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SPATIAL CORRELATIONS IN CYBERSHAKE PHYSICS-BASED GROUND MOTION SIMULATIONS - PRELIMINARY RESULTS

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ABSTRACT

Spatial variations in strong ground motion have a significant impact on performance of distributed infrastructure in earthquakes, and implied risk to portfolios of insured buildings in a region. Currently, spatial ground motion variations in future earthquakes are predicted empirically, and calibrated using ground motion observations from densely recorded earthquakes. While useful, that calibration process requires strong assumptions about stationarity and isotropy of correlations. This paper reports preliminary results from an effort to perform analogous spatial variation estimation using physics-based simulations from the CyberShake platform. This platform contains simulated ground motions from tens of thousands of earthquake rupture scenarios, at locations throughout Southern California, providing a synthetic ground motion catalog that is much richer than we could ever hope to achieve from recordings. That richness allows significant relaxation of stationarity and isotropy assumptions, and provides new insights regarding the role of source and path heterogeneity on the spatial correlation of ground motion amplitudes. The results suggest that the geological condition and directivity of earthquake propagation have significant impact on spatial correlations. Additionally, this work serves as a new dimension of ground motion simulation validation, as the estimated correlations can be compared to results from past earthquakes.

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Spatial variations in strong ground motion have a significant impact on performance of distributed infrastructure in earthquakes, and implied risk to portfolios of insured buildings in a region. Currently, spatial ground motion variations in future earthquakes are predicted empirically, and calibrated using ground motion observations from densely recorded earthquakes. While useful, that calibration process requires strong assumptions about stationarity and isotropy of correlations. This paper reports preliminary results from an effort to perform analogous spatial variation estimation using physics-based simulations from the CyberShake platform. This platform contains simulated ground motions from tens of thousands of earthquake rupture scenarios, at locations throughout Southern California, providing a synthetic ground motion catalog that is much richer than we could ever hope to achieve from recordings. That richness allows significant relaxation of stationarity and isotropy assumptions, and provides new insights regarding the role of source and path heterogeneity on the spatial correlation of ground motion amplitudes. The results suggest that the geological condition and directivity of earthquake propagation have significant impact on spatial correlations. Additionally, this work serves as a new dimension of ground motion simulation validation, as the estimated correlations can be compared to results from past earthquakes.

Introduction

When an earthquake causes shaking in a region, the amplitude of shaking (measured, for example, using spectral acceleration at a given period) varies spatially. Some of the spatial variations of shaking amplitude can be predicted by ground motion models, e.g., [1]. However, there are still significant remaining ("residual") variations in ground motion, and previous studies [2] show that the spatial correlation in residuals is influential when evaluating risk to distributed infrastructure systems.

Currently, many empirical correlation models of ground motion residuals are developed based on semivariogram fitting. While useful, this approach requires stationarity and isotropy assumptions. That is, it assumes that any pair of sites with same relative separation within an earthquake have the same correlation (stationarity), and that the correlation is independent of angular orientation (isotropy). These assumptions are made of necessity, since the real correlation coefficient calculation requires a series of ground motion intensity observations at same pair of

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locations, which is a rare condition in empirical ground motion catalogs. In this paper, we refine these assumptions by adopting CyberShake simulations to calculate the correlation coefficients for ground motion residuals in a region, and compare the results with a correlation model calibrated from empirical ground motions.

Correlation Coefficient of Residuals in Ground Motion

CyberShake is a physics-based ground motion simulation platform which includes simulations of over 415,000 rupture scenarios in the Los Angeles region [3]. With this large data set, sufficient ground motion data are available at individual station pairs to refine the assumptions mentioned above. In this study, ground motion intensities are measured by the geometric mean of spectral accelerations at a given period, for the two horizontal ground motion components. We first calculate the Pearson's correlation coefficients of ground motion intensities, and then argue that the coefficients are the same for the residuals relative to a mean model. The Pearson's correlation coefficient of ground motion intensities between site *i* and site *j* is calculated as:

$$\rho_{ij} = \frac{\sum_{k=1}^{n}(\ln SA_{ik} - \ln \overline{SA}_i)(\ln SA_{jk} - \ln \overline{SA}_j)}{\sqrt{\sum_{k=1}^{n}(\ln SA_{ik} - \ln \overline{SA}_i)^2}\sqrt{\sum_{k=1}^{n}(\ln SA_{jk} - \ln \overline{SA}_j)^2}} \tag{1}$$

where SA_{ik} is the spectral acceleration geometric mean at site *i* under earthquake *k*. In order to assure that the correlation coefficients of ground motion intensities are the same as those of the residuals, we select these *n* earthquakes to have the same magnitude and rupture extent (with only the slip distribution across the rupture varying). For that situation, the ground motion model will predict the same log-mean *SA* for each earthquake. That is, according to the ground-motion model:

$$\ln SA_{ik} = \overline{lnSA_{ik}} + \tilde{\sigma}\epsilon_{ik} \tag{2}$$

where $\overline{lnSA_{ik}}$ is the mean of the log ground motion intensity at site *i* and is estimated by the sample mean of ln*SA*'s from these *n* earthquakes, ϵ_{ik} is a random variable representing ground motion residual at site *i* from earthquake *k,* and $\tilde{\sigma}$ is the corresponding standard deviation of residuals. During a series of earthquakes with the "same" rupture definition, $\tilde{\sigma}$ is constant. Therefore, the correlation coefficients of residual ϵ_{ik} are the same as the correlation coefficients of $ln\, SA_{ik}$, and we can use equation (1) to quantify the spatial correlation in ground motion residuals. In the following text, correlation coefficient refers to the correlation coefficient of residuals.

Preliminary Results

Spatial correlations under stationarity and isotropy assumptions

First, the spatial correlations based on CyberShake simulations are investigated under stationarity and isotropy assumptions. By averaging the correlation coefficients of all pairs of sites separated by same distance in the region, the non-stationary and anisotropic effects are counterbalanced, and the correlation coefficient at two sites only depends on their separation distance. Specifically, the correlation coefficient at distance *h* is calculated as:

$$\hat{\rho}(h) = \frac{1}{N} \sum_{|d(i,j)-h|<b} \rho_{ij} \tag{3}$$

where the summation condition takes the average of the correlation coefficients of all pairs of sites with separation distance from *h* - *b* to *h* + *b*.

We compare the numerical results from equation (3) and the CyberShake data to an empirical model based on recorded ground motions from several past earthquakes [4]. That model predicts that the correlation coefficient decreases exponentially as the distance between the sites increases. Figure 1 shows a comparison of the results. In Figure 1, each data point is an average of the correlation coefficients with $b = 2.5km$. The correlation coefficients observed in CyberShake simulations show the same pattern of decay as the empirical model, but higher correlations at a given distance. This may be because simulations have insufficient heterogeneity in the earthquake source or crustal velocity model to cause variations in amplitudes, but further work is needed to evaluate this observation.

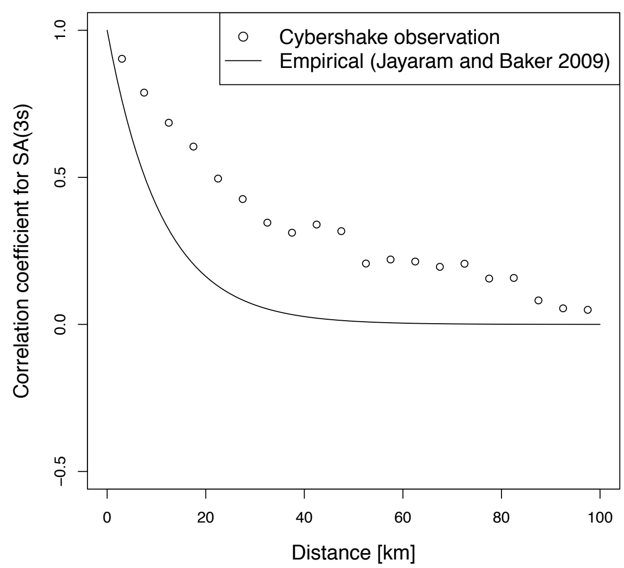
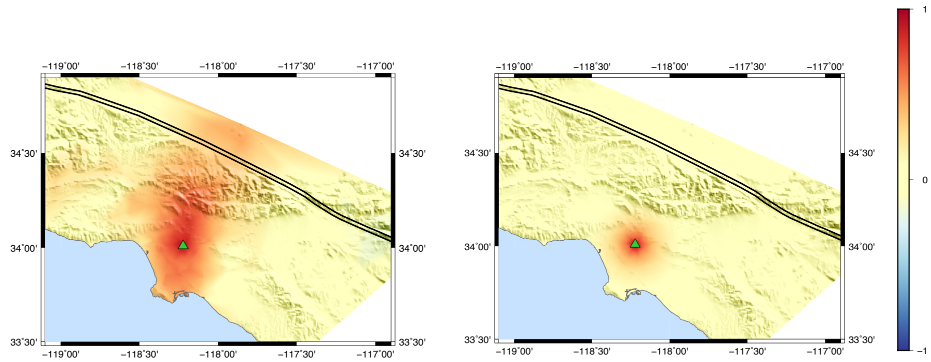


Figure 1. Correlation coefficients for *SA*(3s) versus separation distance.

Dependence of spatial correlations on geological conditions

To investigate the effect of geologic condition on spatial correlations, we select a reference site and calculate the correlation coefficients between that site and any other site. Then a heat map of correlation coefficients is provided to visualize the effect of geological condition, and an equivalent map from the empirical model is also provided for comparison (Figure 2). Figure 2 shows that the correlation generally decreases as the distance from the reference site increases. However, a sedimentary basin in the basin region (roughly corresponding in extent to the dark-shaded region in Figure 2a) shows higher correlations than other areas with stiffer surficial materials. This suggests that ground motions within the basin have similar amplitudes due to shared path effects and shared presence (or lack of) basin amplification. No such similar pattern is seen in the empirical model of Figure 2b, as that model is a function of separation distance only and has no ability to detect or incorporate effects of geology or other nonstationary features.



(a) (b)

Figure 2. Heat map of correlation coefficients with the location denoted with a triangle, for *SA*(3s), (a) Calculation from CyberShake simulations; (b) Empirical model [4]. Correlations are computed for a magnitude 8 Southern San Andreas rupture whose surface projection is indicated by the black lines in the top portion of the figure.

Conclusions

This paper studies spatial correlations in ground motion residuals from CyberShake simulations. Use of simulations rather than recordings allows the relaxation of stationarity and isotropy assumptions typically made in spatial correlation studies. We first verified CyberShake simulations by comparing their spatial correlations with an empirical model under the same assumptions. The results show that their correlation coefficients of residuals in spectral acceleration decrease with distance in roughly the same as the empirical model, but with a slightly higher overall correlation level. Additionally the results showed that CyberShake correlations are magnified in a sedimentary basin, probably due to the enhancement of common path effects. Further work is planned to examine the dependence of spatial correlations on period and rupture properties. The results indicate that advanced ground motion simulations hold promise in allowing refinement of stationarity and isotropy assumptions in empirical ground motion correlation models.

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