PROBABILISTIC HAZARD INCORPORTING 3-D SIMULATIONS INTO NONERGODIC GROUND-MOTION MODELS

N. ABRAHAMSON[1], K. WOODDELL[2]

[1]University of California, Berkeley, USA

[2]Pacific Gas & Electric Company, San Francisco, USA

E-mail contact of main author: abrahamson@berkeley.edu

Abstract.

Using the NGA-W2 data base of recorded ground motions in California and Nevada, an empirically based fully nonergodic ground-motion model including epistemic uncertainty was recently developed for California [1]. This model uses nonergodic GMPEs that include spatially variable coefficients for the constant term and the geometrical spreading term that depend on the coordinates of the site and the source [2]. The epistemic uncertainty in the nonergodic terms is included based on the density of available recordings in the site and source region. In central coastal California, the density of the recorded ground motions remains sparse, leading to large epistemic uncertainties in the nonergodic terms of the ground-motion model. To address this limitation, the Central California Seismic Project (CCSP) was developed to use numerical simulations to contrain the nonergodic terms. As part of the CCSP, Southern California Earthquake Center developed a 3-D crustal model and generated simulated ground motons for a broad range of source locations. The 3-D simulated ground motions are first centered on the GMPEs by removing the differences between the average source scaling and path effects in the simulations as compared to the average scaling for GMPEs for California. Next, for each source/site pair, the differences between the centered 3-D simulated ground motions and the GMPE are used to update the nonergodic, spatially-varying coefficients for spectral acceleration at T=3 sec. This adjusted nonergodic GMPE can be used in seismic hazard studies for central coastal California, capturing the systematic path effects due to the 3-D crustal model.

Key Words: Seismic hazard, path effects, single-path sigma.

1. Introduction

Probabilistic seismic hazard analysis (PSHA) uses ground-motion models to describe the range of ground motions that can occur for a given earthquake scenario in terms of the median and the standard deviation. Typically, empirical ground-motion prediction equations (GMPE) are used. Because of the limited number of ground-motion recordings from large magnitude earthquakes at short distances, GMPEs are usually developed using global data sets that combine the ground-motion data from similar tectonic regions around the world. The GMPEs are assumed to be applicable to all sites in a similar tectonic region. This is called the ergodic assumption [3]. With the large increase in ground-motion data sets over the last decade, there is now enough data to show that ground motions from a particular source region recorded at a particular site are not consistent with the erogdic assumption. For a specific site and earthquakes in a specific source region, the variance of the aleatory variability is only 30-40\% of the ergodic variance [4], [5], [6]. This means that most of the variability treated as randomness in the ergodic approach is actually due to systematic source, path, and site effects. This difference in the ergodic and non-ergodic aleatory variability has a large effect on the seismic hazard, paraticularly at low probability levels that are used in seismic studies for nuclear facilities.

In California, an empirically-based nonergodic ground-motion model, including epistemic uncertainty has been developed based on the NGA-W2 ground-motion data set for California [1]. The constraints on the nonergodic terms depends on the density of recordings and earthquakes. Figure 1 shows the epistemic uncertainty in the median of the peak ground acceleration based on the empirical nonergodic model. The epistemic uncertainties re smallest in the San Francisco and Los Angeles regions due to the density of stations. The Diablo Canyon Power Plant (DCPP) is located in cental California, (approximately -120.9, 35.2). In this region, there is little empirical data to constrain the path effects other than in the Parkfield region. To address this limitation, the Central California Seismic Project (CCSP) was developed, as part of a partnership between Pacific Gas & Electric Company (PG&E) and the Southern California Earthquake Center (SCEC), to use numerical simulations based on 3-D crustal models to constrain the nonergodic path effects in central California which could be applied to the seismic hazard studies at the DCPP. This paper describes the preliminary results from the use of the 3-D simulations as part of a nonergodic PSHA.

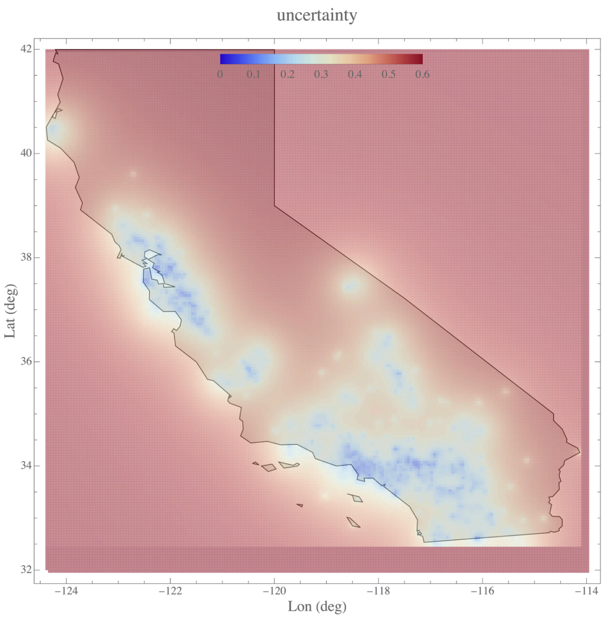

Figure 1. Epistemic uncertainty in the median nonergodic PGA based on the NGA-W2 data set [2].

2. 3-D Simulations to Constrain Path Effects

The ongoing CCSP uses an iterative process to develop the nonergodic ground-motion model. The steps include: (1) develop a 3-D crustal model, (2) conduct kinematic numerical simulations using the 3-D crustal model (following the CyberShake approach), and (3) evaluate the simulations against available geophysical data and available seismograms in the region.

The process is repeated leading to a series of improved 3-D crustal models. Once the results are stable, they are used to develop nonergodic GMPEs for the central Californi region.

2.1 Crustal Velocity Models

SCEC developed both 1-D and 3-D velocity models for the central California region shown in Figure 2. The 3-D crustal model for central California was developed using tomography including ambient-field correlations and earthquake waveforms. Geologic constraints include surface, subsurface, and offshore data on basin, fault, and basement structures. The version CCA-06 of the velocity model is used for the simulations considered in this paper. In addition to the 3-D velocity model, a 1-D model was also developed that is represenative of the average 1-D profile for the region. This 1-D model is used to compare with the 3-D model.

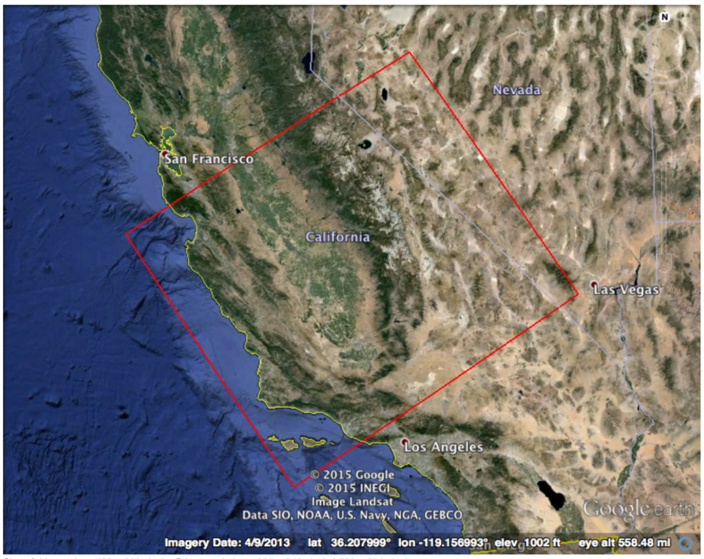

Figure 2. Central California region (red box) used in the CCSP. (from [7])

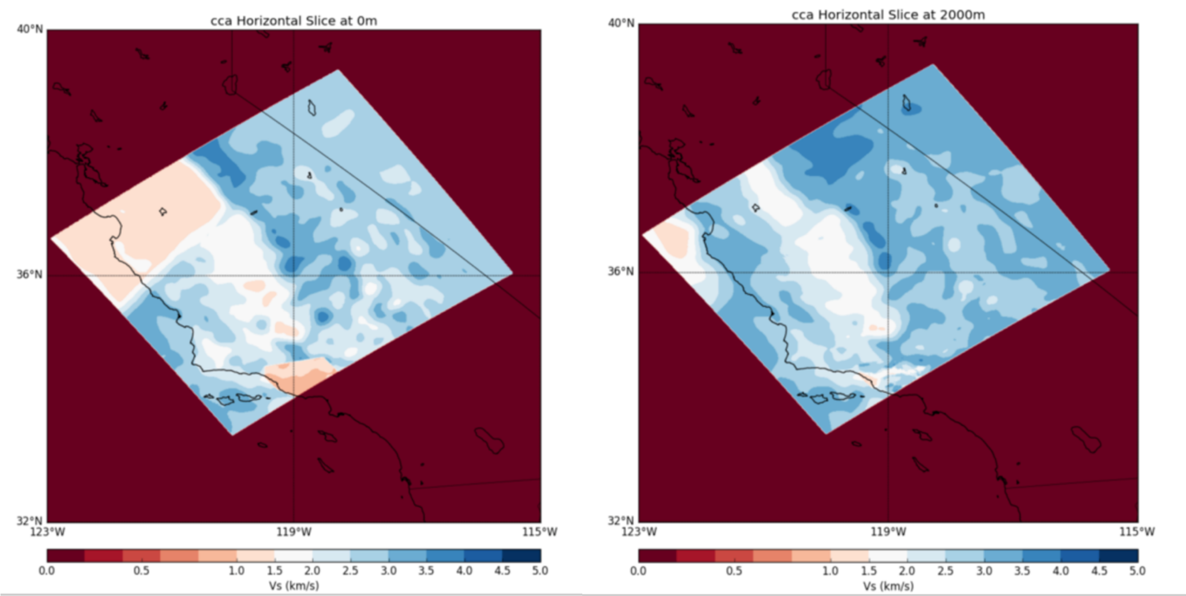

Figure 3. Slices of the 3-D velocity model (CCA-06) at the surface (left panel) and at a depth of 2 km (right panel). (from [7])

2.2 Simulation Scenarios

A range of earthquake scenarios were selected to capture the range of ray paths in the central California region. Seismograms from a total of 3123 scenarios with magnitudes between M6.5 and M8.5 were simulated. For each scenario, 30-40 alterative variations of the rupture properties were generated using the Graves and Pitarka rupture generator given on the SCEC broadband platform. In all, a total of 257,596 scenario/rupture pairs with M>6.5 were simulated for both the 3-D velocity model and the 1-D velocity model. The distribution of the magnitudes and distances to the ECH site (near DCPP) is shown in Figure 3. The set of simulations used in this paper is denoted as CyberShake 17.3b.

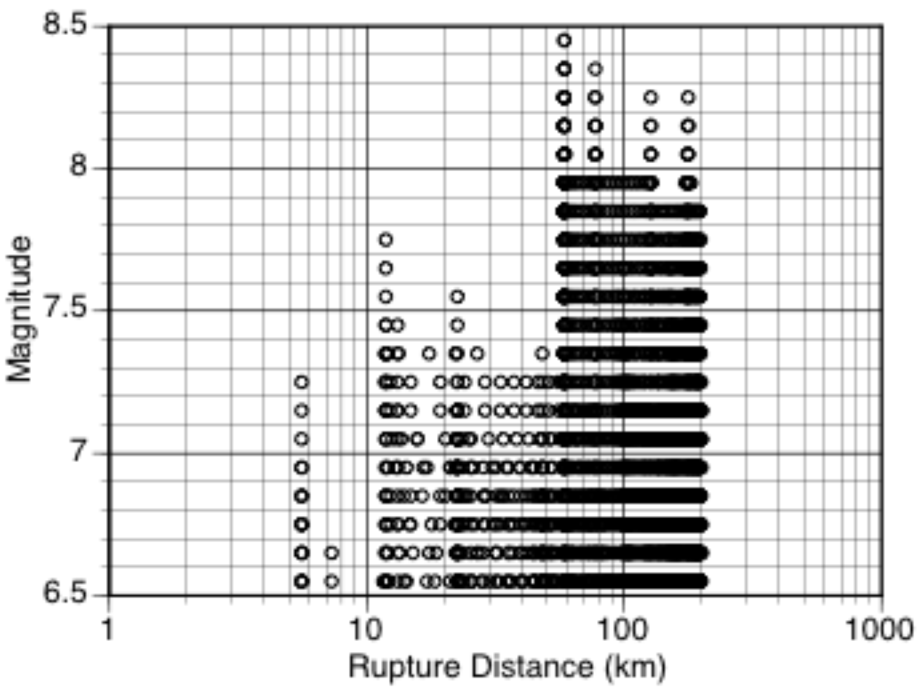

Figure 3. Distribution of magnitudes and rupture distance (measured from station ECH) from the simulations.

3. Application of 3-D Simulations to GMPEs

The simpliest approach is to use the 3-D simulations directly in the PSHA, replacing the GMPEs by the 3-D simulations. This approach is typically preferred by the developers of the 3-D simulation methods; however, it is not preferred by hazard analysts because the epistemic uncertainty in the ground-motion scaling is lost.

An commonly used alternative approach is to run the simulations for a 3-D crustal model and a 1-D crustal model and use the ratio of 3-D/1-D as a measure of the 3-D effects. The idea is that the source scaling used in the simulations will cancel out, leaving only the 3-D path effects. For example, the 3-D/1-D ratio from PSA at T=3 sec at station ECH from the CCSP simulations is shown in Figure 4. This ratio shows the combined site and path effects at ECH for different sources locations. For sources located close to ECH, the path effects are negative corresponding to a reduction of about a factor of 1.5 to 2. For sources located to the north, the path effects are possitive corresponding to an increase of about a factor of 1.5.

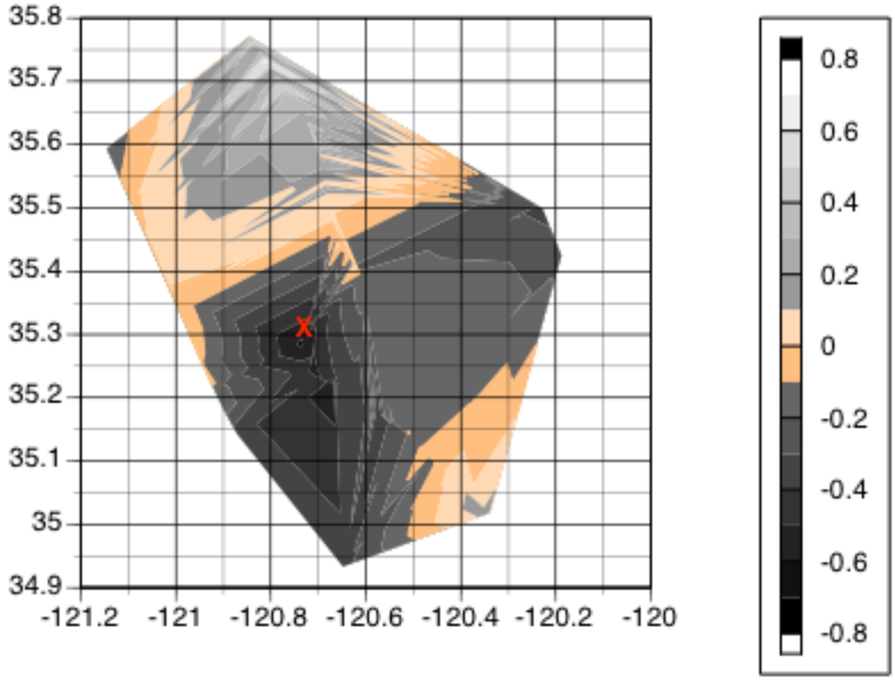

Figure 4. Natural log of the 3-D/1-D ratio of the site and path effects for T=3 sec PSA at station ECH (shown by the red X).

While the 3-D/1-D ratio removes the source scaling from the simulations, this ratio should not be directly applied to adjust the GMPEs because the GMPEs do not correspond to the 1-D case. The issues is that in the GMPEs, the 3-D basin effects are partially correlated with the site terms used in the GMPE. The simulations need to be centered on the scaling in the GMPEs. This centering issue needs to be addressed for all analytical modelling results that are used to modify empirical GMPEs. For example, we have this centering issue when using analytical models for nonlinear site effects and for directivity effects as well as for the 3-D path effects addressed here.

To center the simulations on the GMPEs, ideally, we would use 1-D crustal models that lead to simulated 1-D ground mtions that are consistent with the GMPE scaling. For example, the 1-D crustal model used in the validation of the 1-D simulation method, called 1-D_ref, would be appropriate. The failure to center the 3-D simulation results on the GMPEs is one of the main reasons that 3-D simulations are not used in site-specific PSHA studies.

In the CCSP, a reference 1-D model that is different from the 1-D_ref model was used. In this case, then the difference betweenthe 1-D model used in the simulation and the 1-D_ref model used in the validation should be used as an adjustment factor:

$$Mean\left[\ln\left(\frac{SA_{3D}(T)}{SA_{1D\_ref}(T)}\right)\right]=\frac{1}{N}\sum_{j=1}^{N}\ln\left(\frac{SA_{1D}(T,M_j,R_j)}{SA_{1D\_ref}(T,M_j,R_j)}\right)$$

Finally, the mean bias between the 1-D_ref simulations from the validation and the GMPEs, called $Bias_{valid}(T)$, should be considered in the centering of the 1-D simulations.

For the CCSP 3-D simulations, the combined path and site effect is given by:

$$\ln(path\ \&\ site) = \ln\left(\frac{SA_{3D}(T,M,R)}{SA_{1D}(T,M,R)}\right) - Mean\left[\ln\left(\frac{SA_{1D}(T)}{SA_{1D\_ref}(T)}\right)\right] - Bias_{valid}(T)$$

$$= \delta\theta_4(\vec{x}_{cls})\ln\left(\sqrt{R_{rup}^2+\theta_6^2}\right) + \delta\theta_{0A}(\vec{x}_{site}) + \sum_{i=1}^{nCell}\Delta R_i\left(\vec{x}_{site},\vec{x}_{cls}\right)\delta\theta_{7\_i}$$

where $\vec{x}_{cls}$ is the coordinate of the closest point on the rupture to the site, $\vec{x}_{site}$ is the coorindate of the site, $\Delta R_i\left(\vec{x}_{site},\vec{x}_{cls}\right)$ is the length of the ray path from $\vec{x}_{site}$ to $\vec{x}_{cls}$ within the ith cell (similar to tomography). The nonergodic terms, $\delta\theta_4(\vec{x}_{cls}), \delta\theta_{0A}(\vec{x}_{site})$, and $\delta\theta_{7\_i}$, are estimated using Bayesian regresssion as described in [1]. The results of the regression are maps of the coefficients $\delta\theta_4, \delta\theta_{0A}$, and $\delta\theta_{7\_i}$. The final nonergodic GMPE is given by applying these nonergodic terms to the base ergodic GMPE:

$$GMPE_{nonerg}(T,M,R,V_{S30}) = GMPE_{erg}(T,M,R,V_{S30}) +$$

$$\delta\theta_4(\vec{x}_{cls})\ln\left(\sqrt{R_{rup}^2+\theta_6^2}\right) + \delta\theta_{0A}(\vec{x}_{site}) + \sum_{i=1}^{nCell}\Delta R_i\left(\vec{x}_{site},\vec{x}_{cls}\right)\delta\theta_{7\_i}$$

A suite of alternative ergodic GMPEs can be used to capture the epistemic uncertainty in the base magnitude and distances scaling of the GMPEs.

4. Conclusions

The recent ground-motion data has shown that there are strong nonergodic effects on the GMPE that can have a large effect on the site-specific seismic hazard. We expect that PSHA conducted for nuclear power plants will also begin to use nonergodic models. As part of this move to nonergodic GMPEs, there will also be a greater need for 3-D simulations to supplement the available empirical ground-motion data. The CCSP is developing the 3-D simulations to be used in a nonergodic PSHA. As noted, a key issue for using 3-D simulations is centering the simulations on the empirical GMPEs. One of the limitations of the CCSP results available to date is that 1-D crustal model used to normalize the 3-D simulations was not the 1-D model used in the validation and is consistent with the GMPE scaling. As a result, the current simulation results are useful, but not directly useable in PSHA. This will be addressed in the next set of simulations for the CCSP, but it serves as a good reminder of the importance of interaction between the GMPE developers charged with developing the nonergodic terms and the seismologists running the simulations to be sure that the simulation results in a format that can be applied to GMPEs and implemented in PSHA.

REFERENCES

[1] ABRAHAMSON, N. et al., Probabilistic Seismic Hazard Analysis in California Using Non-Ergodic Ground-Motino Preduction Equations, submitted to Bull. Seism. Soc. Am. (2018)

[2] LANDWEHR, N. et al., A Nonergodic Ground-Motion Model for California with Spatially Varying Coefficients, Bull. Seism. Soc. Am., (2016) v 106, p 2574-2583.

[3] ANDERSON, J. and J. Brune, Probabilistic Seismic Hazard Analysis with the Ergodic Assumption, Seismological Research Letters, (1999), v 70, p 19-28.

[4] LIN, P-S et al, Repeatable Source, Site, and Path Effects on the Standard Deviation for Empirical Ground-Motion Prediction Equations, Bull. Seism. Soc. Am. (2011), v 101, p 2281-2295

[5] MORIKAWA, N. et al., Strong-Motion Uncertainty Determined from Observed Records by Dense Network in Japan, Journal of Seismology, (2008), v 12, p 529-546.

[6] ATKINSON, G., Single-Station Sigma, Bull. Seism. Soc. Am. (2006), v 96, p 446-455.

[7] GOULET, C., 3-D Velocity Model and Initital Results from the SCEC/PG&E Central California Seismic Project, personal communication