COMPDYN 2011
III ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis, V. Plevris (eds.)
Corfu, Greece, 25–28 May 2011

INTRA-EVENT SPATIAL CORRELATION OF GROUND MOTION USING L'AQUILA EARTHQUAKE GROUND MOTION DATA

Gian Paolo Cimellaro[1], Alessandro De Stefano[2], and Andrei M. Reinhorn[2]

[1] Department of Structural and Geotechnical Engineering (DISTR),
Politecnico di Torino, 10129, Turin, Italy
e-mail: gianpaolo.cimellaro@polito.it

[2] Department of Civil, Structural and Environmental Engineering, University at Buffalo, The State University of New York, 14260-4300, Buffalo, New York, USA.
e-mail: reinhorn@buffalo.edu

Keywords: intra-event, inter-event, ground motion correlation, spatial correlation, response spectra.

Abstract. *The intensities f ground motions and structural responses at two sites are correlated. The magnitude of the correlation depends on the distance between the sites and the natural vibration period of the structures. Spatial correlation of intra-event peak ground motion amplitudes at different sites is an important issue for seismic hazard and risk assessment of spatially distributed buildings and infrastructures. Correlated seismic effects cause acute concentration and accumulation of seismic losses, potentially resulting in a catastrophic event. The adequacy of the existing spatial correlation model has been checked using the L'Aquila earthquake ground motion data. Spatial correlations based on the L'Aquila earthquake data decreases gradually with increasing inter-station separation distance. At short separation distances, the estimated spatial correlation data points show large variability around the average trend. At short separation distances such as 1 km, where empirical data are limited and estimates are uncertain, discretion is required in adopting such models for seismic hazard and risk assessment of spatially distributed structures.*

1 INTRODUCTION

Traditional probabilistic seismic hazard analysis (PSHA) is often focused on a single site, however often the seismic hazard analysis for multiple sites is of interest (e.g. for regionally located building assets (portfolio) and spatially distributed systems (lifelines)) therefore correlation of ground motion intensity measures (e.g. peak ground motion, response spectra, etc.) at different location for the same seismic event need to be evaluated. Correlated seismic effects cause acute concentration and accumulation of seismic losses, and increased correlation of ground motion parameters affects the probability distribution of seismic risk for multiple structures due to the simultaneous occurrence of structural damage and collapse. The spatial intra-event correlation can be analyzed empirically for a given area, but a dense observation of records from numerous earthquakes is necessary and it has not been extensively investigated so far. The spatial intra-event correlation of ground motion parameters such as PGA have already been investigated in previous studies by Boore et al. [1] that considered particular earthquakes in California; Wang and Takada [2] considered 5 earthquakes in Japan and the Chi-Chi earthquake in Taiwan; Goda and Atkinson [3] used the K_NET and the KiK-net records collected in Japan to study spatial correlation for peak ground acceleration and pseudo-spectra acceleration. However, not many studies can be found on the correlation of the PSA at different periods and sites using a European database. Therefore this study focuses on estimating the correlation PSAs responses developing empirical equations that are able to predict the correlation coefficient considering both spatial separation distance and natural vibration periods of SDOF systems using a European earthquake set. In the paper intra-event and inter-event spatial correlation models have been proposed and calibrated using the records from the 2009 L'Aquila earthquake in Central Italy. The inter-event correlation is function of the considered ground-motion parameters, whereas the intra-event correlation is a function of the considered ground-motion parameters and the separation distance between two sites of interest. Sensitivity of the observed spatial correlation to the uncertainty in the magnitude and distance is also investigated.

2 CLASSIFICATION OF UNCERTAINTIES

Uncertainties in an attenuation relationship model (AR) can be distinguished between epistemic and aleatory uncertainty. Epistemic uncertainty results from the limited amount of observed data, while aleatory uncertainty describes the disagreement between observations and predictive models which is due to the absence of a physical explanation or due to the parameters that are not included in the predictive equations. Furthermore, the total aleatory variability [4][5] is separated in three independent components:

1. Inter-event variability (*earthquake to earthquake*);
2. Intra-event variability (*site-to-site*);
3. Variability remaining after accounting for the inter-event and the intra-event variability;

Usually the last two components are joined in a single one.

2.1 Inter-event correlation $\eta(T)$

The inter-event correlation describes the correlation among different seismic events (*earthquake –to–earthquake*) at the same site. In other words, earthquake ground motions at different sites caused by the same earthquake have something in common that depends on variation of earthquake source characteristics. So the inter-event residual $\eta(T)$ is a constant across all the sites during a given earthquake.

2.2 Intra-event correlation ε'(*T*)

The intra-event correlation describes the correlation among different sites (*site-to-site*) regarding the same seismic event. In other words, the intra-event variability considers the proposition that earthquake ground motion for a given event at different sites varies to some extent because of peculiarities of propagation path and local site conditions. Therefore, Tsai et al. [6] separated intra-event variability into path-to-path and site-to-site components. The site-to-site correlation depends on the ground conditions of the sites and it will decrease for sites that do not share the same geology, however a systematic research on quantifying the dependence has not been performed so far. Both inter-event and intra-event correlations can be incorporated in probabilistic seismic hazard analysis and risk assessments, because the ratio between joint probabilities and the probabilities at individual sites can vary depending on (i) inter-event correlation or ratio of inter-event and total components of variability, and on (ii) whether or not the hazard is dominated by one source or many sources.

3 DEVELOPMENT OF CORRELATION EQUATIONS

Attenuation relationships (ARs) describe the probability distribution of spectral acceleration at an individual period. A typical empirical AR at *m* locations during *n* seismic events is typically modeled explicitly as a lognormal function as follow

$$\begin{aligned} &\log_{10} S_{a,ij}\left(T_n\right) = f\left(M_j, R_{ij}, \lambda, T_n\right) + \eta_j\left(T_n\right) + \varepsilon_{ij}\left(T_n\right) \\ &i = 1,2,\ldots,m;\ \ \text{j=1,2,…,n} \end{aligned} \tag{1}$$

where $f\left(M_j, R_{ij}, \lambda, T_n\right) = \mu_{log_{10}\left(S_a(T)\right)}\left(M_j, R_{ij}, \lambda, T_n\right)$ is the predicted geometric mean of the logarithm in base 10 of the spectral acceleration Sa provided by the AR for the ith site in the jth seismic event. Equation (1) stands also if instead of Sa is considered PGA or PGV, but in these cases the equation is no longer function of T_n and it is function of the earthquake magnitude *M*, distance *R*, and a set of other explanatory variables *λ* such as local site conditions and faulting mechanism; $\eta_j\left(T_n\right)$ is the inter-event variability with zero mean and standard deviation $\sigma_\eta\left(T_n\right)$; $\varepsilon_{ij}\left(T_n\right)$ is the intra-event variability with zero mean and standard deviation $\sigma_\varepsilon\left(T_n\right)$. Usually the standard deviation of $\varepsilon_{ij}\left(T_n\right)$ is significantly larger than the standard deviation of $\eta_j\left(T_n\right)$, so $\varepsilon_{ij}\left(T_n\right)$ is the dominant contributor to the total $\varepsilon_T\left(T_n\right) = \eta_j\left(T_n\right) + \varepsilon_{ij}\left(T_n\right)$ that is computed for each record of the dataset at a range of periods using a given AR as follow

$$\varepsilon_T\left(T_n\right) = \frac{log_{10}\left(S_a\left(T_n\right)\right) - \mu_{log_{10}\left(S_a\left(T_n\right)\right)}\left(M, R, T_n\right)}{\sigma_{log_{10}\left(S_a\left(T_n\right)\right)}\left(M, T_n\right)} \tag{2}$$

where $\log_{10}(S_a(T_n))$ is the logarithm in base 10 of the observed spectral acceleration value, while $\mu_{log10}(S_a(T_n))$ and $\sigma_{\log 10}(S_a(T_n))$ are evaluated from the AR. The uncertainty εT (Tn) comprises the inter-event $\eta(T_n)$ and the intra-event $\varepsilon_{ij}(T_n)$ uncertainty. The inter-event residual $\eta(T_n)$ is a constant across all the sites during a given earthquake. Therefore, when using records from a single earthquake, estimation of the intra-event (*site-to-site*) correlation

$\rho_\varepsilon\left(\Delta,T_n\right)$ does not require the knowledge of the inter-event residual for the earthquake. However, when the used database contains records from several earthquakes, using the same procedure the total correlation coefficient $\rho_T\left(\Delta,T_{n1,}T_{n2}\right)$ between $\eta_j\left(T_{n1}\right)+\varepsilon_{ij}\left(T_{n1}\right)$ and $\eta_j\left(T_{n2}\right)+\varepsilon_{kj}\left(T_{n2}\right)$ for a randomly selected seismic event at two recording stations separated by the distance (km) is given by the approximated expression [7][8]

$$\rho_T\left(\Delta,T_{n1,}T_{n2}\right)=\frac{\rho_\eta\left(T_{n1,}T_{n2}\right)\left[\sigma_\eta\left(T_{n1}\right)\sigma_\eta\left(T_{n2}\right)+\rho_\varepsilon\left(\Delta,T_{MAX}\right)\sigma_\varepsilon\left(T_{n1}\right)\sigma_\varepsilon\left(T_{n2}\right)\right]}{\sigma_T\left(T_{n1}\right)\sigma_T\left(T_{n2}\right)} \tag{3}$$

where $\rho_\eta\left(T_{n1,}T_{n2}\right)$ represents the correlation between $\eta_j(T_{n1})$ and $\eta_j(T_{n2})$; $\rho_\varepsilon\left(\Delta,T_{MAX}\right)$ is the intra-event spatial correlation focusing on a single vibration period T_n, and T_{MAX} is the larger between T_{n1} and T_{n2}; $\sigma_\eta\left(T_n\right)$ is the standard deviation of the inter-event residuals $\eta_j\left(T_n\right)$; $\sigma_\varepsilon\left(T_n\right)$ is the standard deviation of the intra-event residuals $\varepsilon_{ij}\left(T_n\right)$ and $\sigma_T\left(T_n\right)$ is the standard deviation of the total residuals given in equation (2). The total correlation $\rho_T\left(\Delta,T_{n1,}T_{n2}\right)$ and the intra-event correlation $\rho_\varepsilon\left(\Delta,T_n\right)$ are related through Equation (3), while the inter-event component can be removed from the residuals of earthquake j using the estimation of $\hat{\eta}_j$ [9]

$$\hat{\eta}_j=\frac{\sigma_\eta^2\sum_{i=1}^{n_j}\left[log_{10}\left(S_{a,i,j}\left(T_n\right)\right)-\mu_{log_{10}\left(S_a\left(T_n\right)\right),i,j}\left(M,R,T_n\right)\right]}{n_j\sigma_\eta^2+\sigma_\varepsilon^2} \tag{4}$$

3.1 Evaluation of inter-event spatial correlation

The inter-event correlation is evaluated by using the regression residuals η(Tn) based on the selected ground motion data. For a given pair of two natural vibration periods T_{n1} and T_{n2}, $\rho_\eta\left(T_{n1,}T_{n2}\right)$ is evaluated using the Pearson's linear correlation coefficient. In details, the observed values of $\rho_\eta\left(T_{n1,}T_{n2}\right)$ are determined using the following step-by-step procedure:

1. Select the sites for a given earthquake;
2. Given the $S_a(T_n)$ values at several sites for one earthquake, and given the predicted value at each site using the AR, the residuals values can be determined;
3. The inter-event residual $\eta(T_n)$ is the mean of the residual values and it is associated to a given earthquake, so it will not change from site to site;
4. The inter-event residual $\eta(T_n)$ for different earthquakes is evaluated using step 2 and 3, so if n earthquakes are provided n inter-event residuals $\eta(T_n)$ are determined;
5. Repeating step 1, 2 and 3 for m vibration periods until a $m\times n$ matrix is determined that can be used to determine the inter-event correlation coefficient $\rho_\eta\left(T_{n1,}T_{n2}\right)$ as shown in the example below.

3.2 Evaluation of intra-event spatial correlation

The intra-event correlation is evaluated by using the regression residuals $\varepsilon_{ij}(T_n)$ based on the selected ground motion data. The observed intra-event spatial correlation at a single vibration period $\rho_\varepsilon(\Delta, T_n)$ (i.e., $\rho_\varepsilon(\Delta, T_{n1,} T_{n2})$ with $T_{n1}=T_{n2}$), can be determined using the following step-by-step procedure:

1. Select the sites for a given earthquake;
2. Compute the separation distance Δ for all pairs of sites (or stations);
3. Compute the differences ε using equation (2);
4. Divide the range of Δ into bins so that the separation distance in the same bin is $\Delta \pm \delta/2$;
5. All pairs of sites that fall in the bin centered at *Δ* are used to compute the correlation function $\rho_\varepsilon(\Delta, T_n)$ that will be function of the period and the sites distance *Δ;*

In detail, the observed intra-event correlation $\rho_\varepsilon(\Delta, T_n)$ at a given vibration period is carried out by analyzing regression residuals from the AR using the following equation

$$\rho_\varepsilon(\Delta, T_n) = 1 - \frac{\left[\sigma_d(\Delta, T_n)\right]^2}{2\left[\sigma_\varepsilon(T_n)\right]^2} \tag{5}$$

where $\sigma_d(\Delta, T_n)$ represents the variance of the difference $\varepsilon_{ij}(T_n)$-$\varepsilon_{kj}(T_n)$ calculated at discrete intervals Δ; represents the variance of the difference $\varepsilon_{ij}(T_n)$-$\varepsilon_{kj}(T_n)$ calculated over the entire sample. The observed values of $\rho_\varepsilon(\Delta, T_n)$ given by equation (5) can be compared with the predicted values of the proposed model given by the following equation

$$\rho_\varepsilon(\Delta, T_n) = e^{-\alpha(T_n)\Delta} \tag{6}$$

where $\alpha(T_n)$ is the parameter that needs to be calibrated according to the earthquake data used.

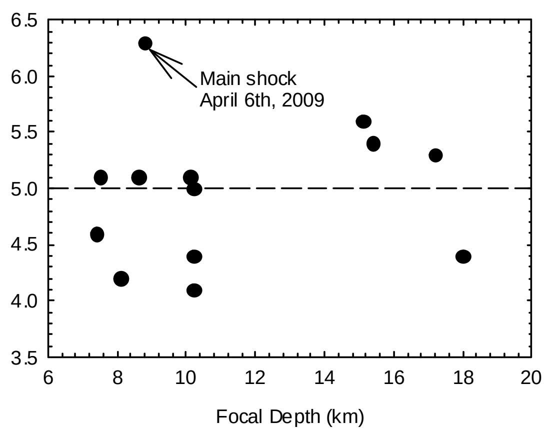

Figure 1: (Moment magnitude-focal depth) distributions of L'Aquila aftershocks.

4 L'AQUILA EARTHQUAKE DATA

All the ground motions used for the calibration of the predictive correlation models in the paper are extracted from the ITACA Database [10], http://itaca.mi.ingv.it/ItacaNet/ (last accessed January 31, 2011). The goal of the work is to investigate the intra-event and inter-event spatial correlation; therefore it is better to focus on well-recorded events that produced numerous observations at different locations such as L'Aquila 2009 earthquake. The selected ground motion set includes L'Aquila main shock and the following 12 main aftershocks and the main seismic characteristics are summarized in Table 1. All events are shallow events with a focal depth between 7 and 18 km and a moment magnitude between 4 and 6.3 as shown in Figure 1. The fault mechanism of all events is normal type. The geographical location of the aftershocks is shown in Figure 2b, while the spatial distribution of the INGV network station is shown in Figure 2a. Totally 4725 records from the 13 earthquakes have been considered for the analysis. The use of this set of record is to assess whether the observed differences in the decaying rate of the spatial correlation of the PGAs persist also for the spatial correlation of the PSAs and to calibrate the predictive correlation models for the region.

	Event (Date - Time)	**Event Name**	**Latitude**	**Longitude**	**M_L**	**M_W**	**Depth (km)**
1	2009-04-06 01:32:29	L'Aquila Main Shock	42.334	13.334	5.8	6.3	8.8
2	2009-04-06 02:37:04	Aquila	42.366	13.340	4.6	5.1	10.1
3	2009-04-06 02:37:04	Aquila	42.362	13.333	4.0	4.4	10.2
4	2009-04-06 23:15:37	Gran Sasso	42.451	13.364	4.8	5.1	8.6
5	2009-04-07 09:26:28	L'Aquila Earthquake	42.342	13.338	4.7	5.0	10.2
6	2009-04-07 17:47:37	L'Aquila Earthquake	42.275	13.464	5.3	5.6	15.1
7	2009-04-07 21:34:29	Aquila	42.380	13.376	4.2	4.6	7.4
8	2009-04-08 22:56:50	Aquila	42.507	13.364	4.3	4.1	10.2
9	2009-04-09 00:52:59	Gran Sasso	42.484	13.343	5.1	5.4	15.4
10	2009-04-09 03:14:52	Aquila	42.338	13.437	4.2	4.4	18.0
11	2009-04-09 04:32:44	Aquila	42.445	13.420	4.0	4.2	8.1
12	2009-04-09 19:38:16	Aquila	42.501	13.356	4.9	5.3	17.2
13	2009-04-13 21:14:24	Aquila	42.504	13.363	4.9	5.1	7.5

Table 1: Summary of the seismic characteristics of the 13 Earthquakes selected from the ITACA database.

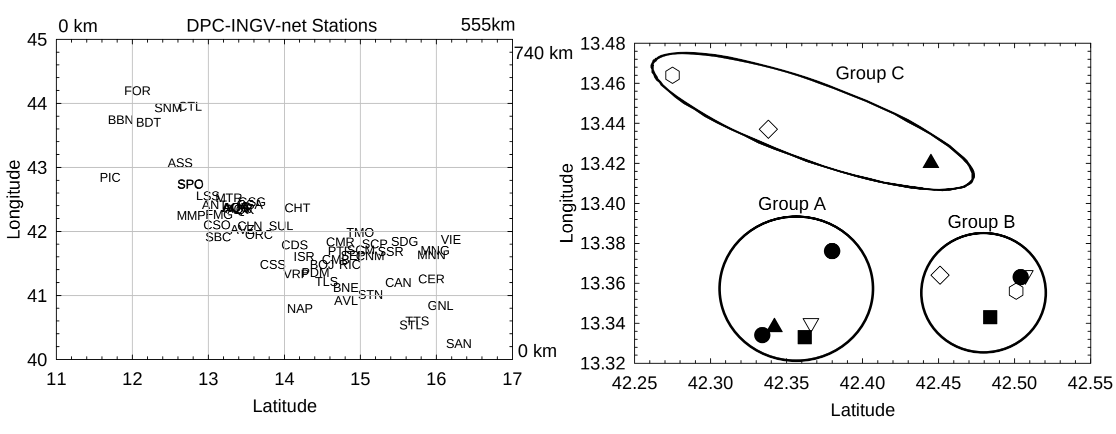

Figure 2: Geographical location of the (a) stations and of the (b) 13 aftershocks of L'Aquila earthquakes divided by groups.

5 NUMERICAL RESULTS

To investigate the variation of the empirical spatial correlation based on the residuals, statistical analysis is conducted individually for a selected major earthquake (L'Aquila Earthquake, 2009) that have a large number of records. The investigation on a single earthquake it is useful because it can provide valuable insights on the variability of spatial correlation among different sites and the dependence of spatial correlation on the vibration period for a given earthquake. To investigate the spatial correlation and carry out sensitivity analysis, a complete set of PSA responses are calculated, and the regression analysis is carried out for PSA for values of Tn ranging from 0.01 to 2 sec. The ε values were computed for each record of the dataset at a range of periods using Ambraseys AR [11]. For each record and period of the dataset, ε values were computed using Equation(2). An analysis of correlations of epsilon values has been carried out using the earthquake records in Table 1 following the procedure described above. In Figure 3 are shown the observed intra-event correlation coefficient $\rho_\varepsilon(\Delta, T_n)$ evaluated using equation (5), when considering only L'Aquila earthquake main shock.

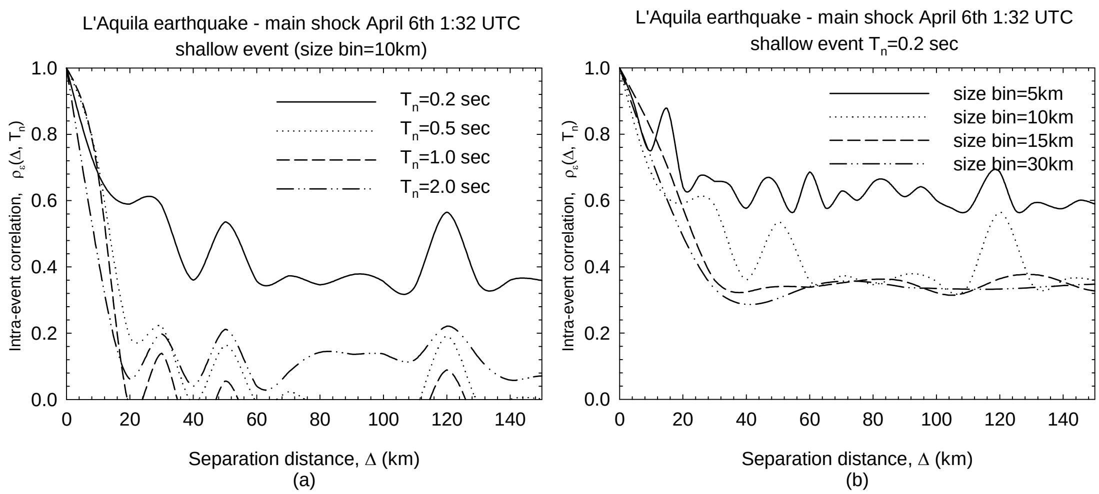

Figure 3: (a) Intra-event spatial correlation for PSA at 0.2, 0.5, 1.0 and 2 sec based on Equation (5) ; (b) Intra-event spatial correlation for PSA at 0.2 sec and different size bins at 5, 10, 15 and 30 km.

It can be observed that there is more correlation at high frequencies ($T_n=0.2s$), while at low frequencies and for separation distances more than 20 km, there is almost no correlation (Figure 3a). When considering the PSA at $T_n=0.2s$ the correlation values are stable for bin size resolutions between 10 and 30 km (Figure 3b).

When considering all earthquake set in Table 1, there is no correlation at low frequencies for distances Δ higher than 20km (Figure 4a). The correlation remains stables for values of bin size between 10 and 15 km, while it is not reliable for bin sizes higher than 30 km at high frequencies (Figure 4b).

An analysis of intra-event correlations of epsilon values at different periods has been carried out using 4725 records from the 13 earthquakes of L'Aquila region. For a given pair of two natural vibration periods T_{n1} and T_{n2}, the observed correlation coefficient $\rho_\varepsilon(\Delta, T_{n1}, T_{n2})$ between $\varepsilon_{ij}(T_{n1})$ and $\varepsilon_{ij}(T_{n2})$ is evaluated using equation (5).

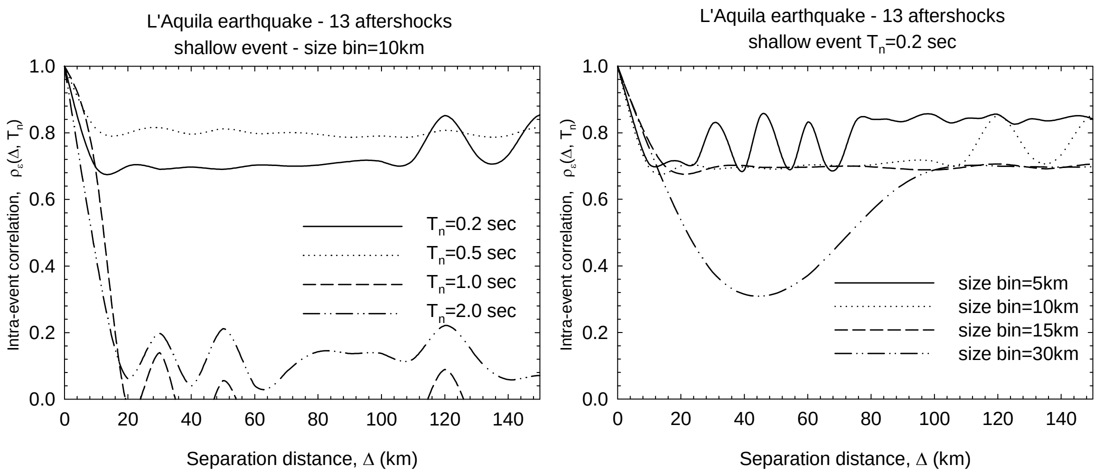

Figure 4: Intra-event spatial correlation for l'Aquila earthquake (a) for different PSAs at different periods; (b) for PSA at 0.2 sec and different size bins.

In Figure 5 are shown the observed intra-event spatial correlation $\rho_\varepsilon(\Delta, T_{n1}, T_{n2})$ for different periods and for bins separation distance of 0-20, 20-40, 40-60 and 60-80 km when all events are included. The shape of the intra-event spatial correlation is not affected significantly by the bin size resolution when all events in Table 1 are considered, while when only L'Aquila earthquake main shock is considered (Figure 6) the observed intra-event spatial correlation is affected by the bin size resolution.

Δ	A0	A1	A2	R^2
0 - 15 km	-0.0859	0.7095	1.0683	0.8613
15 - 30 km	0.8184	0.0912	0.1639	0.7443
30 – 60 km	0.6946	0.2014	0.3008	0.8738
60 – 100km	0.6137	0.2169	0.3842	0.8823

Table 2: Parameters of the correlation coefficient model for equation (7).

5.1 Proposed predictive intra-event correlation equations for ρε(Δ, Tn1, Tn2)

A correlation model of $\rho_\varepsilon\left(\Delta, T_{n1,} T_{n2}\right)$ is proposed and validated by comparison with the observed values of $\rho_\varepsilon\left(\Delta, T_{n1,} T_{n2}\right)$ obtained by Equation (5). Several linear and nonlinear equations were fitted to the observed data of the intra-event correlation coefficients and results were sorted using the r2 value as goodness of fit measure. Finally, the predictive equation was selected based on the number of parameters adopted, the simplicity and the goodness of fit. The proposed predictive intra-event correlation coefficient model between the residual values of a single horizontal component at two differing periods for L'Aquila main event is given by

$$\rho_\varepsilon\left(\Delta, T_{n1,} T_{n2}\right) = A0 + A1 \cdot e^{-T_{\min}} + A2 \cdot e^{-T_{\max}} \quad (7)$$

where $T_{min}=min(T_1,T_2)$ and $T_{max}=max(T_1,T_2)$. The parameters of the model in Equation (7) for different distance range Δ are listed in Table 2, while results of the model for different range distances are shown in Figure 7. The r^2 value that describes the goodness of fit oscillates between 0.7443 and 0.8823 (Figure 7). The uncertainties are probably due to the fact that only the main shock is used and therefore results are sensitive to the separation distance and it is difficult to find a simple predictive model that can be adopted for different distance ranges.

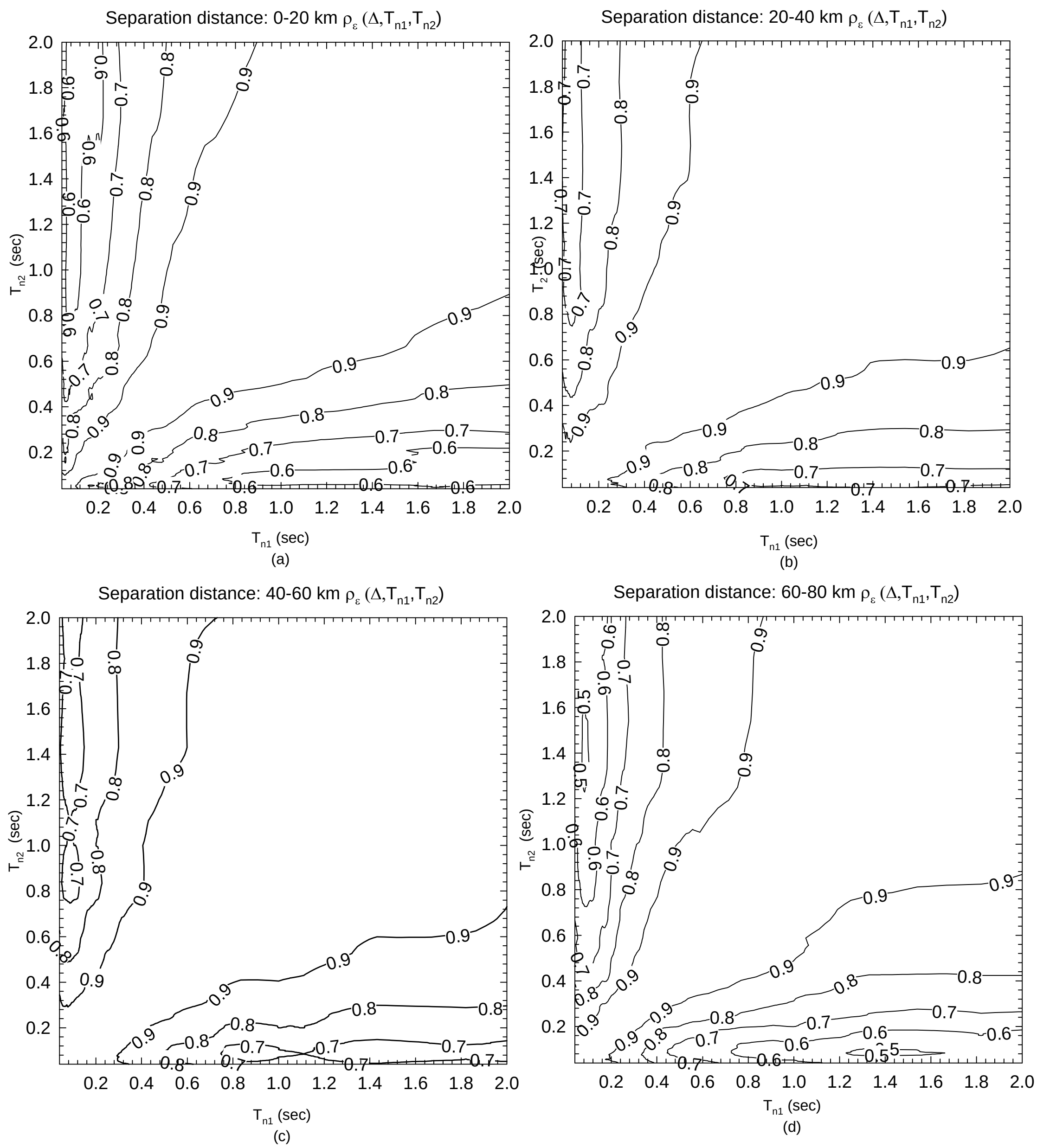

Figure 5: Observed intra-event spatial correlation ρε(Δ, Tn1, Tn2) for separation distance bins of 0-20, 20-40, 40-60 and 60-80 km for all events.

Another analytical predictive equation has been proposed by the author when all earthquakes in Table 1 area are considered.

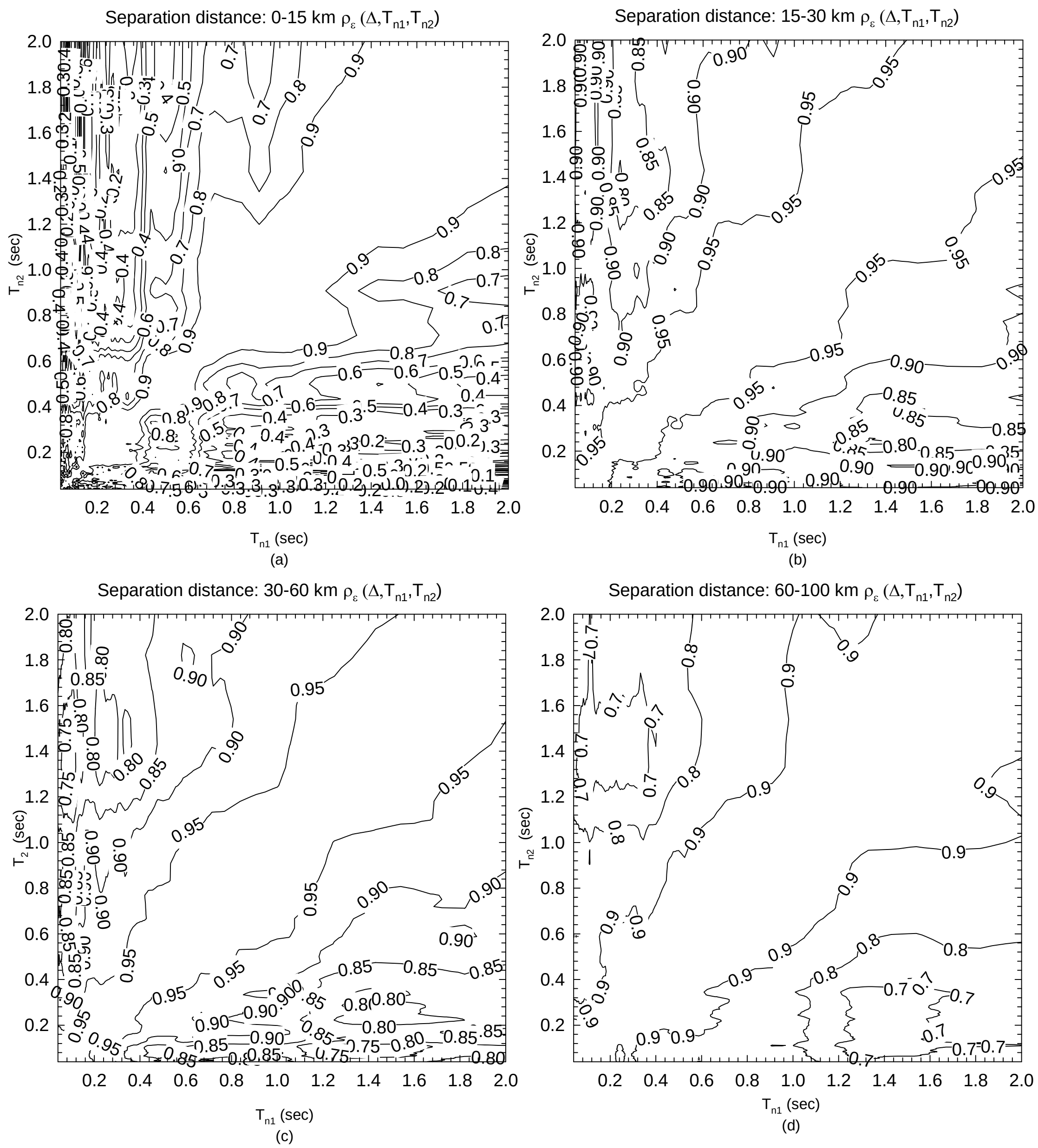

Figure 6: Observed intra-event spatial correlation ρε(Δ, Tn1, Tn2) for separation distance bins of 0-15, 15-30, 30-60 and 60-100 km for L'Aquila main shock event.

The predictive intra-event correlation coefficient model is given by

$$\rho_{\varepsilon}\left(\Delta,T_{n1,}T_{n2}\right)=\left(A0+A1\cdot e^{-T_{\min}}+A2\cdot e^{-T_{\max}}\right)^{-1} \quad (8)$$

where the parameters of the model in Equation (8) for different distance range Δ are listed in Table 3, while the predicted values are shown in Figure 8 for different distance ranges. The r2 value that describes the goodness of fit oscillates between 0.9289 and 0.9496 (Figure 8), showing the robustness of the model for different distance ranges.

Δ	A0	A1	A2	R^2

0 - 20 km	0.7941	1.2669	-0.9924	0.9289
20 - 40 km	0.9180	0.7203	-0.6322	0.9496
40 – 60 km	0.9014	0.7684	-0.6587	0.9420
60 – 80km	0.8480	1.2394	-1.0756	0.8823

Table 3: Parameters of the correlation coefficient model for equation (8).

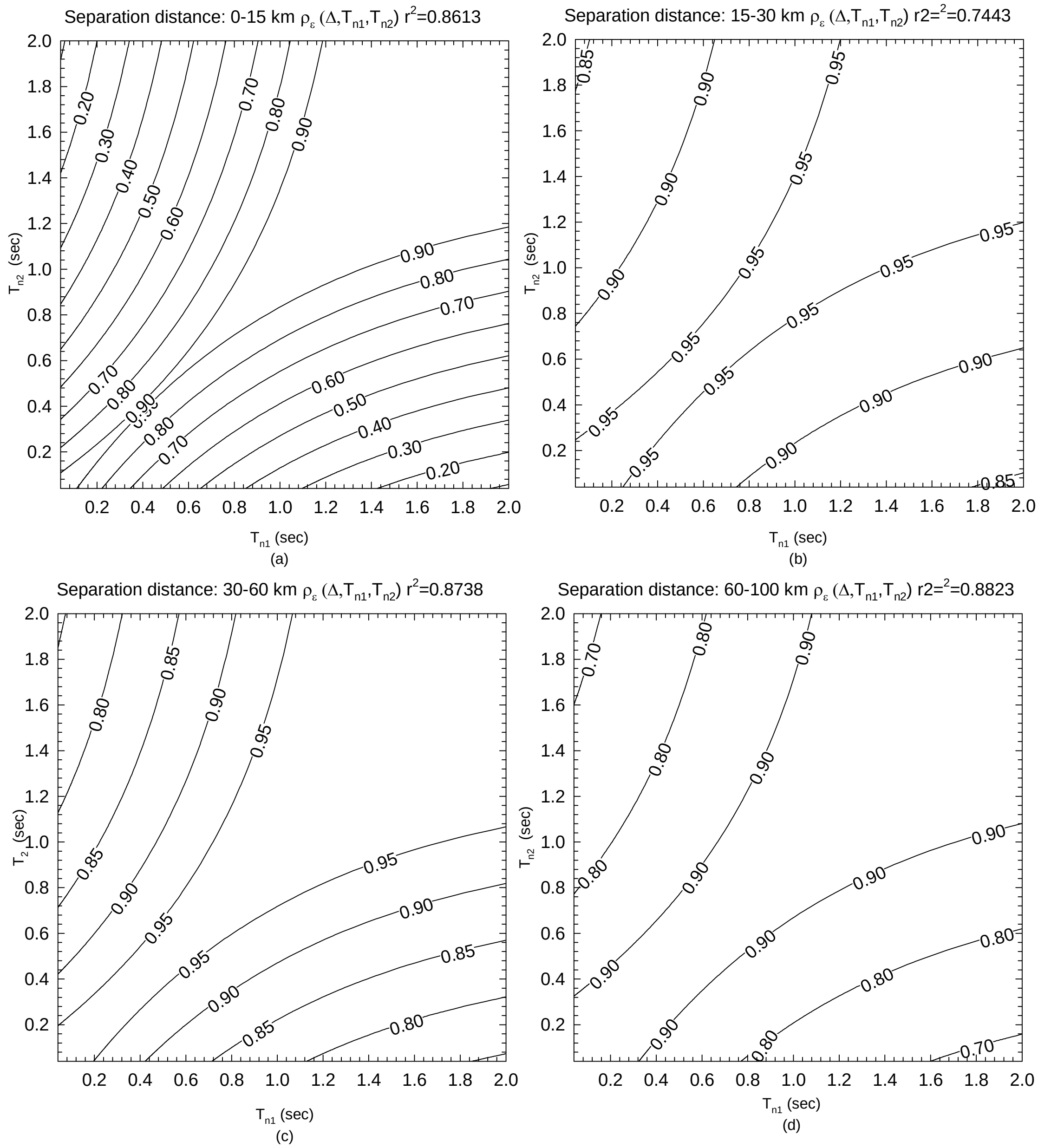

Figure 7: Intra-event spatial correlation model ρε(Δ, Tn1, Tn2) for separation distance bins of 0-15, 15-30, 30-60 and 60-100 km for L'Aquila main shock event.

5.2 Proposed predictive inter-event correlation equations for $\rho_\eta(T_{n1}, T_{n2})$

The inter-event correlation of pseudo spectra acceleration is evaluated by using regression residuals $\eta(T_n)$, based on the records from the earthquakes in Table 1 using the procedure described above. For a given pair of two natural vibration periods T_{n1} and T_{n2}, $\rho_\eta(T_{n1}, T_{n2})$ is evaluated by using the Pearson's linear correlation coefficient. The observed values of $\rho_\eta(T_{n1}, T_{n2})$ are shown in Figure 9a showing that the inter-event correlation decreases monotonically as the inter period separation distance increases. The correlation has been evaluated using the stations that were recording the seismic series of 2009 L'Aquila earthquake. To characterize $\rho_\eta(T_{n1}, T_{n2})$ the following predictive model is proposed

$$\rho_\eta\left(T_{n1,}T_{n2}\right) = e^{\left(A0 + A1/T_{\min} + A2/T_{\min}^{1.5} + \cdot A3/T_{\max} + A4/T_{\max}^{2}\right)} \tag{9}$$

where the parameters of the model are respectively, A0=-0.0045; A1=-0.02256; A2=0.0036; A3=0.0165 and A4=-0.0005.

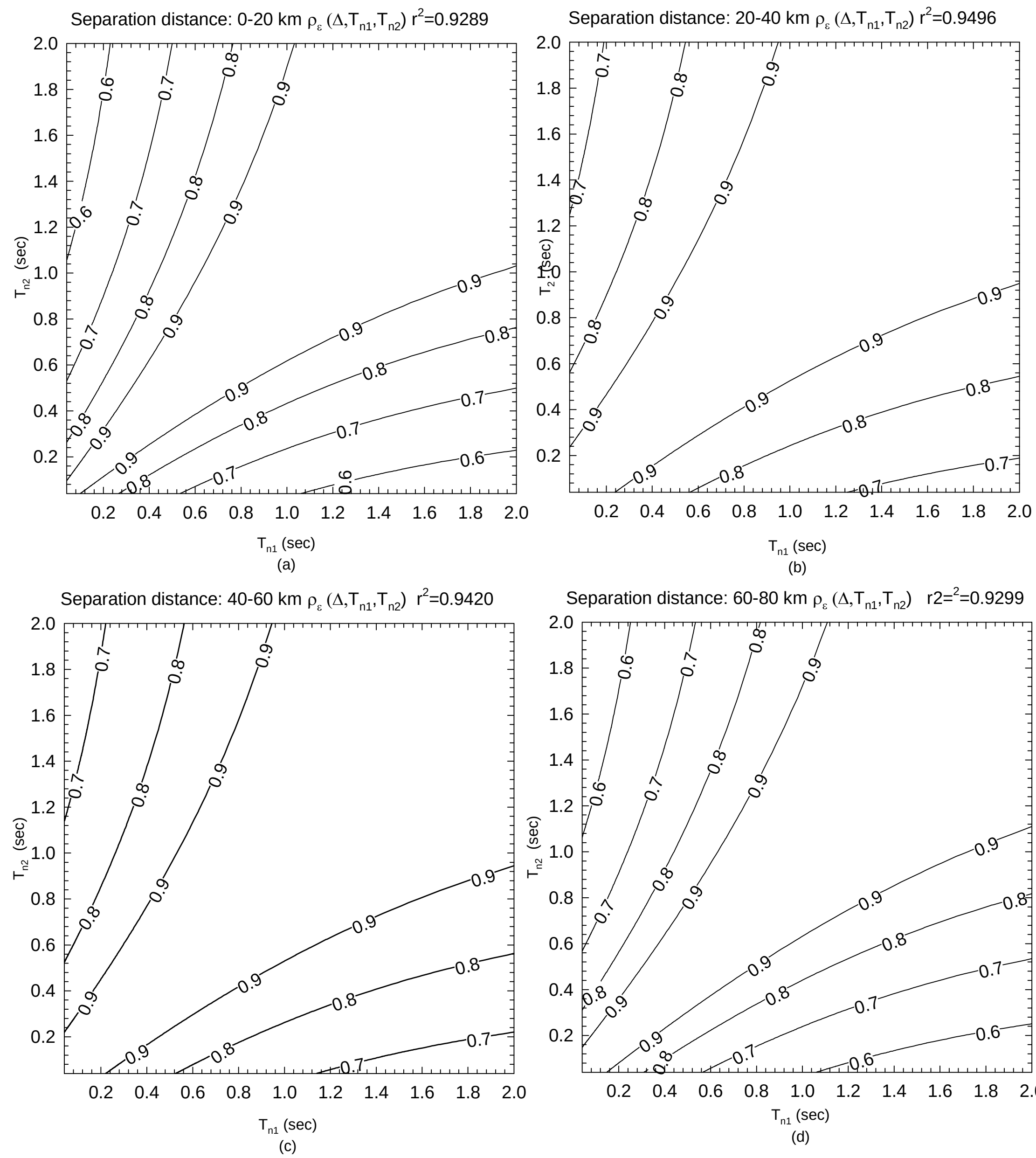

Figure 8: Intra-event spatial correlation model ρε(Δ, Tn1, Tn2) for separation distance bins of 0-20, 20-40, 40-60 and 60-80 km for all events.

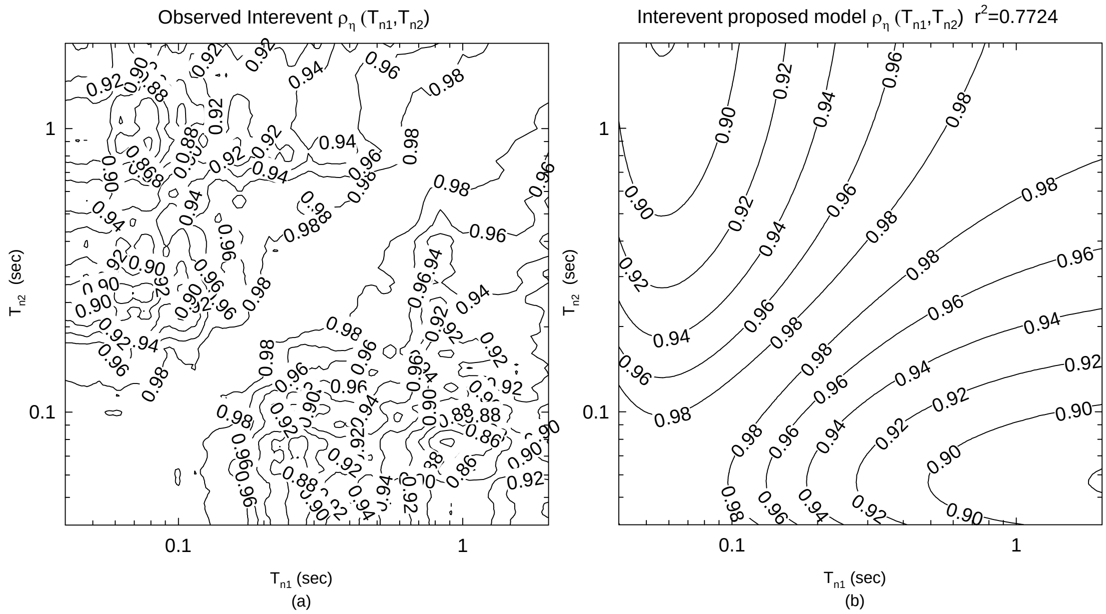

Figure 9: Inter-event correlation model ρη(Tn1, Tn2).

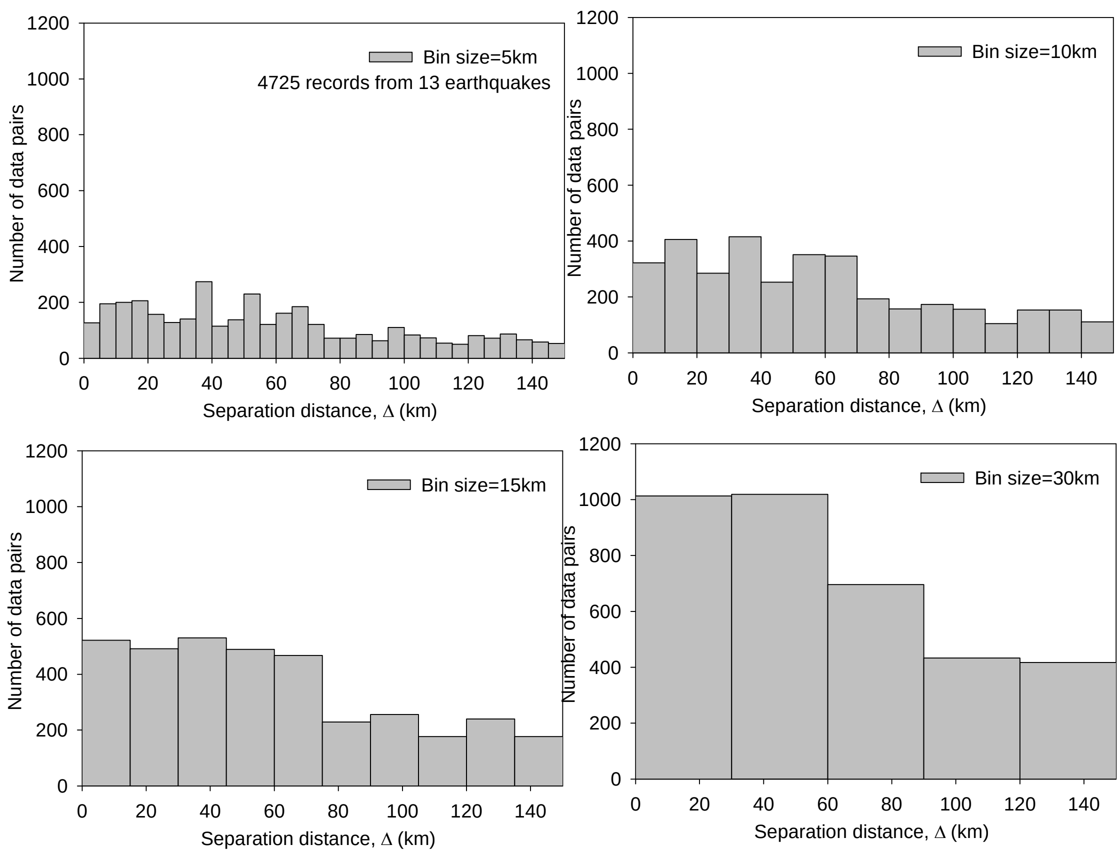

Figure 10: Histogram of the number of strong ground motion data pairs by different size bins.

The predictive values of $\rho_\eta(T_{n1}, T_{n2})$ based on equation (9) are shown in Figure 9b. The comparison of the observed and predictive values of shows a good fit (r^2=0.77) by capturing the observed values of $\rho_\eta(T_{n1}, T_{n2})$ for shallow earthquakes and for the central region of Italy however it is important to mention that results may not be stable due to the limited number of available samples.

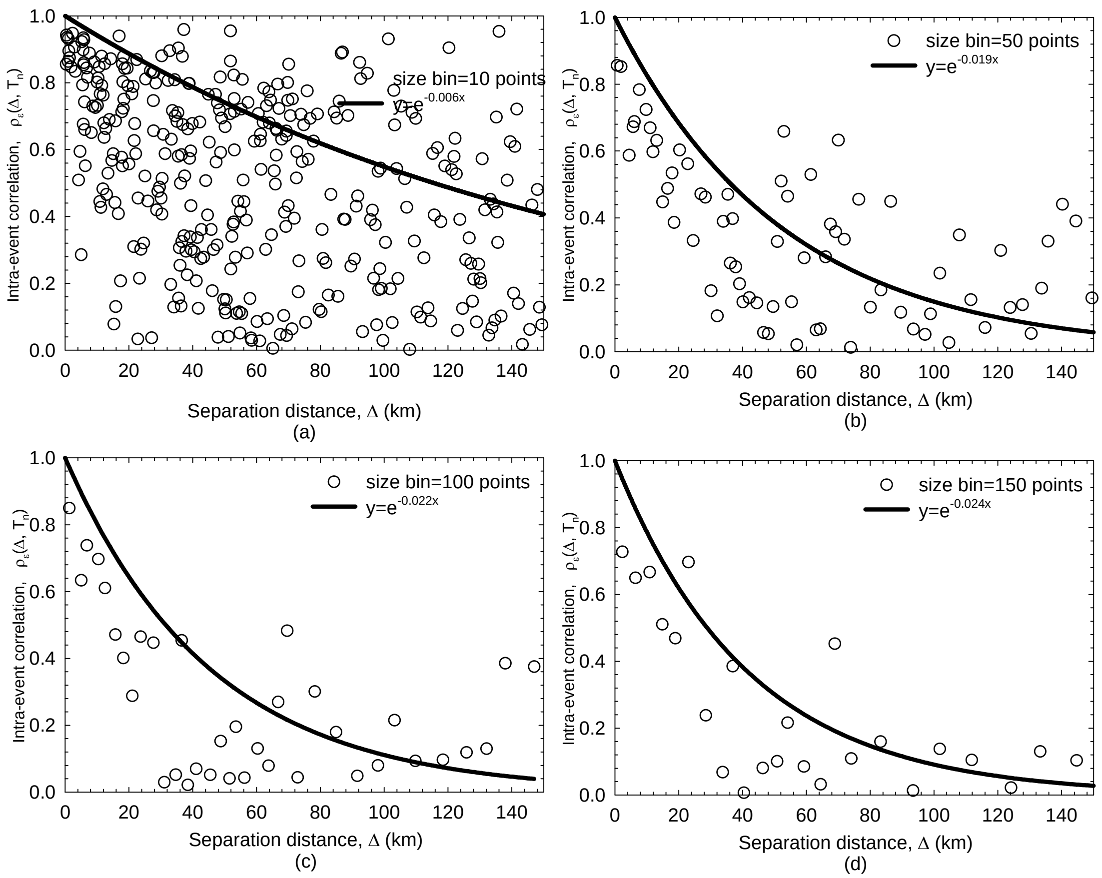

Figure 11: Overall intra-event spatial correlation for PSA at 0.2 sec using all shallow events (13 L'Aquila after-shocks) for different size bins.

5.3 Sensitivity to the size bin resolution

One of the goals of this research is to investigate the intra-event spatial correlation of L'Aquila earthquake ground motions with short separation distances; therefore it is of particular interest to inspect how many data pairs can be selected from the records using different bin size resolutions as shown in the histogram in Figure 10. In order to achieve a good estimate of the correlation coefficient at the short separation distances it is necessary at least 300 data pairs that can be obtained using a bin size resolution of 10 km. At large separation distances above 80 km the number of data pairs from the selected records reduce to half with respect to the short separation distances, regardless the bin size resolution. This brings to the conclusion that the estimation of the correlation coefficient at large separation distances is less accurate with respect to the short separation distances especially when the bin size resolution reduces to 5 km as shown in Figure 10a. This observation should be taken in account when considering results in the figures shown in the paper.

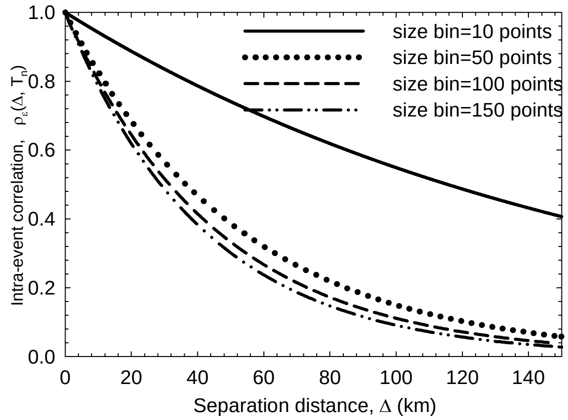

Figure 12: Comparison of fitted curves for intra-event spatial correlation at PSA of 0.2 sec and different size bins.

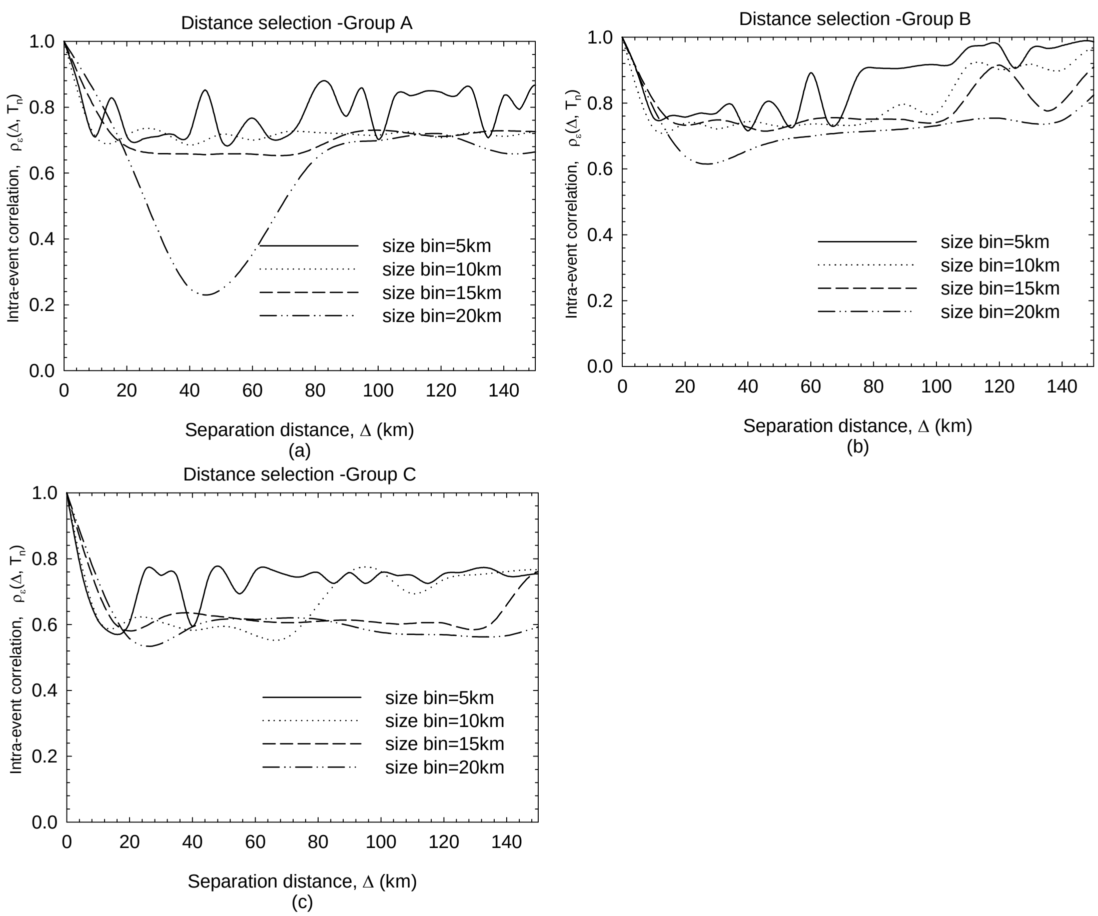

Figure 13: Intra-event spatial correlation for different size bins and PSA of 0.2 sec divided by distance selection.

Observing Figure 11 and Figure 12 it is shown that the intra-event spatial correlations based on the L'Aquila earthquakes aftershocks decrease gradually with increasing inter-station separation distance when the vibration period is 0.2 sec.

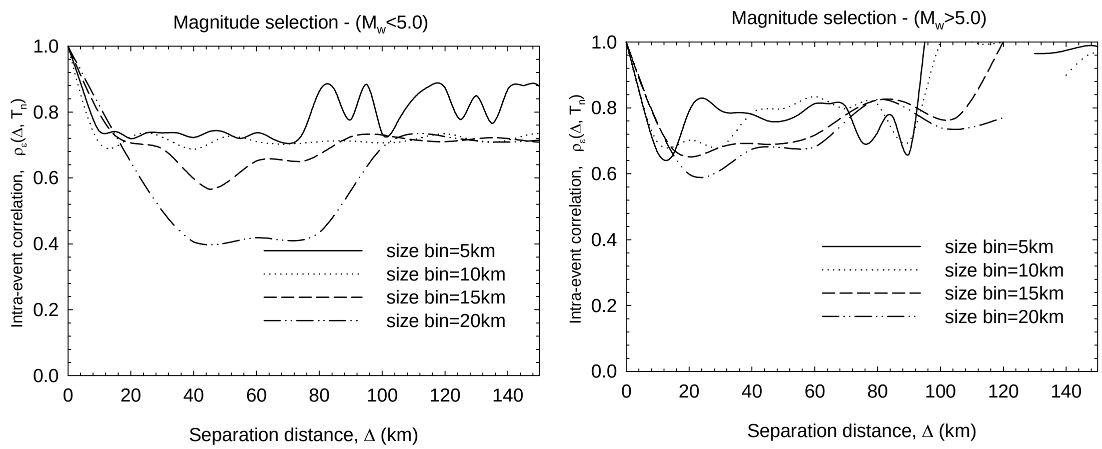

Figure 14: Intra-event spatial correlation for different size bins and PSA of 0.2 sec divided by magnitude selection.

With low resolution of the bin size (Figure 11a) the spatial correlation data points show large variability, so results due to the smaller number of available samples are not stable, therefore the parameters of the model in equation (6) given in Table 4 are uncertain, and discretion is required in adopting such models for seismic hazard and risk assessment of spatially distributed structures.

points	10	50	100	150
$\alpha(T_n=0.2s)$	0.006	0.019	0.022	0.024

Table 4: Parameters of the model for equation (6).

By increasing the bin size resolution to at least 50 points (corresponding to a bin size of about 10 km) the estimation of the parameters of the model in equation (6) is more stable, because a larger database is used and the decaying rate of the intra-event spatial correlation is more reliable as shown in Figure 12. In summary, the results reported by these research efforts reveal different rates of decay of correlation with separation distance that may be caused by regional peculiarities [3], because the site-to-site correlation depends on ground conditions of the sites and it will decrease for sites that do not share the same geology. It is also noted that the decay rate of the spatial correlation of the PSA responses depends on the natural vibration period and it is more gradual for longer natural vibration periods.

5.4 Sensitivity of observed intra-event spatial correlation to magnitude and distance

By grouping the earthquake sets according to the scheme in Figure 2b using the epicentral distance, it seems that the intra-event spatial correlation does not change with the distance when the size of the bin resolution is between 10 and 20 km as shown in Figure 13. This behavior is clear and it explained by the fact that the intra-event spatial correlation depends on the soil type and geological setting. This trend is not followed by the group A when the resolution of the bin size is 20 km that is probably too large, generating numerical errors. In Figure 14 is shown the intra-event spatial correlation coefficient is not affected by the magnitude selection. For large intensity earthquakes (with Magnitude M>5.0) the correlation increases for distances more than 100km, however, as shown before in Figure 10, the estimation of the observed intra-event correlation coefficient at large separation distances is not reliable.

6 CONCLUDING REMARKS

The paper, based on the statistical analysis of the L'Aquila earthquake records in Italy, proposes empirical intra-event and inter-event spatial correlation relations to predict the spatial correlation of the PSA responses to be used for shallow earthquakes in Central Italy.

Results of this paper show that the ground motion correlation structure is highly dependent on local geology and on peculiarities of the propagation path, however the spatial correlation coefficient decreases as the separation distance increases. The analysis results also indicate that the intra-event spatial correlation is not affected by the magnitude. A single generalized spatial correlation model may not be adequate for all European territory or similar larger areas, but it can provide a first preliminary estimation of the correlation. The characteristics are very important for assessment of seismic hazard analysis and spatially distributed systems (lifelines) and Shake Map generation. Due to the limited amount of observed data, the proposed models are affected by epistemic uncertainties. Applicability of the model to other regions remains to be tested. As future earthquakes at closely-spaced locations are recorded, these aspects of intra-event spatial correlation should be further investigated.

ACKNOWLEDGMENTS

The research leading to these results has received funding from the European Community's Seventh Framework Programme - Marie Curie International Reintegration Actions - FP7/2007-2013 under the Grant Agreement n° PIRG06-GA-2009-256316 of the project ICRED - Integrated European Disaster Community Resilience. The author is grateful to Katsuichiro Goda for valuable comments and suggestions that allow improving the paper.

REFERENCES

[1] D.M. Boore, J.F. Gibbs, W.B. Joyner, J.C. Tinsley, and D.J. Ponti. Estimated ground motion from the 1994 Northridge, California, Earthquake at the site of the Interstate 10 and La Cienega Boulevard Bridge collapse, West Los Angeles, California. *Bull. Seism. Soc. Am.*, 93, 2737-2751, 2003.

[2] M. Wang, and T. Takada. Macrospatial correlation model of seismic ground motions. *Earthquake Spectra*, 21, 1137-1156, 2005.

[3] K. Goda, and G.M. Atkinson. Probabilistic Characterization of Spatially Correlated Response Spectra for Earthquakes in Japan. *Bull. Seism. Soc. Am.*, 99(5), 3003-3020, 2009

[4] D.R. Brillinger, and H.K. Preisler. An exploratory analysis of the Joyner-Boore attenuation data. *Bull. Seism. Soc. Am.*, 74, 1441-1450, 1984.

[5] D.R. Brillinger, and H.K. Preisler. Further analysis of the Joyner-Boore attenuation data. *Bull. Seism. Soc. Am.*, 75, 611-614, 1985.

[6] C.C.P. Tsai, Y.H. Chen, and C.H. Liu. The path effect in ground-motion variability: An application of the variance-components technique. *Bull. Seism. Soc. Am*., 96, 1170-1176, 2006.

[7] H.P. Hong, and K. Goda. Orientation-dependent ground-motion measure for seismic-hazard assessment. *Bull. Seismol. Soc. Am*, **97**, 1525-1538, 2007

[8] K. Goda, and H.P. Hong. Spatial Correlation of Peak Ground Motions and Response Spectra. *Bull. Seism. Soc. Am*., 98(1), 354-365, 2008.

[9] N. Abrahamson, and R.R. Youngs. A stable algorithm for regression analyses using the random effects model. *Bull. Seism. Soc. Am*., 82, 505-510, 1992.

[10] Working Group ITACA (2010) - Data Base of the Italian strong motion records: http://itaca.mi.ingv.it.

[11] N.N. Ambraseys, K.A. Simpson, and J. Bommer. Prediction of horizontal response spectra in Europe. *Earthquake Engineering & Structural Dynamics*, 25(4), 371-400, 1996.

[12] G.P. Cimellaro, I.P. Christovasilis, A.M. Reinhorn, A. De_Stefano, and T. Kirova. L`Aquila Earthquake of April 6th, 2009 in Italy: Rebuilding a resilient city to multiple hazard. MCEER Technical Report –MCEER-10-0010, State University of New York at Buffalo (SUNY), Buffalo, New York, 2010.

[13] G.P. Cimellaro, Y.-N. Huang, and A. De_Stefano. "Correlation in spectral accelerations of European ground motion records." Proceedings of the 9th US National and 10th Canadian Conference on Earthquake Engineering (9NCEE), 25-29 July, 2010, Toronto, Canada, Year.