Characterizing spatial correlations in ground motion hazard, and implications for PBEE analysis of systems

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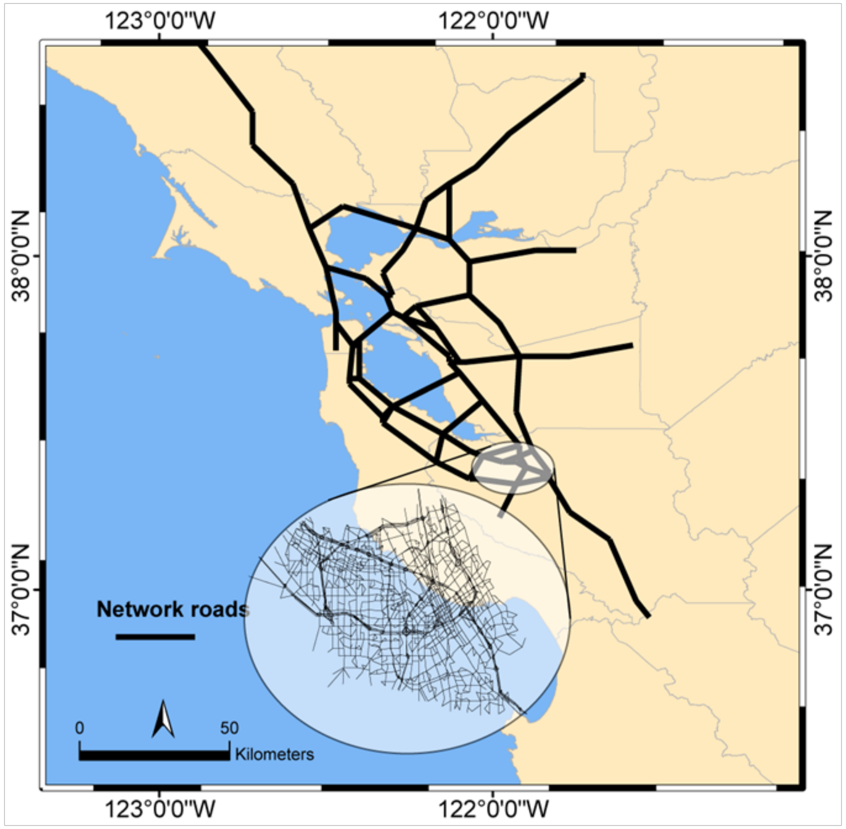
Motivation

- We are interested in assessing seismic risk to distributed infrastructure systems
  - Transportation networks
  - Electrical distribution systems
  - Water/sewer pipelines

- The spatial extent of these systems is a challenge

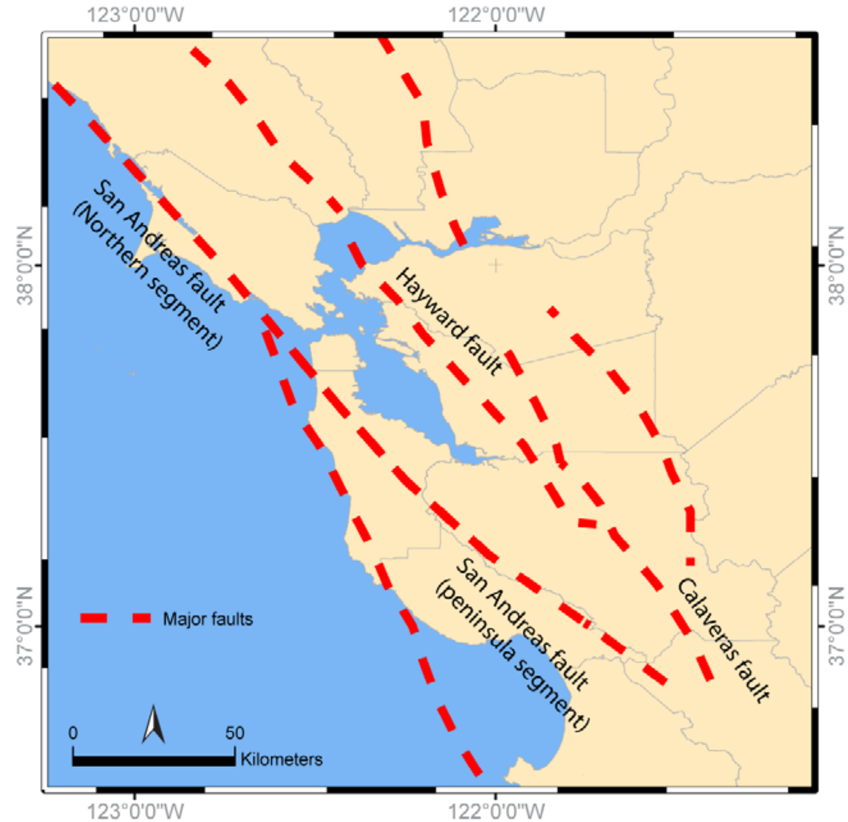
- Spatial correlation of ground motion intensities is a key required input for these analyses



San Francisco Bay Area roadways

Background

Both this work and traditional Probabilistic Seismic Hazard Analysis require seismic source characterization

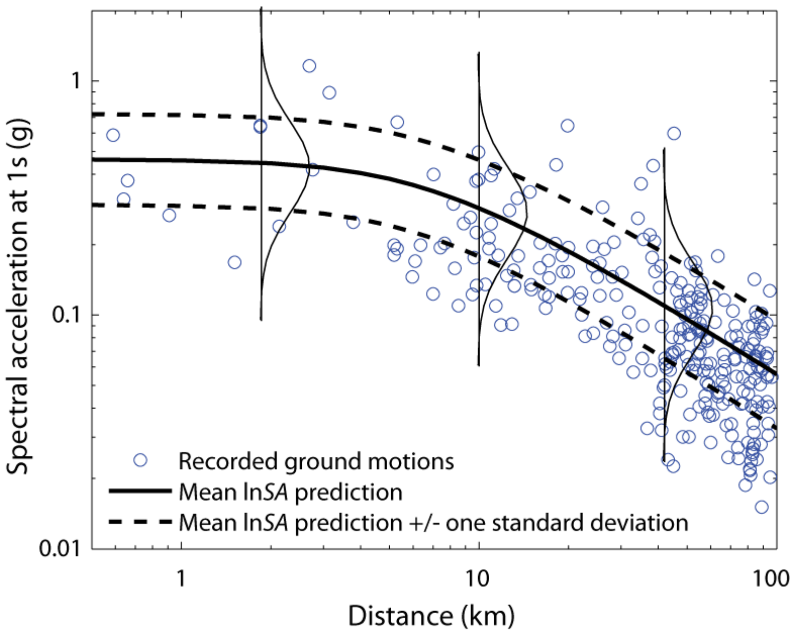


Major Bay Area faults

Background

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.

Observed spectral acceleration values from the 1999 Chi-Chi, Taiwan earthquake



Model form:

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, T, \ldots)} + \sigma_i \varepsilon_i + \tau \eta$$

- $\ln Sa_i(T)$: Spectral acceleration at site "*i*"
- $\overline{\ln Sa_i(M, R, T, \ldots)}$: Predicted mean (log) spectral acceleration
- $\sigma_i \varepsilon_i$: Intra-event variability at site "*i*"
- $\tau \eta$: Inter-event variability (at all sites)

Components of correlation in ground motions

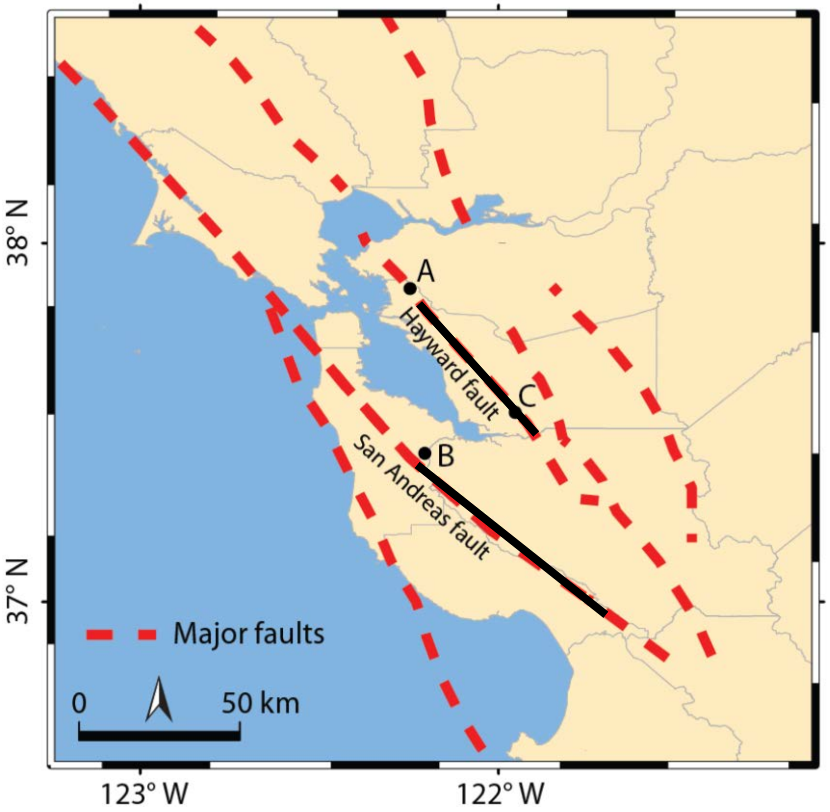
Ground motion predictions at two sites:

$$\ln Sa_{1j} = \overline{\ln Sa(M_j, R_{1j}, V_{s30,1}, T, \ldots)} + \sigma_{1j}\varepsilon_{1j} + \tau_j \eta_j$$

$$\ln Sa_{2j} = \overline{\ln Sa(M_j, R_{2j}, V_{s30,2}, T, \ldots)} + \sigma_{2j}\varepsilon_{2j} + \tau_j \eta_j$$

"Correlation in means"

"Correlation in residuals"



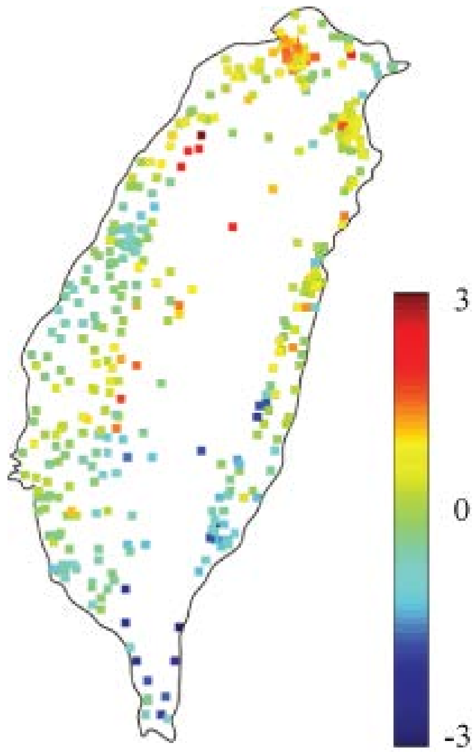
Observed residuals from well-recorded earthquakes

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

$$\varepsilon_i = \ln Sa_i(T) - \overline{\ln Sa_i(M, R_i, T, \ldots)} - \eta$$



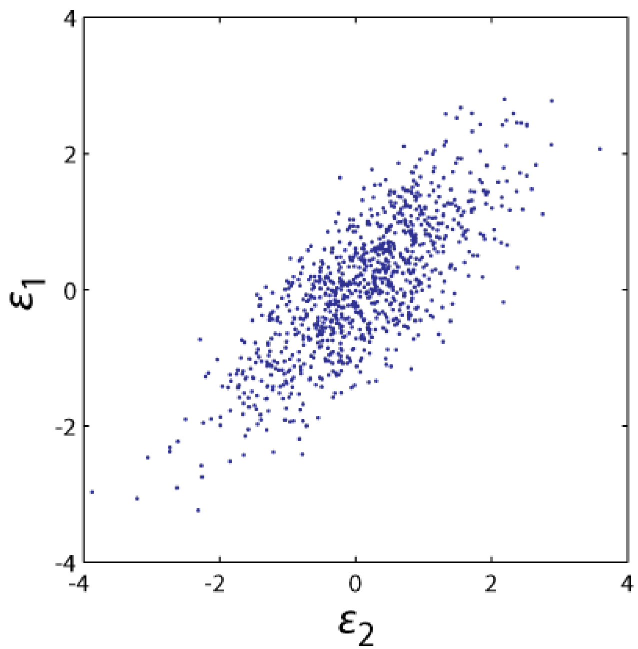
PGA ε's from the 1999 Chi-Chi earthquake

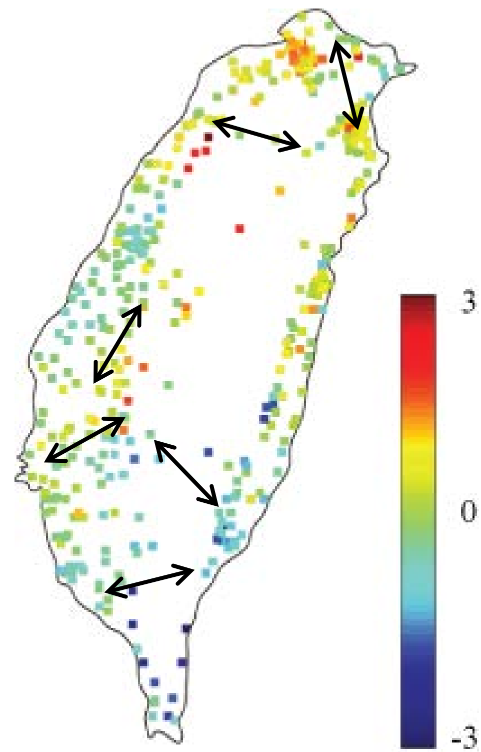
Estimation of correlation (or covariance), assuming stationarity

The stationarity and isotropy assumptions allow us to pool many paired observations with comparable distances

We can then estimate a correlation coefficient

$$\varepsilon_i = \ln Sa_i(T) - \overline{\ln Sa_i(M, R_i, T, \ldots)} - \eta$$





Correlation in means is implied by the source model

Ground motion predictions at two sites:

$$\ln Sa_{1j} = \overline{\ln Sa(M_j, R_{1j}, V_{s30,1}, T, \ldots)} + \sigma_{1j}\varepsilon_{1j} + \tau_j \eta_j$$

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"Correlation in means"

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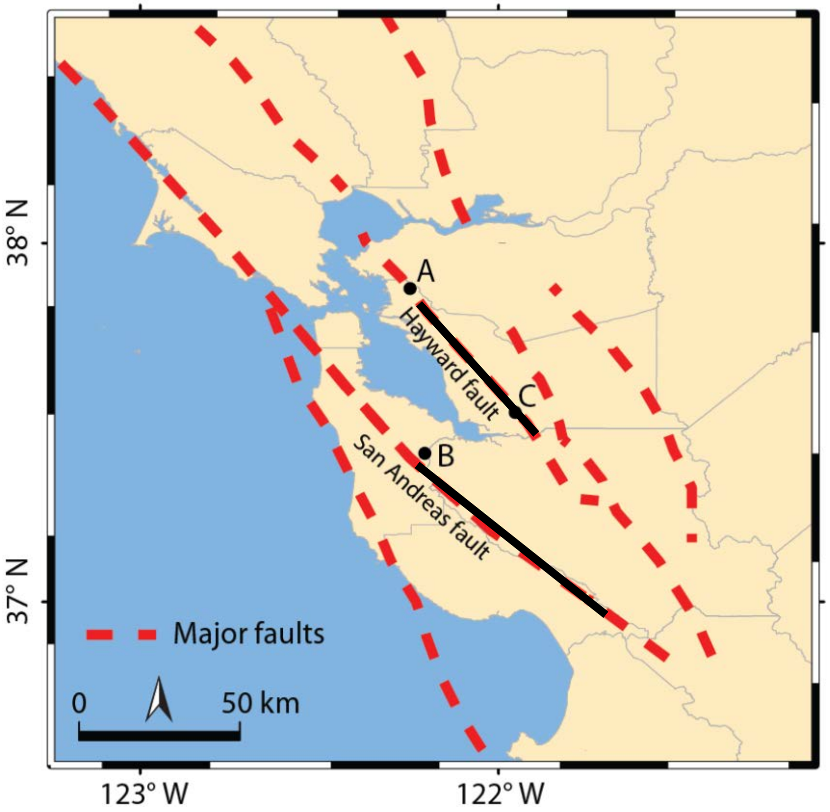
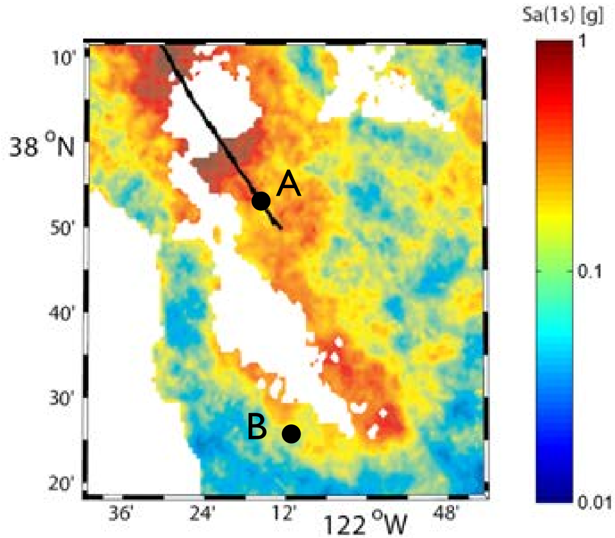
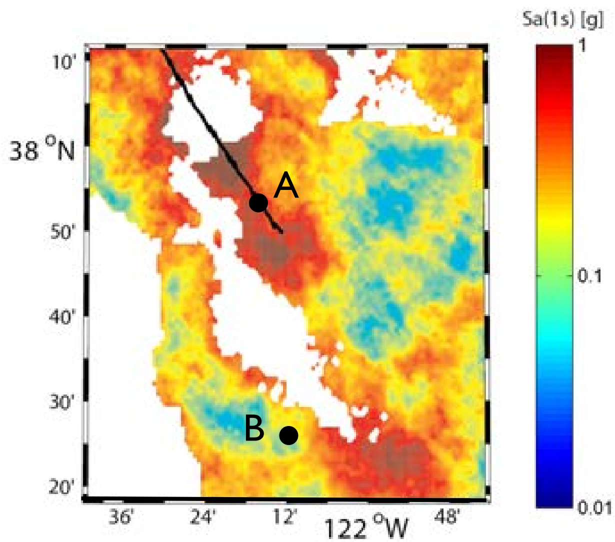


Two simulations of an M7 Northern Hayward event





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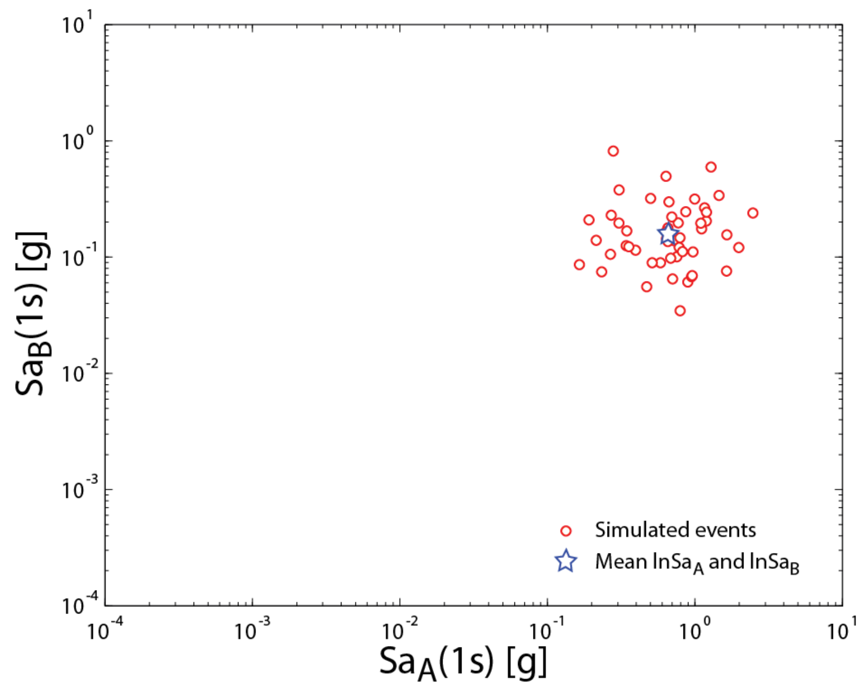
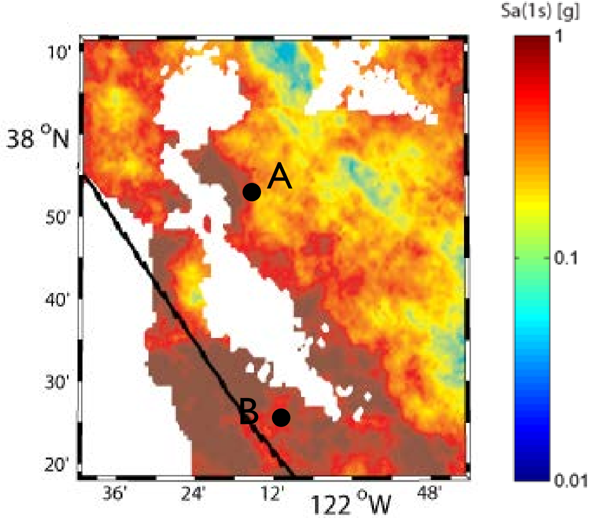
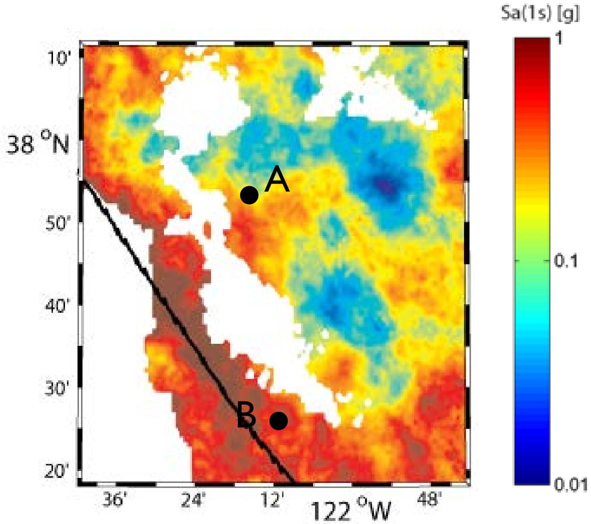


Two M8 San Andreas events, and a synthetic catalog





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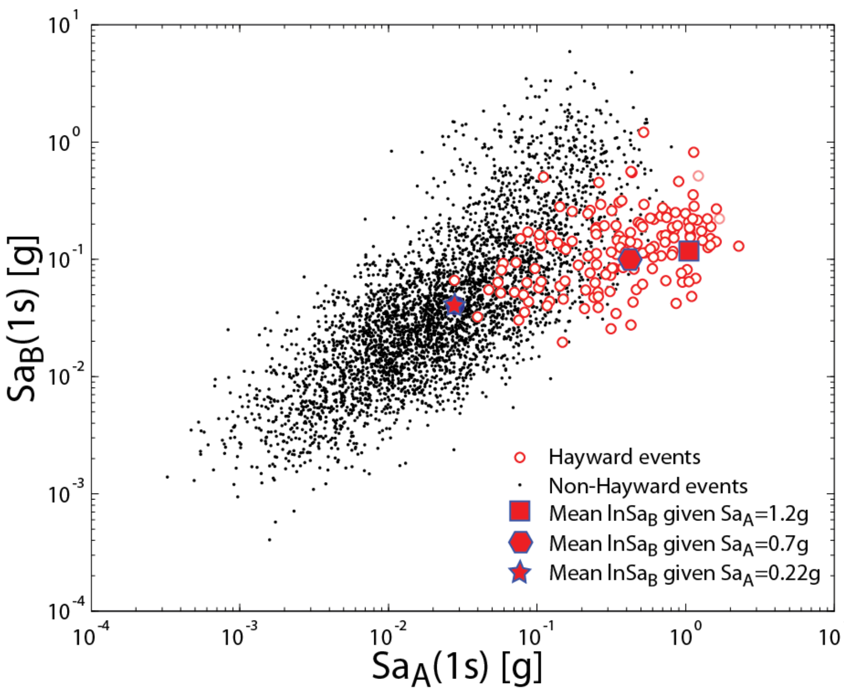
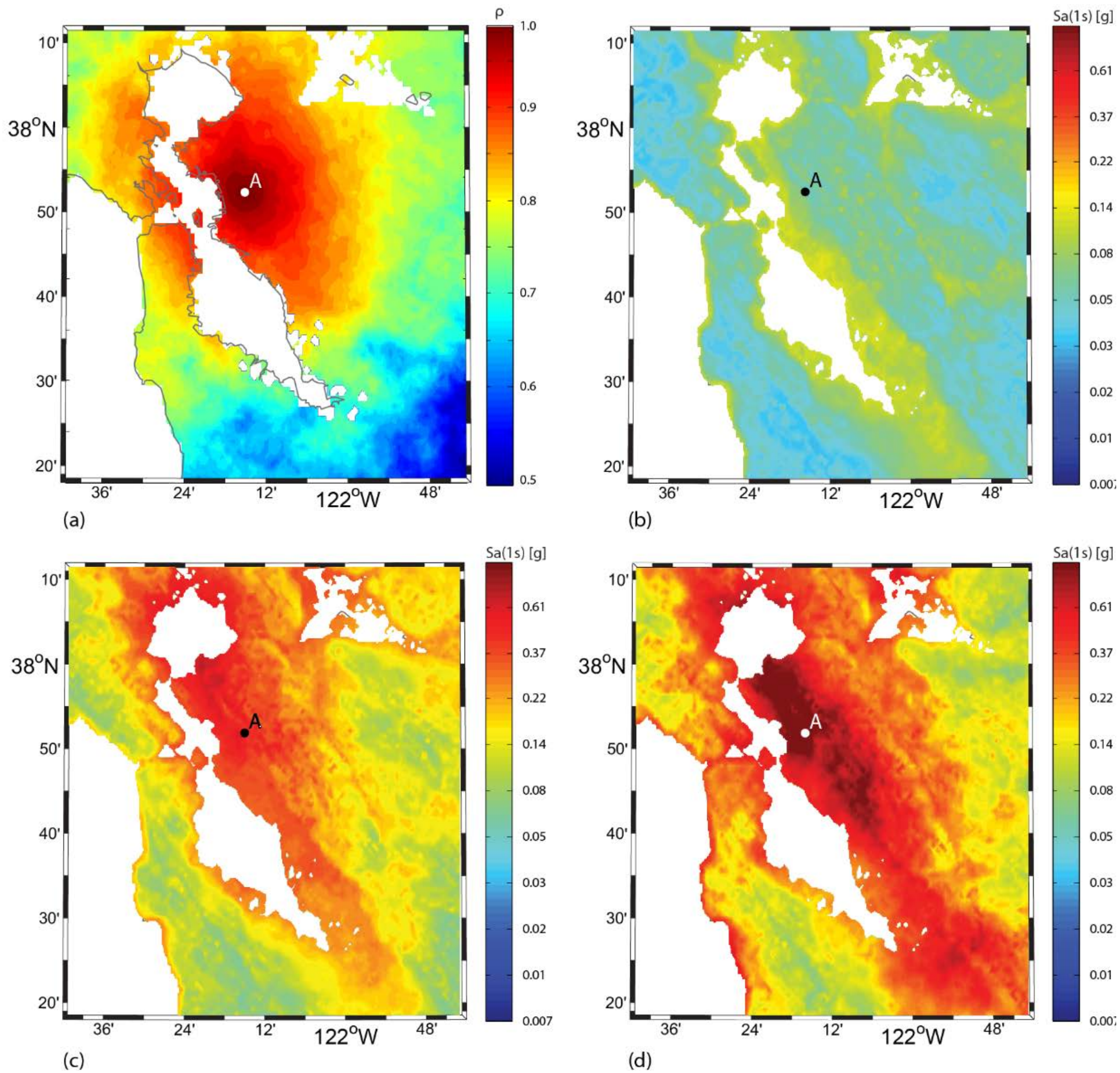


Measures of joint behavior

Correlation with $Sa_A(1s)$

Mean given $Sa_A(1s)=0.22g$

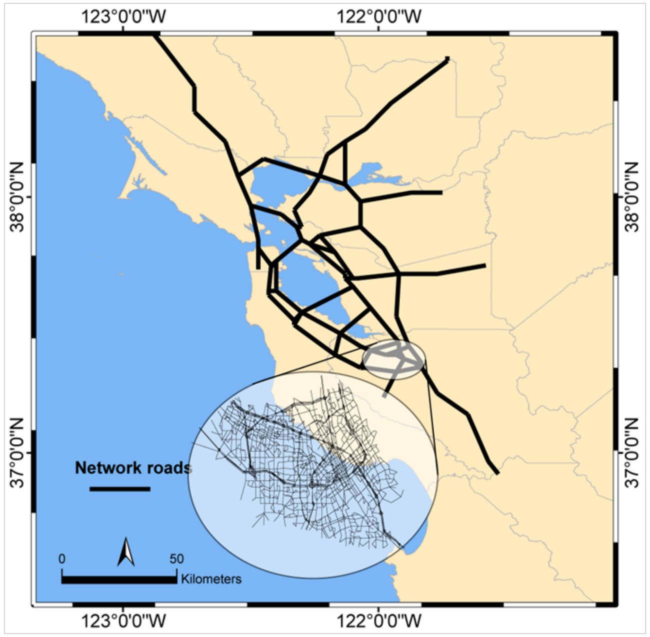


Mean given $Sa_A(1s)=0.7g$

Mean given $Sa_A(1s)=1.2g$

Application: Bay Area transportation network risk

- We studied earthquake-induced travel time delays on the interstate highway network
- Spatially correlated spectral accelerations were simulated using the above models
- Bridge damage states were estimated using HAZUS fragility functions
- Network data and Origin-Destination demands were obtained from CALTRANS and aggregated
- Travel times were obtained using the user-equilibrium model (assuming no travel demand changes)

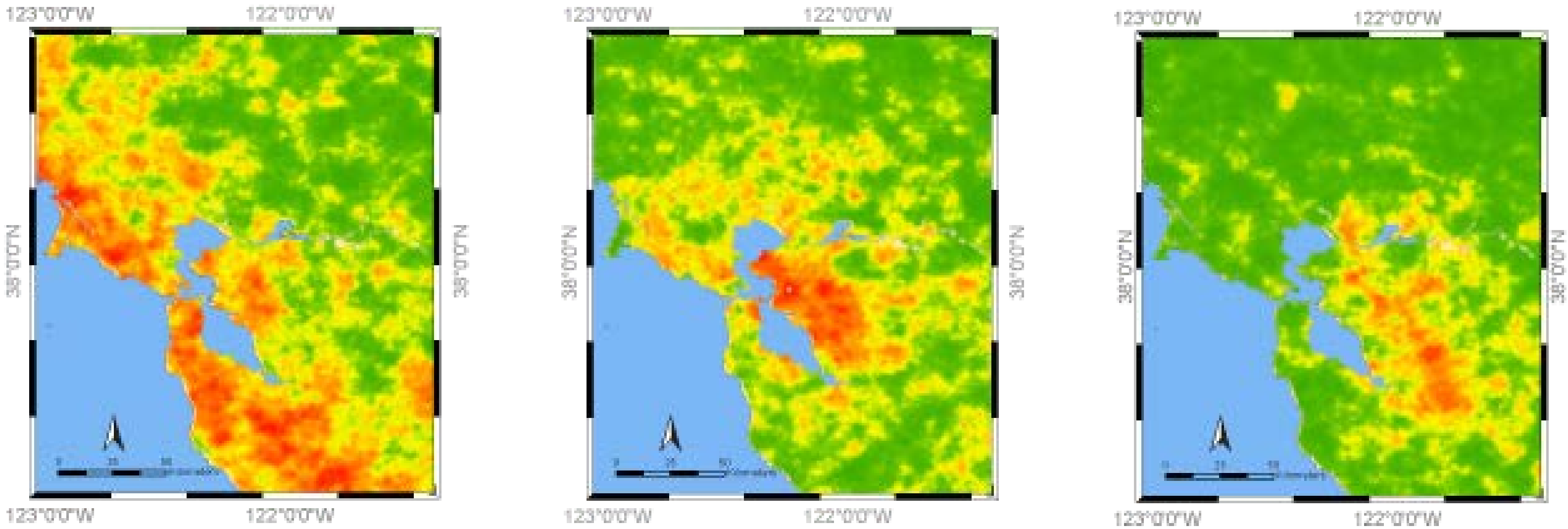


Bay area interstate highways

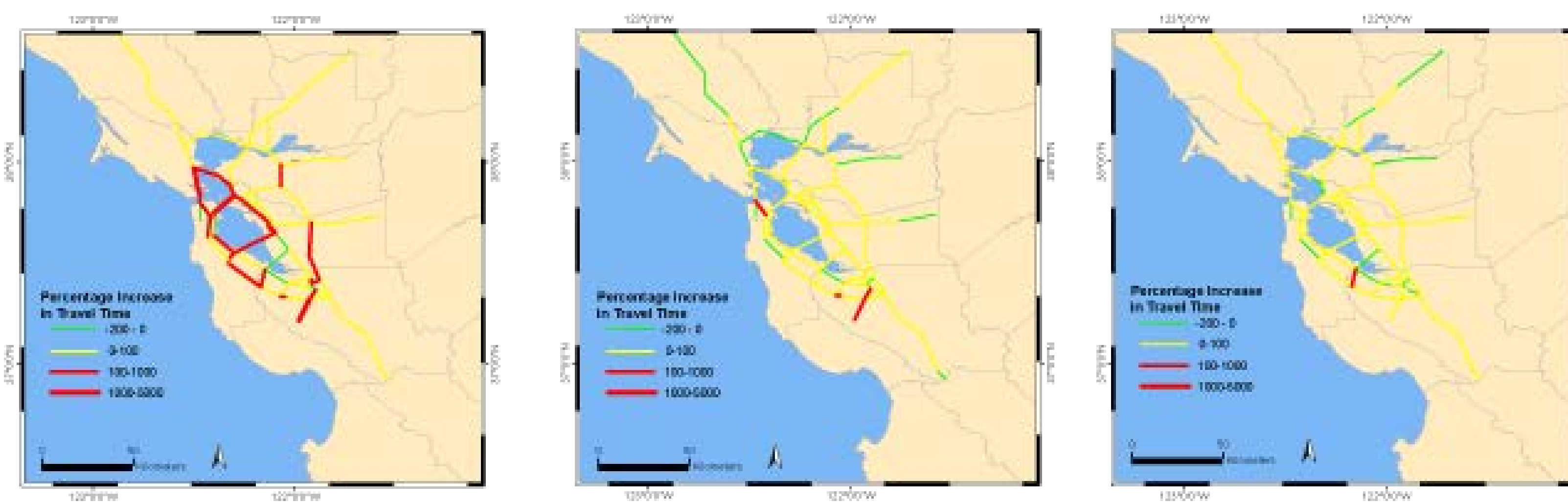
This is a simplified illustrative model

Simulations of highway travel time delays

Ground motion simulations

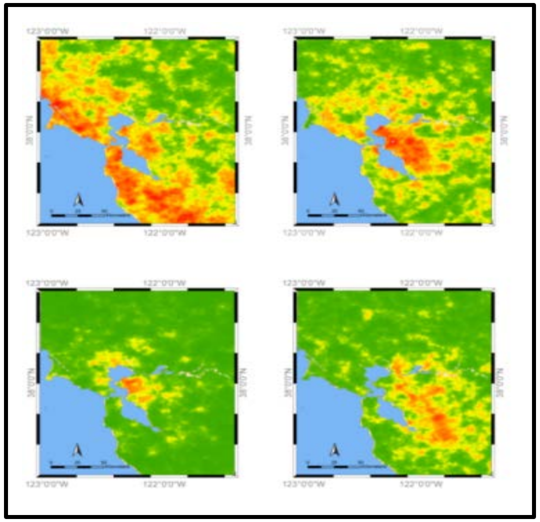


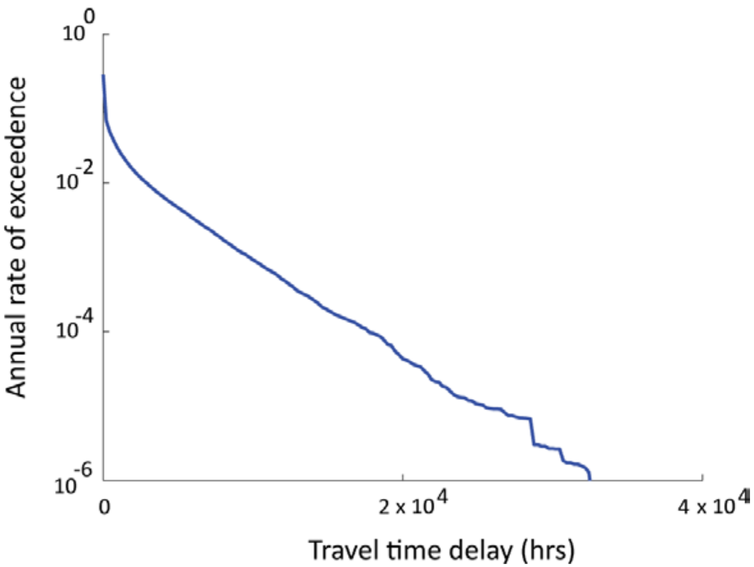
Travel time delay simulations



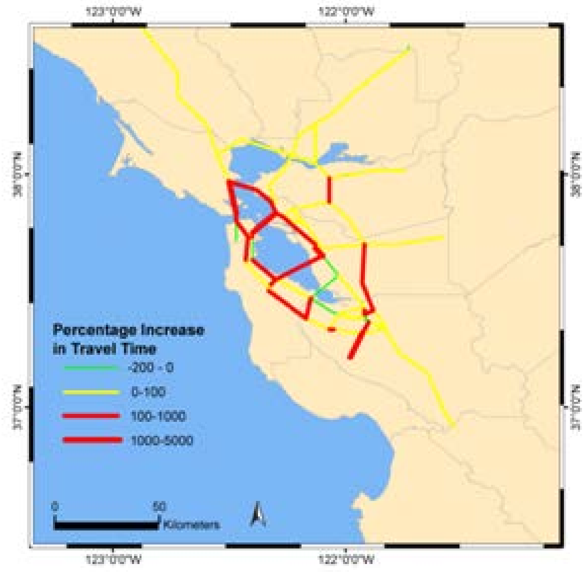
Estimating highway travel time delays

- For each map of spectral accelerations, we can predict the resulting bridge damage and disruption to our network
- We aggregate all these disruptions to compute the rate of disruption exceedence





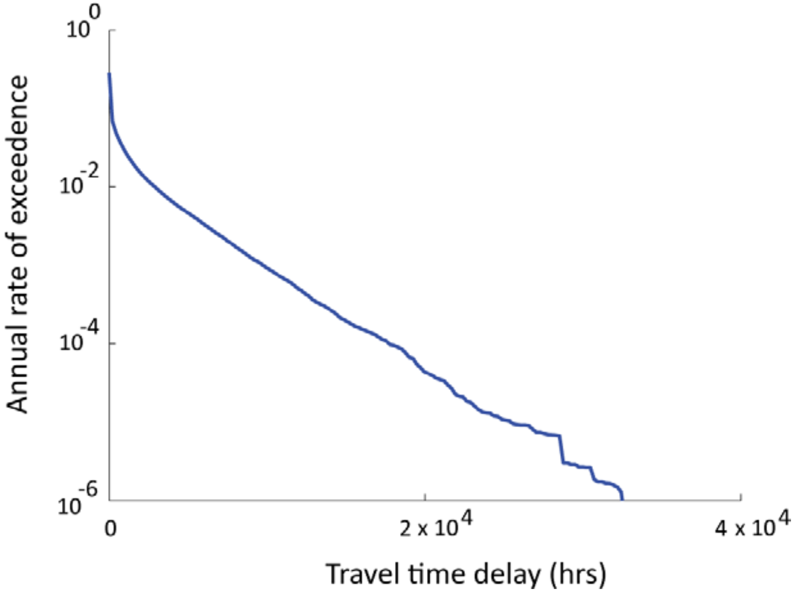
Loss exceedance curve for travel time delays



Deaggregation of seismic loss

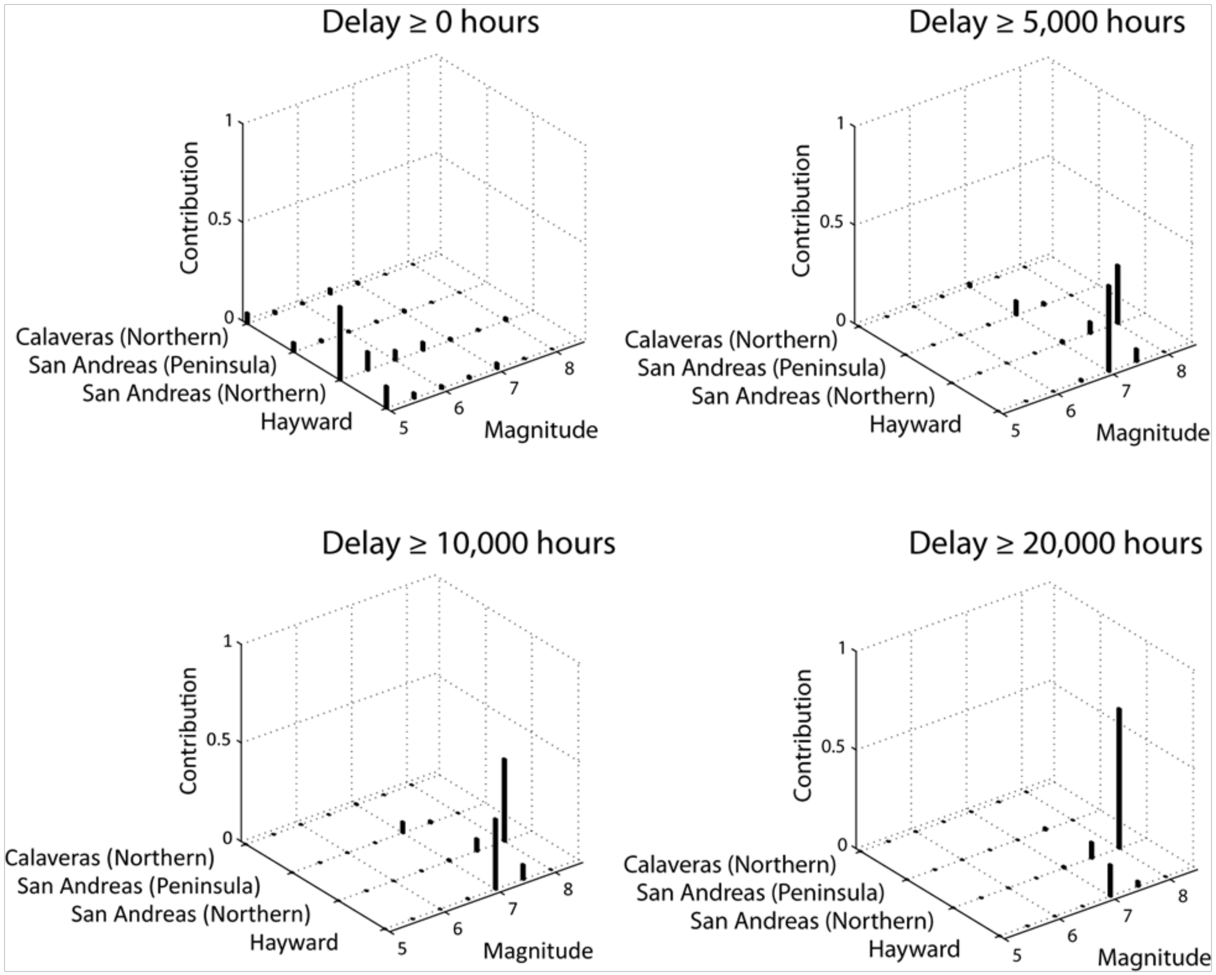
What is the likelihood that various events could have produced the exceedance of a given loss?

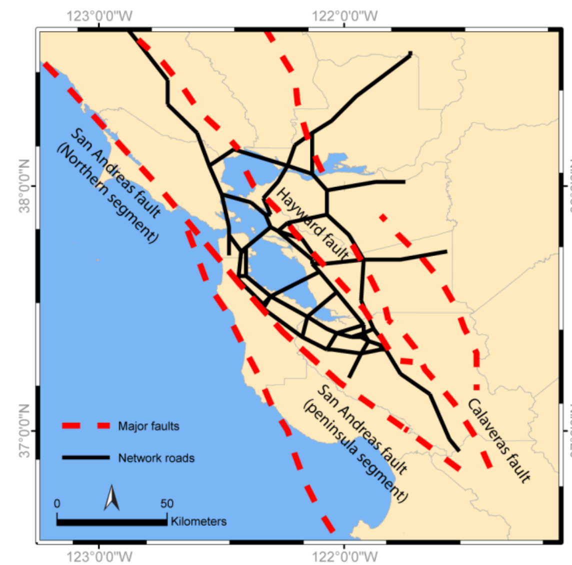
- Which magnitudes?
- Which faults?
- Which residuals?



$$P(Magnitude = m, Fault = f \mid Loss > x) = \frac{\lambda(Loss > x, Magnitude = m, Fault = f)}{\lambda(Loss > x)}$$

We can deaggregate the loss to identify likely causal events



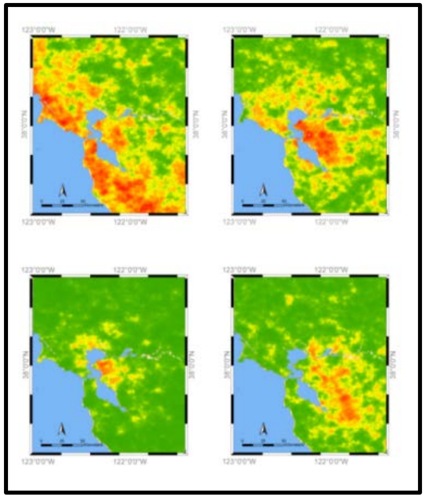


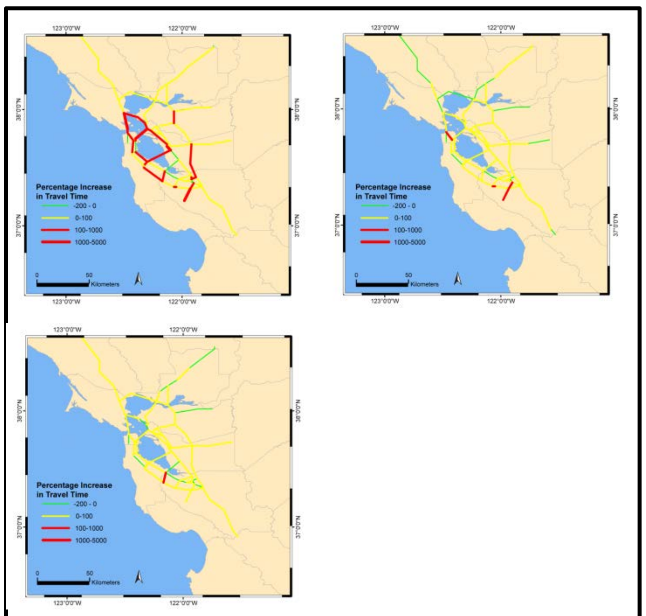
Bay area interstate highways and faults

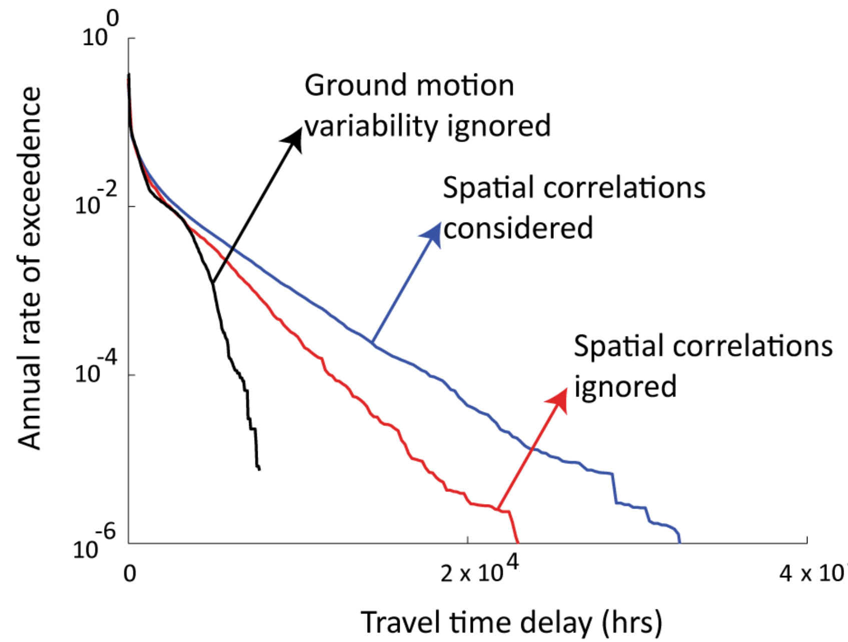
Effect of spatial correlations on loss estimates

We can repeat this exercise omitting the ε correlation, to see the impact of this correlation

$$\ln Sa_i(T) = \overline{\ln Sa_i(M, R, T, \ldots)} + \varepsilon_i + \eta$$





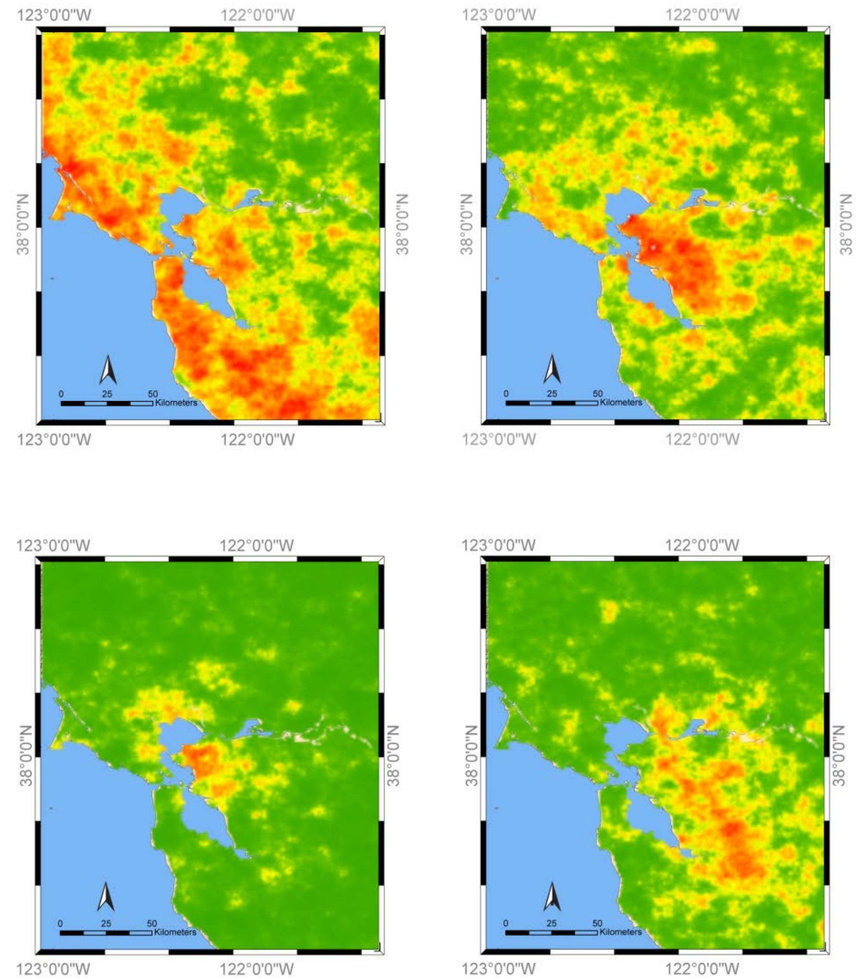


Improving the efficiency of this analysis

The infrastructure disruption calculations may be very expensive

We can reduce the computational time of the basic Monte Carlo approach:

- Preferentially simulate "interesting "events (*importance sampling*)
- Replace similar ground motion maps with a single representative map (*statistical clustering*)



Conclusions

- We have used well-recorded earthquakes to measure spatial correlation of spectral acceleration values
- Using these results, we can generalize traditional probabilistic seismic hazard analysis to characterize ground motion intensities at many sites
- We are studying the impacts of this model on risk to distributed infrastructure
- Computational expense remains a challenge

Research opportunities

Nearer term tasks

- User tools for obtaining spatially distributed hazard
- Algorithms for analyzing performance of very large networks (computer science, multiscale models)
- Engineering Demand Parameters and Decision Variables for system performance
- Identifying component criticality in terms of system Decision Variables

Longer term

- How can lifeline performance be quantified in performance-based assessments of facilities?
- How do urban growth patterns and changes in energy supply affect infrastructure system risk (seismic and other)?
- How can sensing technologies (smart grid, cell phone GPS, aerial photo, “Did you feel it”) be used to calibrate system models, and provide real-time decision support