Characterizing seismic hazard to distributed systems using efficient simulation techniques

Jack Baker & Nirmal Jayaram
Civil & Environmental Engineering
Stanford University
Motivation

- We are interested in assessing seismic risk to distributed transportation networks.
- The spatial extent of these systems is a challenge.
- Spatial correlation of ground motion intensities is an important consideration for these analyses.
Background: seismic sources

Both this work and traditional Probabilistic Seismic Hazard Analysis require seismic source characterization.
Background: ground motion prediction

Ground Motion Prediction ("attenuation") models provide predictions of the distribution of ground motion intensity (e.g., spectral acceleration) as a function of earthquake magnitude, source-to-site distance, etc.

Model form:

\[
\ln Sa_i(T) = \ln Sa_i(M, R, T, \ldots) + \varepsilon_i + \eta
\]

- Spectral acceleration at site "i"
- Predicted mean (log) spectral acceleration
- Inter-event variability (at all sites)
- Intra-event variability at site "i"

Observed spectral acceleration values from the 1999 Chi-Chi, Taiwan earthquake
Ground motion intensity at two sites

\[
\ln Sa_i (T) = \ln Sa_i (M, R_i, T, ...) + \varepsilon_i + \eta
\]

\[
\ln Sa_j (T) = \ln Sa_j (M, R_j, T, ...) + \varepsilon_j + \eta
\]
Observed “residuals” from well-recorded earthquakes

Observations of past earthquakes shows that these residuals are correlated at nearby sites, due to

- Common source earthquake
- Similar location to asperities
- Similar wave propagation paths
- Similar local site effects

Note that this correlation is different than ground motion coherence

\[
\varepsilon_i = \ln Sa_i(T) - \ln Sa_i(M, R_i, T,...) - \eta
\]
Estimation of correlation (or covariance)

If we assume stationarity and anisotropy of the $\varepsilon$’s, we can pool paired observations with comparable distances to estimate a correlation coefficients.
Estimation of correlation from well-recorded earthquakes

We can turn these observations into a predictive model

Empirical semivariogram for PGA ε’s from the 1999 Chi-Chi earthquake
Application: risk to lifeline systems

\[ \ln Sa_i(T) = \ln Sa_i(M, R, T, ...) + \varepsilon_i + \eta \]

We can’t produce PSHA-like maps of hazard, but we can use Monte Carlo simulations to produce a set of ground motion scenarios and associated probabilities.
An aside: comparison with single-site PSHA

If we look at the observed $Sa$ values from these simulations at any single site, they match the distribution from traditional single-site PSHA.
Application: risk to lifeline systems

For each map of spectral accelerations, we can predict the resulting damage and disruption to our network.

Illustrative results using a simplified highway network model
Application: risk to lifeline systems

If we aggregate all these disruptions, we can compute a rate of disruption exceedance
Consideration of correlations has a significant impact here.

We can repeat this exercise omitting the $\varepsilon$ correlation, to see the impact of this correlation.

\[
\ln S_{a_i}(T) = \ln S_{a_i}(M, R, T, \ldots) + \varepsilon_i + \eta
\]
If done correctly, this reduces our computational expense by \(~2\) orders of magnitude.
Improving simulation efficiency: K-means clustering

Group these into a cluster

Select a *single* representative from the cluster to represent *all* simulations in the cluster

This can reduce computational expense by another \(~2\) orders of magnitude
Loss estimation using more efficient techniques

These techniques reduce our computational expense without biasing our estimates of disruption
Conclusions and current status

• We have used well-recorded earthquakes to measure spatial correlation of spectral acceleration values.

• Using this model, we can generalize traditional PSHA to characterize ground motion intensities at many sites.

• This characterization can not be done analytically, but efficient sampling and clustering make simulation tractable.

• We assessed a simplified transportation network to demonstrate that this approach is unbiased with respect to basic Monte Carlo simulation.

• We now hope to use this approach to study more realistic models distributed infrastructure.