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# CORRELATION MODELS FOR STRONG GROUND MOTIONS FROM VRANCEA INTERMEDIATE-DEPTH SEISMIC SOURCE

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## *Abstract*

The issue of correlation models of strong ground motions is widely discussed in the literature. Numerous investigations of residuals obtained on various datasets of strong ground motions with different ground motion prediction equations offer spatial correlation models for either peak ground parameters or spectral response acceleration values. In this study, a dataset of 431 triaxial accelerograms recorded during ten earthquakes originating in the Vrancea intermediate-depth seismic source is used to obtain correlation models for peak ground accelerations and spectral response acceleration values. The inter- and intra-event residuals are obtained using a ground motion prediction equation for the geometric mean of two horizontal orthogonal components developed purposely for Vrancea intermediate-depth seismic source. The observed correlation coefficients for the geometric mean of the two orthogonal horizontal components and for the randomly orientated horizontal component at different vibration periods are obtained using relations available in the literature. Empirical relations of spatial intra-event correlation coefficients with respect to the separation distance between observation sites and correlation lengths based on the geometric mean of two orthogonal horizontal components and on the randomly oriented horizontal component are calculated using the assembled Vrancea ground motion database. The results show that the spatial intra-event correlation decreases as the separation distance increases. Higher correlation coefficients are obtained when considering the geometric mean of the two horizontal components of ground motions than for the randomly orientated horizontal component. A gradual decay of the correlation coefficient with separation distance and long correlation lengths have resulted. The fitted spatial correlation models for Vrancea intermediate-depth seismic source are discussed and compared with other models reported in the literature for different seismo-tectonic contexts.

*Keywords: Vrancea, correlation, models;*

## 1. Introduction

Probabilistic seismic hazard assessment (*PSHA*) dates back to 1968 [1], and represents the most widely used methodology used to determine mean exceedance rates of ground motion parameters, such as the peak ground acceleration (*PGA*), the peak ground velocity (*PGV*) or pseudo-spectral accelerations (*PSA*). One important aspect in *PSHA* is the consideration of uncertainties, which can be divided in epistemic and aleatory, as described in [2, 3, 4, 5, 6, 7]. Epistemic uncertainties come from incomplete knowledge of a certain model/parameter/phenomena [8]. The epistemic uncertainties can be reduced through the addition of new information and data that can offer a better understanding of the phenomena. In *PSHA*, the epistemic uncertainties can be incorporated by using the logic tree method [9]. Aleatory uncertainties derive from the probabilistic nature of the ground motion parameters and they are not reduced through additional data [8]. In other words, as described in [3], the aleatory uncertainties describe the disagreement (differences) between observations and predictive models that is due to the absence of a physical explanation or due to the different variables that are not incorporated in the predictive equations. The aleatory uncertainties are incorporated into *PSHA* through the use of the standard deviation of the scatter of the data about the ground motion prediction equations [4]. Ground motion prediction equations (*GMPE*) are used to describe/estimate the ground motion parameters (*PGA*, *PGV*, *PSA* etc.) at a specific site, depending on earthquake's magnitude, source-site distance, focal depth, site conditions and other parameters. The use of *GMPE*s 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. 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 hazard assessment and seismic risk analysis of such systems requires the use of correlated ground motion parameters. The traditional *PSHA*, also called "point-wise" *PSHA* [10], can still be used in case of isolated structural systems. However, the use of correlated ground motions at different sites during a certain seismic event is required in order to obtain correct seismic loss estimations. The correlation affects the parameters of the probability distribution function for the losses of spatially distributed systems or portfolios during an earthquake, as presented in [3].

Studying the spatial correlation of strong ground motion has gained attention in the last 10-20 years. There are various studies that have either studied the correlation of residuals in order to develop adequate intra- and inter-event correlation models [11, 12, 13, 14], while other studies have focused on incorporating correlation models into ground motion prediction equations, for seismic loss assessment of portfolios or lifelines [3, 5, 15, 16]. Spatial correlation models have been developed for peak ground parameters (*PGV* in [6]; *PGA* in [17, 18]), for pseudo-spectral acceleration values *PSA* [12, 13] or for Arias Intensity [19]. Other researchers studied the influence of local geology on spatial correlation [7, 20]. The databases used in literature for developing correlation models include records from: the 1994 Northridge, California earthquake [17], the 1999 Chi-Chi (Taiwan) earthquake [18, 11, 4], other earthquakes in Taiwan [4], Californian earthquakes [11, 21], earthquakes in Japan (the K-NET and KiK-net networks in [12] and K-NET, KiK-net and SK-net networks in [13]), earthquakes in the Istanbul region (through the IERREWS network) in [14], the European Strong-Motion Database (ESD) and the Italian Accelerometric Archive (ITACA) in [22, 23].

The objective of this paper is to develop an intra-event (within earthquake) correlation model for the peak ground acceleration and for pseudo-spectral accelerations for spectral periods varying from 0.1s to 3.0s using a database consisting of ground motions from 10 earthquakes originating from Vrancea intermediate-depth seismic source; the residuals are computed using a ground motion model developed for the Vrancea intermediate-depth seismic source in [24], the analysis being performed considering firstly the geometric mean of two orthogonal horizontal components of the ground motion parameter and secondly the random horizontal component of the ground motion parameter.

## 2. Ground motion correlation

### 2.1 Correlation coefficients

*GMPE*s estimate the value of a ground motion parameter, as described in the previous section. The general expression for modern *GMPE*s, for site "j", during seismic event "*i*", is as follows:

$$\ln Y_{ij}(T_n) = f\left(M_i, R_{ij}, P_{ij}, T_n\right) + \eta_i(T_n) + \varepsilon_{ij}(T_n) \tag{1}$$

where $i = \overline{1, r}$ and $i = \overline{1, s}$, $Y_{ij}(T_n)$ 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 $\sigma_\varepsilon(T_n)$. The two residuals are assumed to be normally distributed and independent, therefore the total variance of the ground motion parameter is given in Eq. (2):

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

It should be stated that for a given earthquake, $\eta_i(T_n)$ is a constant among all sites (it is assumed that all ground motions from a specific earthquake have some characteristics that separates them from other records). If we consider two different sites "*j*" and "*k*" separated by the distance $\Delta$, for a specific earthquake "*i*", then the total correlation coefficient (as described in [25, 11] between the two residuals ($\eta_i(T_n) + \varepsilon_{ij}(T_n)$ and $\eta_i(T_n) + \varepsilon_{ik}(T_n)$) has the following expression:

$$\rho_T(\Delta,T_n)=\frac{\sigma_\eta^2(T_n)+\rho_\varepsilon(\Delta,T_n)\sigma_\varepsilon^2(T_n)}{\sigma_T^2(T_n)}=\rho_\eta(T_n)+\rho_\varepsilon(\Delta,T_n)\frac{\sigma_\varepsilon^2(T_n)}{\sigma_T^2(T_n)}$$
$$=\rho_\eta(T_n)+\rho_\varepsilon(\Delta,T_n)(1-\rho_\eta(T_n)) \quad (3)$$

where $\rho_\varepsilon(\Delta,T_n)$ represents the intra-event correlation coefficient; $\rho_\eta(T_n)$ represents the inter-event correlation coefficient and has the following expression (as shown in [26]):

$$\rho_\eta(T_n)=\frac{\sigma_\eta^2(T_n)}{\sigma_T^2(T_n)}=\frac{\sigma_\eta^2(T_n)}{\sigma_\eta^2(T_n)+\sigma_\varepsilon^2(T_n)} \quad (4)$$

It should be noted that the general form of the total correlation coefficient is $\rho_T(\Delta,T_{n,1},T_{n,2})$, the general form for the intra-event correlation coefficient is $\rho_\varepsilon(\Delta,T_{n,1},T_{n,2})$ and the general form of the inter-event correlation coefficient is $\rho_\eta(T_{n,1},T_{n,2})$. However, the three coefficients have been presented in a simplified way because in the present study we considered $T_{n,1}=T_{n,2}=T_n$.

Alternatively, the total correlation can be expressed as in [11]:

$$\rho_T(\Delta,T_n)=1-\frac{\sigma_d^2(\Delta,T_n)}{2\sigma_T^2(T_n)} \quad (5)$$

where $\sigma_d^2(\Delta,T_n)$ is the variance between the $\left(\eta_i(T_n)+\ \varepsilon_{ij}(T_n)\right)-\left(\eta_i(T_n)+\ \varepsilon_{ik}(T_n)\right)$, as described in [17].

The correlation coefficient $\rho_\varepsilon(\Delta,T_n)$ is given by definition as:

$$\rho_\varepsilon(\Delta,T_n)=\frac{COV[\varepsilon_{ij}(T_n),\varepsilon_{ik}(T_n)]}{\sigma_\varepsilon^2(T_n)} \quad (6)$$

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

In [11] another expression of the correlation coefficient $\rho_\varepsilon(\Delta,T_n)$ has been given:

$$\rho_\varepsilon(\Delta,T_n)=1-\frac{\sigma_d^2(\Delta,T_n)}{2\sigma_\varepsilon^2(T_n)} \quad (7)$$

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 [11], the following equation should be used:

$$\rho_\varepsilon(\Delta,T_n)=\rho_{gm}(\Delta,T_n)\frac{1+\rho_c(T_n)}{2} \quad (8)$$

where $\rho_{gm}(\Delta,T_n)$ represents 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, defined by [27] as follows:

$$\rho_c(T_n)=0.79-0.023\ln(T_n) \quad (9)$$

## 2.2 Analysis procedure

The objective of this paper is to determine an empirical intra-event correlation model by using a database consisting of 10 earthquake originating from Vrancea intermediate-depth seismic source. The methodology used has been used extensively in literature [11, 12, 13, 14]. The analysis procedure used in order to determine the intra-event correlation model consists of the following steps:

1. Selection of the database used for the analysis and selecting an appropriate *GMPE* in order to calculate the residuals represent the first step in a spatial correlation analysis. It is necessary to select a modern *GMPE*, that differentiates between the intra-event and inter-event variability, with ${\sigma_\eta}^2(T_n)$ and ${\sigma_\varepsilon}^2(T_n)$ respectively.
2. Selection of the ground motion parameter that will be used in the analysis (in some cases this step can be considered implicitly done in step 1, with the selection of the *GMPE*).
3. The analysis of intra-event correlation can be made considering the geometric mean of two orthogonal horizontal components of the strong ground motion parameter, considering the single

random horizontal component of the ground motion parameter, or considering the larger horizontal component of the ground motion parameter.

4. Computation of the total, the inter- and intra-residuals for every seismic event and for every site using the *GMPE* selected in step 1.
5. Pairs of intra-event residuals $(\varepsilon_{ij}, \varepsilon_{ik})$ between two sites "*j*" and "*k*" for a given earthquake "*i*" are determined for every seismic event $(i = \overline{1, r = 10})$ and the differences between the pairs of intra-event residuals are calculated in order to determine the variances $\sigma_d^2(\Delta, T_n)$.
6. The pairs of intra-event residuals (data pairs) are divided into bins according to their interstation distance $\Delta$ and the variance $\sigma_d^2(\Delta, T_n)$ is calculated for every bin.
7. Intra-event correlation coefficients $\rho_\varepsilon(\Delta, T_n)$ are calculated differently, for the geometric mean of two orthogonal horizontal components of the ground motion parameter and for the random horizontal component of the ground motion parameter, according to Eq. (7) and Eq. (8).
8. A functional form for the intra-event spatial correlation $\rho_\varepsilon(\Delta, T_n)$ is chosen and its parameters are determined using non-linear regression.

## 3. Strong ground motion data and data processing

Vrancea intermediate-depth seismic source is one of the few examples of prominent localized intermediate-depth seismicity situated far from active plate boundaries. This earthquake-prone region is situated at the bend of the Carpathian Mountains in Romania and is 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$^2$ [24].

In this study a dataset consisting of 431 triaxial accelerograms (both analogue and digital) recorded during ten earthquakes with moment magnitudes $M_w$ ranging from 5.2 to 7.4 originating from Vrancea intermediate-depth seismic source is used to obtain correlation models for peak ground accelerations and spectral response acceleration values, as well. The Vrancea strong ground motions database used in this study was assembled for the BIGSEES national research project (http://infp.infp.ro/bigsees/default.htm) from several seismic networks of Romania: INFP (National Institute for Earth Physics), INCERC (Building Research Institute), CNRRS (National Centre for Seismic Risk Reduction) and GEOTEC (Institute for Geotechnical and Geophysical Studies). For the 10 seismic events, the characteristics (date of occurrence, focal depth, position of the epicentre and number of records) are presented in Table 1.

Table 1 – Characteristics of the 10 selected seismic events

| Event no. | Date | Latitude | Longitude | $M_W$ | Depth [km] | No. 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 |

Magnitude-focal depths and magnitude-epicentral distances distributions for the 10 used seismic events are shown in Fig. 1 and Fig. 2.

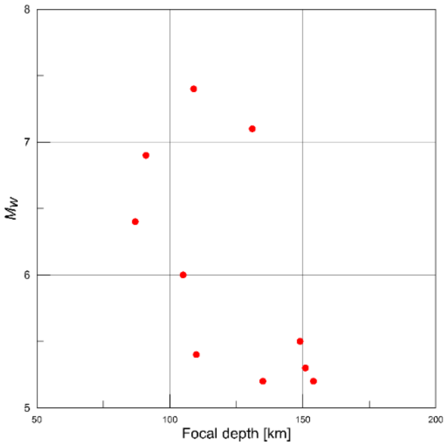


Fig. 1 – Distribution of earthquake magnitude with focal depth

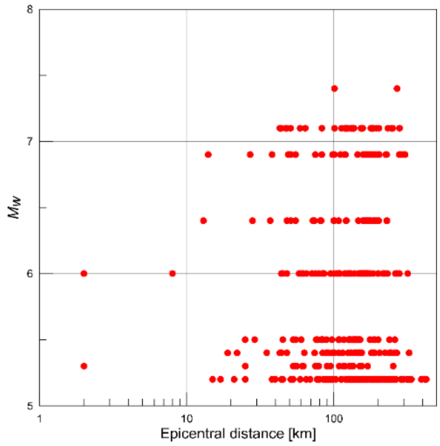


Fig. 2 – Distribution of earthquake magnitude with epicentral distance

## 4. Evaluation of intra-event correlation

In order to develop an intra-event correlation model for the selected database, this chapter follows the steps presented in the analysis procedure (sub-chapter 2.2).

Step 1. In order to evaluate the pairs of intra-residuals, the ground motion prediction equation developed for the Vrancea intermediate-depth seismic source in [24] was chosen in the present study. The *GMPE* was derived from earthquakes with moment magnitudes in the range $5.2 \leq M_w \leq 8.0$ using a national database (formed by the first nine earthquakes from the present study) and an international database (360 strong ground motion records from 29 international earthquakes).

The functional form of the selected *GMPE* developed by [24] is:

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

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 soil class B and $Sb = 0$ otherwise, $Sc = 1$ for soil class C and $Sc = 0$- otherwise, $Ss = 1$ for average soil condition and $Ss = 0$ otherwise.

The independent normal variable $\eta_i$ represents the inter-event residuals (between-earthquake variability of ground motions) with zero mean and $\tau$ standard deviation; the independent normal variable $\varepsilon_{ij}$ represents the intra-event residuals (within-earthquake variability of ground motions) with zero mean and $\sigma$ standard deviation. Both $\tau$ and $\sigma$ are considered spectral period dependent, but are assumed independent of magnitude (other modern *GMPE* consider the standard deviations as functions of the magnitude). Consequently, total variance terms ${\sigma_T}^2$, $\sigma^2$ and $\tau^2$ 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 $\sigma_T$ is defined by:

$$\sigma_T = \sqrt{\sigma^2 + \tau^2} \tag{11}$$

Values for the standard deviations are presented in [24] 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.

Steps 2 and 3. The analysis is performed in terms of *PGA* and *PSA* for spectral periods varying from 0.1 s to 3.0 s, consistent with the *GMPE*'s parameter. Residuals are computed using the geometric mean of two orthogonal horizontal components of *PGA* and *PSA* respectively. Once the intra-correlation model is determined, the correlation model considering a single randomly oriented horizontal component of *PGA* and *PSA* respectively can be derived using Eq. (8).

Step 4. The total residuals $(\eta_i(T_n)+\varepsilon_{ij}(T_n))$ are calculated for all seismic records from the database and are computed from Eq. (1):

$$\eta_i(T_n)+\varepsilon_{ij}(T_n)=\ln Y_{ij}(T_n)-\overline{\ln Y_{\iota J}\left(M_\iota,R_{\iota J},P_{\iota J},T_n\right)} \tag{12}$$

The inter-residuals $\eta_i(T_n)$ are a constant for all sites, for a given seismic event. Because the database consists of 10 seismic events, there are 10 obtained values for $\eta_i(T_n)$. The intra-residuals can be calculated as the difference between the total- and the inter-residuals.

Step 5. Pairs of intra-event residuals are determined for all seismic events. For a given earthquake with "*m*" records, then the number of residual pairs is $[m(m-1)]/2$. For a given earthquake "*i*", for every pair of intra-event residuals between two sites "*j*" and "*k*", the differences $\varepsilon_{ij}(T_n)-\varepsilon_{ik}(T_n)$ are computed. This helps in calculations of the variances $\sigma_d^2(\Delta,T_n)$ in the following step.

Another possibility for steps 4 and 5 is calculating the total residuals and computing pairs of total residuals for every seismic event "*i*". Then, for every pair of total residuals 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 represents an alternative to steps 4 and 5, which offers the same values of the differences (the inter-event component, which is a constant for a given earthquake "*i*", is subtracted), but which does not offer information about the intra- and inter-event residuals.

Step 6. The pairs of intra-event residuals are sorted into bins according to their separation distance *Δ*. A bin can contain pairs from different seismic events, this being permitted through the subtraction of the inter-event component in the previous step. In order to obtain sufficient data pairs per bin, thus insuring small errors, the bin-width of 5 km was chosen, resulting in a minimum number of data pairs per bin of 59. A smaller bin-width (= 2.5km) would have resulted in larger differences between the number of pairs between bins and a small minimum number of pairs per bin. The histogram of the pairs of intra-event residuals with regard to distance is presented in Fig.3 .

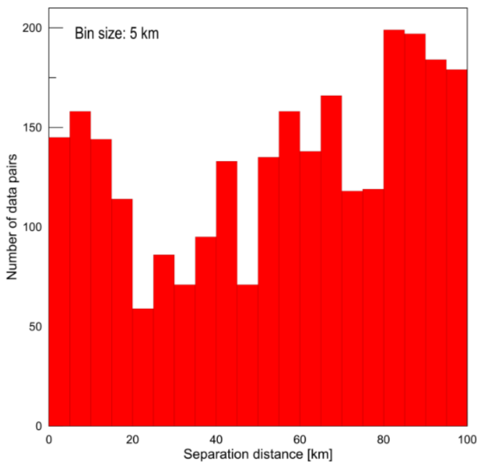


Fig. 3 – Histogram of the number of pairs of intra-event residuals

A total number of 2669 data pairs out of a total number of 11404 pairs was used in the analysis. The number of records, number of data pairs and number of used pairs of residuals from every seismic event are presented in Table 2.

The variances of the residual differences $\sigma_d^2(\Delta,T_n)$ are calculated for every bin and will be used through Eq. (7) in the following step, in order to determine the intra-event correlation coefficients.

Step 7. Intra-event correlation coefficients for the geometric mean of two orthogonal horizontal components of the ground motion parameter are calculated using Eq. (7), where the variances $\sigma_d^2(\Delta,T_n)$ have been determined in the previous step and the intra-event variances ${\sigma_\varepsilon}^2(T_n)$ are obtained from the *GMPE*. The intra-event correlation coefficients based on the randomly orientated horizontal component of the ground motion parameter are determined using Eq. (8), where $\rho_{gm}(\Delta, T_n)$ is the intra-event correlation coefficient computed for the geometric mean according to Eq. (7).

Total correlation coefficients based on the geometric mean of two orthogonal horizontal components of the ground motion parameter and on the randomly orientated horizontal component of the ground motion parameter are obtained using Eq. (5).

Table 2 – Pairs of intra-event residuals used in the analysis

| Event no. | Date | Number of records | Number of available intra-event residuals pairs | Number of used intra-event residuals 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 |

Step 8. Studies in literature [11, 15, 17, 18] determine an empirical relation for the intra-event correlation coefficient by considering a continuous function that can be fitted upon the samples of intra-event correlation coefficients determined in the previous step. In the current study, the functional form of the intra-event spatial correlation coefficient function $\rho_\varepsilon(\Delta, T_n)$ is presented in Eq. (13):

$$\rho_\varepsilon(\Delta, T_n) = \exp(-\alpha(T_n)\Delta^{\beta(T_n)}) \tag{13}$$

where $\alpha(T_n)$ and $\beta(T_n)$ are the model parameters; for the current study, the parameter $\beta(T_n)$ has been considered equal to 0.5, as in [18], regardless of the spectral period value, and the parameter $\alpha(T_n)$ is determined with non-linear regression.

Eq. (13) satisfies the following equations: $\rho_\varepsilon(\Delta, T_n) = 1.0$, for $\Delta = 0$ (for the same site the residuals are considered to be fully correlated) and $\rho_\varepsilon(\Delta, T_n) = 0$, for $\Delta = \infty$ (for two sites with very large separation distance, the spatial correlation is inexistent).

Wang and Takada considered in [18] that the correlation coefficient function $\rho_\varepsilon(\Delta, T_n)$ is characterized by a single parameter called the “correlation length”, which represents the separation distance for which the correlation coefficient $\rho_\varepsilon(\Delta, T_n)$ decreases with $1/e = 0.368$.

Values of the parameter $\alpha(T_n)$ obtained through non-linear regression and the correlation lengths obtained, both for the geometric mean of two orthogonal horizontal components of ground motion parameter and for the randomly orientated horizontal component of the ground motion parameter are presented in Table 3. It can be observed that the correlation lengths have relatively high values, especially for long spectral periods, both for the geometric mean and for the random component. Also, a peak can be observed at a spectral period of 1.6s.

In Fig. 4, 5, 6 and 7 the observed correlation coefficients calculated in step 7 are plotted with the fitted curves obtained using the parameters from Table 3, both for the geometric mean of two orthogonal horizontal components of ground motion parameter and for the randomly orientated horizontal component of the ground motion parameter, for *PGA*, for *PSA* at 0.3 s, *PSA* at 0.7 s and *PSA* at 1.0 s. It is visible that the correlation coefficient $\rho_\varepsilon(\Delta, T_n)$ decreases as the separation $\Delta$ increases. Higher correlation can be observed for the geometric mean compared with the random component, for all four cases, which confirms the results presented in various studies [e.g. 11, 21].

Table 3 – Coefficients and correlation lengths for the developed intra-event correlation model, for *PGA* and spectral period *T* varying from 0.1s to 3.0s, for the geometric mean and for the random component

| Period [s] | Geometric mean | | | Random component | | |
|---|---|---|---|---|---|---|
| | $\alpha$ | $\beta$ | Correlation length [km] | $\alpha$ | $\beta$ | Correlation length [km] |
| T=0s | 0.218 | 0.500 | 21 | 0.227 | 0.500 | 19 |
| T=0.1s | 0.200 | | 25 | 0.215 | | 22 |
| T=0.2s | 0.267 | | 14 | 0.282 | | 13 |
| T=0.3s | 0.255 | | 15 | 0.272 | | 14 |
| T=0.4s | 0.251 | | 16 | 0.268 | | 14 |
| T=0.5s | 0.243 | | 17 | 0.260 | | 15 |
| T=0.6s | 0.193 | | 27 | 0.211 | | 22 |
| T=0.7s | 0.158 | | 40 | 0.177 | | 32 |
| T=0.8s | 0.131 | | 58 | 0.150 | | 44 |
| T=0.9s | 0.127 | | 62 | 0.146 | | 47 |
| T=1.0s | 0.115 | | 76 | 0.134 | | 56 |
| T=1.2s | 0.107 | | 87 | 0.126 | | 63 |
| T=1.4s | 0.102 | | 96 | 0.122 | | 67 |
| T=1.6s | 0.099 | | 102 | 0.119 | | 71 |
| T=1.8s | 0.108 | | 86 | 0.128 | | 61 |
| T=2.0s | 0.126 | | 63 | 0.147 | | 46 |
| T=2.5s | 0.150 | | 44 | 0.172 | | 34 |
| T=3.0s | 0.152 | | 43 | 0.174 | | 33 |

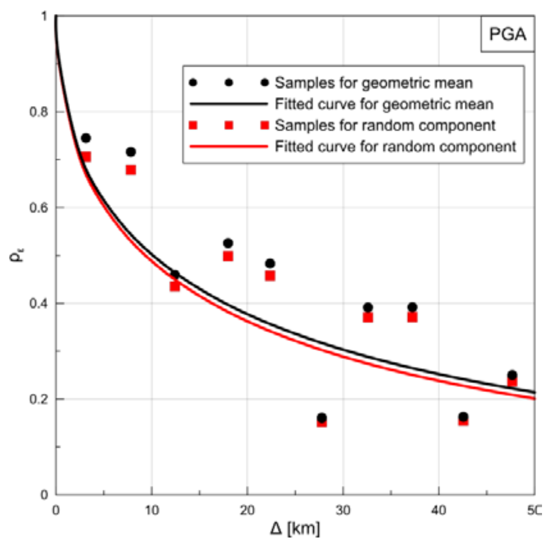


Fig. 4 – Samples of correlation coefficient and the fitted function $\rho_\varepsilon(\Delta, T_n)$ considering the geometric mean and the random component, for *PGA*

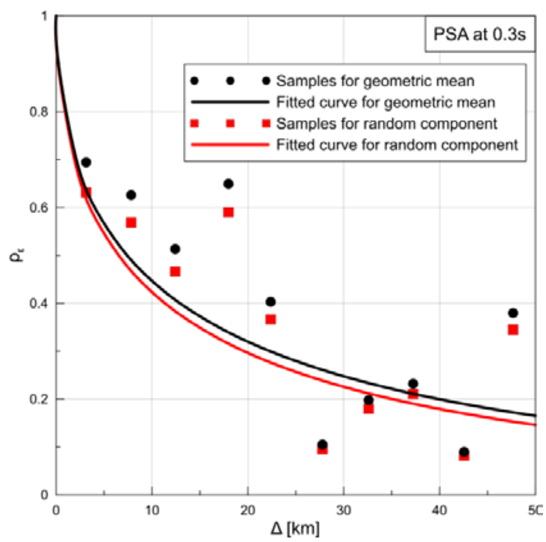


Fig. 5 – Samples of correlation coefficient and the fitted function $\rho_\varepsilon(\Delta, T_n)$ considering the geometric mean and the random component, for *PSA*=0.3 s

The previous observations concerning the decrease of $\rho_\varepsilon(\Delta, T_n)$ with the increase of $\Delta$, the dependency of the correlation coefficient on the spectral period, long correlation lengths for long periods and relatively long correlation lengths for short periods, and higher correlation for the geometric mean results compared with the random component results can all be observed in Fig. 9, which shows the correlation coefficient functions displayed until an separation distance of 100 km, for the geometric mean and the random component, for *PGA*, *PSA* at 0.5 s and at 1.0 s.

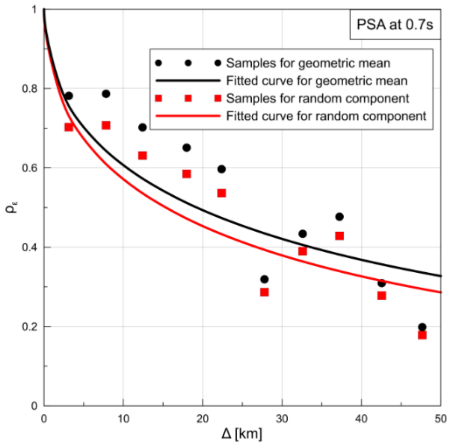


Fig. 6 – Samples of correlation coefficient and the fitted function $\rho_\varepsilon(\Delta, T_n)$ considering the geometric mean and the random component, for *PSA*=0.7 s

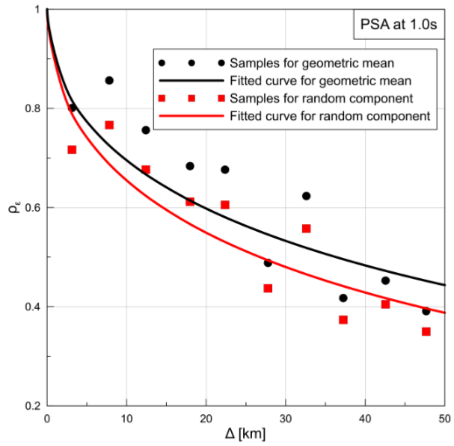


Fig. 7 – Samples of correlation coefficient and the fitted function $\rho_\varepsilon(\Delta, T_n)$ considering the geometric mean and the random component, for *PSA*=1.0 s

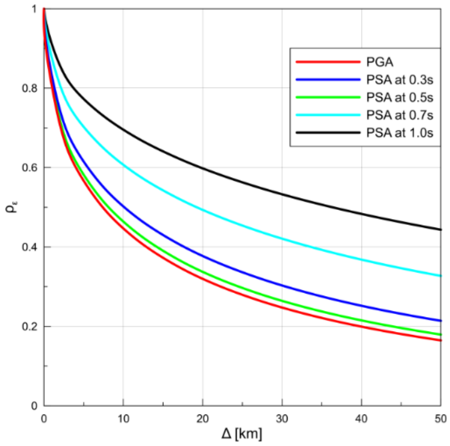


Fig. 8 – Obtained empirical models for *PGA* and for *PSA* at 0.3 s, 0.5 s, 0.7 s and 1.0 s

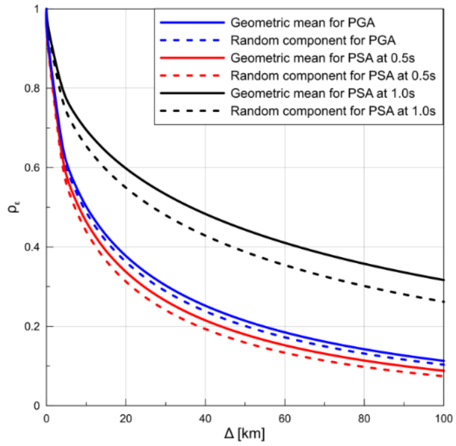


Fig. 9 – Correlation coefficients for the geometric mean and the random component, for *PGA*, *PSA* at 0.5 s and *PSA* at 1.0 s

## 5. Comparison with other correlation models

In order to analyse the correlation model developed in this study, a comparison with other correlation models existing in literature [11, 13] was performed.

The database used in study [11] consists of California and Chi-Chi earthquake records treated separately (for this comparison only the California database results have been used), developing correlation coefficients for the geometric mean and for the larger horizontal component (for this comparison only the geometric mean results have been used). The correlation model presented in [11] adopted the following functional form:

$$\rho_\varepsilon(\Delta, T_n, T_n) = \exp(-\alpha\Delta^\beta) \tag{14}$$

where $\alpha$ and $\beta$ are the model parameters and $\Delta$ is the separation distance between two sites.

The database used in study [13] consists of Japan earthquake records (K-NET, KiK-net and SK-net networks). The correlation model presented in Goda, Atkinson in [13], first developed in [12], adopted the following equation:

$$\rho_\varepsilon(\Delta, T) = \max\{\gamma(\mathrm{T})\exp\left[-\alpha(\mathrm{T})\Delta^{\beta(T)}\right] - \gamma(T) + 1; 0\} \tag{15}$$

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

In Fig. 10 correlation coefficients developed in [11, 13] and in the present study are displayed, for *PGA* and for *PSA* at 1.0s. As remarked in [14], correlation models developed for Japanese data exhibit a more gradual decay with distance and longer correlation lengths compared to the California data, which is clearly visible in Fig. 10. The correlation model developed in the present study shows an even more gradual decay with distance at a spectral period of 1.0s, but offers comparative results to the Japanese data, in the case of *PGA*. This can be caused by regional peculiarities, local geology, peculiarities of the propagation path or the frequency content of ground motion. Future studies can investigate these aspects and perform sensitivity analysis for the present correlation model.

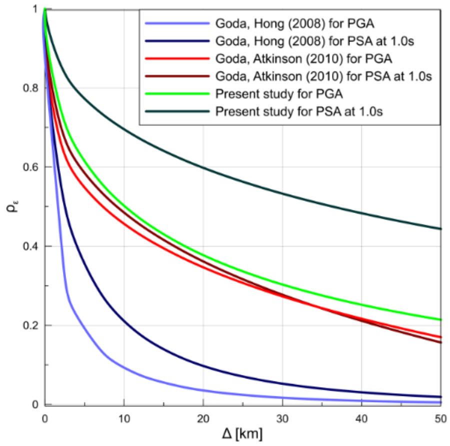


Fig. 10 – Comparison of the correlation model developed in the present study with the models developed by [11, 13] for *PGA* and *PSA* at 1.0s

## 6. Application for Bucharest

Bucharest, the capital city of Romania, has a population of roughly 2 million inhabitants divided into six sectors and which cover an area of about 240km$^2$, according to the latest census from 2011. Based on the information from the same census, the residential building stock of Bucharest comprises 131875 buildings made of various materials (reinforced concrete, masonry, wood, adobe, etc.). However, based on the fact that more than 60% of the existing building stock in Bucharest was built prior to the large Vrancea earthquake of March 1977 ($M_W$ =7.4, $h$ = 94 km) and on its proximity to the Vrancea intermediate-depth seismic source (epicentral distances in the range 80 – 180 km), Bucharest can be considered as one of the cities with the highest seismic risks in Europe. In a future stage of the COBPEE research project, the seismic risk of Bucharest is to be evaluated taking into account the spatial correlation model proposed in this paper. An example of the *PGA* distribution in Bucharest for a $M_W$ = 7.5 earthquake and focal depth of 120 km is shown in Figure 11 below.

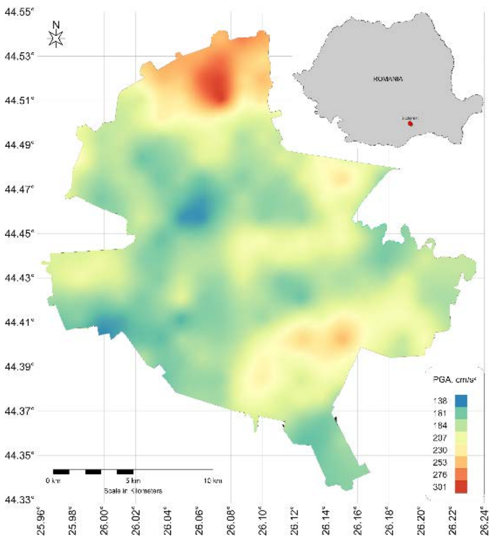


Fig. 11 – *PGA* distribution in Bucharest for an earthquake originating in the Vrancea seismic source with

$M_W$ = *7.5* and focal depth of 120 km

## 7. Conclusions

An intra-event correlation model has been developed for the peak ground acceleration and for pseudo-spectral accelerations for spectral periods varying from 0.1 s to 3.0 s using a database consisting of 10 earthquakes originating from Vrancea intermediate-depth seismic source and a *GMPE* developed for the Vrancea intermediate-depth seismic source, the analysis being performed considering the geometric mean of two random orthogonal components of the ground motion parameter and considering the random horizontal component of the ground motion parameter.

Some aspects regarding the subject of spatial correlation of ground motion have been confirmed: the decrease of the correlation coefficients with respect to separation distance between observation sites, the dependency of the correlation coefficients on the spectral period and higher correlation for the geometric mean results compared with the random component results. The correlation model shows long correlation lengths, especially for long spectral periods, and a gradual decay of the correlation coefficient with separation distance. Through comparisons with two correlation models existing in literature, for California and Japan data respectively, it has surfaced that the correlation model developed for the Vrancea intermediate-depth seismic source in the present study is similar to the ones determined for the Japanese data.

Future studies can concentrate on sensitivity analysis in order to determine the cause of long correlation lengths and the gradual decay of correlation coefficients, studying the impact of the local geology, the frequency content of ground motion and the regional peculiarities on the correlation model, numerical simulation of spatially correlated ground motion parameters or seismic risk analysis for lifelines or building portfolios (like in the case of Bucharest).

## 8. Acknowledgements

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