VALIDATION AGAINST NGA EMPIRICAL MODEL OF SIMULATED MOTIONS FOR M7.8 RUPTURE OF SAN ANDREAS FAULT

L.M. Star[1], J. P. Stewart[1], R.W. Graves[2] and K.W. Hudnut[3]

[1] *Department of Civil and Environmental Engineering, University of California Los Angeles, Los Angeles, California, USA*
[2] *URS Corporation, Pasadena, California, USA*
[3] *US Geological Survey, Pasadena, California, USA*
E-mail: lcoyne@ucla.edu, jstewart@seas.ucla.edu

ABSTRACT:

As part of a loss-estimation and emergency response planning exercise for a major earthquake on the San Andreas fault east of Los Angeles (ShakeOut), ground motions were simulated for a specific Mw 7.8 scenario rupture. The simulation uses a hybrid procedure in which short period components of shaking are computed semi-stochastically and long period components are computed through a deterministic calculation. The simulation considers both heterogeneous fault rupture and wave propagation through the crust and the sedimentary basins in and around Los Angeles. We compare these simulated motions to predictions of empirical ground motion prediction equations developed through the Next Generation Attenuation (NGA) project. We find that high frequency components of the simulated ground motion attenuate more rapidly with distance than the empirical model, whereas long-period components are roughly similar. The average residuals of the simulated event (i.e., event terms), which are expressed in natural log units, range from approximately -0.6 at short periods (near PGA) to approximately 0.8 at long periods (approximately 2- 4 sec). Those values of event terms are generally within the scatter of event terms from actual earthquakes used in the development of the NGA equations.

KEYWORDS: Ground Motions, GMPE, Attenuation Relation, Computer Simulation, Validation

1. INTRODUCTION

The evaluation of earthquake ground motions for engineering applications is generally performed with the use of empirical ground motion prediction equations (GMPEs). Those equations are designed to capture, in an average sense, the effects of earthquake source, travel path, and local site effects on ground motions. The GMPEs provide a median and log-normal standard deviation of ground motion intensity measures (*IMs*) conditional on source, path, and site parameters such as magnitude, distance, and average shear wave velocity in the upper 30 m of the site (V_{s30}). The most comprehensive GMPEs currently available were developed as part of the Next Generation Attenuation (NGA) project, and apply to shallow crustal earthquakes in active tectonic regions.

Despite their widespread use, there are limitations associated with the use of GMPEs for ground motion evaluation. For one, GMPEs only provide estimates of intensity measures and cannot be directly utilized to provide accelerograms, such as might be used for response history analysis of structures. Secondly, ground motions for engineering design purposes are often needed for conditions for which few, if any, recordings are available. Taking southern California as a typical example, the design of duration-sensitive or long-period structures is often controlled by magnitude ~7.8-8.2 earthquakes on the southern San Andreas fault. There are almost no recordings of strike slip events within this magnitude range (Denali being the one event that has produced recordings). Accordingly, the use of GMPEs for such events represents an extrapolation unconstrained by data.

A possible alternative (or at least a compliment) to GMPEs is the use of ground motions computed using seismological simulation techniques. Those techniques vary in their methodology and sophistication, but all simulate to some degree source processes, path effects, and local site response. Relatively sophisticated procedures hold the potential to simulate complex source features (such as spatially variable slip distributions, rise times, and rupture velocities), path effects (geometric spreading and crustal damping), and site effects (wave propagation through basins and shallow site response).

While the literature on seismological simulations is rich, such techniques have not found significant practical applications to date in California or other portions of the western United States. This results from lack of understanding of the relative strengths and weaknesses of different methods, concerns about the availability of the required input data for the procedures (and the quality of the data, where it is available), inadequate validation of the methods against recorded ground motions, as well as general ignorance of simulation procedures within the engineering community that is likely a product of inadequate communication and interaction between earthquake engineers and the seismologists who perform these computations.

Simulation techniques were recently utilized in the USGS-organized Shakeout project (Jones et al., 2008) in which losses and consequences of an M7.8 rupture in southern California were evaluated for emergency planning and public education purposes. Graves et al. (2008) provide a description of the Shakeout ground motion simulations. The reasons for using simulated motions for this scenario exercise were to capture the substantial, and frequency-dependent, site-to-site variation of ground motions, even for nearby sites that appear to be very similar. This variability in ground motion produces spatial variability in damage, which is important for loss estimation and emergency planning. The alternative of using a smooth variation of ground motion associated with a specified percentile from a GMPE was considered less realistic with respect to spatial variability characteristics. An additional advantage to these synthetic ground motions is that specific scenario attributes can be varied such as hypocenter location and rupture velocity that can provide valuable insights into the importance of such attributes on ground motions and damage.

The purpose of this paper is to describe a procedure that has been developed to test the simulated ground motions used for the Shakeout exercise relative to the NGA GMPEs. The procedure specifically seeks to investigate the degree of realism in the source characteristics and distance scaling inherent to the simulated motions. Additional work is needed to address site response and other issues related to the simulated motions. Validations of this type are needed because no recordings exist for a ShakeOut-type event. The four NGA GMPEs used in the validation, are Campbell and Bozorgnia (2008), Abrahamson and Silva (2008), Boore and Atkinson (2008), and Chiou and Youngs (2008). The fifth NGA relation, Idriss (2008), is not used in this investigation because it only applies to rock sites.

Following this introduction, we review the principal attributes of the simulated motions (which include the Shakeout event and similar events with different source attributes). We then describe the validation procedure, including the analysis of scenario "event terms" used to judge the source relative to empirical observations, and the analysis of distance scaling.

2. OVERVIEW OF SIMULATED EVENTS

The ShakeOut Scenario earthquake is a moment magnitude 7.8 earthquake on the southernmost 300 km of the San Andreas Fault, between Bombay beach on the Salton Sea and Lake Hughes. Broadband (0-10 Hz) ground motions are available for a 2 km spaced grid of sites over a 450 km by 226 km area, which spans most of southern California (Graves et al., 2008). The ShakeOut earthquake scenario ruptures from south to north, with the hypocenter located at the far southern endpoint of the fault, at Bombay beach. We also examine two other incarnations of the rupture scenario with hypocenters located at the center and far north end of the fault plane. The simulation uses a hybrid procedure in which short period components of shaking are computed semi-stochastically and long period components are computed through a deterministic calculation (Graves and Pitarka, 2004). The simulation considers both heterogeneous fault rupture and wave propagation through the crust and the sedimentary basins in and around Los Angeles. More information about the rupture model and simulation methodology is available in Graves et al. (2008).

3. EVALUATION OF EFFECTIVE EVENT TERM OF SIMULATED EARTHQUAKE

We begin the analysis by calculating residuals between the intensity measures from the simulation procedure and a particular GMPE as follows:

$$R_i(T) = \ln\left(S_a(T)\right)_{sim,i} - \ln\left(S_a(T)\right)_{GMPE,i} \tag{3.1}$$

where index i refers to a particular location where ground motions were simulated (latitude and longitude), $S_a(T)_{sim,i}$ refers to the 5% damped spectral acceleration of the simulated motion for oscillator period T at location i, $S_a(T)_{GMPE,i}$ refers to the median spectral acceleration for location i predicted by a GMPE considering the earthquake magnitude, site-source distance, and site condition, and R_i is the residual in natural logarithmic units. Residuals are calculated relative to the AS, BA, CB, and CY GMPEs.

For a well "recorded" event such as a simulated earthquake, an event term (η) is the mean value of the residuals calculated using Eqn. 3.1:

$$\eta = mean\left(R\right): i{=}1{:}N \tag{3.2}$$

where N is the number of recordings (or locations with simulated motions) for the event.

Such an event term can be compared to those evaluated empirically from recorded earthquakes during the development of GMPEs using a random effects regression procedure (Abrahamson and Youngs, 1992). The empirical event terms for a particular IM are log-normally distributed with zero mean and a dispersion τ referred to as the inter-event standard deviation.

The most important source attribute influencing ground motions is the energy release, which is measured by moment magnitude. If energy release was the only source parameter affecting ground motions and GMPEs accurately captured the dependence of ground motion on the energy release, all event terms would be zero. However, other source characteristics modeled in the simulations can affect ground motions such as slip distribution, fault rupture area, rupture propagation speed, and slip rise time. Event-to-event variations in those parameters are thought to be a principal cause of the observed dispersion of event terms.

Figure 1 shows "near source" event terms (η_{ns}) for the ShakeOut ground motions (south hypocenter) and the two alternative rupture scenarios (center and north hypocenters). The event terms shown in Figure 1 were calculated using only the sites with rupture distances less than 10km, and hence are different from general event terms reported in Graves et al. (2008), which use sites at all distances. The reason for only including near-source sites in the present work is because of substantial bias in the distance attenuation (discussed below), which we did not want to map into our source descriptor. The results are shown for spectral accelerations at several periods as well as peak acceleration (PGA) and peak velocity (PGV). The error bars shown in Figure 1 indicate ± one inter-event standard deviation (τ). The simulation event terms generally fall within a reasonable range, mostly within one standard deviation. This indicates that the overall ground motion levels from the simulations are consistent with prior experience, and the motions are neither unrealistic nor unprecedented.

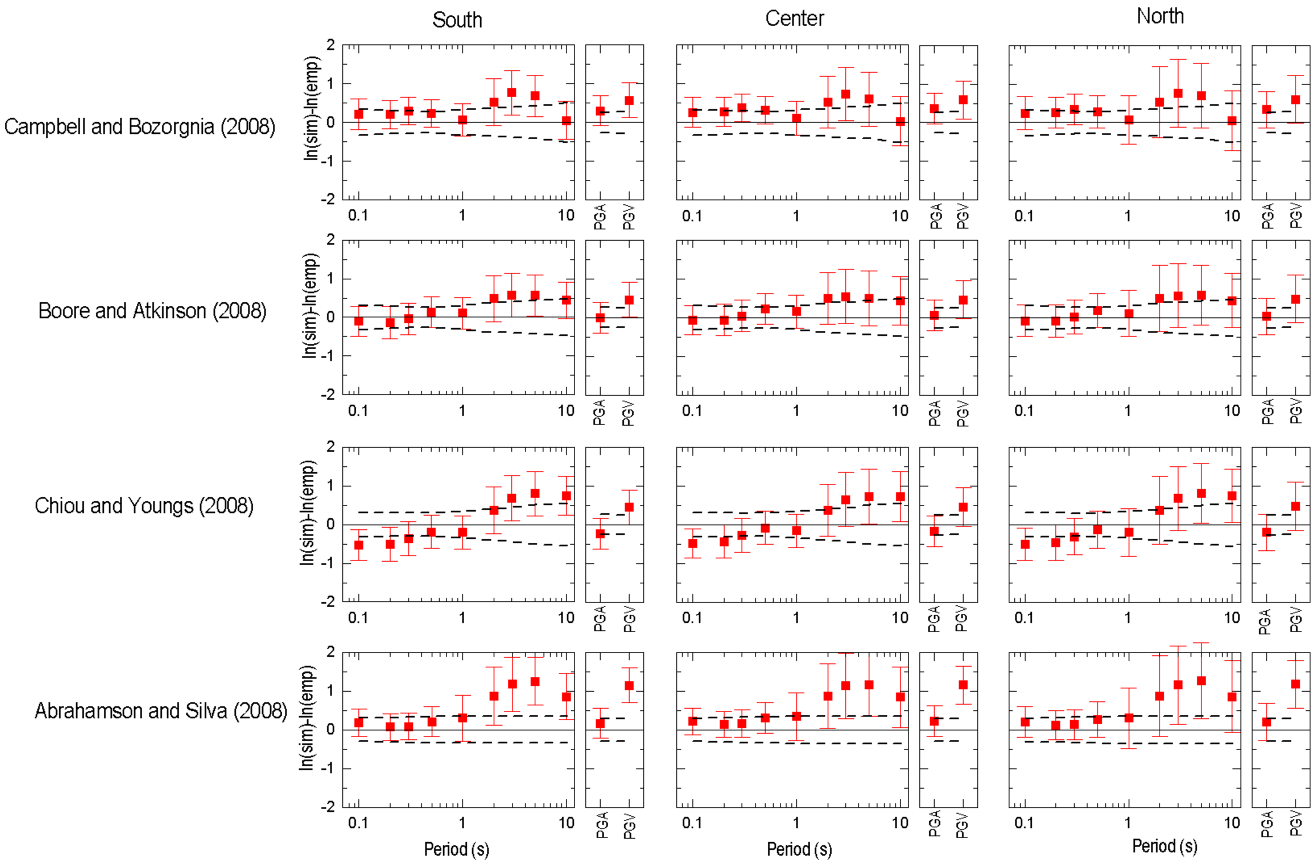

Figure 1: Event terms for the three rupture scenarios of the ShakeOut earthquake, limited to sites with Rrup<10km. The error bars indicate one standard deviation for the residuals. The heavy dashed line represents the inter-event standard deviations from the empirical model.

The event terms for the ShakeOut and related simulations show trends with period that are similar across the three hypocenter scenarios. For all four GMPEs, low frequencies show small or negative average residuals, expressed in natural log units, up to about -0.4. The high frequencies (above 2 second period) show positive event terms up to 1.2. The event terms are more negative for the short periods of the CY GMPE than for the other GMPEs, and the long period motions are larger for the AS GMPE.

4. DISTANCE-SCALING OF SIMULATED MOTIONS

The distance scaling of ground motions is primarily controlled by factors such as geometric spreading of the wave field, anelastic attenuation, scattering effects, multi-pathing and generation of surface waves. The physics-based simulations naturally incorporate these effects through the use of constitutive relations (i.e., the wave equations). However, the choice of the specific parameters used in the computational model (e.g., seismic velocity structure, Q model, etc.) can have a significant impact on the characteristics of distance scaling for a given simulation. The longer wavelength features of these parameters are reasonably well constrained, such as the general nature of the 3D seismic velocity structure provided by the SCEC Community Velocity Model version 4 (CVM4). The shorter wavelength features, such as high frequency anelasticity and scattering, are less well constrained, and may require further refinement through ongoing calibration and validation studies.

The distance scaling produced by the simulation procedure can be compared to that from the GMPEs by examining "intra-event" residuals (ε_i), which are residuals that remain in simulated motion i after the event term has been removed:

$$\varepsilon_i(T) = R_i(T) - \eta(T) \tag{4.1}$$

The relative distance scaling of the simulated motions and GMPEs is investigated by examining the distance-dependence of ε_i (T). If ε_i (T) had no slope with respect to distance, then the two procedures would be producing identical distance scaling. Figure 2 shows the intra-event residuals of the ShakeOut motions (original southern hypocenter) relative to the CB GMPE for the IMs of PGA and T=0.3s, 1.0, and 10 sec spectral acceleration. The notable trend shown in this figure is the strong negative slope of ε_i (T) with rupture distance for low to mid-period ground motions. This is suggestive of faster distance attenuation in the simulated motions than in the GMPE.

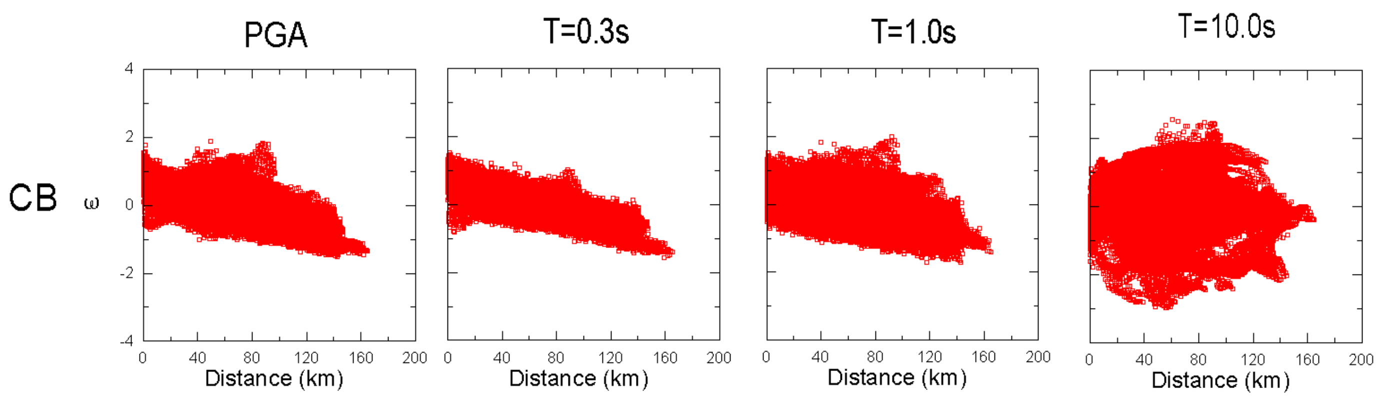

Figure 2: The intra-event residuals of the ShakeOut motions (original southern hypocenter) relative to the CB GMPE for the IMs of PGA and T=0.3s, 1.0, and 10 sec spectral acceleration versus rupture distance.

To further examine the distance attenuation misfit of the NGA models, we regress the synthetic data against the CB functional form to re-evaluate selected coefficients controlling the distance attenuation. The CB distance attenuation function is as follows:

$$F_{DIST} = [c_4 + c_5 M] \times \ln\left(\sqrt{r_i^2 + h^2}\right) \tag{4.2}$$

where r_i is the rupture distance, M is magnitude, and c_4, c_5 and h are coefficients given by the GMPE. The distance attenuation function in Eq. 4.2 is additive with a magnitude term, site term, hanging wall term, and basin depth term to form the complete GMPE. The principal coefficient that is re-evaluated here is the term expressing the magnitude-independent slope of the distance attenuation (c_4). In our regression, all terms other than the distance term are fixed, with the exception of the constant coefficient (c_0), which appears in the magnitude term, and which requires modification when c_4 is changed to fit the data. Accordingly, our regression simultaneously re-evaluates c_0 and c_4 to fit the Shakeout data, with all other coefficients in the GMPE fixed at the published values.

Figure 3 shows the regressed values of c_0 and c_4 for the three ShakeOut scenarios. For the ShakeOut scenarios, the absolute values of the modified distance-attenuation terms (c_4) are more negative than the original values, consistent with the faster distance attenuation in the synthetic data. At short periods the discrepancy between the published and modified distance-attenuation terms is quite large. At long periods the difference is smaller. The modified constant terms ($c_{0,}$) are larger than the published values across all periods. This indicates that the synthetic ground motions are larger than the GMPE-predicted motions at short distances, although the synthetic motions taper off quickly at long distances.

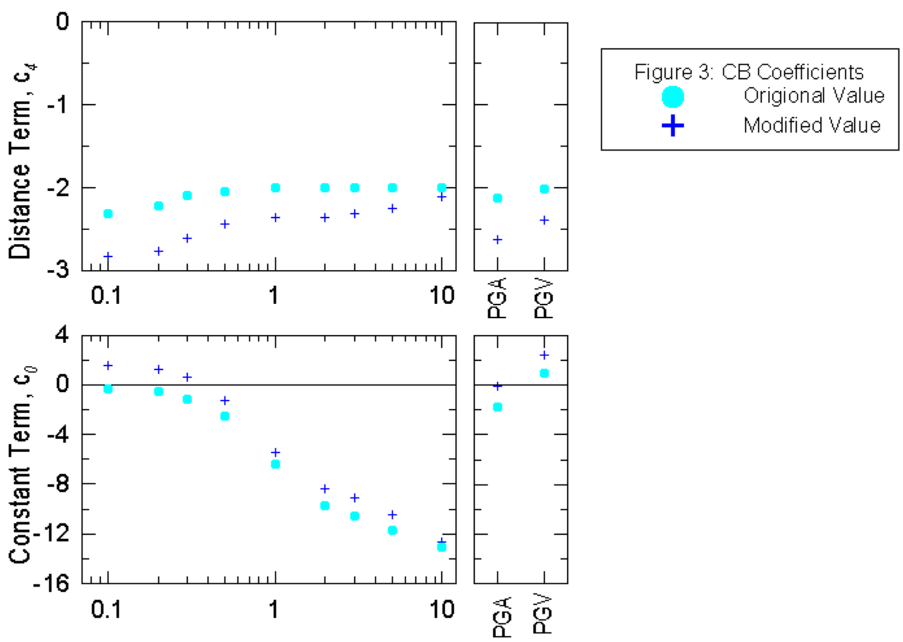

Figure 3: Original CB GMPE distance function coefficients (light blue) and modified coefficients regressed for the three ShakeOut scenarios (navy).

5. CONCLUSIONS

In this paper we investigate the degree to which the ground motions produced by synthetic models of the ShakeOut project scenarios are reasonable with respect to source scaling and distance attenuation contained in the NGA GMPEs. We compare the intensity measures (peak acceleration, peak velocity, and spectral acceleration) with those predicted using the NGA ground motion prediction equations. We begin with a general comparison of the overall synthetic ground motions to the average ground motions predicted using the GMPEs for events of the same magnitude. We evaluate event terms (inter-event residuals) of the synthetic data relative to the NGA GMPEs. The event terms are within a reasonable range, indicating that source model in the simulation procedure is producing motions within the range of previous observation. Analyses of intra-event residuals shows faster distance-attenuation of the simulated data relative to the GMPEs.

ACKNOWLEDGEMENTS

The work of the first two authors was supported by the National Science Foundation under award number # 0618804 through the Pacific Earthquake Engineering Research Center (PEER). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the National Science Foundation.

REFERENCES

Abrahamson, N.A. and Silva, W.J. (2008). Summary of the Abrahamson and Silva NGA ground motion relations. *Earthquake Spectra* **24(S1),** accepted for publication.

Abrahamson, N.A. and Youngs, R. R. (1992). A stable algorithm for regression analyses using the random effects model. *Bulletin of the Seismological Society of America* **82**, 505-510.

Boore, D.M. and Atkinson, G.M. (2008). Ground motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 and 10.0 s. *Earthquake Spectra* **24(S1),** accepted for publication.

Campbell, K.W. and Bozorgnia, Y. (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD, and 5%-damped linear elastic response spectra for periods ranging from 0.01 to 10 s. *Earthquake Spectra* **24(S1),** accepted for publication.

Chiou, B.S.-J. and Youngs, R.R. (2008). Chiou and Youngs PEER-NGA empirical ground motion model for the average horizontal component of peak acceleration and pseudo-spectral acceleration for spectral periods of 0.01 to 10 seconds *Earthquake Spectra* **24(S1),** accepted for publication.

Graves, R., Aagaard, B., Hudnut, K., Star, L., Stewart, J., and Jordan, T. (2008). Broadband Simulations for Mw 7.8 Southern San Andreas Earthquakes: Ground Motion Sensitivity to Rupture Speed. *Geophysical Research Letters*, in preparation.

Graves, R., and Pitarka, A. (2004). Broadband Time History Simulation Using a Hybrid Approach. *Proceedings of the 13th World Conference on Earthquake Engineering., Vancouver, Canada,* paper no. 1098.

Idriss, I.M. (2008). An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes. *Earthquake Spectra* **24(S1)**, accepted for publication.

Jones, L. M., Bernknopf, R., Cox, D., Goltz, J., Hudnut, K., Mileti, D., Perry, S., Ponti, D., Porter, K., Reichle, M., Seligson, H., Shoaf, K., Treiman, J., and Wein, A. (2008). The ShakeOut Scenario: U.S. Geological Survey Open-File Report 2008-1150 and California Geological Survey Preliminary Report 25 [http://pubs.usgs.gov/of/2008/1150/]. Version 1.0, May 22, 2008, 10:00 AM