VALIDATION AGAINST NGA EMPIRICAL MODEL OF SIMULATED MOTIONS FOR M7.15 RUPTURE OF PUENTE HILLS FAULT

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ABSTRACT:

We compare simulated ground motions for a Mw 7.15 scenario rupture of the Puente Hills fault beneath downtown Los Angeles to predictions of empirical ground motion prediction equations developed through the Next Generation Attenuation (NGA) project. We find that the simulated ground motions across a wide range of frequencies attenuate slightly more rapidly with distance than those from the empirical model. The average residuals of the simulated event (i.e., event terms), which are expressed in natural log units, are negligible for spectral periods < 1.0 sec but are positive to approximately 0.5 at long periods (approximately 2- 5 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.

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.

In this short report, we compare simulated ground motions for a rupture of the Puente Hills fault to the NGA GMPEs. We utilize the procedure of Star et al. (2008) that specifically seeks to investigate the degree of realism in the source characteristics and distance scaling inherent to the simulated motions. 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 event. We then compute the scenario "event terms" and evaluate the distance scaling.

2. OVERVIEW OF SIMULATED EVENTS

The simulated earthquake is a moment magnitude 7.15 event on the Puente Hills Fault. The Puente Hills fault produces reverse focal mechanisms. The fault dips at a 27 degree angle and passes beneath downtown Los Angeles. The full dimensions of the fault is assumed to rupture in the scenario event. Broadband (0-10 Hz) ground motions were computed by Graves and Somerville (2006) for a 2 km spaced grid of sites over a 110 km by 90 km grid, which extends up to 60 km from the Puente Hills fault. The earthquake ruptures updip from near the base of the fault plane to within 3 km of the ground surface. 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 and Somerville (2006).

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:

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

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 event terms (η) for the simulated Puente Hills event. The results are shown for spectral accelerations at several periods as well as peak acceleration (PGA) and peak velocity (PGV). The dashed lines 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. There is a trend of nearly zero event terms for periods less than 1.0 sec and positive event terms (indicating over-prediction) for periods between 2 and 5 sec. Those trends are consistently observed for all four GMPEs.

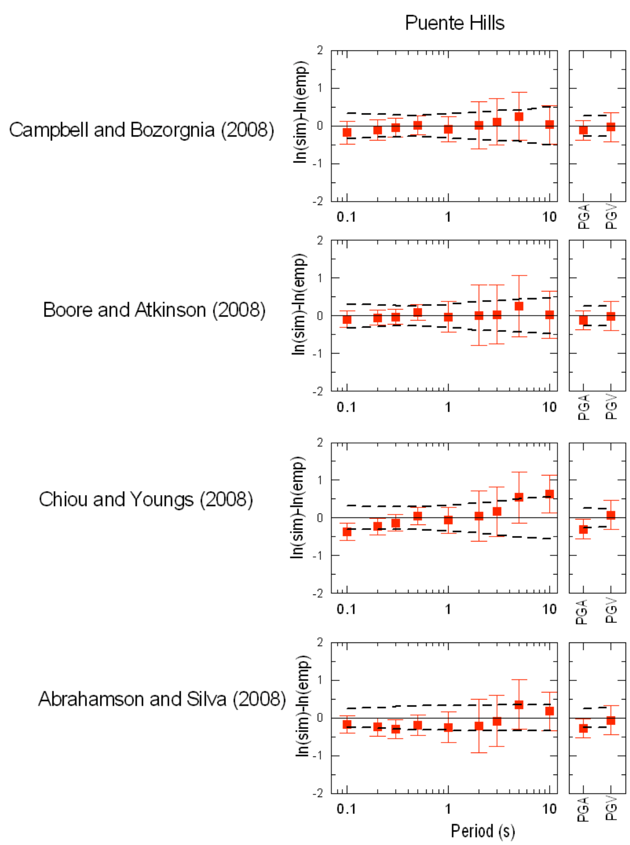

Figure 1: Event terms for the simulated Puente Hills earthquake. The error bars indicate one standard deviation for the residuals. The heavy dashed line represents the inter-event standard deviations from the empirical model.

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 simulated motions relative to the CB GMPE for the IMs of PGA and T=0.3s, 1.0, and 10 sec spectral acceleration. The data indicate a trend of decreasing residual with distance for periods of 1 sec and less. This trend of decreasing residual with distance is suggestive of faster distance attenuation in the simulated motions than in the GMPE. It should be noted that the range of distances examined in this exercise (0-60 km) is smaller than in previous similar work for the southern San Andreas fault (Star et al., 2008), which found steeper slopes in ε-r plots (i.e., much faster distance attenuation in simulations than in GMPEs). The weaker trend in the present exercise may be influenced by the fact that ground motions are not computed at large distance, where any bias in the path formulation in the simulation routine would become more apparent.

We also note the decrease of dispersion in ε with distance at short periods. This will be investigated further in subsequent work.

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:

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

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 simulated data, with all other coefficients in the GMPE fixed at the published values.

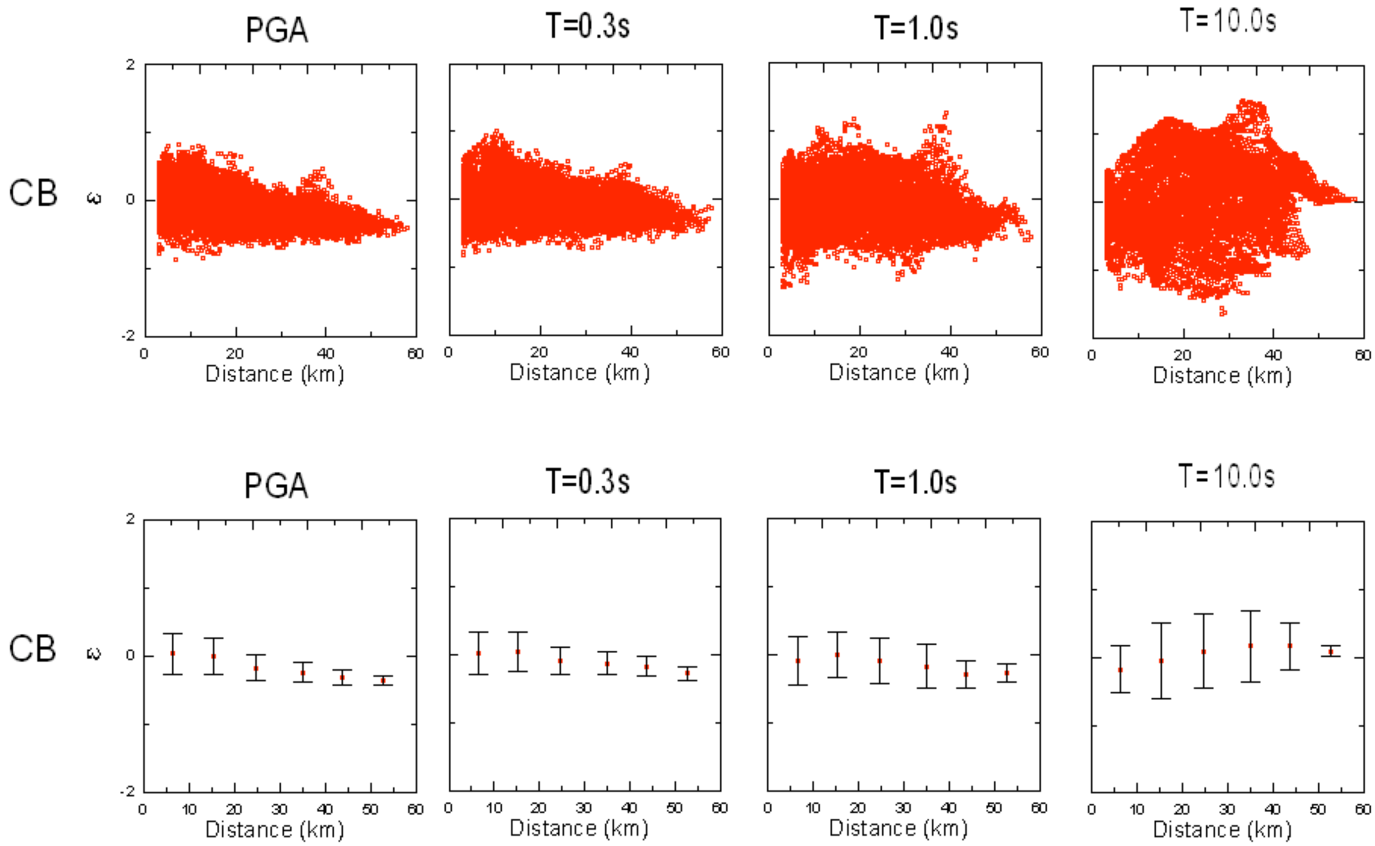

Figure 2: The intra-event residuals of the Puente Hills motions relative to the CB GMPE for the IMs of PGA and *T*=0.3s, 1.0, and 10 sec spectral acceleration versus rupture distance.

Figure 3 shows the regressed values of c_0 and c_4 for Puente Hills scenario. For this scenario, the absolute values of the modified distance-attenuation terms (c_4) are more negative than the original values, consistent with faster distance attenuation in the synthetic data. At short periods (i.e., $T < 0.5$ sec), the discrepancy between the published and modified distance-attenuation terms is larger than at longer periods. The modified constant terms ($c_{0,}$) are larger than the published values for periods less than 10 sec. In almost all cases the differences are statistically significant because the two estimates lie outside of their respective confidence intervals. 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.

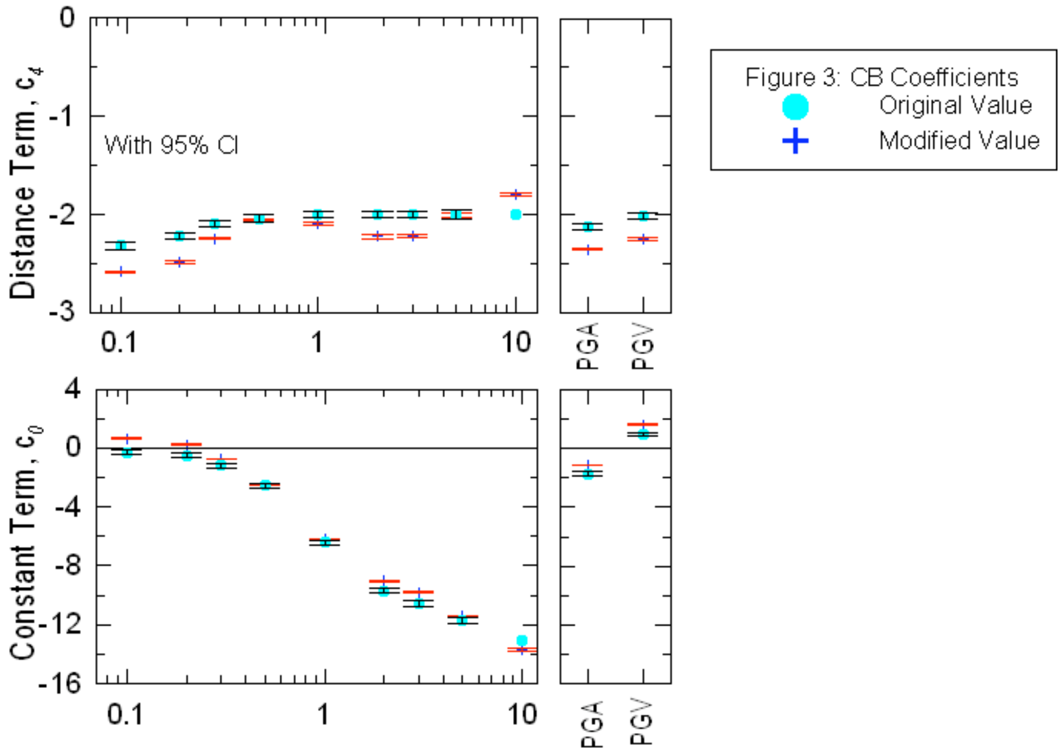

Figure 3: Original CB GMPE distance function coefficients and modified coefficients regressed for the Puente Hills scenario (with ±95% confidence intervals).

5. CONCLUSIONS

In this paper we investigate the degree to which the ground motions produced by a simulation procedure for a rupture of the Puente Hills fault 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 slightly faster distance-attenuation of the simulated data relative to the GMPEs. The apparent bias in the distance scaling is much smaller for the Puente Hills event than for a previously investigated large magnitude southern San Andreas fault rupture.

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.

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