al. (2014) are tested using several well-known goodness-of-fit measures from the literature given in (Scherbaum et al. 2004, 2009) and Delavaud et al. (2012). In addition, the evaluation methodology proposed by Kale and Akkar (2013) is also employed in this study. The strong ground motion database consists of over 350 strong ground motion recordings from ten intermediate-depth Vrancea seismic events. The recordings from the latest Vrancea earthquake with M_W > 5.0 from October 2013 are also included in the database. Besides the statistical evaluation of the ground motion models, the distribution of the residuals (inter-event and intra-event) is also checked. The analyses are performed separately for the fore-arc region and for the back-arc region defined with respect to the Vrancea epicentral region. The results show that the VEA14, YEA97 and ZEA06 ground motion prediction models are graded the best in the case of the fore-arc region, while in the back-arc region the VEA14 and AB03 GMPEs provide the most reliable estimates of the observed ground motions. Finally, a new weighting scheme to be used for the probabilistic seismic hazard assessment (*PSHA*) of Romania is given, considering only the best four ground motion prediction models in both the fore-arc and the back-arc regions. The weighting schemes are based on the computed values of several goodness-of-fit measures (*LLH* and *EDR*), as well as on the distribution of the inter-event and intra-event residuals and on expert judgement, as well.

ACKNOWLDEGEMTS

The results presented in this paper are obtained within the BIGSEES Project financed by the Romanian Ministry of National Education under the Grant Number 72/2012. This support is gratefully acknowledged. The authors are also grateful to Bogdan Grecu from the National Institute of Earth Physics for providing the strong ground motion recordings for the October 2013 Vrancea intermediate-depth earthquake.

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