

Article

Ground Motion Duration Patterns for Vrancea (Romania) Intermediate-Depth Earthquakes

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Abstract: This study is focused on evaluating ground motion durations of Vrancea intermediate-depth earthquakes in Romania, in the context of future updates to the Romanian seismic design code P100-1/2013. The ground motion database compiled for this study consists of about 200 ground motions recorded during five moderate and large Vrancea intermediate-depth earthquakes that occurred in the period of 1977–2004 and had moment magnitudes of $M_W \geq 6.0$. Two empirical models were derived in this study for the significant ground motion duration considering two time intervals (5–75% and 5–95%) for the accumulation of the Arias Intensity I_A . An analysis of the data shows that the mean ratio between D_{5-95} and D_{5-75} is about 2.8. Moreover, the regression also shows that the largest share of variability is due to the within-event component (site term). Among the regression coefficients, the hypocentral distance and the soil conditions appear to have a larger impact on the ground motion duration compared to the earthquake magnitude. It was also observed that the median ground motion durations predicted using the empirical model proposed in this study were much smaller than the ones from the proposed Eurocode 8 draft for the same magnitude range. Finally, geographic trends related to the distribution of residuals were also evaluated using the data from the three earthquakes with the largest number of available ground motion recordings.

Keywords: soil conditions; peak ground acceleration; residuals; variability; azimuthal dependence



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1. Introduction

Ground motion models are particularly useful for predicting the distributions of a particular ground motion parameter (e.g., spectral accelerations, spectral velocities, durations, etc.) in a specific earthquake scenario and under specific soil conditions. Consequently, these models are of paramount importance when developing zonation maps for seismic design purposes, or when evaluating seismic risk considering a particular earthquake scenario.

A significant number of empirical models for the estimation of ground motion duration during shallow earthquakes exist in the literature. Various empirical models were derived for both inter-plate [1–8] and intra-plate shallow earthquakes [9,10].

However, in the case of intermediate-depth earthquakes characterized by focal depths in the range of 60–300 km [11] (as in the case of the Vrancea seismic source in Romania), the number of empirical models is much smaller. For instance, Flores-Mendoza et al. [12] proposed an empirical model for in-slab earthquakes that occur in Mexico. The empirical model developed by Bahrampouri et al. [2] is also applicable to intraslab earthquakes in Japan.

Ground motion duration is a key parameter that considerably influences the seismic response of various types of structures [13–21]. In addition, ground motion duration is a key parameter for simulating ground motion recordings (used for nonlinear time history analyses of structures in areas with few available recordings) for various tectonic regimes and source–site distances. The available ground motion databases for shallow crustal

events consist of tens of thousands of recordings of various tectonic regimes, magnitudes, distances, and soil conditions. On the other hand, the number of available ground motion recordings from intermediate-depth earthquakes is significantly smaller, with available recordings from a small number of regions (e.g., Chile, Iran, Japan, New Zealand, Greece, and Romania). Pulse-like ground motion recordings have been observed during moderate- and large-magnitude Vrancea intermediate-depth earthquakes [22]. In addition, in the case of Bucharest, it appears that the number of pulse-like ground motion recordings increases with the earthquake size. However, the pulse period, as a function of magnitude of intermediate-depth earthquakes, appears to be smaller than that of similar-sized crustal events.

In this context, and in the context of future updates to the current Romanian seismic design code P100-1/2013 [23], this study is focused on the evaluation of the ground motion duration for ground motions recorded during Vrancea intermediate-depth earthquakes for engineering purposes (the current version of the code does not contain any guidance in terms of expected ground motion duration). As such, the model is developed using only data from moderate and large Vrancea earthquakes with moment magnitudes of $M_W \geq 6.0$. In the case of this seismic source, it has to be emphasized that empirical models have been proposed for spectral accelerations [24–26], spectral displacements [27], macroseismic intensities [28,29], or mean periods [30]. An analysis of the possible geographical patterns related to the distribution of ground motion durations during intermediate-depth earthquakes with the largest number of available recordings is performed as well.

2. Ground Motion Database

The ground motion database compiled for this study consists of about 200 recordings from five Vrancea intermediate-depth earthquakes that occurred in the period of 1977–2004 with moment magnitudes of $M_W \geq 6.0$. These events, with moment magnitudes M_W in the range of 6.0–7.4, are the most recent and the largest intermediate-depth earthquakes that occurred in the Vrancea intermediate-depth seismic source in the past 50 years. All of the seismic events in the database are characterized by reverse faulting mechanisms, which are characteristic of this seismic source [31], with faulting direction along the NE-SW direction (four events) or the NW-SE direction (the 31 May 1990 event). A recent study by Petrescu et al. [32] suggests that a weak coupling (or an initiation of decoupling) between the sinking slab and the overriding crust currently exists in the Vrancea seismic source zone.

This database was also used recently in a study by Yaghmaei-Sadegh et al. [30] dealing with empirical models for the mean period T_M of ground motions recorded during intermediate-depth earthquakes. The database consists of a total of 196 ground motions recorded during the five intermediate-depth earthquakes mentioned previously. The soil conditions of each seismic station were defined according to the criteria proposed in the Eurocode 8 draft [33], mainly due to the fact that the shear wave velocity in the upper 30 m of soil deposits ($v_{s,30}$), which has been employed in other studies with the same topic (ground motion duration), is not appropriate for the sites situated in the southern and eastern parts of Romania (sites situated on deep unconsolidated sediments). Some brief characteristics of the Vrancea intermediate-depth earthquakes used in this study are given in Table 1. It can be observed that the maximum peak ground acceleration in the database is 0.30 g. All of the ground motion recordings used in this study were obtained using analog instruments (all of the ground motion recordings from the 1977, 1986, and 1990 events, as well as some recordings from the 2004 event) or digital instruments (the majority of the recordings from the 2004 event).

Due to the characteristics of the available ground motion recordings used in this study (a small number of recordings having peak ground accelerations in excess of 0.1 g), the significant duration [34] is selected as the duration parameter in this study. Similar to the study by Kempton and Stewart [4], two intervals for the definition of a significant duration (5–75% and 5–95% of the time necessary for the accumulation of the Arias Intensity I_A [35]) are employed in this research as well. Similarly to the study by Bahrampouri et al. [2], we

use the geometric mean of the two as-recorded horizontal components as a single duration for both definitions.

Due to the scarcity of the ground motion recordings for soil classes A, D, and E sites, a grouping of the data is applied. Thus, the data from soil classes A and B sites are combined into a single category (15% of the data), and the data from soil classes C, D, and E sites are combined into another category (43% of the data). The final category of ground motions consists only of ground motion recordings from soil class F sites (the remaining 42% of the compiled ground motion recordings).

Table 1. Characteristics of the Vrancea intermediate-depth earthquakes used in this study.

Date	Moment Magnitude M_W	Focal Depth (km)	No. of Ground Motion Recordings	PGA Range (g)
4 March 1977	7.4	94	2	0.1–0.20
30 August 1986	7.1	131	40	0.02–0.30
30 May 1990	6.9	91	52	0.03–0.26
31 May 1990	6.4	87	36	0.01–0.12
27 October 2004	6.0	105	66	0.01–0.21

The distribution of the significant ground motion durations D_{5-75} and D_{5-95} as a function of the hypocentral distances and peak ground accelerations are illustrated in Figures 1 and 2, respectively. No clear trends in the data can be inferred from both Figures 1 and 2. It can be observed, as well, that there are few ground motions recorded at hypocentral distances larger than 300 km.

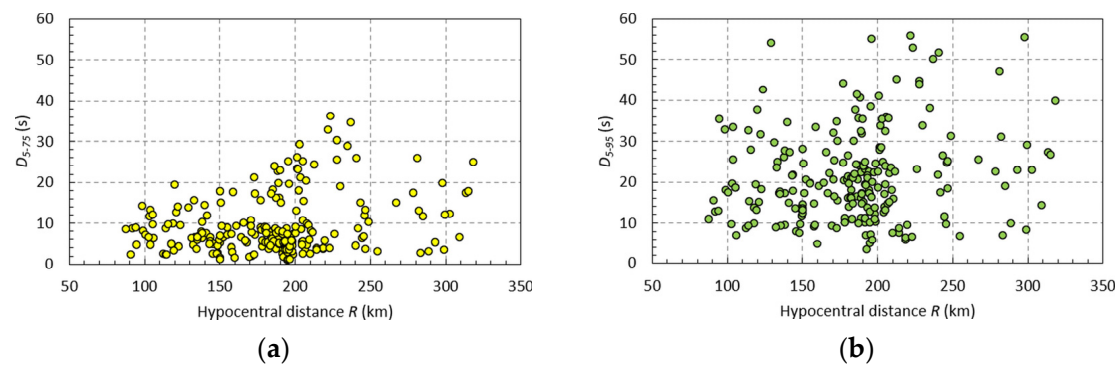


Figure 1. Distribution of the significant ground motion duration as a function of the hypocentral distance: (a) D_{5-75} ; (b) D_{5-95} .

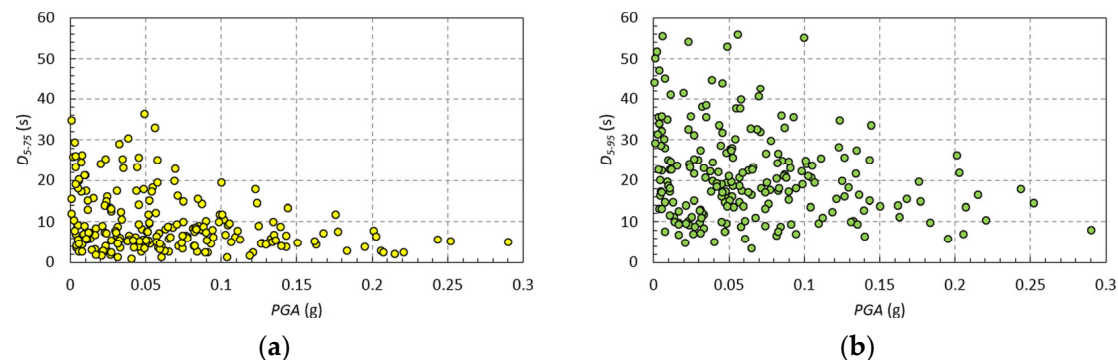


Figure 2. Distribution of the significant ground motion duration as a function of the peak ground acceleration: (a) D_{5-75} ; (b) D_{5-95} .

The correlation between the two significant duration definitions, D_{5-75} and D_{5-95} , is illustrated in Figure 3. A linear trendline between D_{5-75} and D_{5-95} is also shown in Figure 3.

The mean ratio between D_{5-75} and D_{5-95} is 2.8, and the value of the coefficient of variation of this ratio is 0.48. A significant scatter of the data can be also noticed for D_{5-75} values larger than 10 s. The small mean value of D_{5-75} (approximately 9 s) and the large mean ratio between D_{5-75} and D_{5-95} can be attributed to the presence of pulse-like ground motion recordings in the database.

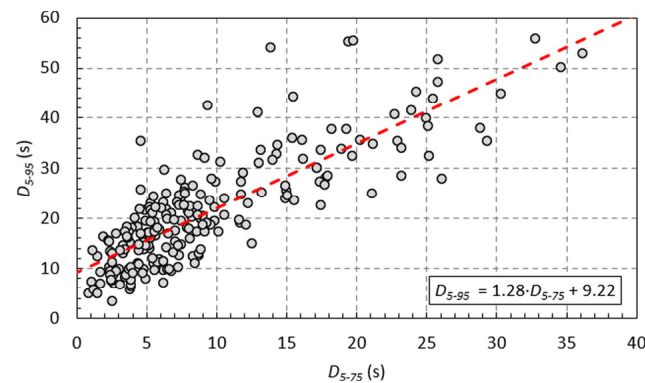


Figure 3. Evaluation of the correlation between D_{5-75} and D_{5-95} . The fitted linear trendline is shown with the red dashed line.

The distribution of the ratio between D_{5-75} and D_{5-95} as a function of the peak ground acceleration of the ground motion recordings is shown in Figure 4. No visible trend can be observed from the data shown in Figure 4. The same observation also holds true for the spectral accelerations at 0.2 s and 1.0 s.

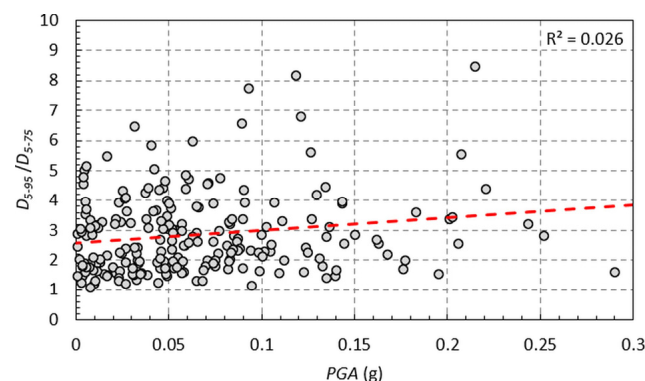


Figure 4. Distribution of the ratio D_{5-95}/D_{5-75} as a function of the peak ground acceleration. The fitted linear trendline is shown with the red dashed line.

3. Empirical Model

The functional form of the lognormal empirical model for the evaluation of the ground motion duration is similar to the one proposed by Rezaee Manesh and Saffari [5] and is given below:

$$\ln D = a_1 + a_2 \cdot (M_w - 6) + a_3 \cdot \ln R + a_4 \cdot S_{CDE} + a_5 \cdot S_F + \sigma_T \quad (1)$$

A nonlinear random effects regression is performed for the two significant ground motion durations (D_{5-75} and D_{5-95}). In rel. (1), D is the significant ground motion duration, R is the hypocentral distance, a_1 – a_5 are the regression coefficients, and σ_T is the total standard deviation including within- and between-event standard deviations. The total standard deviation σ_T is partitioned into intra-event (within event) standard deviation σ and inter-event (between event) standard deviation τ . In Equation (1), $S_{CDE} = 1$ – for soil classes C, D, and E sites and $S_{CDE} = 0$ – otherwise, and $S_F = 1$ – for soil class F sites and $S_F = 0$ – otherwise. Thus, the basic relation is valid for both soil classes A and B sites altogether.

The regression coefficients of the two empirical relations for D_{5-75} or D_{5-95} are given in Table 2.

Table 2. Regression coefficients for D_{5-75} and D_{5-95} .

Parameter	a_1	a_2	a_3	a_4	a_5	σ	τ	σ_T
D_{5-75}	0.275	0.180	0.417	−0.533	−0.711	0.587	0.110	0.598
D_{5-95}	2.506	0.027	0.134	−0.388	−0.350	0.492	0.130	0.509

It can be observed from Table 2 that the computed standard deviations have the same order of magnitude as those obtained in other studies in the literature (e.g., [2,4]). In addition, it can be observed that the largest share of the variability is due to the within-event component. It can also be noticed that the contribution of the earthquake magnitude term (a_5 coefficient) is significantly smaller for D_{5-95} as compared to D_{5-75} , which is the opposite of what was observed in the study by Kempton and Stewart [4].

The variation of the median D_{5-75} and D_{5-95} as a function of the earthquake magnitude and soil class for three hypocentral distances ($R = 100$ km, $R = 200$ km, and $R = 300$ km) is shown in Figure 5. It can be observed from Figure 5 that the differences between both significant durations evaluated using the proposed empirical model for site classes C, D, and E on one hand and site class F on the other hand are small. Thus, the only noticeable difference in terms of duration is between the soil classes A and B sites and all of the other soil classes. In addition, the impact of the earthquake magnitude on the ground motion duration is rather limited. On the other hand, the hypocentral distance has a more consistent impact for both ground motion duration definitions. Nevertheless, the ground motion durations evaluated using the empirical model proposed in this study are much smaller than the ones proposed in the Eurocode 8 draft [33] for the same magnitude range.

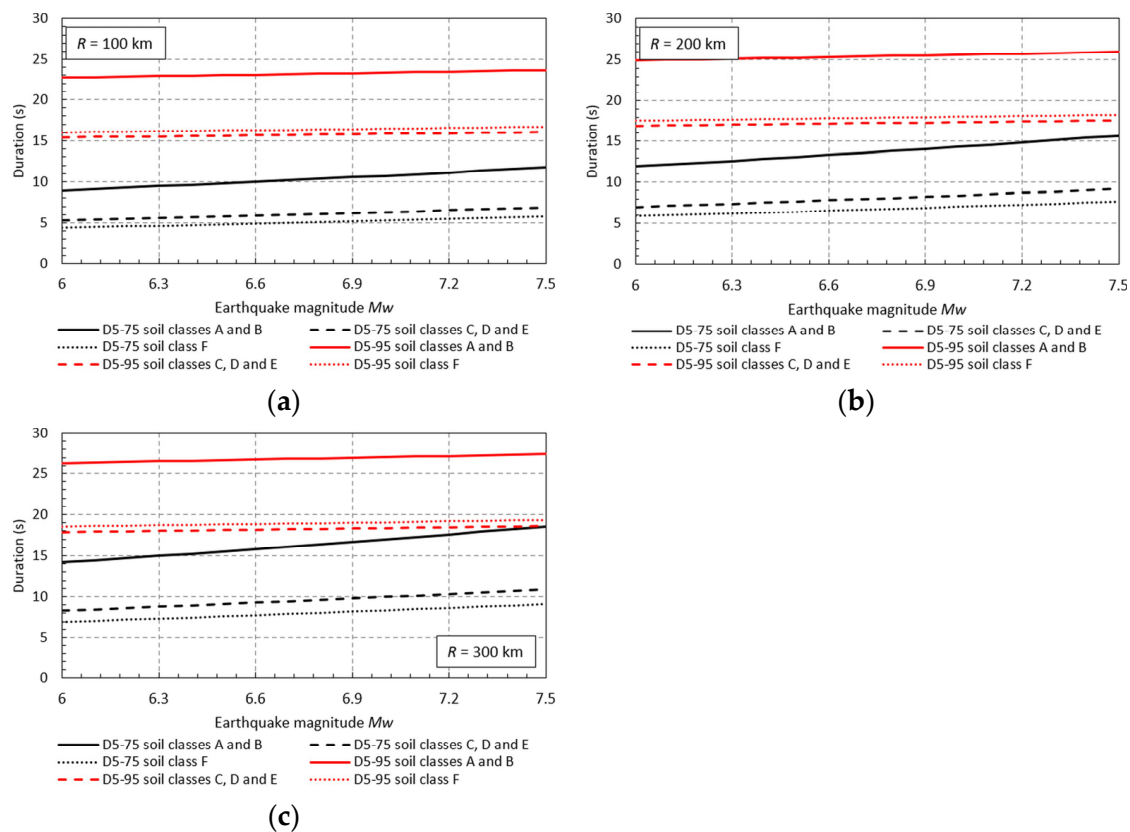


Figure 5. Variation of D_{5-75} and D_{5-95} as a function of the earthquake magnitude and soil class for (a) $R = 100$ km; (b) $R = 200$ km; and (c) $R = 300$ km.

The histograms of the residuals (difference between the observed and predicted values) for D_{5-75} and D_{5-95} are analyzed in Figure 6. The mean values of the residuals are -0.03 for both D_{5-75} and D_{5-95} , while the median values of the residuals are 0.01 for D_{5-75} and 0.03 for D_{5-95} , respectively. From the two plots, it can be observed that the distribution of the residuals for D_{5-75} is more symmetrical about zero compared to the residuals' distribution for D_{5-95} .

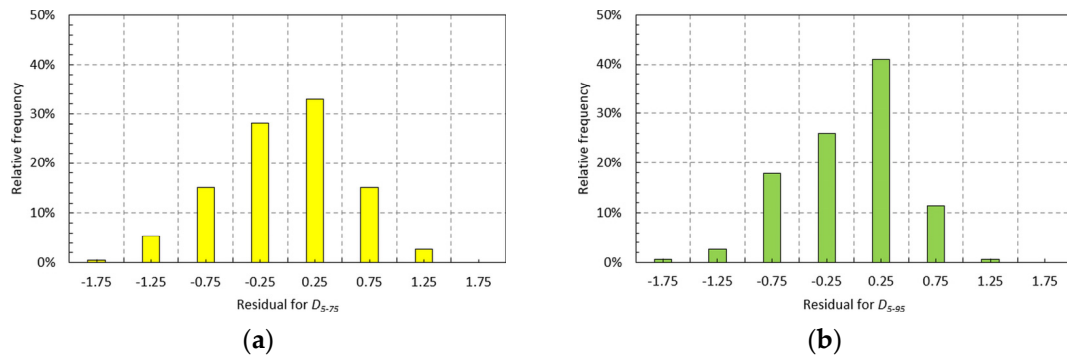


Figure 6. Histograms of the residuals for (a) D_{5-75} ; (b) D_{5-95} .

The distributions of the residuals with respect to the earthquake magnitude and hypocentral distance are presented in Figures 6 and 7, respectively. It can be observed from both Figures 7 and 8 that the fitted trendlines are horizontal (in the case of the residual distribution as a function of the hypocentral distance) or have a very small slope in the case of the residual distribution with respect to the earthquake magnitude, thus revealing no noticeable influence of either of the analyzed parameters.

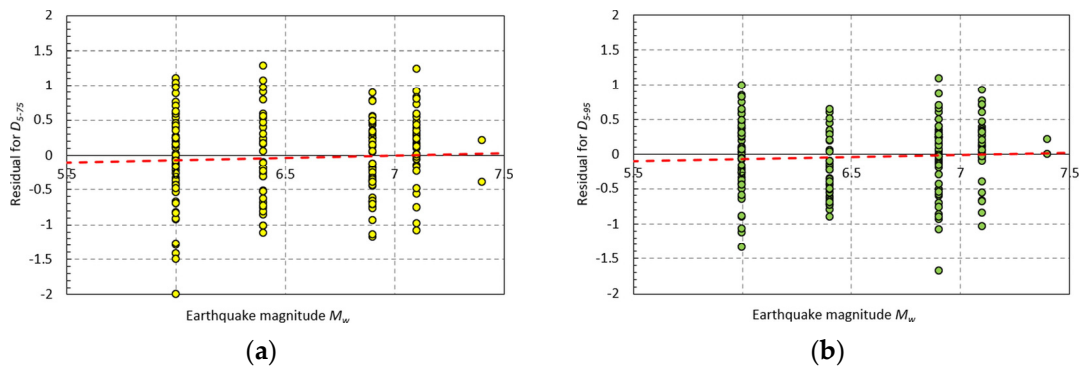


Figure 7. Distribution of the residuals as a function of the earthquake magnitude for (a) D_{5-75} ; (b) D_{5-95} . The fitted linear trendlines are shown with the red dashed lines.

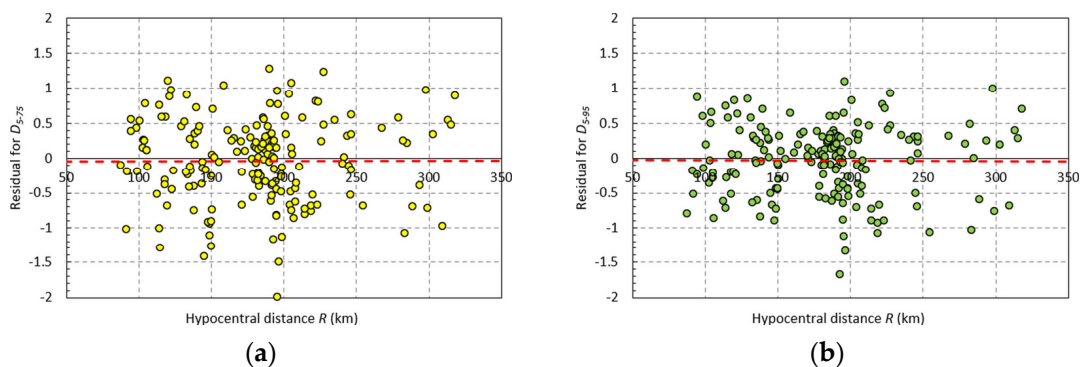


Figure 8. Distribution of the residuals as a function of the hypocentral distance for (a) D_{5-75} ; (b) D_{5-95} . The fitted linear trendlines are shown with the red dashed lines.

Subsequently, the distribution of the residuals as a function of the site class (three site classes) is evaluated for both D_{5-75} and D_{5-95} in Figures 9 and 10, respectively. The values of the skewness coefficients for the residuals are in the range between -0.82 (for soil class F sites in the case of the D_{5-95} definition) and 0.15 (for soil class C, D, and E sites in the case of D_{5-75} definition).

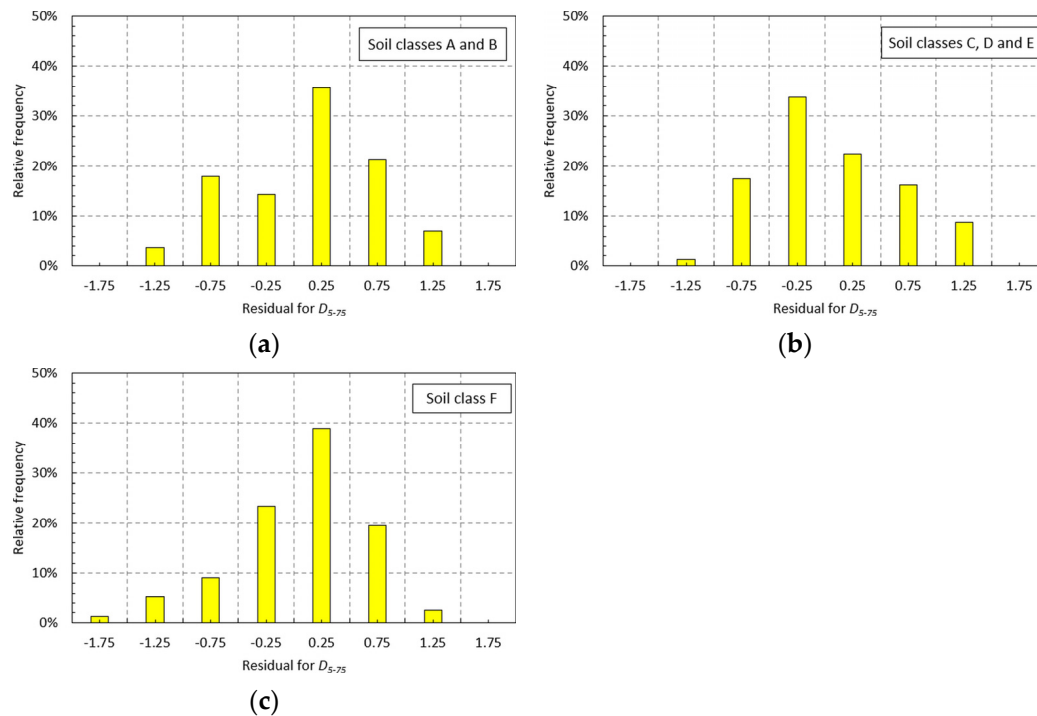


Figure 9. Histograms of the residuals for D_{5-75} as a function of the soil class: (a) soil classes A and B; (b) soil classes C, D, and E; (c) soil class F.

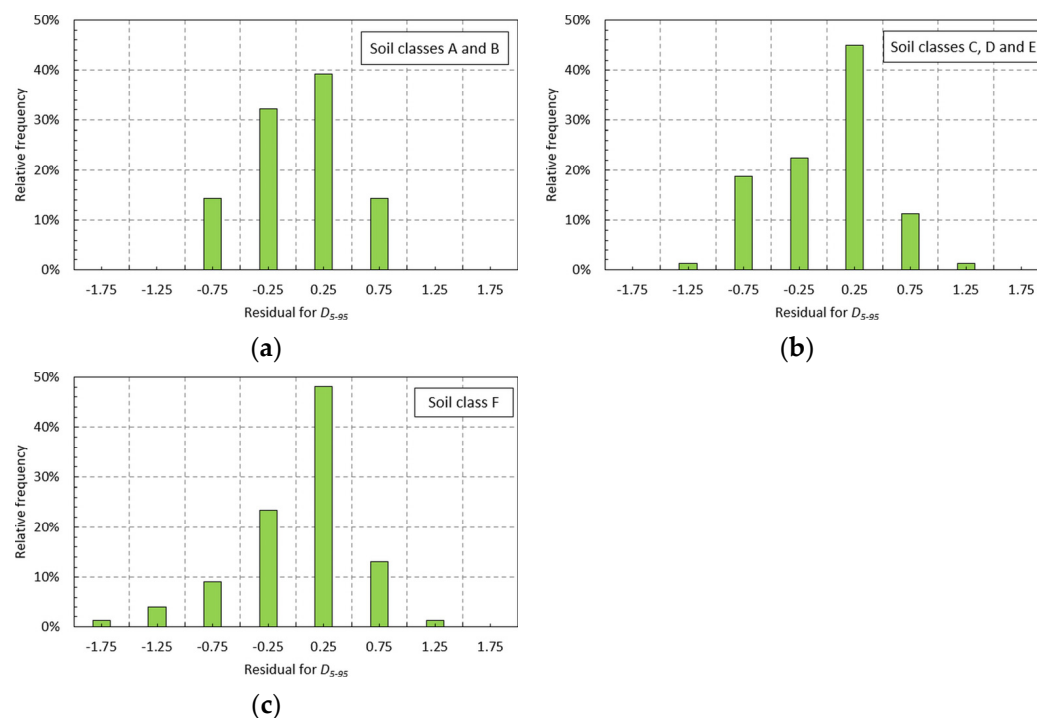


Figure 10. Histograms of the residuals for D_{5-95} as a function of the soil class: (a) soil classes A and B; (b) soil classes C, D, and E; (c) soil class F.

The mean, median, and standard deviations of the residuals as a function of the site class are reported in Table 3. It can be observed from Table 3 that the larger values of the mean and median of the residuals for all of the soil classes are obtained for the D_{5-75} definition.

Table 3. Statistics of the residuals as a function of the site class for D_{5-75} and D_{5-95} .

Soil Classes	Mean		Median		Standard Deviation	
	D_{5-75}	D_{5-95}	D_{5-75}	D_{5-95}	D_{5-75}	D_{5-95}
Soil classes A and B	0.13	0.04	0.21	0.05	0.56	0.49
Soil classes C, D, and E	0.05	0.02	−0.05	0.06	0.59	0.51
Soil class F	0.07	0.02	0.16	0.09	0.64	0.49

The distribution of the residuals for the two significant ground motion durations, D_{5-75} and D_{5-95} , with respect to the peak ground acceleration of the recordings (defined as the geometric mean of the two as-recorded horizontal components) is illustrated in Figure 11. It can be observed that the fitted trendlines have a small negative slope, thus denoting an over-estimation of the empirical values as compared to the observed ones for larger peak ground accelerations. The main reason for this aspect is related to the lack of ground motion recordings with large peak ground accelerations in the compiled database that are necessary for constraining the regression parameters.

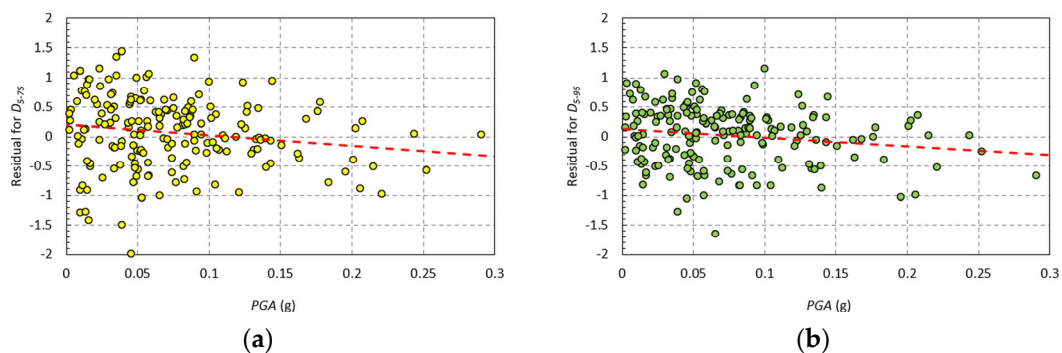


Figure 11. Distribution of the residuals with respect to the peak ground acceleration of the ground motion recordings for (a) D_{5-75} ; (b) D_{5-95} . The fitted linear trendlines are shown with the red dashed lines.

The distribution of the inter-event and intra-event residuals with respect to the earthquake magnitude and hypocentral distance is analyzed in Figures 12 and 13, respectively. No visible trends can be observed from the distributions of the inter- or intra-event residuals. The inter-event residual corresponding to the 31 May 1990 earthquake, which, as previously mentioned, has a different strike compared to the other events in the database, is similar to that of the other four earthquakes. Nevertheless, the influence of the earthquake strike on the ground motion duration needs further checks using more data.

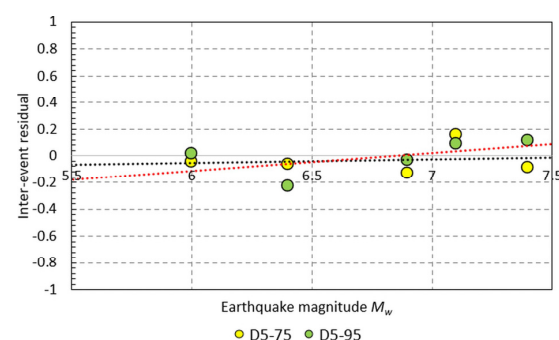


Figure 12. Distribution of the inter-event residuals as a function of the earthquake magnitude for D_{5-75} and D_{5-95} . The fitted linear trendlines are shown with the black and red lines.

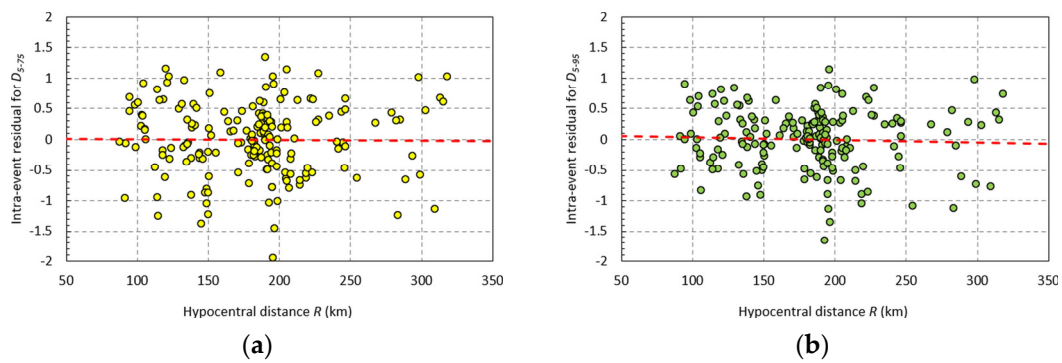


Figure 13. Distribution of the intra-event residuals as a function of the hypocentral distance for (a) D_{5-75} ; (b) D_{5-95} . The fitted linear trendlines are shown with the red dashed lines.

4. Discussion of the Results

An analysis of the geographical distribution of the residuals is performed in this section for the three earthquakes with the largest number of ground motion recordings in the database that was compiled for this study (the 30 August 1986; 30 May 1990; and 27 October 2004 events). The soil conditions of the recording seismic stations (three categories of soil conditions, as defined in this study) are shown in Figure 14. It has to be emphasized that long-period spectral amplifications have been observed for the seismic stations located in the southern part of Romania [36]. In addition, in the study by Pavel et al. [37], the site response analyses performed using the data from five deep boreholes in Bucharest showed a significant impact of the rock ground motion amplitude (and earthquake magnitude) on the frequency content of the free-field ground motion. The azimuthal dependence of the ground motion amplitudes of Vrancea intermediate-depth earthquakes has been studied by Sokolov et al. [25], Pavel and Vacareanu [38], and Pavel [39]. An important observation of these studies is related to the significant attenuation differences between the areas situated in the front of the Carpathian Mountains (fore-arc region) compared to the areas behind the mountain range (back-arc region).

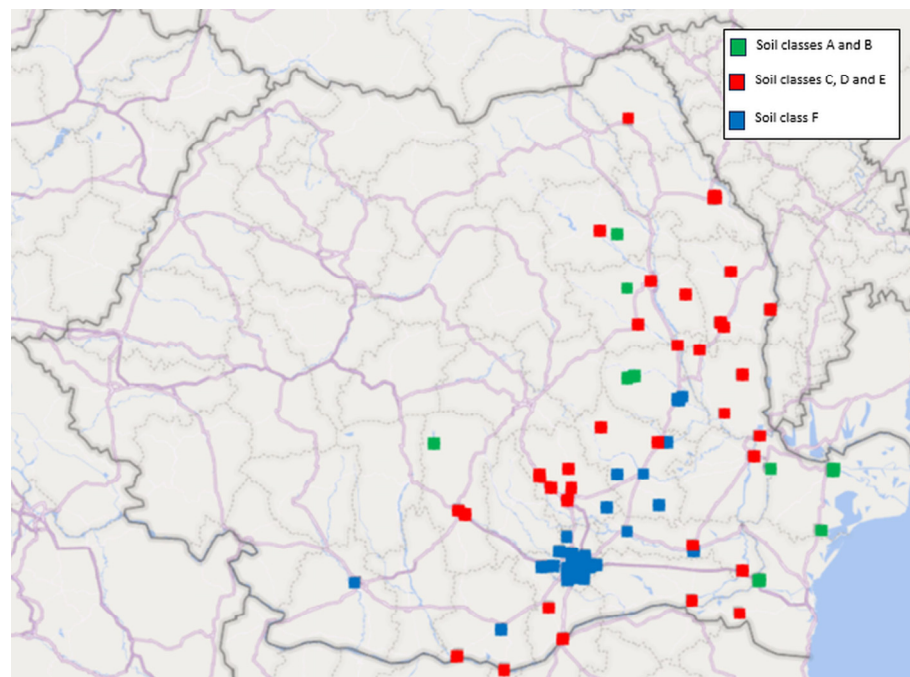


Figure 14. Soil classes for the recording seismic stations used in this study.

Figures 15–17 show the geographical distribution of the residuals for the three earthquakes in the database with the largest number of available ground motion recordings (the events of 30 August 1986; 30 May 1990; and 27 October 2004). In Figures 15–17, the size of the residuals (difference between observed and predicted value) for a particular seismic station and event is proportional to the size of the circles. It can be observed that for all three events, the residuals of the seismic stations situated towards the northeastern part of Romania are small, thus yielding predictions close to the observed values for both significant duration definitions. In the Dobrogea area, situated in the eastern part of Romania and bordering the Black Sea, the residuals are, in almost all cases, positive, showing larger observed durations compared to the median predictions using the proposed empirical model. In the case of Bucharest, except for the 1986 earthquake, for which the residuals are almost all positive, in the case of the other two events (1990 and 2004 earthquakes), the residuals are both positive and negative, without a specific trend. Finally, larger residuals can be observed toward the southwestern part of Romania (including Craiova), but this aspect needs further validations with more ground motion recordings.

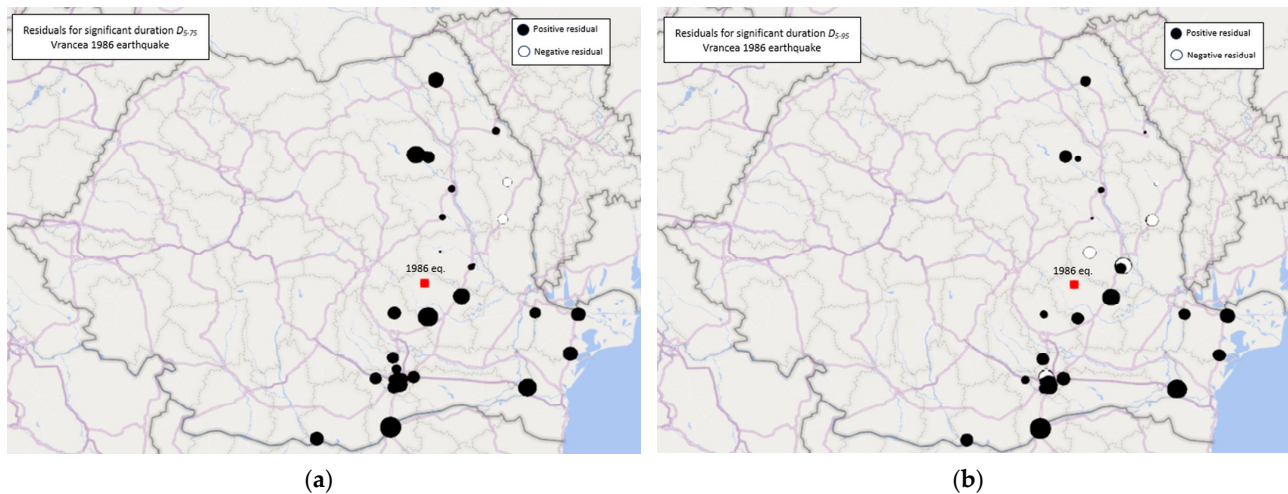


Figure 15. Geographical distribution of the residuals for the Vrancea intermediate-depth earthquake of 30 August 1986 for (a) $D_{5.75}$; (b) $D_{5.95}$. The epicenter of the Vrancea 1986 earthquake is shown with a red square.

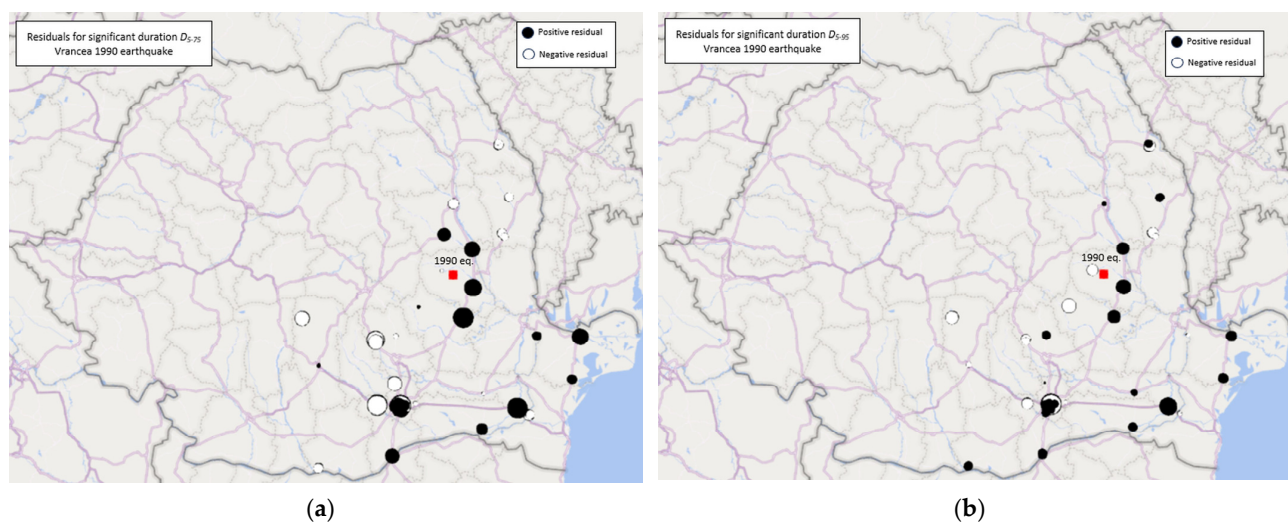


Figure 16. Geographical distribution of the residuals for the Vrancea intermediate-depth earthquake of 30 May 1990 for (a) $D_{5.75}$; (b) $D_{5.95}$. The epicenter of the Vrancea 1990 earthquake is shown with a red square.

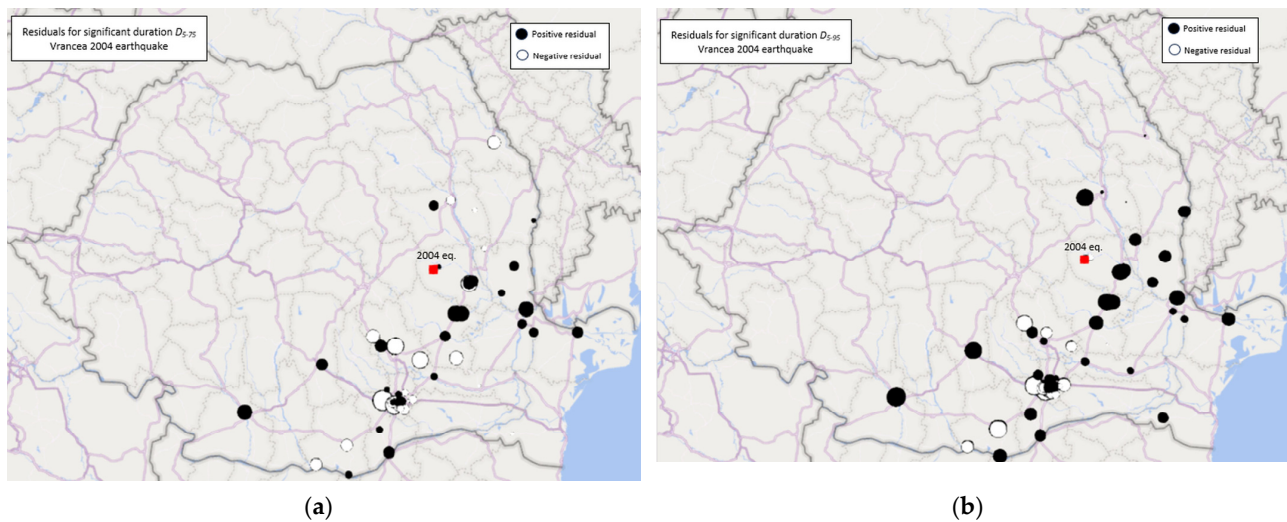


Figure 17. Geographical distribution of the residuals for the Vrancea intermediate-depth earthquake of 27 October 2004 for (a) D_{5-75} ; (b) D_{5-95} . The epicenter of the Vrancea 2004 earthquake is shown with a red square.

5. Conclusions

In this research, in the context of the future update of the Romanian seismic design code P100-1/2013 [23], the duration of ground motions recorded during Vrancea (Romania) intermediate-depth earthquakes is studied. The compiled ground motion database consists of about 200 recordings from five moderate and large Vrancea intermediate-depth earthquakes that occurred in the period of 1977–2004 with moment magnitudes $M_W \geq 6.0$ (the largest recorded events produced in this seismic source in the past 50 years). The empirical models were derived for two definitions of the significant ground motion duration (based on the time intervals of 5–75% and 5–95% for the accumulation of the Arias Intensity I_A). The proposed empirical model can be further employed in the future for a probabilistic assessment of the ground motion duration using, for instance, the seismic source model proposed by Pavel et al. [40]. The relevant observations of this study are summarized below:

- The mean ratio between the two significant ground motion definitions, D_{5-75} and D_{5-95} , is 2.8, while the value of the coefficient of variation of the ratio is 0.48.
- This study also shows that the mean value of D_{5-75} is quite small (approximately 9 s), and this aspect, along with the large mean ratio between D_{5-75} and D_{5-95} , can be both attributed to the presence of pulse-like ground motion recordings in the database.
- The regression data show that the largest share of the variability is due to the within-event component. Moreover, no significant bias in the regression data is observed as a function of the earthquake magnitude or hypocentral distance.
- The analysis of the inter- and intra-event residuals does not show any visible trends of over- or under-estimations.
- The median ground motion durations predicted using the empirical model developed in this study are much smaller than the ones proposed in the Eurocode 8 draft [33] for the same magnitude range (applicable to crustal earthquakes).
- The contribution of the earthquake magnitude term (a_s regression coefficient) in the regression is significantly smaller for D_{5-95} compared to D_{5-75} .
- The only noticeable difference in terms of duration for the considered magnitude and hypocentral distance range is between the soil classes A and B sites and the other sites for both D_{5-75} and D_{5-95} .
- Larger values of the mean and median residuals for all soil classes are obtained for D_{5-75} compared to D_{5-95} .
- A slight over-estimation of the empirical values compared to the observed ones is inferred for the ground motions having larger peak ground accelerations. The main

- reason for this aspect is related to the lack of ground motion recordings with large peak ground accelerations, which are necessary for constraining the regression parameters.
- The geographic trends related to the distribution of the residuals were also evaluated using the data from the three earthquakes with the largest number of available ground motion recordings (events in 1986, 1990, and 2004). It is observed that the residuals for the seismic stations situated towards the northeastern part of Romania are small, thus showing a similarity between the predictions and observations. In the Dobrogea area, situated in the eastern part of Romania and bordering the Black Sea, the residuals are, in almost all cases, positive, showing larger observed durations compared to the empirical predictions. In the case of Bucharest, no clear trend is observed from the available data. It is clear that in order to further validate any possible azimuthal dependence of ground motion duration, more data from moderate and large magnitude Vrancea intermediate-depth earthquakes is necessary.

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Conflicts of Interest: The authors declare no conflict of interest.

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