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DOCTORAL SCHOOL

Research report no. 2

Spatial correlation analysis of ground motions generated by shallow and Vrancea intermediate-depth earthquakes using the BIGSEES database

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Introduction

The PhD thesis entitled „The influence of ground motion spatial correlation on the seismic hazard and risk analyses results in Romania” tries to study the seismic hazard and risk analyses in Romania by using a relatively new concept in earthquake engineering, the ground motion spatial correlation.

The present research report entitled „Spatial correlation analysis of ground motions generated by shallow and Vrancea intermediate-depth earthquakes using the BIGSEES database” is the second research report in the PhD thesis, with the objective of obtaining spatial correlation models using a database consisting of shallow and Vrancea intermediate-depth earthquakes that contribute to Romania’s seismic hazard, the first research report entitled „Theoretical aspects and the state of the art regarding ground motion spatial correlation” (Craciun 2016) being an introduction in the subject of spatial correlation.

The present paper is based on the author’s article Vacareanu et al. 2017 entitled „Correlation models for strong ground motions from Vrancea intermediate-depth seismic source”, where an intra-event correlation model was developed by using a database consisting of ten Vrancea intermediate-depth earthquakes. Nevertheless, the present research report goes beyond the research presented in Vacareanu et al. (2017), tackling other subjects, as discussed in the next chapters.

Seismic hazards is related to the recurrence of causes (ground motion parameters during an earthquake). Seismic hazard analysis is a subject situated at the border between engineering seismology and earthquake engineering, involving both seismologists and structural engineers with results of professional and public interest. (Văcăreanu et al. 2015a).

The main objective of a seismic hazard assessment is quantifying a ground motion parameter produced as a result of an earthquake. In other words, seismic hazard assessment estimates the level of a ground motion parameter that defines the seismic motion (the peak ground acceleration PGA, the peak ground velocity PGV, spectral or pseudo-spectral acceleration etc.) that will be produced by a future earthquake (Sucuoglu and Akkar 2014). There are three approaches to the seismic hazard assessment: deterministic, neodeterministic or probabilistic. Choosing the type of analysis is influenced by its purpose and by the seismicity level (Văcăreanu et al. 2015).

Probabilistic Seismic Hazard Assessment (PSHA) originates in 1968 (Cornell 1968), being currently used on an international level for the seismic hazard analyses. The result of PSHA is the mean annual frequency of a future seismic event (Văcăreanu et al. 2015a).

An important step in PSHA is considering the uncertainties, which can be classified in aleatory and epistemic uncertainties. The epistemic uncertainties derive from the incomplete knowledge of a model/parameter/phenomenon and can be reduced through a better understanding of the phenomenon or through obtaining additional data (Vacareanu et al. 2015a). In PSHA, the epistemic uncertainties are taken into account through the use of the logic tree method.

Aleatory uncertainties are related to the probabilistic nature of the ground motion parameters and can’t be reduced through the use of additional data (Vacareanu et al. 2015a). In other words, as described in Sokolov and Wenzel (2011), the aleatory uncertainties describe the differences between the observed and the predicted models, which is caused by the absence of physical explanations or by certain variables that are not incorporated in the prediction equations.

Aleatory uncertainties are incorporated in PSHA through the standard deviation of the data resulted by using the ground motion prediction equations (Sokolov et al. 2010). The ground motion prediction equations are used to describe/estimate the ground motion parameters (PGA, PGV, PSA etc.) for a given site, depending on earthquake's magnitude, the site-source distance, focal depth, site conditions and other parameters.

The use of GMPEs in estimating ground motion parameters introduces both epistemic and aleatory variability; the latter can be separated in inter-event variability (between earthquakes) and intra-event (within earthquake) variability. Next generation ground motion models take the variability separation in inter-event and intra-event into account by separating the total standard deviation into inter-event and intra-event standard deviation.

The traditional PSHA (as described above) does not offer any information about simultaneous ground motions in different sites, which is of interest in the case of spatially distributed systems (lifelines) and regionally located building assets (portfolio). The spatial correlation concept affirms and demonstrates that ground motion amplitudes for two given sites are correlated, the correlation coefficient depending on the separation distance between the two sites. A spatial correlation model is required in order to assess the seismic hazard of such systems/structures (the purpose of the present research paper), followed by the numerical simulation of the spatially correlated ground motion parameters (the third's research report's objective).

Seismic risk is obtained by combining seismic hazard (ground motion intensity) with seismic vulnerability (the possibility of different structures to be damaged by the ground motion). Seismic risk is related to the recurrence of effects, being a consequence of the hazard taking place and of the vulnerability of the structures exposed to the hazard.

In order to perform seismic risk analyses (evaluation of seismic related losses) for spatially distributed systems, it is necessary to consider the spatial correlation in assessing the seismic hazard. As mentioned in McGuire (2004), in order to perform seismic risk analyses on spatially distributed systems, a more sophisticated analysis of the seismic hazard compared with the case of a single site is required. The use of correlated ground motions in different sites is necessary in order to obtain correct estimations of seismic related losses. As presented in Sokolov and Wenzel (2011), the correlation affects the probability density function parameters used to calculate the seismic losses in the case of spatially distributed systems or portfolios.

1. Ground motion correlation

The present chapter objective is to introduce and present the theoretical aspects and the analysis procedure required to develop a spatial correlation model for the Romanian seismic hazard. A first step in the spatial correlation analysis is developing a spatial correlation model, existing, in this regard, two approaches in the literature: using correlation coefficients and using semi-variograms, which were discussed in research report no. 1. In the present research report, the purpose is developing a spatial correlation model using correlation coefficients, all the following being based on this methodology.

1.1. Correlation coefficients

Classic Probabilistic Seismic Hazard Assessment implies the use of the Ground Motion Prediction Equations. The uncertainties related to the use of PSHA can be classified in aleatory and epistemic uncertainties. The epistemic uncertainties, as previously mentioned, are related to the available knowledge and derive from limited data or from approximate calculus models; the possibilities of reducing them include additional data or a better understanding of the phenomena. The aleatory uncertainties derive from the inherent nature of the phenomenon, which is associated to its natural variability, and cannot be reduced through addition data or a better knowledge (Vacareanu et al. 2015a).

The Ground Motion Prediction Equations (GMPE) describe the amplitude of a ground motion parameter (both as median value and as standard deviation) depending on magnitude, site-source distance, focal depth, local site conditions and other parameters.

The general form of a modern GMPE is as follows:

$$\ln Y_{ij}(T_n) = f\left(M_i, R_{ij}, P_{ij}, T_n\right) + \eta_i(T_n) + \varepsilon_{ij}(T_n) \tag{1.1}$$

where $i = \overline{1,s}$ and $i = \overline{1,r}$, $Y_{ij}(T_n)$ is the ground motion parameter at the natural vibration T_n for site j, during earthquake i, M_i is the earthquake magnitude (usually the moment magnitude), R_{ij} is the source-site distance (epicentral distance, hypocentral distance, Joyner-Boore distance etc.), P_{ij} represents other parameters (focal depth, site conditions etc.); $f\left(M_i, R_{ij}, P_{ij}, T_n\right)$ is a function that predicts the mean value of the ground motion parameter depending on M_i, R_{ij}, P_{ij} ($f\left(M_i, R_{ij}, P_{ij}, T_n\right) = \overline{\ln Y_{ij}\left(M_i, R_{ij}, P_{ij}, T_n\right)}$); $\eta_i(T_n)$ represents the inter-event residual, with zero mean and standard deviation $\sigma_\eta(T_n)$, and $\varepsilon_{ij}(T_n)$ represents the intra-event residual, with zero mean and standard deviation $\sigma_\varepsilon(T_n)$.

It can be stated that $\ln Y_{ij}(T_n)$ is modeled as a normal random variable with the mean $\overline{\ln Y_{ij}\left(M_i, R_{ij}, P_{ij}, T_n\right)}$ and the standard deviation:

$$\sigma_T(T_n) = \sqrt{\sigma_\eta{}^2(T_n) + \sigma_\varepsilon{}^2(T_n)} \tag{1.2}$$

For a given earthquake i, $\eta_i(T_n)$ is a constant for all sites, (it is assumed that all ground motions from a specific earthquake present some characteristics that separate them from other records).

Considering the aspects presented above, equation (1.1) can be written as:

$$\ln Y_{ij}(T_n) = \overline{\ln Y_{ij}\left(M_i, R_{ij}, P_{ij}, T_n\right)} + \overline{\eta_i}(T_n)\sigma_\eta(T_n) + \overline{\varepsilon_{ij}}(T_n)\sigma_\varepsilon(T_n) \tag{1.3}$$

where $\overline{\eta_i}(T_n)$ and $\overline{\varepsilon_{ij}}(T_n)$ are called normalized inter- and intra-event residuals respectively, both being normal random variables, with zero mean and a standard deviation equal to one, and $\sigma_\eta(T_n)$ and $\sigma_\varepsilon(T_n)$ are inter- and intra-event standard deviation respectively.

In literature, random variability is considered to be composed of inter-event (between earthquakes variability) and intra-event variability (between sites variability for a given earthquake). Inter-event correlation is considered to be constant for a given earthquake which means that all ground motions from that earthquake have some characteristics that separates them from other records (Cimellaro et al. 2011). Intra-event correlation describes the correlation between the ground motions recorded in different sites for a given earthquake. It is considered that that variability between different sites during an earthquake is caused by the wave propagation and by local site conditions (Cimellaro et al. 2011). In this sense, inter-event, intra-event and total correlation coefficients are defined in literature, being used to study the ground motion spatial correlation.

In order to present some theoretical aspects concerning the correlation coefficients, we consider two different sites separated by the distance *Δ*, for a specific earthquake *i*. The ground motion variability similarity between two sites *j* and *k* (in other words $\eta_i(T_n) + \varepsilon_{ij}(T_n)$ and $\eta_i(T_n) + \varepsilon_{ik}(T_n)$) can be described by the correlation coefficient $\rho_T(\Delta, T_n)$, also called total correlation coefficient (eg: Park et al. 2007; Goda and Hong 2008a), given by Sokolov and Wenzel 2013:

$$\begin{aligned}\rho_T(\Delta, T_n) &= \frac{\sigma_\eta^2(T_n) + \rho_\varepsilon(\Delta, T_n)\sigma_\varepsilon^2(T_n)}{\sigma_T^2(T_n)} = \rho_\eta(T_n) + \rho_\varepsilon(\Delta, T_n)\frac{\sigma_\varepsilon^2(T_n)}{\sigma_T^2(T_n)} \\ &= \rho_\eta(T_n) + \rho_\varepsilon(\Delta, T_n)(1 - \rho_\eta(T_n))\end{aligned} \tag{1.4}$$

where $\rho_\varepsilon(\Delta, T_n)$ represents the intra-event correlation coefficient (between ε_{ij} și ε_{ik}), and $\rho_\eta(T_n)$ represents the inter-event correlation coefficient and has the following expression (Wesson and Perkins, 2001):

$$\rho_\eta(T_n) = \frac{\sigma_\eta^2(T_n)}{\sigma_T^2(T_n)} = \frac{\sigma_\eta^2(T_n)}{\sigma_\eta^2(T_n) + \sigma_\varepsilon^2(T_n)} \tag{1.5}$$

It should be mentioned that the general form of the total correlation coefficient is $\rho_T(\Delta, T_{n,1}, T_{n,2})$, that of the intra-event correlation coefficient is $\rho_\varepsilon(\Delta, T_{n,1}, T_{n,2})$ and that of the inter-event correlation coefficient is $\rho_\eta(T_{n,1}, T_{n,2})$. Nevertheless, for simplicity, the three correlation coefficient have been presented for the case $T_{n,1} = T_{n,2} = T_n$.

The total correlation coefficient can also be expressed as (Goda și Hong, 2008a):

$$\rho_T(\Delta, T_n) = 1 - \frac{\sigma_d^2(\Delta, T_n)}{2\sigma_T^2(T_n)} \tag{1.6}$$

where $\sigma_d^2(\Delta, T_n)$ is the variance between the differences $\left(\eta_i(T_n) + \varepsilon_{ij}(T_n)\right) - \left(\eta_i(T_n) + \varepsilon_{ik}(T_n)\right)$ (Boore et al. 2003).

The intra-event correlation coefficient $\rho_\varepsilon(\Delta, T_n)$ can be defined as:

$$\rho_\varepsilon(\Delta, T_n) = \frac{COV[\varepsilon_{ij}(T_n), \varepsilon_{ik}(T_n)]}{\sigma_\varepsilon^2(T_n)} \tag{1.7}$$

where $COV[\varepsilon_{ij}(T_n), \varepsilon_{ik}(T_n)]$ is the covariance between $\varepsilon_{ij}(T_n)$ and $\varepsilon_{ik}(T_n)$.

In Goda and Hong (2008a) another expression of the intra-event correlation coefficient $\rho_\varepsilon(\Delta, T_n)$ has been given:

$$\rho_{\varepsilon}(\Delta, T_n) = 1 - \frac{\sigma_d^2(\Delta, T_n)}{2\sigma_\varepsilon^2(T_n)} \tag{1.8}$$

In should be stated that the previous equations are available to the residuals calculated for a single randomly oriented horizontal component. If the residuals are determined using the geometric mean of two orthogonal horizontal components, then, as described in (Goda și Hong 2008a), the following equation should be used:

$$\rho_{\varepsilon}(\Delta, T_n) = \rho_{gm}(\Delta, T_n)\frac{1 + \rho_c(T_n)}{2} \tag{1.9}$$

where $\rho_{gm}(\Delta, T_n)$ is the correlation coefficient calculated using the geometric mean of the two orthogonal horizontal components of the ground motion parameter; $\rho_c(T_n)$ is the correlation coefficient for the two orthogonal horizontal components of the ground motion parameter, which is defined by Baker and Cornell (2006) by using an empirical equation that depends on the spectral period T_n:

$$\rho_c(T_n) = 0.79 - 0.023\ln(T_n) \tag{1.10}$$

1.2. Analysis procedure

The methodology used in this research report is based on the methodology presented in the author's article (Vacareanu et al. 2017), which is based itself on existing procedures (Goda and Hong 2008a, Goda and Atkinson 2009, 2010, Wagener et al. 2016). The analysis procedure used to develop an intra-event correlation model includes the following steps:

1. Choosing the database used to perform the analysis and selecting a modern GMPE in order to calculate the residuals. The selection of a modern GMPE, that presents the intra- and inter-event variability differently, is necessary, specifying in this regard ${\sigma_\eta}^2(T_n)$ and ${\sigma_\varepsilon}^2(T_n)$. A GMPE can be derived using a database that corresponds to the analyzed database.
2. Choosing the ground motion parameter used to perform the analysis, which can be done implicitly in step 1, through choosing the GMPE.
3. The intra-event correlation analysis can be performed using the geometric mean of the horizontal components of the ground motion parameter, using a random horizontal component of the ground motion parameter or using the larger horizontal component of the ground motion parameter. It should be stated that these aspects refer to the ground motion parameter chosen in step 2.
4. The total, intra- and inter-event residuals calculus for every seismic event and for every site where ground motion records are available, by using the chosen GMPE.
5. Residual pairs $(\varepsilon_{ij}, \varepsilon_{ik})$ for two sites *j* and *k*, for a given earthquake *i* are determined for every considered seismic event $i = \overline{1, r = 10}$. In order to calculate the variances $\sigma_d^2(\Delta, T_n)$, the differences between the residual pairs are computed.
6. The intra-event residual pairs are sorted into bins according to their separating distance; the variances $\sigma_d^2(\Delta, T_n)$ of the residual pairs are calculated for all pairs that fall in the same bin.
7. The correlation coefficients $\rho_\varepsilon(\Delta, T_n)$ are computed for the geometric mean of the two horizontal components of the ground motion parameter and for the random horizontal component of the ground motion parameter, by using equations (1.8) and (1.9).
8. A functional form, whose parameters are determined through nonlinear regression, is proposed for the previously determined correlation coefficients;

2. Database and data processing

The seismic sources that contribute to the Romanian seismic hazard are defined in the INFCDP studies (National Institute of Research-Development for Earth Physics). It is said in Vacareanu et al. (2015a) that the Romanian seismicity is given by a combination of the Vrancea intermediate-depth seismic source and 13 shallow seismic sources located in Romania, Bulgaria, Serbia and Hungary. The perimeters of these seismic sources, initially defined in Radulian et al. (2000), were modified and improved by INCFCDP inside of the research project BIGSEES, based on recent observations and results. The seismic sources that contribute to the Romanian seismic hazard, as defined in BIGSEES, are presented in Figure 2.1.

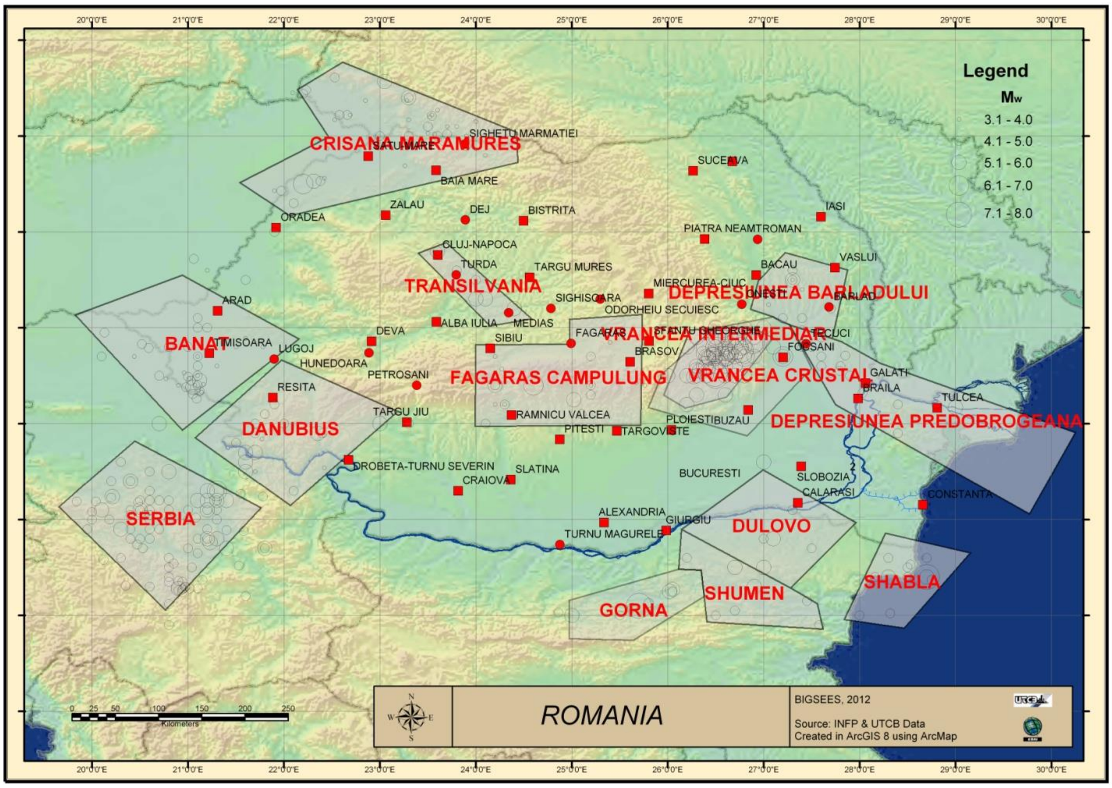

Figure 2.1 – Seismic sources contributing to the Romanian seismic hazard (Vacareanu et al. 2015a).

In Vacareanu et al. (2017), a spatial correlation model for the Vrancea intermediate-depth seismic source using 10 seismic events was developed. In the present report, the main objective is developing a spatial correlation model for the Vrancea intermediate-depth seismic source and for the shallow seismic sources that affect Romania's seismic hazard. In this regard, the two different types are treated separately, in the following sub-chapters.

2.1. Database containing Vrancea intermediate-depth earthquakes

The Vrancea intermediate-depth seismic source is one of the classical examples of intermediate-depth seismicity not localized near the vicinity of active tectonic plates. The region in question is localized at the bend of the South-Eastern Carpathians, concentrated within a very small volume, spanning vertically from about 60 km to 170 km in depth and horizontally over an area of about 70x30 km^2 (Vacareanu et al. 2015b). The Vrancea intermediate-depth seismic source is the source with the biggest contribution to the Romanian seismic hazard.

In this research report, the intermediate-depth earthquakes database contains ground motion records generated by earthquakes with moment magnitude $M_w > 5$ originating from the intermediate-depth seismic source, being used to develop a spatial correlation model for the peak ground acceleration (PGA) and spectral accelerations at various spectral periods. The database was developed for the BIGSEES national research project (http://infp.infp.ro/bigsees/default.htm) from the national seismic networks of: INCDFP (National Institute of Research-Development for Earth Physics), URBAN-INCERC (National Institute for Research and Development in Constructions, Urban Planning and Sustainable Spatial Development), CCERS (Seismic Risk Assessment Research Center) and GEOTEC (Institute for Geotechnical and Geophysical Studies), containing 431 triaxial acceleration records recorded during 10 earthquakes with M_w varying from 5.2 to 7.4. The characteristics (date of occurrence, focal depth, position of the epicenter and the number of records) of the 10 earthquakes are presented in Table 2.1.

Table 2.1 – Characteristics of the 10 intermediate-depth seismic events

Event number	Date	Latitude	Longitude	M_W	Focal depth [km]	Number of records
1	04.03.1977	45.34	26.30	7.4	109	2
2	30.08.1986	45.52	26.49	7.1	131	40
3	30.05.1990	45.83	26.89	6.9	91	52
4	31.05.1990	45.85	26.91	6.4	87	36
5	28.04.1999	45.49	26.27	5.3	151	25
6	27.10.2004	45.84	26.63	6.0	105	66
7	14.05.2005	45.64	26.53	5.5	149	40
8	18.06.2005	45.72	26.66	5.2	154	37
9	25.04.2009	45.68	26.62	5.4	110	46
10	06.10.2013	45.67	26.58	5.2	135	87

The moment magnitude-focal depth and moment magnitude-epicentral distances relations are presented in Fig. 2.2 and 2.3, for the 10 intermediate-depth earthquakes.

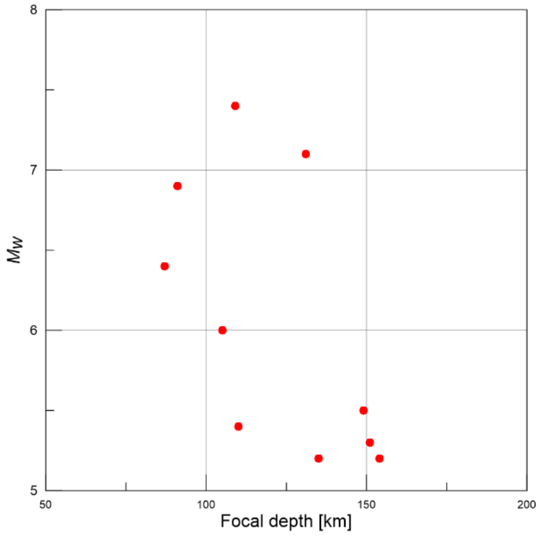

Figure 2.2 – Distribution of magnitude with focal depth for the intermediate-depth earthquakes.

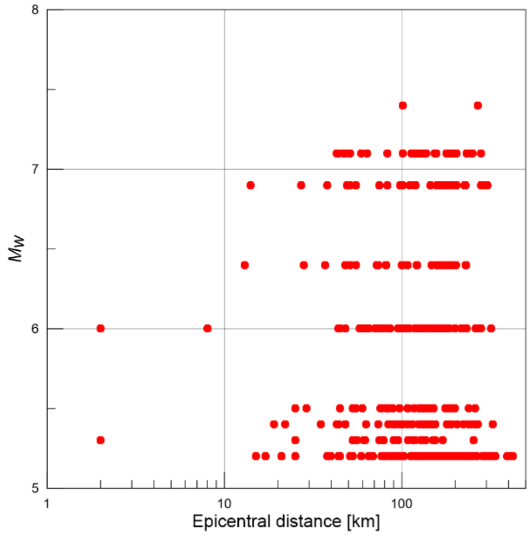

Figure 2.3 – Distribution of magnitude with epicentral distances for the intermediate-depth earthquakes.

The strong ground motions database consists of both analogue and digital recordings (the latter 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 2006) and using a band-pass Butterworth filter of fourth order with cut-off frequencies of 0.05 Hz and 50 Hz.

2.2. Database containing shallow earthquakes

As previously mentioned, to the Romanian seismic hazard contribute the following: the Vrancea intermediate-depth seismic source and 13 other shallow seismic sources (generating earthquakes of local importance to the Romanian seismic hazard) situated on the Romanian, Bulgarian, Serbian and Hungarian territories, named as follows: Banat, the Bârlad Depression, Crișana, Danubius, Făgăraș, the Pre-Dobrogeană Depression, Serbia, Transilvania, shallow Vrancea, Dulovo, Shabla, Gorna and Shumen. To the described seismicity, the background seismicity (shallow seismic events with $M_w < 5$) is added. Background seismicity consists of all events produced in areas that don't fall into the perimeters of the known seismic sources, predominately taking place in northern Oltenia, the Hațeg Depression, the eastern Romanian Plain, the Moldavian platform and the orogeny of the Eastern Carpathians.

The shallow earthquakes database contains ground motion records generated by earthquakes with moment magnitude $M_w > 4$ originating from the shallow seismic sources (including background seismicity) that contribute to the Romanian hazard, being used to develop a spatial correlation model for the peak ground acceleration (PGA) and spectral accelerations at different period values. The database was specifically developed for the present research report, originating from the ESM database (Engineering Strong-Motion database) conceived for the European project NERA (Network of European Research Infrastructures for Earthquake Risk Assessment and Mitigation) and maintained by WG5 and ORFEUS. The database consists of 255 triaxial accelerograms recorded during 10 shallow earthquakes with moment magnitude M_w from 4.1 to 5.6. The characteristics (date of occurrence, focal depth, position of the epicenter and the number of records) of the 10 earthquakes are presented in Table 2.1.

Table 2.2 – Characteristics of the 10 shallow seismic events

Event number	Date	Latitude	Longitude	M_W	Focal depth [km]	Number of records
1	13.12.2005	45.72	26.67	5.1	35	2
2	06.09.2008	45.80	26.56	4.3	16.7	14
3	24.06.2011	47.37	25.83	4.4	10.7	9
4	08.09.2013	45.60	22.86	4.6	4	17
5	08.09.2013	45.60	22.88	4.4	10	18
6	31.10.2014	45.13	22.18	4.1	13	17
7	22.11.2014	45.87	27.16	5.6	39	81
8	07.12.2014	45.88	27.21	4.4	40	42
9	29.12.2015	45.46	24.18	4.3	2	22
10	23.09.2016	45.76	26.63	5.5	35	33

The moment magnitude-focal depth and moment magnitude-epicentral distances relations for the 10 earthquakes generated by shallow seismic sources are presented in Fig. 2.4 and 2.5 respectively.

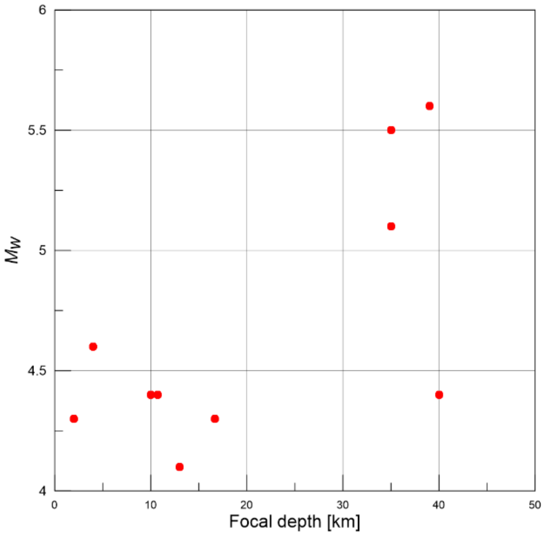

Figure 2.4 – Distribution of magnitude with focal depth for the shallow earthquakes.

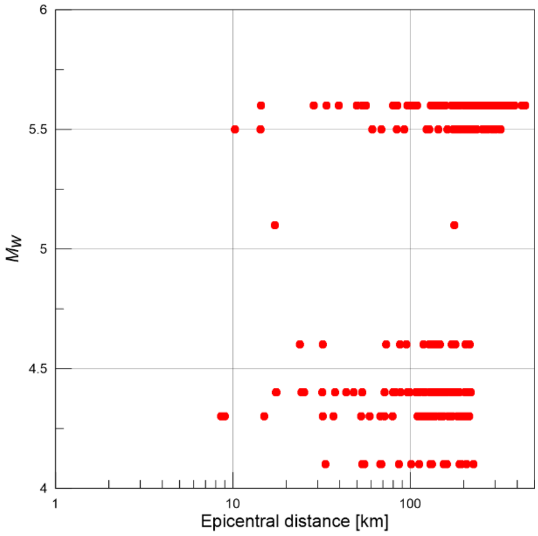

Figure 2.5 – Distribution of magnitude with epicentral distances for the shallow earthquakes.

The shallow earthquakes database contains digital recordings, the processing following the procedure described in Paolucci et al. (2011), with a second order Butterworth acasual filter with the low-cut frequency varying between 0.10 and 0.30 Hz and the high-cut frequency of 30 Hz.

3. Evaluation of intra-event correlation

In order to develop an intra-event correlation model, the present chapter follows the steps presented in subchapter 1.2. The two databases were treated separately, at least in the first stage, due to reasons concerning the seismic origin, choosing a ground motion prediction equation and the different influence on developing a possible correlation model. For this reasons, in the following, only the differences between the two databases will be mentioned.

Step 1 consists of choosing a ground motion prediction equation for the two databases. Concerning the intermediate-depth earthquakes database, the GMPE developed in Vacareanu et al. (2015b) was chosen, while for the shallow earthquakes database, the author chose the GMPE presented in Cauzzi et al. (2015).

For the Vrancea intermediate-depth seismic source, a GMPE was developed in Vacareanu et al. (2014), other GMPE's being recommended in Delavaud et al. (2012). Nevertheless, for the developing of a spatial correlation model, the GMPE presented n Vacareanu et al. (2015b) was chosen. The equation was obtained using seismic events with moment magnitude in the interval $5.2 \leq M_w \leq 8.0$ using a national database (formed by the first 9 earthquakes of the present database used for developing the spatial correlation model) and an international database (formed by 360 ground motion records from 29 earthquakes), reaching 1408 horizontal components of the ground motion parameter.

The main characteristics of the GMPE presented in Vacareanu et al. (2015b) are: a larger database than the one used in Vacareanu et al. (2014), considering the site conditions in the regression analysis, taking into account the differences in attenuation between fore-arc and back-arc regions and separation of the intra- and inter-event components of the GMPE's standard deviation. The reasons for choosing this GMPE are its modern form and its applicability for the present database (9 earthquakes out of a total of 10 have been used to develop the GMPE).

The functional form of the GMPE presented in Vacareanu et al. (2015b) is:

$$\begin{aligned}\ln y_{ij}(T) = {} & c_1(T) + c_2(T)\left(M_{w,i} - 6\right) + c_3(T)\left(M_{w,i} - 6\right)^2 + c_4(T)\ln R_{ij} \\ & + c_5(T)\left(1 - ARC_j\right)R_{ij} + c_6(T)ARC_j R_{ij} + c_7(T)h_i + c_8(T)Sb_j + c_9(T)Sc_j \\ & + c_{10}(T)Ss_j + \eta_i + \varepsilon_{ij}\end{aligned} \tag{3.1}$$

where i is the earthquake index, j is the recording station's index, y_{ij} is the geometric mean of the two horizontal components of either PGA (expressed in cm/s^2) or 5% damped response spectral acceleration (expressed in cm/s^2) for a given spectral period T, $M_{w,i}$ is the moment magnitude of earthquake i, R is the hypocentral distance (in km), the ARC term introduces the recording site location with respect to the mountain arc ($ARC = 0$ for back-arc sites and $ARC = 1$ for fore-arc sites), h is the focal depth (in km) and c_k $(k = 1 - 10)$ are coefficients determined from the data set by regression analysis at each spectral period T, $Sb = 1$- for ground type B and $Sb = 0$- otherwise, $Sc = 1$- for ground type C and $Sc = 0$- otherwise, $Ss = 1$- for average soil condition and $Ss = 0$- otherwise.

The independent normal variable η_i represents the inter-event residuals (between-earthquake variability of ground motions) with zero mean and τ standard deviation; the independent normal variable ε_{ij} represents the intra-event residuals (within-earthquake variability of ground motions) with zero mean and σ standard deviation. Both τ and σ are considered spectral period dependent, but are assumed independent of magnitude (homoscedastic). We can affirm that the variances ${\sigma_T}^2$, σ^2 and τ^2 are equivalent to ${\sigma_T}^2(T_n)$, ${\sigma_\varepsilon}^2(T_n)$ and ${\sigma_\eta}^2(T_n)$ respectively, as defined in the present study.

The total standard deviation σ_T is defined by:

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \tag{3.2}$$

Values for the standard deviations are presented in Vacareanu et al. (2015b) for PGA and different spectral period values from T=0.1 s to T=3.0 s and are used in the present study for the necessary computations.

For the shallow seismic sources that contribute to the Romanian hazard, the GMPE developed in Cauzzi et al. (2015) was chosen. The equation was obtained using 98 global seismic events with moment magnitude in the interval $4.5 \leq M_w \leq 7.9$, with focal depths up to 23 km.

The main characteristics of the GMPE developed in Cauzzi et al. (2015) are: considering the site conditions in the regression analysis, considering the faulting style and a clear separation between the intra- and inter-event components of the GMPE's standard deviation. The reasons for choosing this GMPE are its modern form and its applicability for the present database (composed of only shallow events).

The functional form of the GMPE presented in Cauzzi et al. (2015) is:

$$log_{10}\, y = f_M + f_R + f_S + f_{SOF} + \varepsilon \tag{3.3}$$

where:

$$f_M = c_1 + c_2 M_W + c_3 M_W^2 \tag{3.4}$$

$$f_R = (r_1 + r_2 M_W)\, log_{10}(R_{RUP} + r_3) \tag{3.5}$$

$$f_S = s_B S_B + s_C S_C + s_D S_D \text{ sau} \tag{3.6}$$

$$f_S = b_V\, log_{10}\left(\frac{V_{S,30}}{V_A}\right) \text{ sau} \tag{3.7}$$

$$f_S = b_{V800}\, log_{10}\left(\frac{V_{S,30}}{800}\right) \tag{3.8}$$

$$f_{SOF} = f_N F_N + f_R F_R + f_{SS} F_{SS} \tag{3.9}$$

where y is the 5%-damped displacement response spectrum (*DRS*) in cm or the peak ground velocity (*PGV*) or the peak ground acceleration (*PGA*), in cm/s and cm/s^2 respectively; pseudo-spectral acceleration values can be obtained as follows:

$$\mathrm{PSA(T; 5\%)} = \mathrm{DRS(T; 5\%)} \times \left(\frac{4\pi^2}{\mathrm{T}^2}\right) \tag{3.10}$$

$$\mathrm{PGA} \sim \mathrm{PSA(0.015; 5\%)} \tag{3.11}$$

The seismic action is represented by the geometric mean of the two horizontal components of the displacement response spectrum (*DRS*), the peak ground velocity (*PGV*) or the peak ground acceleration (*PGA*) respectively, for different values of the spectral period *T*.

$c_1, m_1, m_2, r_1, r_2, r_3, s_B, s_C, s_D, b_V, b_{V800}, V_A, f_N, f_R$ and f_{SS} are numerical coefficients function of period, determined through regression;

ε is the random error term assumed to be normally distributed with zero mean and standard deviation $\sigma(\log_{10} y)$ and can be expressed as follows:

$$\sigma = \sqrt{\phi^2 + \tau^2} \tag{3.12}$$

It should be mentioned that the variances σ^2, ϕ^2 and τ^2 are equivalent to ${\sigma_T}^2(T_n)$, ${\sigma_\varepsilon}^2(T_n)$ and ${\sigma_\eta}^2(T_n)$ respectively, as defined in the present research report.

According to available data, three alternatives are presented for calculating the site amplification, either based on ground types (equation (3.6)), or based on $V_{S,30}$ values. $V_{S,30}$ is defined as the travel-time averaged shear-wave velocity in the uppermost 30m of soil column. S_B, S_C and S_D are dummy variables for the main ground types defined in EN 1998-1 (CEN, 2004), with the following values:

$$S_B = S_C = S_D = 0, \text{for ground type A } (V_{S,30} \geq 800m/s^2) \quad (3.13)$$

$$S_B = 1 \text{ și } S_C = S_D = 0, \text{for ground type B } (360m/s^2 \leq V_{S,30} < 800m/s^2) \quad (3.14)$$

$$S_C = 1 \text{ și } S_B = S_D = 0, \text{for ground type C } (180m/s^2 \leq V_{S,30} < 360m/s^2) \quad (3.15)$$

$$S_D = 1 \text{ și } S_B = S_C = 0, \text{for ground type D } (180m/s^2 < V_{S,30}) \quad (3.16)$$

F_N, F_R and F_{SS} are dummy variables equal to 1 for normal, reverse and strike-slip respectively, otherwise 0; in the case of unspecified type of focal mechanism, then f_{SOF} will be set to 0.

In steps 2 and 3 the analysis is performed in terms of the peak ground acceleration and spectral accelerations at periods varying from 0.1 s to 3.0 s, consistent with the GMPE's parameter. Residuals are determined using the geometric mean of the two horizontal components of PGA and PSA respectively. Once the intra-event correlation model is determined, a correlation model for the random horizontal component can be developed for PGA and PSA respectively, using equation (1.9).

Total residuals $(\eta_i(T_n) + \varepsilon_{ij}(T_n))$ are calculated in *step 4*, for all records of both databases, using the following equations:

$$\eta_i(T_n) + \varepsilon_{ij}(T_n) = \ln Y_{ij}(T_n) - \overline{\ln Y_{\iota J}\left(M_\iota, R_{\iota J}, P_{\iota J}, T_n\right)} \quad (3.17)$$

In Cimellaro et al. (2011) the methodology to obtain the inter-event residuals $\eta_i(T_n)$ is presented, as the mean of the total residuals for a given earthquake, the residuals $\eta_i(T_n)$ being a constant for all sites during a seismic event. In both databases there is a number of 10 earthquakes, therefore 10 values of the inter-event residuals will result for every considered spectral period. The intra-event residuals are then calculated as differences between the total and the inter-event residuals.

In *step 5* the intra-event residual pairs are determined for every seismic event. For a given earthquake *i* with *m* number of records, the number of residual pairs is $[m(m-1)]/2$. For every earthquake *i*, for every intra-event residual pairs between two sites *j* and *k*, the differences $\varepsilon_{ij}(T_n) - \varepsilon_{ik}(T_n)$ are determined, with the objective of obtaining the variances $\sigma_d^2(\Delta, T_n)$ in the next step.

An alternative to steps and 5 is the calculus of the total residuals followed by obtaining the residual pairs for every seismic event *i*. For every residual pair between two sites *j* and *k*, the differences $\left(\eta_i(T_n) + \varepsilon_{ij}(T_n)\right) - \left(\eta_i(T_n) + \varepsilon_{ik}(T_n)\right)$ are computed. This option offers identical values to the ones obtained using steps 4 and 5 (the inter-event component, which is a constant for every site for a given seismic event, is subtracted), but does not offer any information about the intra- and inter-event residuals.

Sorting the intra-event residual pairs into bins depending on de separation distance between the two sites *Δ*, is the main operation of *step 6*. A bin can contain residual pairs that belong to different earthquakes because the inter-event component is eliminated through subtraction in the previous step.

Concerning the intermediate-depth earthquakes database, in the author's article (Vacareanu et al. 2017), the bin size was chosen to be equal to 5 km, thus obtaining a sufficient number of residual pairs per bin, which implies small errors, resulting in a minimum number of pairs per bin of 59. It was considered that a smaller bin width (for example 2.5 km) would have led to a bigger difference of the number of pairs between bins compared to the first situation. Nevertheless, the present research report takes a step forward, so that, in the chapter concerning the sensitivity analysis, a research about the influence of the bin size on the results was employed; in this sense, the intermediate-depth earthquakes database was also sorted using a bin width of 2.5 km (resulting a minimum number of residual pairs per bin of 28). The histograms of the intra-event residual pairs with regard to distance, for a bin width of 5 km and 2.5 km respectively are presented in Fig. 3.1 and 3.2.

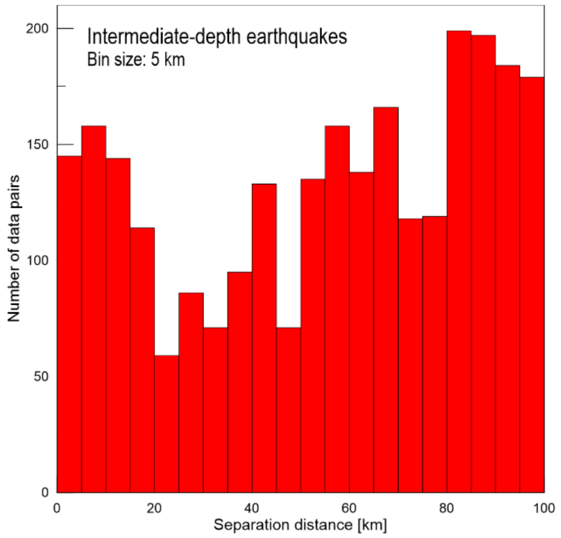

Figure 3.1 – Histogram of the number of intra-event residual pairs, for the intermediate-depth earthquakes database and a bin size of 5 km.

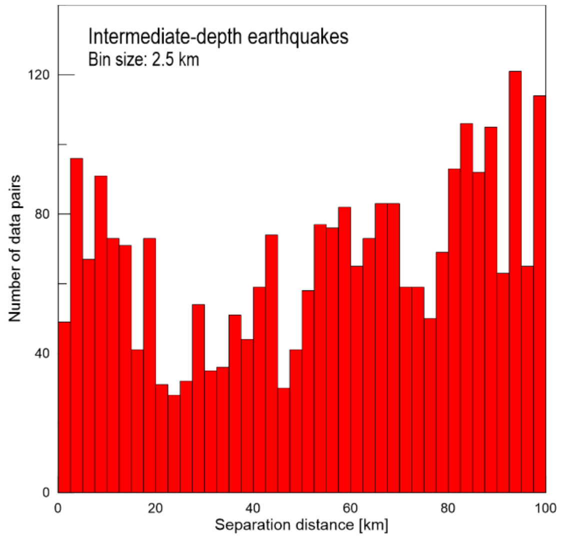

Figure 3.2 – Histogram of the number of intra-event residual pairs, for the intermediate-depth earthquakes database and a bin size of 2.5 km.

Out of 11404 residual pairs, only 2669 pairs were used in the analysis, until a separation distance of 100 km. Evidently, the number of pairs used in the analysis does not depend on the bin size. The number of records, the number of available residual pairs and the number of used residual pairs for every intermediate-depth seismic event are presented in Table 3.1.

Table 3.1 – Number of residual pairs for the intermediate-depth earthquakes database.

Event number	Date	Number of records	Number of available intra-event residual pairs	Number of used intra-event residual pairs
1	04.03.1977	2	1	0
2	30.08.1986	40	780	199
3	30.05.1990	52	1326	268
4	31.05.1990	36	630	144
5	28.04.1999	25	300	99
6	27.10.2004	66	2145	717
7	14.05.2005	40	780	245
8	18.06.2005	37	666	229
9	25.04.2009	46	1035	242
10	06.10.2013	87	3741	526

Concerning the shallow earthquakes database, the bin size was chosen equal to 5 km, obtaining a sufficient number of residual pairs per bin, which implies small errors, resulting a minimum number of pairs per bin of 15. Considering the relatively small minimum number of pairs per bin, a bin width of 2.5 km was not considered because of the very small and insufficient (for obtaining reliable results) number of residual pairs that would have resulted. Furthermore, a minimum number of 15 residual pairs per bin is also questionable. The histogram of the intra-event residual pairs with regard to distance, for a bin width of 5 km is presented in Fig. 3.3.

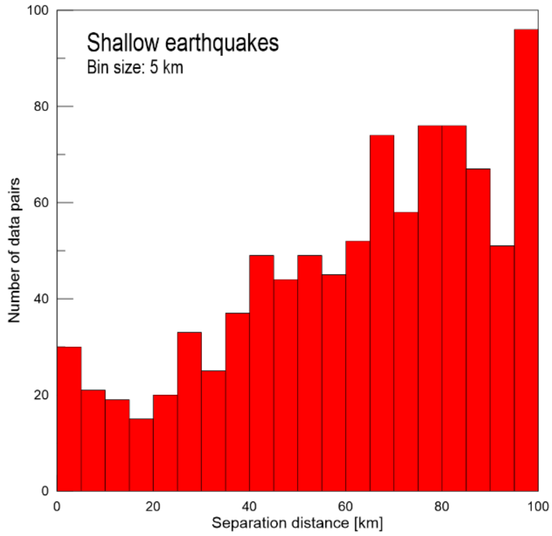

Figure 3.3 – Histogram of the number of intra-event residual pairs, for the shallow earthquakes database and a bin size of 5 km.

Out of 5413 residual pairs, only 841 pairs were used in the analysis, until a separation distance of 100 km. The number of records, the number of available residual pairs and the number of used residual pairs for every shallow seismic event are presented in Table 3.2.

Table 3.2 – Number of residual pairs for the shallow earthquakes database.

Event number	Date	Number of records	Number of available intra-event residual pairs	Number of used intra-event residual pairs
1	13.12.2005	2	1	0
2	06.09.2008	14	91	38
3	24.06.2011	9	36	14
4	08.09.2013	17	136	36
5	08.09.2013	18	153	41
6	31.10.2014	17	136	39
7	22.11.2014	81	3240	544
8	07.12.2014	42	861	264
9	29.12.2015	22	121	52
10	23.09.2016	33	528	86

The variances $\sigma_d^2(\Delta, T_n)$ of the differences between the residual pairs are calculated for every bin, being used in the next step to determine the intra-event correlation coefficients, using equation (1.8).

The correlation coefficients for the geometric mean of the horizontal components of the ground motion parameter are determined in *step 7* using equation (1.8), where the variances $\sigma_d^2(\Delta, T_n)$ were calculated in the previous step and the variances ${\sigma_\varepsilon}^2(T_n)$ are given by the ground motion prediction equation, justifying the motivation of choosing a modern GMPE, that treats the inter- and intra-event components of the standard deviation separately. The intra-event correlation coefficients calculated for the random horizontal component of the ground motion parameter are obtained using equation (1.9), where $\rho_{gm}(\Delta, T_n)$ is the intra-event correlation coefficient determined using equation (1.8).

The total correlation coefficients determined for the geometric mean of the horizontal components or for the random horizontal component of the ground motion parameter can be obtained using equation (1.6), where the variances $\rho_{gm}(\Delta, T_n)$ were determined in the previous step and the variances ${\sigma_T}^2(T_n)$ are given by the GMPE.

<u>*Step 8*</u> consists of choosing a functional form for developing an intra-event correlation model. Some studies (eg: Goda and Hong 2008a, b, Boore et al. 2003, Wang and Takada 2005, Goda and Atkinson 2009, 2010) determined an empirical relation for the intra-event correlation coefficients based on a continuous function that can be fitted upon the empirical correlation coefficients calculated in the previous step. In the present paper, as in the author's study (Vacareanu et al. 2017), the chosen functional form for the intra-event correlation coefficients is the following:

$$\rho_\varepsilon(\Delta, T_n) = \exp(-\alpha(T_n)\Delta^{\beta(T_n)}) \tag{3.18}$$

where $\alpha(T_n)$ and $\beta(T_n)$ are the model parameters; identical to the methodology Vacareanu et al. (2017) and in Wang and Takada (2005), in the present study, the parameter $\beta(T_n)$ was considered equal to 0.5, spectral period independent, and the parameter $\alpha(T_n)$ is determined through nonlinear regression.

The following should be mentioned: equation (3.18) satisfies the following: $\rho_\varepsilon(\Delta, T_n) = 1.0$, for $\Delta = 0$ (for a given site j, the residuals are considered to be fully correlated) and $\rho_\varepsilon(\Delta, T_n) = 0$, for $\Delta = \infty$ (zero correlation for two very distant sites).

The experimental intra-event correlation coefficients obtained in the previous step for the geometric mean of the horizontal components of the ground motion parameter and the fitted continuous function with regard to the separation distance *Δ*, for the intermediate-depth earthquakes database, for PGA, PSA at T=0.5 s, PSA at T=1.0 s and PSA at T=2.0 s respectively are plotted in Fig. 3.4 - 3.7.

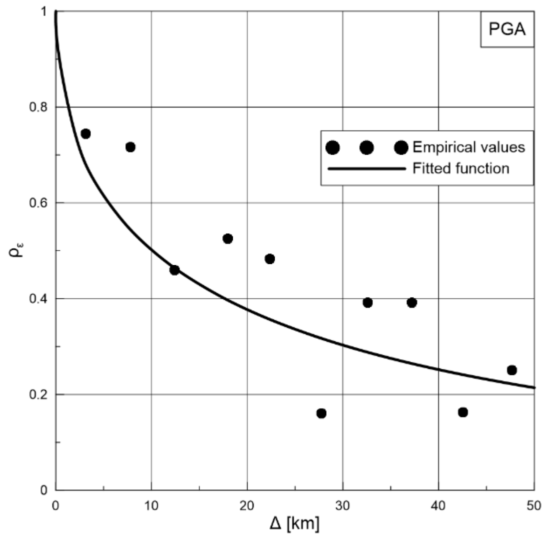

Figure 3.4 – Experimental values calculated for the geometric mean and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PGA.

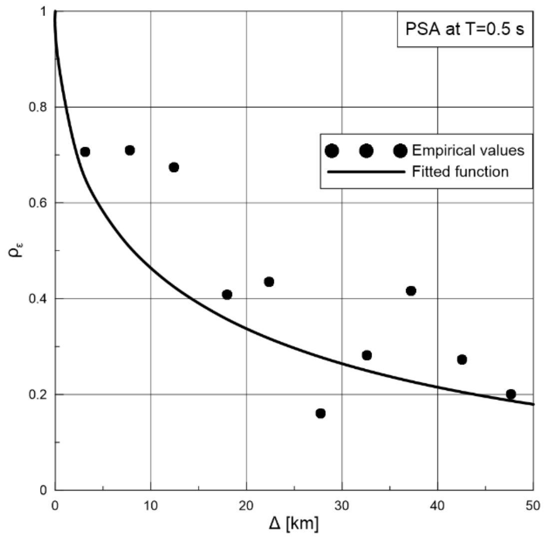

Figure 3.5 – Experimental values calculated for the geometric mean and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PSA at T=0.5 s.

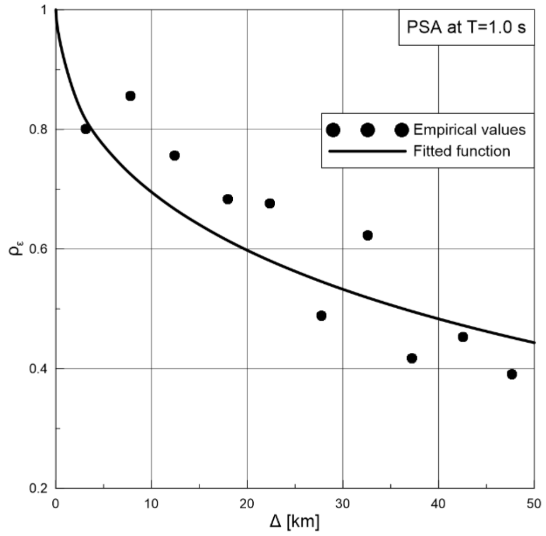

Figure 3.6 – Experimental values calculated for the geometric mean and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PSA at T=1.0 s.

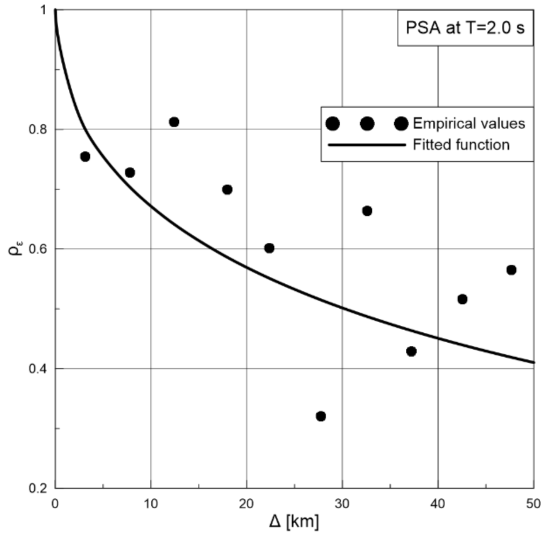

Figure 3.7 – Experimental values calculated for the geometric mean and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PSA at T=2.0 s.

The experimental intra-event correlation coefficients obtained in the previous step for the random horizontal component of the ground motion parameter and the fitted continuous function with regard to the separation distance *Δ*, for the intermediate-depth earthquakes database, for PGA, PSA at T=0.5 s, PSA at T=1.0 s and PSA at T=2.0 s respectively are plotted in Fig. 3.8 - 3.11.

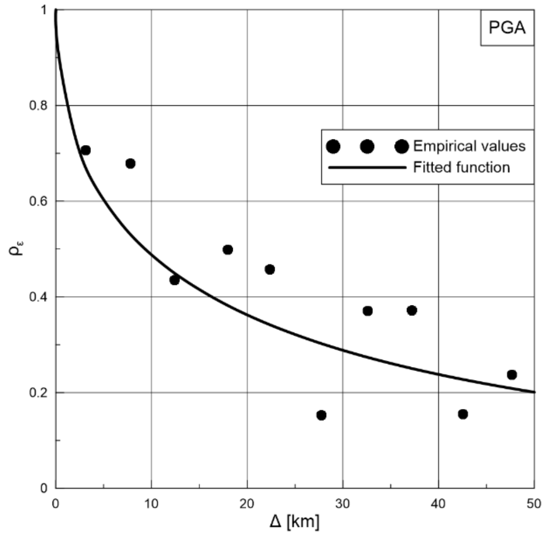

Figure 3.8 – Experimental values calculated for the random component and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PGA.

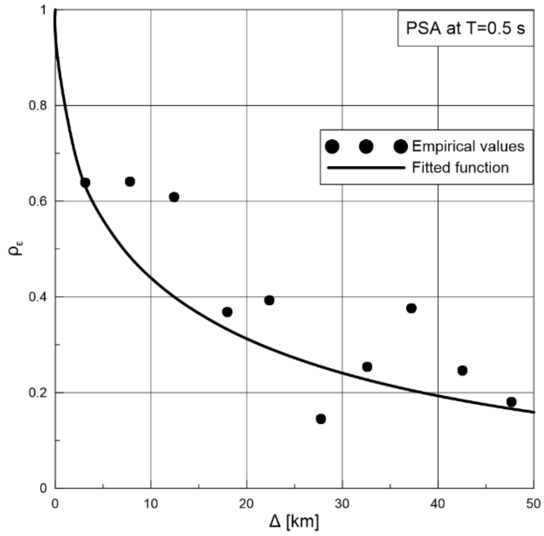

Figure 3.9 – Experimental values calculated for the random component and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PSA at T=0.5s.

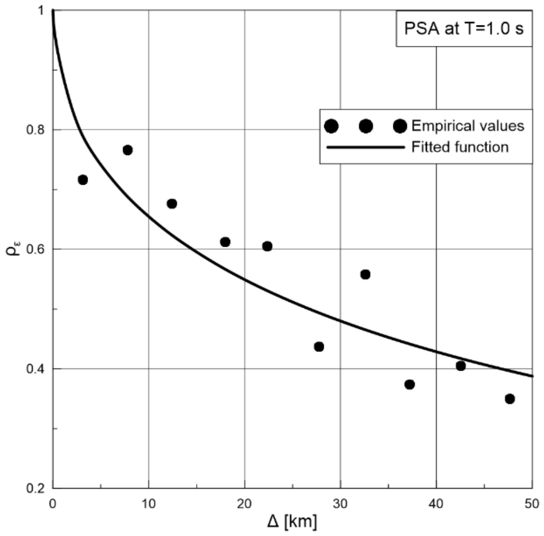

Figure 3.10 – Experimental values calculated for the random component and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PSA at T=1.0 s.

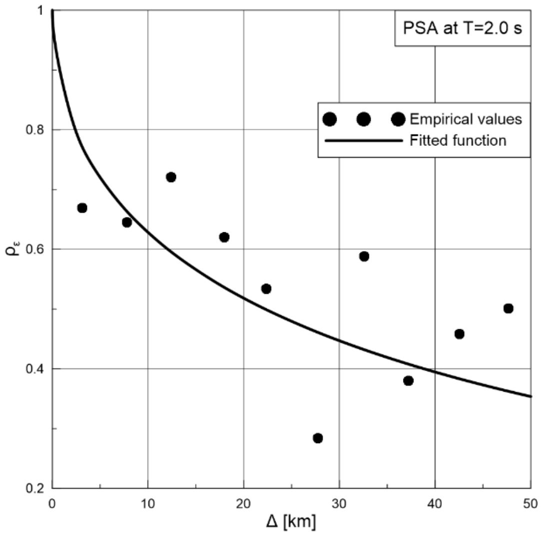

Figure 3.11 – Experimental values calculated for the random component and the continuous fitted function, with regard to distance, for the intermediate-depth database, for PSA at T=2.0 s.

The present research report and the author's article Vacareanu et al. (2017) considered, similarly to Wang and Takada (2005), the parameter $\beta(T_n)$ equal to 0.5, spectral period independent. Also, in Wang and Takada (2005) the notion of correlation length appears for the first time; the coefficient $\rho_\varepsilon(\Delta, T_n)$ (intra-event correlation coefficient) is considered to be characterized by only one parameter called correlation length, which is the separation distance for which the correlation coefficient decreases with $1/e = 0.368$.

The parameter $\alpha(T_n)$ values obtained through nonlinear regression and the correlation lengths (as defined by Wang and Takada, 2005) are presented in Table 3.3. Both the $\alpha(T_n)$ values for the geoemetric mean of the horizontal components of the ground motion parameter and for the random horizontal component of the ground motion parameter are presented. High correlation lengths can be observed, especially for long periods, for both cases (geometric mean and random component).

Table 3.3 – Parameters of the intra-event correlation model developed for the intermediate-depth earthquakes database, for a bin size of 5 km.

Period [s]	Geometric mean of the horizontal components			Random horizontal component		
	α	β	Correlation length [km]	α	β	Correlation length [km]
T=0.0 s	0.218	0.500	21	0.227	0.500	19
T=0.1 s	0.200		25	0.215		22
T=0.2 s	0.267		14	0.282		13
T=0.3 s	0.255		15	0.272		14
T=0.4 s	0.251		16	0.268		14
T=0.5 s	0.243		17	0.260		15
T=0.6 s	0.193		27	0.211		22
T=0.7 s	0.158		40	0.177		32
T=0.8 s	0.131		58	0.150		44
T=0.9 s	0.127		62	0.146		47
T=1.0 s	0.115		76	0.134		56
T=1.2 s	0.107		87	0.126		63

T=1.4 s	0.102		96	0.122		67
T=1.6 s	0.099		102	0.119		71
T=1.8 s	0.108		86	0.128		61
T=2.0 s	0.126		63	0.147		46
T=2.5 s	0.150		44	0.172		34
T=3.0 s	0.152		43	0.174		33

In the author's article Vacareanu et al. (2017), obtaining the parameters $\alpha(T_n)$ through nonlinear regression was done in accordance to some negative values of the correlation coefficients calculated in step 7, whose first appereance (first bin to provide a negative correlation coefficient) is different depending on the spectral period. In this regard, the minimum number of available data for the regression analysis was 12 values, the use of the first 12 values being decided on other period values, were more values were available. Nevertheless, in the present paper, performing the regression analysis with the maximum number of available data was considered, despite the different number of data between different period values. In this sense, the parameters of the functional form are presented in Table 3.4.

Table 3.4 – Parameters of the intra-event correlation model developed for the intermediate-depth earthquakes database, for a bin size of 5 km, with the improved regression analysis.

Period [s]	Geometric mean of the horizontal components			Random horizontal component		
	α	β	Correlation length [km]	α	β	Correlation length [km]
T=0.0 s	0.211	0.500	22	0.220	0.500	21
T=0.1 s	0.220		21	0.233		18
T=0.2 s	0.259		15	0.274		13
T=0.3 s	0.251		16	0.266		14
T=0.4 s	0.262		15	0.278		13
T=0.5 s	0.249		16	0.266		14
T=0.6 s	0.199		25	0.217		21
T=0.7 s	0.197		26	0.214		22
T=0.8 s	0.168		35	0.186		29
T=0.9 s	0.173		33	0.191		27
T=1.0 s	0.143		49	0.160		39
T=1.2 s	0.159		40	0.175		33
T=1.4 s	0.162		38	0.178		32
T=1.6 s	0.166		36	0.181		31
T=1.8 s	0.201		25	0.216		21
T=2.0 s	0.228		19	0.246		17
T=2.5 s	0.150		44	0.172		34
T=3.0 s	0.152		43	0.174		33

By comparison of the two tables, major differences can be observed in the interval 0.7 s – 2.0 s, for the other spectral period values the differences being minor or zero (in the case of long periods, 2.5 s and 3.0 s).

The initial and the improved model are presented, for the geometric mean and for the random horizontal component of the ground motion parameter respectively in Fig. 3.12 and 3.13, for PGA and PSA at T=1.0 s. Minor differences for PGA and a smaller decrease in correlation compared to the initial model for PSA at T=1.0 s, both for the geometric mean and for the random component, are observed.

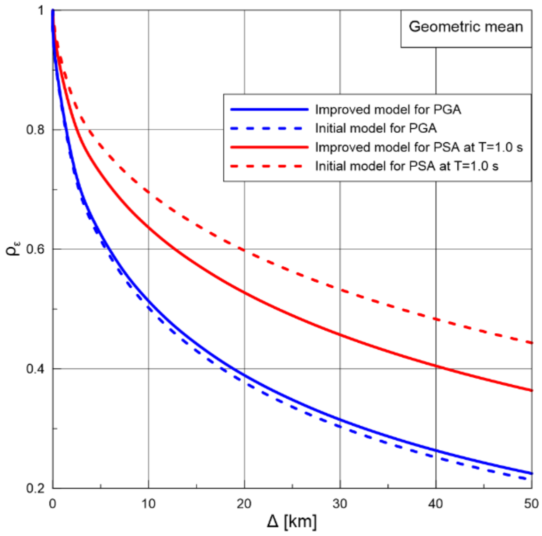

Figure 3.12 – Comparison between the initial and the improved model, for PGA and PSA at T=1.0 s, for the geometric mean.

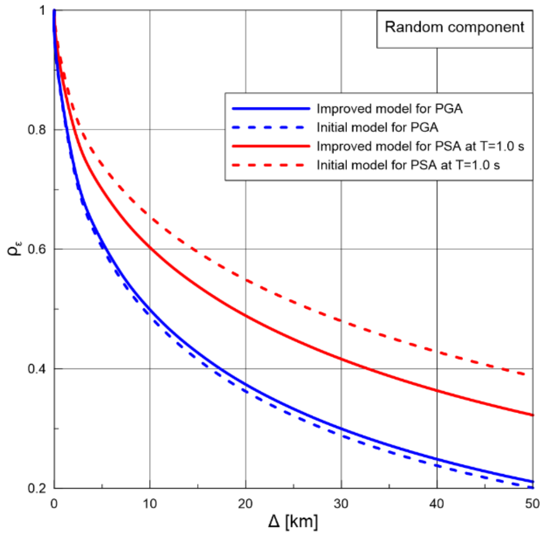

Figure 3.13 – Comparison between the initial and the improved model, for PGA and PSA at T=1.0 s, for the random component.

In future research studies, as well as in the following research report, the use of the second (improved) model was decided, because the improved regression analysis takes into account all the available data, despite the different number between spectral periods.

The experimental values presented in step 7 and the continuous functions obtained using the parameters presented in Table 3.4, for the geometric mean of the horizontal components and for the random horizontal component of the ground motion parameter, for PGA and PSA at T=0.3 s, 0.7 s and 1.0 s are presented in Fig. 3.14 – 3.17.

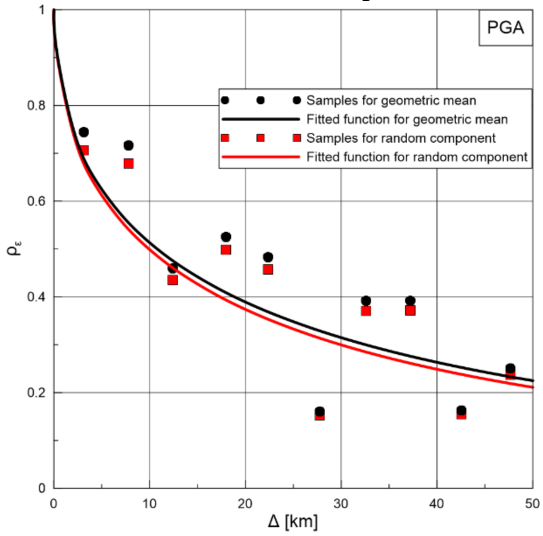

Figure 3.14 – Experimental values and correlation models developed for the geometric mean and the random component, for PGA.

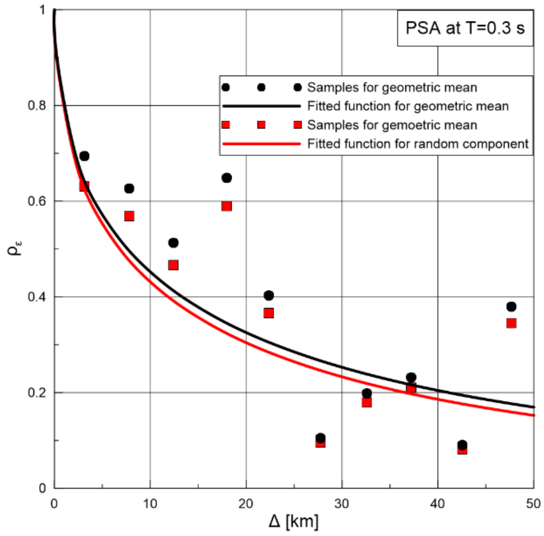

Figure 3.15 – Experimental values and correlation models developed for the geometric mean and the random component, for PSA at T=0.3 s.

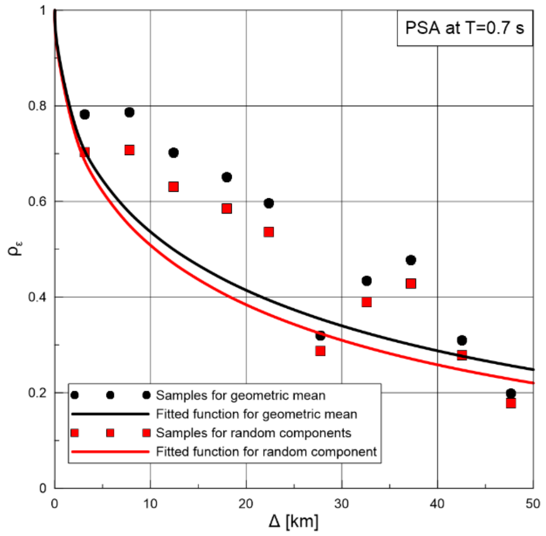

Figure 3.16 – Experimental values and correlation models developed for the geometric mean and the random component, for PSA at T=0.7 s.

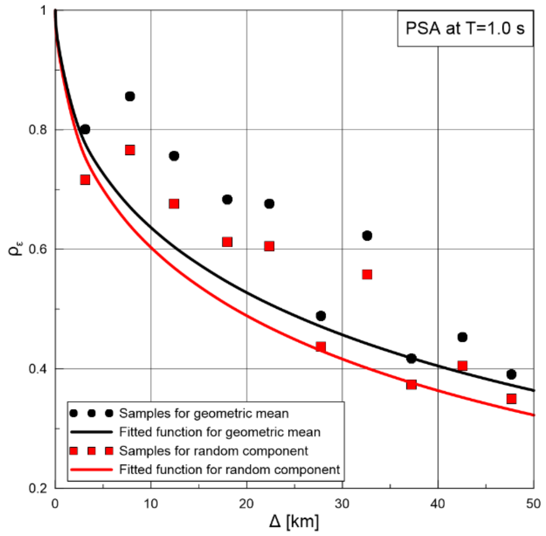

Figure 3.17 – Experimental values and correlation models developed for the geometric mean and the random component, for PSA at T=1.0 s.

The decrease of the correlation coefficient $\rho_{\varepsilon}(\Delta, T_n)$ with the increase of the correlation distance *Δ* is observed in Fig. 3.14 – 3.17. Also, higher correlation in the case of the geometric mean of the horizontal components compared to the random horizontal component is observed for all four cases, which confirms the results found in other studies (eg: Goda and Hong 2008a, Hong et al. 2009).

The dependency of the correlation coefficient $\rho_{\varepsilon}(\Delta, T_n)$ on the spectral period T_n is visible in Fig. 3.18 and 3.19, where the obtained correlation models are presented in a comparative way for different spectral period values. In Fig. 3.18 a small variation of the correlation coefficient $\rho_{\varepsilon}(\Delta, T_n)$, for the short period values, is visible. Also, a high correlation in the case of long periods is an important observation derived from Fig. 3.19, the residuals being correlated over long distances.

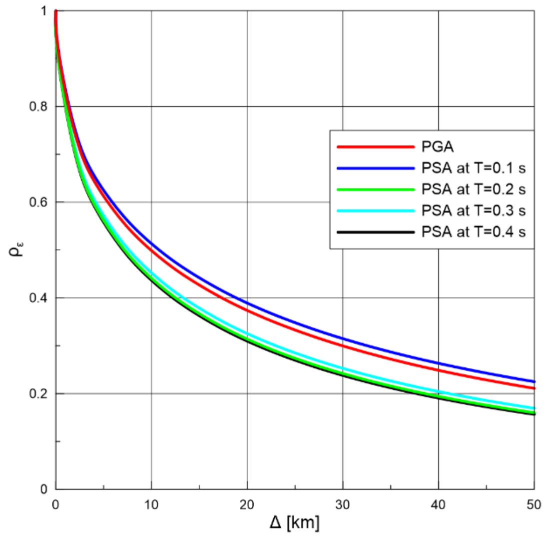

Figure 3.19 – Correlation models developed for the geometric mean, for PGA and PSA at T=0.1 s, 0.2 s, 0.3 s and 0.4 s.

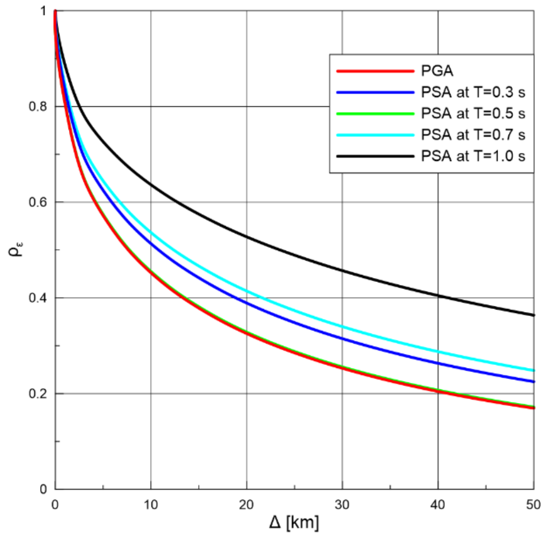

Figure 3.19 – Correlation models developed for the geometric mean, for PGA and PSA at T=0.3 s, 0.5 s, 0.7 s and 1.0 s.

The previous observations concerning the decrease of the correlation coefficients $\rho_{\varepsilon}(\Delta, T_n)$ with the increase of the separation distance *Δ*, the dependency of the correlation coefficients on the spectral period, long correlations lengths for long periods, relatively long correlation lengths for short periods and higher correlations for the geometric mean of the horizontal components results compared to the random horizontal component case can all be observed in Fig. 3.20, where the correlation models are presented, for a maximum separation distance of 100 km, for the geometric mean and for the random component, for PGA and PSA at T=0.5 s and T=1.0 s.

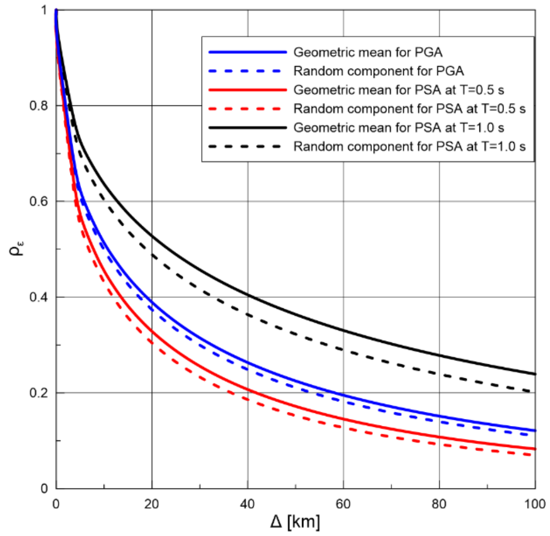

Figure 3.20 – Correlation models for the geometric mean of the horizontal components and for the random horizontal component, for PGA and for PSA at T=0.5 s and at T=1.0 s.

Concerning the shallow earthquakes database, unfortunately, the small number of available data could not lead to reliable results. Because of the small number of residual pairs, especially at short distances, the regression analysis of the parameter $\alpha(T_n)$ could not be performed. The small number of available data was also observed for the intermediate-depth eaethquakes database, but, despite this, the larger number of available recordings was sufficient to obtain high confidence results.

The decrease of spatial correlation for the shallow earthquakes database is much faster than in the first case (intermediate-depth earthquakes database), for a bin size of 5 km, the first negative values occurring in the first 10-15 km. Adopting a smaller bin width would have solved the negative correlation coefficients problem, but the very small number of pairs per bin (the minimum number of residual pairs per bin, for a bin size of 2.5 km, is equal to 6) would have let to unreliable results. Another important aspect is the fact that the 10 shallow seismic events that form the database are major shallow earthquakes generated by the seismic sources that contribute to the Romanian seismic hazard and among the only ones for which recordings are available, therefore enlarging the database by adding other shallow earthquakes was not possible, at least not for a distinguishable increase in the recordings number.

In the next research report, whose objective is the numerical simulation of the spatial correlated ground motion parameters, a spatial correlation model available in the literature for shallow earthquakes will be adopted. Nevertheless, the author's intention of developing a correlation model for the shallow seismic sources represents another reason for the necessary development of the national seismic networks, thus obtaining a dense array of seismic networks, like in Japan, California, United States of America, Turkey etc.).

4. Comparison with other correlation models

In the present chapter, the intra-event correlation model developed for the intermediate-depth earthquakes database will be analyzed by comparison with other models developed in literature (Goda and Hong, 2008a and in Goda and Atkinson, 2010).

The database used in Goda and Hong (2008a) is composed of ground motion records of Californian and the Chi-Chi earthquakes treated separately (for comparison only the Californian database model was used). Spatial correlation models were developed for the geometric mean of the horizontal components and for the random horizontal component of the ground motion parameter (for comparison only the geometric mean results were used), for PGA and for spectral accelerations at different spectral period values. The spatial correlation model developed in Goda and Hong (2008a) has the following functional form:

$$\rho_\varepsilon(\Delta, T_n, T_n) = \exp(-\alpha\Delta^\beta) \tag{4.1}$$

where α and β are the model parameters, and Δ is the separation between two sites.

The database used in Goda and Atkinson (2010) is composed of Japanese ground motion records (in the K-NET, KiK-net and SK-net networks). The spatial correlation model developed in Goda and Atkinson (2010) has the following functional form:

$$\rho_\varepsilon(\Delta, T) = \max\{\gamma(\mathrm{T})\exp\left[-\alpha(\mathrm{T})\Delta^{\beta(T)}\right] - \gamma(T) + 1; 0\} \tag{4.2}$$

where $\alpha(T)$, $\beta(T)$ and $\gamma(T)$ are the model parameters, and Δ is the separation between two sites.

The correlation models developed in Goda and Hong (2008a), Goda and Atkinson (2010) and in the present research report are presented, comparatively in Fig. 4.1, for PGA and for PSA at T=1.0 s. The correlation models developed in Goda and Hong (2008a), Goda and Atkinson (2010), Wang and Takada (2005) and in the present research report are presented, comparatively in Fig. 4.2, for PGA, obtained for the geometric mean of the horizontal components of the ground motion parameters.

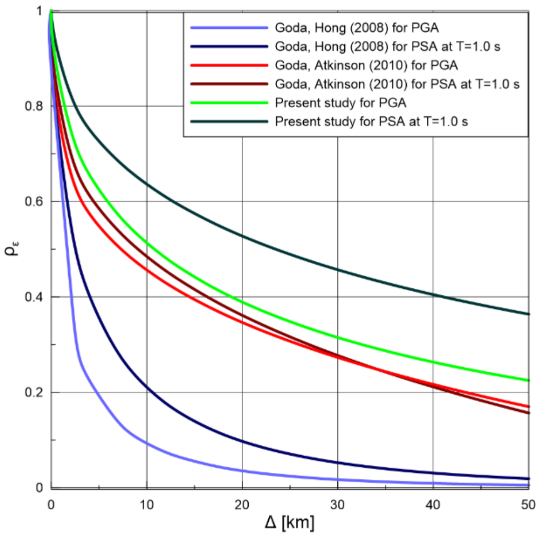

Figure 4.1 – Comparison between the present study and two other correlation models available in the literature using the geometric mean of the horizontal components, for PGA and PSA at T=1.0 s.

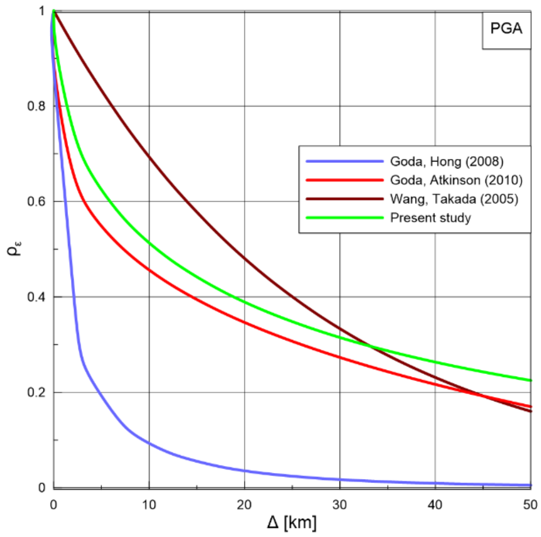

Figure 4.2 – Comparison between the present study and three other correlation models available in the literature using the geometric mean of the horizontal components, for PGA.

An observation presented in Wagener et al. (2016) is visible in Fig. 4.1, where the correlation models developed for Japanese earthquakes decrease more gradually and present longer correlation lengths than those of the correlation models developed for Californian earthquakes. The correlation model developed in the present study decreases even more gradually than the Japanese results, but offers similar results in the case of the PGA. This can be caused by regional peculiarities, local geology, wave propagation or the ground motion frequency content. High correlation for PGA at short distances and a faster decrease for the model developed in Wang and Takada (2005) can be observed in Fig. 4.2. The similarity between the model developed in the present study and the model developed in Goda and Atkinson (2010) is once again observed for PGA.

5. Sensitivity analysis

Analyzing the influence of the bin width on the correlation model, developing a total correlation model, important for the numerical simulation of the spatial correlated ground motion parameters, and comparisons with the intra-event correlation model developed in chapter 3 were the objective of the present chapter. Future sensitivity analysis research studies include: comparative analyses between the empirical intra-event correlation coefficients obtained using different seismic events, analysis concerning the geotechnical conditions on the correlation model, using the semi-variogram approach in developing a correlation model and comparisons with the model developed in the present study etc.

5.1. Analysis regarding the bin size

As mentioned in chapter 3, the residual pairs originating from the intermediate-depth earthquakes database were also sorted using a bin width of 2.5 km, in order to perform a sensitivity analysis on the influence of the bin size on the correlation model. It should be noted that the minimum number of residual pairs per bin is 28, obtained for one of the pairs from the first 30 km. The histogram of the intra-event residual pairs with regard to distance, for the intermediate-depth earthquakes database and a bin size of 2.5 km is presented in Fig. 3.2 and the number of records, number of available residual pairs and number of used residual pairs for the intermediate-depth earthquakes database are presented in Table 3.1 The functional form parameter values determined through nonlinear regression for a bin size of 2.5 km are presented in Table 5.1.

Table 5.1 – Parameters of the intra-event correlation model developed for the intermediate-depth earthquakes database, for a bin size of 2.5 km.

Period [s]	Geometric mean of the horizontal components			Random horizontal component		
	α	β	Correlation length [km]	α	β	Correlation length [km]
T=0.0 s	0.183	0.500	30	0.197	0.500	26
T=0.1 s	0.212		22	0.234		18
T=0.2 s	0.198		26	0.222		20
T=0.3 s	0.173		33	0.198		26
T=0.4 s	0.187		29	0.213		22
T=0.5 s	0.179		31	0.206		24
T=0.6 s	0.152		43	0.180		31
T=0.7 s	0.212		22	0.229		29
T=0.8 s	0.147		46	0.165		41
T=0.9 s	0.146		47	0.164		42
T=1.0 s	0.129		60	0.147		51
T=1.2 s	0.141		50	0.160		56
T=1.4 s	0.162		38	0.179		58
T=1.6 s	0.155		42	0.173		64
T=1.8 s	0.154		42	0.174		48
T=2.0 s	0.097		106	0.129		60
T=2.5 s	0.145		48	0.178		32
T=3.0 s	0.167		36	0.200		25

The intra-event correlation models developed for a bin size of 5 km (developed in chapter 3) and for a size of 2.5 km (presented in the present chapter) determined for the geometric mean of the horizontal components and for the random horizontal component of the ground motion parameter, for PGA, PSA at T=0.7 s and PSA at T=1.0 s are presented, comparatively, in Fig. 5.1-5.4. Higher correlations are observed for a bin size of 2.5 km, for most spectral periods, in comparison with the model developed in chapter 3. Also, for some spectral period values (eg: T=0.7 s, 1.4 s and 3.0 s), higher correlation is observed for the model developed using a bin size of 5 km, as seen in Fig. 5.3 and 5.4, for the case T=0.7 s.

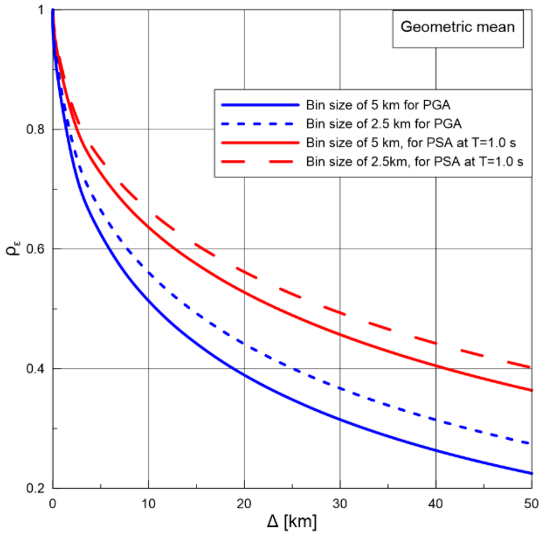

Figure 5.1 – Comparison between the correlation models developed for a bin size of 2.5 km and 5 km, using the geometric mean of the horizontal components, for PGA and PSA at T=1.0 s.

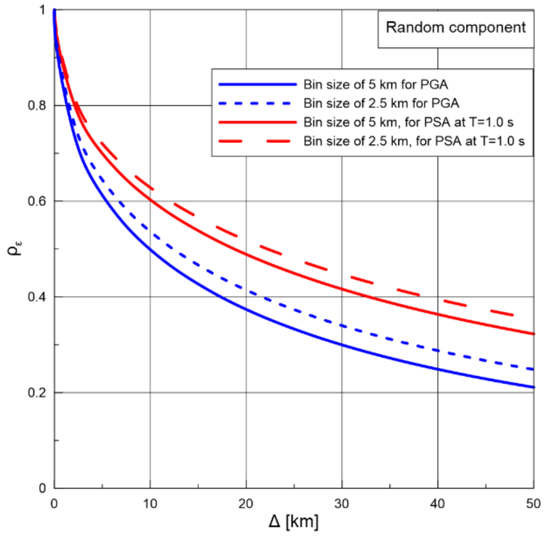

Figure 5.2 – Comparison between the correlation models developed for a bin size of 2.5 km and 5 km, using the random horizontal component, for PGA and PSA at T=1.0 s.

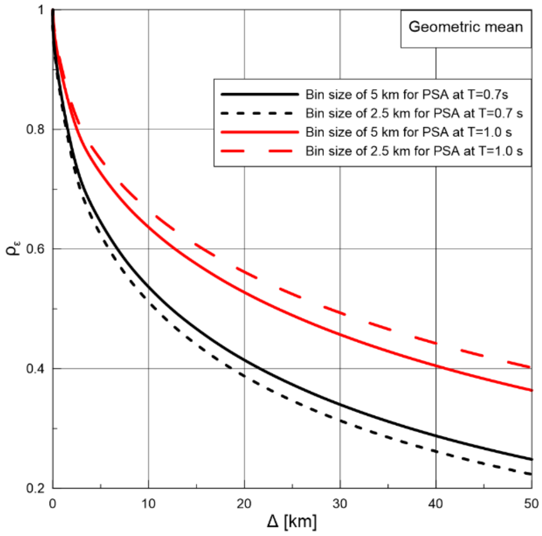

Figure 5.3 – Comparison between the correlation models developed for a bin size of 2.5 km and 5 km, using the geometric mean of the horizontal components, for PSA at T=0.7 s and T=1.0 s.

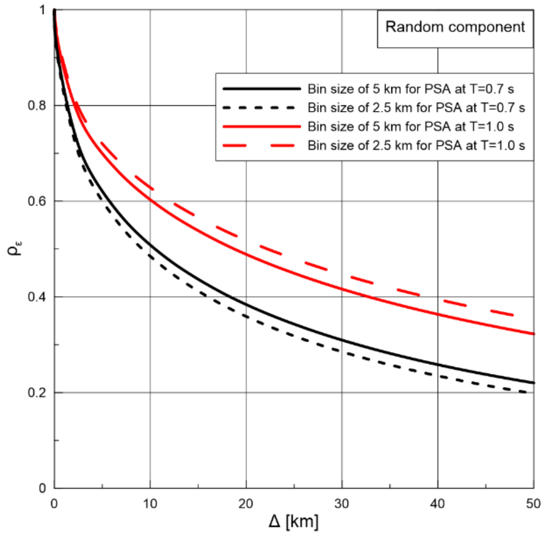

Figure 5.4 – Comparison between the correlation models developed for a bin size of 2.5 km and 5 km, using the random horizontal component, for PSA at T=0.7 s and T=1.0 s.

The correlation models developed in Goda and Atkinson (2009) were shown to be independent on the bin size, which does not follow the results of present research. Nevertheless, it should be noted that the number of residual pairs for the database used in Goda and Atkinson (2009) is much greater (for the first bin, the pair number is equal to 483, 173 and 265 for the entire database, the database containing shallow earthquakes and for the database containing intermediate-depth earthquakes respectively) than the one used for the Vrancea intermediate-depth earthquakes database used in the present paper. The reason for this is thought to be the small number of residual pairs per bin, for a bin size of 2.5 km, which could result in questionable results. Considering the small number of residual pairs per bin in comparison to the model developed for a bin width of 5 km and especially in comparison with other models existing in literature, the need to further develop the national seismic networks, becomes obvious, once again. For this reasons, in future research papers, only the correlation model developed in chapter 3 will be considered (bin width of 5 km).

5.2. Analysis regarding total correlation coefficients

The purpose of this subchapter is developing correlation models using total correlation coefficients and performing comparisons with the developed intra-event correlation model. The next step in performing seismic hazard and risk analysis for Romania taking into account the ground motion spatial correlation is the numerical simulation of the spatially correlated ground motion parameters, which is the objective of research report number 3, being based on the total correlation coefficients. In this sense, obtaining such models and comparing them with the intra-event models justifies its importance.

The total correlation coefficients $\rho_T(\Delta, T_n)$ can be obtained using equation (1.6), where $\sigma_d^2(\Delta, T_n)$ represents the variance of the intra-event residuals (or total, the two being identical) and $\sigma_T^2(T_n)$ is the total variance given by the ground motion prediction equation, both variances being spectral period dependent.

The steps for developing a total correlation model and the functional dorm are identical to the ones described in chapter 3, the only difference being the values of the total empirical coefficients. The functional form parameter values determined through nonlinear regression for a bin size of 5 km are presented in Table 5.2.

Table 5.2 – Parameters of the total correlation model developed for the intermediate-depth earthquakes database, for a bin size of 5 km.

Period [s]	Geometric mean of the horizontal components		Random horizontal component	
	α	β	α	β
T=0.0 s	0.108		0.116	
T=0.1 s	0.126		0.136	
T=0.2 s	0.105		0.12	
T=0.3 s	0.119		0.131	
T=0.4 s	0.099		0.115	
T=0.5 s	0.109		0.125	
T=0.6 s	0.107		0.123	
T=0.7 s	0.112		0.125	
T=0.8 s	0.105	0.500	0.118	0.500
T=0.9 s	0.110		0.124	
T=1.0 s	0.097		0.111	
T=1.2 s	0.094		0.108	
T=1.4 s	0.095		0.109	
T=1.6 s	0.086		0.101	
T=1.8 s	0.095		0.11	
T=2.0 s	0.110		0.125	
T=2.5 s	0.109		0.124	
T=3.0 s	0.106		0.122	

The intra-event and total correlation models developed in the present study for a bin width of 5 km, for the geometric mean of the horizontal components and for the random horizontal component of the ground motion parameter respectively, for PGA and PSA at T=1.0 s, are presented, comparatively, in Fig. 5.5 and 5.6. Some previously presented aspects are confirmed, being valid for the total correlation model (higher correlations for PSA at T=1.0 s than for PGA and higher correlations for the geometric mean than for the random horizontal component). An obvious aspect is also confirmed: higher total correlations than the intra-event correlations (which was clear from the calculus relations of the empirical coefficients, $\sigma_T^2(T_n)$ having higher values than $\sigma_\varepsilon^2(T_n)$, which leads to higher total coefficients).

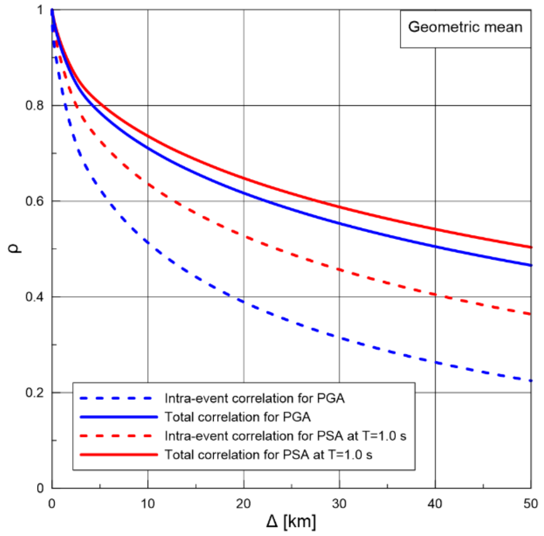

Figure 5.5 – Comparison between the total and intra-event correlation model, for a bin size of 5 km, using the geometric mean of the horizontal components, for PGA and PSA at T=1.0 s.

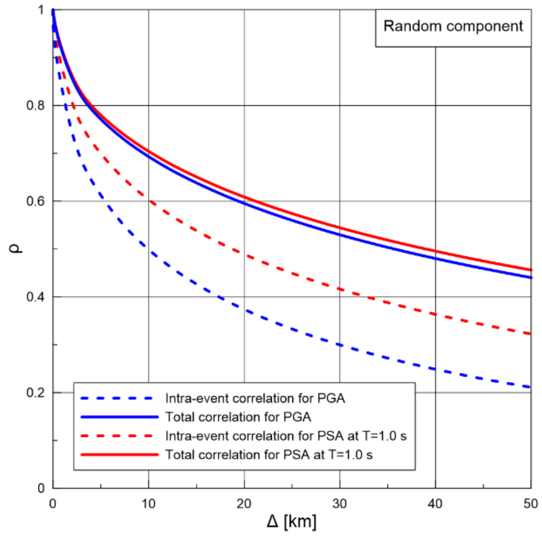

Figure 5.6 – Comparison between the total and intra-event correlation model, for a bin size of 5 km, using the random horizontal component, for PGA and PSA at T=1.0 s.

The total correlation model developed for the intermediate-depth earthquakes database is a step forward in the PhD thesis, due to the importance it has in the next step (numerical simulation of spatial correlated ground motion parameters).

Conclusions

The objective of the present research report was developing a spatial correlation model using a database composed of shallow and intermediate-depth earthquakes generated by the seismic sources that contribute to the Romanian seismic hazard. The spatial correlation model is important for the numerical simulation of the spatial correlated ground motion parameters, a step that will be presented in the next research report, with the final purpose of performing seismic hazard and risk analyses for Romania with the consideration of spatial correlation, that has an important impact on building portfolios (eg: bridges, buildings) or spatially distributed systems (lifelines).

A spatial correlation model was developed for a database consisting of 10 intermediate-depth earthquakes generated by the Vrancea intermediate-depth seismic source and the development of a correlation model for a database consisting of 10 shallow earthquakes generated by seismic sources that contribute to Romanian hazard was tried. The first correlation model was developed choosing the peak ground acceleration (PGA) and the pseudo-spectral accelerations (PSA) for a critical damping of 5% at various spectral periods as the parameter. Also, the calculus was performed both in terms of the geometric mean of the two horizontal components of the ground motion parameter and in terms of the random horizontal component of the ground motion parameter. A spatial correlation model for the database containing shallow earthquakes could not be developed due to the limited number of data available; in future calculus, a spatial correlation model developed for shallow earthquakes existing in literature will be adopted.

Concerning the intra-event correlation model, some aspects discussed in other studies have been confirmed: the correlation dependency on the spectral period and higher correlations in the case of the geometric mean of the horizontal components of the ground motion parameter compared to the case of the random horizontal component of the ground motion parameter, performing, in this regard, comparisons with other models available in the literature.

In the chapter concerning the sensitivity analysis some remarks were made concerning the influence of the bin size on the obtained results (some differences were observed and a possible reason could be the limited amount of data in the case of the bin size of 2.5 km) and a total correlation model was developed for the intermediate-depth earthquakes database, which will used for the numerical simulation of the spatial correlated ground motion parameters.

Future research directions include: possible comparisons between the empirical correlation coefficients obtained for different seismic events, the influence of the geotechnical conditions on the spatial correlation, using the semi-variogram approach to determine a spatial correlation model, seismic risk analyses for building portfolios, seismic loss estimation following a major earthquake on the urban infrastructure, building portfolios or lifelines etc.

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