

GEM-PEER Global GMPEs Project Guidance for Including Near-Fault Effects in Ground Motion Prediction Models



J.W. Baker

Stanford University, Stanford, CA, USA

Y. Bozorgnia & C. Di Alessandro

PEER Center, University of California, Berkeley, CA, USA

B. Chiou

California Department of Transportation, Sacramento, CA, USA

M. Erdik

Bogazici University, Istanbul, Turkey

P. Somerville

URS Corporation, CA, USA; and Macquarie University, Sydney, Australia

W. Silva

Pacific Engineering and Analysis, El Cerrito, CA, USA

SUMMARY

Most ground-motion prediction equations (GMPEs) do not provide predictions that account explicitly for near-fault effects such as rupture directivity. A variety of models are available, however, that modify GMPE predictions to account for forward or backward directivity, or to capture polarization of response spectra in the near-fault region. In addition to standard GMPE parameters such as earthquake magnitude and distance, these models typically use the earthquake hypocenter location and possibly other information about slip direction to infer whether a given site is likely to experience directivity effects, and amplifies or de-amplifies the GMPE prediction appropriately. This paper presents an overview of published methods for adjusting GMPEs to include these effects. Recommendations will be arrived at by surveying all published models of this type, noting the ground motion data sets used in their calibration and the range of seismological conditions for which they are valid (e.g., active crustal earthquakes versus subduction or stable continental earthquakes). This work aims to produce recommendations for adoption by the Global Earthquake Model (GEM) project. These topics comply with the objectives of the GEM Global GMPEs project, coordinated by the Pacific Earthquake Engineering Research Center (PEER).

Keywords: Ground motion prediction models, attenuation, directivity, directionality

1. INTRODUCTION

This manuscript describes available models for accounting for near-fault effects in ground motion prediction equations. Specifically, two phenomena—directivity and directionality—are described and potential methods for accounting for these issues are discussed. The first phenomenon of interest is near-fault directivity. Ground motion prediction equations (GMPE's) provide predicted distributions of ground motion parameters as a function of explanatory variables such as earthquake magnitude, rupture distance and site conditions. One ground motion phenomenon that is not well-captured by standard explanatory variables is near-fault directivity, which occurs when a fault rupture propagates towards the site at approximately the shear wave velocity, causing most of the seismic energy to arrive as a high-amplitude, short-duration ground motion. Near-fault directivity can be included in GMPE's, however, by taking advantage of GMPE-adjustment models. These adjustment models specify modifications to the underlying GMPE, as a function of additional explanatory variables that are not included in the underlying GMPE but which are indicative of conditions under which directivity is or is not expected.

The second phenomenon of interest is ground motion directionality. Ground motions produce shaking in three dimensional space (they also produce rotations though those are typically ignored). When using a GMPE to predict a ground motion parameter associated with horizontal shaking, the two-directions of shaking in the horizontal plane must be considered. The predicted ground motion parameters (e.g., spectral acceleration at a specified period, peak ground acceleration, or peak ground velocity) can be defined in a variety of ways with regard to multicomponent horizontal shaking. Common methods to quantify spectral acceleration two-component horizontal shaking are to take the geometric mean of the spectral accelerations of the two as-recorded ground motion components, to take the maximum spectral acceleration observed when looking over all horizontal orientations, or to take the median spectral acceleration observed when looking over all horizontal orientations. A given GMPE will specify the definition of spectral acceleration being predicted, and if that definition differs from the definition desired by the hazard analyst, a model for converting between definitions is needed. Such models are discussed below. This phenomenon is grouped with “near-fault effects” in some cases, because the relationship between these various definitions depends upon the polarization of the ground motion, and some aspects of polarization may differ in the near-field relative to the far field.

Before discussing the above two phenomena in more detail, a few other near-fault effects should be mentioned briefly for completeness. In addition to influencing ground motion peak spectral amplitudes, near-fault directivity also affects ground motion duration. In forward-directivity cases, where wave arrivals are compressed in time, ground motion durations are generally decreased, while in backward-directivity cases the durations are increased relative to no-directivity conditions. This can be observed in Figure 1.1, which shows observed ground motions from the 1992 Landers earthquake in forward-directivity and backward-directivity conditions. Somerville et al. (1997) proposed adjustments to ground motion duration based on geometric parameters associated with directivity. But because prediction of ground motion duration is not a focus of this project, and because no other duration-modification models exist, this issue is not discussed further.

In addition to directivity, another near-fault effect of potential interest is static fling. “Fling step” is permanent ground displacement caused by faulting and crustal deformation. While fling step may have some effect on dynamic response of structures, there are no resources available today to include the effect in GMPEs. Due to the lack of models for modifying GMPEs to include fling step, this issue is not discussed further here. Finally, these crustal deformations can result in static displacement offsets at crossings of surface-rupturing earthquakes. These deformations can be damaging to infrastructure and other systems that cross over faults. There are models available for predicting these deformations, but they are outside the scope of this project and therefore not discussed further.

2. DIRECTIVITY EFFECTS

Directivity causes variations in ground motion spectral accelerations that are not accounted for fully by standard ground motion prediction equations. Directivity effects generally increase spectral accelerations at locations where the rupture has propagated towards the site of interest, for periods longer than approximately 0.5 seconds. At locations where the rupture has propagated away from the site, spectral accelerations are generally decreased. Also associated with the “forward-directivity” high amplitude conditions is the presence of a short-duration velocity pulse. Examples of ground motions exhibiting effects of forward and backward directivity were shown in Figure 2.1. Because the directivity effect depends upon rupture direction, additional predictor parameters not included in most GMPEs are needed to account for this effect. Most directivity models utilize some description of the amount of the rupture that has ruptured towards the site of interest in order to predict this effect. The following sub-sections will discuss specific models for predicting directivity effects. As the reference GMPE will vary with the type of seismic region being considered, directivity-modification models are also grouped according to tectonic region.

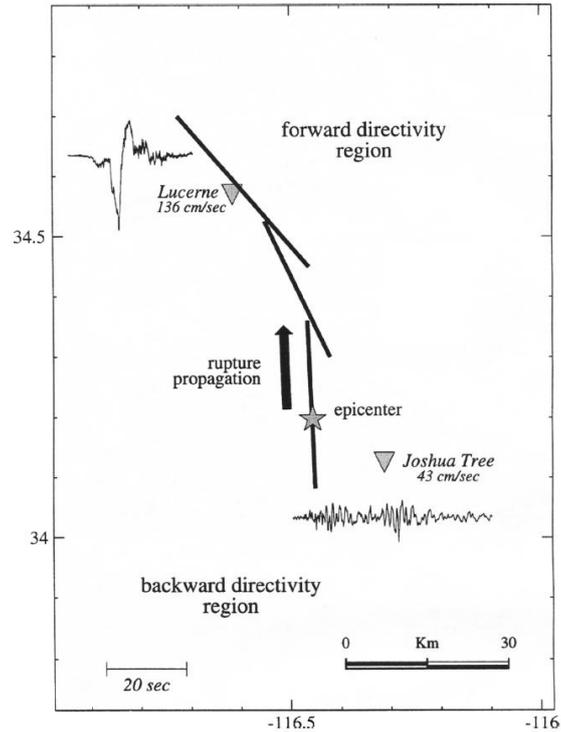


Figure 2.1: Strike normal ground velocities from the 1992 Landers earthquake (from Somerville et al. 1997).

2.1 Models for active shallow crustal tectonic regions

Several models have been published that modify a base GMPE to include directivity effects (Somerville et al. 1997, Abrahamson 2000, Rowshandel 2006, Spudich et al. 2004, Spudich and Chiou 2008, Rowshandel 2010, Shahi and Baker 2011). These models share several features in common. They all provide ratios by which to multiply the base GMPE's predicted median and log standard deviation, as a function of parameters related to the geometry of the fault rupture. They all were developed with respect to active crustal earthquake datasets and GMPEs. They all require specification of the hypocenter location in addition to the standard predictive parameters used by base GMPEs, and some require additional information such as slip direction (i.e., point-source descriptions of earthquakes or descriptions that do not specify a hypocenter are not suitable for directivity predictions). Most models also provide predictions that vary with rupture mechanism.

One distinction among of the above models is that some are "broadband" in that the modification of the GMPE's predicted response spectrum with period is fixed in shape, while others are "narrowband" in that the amplification with period is functionally dependent on earthquake magnitude and possibly other parameters (Somerville 2003). Among existing models, the Somerville et al. (1997) model and closely related Abrahamson (2000) model are the most popular for hazard calculations at the moment, due to the relatively simple parameters used in the predictions, and because they are the oldest and best understood models.

The above models all utilize knowledge of a hypocenter location and rupture extent (and possibly additional information) in order to make predictions of the effect of directivity. This creates challenges for implementation in probabilistic seismic hazard analysis or other related ground motion predictions, because it requires a seismic source model that includes randomly occurring hypocenter locations, and requires increased complexity and computation time in the prediction of ground motions (Abrahamson 2000). To overcome this challenge, a concept has been proposed for development of future models that avoid using a hypocenter-dependent ground motion prediction, and instead modify a non-directivity GMPE (e.g., by inflating the model σ in the near field) to account for potential higher amplitude Sa 's that might occur due to the possible occurrence of directivity effects (Norm

Abrahamson personal communication 2011). The modification could be calibrated by fixing a rupture extent, randomly locating hypocenters (e.g., Mai, Spudich and Boatwright 2005), computing S_a distributions for each case, and computing the distribution of S_a values implied by the aggregate set of predictions. The resulting model adjustment would be magnitude and distance dependent, and possibly dependent on the location of the site of interest along fault. Predictions using this approach would differ from predictions using a non-directivity GMPE in that the non-directivity GMPEs' near-fault predictions are calibrated to predict ground motions representative of the conditions well-represented in the reference ground motion library, rather than "average directivity" conditions. As a point of reference regarding current state-of-the art in ground motion prediction when random hypocenters are not included in the source model, the US Geological Survey (which calculates hazard without randomized hypocenters) currently makes no modifications to GMPEs to account for near-fault effects (Nico Luco personal communication, 2011).

The in-development NGA West 2 models for crustal earthquakes aim to include predictions that utilize directivity-related geometry (that will replace the above modification models), as well as an "average directivity" prediction that can be used instead if the directivity-related geometry is not available (Spudich et al. 2012). These soon-to-be-available models will be the first documented cases of this approach being implemented.

2.2 Models for stable continental regions

There are no known models for predicting the effects of directivity in stable continental regions (SCRs). While directivity effects should exist in SCR earthquakes, calibration of an appropriate model is not feasible in the near future, due to several practical problems. The most straightforward problem is that the very limited number of observations of near-field ground motions from SCR earthquakes prevents calibration of a predictive model from data. Second, while one might consider adopting a directivity model for active shallow crustal regions for use in an SCR, there are unresolved issues associated with this concept. For example, higher stress drops in stable continental regions may affect magnitude-area relationships and thus indirectly affect resulting directivity (which is dependent on magnitude and rupture dimensions) in unforeseen ways.

As a point of reference regarding state-of-the art in these regions, the US Nuclear Regulatory Commission does not have provisions for accounting for directivity effects in site-specific hazard analyses in stable continental regions (Annie Kammerer personal communication, 2011). We could find no examples worldwide of cases where directivity effects have been considered when assessing seismic hazard in a stable continental region.

2.3 Models for subduction regions

There are no known predictive models for directivity in either intraslab or interface subduction earthquakes. Note that from rupture geometry, no onshore directivity would be expected from subduction events. There may be directivity parallel to strike due to compression of propagating waves.

2.4 Use of ground motion simulations to calibrate directivity predictions

One other potential source of guidance for modifying GMPEs to include directivity effects is numerical ground motion simulations. Simulations are ideal in their ability to produce near-field ground motion data needed to study directivity, and to study variation in response spectra as earthquake geometry is varied systematically. On the other hand, simulation models require accurate representation of the earthquake source if resulting directivity effects are to be consistent with empirical observations.

A variety of researchers have performed ground motion simulations and reported features in the resulting ground motions related to directivity. For example, Si and Midorikawa (2004) and Hikita (2006) report observations of directivity effects from numerical simulations of active crustal

earthquakes. Kato et al. (2002) report observing directivity in numerical simulations of subduction events when the rupture propagates in the up-dip direction, but not when it propagates along strike. Sesetyan (2007) studied the spatial variation of directivity effects from simulated time histories. Fault-normal to average spectral acceleration ratios were studied and models for predicted ratios as a function of source geometry are provided. Collins et al. (2006) studied ground motions from three simulation procedures, and looked at response spectra residuals relative to GMPEs to search for evidence of directivity effects of the form predicted by the Somerville et al. (1997) model. While some directivity effects were present, the results were inconsistent between the three models. The results from the Collins et al. (2006) study were interpreted as promising with regard to the future potential of numerical simulations to guide calibration of ground motion prediction equations for effects such as directivity and magnitude scaling, no such calibration was done using these data.

While these and other similar documents indicate the future role of simulations in studying and predicting directivity effects, to date no predictive models for the impact of directivity on response spectra have been produced on the basis of ground motion simulations, and thus this field of research has not yet provided results of use to the GEM project.

3. DIRECTIONALITY EFFECTS

Ground motions vary in intensity as a function of the orientation of interest, so there are a variety of ways to quantify intensity for multi-component ground motions. Many ground motion prediction equations predict the geometric mean of the response spectra of two horizontal components of ground motion. In some cases it may be of greater interest to know the maximum spectral value, over all possible directions, of spectral acceleration at a given periods. In addition, there are a variety of other definitions of ground motion parameters from multicomponent ground motions. For the purposes of vulnerability predictions, it is important that the ground motion intensity measure be consistent between the ground motion prediction and the vulnerability calculation, so some adjustment of ground motion predictions may be needed in some cases.

A review of most common definitions, including models for converting between definitions, is provided by Beyer and Bommer (2006). The ground motion parameter definitions likely to be of interest to GEM (because they are predicted by recommended GMPEs or because they may be of use for inputs to fragility functions) are summarized in Table 3.1. The table uses notation for spectral accelerations, but the definitions can also be applied to PGA or PGV values.

Note that for a given ground motion, the orientation associated at $Sa_{RotD50}(T_1)$ with in general differ from the orientation associated with $Sa_{RotD50}(T_2)$, where T_1 and T_2 are non-equal periods. The same is true for orientations of $Sa_{RotD100}$ values. The desire to find a single principle orientation for a given ground motion led to the development of the $Sa_{GMRot150}$ definition, although identifying the single orientation results in added complexity in that definition (Boore et al. 2006).

Table 3.1: Selected definitions of spectral accelerations for multi-component ground motions

Notation	Description
Sa_{GM}	Geometric mean of spectral accelerations of the two as-recorded horizontal components
Sa_{RotD50}	Median (i.e., 50 th percentile) value of spectral accelerations computed over all rotation angles for a given ground motion
$Sa_{RotD100}$	Maximum direction (i.e., 100 th percentile) value of spectral accelerations computed over all rotation angles for a given ground motion
$Sa_{GMRotD50}$	Median value of geometric mean spectral accelerations computed over all rotation angles for a given ground motion
$Sa_{GMRot150}$	Geometric mean spectral acceleration, computed at an orientation which minimizes the sum of differences between $Sa_{GMRotD50}$ and $Sa_{GMRot150}$ over the usable range of oscillator periods

Most published GMPEs are for Sa_{GM} (most models prior to 2006, and many after 2006), $Sa_{GMRot150}$ (the

2008 NGA West models and some others after 2006) or $Sa_{GMRotD50}$ (the NGA East and NGA West 2 models, and some other models in current development). When converting GMPEs to predict Sa 's with the various definitions in Table 3.1, one needs a ratio by which to modify median Sa predictions, as well a ratio by which to modify the predicted log standard deviation. Those ratios in general vary by period and seismological region, as will be discussed below.

Before proceeding to consider modifications of Sa definition, it is important to emphasize that the Sa definition used in the GMPE and hazard component must be consistent with the Sa definition used by the fragility functions to predict damage. That is, GEM should not modify GMPEs to produce a maximum direction Sa prediction unless the structural fragility functions use a maximum direction Sa as input (see, e.g., Baker and Cornell 2006, Beyer and Bommer 2006 for further discussion).

3.1 Models for converting between Sa_{GM} , Sa_{RotD50} and $Sa_{GMRot150}$

$Sa_{GMRot150}$ (Boore et al. 2006) and Sa_{RotD50} (Boore 2010) were proposed as refinements to the traditional Sa_{GM} parameter, which remove the dependence of a ground motion's Sa on the orientation of the recording instrument. All three parameters will be similar for a given ground motion, and in a probabilistic sense they will have similar means and standard deviations for ground motions resulting from a given earthquake and site condition. Beyer and Bommer (2006) found that $Sa_{GMRot150}$ has the same mean value as Sa_{GM} , and that the ratio between the two had a very small log standard deviation (0.03 to 0.04), indicating that their values are nearly identical for recorded ground motions. Boore (2010) found that the geometric mean ratio of $Sa_{RotD50}/Sa_{GMRot150}$ of recorded ground motions was slightly larger than 1, as shown in Figure 3.1. Boore (2010) also reports that log standard deviations of $Sa_{RotD50}/Sa_{GMRot150}$ ratios vary from 1.05 to 1.07, depending upon period. But that standard deviation includes uncertainty in both Sa_{RotD50} and $Sa_{GMRot150}$, so the log standard deviation is not additive to the log standard deviation for a predictive model for $Sa_{GMRot150}$; the log standard deviation for a Sa_{RotD50} GMPE would be larger than the log standard deviation for a $Sa_{GMRot150}$ GMPE by less than 4% (Boore 2010).

All of the studies cited in this section were calibrated using ground motions from shallow crustal earthquakes in active seismic regions. To date no similar models have been produced using ground motions from other regions.

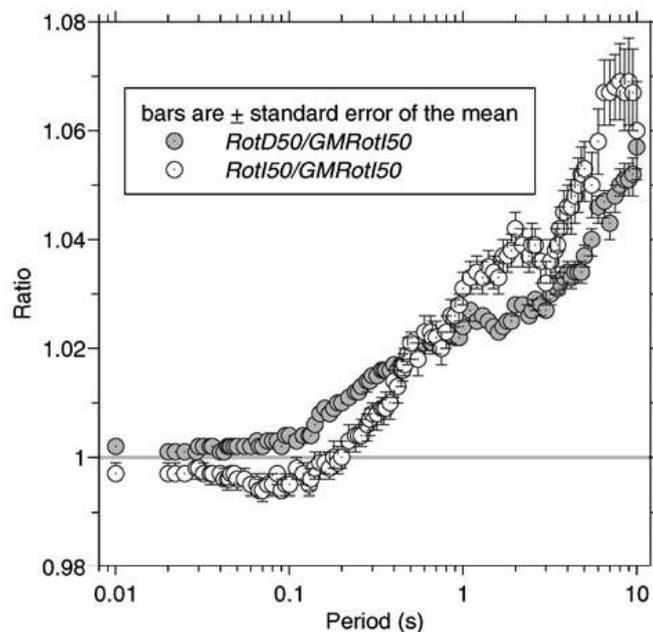


Figure 3.1: Geometric mean ratio of $Sa_{RotD50}/Sa_{GMRot150}$ observed from the PEER NGA West database (figure adapted from Boore 2010).

3.2 $Sa_{RotD100}$ Models for active shallow crustal tectonic regions

A variety of researchers have studied ratios between $Sa_{RotD100}$ and $Sa_{GMRot150}$ values in observed ground motions from earthquakes in active shallow crustal tectonic regions (Beyer and Bommer 2006, Watson-Lamprey and Boore 2007, Huang et al. 2008, 2010). Additionally, the NGA West 2 project is currently performing the same calculations from a newly-expanded database of recorded strong ground motions. Figure 3.2 shows predictions of geometric mean $Sa_{RotD100}/Sa_{GMRot150}$ ratios from the above-cited sources, as well as comparable unpublished results from the NGA West 2 project¹.

All four sets of ratios in Figure 3.2 are very similar. This is in part because the data sets used in each case were similar, and in part because these ratios appear to be very stable in general, as will be discussed more later. First, a brief summary of the data sets used for calibration is provided. The Beyer and Bommer (2006) ratios were developed from 949 ground motions in the PEER NGA database, with magnitudes ranging from 4.2 to 7.9 and distances ranging from 5km to 200 km. The Beyer and Bommer ratios plotted in Figure 3.2 are from a fitted function rather than raw data, and this is the likely source of the slight discrepancy between those ratios and the others at periods of approximately 1s. The Watson-Lamprey and Boore (2007) ratios used the entire PEER NGA database with two-component recordings—a total of 3529 ground motions—but only considered spectra for periods less than the maximum usable period as documented in that database. The Huang et al. (2008, 2010) ratios are median ratios from 91 ground motions in the PEER NGA database, selected to have magnitudes of greater than 6.5, distances of less than 15km, and to exclude recordings from the Chi-Chi, Taiwan. Although not reported here, Campbell and Bozorgnia (2008) performed a similar study using 1561 ground motions from the NGA West database, and reported similar ratios.

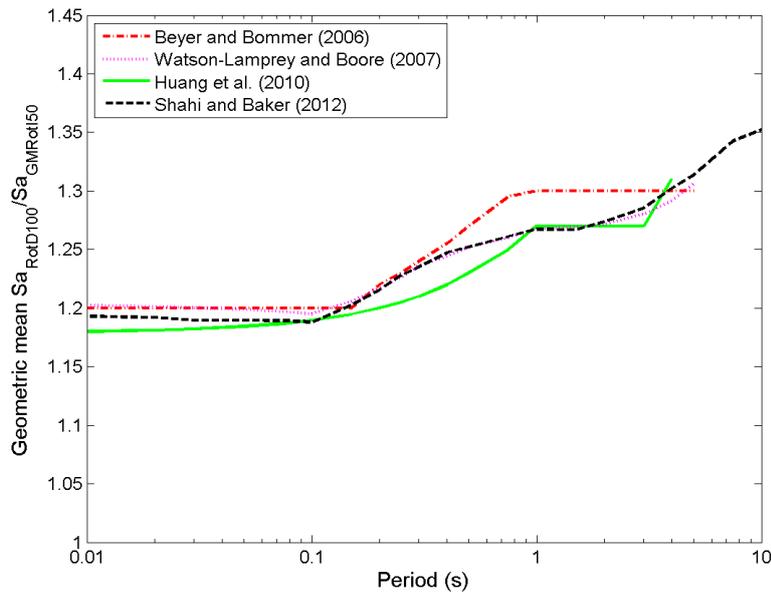


Figure 3.2: Geometric mean ratios of $Sa_{RotD100}/Sa_{GMRot150}$ in active shallow crustal tectonic regions, from published studies and the NGA West 2 project.

The Shahi and Baker (2012) data shown in Figure 3.2 uses the expanded NGA West 2 database with approximately 3000 ground motions utilized for these calculations, and uses a mixed-effects model to estimate median ratios in a manner that prevents well-recorded earthquakes from disproportionately influencing the results. The NGA West 2 project does not consider $Sa_{GMRot150}$ values, so to facilitate comparison the ratios in Figure 3.2 were obtained by computing geometric mean $Sa_{RotD100}/Sa_{RotD50}$ ratios, and then multiplying those by the geometric mean $Sa_{RotD50}/Sa_{GMRot150}$ ratios from Boore (2010).

¹ The NGA West 2 project data does not include $Sa_{GMRot150}$ values, so the ratios in Figure 3.2 were obtained by computing geometric mean $Sa_{RotD100}/Sa_{RotD50}$ ratios, and then multiplying those by the geometric mean $Sa_{RotD50}/Sa_{GMRot150}$ ratios from Boore (2010).

The models in Figure 3.2 generally find that $Sa_{GMrot150}$ predictions should be multiplied by approximately 1.2 at short periods ($T < 0.1s$) and approximately 1.3 at longer periods ($T > 1s$). None of the authors found strong trends in these ratios with magnitude, distance or directivity indicators. Watson-Lamprey and Boore (2007) noted slight distance, magnitude and radiation pattern dependence, but noted that “for most engineering applications the conversion factors independent of those variables can be used.” Similarly, the NGA West 2 data set indicates a slight trend with distance (with distances of $< 3km$ having ratios approximately 0.02 larger than the average ratios for the entire library of ground motions), but the effect is small in terms engineering impact. Similarly, the differences between the four models in Figure 3.2 are often less than 0.02 and the results can similarly be interpreted as essentially identical.

The standard deviation for $Sa_{RotD100}$ predictions is slightly larger than the standard deviation for $Sa_{GMrot150}$ predictions (Beyer and Bommer 2006, Watson-Lamprey and Boore 2007). For example, Watson-Lamprey and Boore (2007) report that the Boore and Atkinson (2008) GMPE log standard deviation of 0.645 for $Sa_{GMrot150}(1s)$ would be increased to 0.666 for $Sa_{RotD100}(1s)$ —an increase of 3%, and a variation that is less than the typical variation of standard deviations between GMPEs predicting the same ground motion parameter. For this reason, the standard deviation of $Sa_{RotD100}$ might be reasonably approximated as equal to the standard deviation of $Sa_{GMrot150}$. This approximation has practical advantages, because if only the geometric mean of Sa is affected by the change of definition, it is possible to convert between definitions even after a hazard analysis has been performed for one definition. For example, the USGS multiplies spectral acceleration values with a given return period by the constants specified in NEHRP (2009) in order to make $Sa_{RotD100}$ maps from $Sa_{GMrot150}$ maps, rather than re-computing the maps with new GMPMs for $Sa_{RotD100}$ that have been modified to include both median and standard deviation adjustments. If a more refined estimate of the standard deviation of $Sa_{RotD100}$ is desired, Beyer and Bommer (2006) and Watson-Lamprey and Boore (2007) provide models for this minor adjustment.

3.3 $Sa_{RotD100}$ models for other regions

The only published $Sa_{RotD100}/Sa_{GMrot150}$ ratios from stable continental region (SCR) ground motions are from Huang et al. (2010). These ratios, shown in Figure 3.3, ratios were computed from 63 Central and Eastern North American ground motions with magnitudes of 4 or greater were used. Those reported ratios are larger than the ratios from active seismic region crustal earthquakes, as represented by the Watson-Lamprey and Boore (2007) ratios.

Similar ratios were computed from the NGA East ground motion database (Baker 2012). As with Baker and Shahi (2012), in this case geometric mean ratios of $Sa_{RotD100}/Sa_{RotD50}$ were computed from the database, and were multiplied by the geometric mean $Sa_{RotD50}/Sa_{GMrot150}$ ratios from Boore (2010) to obtain $Sa_{RotD100}/Sa_{GMrot150}$ ratios. This database consists of 5896 stable continental region ground motions ranging in magnitude from 2 to 7 and in epicentral distance from 1 to 3000 km. There were no observed trends in $Sa_{RotD100}/Sa_{GMrot150}$ ratios with magnitude or distance, so the entire dataset was used to compute these ratios, though due restrictions on the usable period range, at some periods only a small fraction of the motions could be used for the analysis. The ratios from the NGA East data are shown in Figure 3.3, and are much closer to the active shallow crustal tectonic region ratios than they are to the Huang et al. ratios. The Huang et al. study used a small data set, so the results were perhaps influenced by that limited data. Further, these $Sa_{RotD100}/Sa_{GMrot150}$ ratios should be influenced primarily by polarization of the ground motion, and there isn't reason to expect significantly different polarization in SCR ground motions relative to motions from active seismic region crustal earthquakes. For these reasons, we expect the Baker (2012) ratios from the NGA East data to be the most reliable representation of $Sa_{RotD100}/Sa_{GMrot150}$ ratios for Stable Continental Regions.

There are currently no published models of $Sa_{RotD100}/Sa_{GMrot150}$ ratios from ground motions in subduction regions, and so no results for subduction regions are presented here.

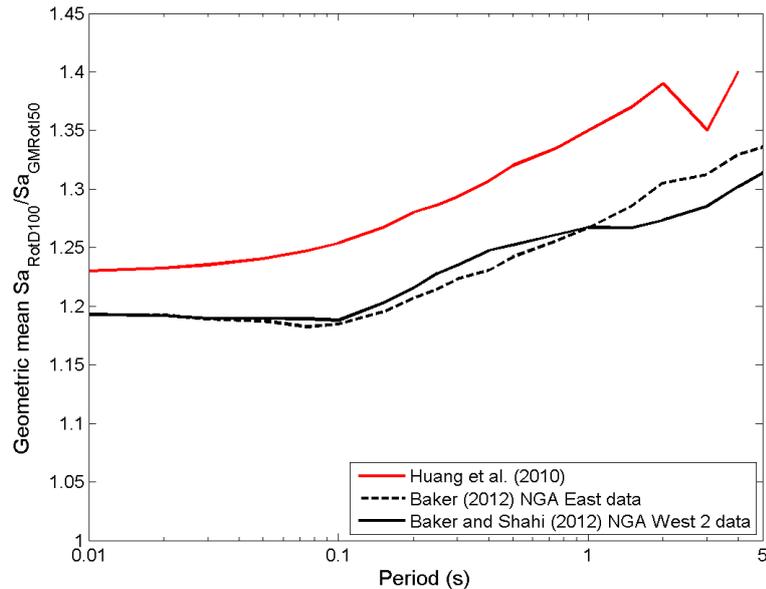


Figure 3.3: Geometric mean ratios of $Sa_{RotD100}/Sa_{GMRot150}$ in stable continental regions from Huang et al. (2010) and the NGA East project (Baker 2012), compared with the equivalent Baker and Shahi (2012) ratios for active shallow crustal tectonic regions.

4. CONCLUSIONS

This paper has reviewed available models for adjusting GMPE's to account for near-fault directivity effects, or to convert a GMPE to predict an alternated definition of spectral acceleration for a multicomponent ground motion. Future GMPE's may account for these effects directly, but current GMPEs require these additional models to perform such adjustments.

There are a number of publications providing empirically calibrated results of this type for ground motions from shallow crustal earthquakes in active seismic regions, but there are fewer such models for ground motions from stable continental regions or subduction regions. While directionality models appear to be somewhat stable from seismic region to seismic region, it is not clear that the same stability holds for directivity models.

The models surveyed in this paper will be used to produce recommendations for adoption by the Global Earthquake Model (GEM) project, in the case that such modifications are needed in GEM calculations. These topics comply with the objectives of the GEM Global GMPEs project, coordinated by the Pacific Earthquake Engineering Research Center (PEER).

ACKNOWLEDGEMENT

This study was funded by the GEM Foundation as part of the Pacific Earthquake Engineering Research Center's (PEER's) Global GMPEs project. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect those of the sponsors.

REFERENCES

- Abrahamson, N. A. (2000). "Effects of rupture directivity on probabilistic seismic hazard analysis." *Sixth International Conference on Seismic Zonation*, Earthquake Engineering Research Inst., Oakland, California.
- Archuleta, R.J., 1982. Analysis of near-source static and dynamic measurements from the 1979 Imperial Valley earthquake. *Bulletin of the Seismological Society of America*, 72(6A), pp.1927 -1956.
- Baker (2012). Ratios of $Sa_{RotD100} / Sa_{RotD50}$ in NGA East data. Internal project report.
- Baker, J. W., and Cornell, C. A. (2006). "Which spectral acceleration are you using?" *Earthquake Spectra*, 22(2), 293-312.
- Beyer, K., and Bommer, J. J. (2006). "Relationships between Median Values and between Aleatory Variabilities

- for Different Definitions of the Horizontal Component of Motion.” *Bulletin of the Seismological Society of America*, 96(4A), 1512-1522.
- Boore, D. M. (2010). “Orientation-Independent, Nongeometric-Mean Measures of Seismic Intensity from Two Horizontal Components of Motion.” *Bulletin of the Seismological Society of America*, 100(4), 1830-1835.
- 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 s and 10.0 s.” *Earthquake Spectra*, 24(1), 99-138.
- Boore, D. M., Watson-Lamprey, J., and Abrahamson, N. A. (2006). “Orientation-Independent Measures of Ground Motion.” *Bulletin of the Seismological Society of America*, 96(4A), 1502–1511.
- Collins, N., Graves, R. W., and Somerville, P. G. (2006). *Comparison of validations of ground motion simulation procedures*. Report to the PEER-Lifelines Program, Project 1C02d. URS Corporation, Pasadena Office. 26p.
- Hikita, T. (2006). “Characteristics of Strong ground motions at the forward rupture direction.” *12th Japan Earthquake Engineering Symposium*. 4p.
- Howard, J. K., Tracy, C. A., and Burns, R. G. (2005). “Comparing Observed and Predicted Directivity in Near-Source Ground Motion.” *Earthquake Spectra*, 21(4), 1063-1092.
- Huang, Y.-N., Whittaker, A. S., and Luco, N. (2008). “Maximum Spectral Demands in the Near-Fault Region.” *Earthquake Spectra*, 24(1), 319-341.
- Huang, Y.-N., Whittaker, A. S., and Luco, N. (2010). *Maximum Spectral Demand in the United States*. USGS Open File Report, in preparation, 217p.
- Kato, K., Masayuki, T., and Kazuhiko, Y. (2002). “Rupture directivity effect in near fault regions-numerical studies for the great inter-plate earthquakes.” *Proceedings of the Japan Earthquake Engineering Symposium*. p145-150.
- Mai, P. M., Spudich, P., and Boatwright, J (2005). “Hypocenter Locations in Finite-Source Rupture Models.” *Bulletin of the Seismological Society of America*, 95(3), 965-980.
- NEHRP (2009). *NEHRP Recommended Seismic Provisions for New Buildings and Other Structures*. 406.
- Rowshandel, B. (2006). “Incorporating Source Rupture Characteristics into Ground-Motion Hazard Analysis Models.” *Seismological Research Letters*, 77(6), 708-722.
- Rowshandel, B. (2010). “Directivity Correction for the Next Generation Attenuation (NGA) Relations.” *Earthquake Spectra*, 26(2), 525-559.
- Sesetyan, Karin (2007), *Characterization of Response Spectra For Near Field Conditions by Earthquake Ground Motion Simulation*, PhD. Thesis, Bogazici University, İstanbul
- Shahi, S. K., and Baker, J. W. (2011). “An Empirically Calibrated Framework for Including the Effects of Near-Fault Directivity in Probabilistic Seismic Hazard Analysis.” *Bulletin of the Seismological Society of America*, 101(2), 742-755.
- Shahi, S. K., and Baker, J. W. (2012). “Preliminary NGA-West 2 models for ground-motion directionality.” *Proceedings of 15th World Conference on Earthquake Engineering*, Lisbon, Portugal, 10p.
- Si, H., and Midorikawa, S. (2004). “Evaluation of rupture directivity effects on strong ground motion based on hybrid simulation method.” *13th World Conference on Earthquake Engineering*. Vancouver, B.C., Canada, 11p.
- Somerville, P. G. (2003). “Magnitude scaling of the near fault rupture directivity pulse.” *Physics of the earth and planetary interiors*, 137(1), 12.
- Somerville, P. G., Smith, N. F., Graves, R. W., and Abrahamson, N. A. (1997). “Modification of Empirical Strong Ground Motion Attenuation Relations to Include the Amplitude and Duration Effects of Rupture Directivity.” *Seismological Research Letters*, 68(1), 199-222.
- Spudich, P., and Chiou, B. S. J. (2008). “Directivity in NGA Earthquake Ground Motions: Analysis Using Isochrone Theory.” *Earthquake Spectra*, 24(1), 279-298.
- Spudich, P., Chiou, B. S., Graves, R. W., Collins, K. R., and Somerville, P. G. (2004). *A formulation of directivity for earthquake sources using isochrone theory*. 54.
- Spudich, P., Somerville, P. G., Shahi, S. K., Rowshandel, B., Chiou, B. S. J., Bayless, J., and Baker, J. W. (2012). “Directivity models produced for the Next Generation Attenuation West 2 (NGAW2) project.” *Proceedings of 15th World Conference on Earthquake Engineering*, Lisbon, Portugal.
- Watson-Lamprey, J., and Boore, D. M. (2007). “Beyond SaGMRotI: Conversion to SaArb, SaSN, and SaMaxRot.” *Bulletin of the Seismological Society of America*, 97(5), 1511-1524.