Spatial Correlation of Ground-Motion IMs and Implications for Seismic Risk Assessment Studies

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Outline of the Presentation

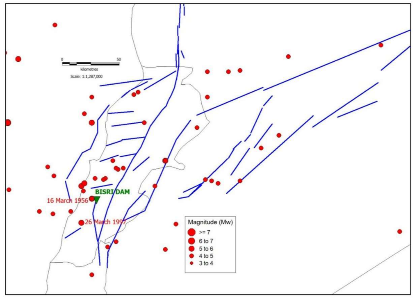
- Background of studies on spatial correlations of GM IMs
- Previous research works
- Motivations of my studies
- Methodology and developed models
- Application of the developed model on the seismic risk assessment studies

Background of Studies

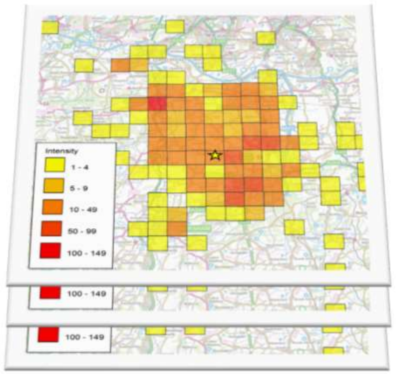
Event-Based Seismic Hazard and Risk Assessment

Event-based Seismic Hazard Assessment

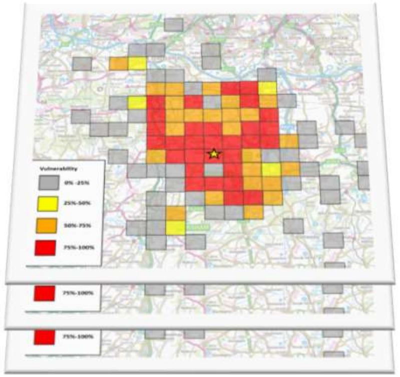
Event Simulation



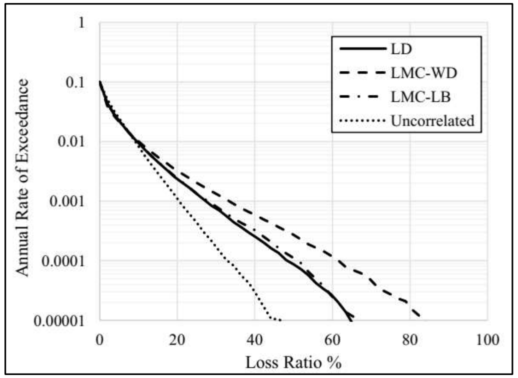
Intensity Measures Maps



Damage (Loss)Distributions



Earthquake Risk and Resilience Assessment



Background of Studies

- Empirical ground-motion models:

$$\ln(Y_{ij}) = \ln(\overline{Y_{ij}}) + \delta_{ij}, \qquad \delta_{ij} = \eta_j + \varepsilon_{ij},$$

- The intra-event residuals of the intensity measures of an earthquake events over a spatially distributed region $\{\varepsilon'(\boldsymbol{s}_1), \varepsilon'(\boldsymbol{s}_2), \ldots, \varepsilon'(\boldsymbol{s}_n)\}$ are considered as the realization of a random field.

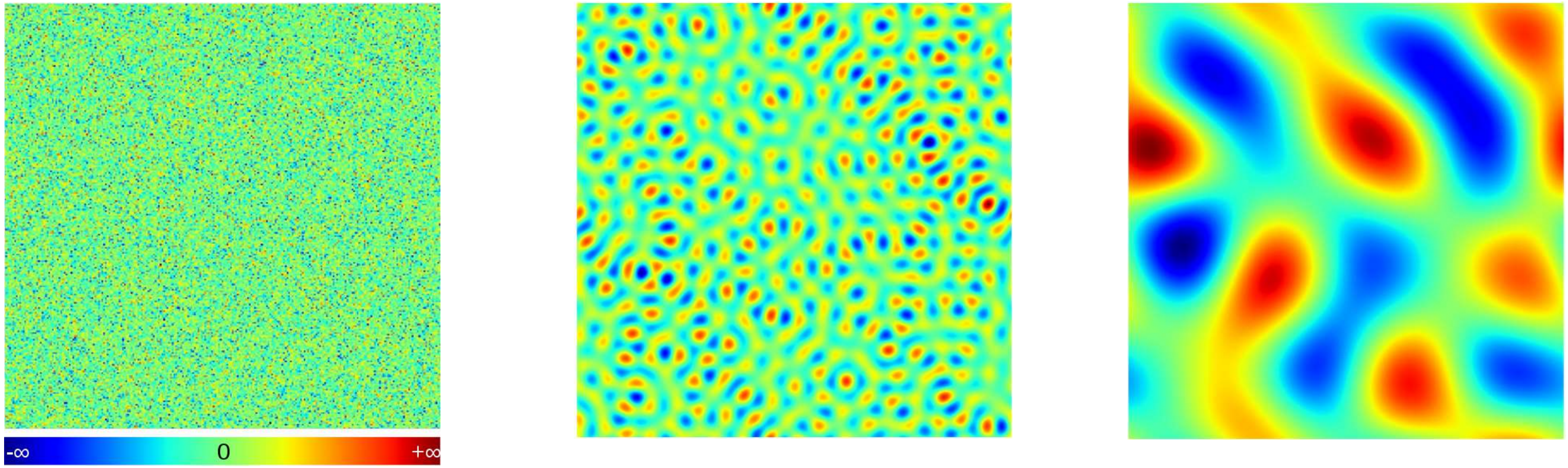
- This random filed is considered to be Gaussian.
  - Its variables or any linear combination of them follows a gaussian distribution.
  - The joined distribution of variables in two separated points would be Gaussian.

$$\mu_{X|Y=y} = \mu_X + \rho\sigma_X\left(\frac{y-\mu_Y}{\sigma_Y}\right), \qquad \sigma_{X|Y=y} = \sigma_X\sqrt{1-\rho^2},$$

$$\rho = \frac{\mathrm{Cov}(X,Y)}{\sigma_x\sigma_y},$$

Background of Studies

Visual Representation of Correlation in a RF



Source of Images:
https://structures.uni-heidelberg.de/blog/posts/gaussian-random-fields/index.php

Background of Studies

- The RF of the intra-event residuals of ground-motion IMs are assumed to be **Stationary**.

$$E[\varepsilon(\boldsymbol{s}_i)] = m, \qquad \text{for all } \boldsymbol{s}_i \in \mathbb{R}^2,$$

$$\mathrm{Cov}[\varepsilon(\boldsymbol{s}_i), \varepsilon(\boldsymbol{s}_j)] = C(\boldsymbol{h}), \quad \boldsymbol{h} = \boldsymbol{s}_i - \boldsymbol{s}_j, \quad \text{for all } \mathbf{s}_i \text{ and } \mathbf{s}_j \in \mathbb{R}^2,$$

- In spatial statistics context, the **variogram function** is defined as:

$$2\gamma(\boldsymbol{h}, \boldsymbol{s}) = \mathrm{Var}\big(Z(\mathbf{s} + \mathbf{h}) - Z(\mathbf{s})\big),$$

which for a stationary RF it would be independent of location (***s***):

$$2\gamma(\boldsymbol{h}) = \mathrm{Var}(Z(\mathbf{s} + \mathbf{h}) - Z(\mathbf{s})),$$

$$\gamma(\boldsymbol{h}) = 1 - C(\boldsymbol{h}),$$

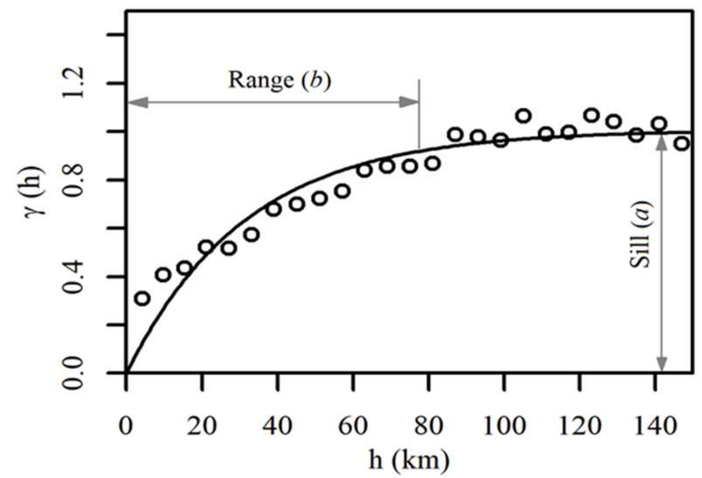
$$\rho(\boldsymbol{h}) = \frac{C(\boldsymbol{h})}{C(\mathbf{0})}.$$

Background of Studies

- If we assume that the variogram function is independent of direction (i.e. the variogram is a function of the norm of the lag distance $h = |\boldsymbol{h}|$), the RF is called **Isotropic**.

$$\hat{\gamma}\,(h) = \frac{1}{2}E\left[\left(\varepsilon(s+h) - \varepsilon(s)\right)^2\right]$$

$$\gamma(h) = a\left[1 - exp\left(-\frac{3h}{b}\right)\right]$$



Background of Studies

- For a **Multivariate** RF (variables *i* and *j*):

$$\gamma_{ij}(h) = \frac{1}{2} E\left[\left(Z_i(s+h) - Z_i(s)\right)\left(Z_j(s+h) - Z_j(s)\right)\right],$$

$$\begin{aligned} C_{ij}(h) &= \mathrm{Cov}(Z_i(s), Z_j(s+h)) \\ &= \mathrm{E}[(Z_i(s) - E[Z_i(s)])\left(Z_j(s+h) - E\left[Z_j(s+h)\right]\right), \end{aligned}$$

$$\rho_{ij}(h) = \frac{C_{ij}(h)}{\sqrt{C_{ii}(0) \times C_{jj}(0)}} = \frac{C_{ij}(0)}{\sqrt{C_{ii}(0) \times C_{jj}(0)}} - \frac{\gamma_{ij}(h)}{\sqrt{C_{ii}(0) \times C_{jj}(0)}},$$

$$\boldsymbol{\Gamma}(h) = \left[\gamma_{ij}(h)\right] = \begin{bmatrix} \gamma_{11}(h) & \dots & \gamma_{1n}(h) \\ \vdots & \ddots & \vdots \\ \gamma_{n1}(h) & \cdots & \gamma_{nn}(h) \end{bmatrix}, \qquad \boldsymbol{C}(h) = \left[C_{ij}(h)\right], \qquad \boldsymbol{R}(h) = \left[\rho_{ij}(h)\right],$$

Background of Studies

- Accordingly, if we have n location and are going to consider k variable in each point**, the Event Matrix** ($\mathbf{C}_e$) would be in the form of :

$$\mathbf{C}_e = \begin{bmatrix} \mathbf{C}(\mathbf{s}_1, \mathbf{s}_1) & \dots & \mathbf{C}(\mathbf{s}_1, \mathbf{s}_n) \\ \vdots & \ddots & \vdots \\ \mathbf{C}(\mathbf{s}_n, \mathbf{s}_1) & \cdots & \mathbf{C}(\mathbf{s}_n, \mathbf{s}_n) \end{bmatrix}_{nk \times nk} , \qquad \mathbf{C}(\boldsymbol{h}) = \left[C_{ij}(\mathbf{h})\right]_{k \times k} , \qquad \mathbf{h} = \mathbf{s}_i - \mathbf{s}_j$$

- The event matrix must be **positive-definite**. Therefore, it is essential to employ a valid form of semivariogram or covariogram functions. Utilizing an arbitrary function that merely fits the experimental data well would not yield a valid model of random fields (RF).

Previous research works and outcomes

The values of an earthquake intensity measure over a spatially distributed region are considered as the realization of a random field.

Variability of Correlation Coefficient

- Boore et al. (2003)
- Wang & Takada (2005)
- Crowley & Boomer (2006)
- Goda & Hong (2008)
- Hong et al. (2009)
- Goda & Atkinson (2009)

Utilizing Spatial Statistics Approaches

- Jayaram & Baker (2008)

Marginal Isotropic Models

- Jayaram & Baker (2008)
- Sokolov et al. (2011)

Multivariate Isotropic Models

- Loth & Baker (2013)
- Wang & Du (2013)
- Markhvida et al. (2018)

Marginal Anisotropy Models

- Garakaninezhad & Bastami (2017)
- Abbasnejadfard et al. (2021)

Multivariate Anisotropy Models and Application

- Abbasnejadfard et al. (2020)
- Abbasnejadfard et al. (2021)

Investigating Stationarity
Simulation-Based Studies
Other Influencing Factors

Motivations of Studies

01 Accounting for anisotropy of spatial correlations in earthquake risk analysis.

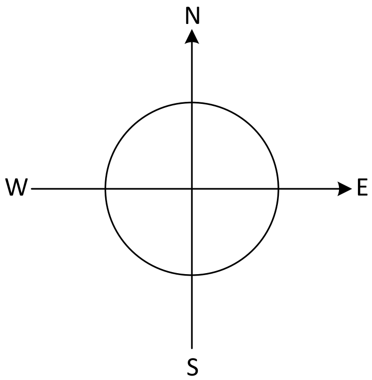
02 Incorporating multiple variables of earthquake intensity measures.

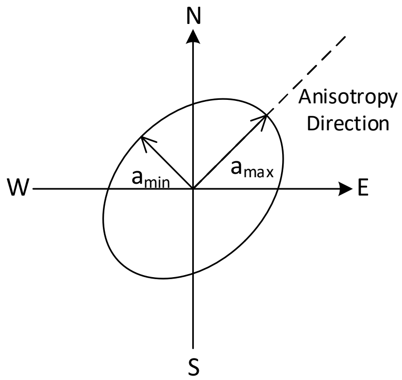
03 Ensuring a positive-definite covariance matrix for a valid spatial model.

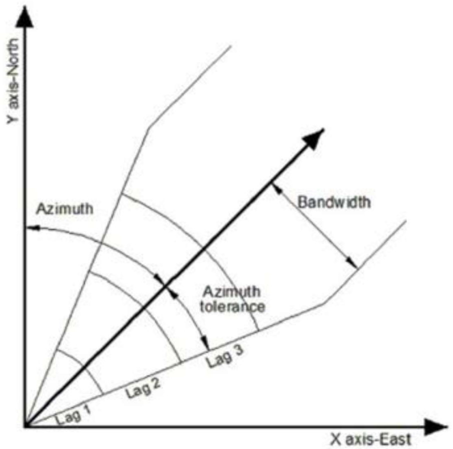
04 Identifying influencing factors for a reliable and accurate predictive model.

05 Evaluating the benefits of using a sophisticated method for earthquake risk estimation.

Preliminary Investigations

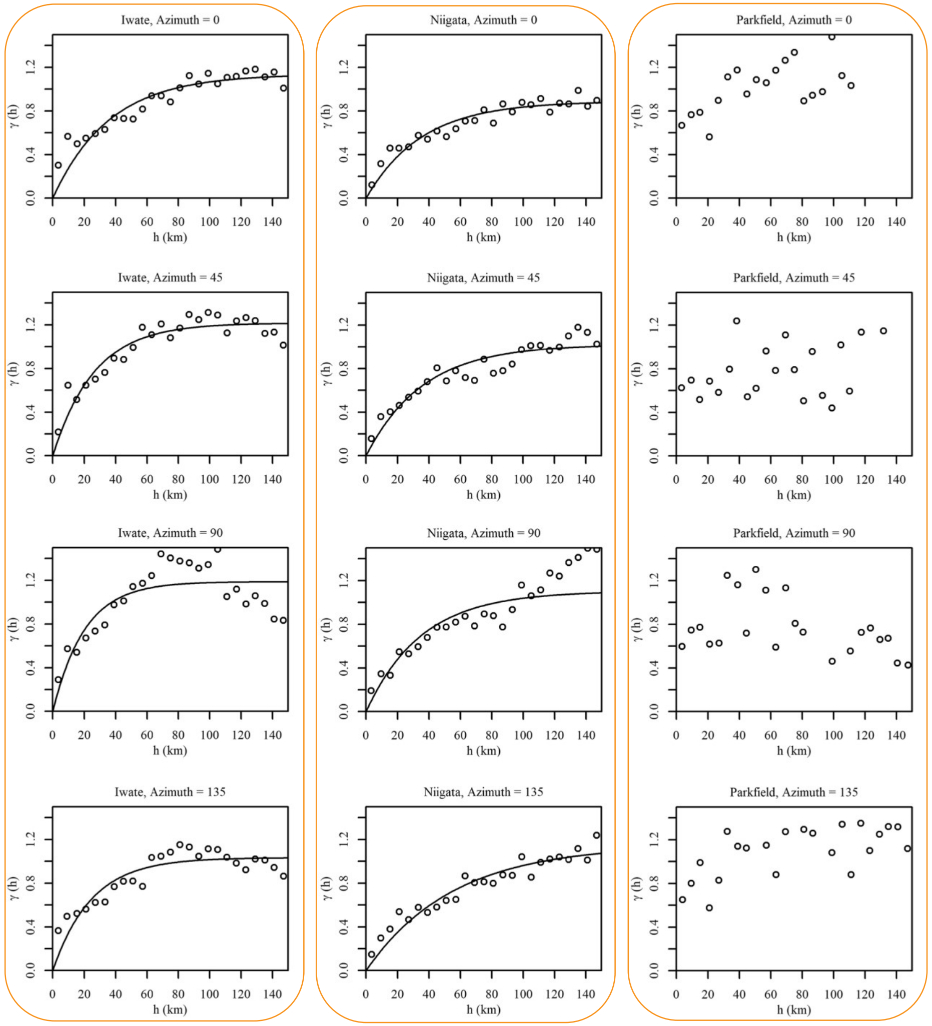


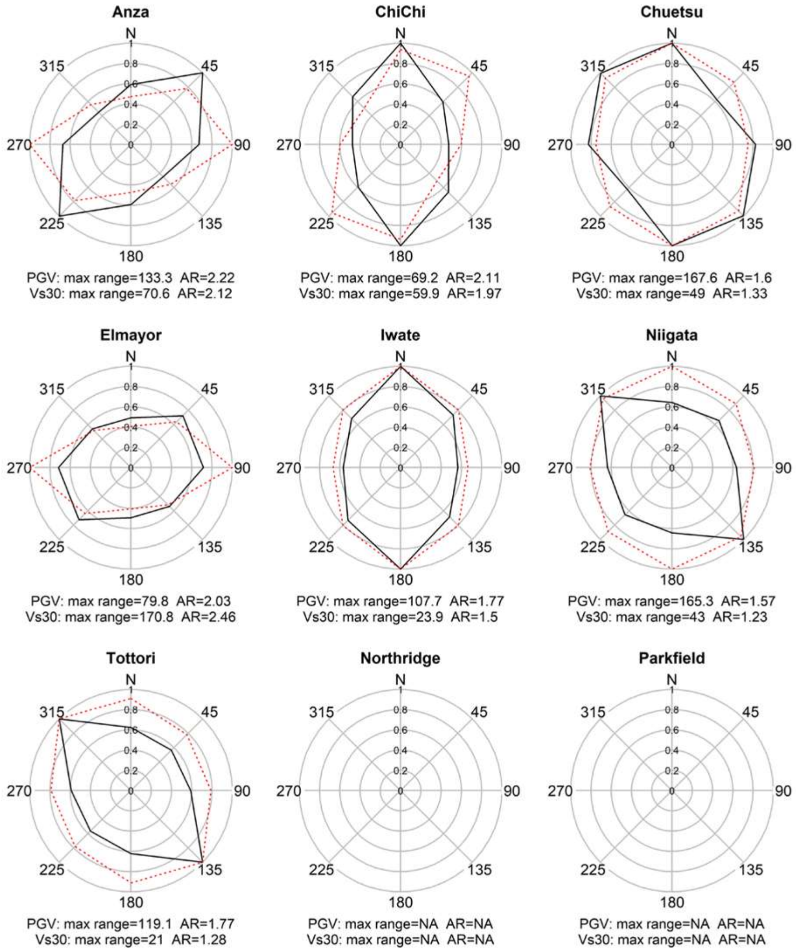




Earthquake Name	Year	Magnitude	Location	Number of Selected Records
Northridge	1994	6.7	California	146
Alum Rock	2007	5.4	California	137
Tottori	2000	6.6	Japan	414
Niigata	2004	6.6	Japan	530
Parkfield	2004	6	California	135
Anza	2005	5.2	California	132
Chuetsu	2007	6.8	Japan	613
Iwate	2008	6.9	Japan	367
Chino Hills	2008	5.4	California	197
Fukushima	2011	6.7	Japan	283

Preliminary Investigations





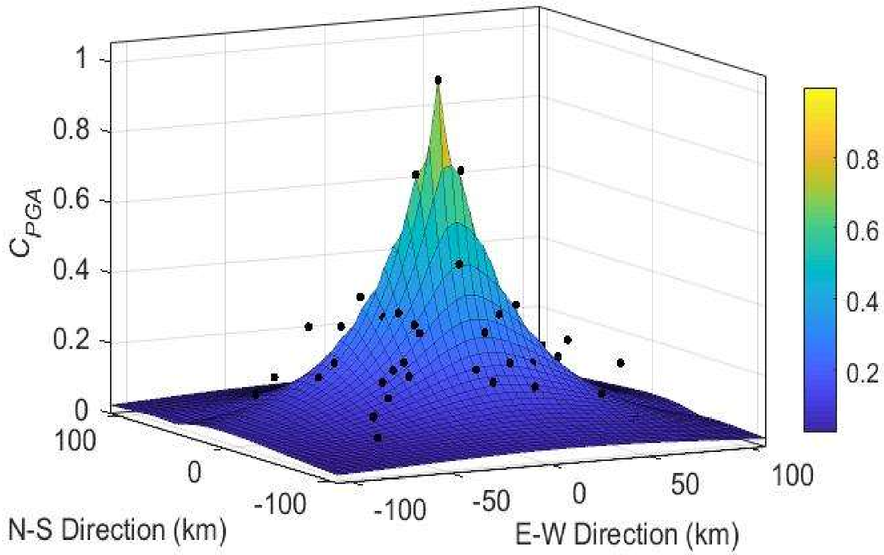
Methodology

Latent Dimensions for Multivariate Anisotropic Model

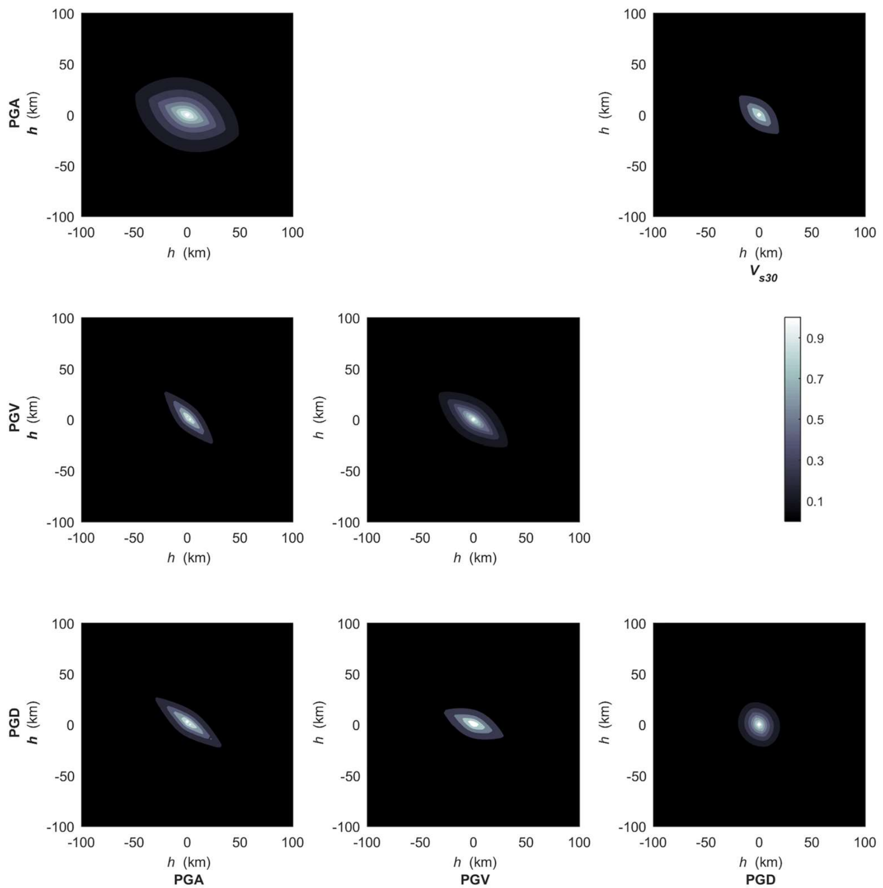
Apanasovich TV, Genton MG.
Cross-covariance functions for multivariate random fields based on latent dimensions.
Biometrika. 2010 Mar 1;97(1):15-30.

$$C_{\alpha\beta}(\mathbf{s}_1,\mathbf{s}_2):\ \mathbf{s}_1,\mathbf{s}_2 \in \mathrm{R}^n \quad \Rightarrow \quad C\left((\mathbf{s}_1,\xi_\alpha),(\mathbf{s}_2,\xi_\beta)\right)$$

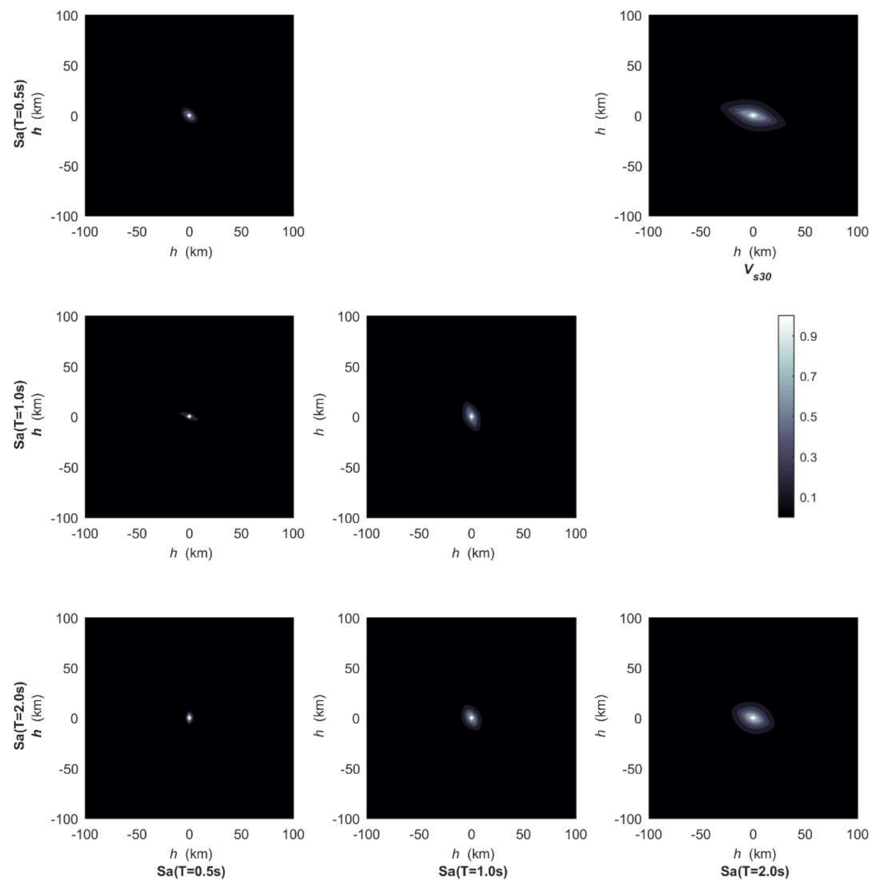
$$C_{\alpha\beta}(\mathbf{h}) = C(\mathbf{h},\upsilon_{\alpha\beta} - \boldsymbol{\Gamma}_\xi \mathbf{h}) = \frac{\sigma_{\alpha\beta}}{\left|\upsilon_{\alpha\beta} - \gamma\boldsymbol{\omega}^{\mathrm{T}}\mathbf{h}\right|+1}\exp\left\{-\frac{a\|\mathbf{h}\|}{\left(\left|\upsilon_{\alpha\beta} - \gamma\boldsymbol{\omega}^{\mathrm{T}}\mathbf{h}\right|+1\right)^{1/2}}\right\}$$



Results



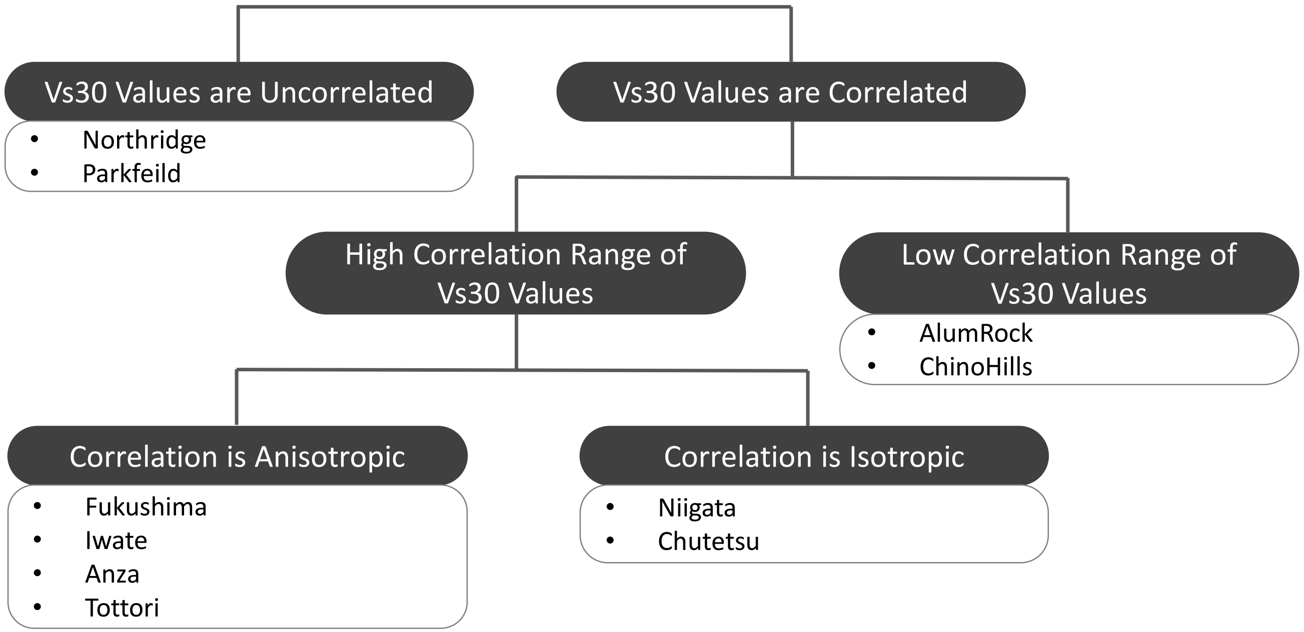
Cross-covariance models of PGA, PGV, PGD, and marginal-covariance model of *Vs*30 values of the **Fukushima** 2011 earthquake



Cross-covariance models of SA at T = 0.5, 1.0 and 2.0 s and marginal-covariance model of *Vs*30 values of the **AlumRock** 2011 earthquake

Results

Remarkable Impact of Local Site Conditions on Spatial Correlation Patterns of Earthquake Intensity Measures



Latent Dimensions Model

Estimating Maximum Range of the Covariance Model Based on the Maximum Range of the Spatial Correlations of Vs30 Values

$$a_{\alpha\beta} = C_a^{-1} a_{Vs30}^2$$

Estimating Anisotropic Ratio of the Covariance Model Based on the Anisotropic Ratio of the Spatial Correlations of Vs30 Values

$$\gamma_{\alpha\beta} = C_\gamma \gamma_{Vs30}$$

Estimating the Latent Distance Values for Different Combinations of Earthquake Intensity Measures and Based on the Investigated Regions

$$\left(\left|\upsilon_{\alpha\beta} - \gamma \boldsymbol{\omega}^{\mathrm{T}} \mathbf{h}\right| + 1\right)^{1/2} > 1$$

$$C_{\alpha\beta}(\mathbf{h}) = C(\mathbf{h}, \upsilon_{\alpha\beta} - \boldsymbol{\Gamma}_\xi \mathbf{h}) = \frac{\sigma_{\alpha\beta}}{\left|\upsilon_{\alpha\beta} - \gamma \boldsymbol{\omega}^{\mathrm{T}} \mathbf{h}\right| + 1} \exp\left\{ -\frac{a\|\mathbf{h}\|}{\left(\left|\upsilon_{\alpha\beta} - \gamma \boldsymbol{\omega}^{\mathrm{T}} \mathbf{h}\right| + 1\right)^{1/2}} \right\}$$

Publications

Geophysical Journal International

Geophys. J. Int. (2020) **222,** 1449–1469
Advance Access publication 2020 May 21
GJI Seismology

doi: 10.1093/gji/ggaa255

Investigation of anisotropic spatial correlations of intra-event residuals of multiple earthquake intensity measures using latent dimensions method

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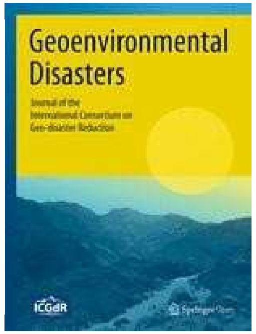
[2] *Department of statistics, Imam Khomeini International University, Postal Code 3414896818, Qazvin, Iran*

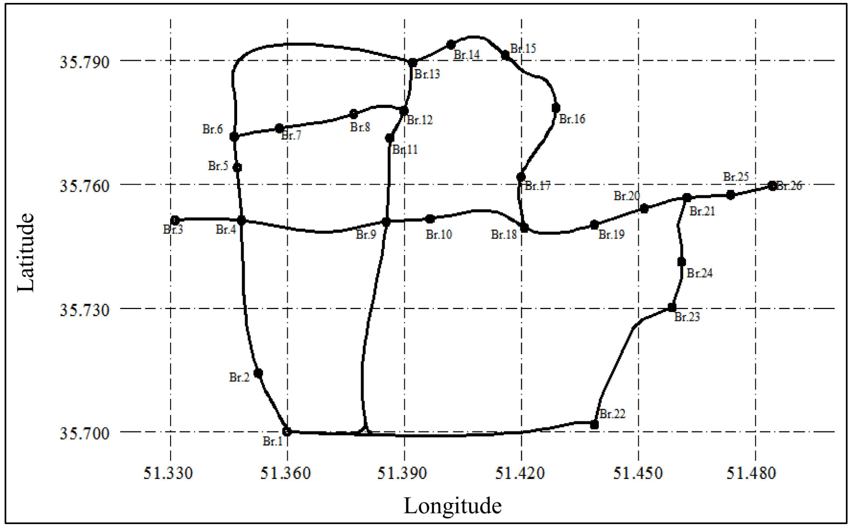
Investigating the spatial correlations in univariate random fields of peak ground velocity and peak ground displacement considering anisotropy

Morteza Abbasnejadfard, Morteza Bastami & Afshin Fallah

Geoenvironmental Disasters **8**, Article number: 24 (2021) | Cite this article



Application of the Developed Model



Three V_{s30} Models with:

- Low
- Medium
- High

range of spatial correlation

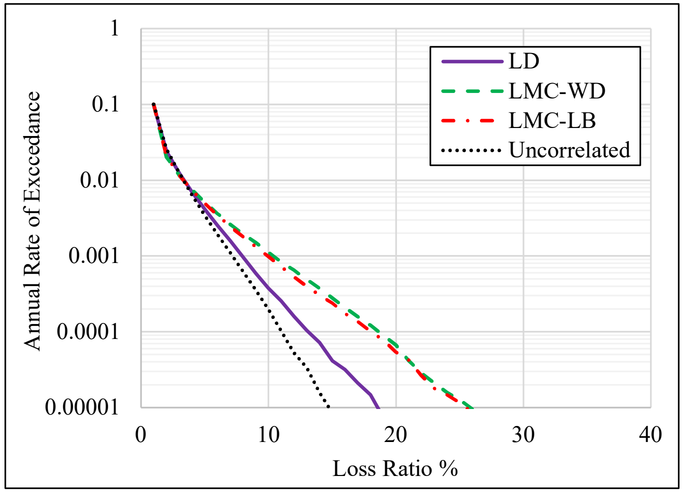
Application of the Developed Model

Utilized Spatial Correlation Models

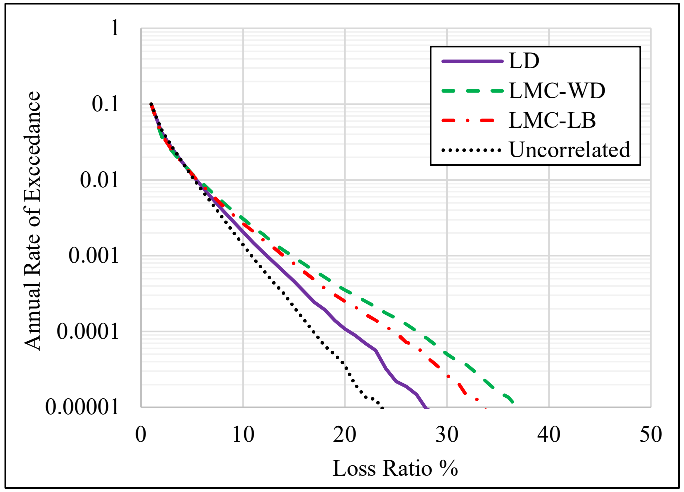
Model	Reference	Specification
Uncorrelated	-	• No Correlation is considered
LMC-LB	Loth, C. and Baker, J.W., 2013. A spatial cross-correlation model of spectral accelerations at multiple periods. *Earthquake Engineering & Structural Dynamics*, *42*(3), pp.397-417.	• Multivariate • Isotropic • Regardless of local site conditions
LMC-WD	Du, W. and Wang, G., 2013. Intra-event spatial correlations for cumulative absolute velocity, Arias intensity, and spectral accelerations based on regional site conditions. *Bulletin of the Seismological Society of America*, *103*(2A), pp.1117-1129.	• Multivariate • Isotropic • Considering local site conditions
LD	Abbasnejadfard, M., Bastami, M. and Fallah, A., 2020. Investigation of anisotropic spatial correlations of intra-event residuals of multiple earthquake intensity measures using latent dimensions method. *Geophysical Journal International*, *222*(2), pp.1449-1469.	• Multivariate • Anisotropic • Considering local site conditions

Application of the Developed Model

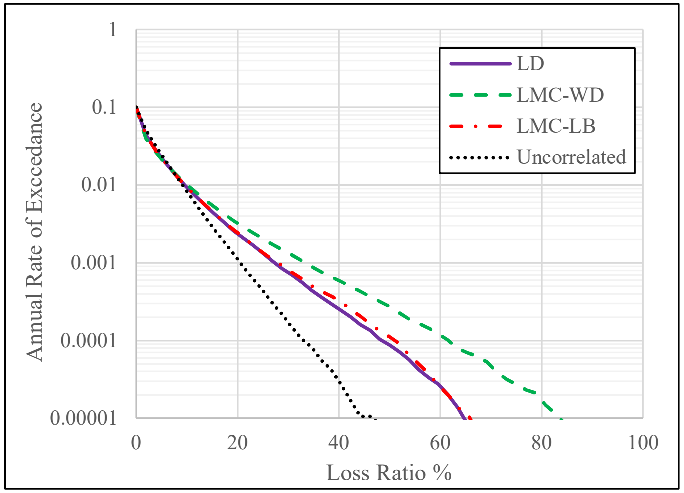
Low V_{s30} Correlation Range



Medium V_{s30} Correlation Range



High V_{s30} Correlation Range



Publications

Analyzing the effect of anisotropic spatial correlations of earthquake intensity measures on the result of seismic risk and resilience assessment of the portfolio of buildings and infrastructure systems

Original Article | Published: 17 August 2021

19, 5791–5817 (2021)

Morteza Abbasnejadfard, Morteza Bastami, Afshin Fallah & Alireza Garakaninezhad

Potential Future Study Areas

- It is necessary to calculated anisotropic spatial correlation parameters of local VS30 values to make LD method applicable in different regions.
- It is necessary to utilized local ground-motion IMs to determine local parameters for LD method.
- All the calculations are based on the assumption that the RF of ground-motion Ims is stationary. This assumption may not hold in some cases, given the large influence of the local site condition on earthquake intensity measures, especially in areas with complex geological conditions.
- The characterization of spatial correlation for ground-motion IMs neglects potential influencing factors such as source effects and path effects.

Using a physics-based simulation approach can be effective for examining assumptions related to stationarity and other influential factors.

Thank You!