HYBRID EMPIRICAL GROUND MOTION MODEL FOR PGA AND 5% DAMPEDLINEAR ELASTIC RESPONSE SPECTRA FROM SHALLOW CRUSTAL EARTHQUAKES IN STABLE CONTINENTAL REGIONS: EXAMPLE FOR EASTERN NORTH AMERICA

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ABSTRACT

The widespread application of the hybrid empirical method (HEM) has made it a viable approach for developing ground motion prediction equations in regions where there are few strong motion recordings but there are ample weak motion data from small-magnitude earthquakes. The HEM uses empirical estimates of ground motion in one region (the host region) to provide estimates of ground motion in another region (the target region) by taking into account the differences in stress drop, source properties, crustal damping, regional crustal structure, and generic site conditions (amplification and damping) between the two regions. Empirical ground motion estimates in the host region are transferred to the target region using regional adjustment factors derived from stochastic simulation. In this study, I used the formal mathematical framework of the HEM and an updated seismological model for eastern North America (ENA) to derive a tentative set of updated ENA hybrid empirical hard-rock ground motion estimates for PGA, PGV and 5% damped linear elastic response spectra. For the preliminary results presented in this paper, I estimated ground motions in ENA (the target region) from a new empirical ground motion prediction equation developed for WNA (the host region). The seismological parameters that were used to develop the regional adjustment factors were taken from recent studies of weak motion data in the two regions. The preliminary results identified several issues and uncertainties that will need to be addressed or resolved before an updated reliable hybrid empirical ground motion prediction equation can be developed for ENA.

KEYWORDS: Attenuation, Ground Motion Prediction, Stable Continental Regions, Eastern North America

1. INTRODUCTION

The number and use of ground motion prediction equations for seismic hazard studies in eastern North America (ENA) and other stable continental regions (SCRs) has progressed rapidly over the last decade. As a result of the limited number of strong motion recordings in ENA, these models have been developed using a variety of theoretical and semi-theoretical methods (Campbell, 2003, 2007). One method that has gained increasing popularity during the last decade is the hybrid empirical method (HEM) first introduced in the early 1980s and later documented by Campbell (2001, 2003). Of the seven ENA ground motion models that have been selected for use in the 2007 update of the U.S. national seismic hazard maps (Petersen et al., 2008), two were developed using the HEM. Of the remaining five, four were developed using the stochastic method and one was derived using the numerical method. Other recent applications of the HEM include ENA (Tavakoli and Pezeshk, 2005; Atkinson, 2008), Central Europe (Scherbaum et al., 2005), the U.S. Pacific Northwest (Atkinson, 2005), and southern Spain and southern Norway (Douglas et al., 2006). Atkinson (2008) introduced what she refers to as the referenced empirical approach that is based on the HEM but uses empirical rather than theoretical regional adjustment factors.

In this study, I used the HEM to develop a set of hybrid empirical hard-rock ground motion estimates for ENA (hereafter referred to as HE-GMPE) to serve as a tentative update to the ground motion prediction equations developed by Campbell (2003, 2004). The updated HE-GMPE incorporates a revised ENA seismological model that was developed from an expanded set of weak motion data (Atkinson, 2004; Atkinson and Boore, 2006) and a revised empirical ground motion prediction equation (hereafter referred to as E-GMPE) that was developed from an expanded set of strong motion data from western North America (WNA) and other active tectonic regimes (Campbell and Bozorgnia, 2008). The new HE-GMPE is shown to provide ground motion estimates at moderate-to-large magnitudes that are similar to those predicted from the point-source stochastic model at large distances and the finite-source stochastic model at moderate-to-large distances when the same ENA seismological model is used to perform the ground motion simulations. As discussed later, I found that this agreement could only be achieved if a larger stress drop was used with the point-source stochastic model. Because of its reliance on a well-constrained E-GMPE, the HE-GMPE offers an alternative, more empirically based, method for predicting near-source ground motions from large-magnitude earthquakes in ENA and other SCRs.

2. APPLICATION OF THE HYBRID EMPIRICAL METHOD

The full implementation of the HEM requires five steps: (1) the selection of the host and target regions, (2) the calculation of empirical ground motion estimates for the host region, (3) the calculation of regional adjustment factors between the target and host regions, (4) the calculation of hybrid empirical ground motion estimates for the target region, and (5) the development of a hybrid empirical ground motion prediction equation for the target region. I refer the reader to Campbell (2003) for a detailed explanation of the mathematical framework involved in applying these steps. For the current paper, I selected the target region to be that area of ENA bounded on the west by the Rocky Mountains and on the south by the Gulf Coast region. I selected the host region to be that area of WNA located west of the eastern front of the Rocky Mountains. Because of the preliminary nature of this study, I did not execute step 5 and formally develop a ground motion prediction equation. Instead, I directly used the ground motion estimates from step 4.

2.1. WNA Empirical Ground Motion Estimates

The E-GMPE of Campbell and Bozorgnia (2008) was used to derive the empirical ground motion estimates in WNA. This model was developed for the Pacific Earthquake Engineering Research Center (PEER) Next Generation Attenuation (NGA) project. Although most of the strong motion recordings used to develop the E-GMPE come from California, many other relevant recordings come from other parts of the world with tectonic characteristics similar to California and WNA (Campbell and Bozorgnia, 2008). The validity of using strong motion data from crustal earthquakes in these other geographical regions has been verified for southern Europe and the Middle East by (Campbell and Bozorgnia (2006) and Stafford et al. (2007), for Taiwan by Lin (2007), and for Iran, New Zealand and South America in several unpublished studies. The empirical ground motion parameters were defined as the orientation-independent geometric mean of the two horizontal components of peak ground acceleration (PGA), peak ground velocity (PGV), and 5% damped pseudo-absolute acceleration response spectra (PSA) for periods ranging from 0.01–10 s.. The E-GMPE was evaluated for moment magnitudes (**M**) ranging from 3.5 to 8.0 in increments of 0.5 and 16 earthquake rupture distances (R_{RUP}) ranging from 1–70 km. The reason for restricting the calculations to near-source distances is explained later in the paper. The remaining explanatory variables in the E-GMPE were assigned values that are consistent with the WNA seismological model (Campbell, 2007).

2.2. WNA-to-ENA Regional Adjustment Factors

Based on its success in modeling a wide range of ground motion parameters (Boore, 2003), I selected the point-source stochastic method and a Brune omega-square single-corner source spectrum to calculate the median seismological estimates of ground motion. As I discuss later, the exact form of the source spectrum used in the stochastic simulations does not have a significant impact on the HEM as long as the same spectral shape is used in both ENA and WNA. A general discussion of the application of the stochastic method within the mathematic framework of the HEM is given in Campbell (2003) and its specific application in the present study is given in Campbell (2007). Representative stochastic model parameters for WNA are the same as those used to develop the previous HE-GMPE (Campbell, 2003, 2004). I did not find it necessary to adjust the previously selected values for stress drop ($\Delta\sigma$) and site attenuation (κ_0) after comparing the empirical generic-rock response spectrum predicted from the E-GMPE with the response spectrum predicted from the WNA point-source stochastic model for moderate magnitudes and short distances, where finite-source and attenuation effects are negligible (Campbell, 2007).

Representative stochastic model parameters for ENA were updated based on the seismological models of Atkinson (2004) and Atkinson and Boore (2006). These latter investigators performed stochastic finite-source ground motion simulations for two different generic site profiles: (1) a traditional ENA hard-rock profile and (2) a softer National Earthquake Hazard Reduction Program (NEHRP) B–C (V_{S30} = 760 m/s) site profile. Since I restricted the current study to hard-rock site conditions ($V_{S30} > 2000$ m/s), I used the hard-rock site profile to conduct the ENA stochastic ground motion simulations. There are three notable differences between the ENA seismological parameters used in the current study and those used by Campbell (2003): (1) the median stress drop was increased from 150 bars to 280 bars, (2) the geometric spreading coefficient n in the distance decay term r^n was decreased from –1.0 to –1.3 for hypocentral distances less than 70 km, and (3) the hard-rock crustal amplification at short periods was increased from a value slightly over unity to 1.41 to be consistent with a reduction in surface shear-wave velocity from 2800 m/s to 2000 m/s. The ENA and WNA parameters used for the stochastic simulations are summarized in Table 1.

Table 1. Median seismological parameters used in the stochastic models

Parameter	WNA	ENA
Source spectrum	Brune omega-square single corner	Brune omega-square single corner
Shear velocity at source (km/s)	3.5	3.7
Density at source (gm/cc)	2.8	2.8
Stress drop (bars)	100	280
Source duration (s)	$1/f_0$ (f_0 = source corner frequency)	$1/f_0$ (f_0 = source corner frequency)
Geometric attenuation	$r^{-1.0}$; $r < 40$ km $r^{-0.5}$; $r \geq 40$ km	$r^{-1.3}$; $r < 70$ km $r^{+0.2}$; $70 \leq r < 140$ km $r^{-0.5}$; $r \geq 140$ km
Path duration (s)	$0.05r$	1; $r < 10$ km $+0.16r$ $10 \leq r < 70$ km $-0.13r$ $70 \leq r < 130$ km $+0.04r$ $r \geq 130$ km
Path attenuation (Q)	$180\,f^{\,0.45}$	$893\,f^{\,0.32}$ (1000 minimum)
Site profile	WNA generic rock (V_{S30} = 620 m/s)	ENA hard rock (V_{S30} = 2000 m/s)
Site amplification	¼-wavelength method	¼-wavelength method
Site attenuation, κ_0 (s)	0.04	0.005

2.3. ENA Hybrid Empirical Ground Motion Estimates

I calculated the median hybrid empirical ground motion estimates using the formulation of Campbell (2003), assuming that the hypocentral distance used in the stochastic model (r) could be equated to the fault distance measure (R_{RUP}) used in the E-GMPE for purposes of applying the regional adjustment factors. An important limitation of the empirical and hybrid empirical ground motion estimates is their reduced reliability beyond 100 km. Consistent with the approach taken by Campbell (2003), I avoided this limitation by substituting the hybrid empirical estimates with the ENA stochastic simulations for distances beyond 70 km.

3. DISCUSSION

There are five important issues that were identified during the course of the study that will need to be addressed or resolved before an updated ENA ground motion prediction equation can be developed. These issues are (1) whether a Brune omega-square single-corner source spectrum is appropriate for estimating regional adjustment factors for large-magnitude earthquakes, (2) what value of stress drop should be used for ENA earthquakes and whether this stress drop is model dependent, (3) what rate of near-source geometric attenuation should be used for ENA and WNA ground motions, (4) whether the E-GMPE is valid at small magnitudes, and (5) whether the magnitude-saturation characteristics of ground motion predicted by the E-GMPE at large magnitudes is transferable to ENA. Until these issues are addressed satisfactorily, they represent a significant source of epistemic uncertainty that will need to be accounted for in the HE-GMPE.

3.1. Source Spectrum

Tavakoli and Pezeshk (2005) proposed that the use of a Brune single-corner source spectrum by Campbell (2003, 2004) caused his HE-GMPE to underestimate ground motion amplitudes from near-source large-magnitude earthquakes in ENA. This conclusion was based on published studies that found that the use of a double-corner source spectrum together with a focal depth that increases with magnitude was required to match a dataset of strong motion recordings from moderate-to-large earthquakes in California. These authors noted that other researchers also had proposed the use of a double-corner source spectrum to model the source spectra of large earthquakes in ENA. This lead Tavakoli and Pezeshk to suggest that using a double-corner source spectrum with Campbell's (2003) HEM constituted an improvement in the method.

Campbell (2008) thoroughly reviewed this issue and concluded that it appears that Tavakoli and Pezeshk incorrectly used a magnitude-dependent stress drop together with a double-corner source spectrum in the parameterization of their WNA seismological model. Although their use of a double-corner source spectrum in both ENA and WNA does not necessarily constitute an error, Campbell presents ample evidence to suggest that such a spectrum is only necessary when the point-source stochastic method is used to estimate *absolute* amplitudes of ground motion from large-magnitude earthquakes. The HEM avoids this issue by using *relative* rather than *absolute* ground motion amplitudes, which requires only that the source spectral shape be the same in the host and target regions. Campbell found that there is sufficient evidence to suggest that source spectral shapes are the same (within observational uncertainty) in ENA and WNA once differences in stress drop are taken into account, but this still remains a potential source of uncertainty.

3.2. Stress Drop

Atkinson and Boore (2006) used their updated set of ENA seismological parameters along with a finite-source stochastic simulation model (EXSIM) to infer a median stress drop of 140 bars for eight instrumentally recorded events in ENA. However, using these same seismological parameters (Table 1) with a point-source stochastic simulation model (SMSIM), I found that a stress drop of approximately 280 bars was required to closely match their response spectral results (Fig. 1). The same conclusion can be made for the HE-GMPE at large magnitudes. The discrepancy between the HE-GMPE and the stochastic models at small magnitudes is discussed in a subsequent section. The apparent need for a larger stress drop in the SMSIM model is critical, since the point-source stochastic model is used in the HEM. A similar discrepancy has been noted by Motazedian and Atkinson (2005) and Assatourians (2008). More study is needed in order to understand the cause for this discrepancy in the stress drops between EXSIM and SMSIM.

3.3. Near-Source Geometric Attenuation

An empirical near-source geometric spreading coefficient (n) of –1.0 was used in both WNA and ENA to develop the regional adjustment factors in Campbell (2003, 2004). As a result, the near-source ground motions predicted by this HE-GMPE were found to be consistently larger than those predicted by WNA empirical relations at all distances. Atkinson (2004), using an expanded weak and strong motion database, revised the ENA near-source spreading coefficient to –1.3. Campbell (2007) found that this higher rate of attenuation can lead to the prediction of similar or lower ground motions in ENA than in WNA at near-source distances using the seismological parameters listed in Table 1, which appears to contradict intensity observations in these two regions (Atkinson and Wald, 2007).

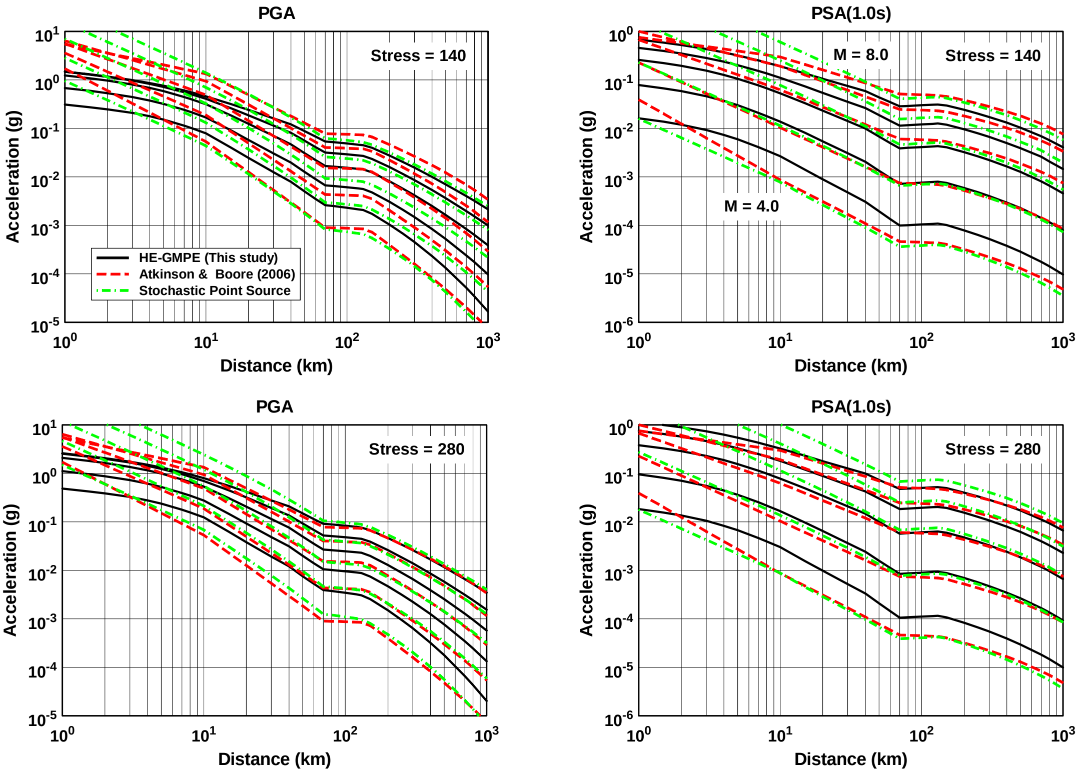

Figure 1. Ground motion predictions on ENA hard rock for stress drops of 140 and 280 bars.

As noted previously, it is actually the relative difference and not the absolute values of ground motion and, therefore, geometric attenuation in ENA and WNA that is important in applying the HEM. Therefore, the issue is whether the regional difference in geometric attenuation in Table 1, which is based on studies in southern California and in southeastern Canada and northeastern U.S., is both scientifically justifiable and transferable to other regions of WNA and ENA. In order to address this issue, Campbell (2007) reviewed the scientific literature to see if he could find other studies that could either support or refute a difference in geometric attenuation between these two regions. He concluded from the diverse range of observed and theoretical geometric spreading coefficients available in the literature that there are large regional differences in attenuation that are not easily quantified in terms of simple tectonic environments, such as ENA and WNA. Furthermore, recent studies have suggested that a spreading coefficient of –1.3 might also be appropriate for WNA (Campbell, 2007; Malagnini et al., 2007; Atkinson and Morrison, 2008). This issue is a current topic of research.

3.4. Small-Magnitude Scaling

Atkinson (2007) compiled a set of small-magnitude intensity (MMI) and ground motion data collected from the U.S. Geological Survey “Did You Feel It?” and ShakeMap projects and compared them to the empirical ground motion predictions of Boore and Atkinson (2008). MMI was converted to ground motion using updated relationships between MMI and PGA, PGV and PSA. She found that there is a general attenuation discrepancy between the MMI-based ground motion predictions and the Boore-Atkinson E-GMPE. At moderate-to-large distances, the E-GMPE appears to be overestimating both the MMI-based and recorded ShakeMap ground-motion data for small-to-moderate events. I found a similar discrepancy with the E-GMPE used in this study (Campbell and Bozorgnia, 2008). This discrepancy (Fig. 2) suggests that the WNA empirical relations predict a near-source attenuation rate that is too shallow compared to the small-magnitude intensity and ground motion data. Atkinson (2007) suggests that an adjustment factor could be used to correct for this discrepancy.

Otherwise, the HE-GMPE will overestimate ground motions at moderate distances. It also appears from Figs. 1 and 2 that the near-source saturation of ground motion with distance at small magnitudes predicted by the E-GMPE is not supported by the larger set of small-magnitude data. These issues are currently under investigation by several researchers.

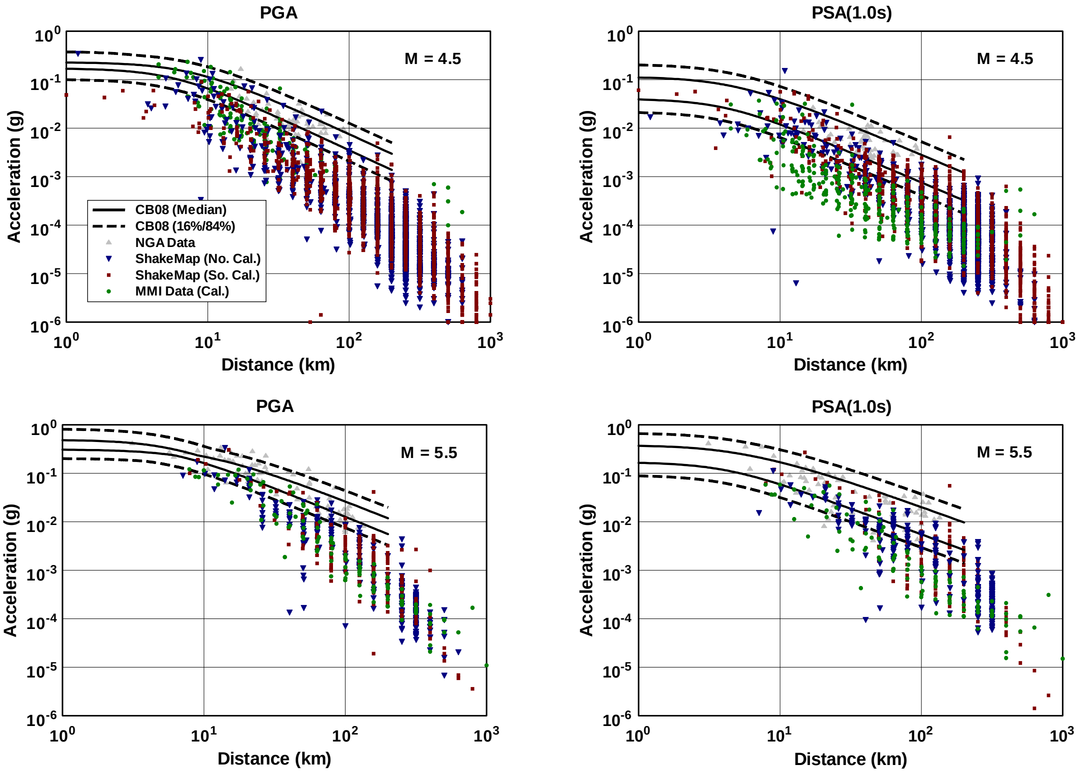

Figure 2. Comparison of Campbell and Bozorgnia (2008) with NGA, ShakeMap, and MMI Data.

3.5. Large-Magnitude Scaling

One major assumption in the present application of the HEM that has not been thoroughly validated is whether the magnitude-saturation characteristics predicted by the E-GMPE are directly transferable to ENA. The key issue is whether the observed and modeled saturation of ground motion and the possible physical mechanisms that are used to explain this saturation can be expected to occur in ENA. This issue is closely related to the stress-drop issue noted above. The ENA finite-source stochastic simulations of Atkinson and Boore (2006) predict that near-source saturation occurs at a larger magnitude than the WNA empirical model of Campbell and Bozorgnia (2008) if a stress drop of 140 bars is used in ENA. For a stress drop of 280 bars, the Atkinson-Boore and HE-GMPE estimates derived in this study are similar at large magnitudes. Campbell (2007) reviewed this issue and noted that there is a lack of understanding on what physical mechanisms might lead to the ground motion saturation observed for large earthquakes in active tectonic regimes and, therefore, whether these mechanisms are also valid in stable tectonic regimes. He concluded from these observations that the assumption that the saturation predicted by WNA ground motion prediction equations is transferable to ENA is a viable alternative hypothesis but a significant source of epistemic uncertainty and needs further study.

3. CONCLUSIONS

The widespread application of the HEM has made it a viable approach for developing ground motion prediction equations in regions where there are few strong motion recordings but there are ample weak motion data from small-magnitude earthquakes. The method has been successfully applied in ENA, the U.S. Pacific Northwest, Central Europe, southern Spain, and southern Norway. In this paper, I demonstrated the use of the HEM by revising the HE-GMPE developed by Campbell (2003, 2004) with an updated E-GMPE for WNA (Campbell and Bozorgnia, 2008) and an updated seismological model for ENA (Atkinson, 2004; Atkinson and Boore, 2006). These updates identified some issues that need to be addressed before an revised HE-GMPE can be reliably developed. These issues are (1) whether a Brune omega-square single-corner source spectrum is appropriate for estimating regional adjustment factors for large-magnitude earthquakes, (2) what value of stress drop should be used for ENA earthquakes and whether this stress drop is model dependent, (3) what rate of near-source geometric attenuation should be used for ENA and WNA ground motions, (4) whether the E-GMPE is valid at small magnitudes, and (5) whether the magnitude-saturation characteristics of ground motion at large magnitudes predicted by the E-GMPE is transferable to ENA. There has been some progress made in addressing these issues, but much more work needs to be done. These and other issues regarding the estimation of ground motion in ENA will be addressed in a new NGA-East project that will build on the success of the NGA-West project. Until these issues are adequately resolved, they remain a significant source of epistemic uncertainty.

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