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Scaling of ground motions from Vrancea (Romania) earthquakes

Florin Pavel* and Radu Vacareanu

Seismic Risk Assessment Research Centre, Technical University of Civil Engineering Bucharest, Bd. Lacul Tei no. 122-124, Sector 2, 020396, Bucharest, Romania

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Abstract. This paper evaluates the scaling of ground motions recorded from nine intermediate-depth earthquakes produced in the Vrancea seismic zone in Romania. The considered ground motion database consists of 363 horizontal recordings obtained on soil classes B and C (according to Eurocode 8). An analysis of the inter- and intra-event spectral accelerations is performed in order to gain information regarding the magnitude and distance scaling of the Vrancea ground motions. The analyses reveal a significant influence of the earthquake magnitude and focal depth on the distance scaling and different magnitude and distance scaling for the two soil classes. A linear magnitude and distance scaling is inferred from the results for the range of magnitudes $5.2 \leq M_W \leq 7.1$. The results obtained are checked through stochastic simulations and the influence of the stress drop and kappa values on the ground motion levels is assessed. In addition, five ground motion models which were tested in other studies using recordings from Vrancea earthquakes are analyzed in order to evaluate their corresponding host stress drop and kappa. The results show generally a direct connection between the host kappa values and the host stress drop values. Moreover, all the ground motion models depict magnitude dependent host kappa and stress drop levels.

Keywords: spectral acceleration; kappa; stress drop; magnitude and distance scaling; ground motion models; soil class

1. Introduction

The magnitude and distance scaling of ground motions represents one of the main issues in the regression of predictive models. Generally, the ground motion models are derived using recordings from similar tectonic regimes, albeit from different geographical regions. The magnitude M_W of the earthquakes used in the regression starts from M_W=5 (or even 4) and can go up to M_W=8 (or even larger values, depending on the tectonic regime). Therefore, both small and large magnitude seismic events are used in the regression. Several studies from the literature have revealed scaling differences between large and small earthquakes. Through stochastic simulations, Douglas and Jousset (2011) reveal a nonlinear magnitude scaling for long period spectral accelerations and for earthquakes with $M_W \geq 4$. On the contrary, in the case of short period spectral accelerations and for earthquakes having $M_W \geq 5$, a linear dependence can be assumed. In addition, the influence of the

*Corresponding author, Ph.D., E-mail: florin.pavel@utcb.ro

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spectral decay parameter *k* (Anderson and Hough 1984) is much larger for the smaller magnitude seismic events than in the case of the large magnitude earthquakes. Douglas and Jousset (2011) indicate that both a linear and a nonlinear type of magnitude scaling are inferred from the currently used ground motion models. Bommer *et al*. (2007) show that a ground motion model should be used only for the magnitude range of the earthquakes from which they were derived. Moreover, the models may be unreliable even for magnitudes which are equal to the limit magnitudes of the dataset. Boore *et al*. (2009) show that the high frequencies tend to attenuate faster with the distance as compared to the low frequencies, especially for source-to-site distances in excess of 200 km. Boatwright *et al*. (2003) evaluate the distance and magnitude dependence of the peak ground acceleration (*PGA*) and peak ground velocity (*PGV*) using ground motions from earthquakes in northern California. The authors show that for distances R>100 km, the ground motions attenuate faster than the attenuation assumed by a simple power law. As such, Boatwright *et al*. (2003) propose a function combining both a power law and an exponential distance decay.

The Vrancea subcrustal seismic zone represents an area of concentrated intermediate-depth seismicity located at the bend of the Carpathian Mountains. A more in-depth description of the characteristics of this seismic source can be found, for instance, in the paper of Vacareanu *et al*. (2015). However, it is important to note that the moment release rate of this subcrustal seismic source which has an area not exceeding 3000-4000 km^2 (depending on the reference considered) is of the same order of magnitude as that of southern California as shown by Wenzel *et al*. (1998).

In this study the magnitude and distance dependence of ground motions from Vrancea earthquakes are investigated. The procedure used in the research involves the calculation of the inter- and intra-event spectral accelerations which are basically similar with the inter- and intra-event residuals defined in the literature (e.g., Strasser *et al*. 2009). The results obtained are checked through stochastic simulations (Boore 2003) performed using the software SMSIM (Boore 2005). Moreover, the influences of the stress drop and kappa on the ground motion levels are also investigated. Finally, the host kappa and stress drop levels are assessed for five ground motion models proposed for the Vrancea subcrustal seismic source in the study of Pavel *et al*. (2014).

2. Ground motion database

The ground motion database employed in this study consists of 363 horizontal ground motions recorded during nine intermediate-depth Vrancea (Romania) earthquakes which occurred in the period 1986 - 2013. This database represents a subset of the database compiled for the BIGSEES national research project (http://infp.infp.ro/bigsees/default.htm) and which was also used in the evaluation of the ground motion models by Pavel *et al*. (2014). In this study, only the recordings obtained on soil classes B and C according to EN 1998-1 (2004) are used. 144 recordings come from soil class B conditions, while the rest (219) were obtained on soil class C conditions. The soil conditions for the recording seismic stations were assigned using borehole data collected for the BIGSEES national research project and using the topographic method of Wald and Allen (2007). The analyzed ground motions were recorded by both digital and analogue instruments with the largest part (around 65%) being obtained on digital instruments. Unfortunately, there are no digital recordings for seismic events having M_W>6.0. All the digital recordings were processed using a band-pass Butterworth filter of 4th order with cut-off frequencies of 0.05 Hz and 50 Hz. Table 1 shows the main characteristics of the nine Vrancea intermediate-depth earthquakes, as well as the

Table 1 Characteristics of the analysed Vrancea earthquakes

Earthquake date	Lat. N	Long. E	M_W	*h* (km)	No. of strong ground motions
30.08.1986	45.52	26.49	7.1	131	36
30.05.1990	45.83	26.89	6.9	91	48
31.05.1990	45.85	26.91	6.4	87	34
28.04.1999	45.49	26.27	5.3	151	20
27.10.2004	45.84	26.63	6.0	105	58
14.05.2005	45.64	26.53	5.5	149	35
18.06.2005	45.72	26.66	5.2	154	33
25.04.2009	45.68	26.62	5.4	110	36
06.10.2013	45.67	26.58	5.2	135	63

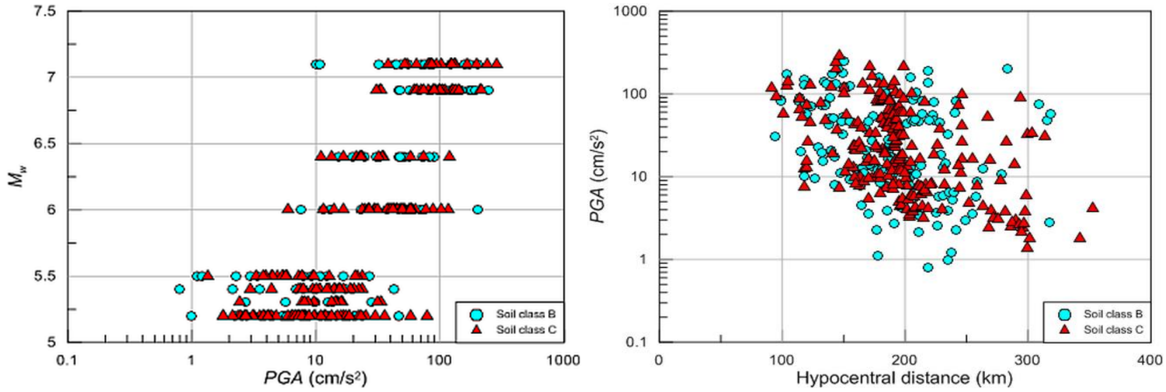

Fig. 1 Distribution of peak ground acceleration (*PGA*) with earthquake magnitude M_W (left) and hypocentral distance *R* (right)

corresponding number of ground motions for each seismic event.

Figure 1 shows the distribution of the peak ground acceleration (*PGA*) with the earthquake moment magnitude M_W and hypocentral distance of the recording seismic station.

One can observe from Figure 1 that the majority of the recordings come from hypocentral distances R = 100 – 200 km and that there are very few recordings at hypocentral distances $R <$ 100 km or $R >$ 300 km.

3. Scaling of ground motions from Vrancea earthquakes

The procedure for evaluating the scaling of the ground motions recorded from Vrancea (Romania) earthquakes is based on the computation of the inter- and intra-event spectral accelerations (in log units). The inter-event spectral acceleration represents the mean value for an individual earthquake (obtained by averaging all the individual observations), while the intra-event spectral acceleration is computed by subtracting from the observed values the inter-event values determined previously for each earthquake.

$$Y_{es} = \delta B_e + \delta W_{es} \tag{3.1}$$

In relation (3.1), Y_{es} is the observed ground motion (in log units) at station s during the earthquake e, δB_e is the inter-event spectral acceleration during the earthquake e and δW_{es} represents the intra-event spectral acceleration at station s during the earthquake e. δB_e is obtained using relation (3.2)

$$\delta B_e = \frac{\sum_{s=1}^{N_s} Y_{es}}{N_s} \tag{3.2}$$

where N_s is the number of seismic stations which have recordings for earthquake e.

Finally, δW_{es} is obtained by applying relation (3.1) in which δB_e is subtracted from Y_{es}. The computation of the inter- and intra-event spectral accelerations is performed separately for the two soil classes in the database (B and C) and for three spectral periods (T=0.0 s, T=0.5 s and T=2.0 s).

The distribution of the inter-event spectral acceleration (computed separately for soil class B and C) with the earthquake moment magnitude M_W (magnitude scaling) is shown in Fig. 2. In addition, linear trendlines are fitted using the data corresponding to each soil class.

One can observe from Fig. 2 that the inter-event spectral accelerations for soil class B and C are similar for T=0.0 s. However, for T=2.0 s, the inter-event spectral acceleration is larger for soil class C. This result is not a surprise as one would expect that the long-period spectral ordinates are larger for soil class C sites as compared to the soil class B sites. In addition, it is also noteworthy the fact that the slope of the fitted trendline increases with the spectral period from 0.60 for T=0.0 s up to around 1.0 for T=2.0 s. This means that the long-period spectral ordinates increase much faster than the short-period ones, and thus for an earthquake with M_W=7.5 the ordinates at T=0.0 s are almost similar with the ones for T=2.0 s if one considers a linear trend.

Next, the distribution of the intra-event spectral acceleration with the hypocentral distance (distance scaling) is checked in Fig. 3 as a function of the soil class. Trendlines are again fitted using the data for each soil class in order to check the distance scaling.

From Fig. 3, one can make several observations: the first one is that the intra-event spectral accelerations are larger for soil class C conditions for hypocentral distance R<200 km and larger

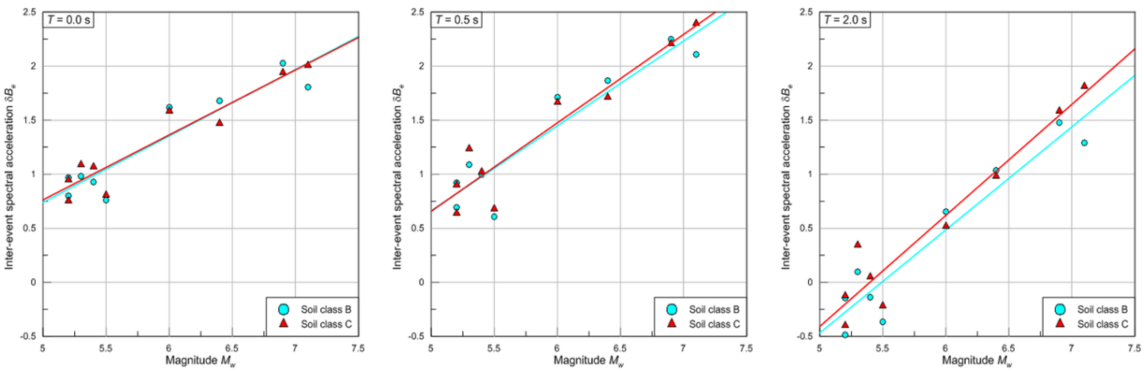

Fig. 2 Distribution of inter-event spectral accelerations with earthquake magnitude M_w for three spectral periods T=0.0 s, T=0.5 s and T=2.0 s

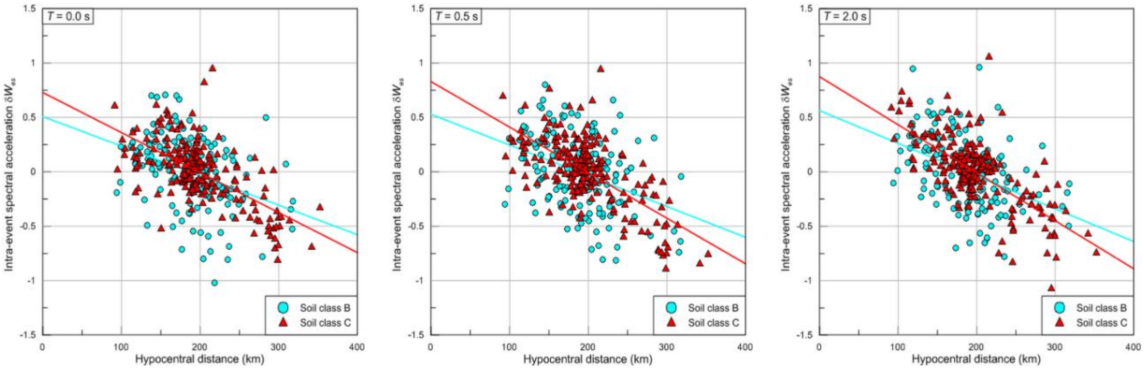

Fig. 3 Distribution of intra-event spectral accelerations with hypocentral distance for three spectral periods T=0.0 s, T=0.5 s and T=2.0 s

for soil class B sites for hypocentral distances R>200 km. Next, the slope of the fitted trendline is always larger for the soil class C sites and the difference between the slopes of the trendlines for soil class B and C increases with the spectral period. Moreover, in all cases the distance R=200 km appears to be the hypocentral distance at which the intra-event spectral accelerations are equal to zero for both soil classes.

Next, in order to gain better insight into the distribution of the intra-event spectral accelerations, the influence of the earthquake magnitude is evaluated in Fig. 4. The event magnitude is divided into three bins: M_W<5.5 (four events), 5.5≤M_W<6.5 (three events) and M_W≥6.5 (two events).

Some very interesting comments can be made with regard to Fig. 4. The first comment is that the smallest slope for the fitted trendlines is encountered for the magnitude bin which contains the largest seismic events. As such, the larger magnitude seismic events tend to attenuate slower as compared to the smaller magnitude ones. Next, the difference between the slopes corresponding to the three magnitude bins diminishes with the increase of the spectral period. The smallest difference between the three trendlines is encountered as previously noticed at R=200 km.

Subsequently, another earthquake parameter which can influence the distance scaling in the case of intermediate-depth seismic events is the event focal depth. In this case, the data are

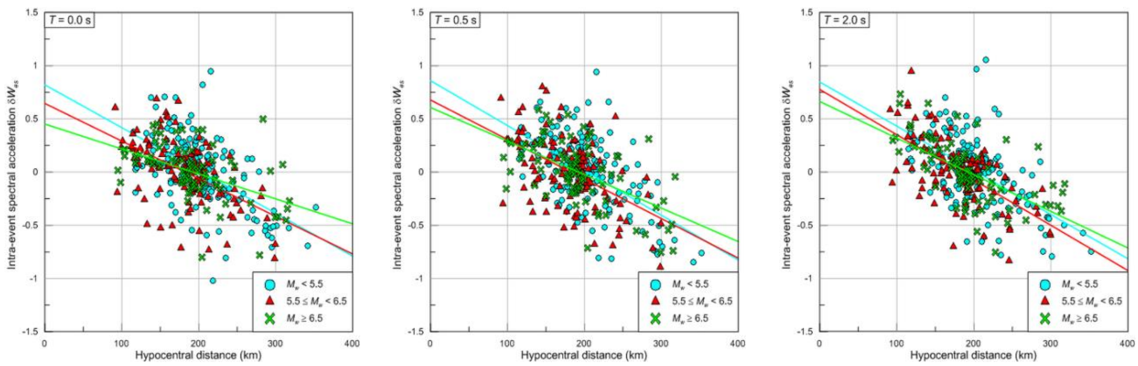

Fig. 4 Distribution of intra-event spectral accelerations with hypocentral distance as a function of the earthquake magnitude for three spectral periods T=0.0 s, T=0.5 s and T=2.0 s

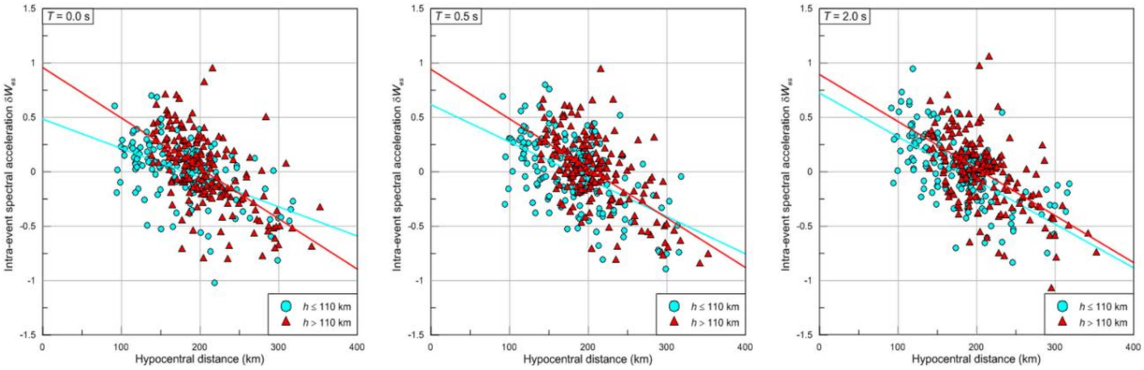

Fig. 5 Distribution of intra-event spectral accelerations with hypocentral distance as a function of the earthquake focal depth for three spectral periods *T*=0.0 s, *T*=0.5 s and *T*=2.0 s

grouped into two focal depth bins: $h \leq 110$ km (four events) and $h > 110$ km (five events). The results are depicted in Fig. 5.

Fig. 5 contains some noticeable results, as well. It appears, especially for hypocentral distances $R < 200$ km that the intra-event spectral accelerations are larger for earthquakes with focal depths $h > 110$ km. The attenuation is also larger for the same category of seismic events (focal depths $h > 110$ km). In this case too, the slope difference between the fitted trendlines decreases with the increase of the spectral period. For $T = 2.0$ s the two trendlines have almost similar slopes. An explanation for the above mentioned situation might be found in the study of Bokelmann and Rodler (2014) who mention that the oceanic lithosphere is still attached to the crust up to around 120 km in depth, while a detachment has occurred (or is occurring) in the deeper part of the Vrancea seismic region. Thus, the seismic waves generated by earthquakes produced in the upper and lower part of the Vrancea seismic zone travel through materials having different characteristics and this passage may lead to non-similar wave attenuations.

The results shown previously suggest a linear scaling for both the magnitude and the source-to-site distance. However, one has to take into account the fact that the largest magnitude event in the dataset is the earthquake of August 1986 with $M_W = 7.1$. Therefore, the computed magnitude and distance scaling are valid only in the range $M_W = 5.2$ - 7.1. The scaling for larger magnitude earthquakes originating from Vrancea source can only be surmised at this moment since the recordings from larger magnitude events are missing (the March 4, 1977 $M_W = 7.4$ earthquake was recorded in Romania in only one seismic station in Bucharest). It is to be expected that a sort of capping of the ground motion levels appears from a certain magnitude level onwards, but this magnitude level can't be assessed using the available ground motion recordings. Due to this fact, the databases used for the derivation of ground motion models for Vrancea subcrustal seismic source should contain ground motions recorded in other countries in which larger magnitude intermediate-depth earthquakes occurred (i.e., Chile, Japan, Mexico, etc.) even though the tectonic regime is not exactly similar with that of Vrancea.

Douglas and Jousset (2011) have evaluated the influence of the spectral decay parameter kappa (Anderson and Hough 1984) and of the stress drop on the magnitude scaling using stochastically simulated ground motions (Boore 2003). In this research, we have also evaluated the impact of kappa and of the stress drop on the magnitude scaling. The ground motions were simulated using the SMSIM software (Boore 2005) and using the *Q(f)* function proposed by (Pavel 2015). The focal depth of the earthquake is h=70 km and the epicentral distance is d=10 km. The soil amplification is taken from the Boore and Joyner (1997) and it corresponds to a soil class B site. In Fig. 6 the influence of the kappa parameter on the ground motion levels is evaluated for a constant stress drop value Δσ=60 bars. Three values of k are used: k=0.035 s, k=0.070 s and k=0.105 s.

From Fig. 6 one can observe that the magnitude scaling can be approximated through a linear function only for T=0.0 s. For the other two spectral periods, T=0.5 s and T=2.0 s, the scaling can be approximated only through a nonlinear function. However, for smaller magnitude ranges (like the magnitude range of the dataset used in this study) a linear approximation is also valid. Moreover, the influence of the spectral decay parameter k decreases with the increase of the spectral period. At T=2.0 s, the spectral ordinates for the three k values are almost similar. The values of the simulated ground motions are as expected larger than the inter-event spectral acceleration, previously determined. However, if we consider also the intra-event spectral acceleration the two values (simulated and observed) have similar orders of magnitude.

Subsequently, the impact of the stress drop $\Delta\sigma$ on the magnitude scaling is evaluated. The main assumptions from the previous case are also used. The only difference is that $\Delta\sigma$ has three values: 60 bars, 100 bars and 140 bars and k=0.070 s. The results are illustrated in Fig. 7 from which it is clear that the influence of the stress drop on the magnitude scaling increases with the increase of the magnitude. Moreover, the magnitude scaling tends to become nonlinear for longer spectral

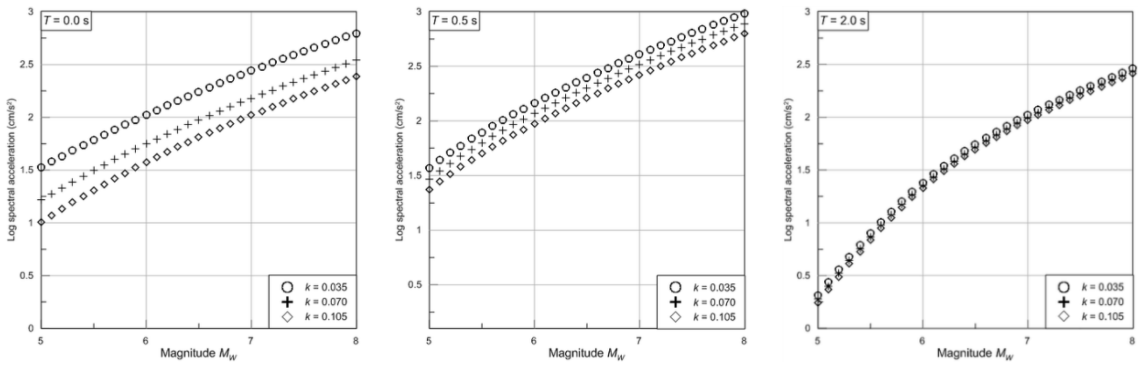

Fig. 6 Magnitude scaling of simulated ground motions as a function of k for three spectral periods T=0.0 s, T=0.5 s and T=2.0 s

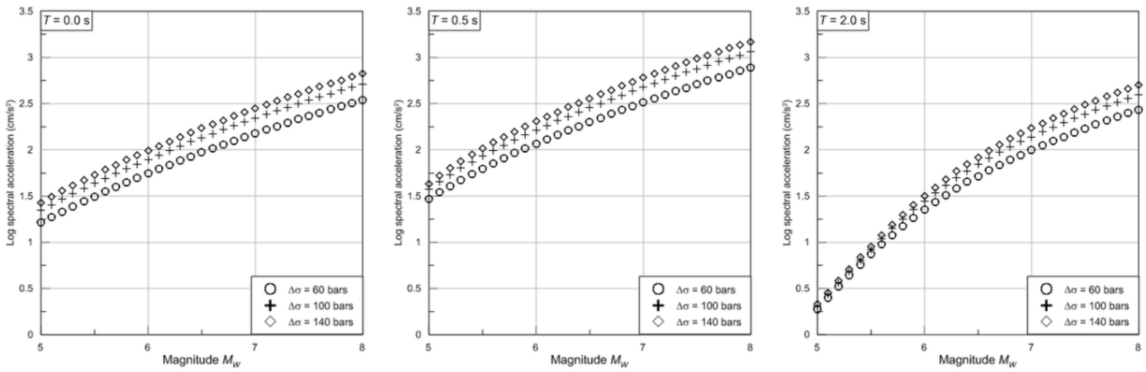

Fig. 7 Magnitude scaling of simulated ground motions as a function of $\Delta\sigma$ for three spectral periods T=0.0 s, T=0.5 s and T=2.0 s

periods. It appears as noted by Douglas and Jousset (2011) that *k* has a greater influence for smaller magnitudes, while in the case of larger magnitudes the stress drop appears to have a greater effect on predicted spectral accelerations. The linear approximation of the magnitude scaling holds true for limited magnitude ranges, similarly with the case shown in Fig. 6.

4. Scaling of ground motion models

Four ground motion models - Atkinson and Boore (2003), Lin and Lee (2008), Youngs *et al*. (1997) and Zhao *et al*. (2006) were recommended for the Vrancea subcrustal seismic source in the SHARE project as shown in the paper of Delavaud *et al*. (2012). The four above-mentioned ground motion models, as well as the recently derived model of Vacareanu *et al*. (2015) were tested using a ground motion database recorded during Vrancea earthquakes in several studies, such as: Vacareanu *et al*. (2013) or Pavel *et al*. (2014). The testing procedure have shown that some of the ground motion models, namely: Vacareanu *et al*. (2015) or Youngs *et al*. (1997) provide a better fit with the observed data, while others, such as: Atkinson and Boore (2003) and Lin and Lee (2008) do not fit as well with the observed ground motions.

Recently, Al Atik et al. (2014) have proposed a method for deriving *k* scaling of ground motion models based on an inverse random vibration theory approach. The inverse random vibration theory is applied using the software Strata (Kottke and Rathje, 2008). In this research we derive

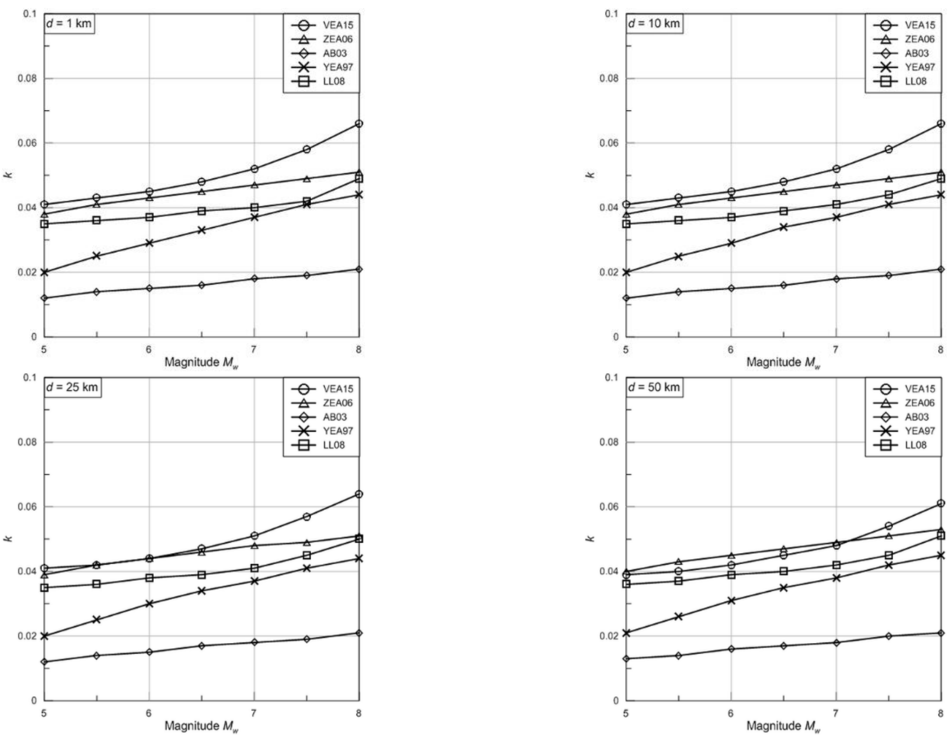

Fig. 8 Host kappa values for five ground motion models for Vrancea subcrustal seismic source computed at *d*=1 km, 10 km (top row), 25 km and 50 km (bottom row)

the host *k* for the five ground motion models used for the Vrancea subcrustal seismic source. The kappa values are obtained for an earthquake with a focal depth *h*=70 km and for four epicentral distances *d*=1 km, 10 km, 25 km and 50 km. The magnitude range of the considered earthquakes is M_W=5 - 8. The evaluation is performed for the ground motion models derived for hard soil (Vacareanu *et al*. 2015, Zhao *et al*. 2006, Atkinson and Boore 2003) denoted as VEA15, ZEA06 and AB03 or rock conditions (Youngs *et al*. 1997, Lin and Lee 2008) and denoted hereinafter as YEA97 and LL08. The derived kappa values are illustrated in Fig. 8.

There are many remarks to be made with regard to the results from Fig. 8. The first remark is that the *k* values are almost similar for the four epicentral distances (1 km, 10 km, 25 km and 50 km), with the exception of the ground motion model of Vacareanu *et al*. (2015) which has the largest kappa values and consequently the largest differences between the values. Next, one can notice the fact that the increase in kappa values does not have a linear trend with the earthquake magnitude, especially for M_W>7. The ground motion models derived for rock conditions do not have the smallest host *k* values. In fact, the smallest host *k* is obtained for the ground motion model of (Atkinson and Boore 2003) for hard soil conditions. Another very interesting observation is that the *k* values increase with the epicentral distance for all the ground motion prediction models, with the exception of the Vacareanu *et al*. (2015) model for which decreasing host kappa values were obtained. This observation is similar with the one made by Pavel (2015) who has derived *k* values using the strong ground motion recordings from three Vrancea subcrustal earthquakes: the seismic events of August 30, 1986, May 30, 1990 and May 31, 1990 and who has shown also a trend of decreasing *k* values with the source-to-site distance. Based on the obtained host *k*, one can derive *k* scaling functions for various *k* target values using the procedure proposed by Al Atik *et al*. (2014). For other magnitude levels and source-to-site distances different than the ones used in this study, the host *k* values have to be computed again.

Using the host *k* values, the corresponding host stress drop levels are computed for each of the five ground motion models. The procedure involves the simulation of ground motions using SMSIM (Boore, 2005) software for the previously determined host k values and comparing their response spectra with the response spectra from the ground motion model. The host stress drops

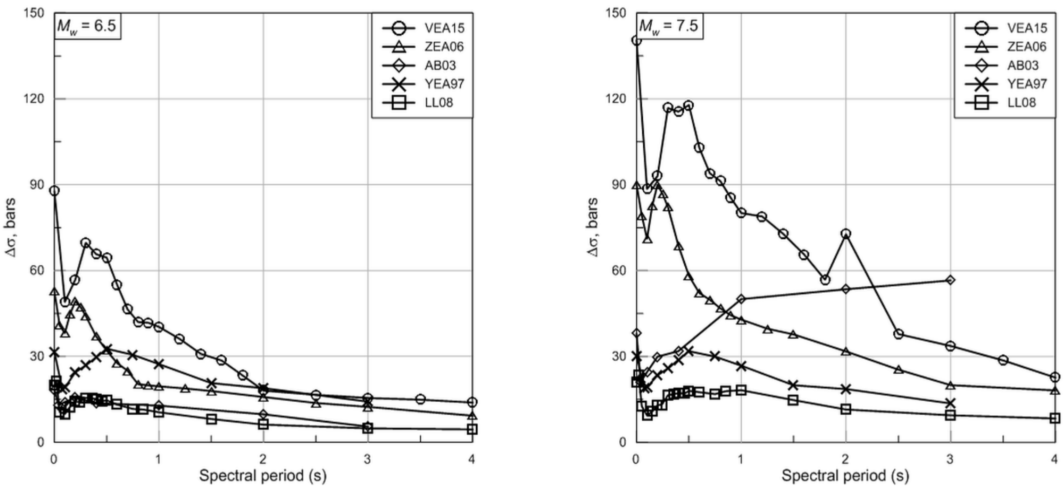

Fig. 9 Host stress drop values for five ground motion models for Vrancea subcrustal seismic source computed at *d*=25 km for two earthquakes with M_W=6.5 and M_W=7.5

are computed for a site situated at an epicentral distance of 25 km and affected by two earthquakes having M_W=6.5 and M_W=7.5 produced at a focal depth h=70 km. The host stress drops are shown in Fig. 9.

It is interesting to note that the largest host stress drops are obtained for the ground motion models having the largest host k values (VEA15 or ZEA06). The exception is the model of Atkinson and Boore (2003) which has very small host k values, but the corresponding host stress drops are also large (for spectral periods in excess of 1 s). Generally, the largest stress drops are obtained for short spectral periods. The increase of the earthquake magnitude from M_W=6.5 to M_W=7.5 implies a corresponding increase of the host stress drop levels. Apparently, the ground motion model of Lin and Lee (2008) is the closest one to a constant stress drop model.

The analyses performed show that the five tested ground motion models have magnitude dependent host kappa and stress drop levels. Moreover, a distance dependent kappa is also inferred from the analyses albeit the trend may be either decreasing as in the case of the Vacareanu *et al*. (2015) model or increasing as in the case of the other four ground motion models.

5. Conclusions

This research focuses on the evaluation of the scaling for ground motions generated by earthquakes originating in the Vrancea subcrsutal seismic source in Romania. A database consisting of more than 300 ground motions recorded on soil classes B and C (EN 1998-1, 2004) during nine intermediate depth earthquakes is used in the study. For each earthquake and for each seismic station, the inter- and intra-event spectral accelerations are computed in log units. The results show that the magnitude and distance scaling can be approximated quite well through a linear function, for the range of magnitudes used in the study M_W=5.2 - 7.1. A considerable influence of the soil class which appears to increase with the spectral period is observed, while on the contrary, the influence of the earthquake magnitude and focal depth is larger for shorter spectral periods. The effects of the kappa and stress drop on the ground motion levels are evaluated through stochastic simulations (Boore 2003). A conclusion similar with the one of Douglas and Jousset (2011) according to which k has a greater influence for smaller magnitudes, while in the case of larger magnitudes the stress drop appears to have a greater effect on the predicted spectral accelerations, is inferred from the analyses. The simulations also show a nonlinear magnitude scaling if a magnitude range broader than the one from the dataset is considered, especially for longer spectral periods. The host kappa and stress drop values are computed for five ground motion models applicable for the Vrancea subcrustal seismic source. Both the host kappa and stress drop appear to be magnitude dependent. Moreover, kappa seems to be distance dependent with an increasing trend for four ground motion models and a decreasing trend for the fifth one (Vacareanu *et al*. 2015). The decrease of the kappa values with the source-to-site distance for ground motions from Vrancea earthquakes has also been highlighted in a recent study by Pavel (2015). The host stress drop is also influenced by the spectral period, with only one model (Lin and Lee 2008) resembling a constant stress drop model. In addition, a direct connection between kappa and the stress drop is visible for several (but not all) ground motion models in the sense that large kappa levels induce large corresponding stress drops. The results shown in this paper highlight again, as do other studies from the literature (e.g., Bommer *et al*. 2007), the fact that ground motion models should be derived using databases of recordings originating from earthquakes with magnitude ranges as broad as possible in order to capture the nonlinear scaling of ground motions.

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