Spatial Correlation of Ground Motions in Seismic Hazard Assessment

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Outline

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- Spatial Correlations of Ground-Motion Parameters
  - Estimation of spatial correlations
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- Simulation of Spatial Correlated Ground Motions
  - Test using stochastic finite-fault program (EXSIM)
  - Potential simulation method
- Summary

Introduction

- What is spatial correlation?

  The similarity of ground motions at two sites.

- Spatial correlation of ground motion parameters

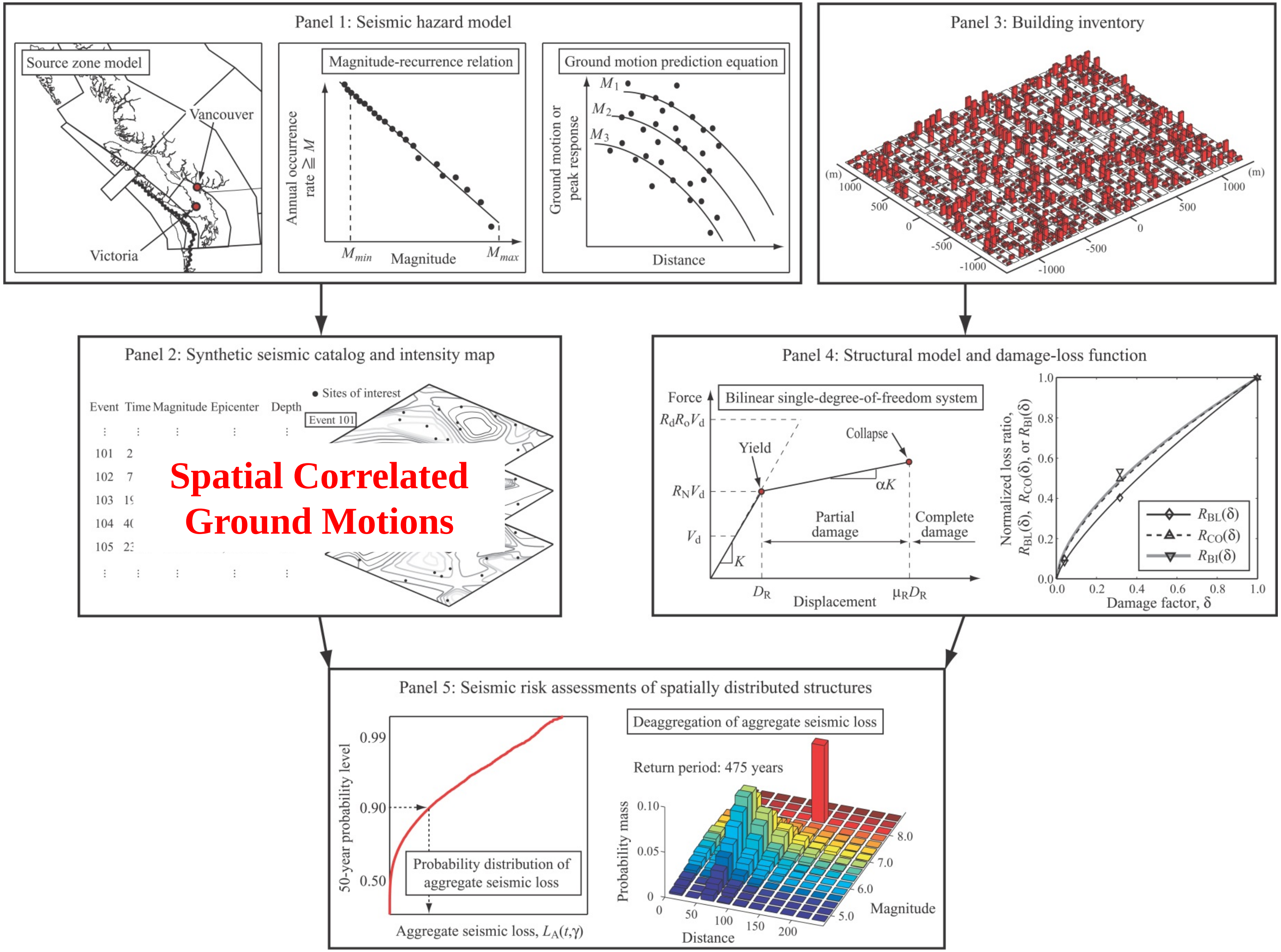
  Ground Motion Prediction Equation:

$$\ln A_{ij} = f(M_i, R_{ij}, \theta_{ij}) + \eta_j + \varepsilon_{ij}$$

  η_j and ε_{ij} represent the interevent variability and the intraevent variability, respectively.

- Spatial correlation is important for seismic hazard assessment of spatially distributed structures and/or structures with large foot print, such as highway and pipeline.

Simulation-Based Seismic Risk Analysis Framework



Estimation of Spatial Correlations

- The total correlation coefficient (between $\eta_j(T_1)+\varepsilon_{ij}(T_1)$ and $\eta_j(T_2)+\varepsilon_{kj}(T_2)$):

$$\rho_T(\Delta,T_1,T_2)=\frac{\rho_\eta(T_1,T_2)\sigma_\eta(T_1)\sigma_\eta(T_2)+\rho_\varepsilon(\Delta,T_1,T_2)\sigma_\varepsilon(T_1)\sigma_\varepsilon(T_2)}{\sigma_T(T_1)\sigma_T(T_2)}$$

or $$\rho_T(\Delta,T_1,T_2)=\frac{[\sigma_T(T_1)]^2+[\sigma_T(T_2)]^2-[\sigma_d(\Delta,T_1,T_2)]^2}{2\sigma_T(T_1)\sigma_T(T_2)}$$

where $[\sigma_d(\Delta,T_1,T_2)]^2$: variance of $[\eta_j(T_1)+\varepsilon_{ij}(T_1)]-[\eta_j(T_2)+\varepsilon_{kj}(T_2)]$ (Boore *et al*., 1997)

Estimation of Spatial Correlations

- The intraevent spatial correlation coefficient (i.e., spatial correlation within a single event) can be expressed as:

$$\rho_\varepsilon(\Delta, T_1, T_2) = 1 - \frac{[\sigma_d(\Delta, T_1, T_2)]^2}{2\sigma_\varepsilon(T_1)\sigma_\varepsilon(T_2)}$$

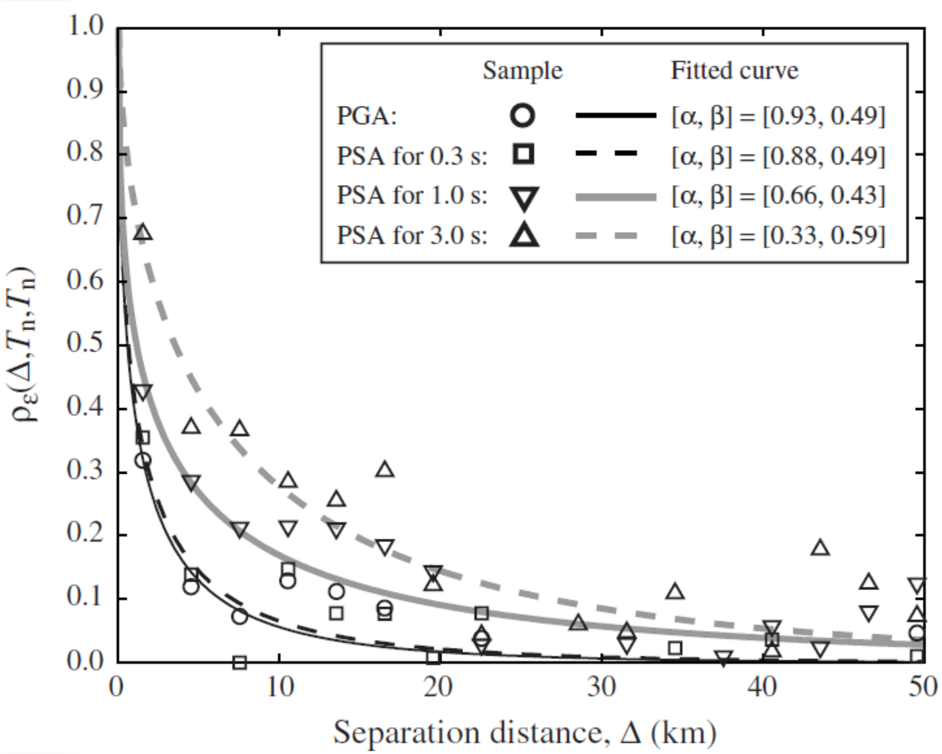
- If T_1 and T_2 equal to $\underline{T}$, we have:

$$\rho_\varepsilon(\Delta, T) = 1 - \frac{[\sigma_d(\Delta, T)]^2}{2[\sigma_\varepsilon(T)]^2}$$

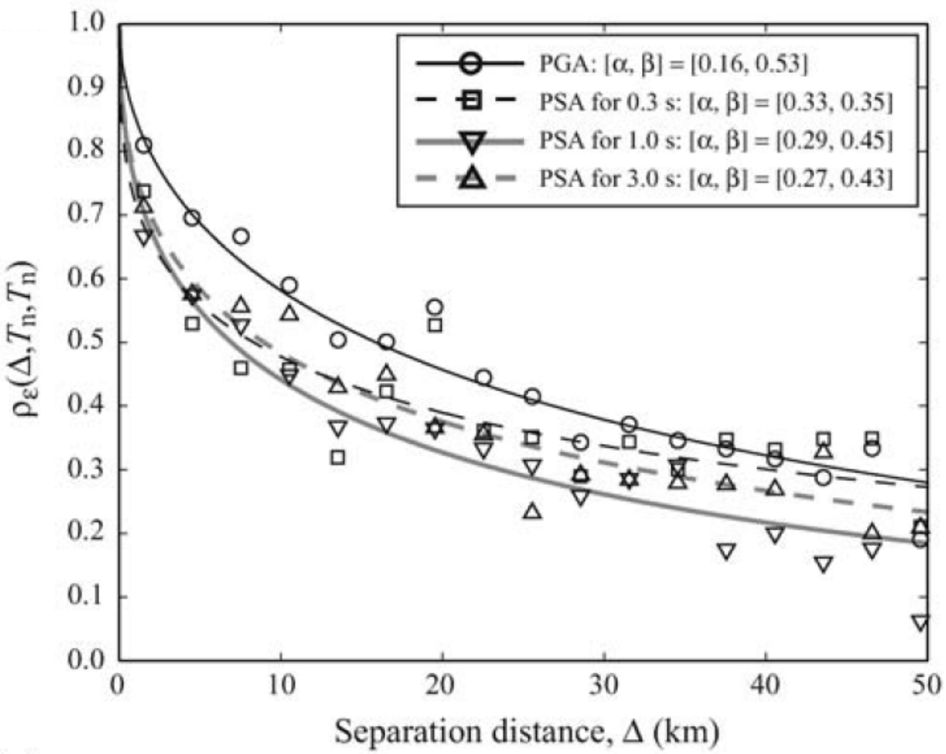
- Empirical relation for $\rho_\varepsilon(\Delta,T)$:

$$\rho_\varepsilon(\Delta, T) = \exp\left(-\alpha\Delta^\beta\right)$$

Observed Spatial Correlations



California records



Chi-Chi records

Simulation of Spatial Correlated Ground Motions

- EXSIM stochastic finite-fault program (Motazedian and Atkinson (2005)), a freely-available and widely-used program that has been validated under a range of conditions.

- Chi-Chi Earthquake

Intraevent Spatial Correlation Characteristics of EXISM

- Ground Motion Prediction Equations (GMPEs):

$$\ln A = c_0 + c_1 \ln R + c_2 R + c_3 \ln\left(\frac{V_{S30}}{V_{\text{ref}}}\right) + \varepsilon$$

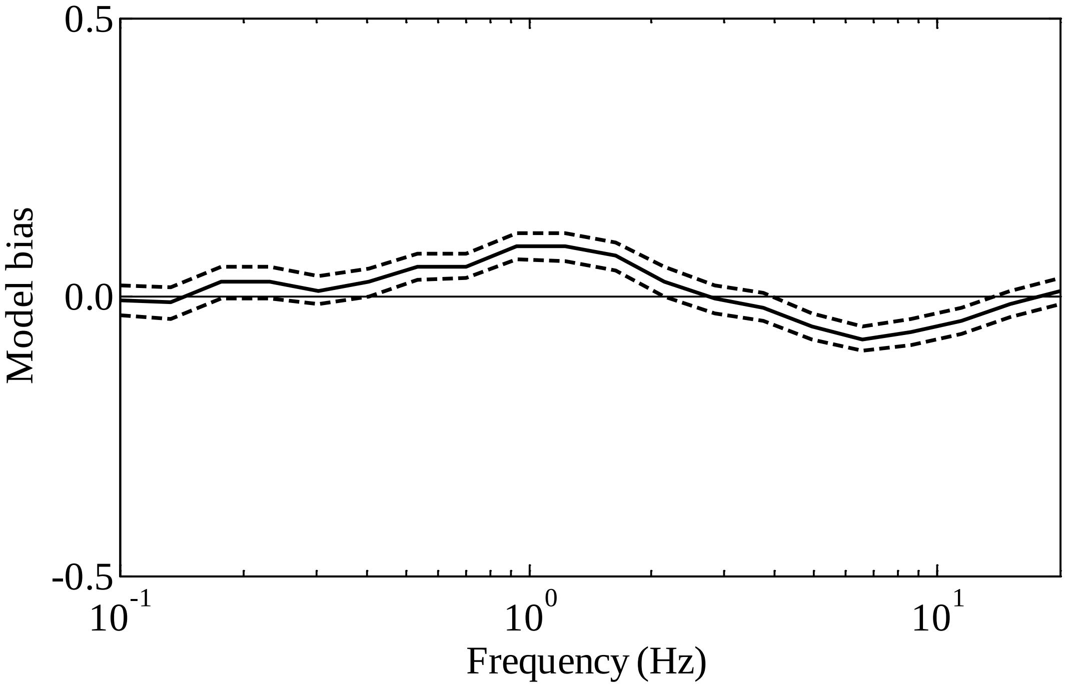
where A is the ground-motion parameter; $R = \sqrt{R_{rup}^2 + h^2}$, where R_{rup} is the closest distance from the recording site to the fault rupture plane and h is an "added depth" term that builds in near-source saturations due to finite-fault effects. V_{ref} = 760 m/s, c_0, c_1, c_2 and c_3 are regression coefficients to be determined, and ε is the intraevent residual.

Model Parameters in EXSIM

Parameter	Parameter value
Fault orientation (strike/dip)	5° /34°
Fault dimensions along strike and dip (km)	110 by 40
Depth of the upper edge of the fault (km)	0
Mainshock moment (dyne·cm)	2.8×10^{27}
Subfault dimensions (km)	5×5
Stress parameter Δσ (bar)	100
Radiation-strength factor	1.0
Number of subsources summed	176
$Q(f)$	$117 \cdot f^{0.77}$
Geometric spreading	$1/R$ for $R < 50$ km $1/R^0$ for 50 km $\leq R < 150$ km $1/R^{0.5}$ for $R \geq 150$ km
Windowing function	Cosine-tapered boxcar
Kappa (sec)	0.06
Crustal amplification	Boore and Joyner (1997) western North America generic rock site
Crustal shear-wave velocity (km/sec)	3.2
Rupture velocity (km/sec)	$0.8 \times$ (shear-wave velocity)
Crustal density (g/cm³)	2.7

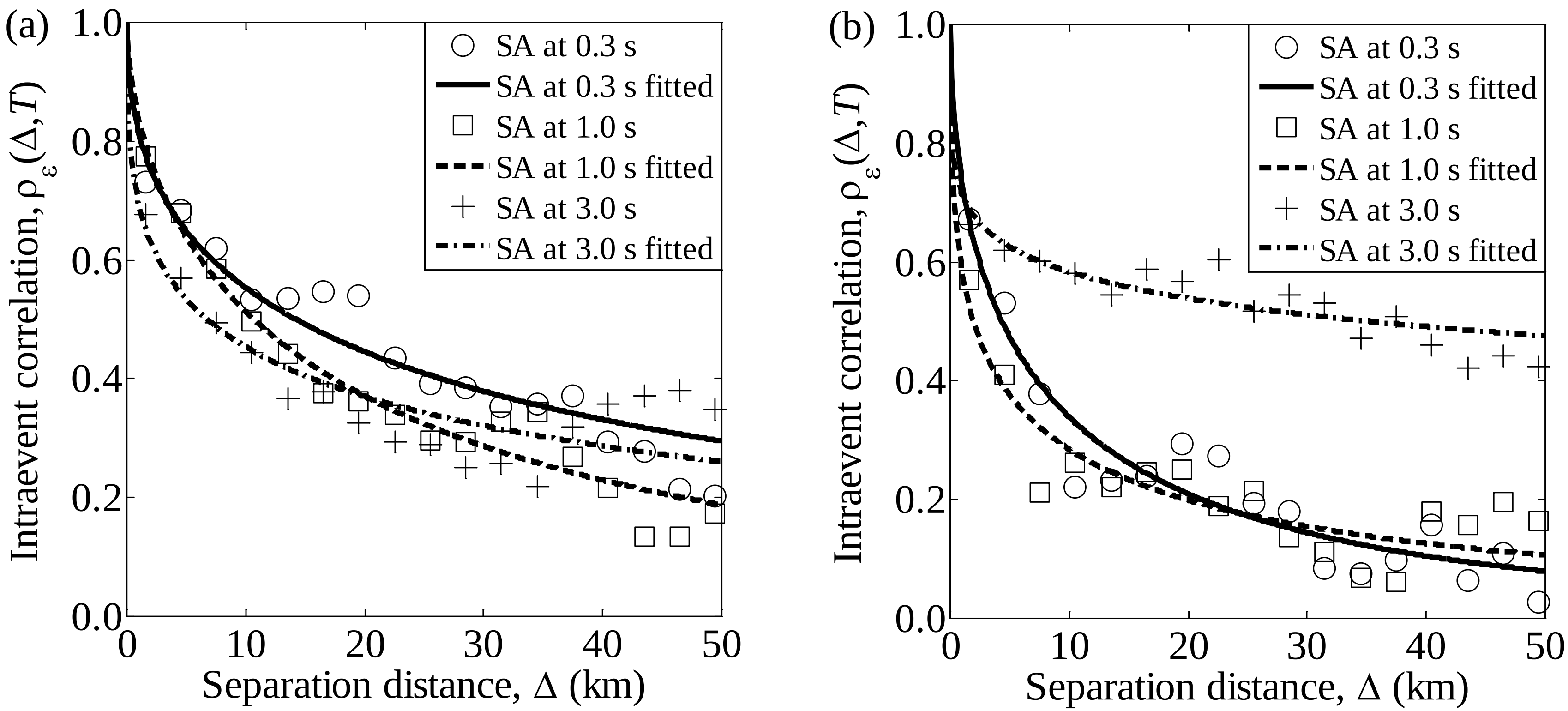
Intraevent Spatial Correlation Characteristics of EXISM

Model bias ($\log_{10}$[Obs./Sim.]) of EXSIM simulations



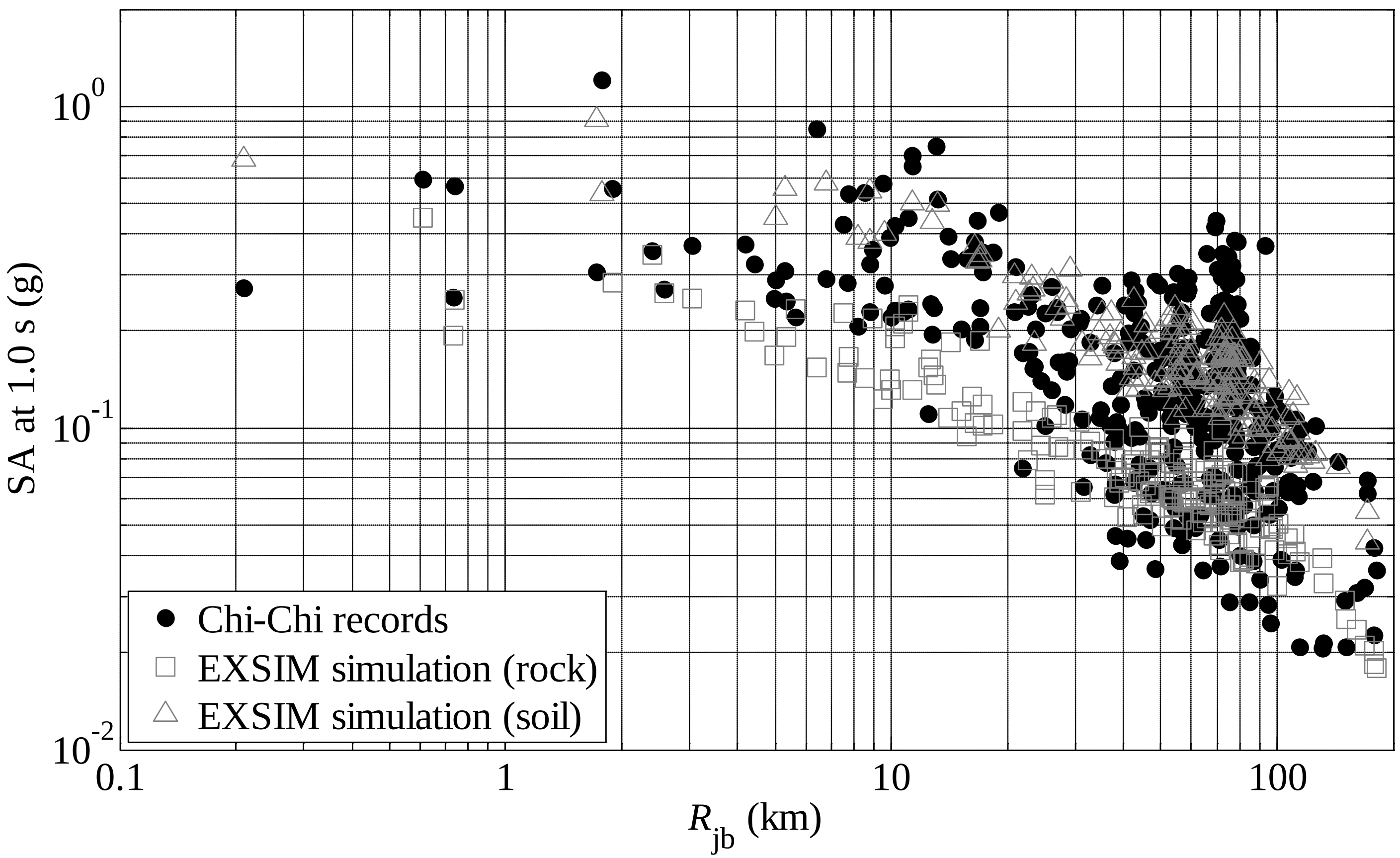
Averaged model bias at 389 stations.
95% confidence interval of the mean is shown in dashed lines.

Intraevent Spatial Correlation Characteristics of EXISM



Estimated intraevent spatial correlation coefficient $\rho_{\varepsilon}(\Delta,T)$ samples and their fitted curves of SAs for T equal to 0.3, 1.0 and 3.0 sec: (a) using the Chi-Chi records; (b) using simulation records (one trial).

Intraevent Spatial Correlation Characteristics of EXISM



Ground motions of Chi-Chi records and simulation (one trial) versus R_{jb} (closest horizontal distance from site to surface projection of the rupture) in units of g for SA at 1.0 sec.

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Intraevent Spatial Correlation Characteristics of EXISM

We introduce an additional intraevent variability (i.e., an error term $\varepsilon_{\mathrm{E}}(T)$) to the ground-motion parameter from the EXSIM simulations, $\varepsilon_{\mathrm{sim}}(T)$, whose standard deviation is $\sigma_{\varepsilon\mathrm{sim}}(T)$, such that the new error term from the simulations after this post-processing, $\varepsilon'_{\mathrm{sim}}(T)$, is given by,

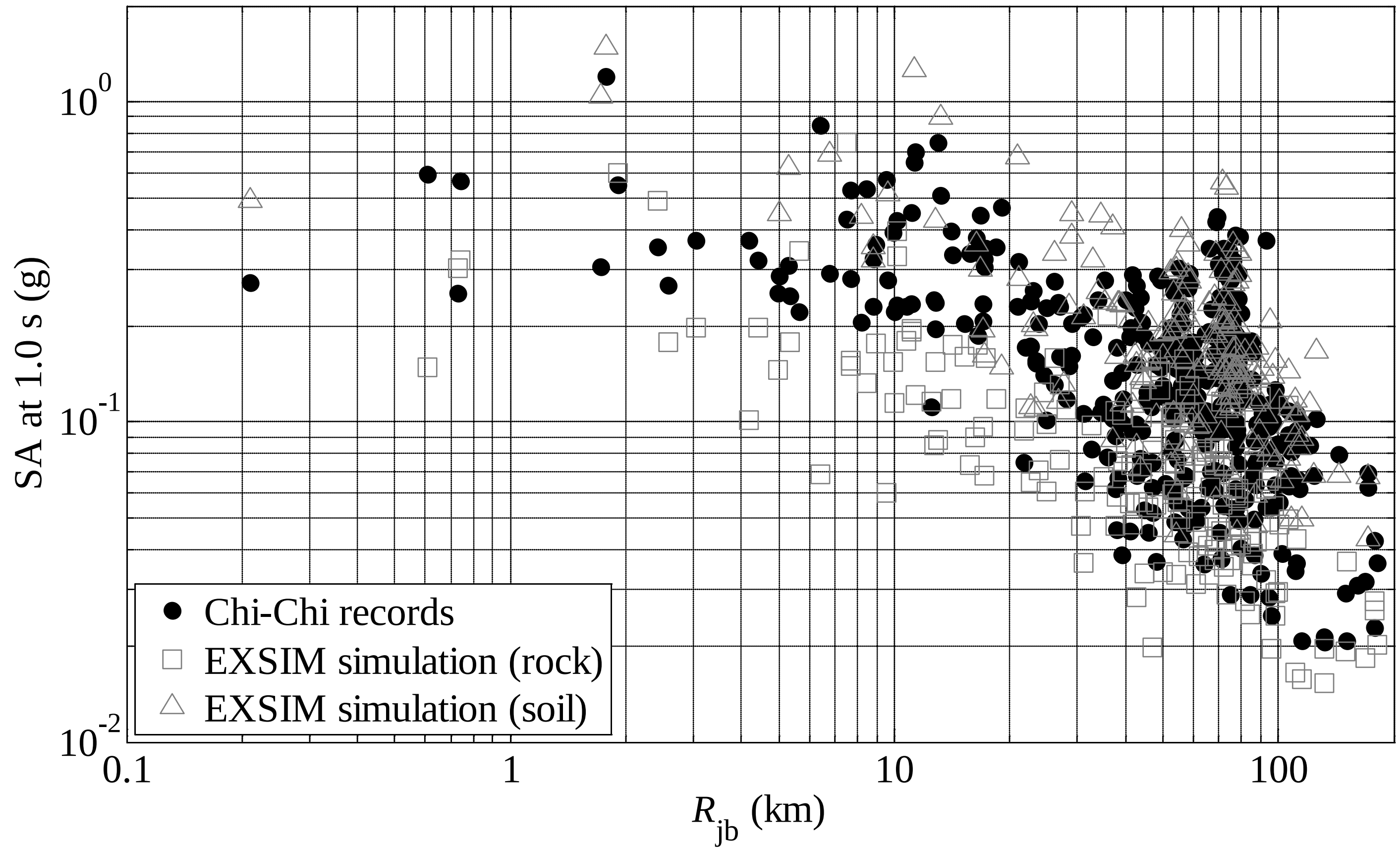
$$\varepsilon'_{\mathrm{sim}}(T) = \varepsilon_{\mathrm{sim}}(T) + \varepsilon_{\mathrm{E}}(T)$$

where $\varepsilon_{\mathrm{E}}(T)$ is a normal variate with zero mean and standard deviation of $\sigma_{\mathrm{E}}(T)$ such that the variance of $\varepsilon'_{\mathrm{sim}}(T)$, $\sigma^2_{\varepsilon}(T)$, equals the variance obtained from the actual records:

$$\sigma^2_{\varepsilon}(T) = \sigma^2_{\varepsilon\mathrm{sim}}(T) + \sigma^2_{\mathrm{E}}(T)$$

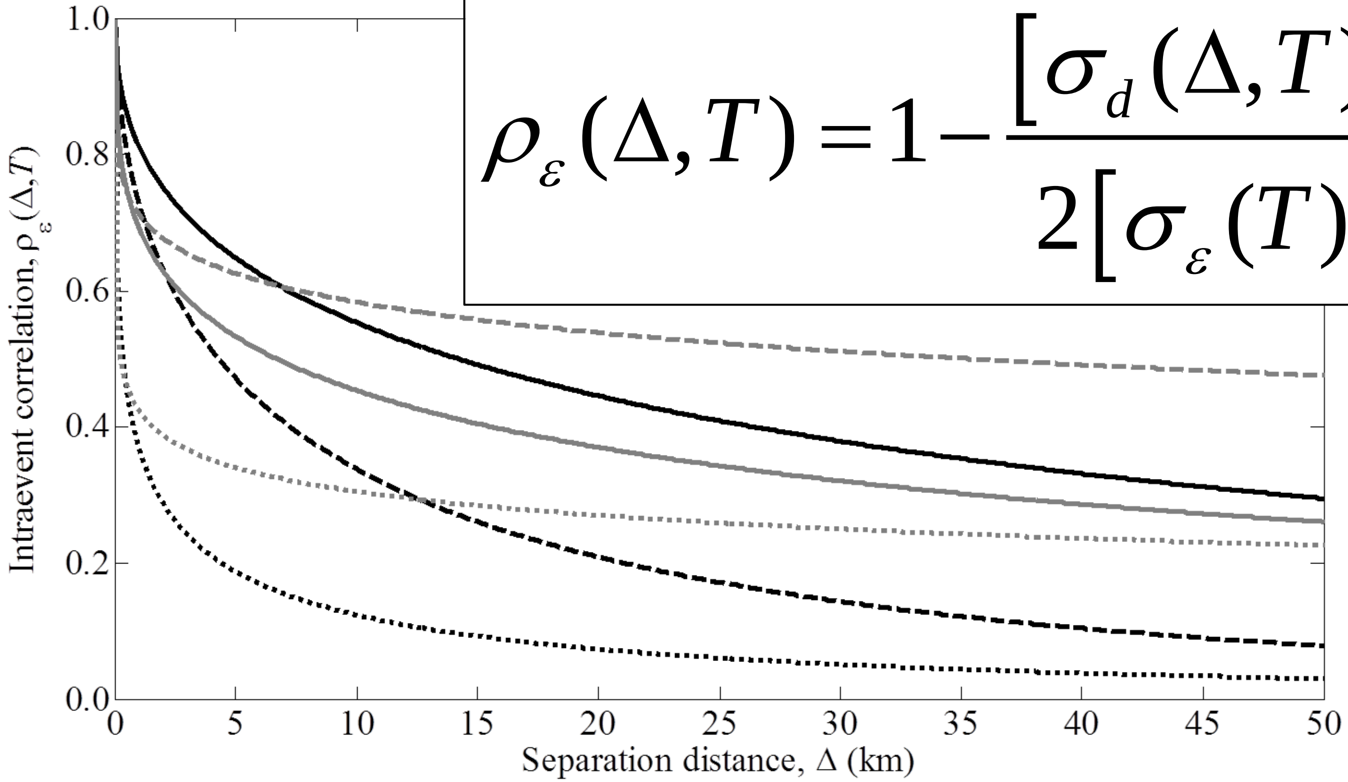
Intraevent Spatial Correlation Characteristics of EXISM

After post-processing:



Intraevent Spatial Correlation Characteristics of EXISM

$$\rho_\varepsilon(\Delta,T) = 1 - \frac{[\sigma_d(\Delta,T)]^2}{2[\sigma_\varepsilon(T)]^2}$$



Comparison of the intraevent spatial correlation coefficient of the Chi-Chi records, EXSIM simulation and modified simulation with added variability for SA at 0.3 and 3.0 sec (only fitted curves are shown)

Potential Simulation Method for Spatially Correlated Ground Motions

- Coherency,

$$\left|\bar{\gamma}_{jk}(\omega)\right| = \frac{\left|\bar{S}_{jk}(\omega)\right|}{\sqrt{\bar{S}_{jj}(\omega)\bar{S}_{kk}(\omega)}}$$

is a measure of "similarity" in the seismic motions, and indicates the degree to which the data recorded at the two stations are related by means of a linear transfer function.

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Summary

- Spatial correlation is important in seismic hazard assessment
- Spatial correlations of ground motion parameters (PGA, SAs) are investigated
- The widely-used stochastic simulation technique fails to reproduce observed spatial correlations
- Potential simulation method: coherency-based method

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Detailed information on this talk can be found in:

Taojun Liu, Gail M. Atkinson, Hanping Hong, and Karen Assatourians (2011) Intraevent Spatial Correlation Characteristics of Stochastic Finite-Fault Simulations, submitted to *Bulletin of the Seismological Society of America*.

Goda, K. and Hong, H.P. (2008) Spatial correlation of peak ground motions and response spectra, *Bulletin of the Seismological Society of America*, **98**, 1: 354-365.

Goda, K. and Hong, H.P. (2008) Estimation of Seismic Loss for Spatially Distributed Buildings, *Earthquake Spectra*, **24**, pp. 889-910.

Hong, H.P., Goda, K. and Davenport, A. G. (2006) Seismic hazard analysis: a comparative study, *Canadian Journal of Civil Engineering*, **33**(9), 1156-1171.

Thank you!