Earthquakes and Structures, *Vol. 6, No. 1 (2014) 001-018*
DOI: http://dx.doi.org/10.12989/eas.2014.6.1.001

On the variability of strong ground motions recorded from Vrancea earthquakes

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(Received June 25, 2013, Revised July 15, 2013, Accepted October 21, 2013)

Abstract. The main focus of this paper is the analysis of the different components of the variability for strong ground motions recorded from earthquakes produced by the Vrancea subcrustal seismic source. The analysis is performed for two ground motion prediction equations: Youngs *et al.* (1997) and Zhao *et al.* (2006), recommended within the SHARE project for the Vrancea subcrustal seismic source and which are proposed in the work of Delavaud *et al.* (2012) and graded best in Vacareanu *et al.* (2013c). The first phase of the analysis procedure consists of a grading procedure. In the second phase, the single station sigma procedure is applied for both attenuation models in order to reduce some parts of ground motion models' variability produced by the ergodic assumption. The strong ground motion database which is used throughout the study consists of over 400 accelerograms recorded from 9 Vrancea intermediate-depth seismic events. The results of the single station sigma analysis show significant reduction of the standard deviations, especially in the case of the Youngs *et al.* (1997) attenuation model, which is also graded better than the other selected GMPE.

Keywords: ground motion prediction equation; strong ground motion database; single station sigma; seismic hazard

1. Introduction

The dominant source of seismic hazard for most part of Romania is the Vrancea intermediate-depth seismic region which produces earthquakes with hypocentral depths between 60 and 170 km (Lungu *et al.* 2000). Usually, the focal depths (Marmureanu *et al.* 2010) are in the range of 90 to 120 km as in the case of the seismic events of 1738, 1838, 1977 or in the range of 130 to 150 km like for the earthquakes of 1802, 1940, 1986. Most intermediate depth earthquakes occurring in the Vrancea intermediate-depth seismic source have a rupture area propagating on the NE-SW direction, tangent to the Carpathian Mountains. The epicentral Vrancea area is confined to a rectangle of 40 x 80 km^2 (Lungu *et al.* 2000), 30 x 70 km^2 (Ismail-Zadeh *et al.* 2012) or 20 x 60 km^2 (Sokolov *et al.* 2008) having the long axis oriented on the direction N45E and centred at about 45.6^o Lat. N and 26.6^o Long. E. A more complex shape of this seismic source was defined by the

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

National Institute for Earth Physics for the SHARE project (Vacareanu *et al.* 2013a). The Vrancea subcrustal seismic source is surrounded towards the exterior of the Carpathian Mountains by a zone of about 7000 km^2 in which crustal earthquakes are produced (Marmureanu *et al.* 2010). On average 3 to 5 earthquakes of $M_W > 6.5$ occur 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) and May 1990 ($M_W = 6.9$, $h = 91$ km), respectively.

The focal mechanisms of Vrancea subcrustal earthquakes exhibit an extension in the vertical direction and compression in the horizontal direction (Radulian *et al.* 2000). The mechanisms of the earthquakes generated by the Vrancea subcrustal source have not been reliably identified yet and several assumptions have been suggested in the literature. One such assumption is that of an end of a subduction process (Mocanu 2010). Some authors (Sperner *et al.* 2001). suggest that the subducting slab is still coupled to the upper lithosphere while being pulled down by gravitational forces, while others (Milsom 2005) mention a form of slab detachment due to the movement of the Vrancea seismic zone away from the areas of recent volcanic activity By studying the crustal stress observation in (Müller *et al.* 2010), it is concluded that the subducted slab beneath Vrancea is only weakly coupled to the crust..In the work of Bazacliu and Radulian (1999), it is suggested that there are at least two active zones in the subcrustal lithosphere, separated by a possible transition zone situated at a depth of about 100 km and also that there is no interdependence in the seismic activities of the two zones. A more comprehensive study regarding the geodynamic models for the Vrancea subcrustal seismic source can be found in the work of (Ismail-Zadeh *et al.* 2012).

The paper of Delavaud *et al.* (2012) concerns the ground motion models used for the probabilistic seismic hazard assessment in Europe (SHARE project). In this paper, the Vrancea seismic source is defined as an area of “*deep focus non-subduction earthquakes*". The four recommended ground motion prediction equations (GMPE) are: Youngs *et al.* (1997), Zhao *et al.* (2006), Atkinson and Boore (2003) and Lin and Lee (2008). The characteristics of these four GMPEs selected within the SHARE project for the Vrancea subcrustal seismic source are given in Table 1 below using also data from (Douglas 2012).

The analyses within this study are conducted in two stages: in the first stage, the selected GMPEs are graded using several goodness-of-fit measures presented in the work of (Scherbaum *et*

Table 1 Characteristics of the datasets for the considered attenuation models

GMPE	Database	No. of horizontal records	No. of earthquakes	Magnitude range	Source-to-site range	Depth range	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

al. 2004, 2009) and (Delavaud *et al.* 2012). The analysis of the inter-event and intra-event residuals is also performed in this stage (Stafford *et al.* 2008), (Scassera *et al.* 2009), (Shoja-Taheri *et al.* 2010). In the second stage of the analysis the single-station sigma approach is applied for several seismic stations in order to reduce some part of the ergodic assumption from the attenuation models (Abrahamson and Hollenback 2012), (Chen and Faccioli 2013). In this study only the two attenuation models - Youngs *et al.* (1997) and Zhao *et al.* (2006) - which are derived from the largest dataset of earthquakes are analyzed. The Youngs *et al.* model and the Zhao *et al.* model are also recommended by additional studies regarding the seismic hazard in Romania, performed on a limited database (Vacareanu *et al.* 2013b, Vacareanu *et al.* 2013c).

2. Strong ground motion database

In this study a total of 233 strong ground motions (465 horizontal components) recorded during nine intermediate-depth Vrancea seismic events with a moment magnitude $5.2 \leq M_W \leq 7.4$ in over 100 seismic stations in Romania, Republic of Moldova, Bulgaria and Serbia are used. The seismic events from the Vrancea intermediate-depth seismic source occurred between 1977 and 2009. The selection of accelerograms recorded during earthquakes having $M_W > 5.0$ is due to the very limited effects of smaller magnitude seismic events. The characteristics of these earthquakes (date, epicentre position, moment magnitude M_W, focal depth h and number of strong ground motion records) are given in Table 2 (according to National Institute for Earth Physics, Romania). All the analyzed strong ground motions are collected for the BIGSEES research project and were recorded by four seismic networks: INCERC (Building Research Institute), INFP (National Institute of Earth Physics), NCSRR (National Centre for Seismic Risk Reduction) and GEOTEC (Institute for Geotechnical and Geophysical Studies). Only strong ground motions with peak ground accelerations (PGA) > 0.05 m/s^2 are selected in the database.

The position of the 112 recording stations, as well as the corresponding soil classes according to NEHRP 94 are shown in Fig. 1. The soil conditions are taken from the work of (Trendafilovski *et al.* 2009) and from borehole data assembled within the BIGSEES national research project.

Table 2 Characteristics of the considered seismic events (www.infp.ro)

Earthquake date	Lat. N	Long. E	M_W	h (km)	No. of triaxial accelerograms
04.03.1977	45.34	26.30	7.4	109	3
30.08.1986	45.52	26.49	7.1	131	38
30.05.1990	45.83	26.89	6.9	91	46
31.05.1990	45.85	26.91	6.4	87	25
28.04.1999	45.49	26.27	5.3	151	11
27.04.2004	45.84	26.63	6.0	105	50
14.05.2005	45.64	26.53	5.5	149	15
18.06.2005	45.72	26.66	5.2	154	18
25.04.2009	45.68	26.62	5.4	110	27

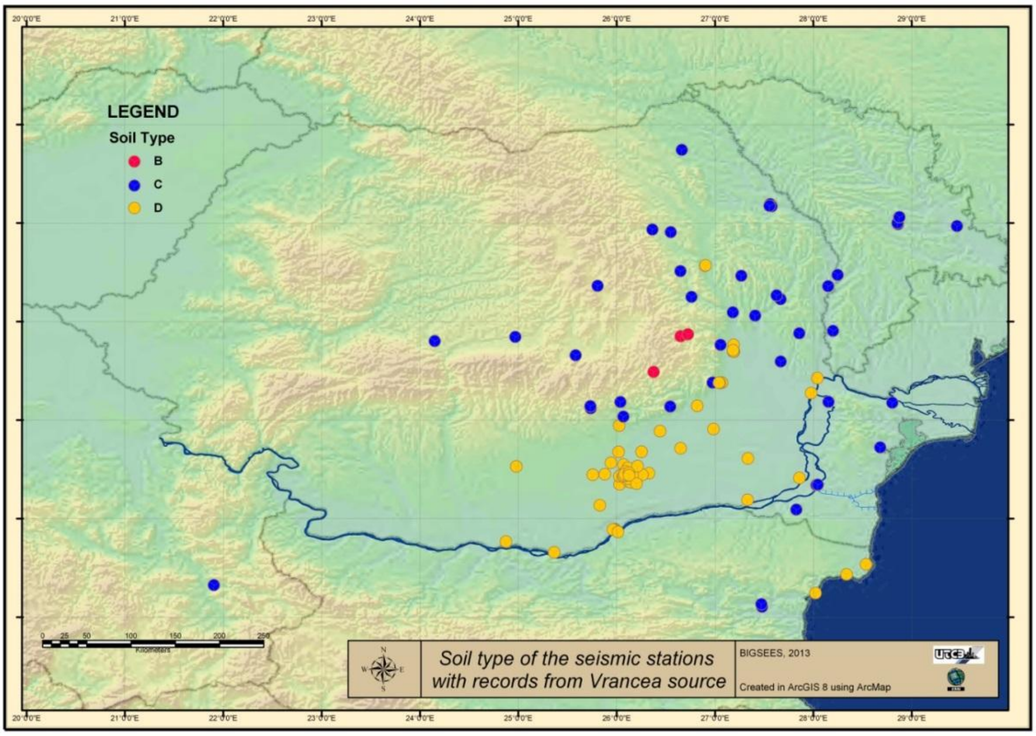


Fig. 1 Distribution of recording seismic stations and the corresponding soil conditions according to NEHRP 94

The distribution of the moment magnitude M_W with the epicentral distance of the recording seismic station is shown in Fig. 2.

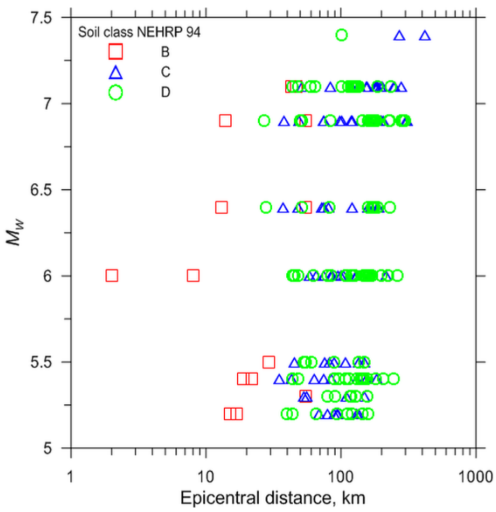


Fig. 2 Distribution of the earthquake magnitude M_W with the epicentral distance of the recording station

3. Analysis of GMPEs

The GMPEs are applied for each strong ground motion record according to the soil class given in Figure 1. In the case of the Youngs *et al.* (1997), attenuation model are applied both the soil and the rock functional form. For Zhao *et al.* (2006) GMPE, three functional forms developed for soil class I, II and III are used. The correspondence between the various soil classes is given in Table 3.

The analysis and grading procedure of the two selected GMPEs is performed using the database presented in Cap. 2. In this study are employed the same grading schemes like in the paper of (Vacareanu *et al.* 2013c). The first method is the one given by Scherbaum *et al.* (2004) in which several goodness-of-fit measures are proposed. The method is based on the computation of the normalized residuals *NRES*. The grading scheme is based on the median of the likelihood *LH* (*MEDLH*) and on the mean, median and standard deviation of the normalized residuals *NRES* (*MEANNR*, *MEDNR* and *STDNR*). The grading scheme is summarized in Table 4.

The mean and median values of the normalized residuals and likelihoods, as well as the standard deviations σ are obtained using the "delete-1" jackknife resampling (Wu 1986) of their estimators. The values of the overall goodness-of-fit parameters are presented for the two considered GMPEs in Table 5.

In Table 6 the candidate models are ranked using the average sample log-likelihood, noted *LLH* and the data support index, noted *DSI*. The definitions of the two indicators can be found in the work of Scherbaum *et al.* (2009) and Delavaud *et al.* (2012).

Table 3 Correspondence of various soil classes definitions

EN 1998-1 soil class	NEHRP soil class	Zhao *et al.* (2006) soil class
A	B	I
B	C	II
C	D	III
D	E	IV

Table 4 Grading scheme of Scherbaum *et al.* (2004)

Class	*MEDLH*	Absolute value of *MEANNR*	Absolute value of *MEDNR*	*STDNR*
A	> 0.4	< 0.25	< 0.25	< 1.125
B	> 0.3	< 0.5	< 0.5	< 1.25
C	> 0.2	< 0.75	< 0.75	< 1.5
D	Does not fulfill the criteria for classes A, B or C			

Table 5 Statistical indicators for the considered attenuation models for all periods

Model name	*MEANNR*	σ	*MEDNR*	σ	*STDNR*	σ	*MEDLH*	σ	Grade
Youngs *et al.* (1997)	0.033	0.018	0.092	0.004	0.861	0.014	0.575	0.001	A
Zhao *et al.* (2006)	0.395	0.023	0.432	0.041	1.168	0.016	0.382	0.006	B

Table 6 Ranking of the considered attenuation models

Model name	*LLH*	*DSI*
Youngs *et al.* (1997)	1.164	28.476
Zhao *et al.* (2006)	2.009	-28.476

It is clear from the values given in Table 5 and Table 6 that the Youngs *et al.* (1997) GMPE provides a better fit for the available database of strong ground motions and is graded as a class A ground motion prediction model. The distribution of the normalized residuals with distance for the two considered GMPEs is shown in Fig. 3.

From Fig. 3 one can notice the under-estimation of the Zhao *et al.* (2006) GMPE, especially for epicentral distances in excess of 250 km. The distribution of the normalized residuals for the Youngs *et al.* (1997) GMPE appears to be more compact, without a visible trend or bias for epicentral distances up to 300 km.

The analysis of the normalized inter-event and intra-event variability is performed only for the Zhao *et al.* (2006) attenuation model. In Fig. 4 the total, inter-event and intra-event histograms for normalized residuals *NRES* for the Zhao GMPE are shown.

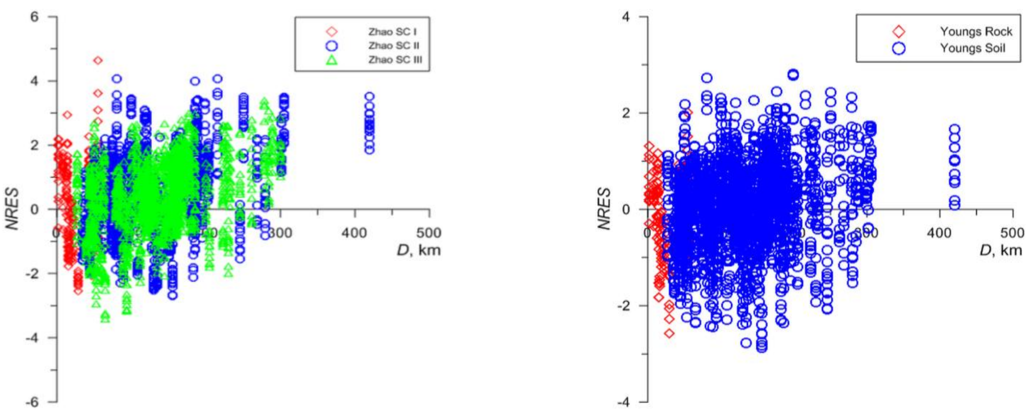


Fig. 3 Normalized residuals versus distance for the considered GMPEs

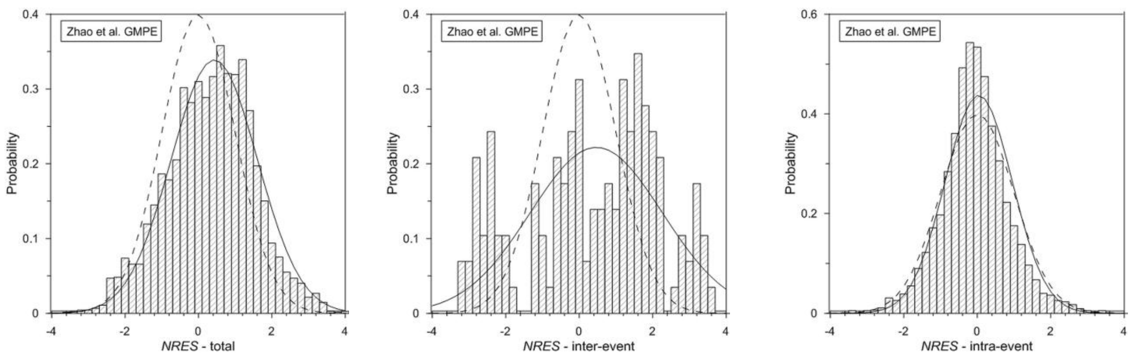


Fig. 4 Histograms of the total, inter-event and intra-event normalized residuals *NRES* for Zhao *et al.* GMPE. The plots also include the standard normal distribution (*dashed black line*) and the normal distribution fitted to the normalized residuals (*solid black line*)

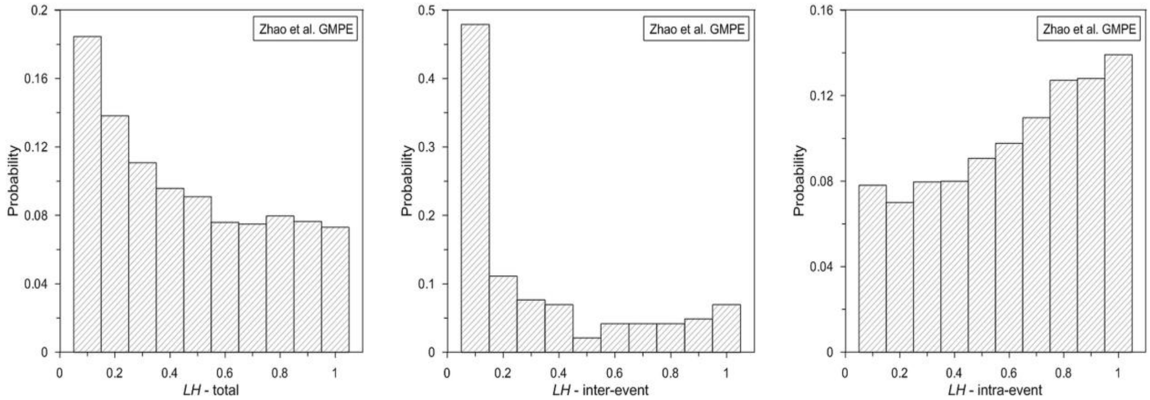


Fig. 5 Histograms of the total, inter-event and intra-event likelihood *LH* for Zhao *et al.* GMPE

From Fig. 4 one can notice that the main source of variability lays in the inter-event residuals. Nevertheless, the intra-event normalized residuals appear to follow the normal probability distribution. The total distribution of the normalized residuals is close to the normal distribution having the mean shifted to the right of zero.

The distribution of the likelihood values *LH* is presented in Fig. 5. The total and the intra-event likelihoods are close to an uniform distribution. However, the inter-event likelihood has an unbalanced distribution shifted towards zero.

A more in-depth analysis of the mean, median and standard deviation of the normalized residuals *NRES* (*MEANNR*, *MEDNR* and *STDNR*) and of the median of the likelihood *LH* (*MEDLH*) is shown in Fig. 6. The total values, as well as the inter-event and intra-event for all the four above-mentioned parameters are shown. From Fig. 6, it is clear that the intra-event values have a smaller variability in the analyzed period range. The high values of the inter-event values for *MEANNR*, *MEDNR* and *STDNR* combined with the small values for *MEDLH* grade the Zhao *et al.* (2006) ground motion prediction model lower than the Youngs *et al.* (1997) model.

The overall performance of the Youngs *et al.* (1997) GMPE is checked in Fig. 7 in which the histograms of the normalized residuals *NRES* and of the likelihood *LH* are presented. One can notice from Fig. 7 that the distribution of the normalized residuals closely matches the normal distribution, while the distribution of likelihood values is almost uniform. However, one might see that the distributions of likelihoods for the two considered GMPEs are opposite. The larger *LH* values for the Youngs GMPE are shifted to the right, while in the case of the Zhao model they are shifted to the left.

An additional comment related to Table 3 refers to the standard deviations of the normalized residuals of the considered attenuation models. The variability of the strong ground motion database is lower than the intrinsic variability of the Youngs GMPE (*STDNR* < 1) and is larger in the case of the Zhao GMPE (*STDNR* > 1).

From the considerations made above it is obvious that the Youngs *et al.* (1997) GMPE fits better the available database of strong ground motions recorded from intermediate-depth Vrancea earthquakes. Nevertheless, the distribution of the normalized residuals with the earthquake magnitude, M_W and earthquake depth, h can provide additional relevant information related to the overall performance of this attenuation model. The two distributions are presented in Fig. 8.

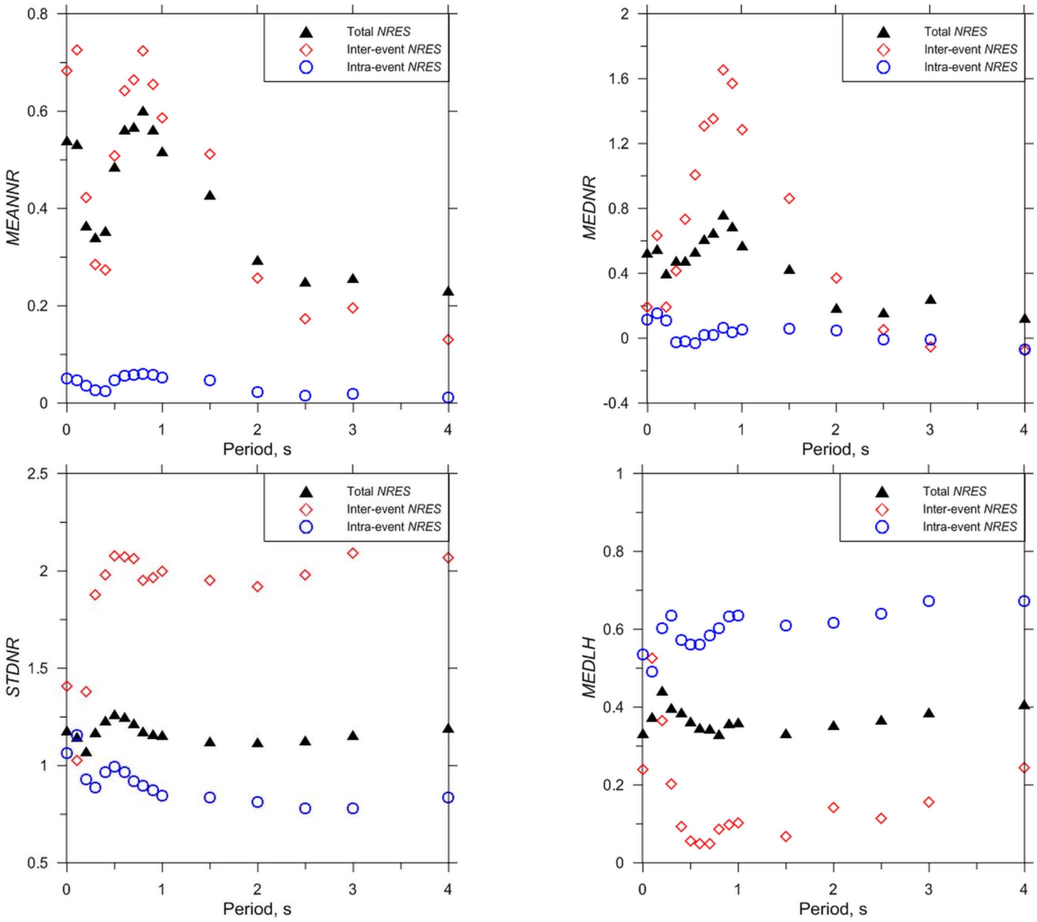


Fig. 6 Variation of the grading parameters from Scherbaum *et al.* (2004) with period for the Zhao *et al.* (2006) GMPE

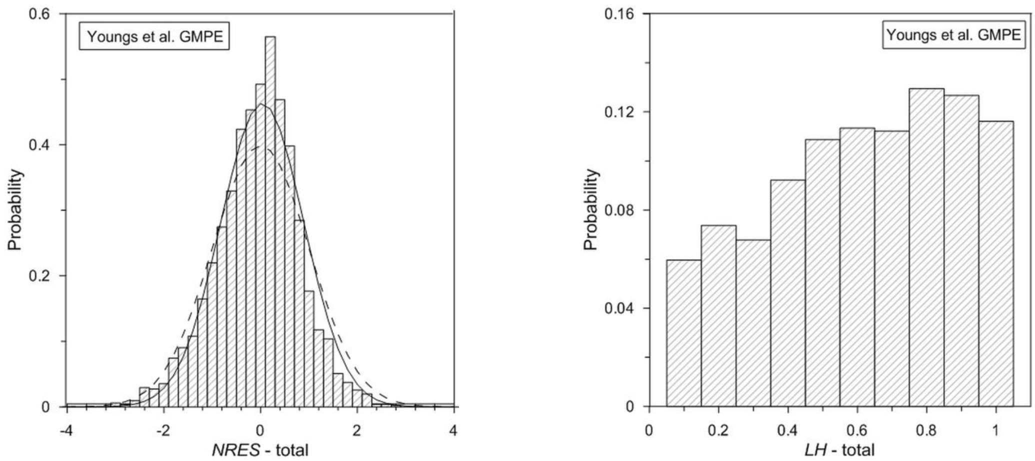


Fig. 7 Histograms of the total event normalized residuals *NRES* and total likelihood *LH* for Youngs *et al.* GMPE. The plots also include the standard normal distribution (*dashed black line*) and the normal distribution fitted to the normalized residuals (*solid black line*)

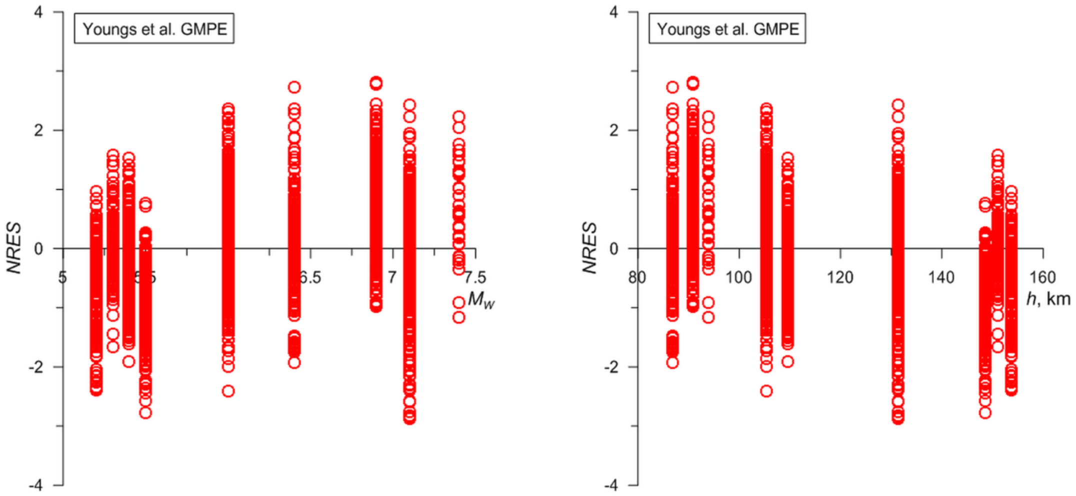


Fig. 8 Normalized residuals *NRES* for Youngs *et al.* GMPE versus earthquakes magnitude M_W and focal depth h

From Fig. 8 one can notice that despite the very good overall performance of the Youngs *et al.* (1997) GMPE, this model underestimates the observed ground motions in the case of large magnitude earthquakes ($M_W > 6.5$) or in the case of seismic events with smaller focal depths ($h <$ 110 km). Consequently, there are overestimations for smaller magnitude earthquakes or for deeper events. Overall, it appears that the underestimations and overestimations cancel each other leading to a very good overall performance of the model.

4. Single-station sigma approach

A ground motion prediction equation (GMPE) shows the distribution of a ground motion parameter in terms of the median value and of the standard deviation (Chen and Faccioli 2013) with respect to the site-to-source distance. Generally, the attenuation models are based on the ergodic assumption (Abrahamson and Hollenback 2012). An ergodic assumption considers that the variability across space is identical to the variability across time for a site (Abrahamson and Hollenback 2012). As mentioned in the work of (Abrahamson and Hollenback 2012), the single station sigma model tries to remove parts of the ergodic assumption by focusing on the influence of the site response on the variability. The variability obtained using this model appears to be smaller than the ergodic variability and is more representative for a particular site. A detailed description of this method can be found in the papers of (Atkinson 2006, Rodriguez-Marek *et al.* 2011, Abrahamson and Hollenback 2012, Chen and Faccioli 2013).

The application of the single-station sigma method is performed for a number of nineteen seismic stations which have recorded strong ground motions from eight Vrancea intermediate-depth earthquakes produced between 1986 and 2009 (see Table 2). The information for the analyzed seismic stations is listed in Table 7.

Ninety-seven strong ground motion records are used in the analysis. Due to the very limited number of available strong ground motion recorded during the April 1999 seismic event for soil

Table 7 Selected seismic stations for single-station sigma method

Station code	NEHRP soil class	No, of earthquakes recorded	No. of strong ground motions
CRC CVD GHR GRE IAS SEC TUD TLC	C	8	40
BAC CNC FOC GRG INC MAG PET PLS POG RMS URZ	D	7	57

class D seismic stations, this event was discarded from the analysis (only for soil class D stations).

The computation method is described in the papers of (Abrahamson and Hollenback 2012), (Chen and Faccioli 2013). The total standard deviation of an attenuation model without the site-to-site variability is (Abrahamson and Hollenback 2012)

$$\sigma_{ss} = \sqrt{\tau^2 + \phi_{ss}^2} \tag{1}$$

where τ is the standard deviation of the inter-event residual δB_e and $\emptyset_{ss}$ is the standard deviation of the intra-event residual δW_{es}.

The computations for the single-station sigma method are performed using the Youngs *et al.* (1997) attenuation model developed for soil conditions and the Zhao *et al.* (2006) model developed for soil class II (NEHRP soil class C) and soil class III (NEHRP soil class D).

Fig. 9 shows the distribution of the inter-event residuals with the epicentral distance of the recording seismic station for four periods T = 0.0 s (*PGA*), 0.3 s, 0.5 s and 1.0. It is clear from the four graphs that the variability of the ground motions increases with the period. For instance, the inter-event residuals for T = 1.0 s are more spread than the inter-event residuals for the other three computed periods. Nevertheless, the distribution of the residuals from the Youngs *et al.* GMPE appears to be more compact than in the case of the Zhao *et al.* GMPE.

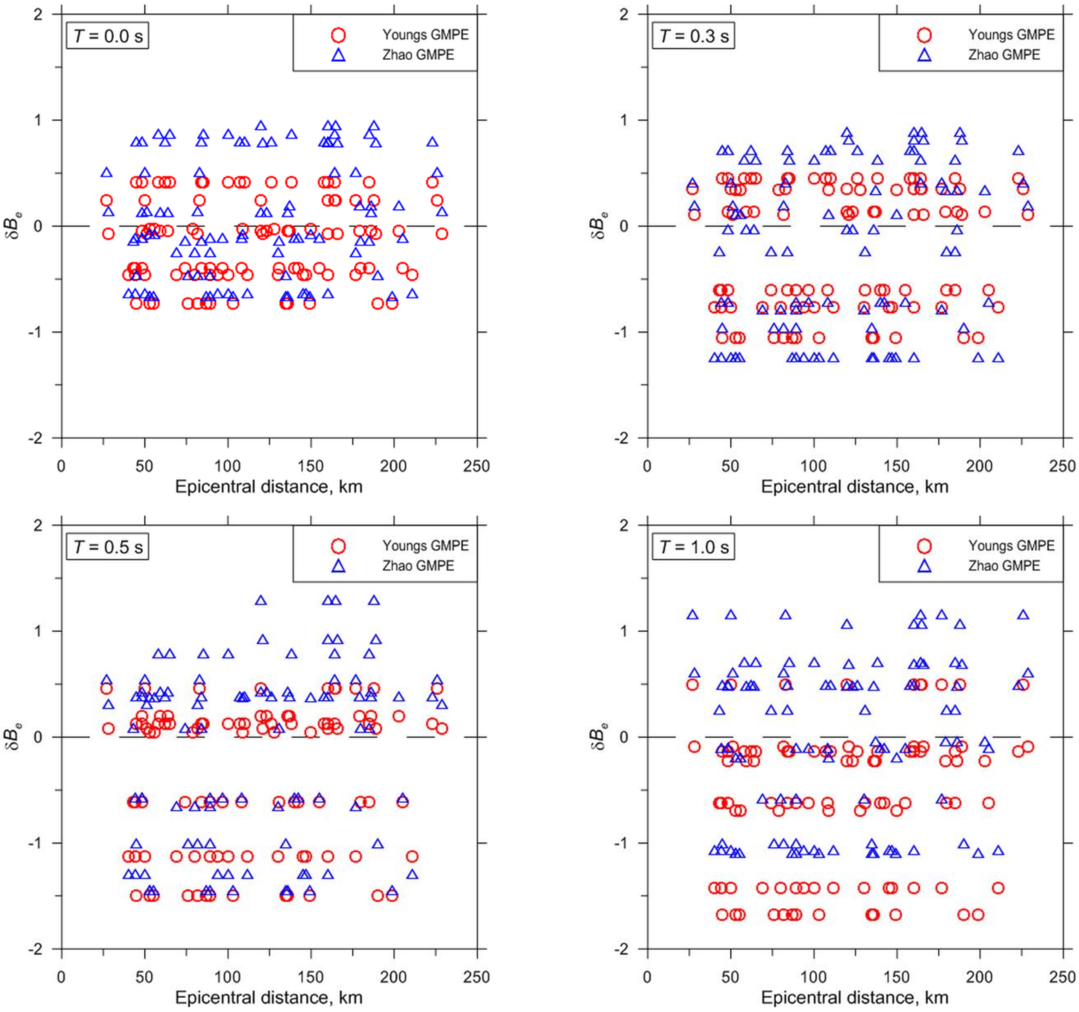


Fig. 9 Comparison of the dependence of the inter-event residual *δBe* with the epicentral distance for the Youngs *et al*. (1997) GMPE and the Zhao *et al.* (2006) GMPE

The four graphs in Fig. 10 show the distribution of the intra-event residuals with the epicentral distance. In this case, however, the distribution of the residuals doesn't appear to follow any pattern and the results appear similar for the two attenuation models used in the analyses.

The term $\delta S2S_S$ is described in the paper of (Chen and Faccioli 2013) as a site term representing the average inter-event residual for station *s*. As noted in (Chen and Faccioli 2013), a positive $\delta S2S_S$ implies that the records of station *s* exceed the median ground motion, while a negative value shows that the observations fall on average below the median ground motion. The site terms can be transformed into spectrum amplification factors (with respect to the median value) by using the relation $e^{\delta S2SS}$. The site terms and the spectrum amplification factors are displayed in Fig. 11 for six stations (FOC, INC, MAG, CRC, CVD, IAS) and for the two attenuation models. In the case of the spectrum amplification factors values larger than unity show amplifications, while smaller values show de-amplifications.

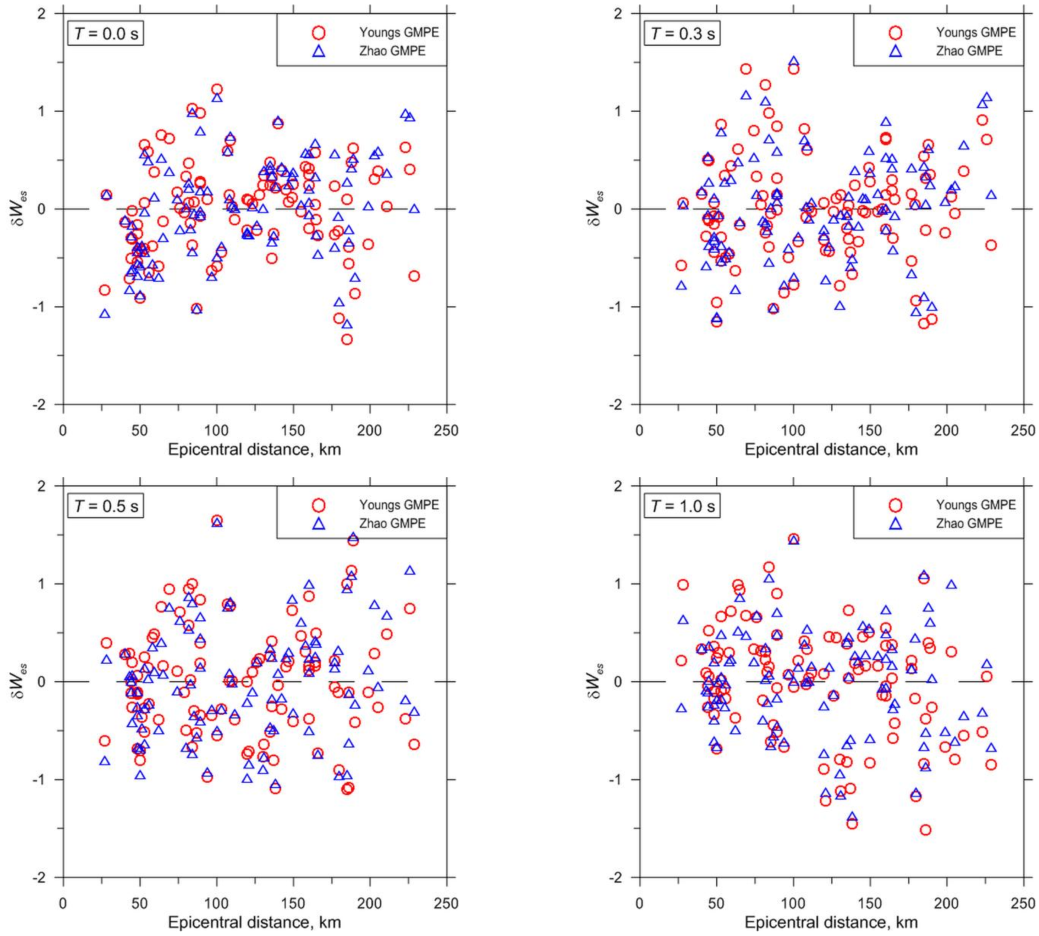
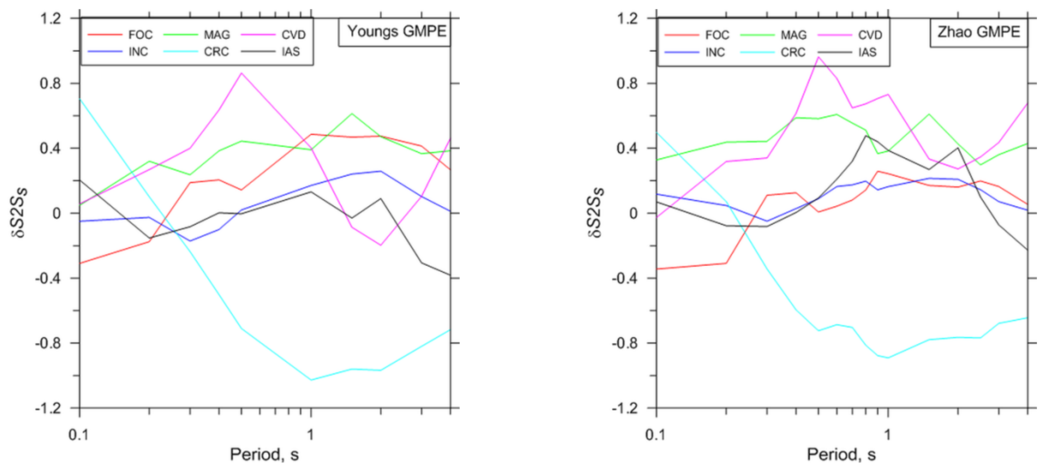


Fig. 10 Comparison of the dependence of the intra-event residual *δWes* with the epicentral distance for the Youngs *et al.* (1997) GMPE and the Zhao *et al.* (2006) GMPE



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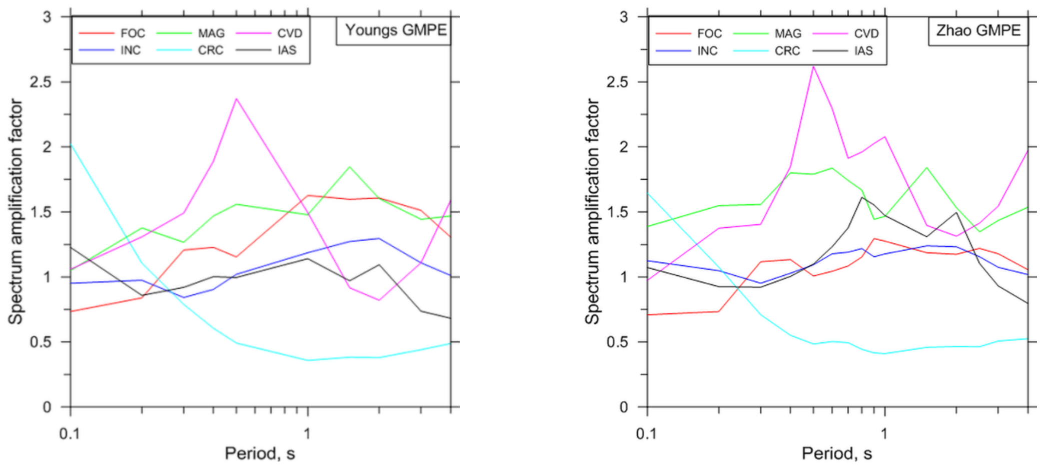

Fig. 11 Site terms and spectrum amplification factors for six seismic stations using Youngs *et al.* GMPE (*left*) and Zhao *et al.* GMPE (*right*)

Table 8 Comparison of single-station sigma values for *PGA* for the analyzed seismic stations

Station code	Youngs *et al.* (1997) GMPE			Zhao *et al.* (2006) GMPE		
	$\varnothing_{ss}$	τ	σ_{ss}	$\varnothing_{ss}$	τ	σ_{ss}
CRC	0.22	0.38	0.44	0.31	0.56	0.64
CVD	0.38	0.38	0.54	0.26	0.56	0.62
GHR	0.37	0.38	0.53	0.29	0.56	0.63
GRE	0.20	0.38	0.43	0.11	0.56	0.57
IAS	0.54	0.38	0.66	0.53	0.56	0.77
SEC	0.69	0.38	0.79	0.72	0.56	0.91
TUD	0.40	0.38	0.55	0.46	0.56	0.72
TLC	0.58	0.38	0.69	0.43	0.56	0.70
BAC	0.18	0.38	0.42	0.27	0.55	0.61
CNC	0.31	0.38	0.49	0.24	0.55	0.60
FOC	0.51	0.38	0.63	0.54	0.55	0.77
GRG	0.55	0.38	0.66	0.50	0.55	0.74
INC	0.30	0.38	0.48	0.29	0.55	0.62
MAG	0.14	0.38	0.40	0.22	0.55	0.59
PET	0.52	0.38	0.64	0.54	0.55	0.77
PLS	0.43	0.38	0.58	0.44	0.55	0.70
POG	0.29	0.38	0.47	0.27	0.55	0.61
RMS	0.31	0.38	0.49	0.27	0.55	0.61
URZ	0.24	0.38	0.45	0.22	0.55	0.59

It is noticeable from Fig. 11 that the results for the six seismic stations are consistent for both GMPEs. The largest amplifications are encountered for the CVD (Cernavoda) station, while the largest de-amplifications occur at station CRC (Carcaliu) for periods in excess of 0.3 s. The amplifications for stations INC (Bucharest-INCERC) and IAS (Iasi) appear similar and are about 1.0 for the entire period range. It is also noteworthy the fact that the largest and smallest amplifications appear for the seismic stations having soil class C, while the results for the soil class D stations (FOC, INC and MAG) appear to have a more limited variability.

All the single-station sigma values for the analyzed seismic stations are reported in Table 8, together with the corresponding standard deviations of the inter-event and intra-event residuals.

The results from Table 8, which compare the single-station sigma values obtained using the two ground motion models, reveal a much larger inter-event variability (τ) in the case of the Zhao *et al.* (2006) GMPE, while the results for the intra-event variability ($\emptyset_{ss}$) appear similar in both cases. Consequently, the increased inter-event variability of the Zhao *et al.* model leads to larger single-station sigma values.

The reduction in the values of the ergodic standard deviation and the average non-ergodic standard deviation are shown in Table 9 for six periods (0.0 s, 0.3 s, 0.5 s, 1.0 s, 1.5 s and 2.0 s). The average values are computed for all the analyzed seismic stations. In the case of the Youngs *et al.* GMPE there is a significant reduction of the standard deviation especially in the short and long period range. The single-station sigma values computed using the Zhao *et al.* GMPE are larger than the ergodic values given in the GMPE, with the exception of the peak ground acceleration (*PGA*), for which the values are similar. Therefore, one can conclude that the Youngs *et al.* GMPE fits better with the available recorded database and leading thus to lower single-station sigma values.

The reductions in the variability obtained in this study are compared in Table 10 with other values reported in the literature (Abrahamson and Hollenback 2012).

Table 9 Comparison of ergodic and non-ergodic single-station sigma weighted average values

Period	Youngs *et al.* (1997) GMPE			Zhao *et al.* (2006) GMPE		
	Ergodic standard deviation	Single-station sigma	Reduction, %	Ergodic standard deviation	Single-station sigma	Reduction, %
0.0 s	0.86	0.54	37	0.68	0.67	1
0.3 s	0.86	0.74	14	0.73	0.88	-21
0.5 s	0.86	0.84	2	0.71	0.94	-32
1.0 s	0.86	0.82	5	0.72	0.86	-19
1.5 s	0.91	0.74	17	0.72	0.81	-13
2.0 s	0.96	0.66	31	0.73	0.81	-11

Table 10 Reported single-station sigma values from literature for *PGA* (Abrahamson and Hollenback 2012)

Study	Rodriguez-Marek *et al.* (2011)	Atkinson (2006)	Lin *et al.* (2011)	Chen and Tsai (2002)	This study
Ergodic standard deviation	0.80	0.71	0.68	0.73	0.86
Non-ergodic standard deviation	0.67	0.62	0.62	0.63	0.54
Reduction, %	16	13	9	14	37

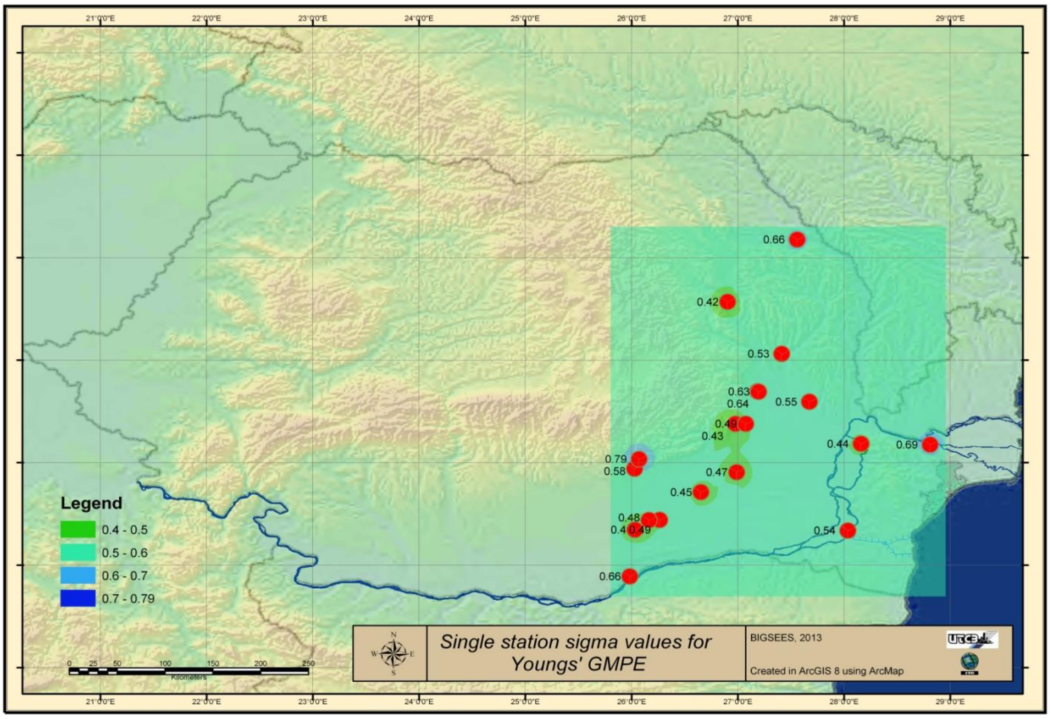

Fig. 12 Single-station sigma values for the Youngs *et al.* (1997) GMPE

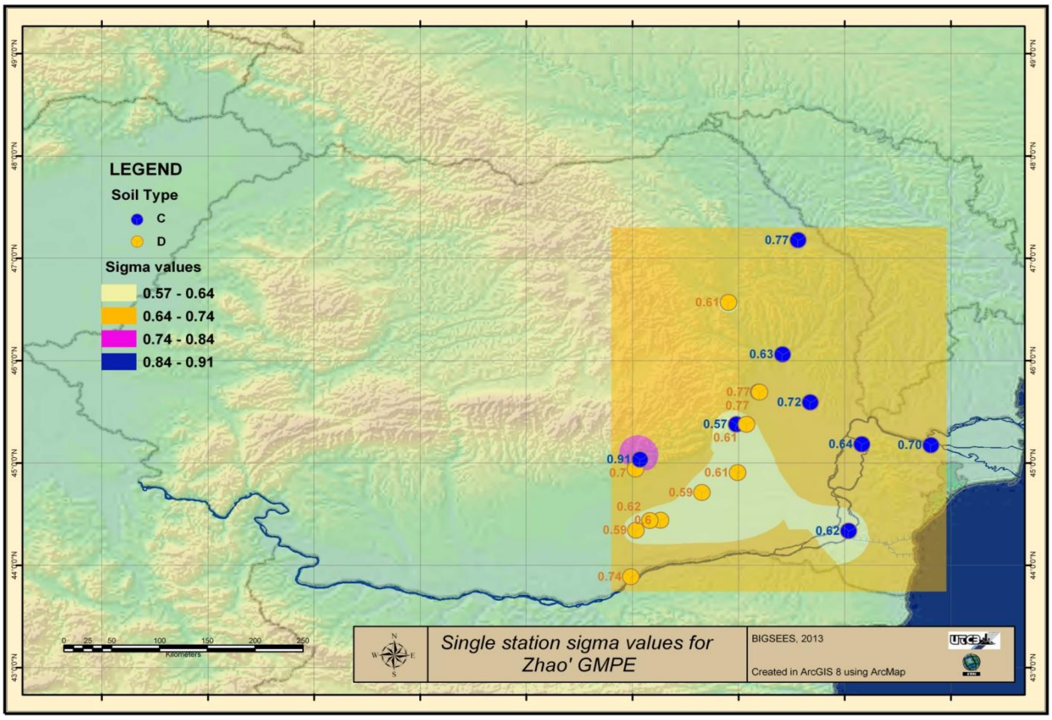

Fig. 13 Single-station sigma values for the Zhao *et al.* (2006) GMPE

In Figs. 12 and 13, respectively are shown two maps of single-station sigma values obtained using the two attenuation models.

It has to be highlighted the fact that in this research a 37% reduction of the values of the standard deviation is obtained when using the Youngs *et al.* (1997) GMPE leading thus to an average value of non-ergodic sigma of just 0.54, as shown in Table 10.

5. Conclusions

The main purpose of this research is the analysis of the different components of the variability in the case of strong ground motions recorded from earthquakes produced by the Vrancea subcrustal seismic source.. In the first stage of the analysis, the two GMPEs recommended for the Vrancea subcrustal seismic source are graded, while in the second stage the single-station sigma approach is applied in order to reduce the variability of the ground motion. The most important findings of this research could be summarized as follows:

- The Youngs *et al.* (1997) GMPE performs better than the Zhao *et al.* (2006) GMPE considering the values of the goodness-of-fit parameters. However, from the distribution of the normalized residuals Youngs *et al.* ground motion model appears to overestimate small magnitude and/or deeper seismic events and underestimate larger magnitude and/or shallower earthquakes;
- The average value of the single-station sigma reduction for *PGA* is about 37% in the case of the Youngs *et al.* (1997) attenuation model and at the most about 1% in the case of the Zhao *et al.* (2006) GMPE. The results obtained using the Youngs *et al.* model show reductions on the entire period range, but the most consistent ones are in the short and long period range;
- Both the grading procedure and the single-station sigma analysis reveal a much larger inter-event variability in the case of the Zhao *et al.* (2006) GMPE;
- The inter-event variability increases for the two ground motion prediction models with the spectral period. However, this pattern does not apply in the case of the intra-event variability;
- Both the Youngs and the Zhao attenuation models can be used in a logic-tree approach for the probabilistic analysis of the seismic hazard from the Vrancea subcrustal seismic source.

Acknowledgments

Funding for this research was provided within BIGSEES Project by the Romanian National Authority for Scientific Research (ANCS) under the Grant Number 72/2012. This support is gratefully acknowledged. 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 encouraging comments of an anonymous reviewer.

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