CAMPBELL-BOZORGNIA 2014 NGA-WEST2 GMPE: COMPARISON WITH REPRESENTATIVE MODELS PREPARED FOR NBCC2015

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ABSTRACT: We used an expanded PEER NGA-West2 ground-motion database to develop new ground-motion prediction equations (GMPEs) for the average horizontal components of PGA, PGV, and acceleration response spectra (PSA) at periods of T = 0.01–10s. In addition to those terms included in our (now superseded) 2008 NGA-West1 GMPE, our new GMPE includes a more detailed hanging-wall term, magnitude-dependent hypocentral depth and fault dip scaling terms, a regionally independent geometric attenuation term, regionally dependent anelastic attenuation and site response terms, and magnitude-dependent aleatory variability terms. The greatly expanded NGA-West2 database provides better constraints on magnitude scaling and attenuation of small-to-moderate magnitude earthquakes, where the 2008 GMPEs are known to be biased. For larger earthquakes, the GMPEs continue to be based on a global set of earthquakes. We consider our new GMPEs to be valid for estimating PGA, PGV and PSA from shallow crustal earthquakes in active tectonic regions for $R_{RUP} \le 300$ km and $M \ge 3.3$. A comparison of our GMPEs with those prepared for the 2015 National Building Code of Canada (NBCC2015) indicates that the medians generally agree within the bounds of epistemic uncertainty, except for $T < 0.1$s, but that the NBCC2015 GMPEs have lower standard deviations.

1. Introduction

One of the major advances in ground-motion prediction equations (GMPEs) in the last 10 years has been the initiation of the Next Generation Attenuation (NGA) program. The NGA program is a multidisciplinary research program coordinated by the Pacific Earthquake Engineering Research Center (PEER) with extensive technical interactions among many individuals and organizations. The NGA program was the first to bring together experts in GMPE development into the framework of a single project, where they share a common uniformly processed and high quality strong motion database and interact with one another on a regular basis. The concept of the program is to eliminate unnecessary uncertainty in individually derived GMPEs that arises when databases and functional forms are developed in isolation.

The first phase of the NGA project (NGA-West1) was initiated in 2003. According to Power et al. (2008), the objective of the NGA-West1 project was to develop new average horizontal GMPEs for shallow earthquakes in active crustal regions through a comprehensive and highly interactive research program. Five sets of GMPEs were developed by teams working independently but interacting with one another throughout the development process (Abrahamson et al., 2008; Power et al., 2008). The development of the GMPEs was supported by other project components, which included: (1) developing an updated and expanded PEER database of globally recorded ground motions throughout the world, which included supporting information (metadata) on the earthquake source, travel path, site conditions, and record quality (Chiou et al., 2008); (2) conducting supporting research projects to provide constraints on the selected functional forms of the GMPEs; and (3) conducting a program of interactions throughout the development process to provide input and reviews from both the scientific research and engineering user communities. The NGA-West1 GMPEs have been adopted for use in active shallow crustal regions throughout the world. This acceptance is driven to some extent by several studies that have shown, either through model comparisons or statistical analyses, that one or more of these GMPEs provide reasonable predictions, sometimes with minor adjustments, of moderate-to-large magnitude earthquake ground motions for shallow crustal earthquakes in active tectonic regions throughout the world (Campbell, 2015).

Beginning in 2009, a second phase of the NGA project (NGA-West2) was initiated that addressed several key issues in ground-motion seismic hazard analysis that was not addressed in phase 1 (Bozorgnia et al., 2014). All five of the original NGA teams participated in the project (Abrahamson et al., 2014; Boore et al., 2014; Campbell and Bozorgnia, 2014; Chiou and Youngs, 2014; Idriss 2014). This phase of the NGA program included: (1) updating the NGA database to extend the magnitude range to 3.0–7.9 and to include worldwide earthquakes that had occurred from 2003 through 2011 (Ancheta et al., 2014); (2) updating the NGA-West1 average horizontal component GMPEs with recordings from the new database; (3) developing factors to scale the response spectrum to damping values other than 5% (Rezaeian et al., 2014a); (4) quantifying the effects of directivity and directionality for the horizontal component of ground motion (Shahi and Baker, 2014; Spudich et al., 2014); (5) resolving discrepancies between the National Earthquake Hazards Reduction Program (NEHRP) site amplification factors (BSSC, 2009) and NGA-West2 site amplification factors (Stewart and Seyhan, 2014); (6) analysis of epistemic uncertainty associated with the NGA-West2 GMPEs (Al Atik and Youngs, 2014); (7) developing GMPEs for the vertical component of ground motion (PEER, 2013); (8) developing a new engineering definition of an aftershock (Wooddell and Abrahamson, 2014); and (9) developing a new nonlinear site amplification model (Kamai et al, 2014). All five of the NGA-West2 GMPEs were used in the development of the 2014 U.S. national seismic hazard maps (Rezaeian et al., 2014b).

Atkinson and Adams (2013) used a simple and efficient approach to derive a set of GMPEs and their associated epistemic uncertainty to use in the development of seismic hazard maps in Canada. The approach defines a lower, central, and upper GMPE for each type of event that contributes to the hazard, by considering alternative published GMPEs and data that may be used to constrain these models. The proposed GMPEs were used to develop the Canada national seismic hazard maps that are being considered for use in the 2015 edition of the seismic provisions in the National Building Code of Canada (NBCC2015). The 2008 NGA-West1 GMPEs were used to develop the lower, central, and upper GMPEs for shallow crustal events in western Canada, because at the time the 2014 NGA-West2 GMPEs were still under development. Now that the NGA-West2 GMPEs are finalized and published, it is important that they be compared with the GMPEs used in NBCC2015 to see if these models adequately capture epistemic uncertainty. As a first step towards such a validation, we compare our horizontal NGA-West2 GMPE (Campbell and Bozorgnia, 2014) for western North America and other active tectonic regions with the western Canada GMPE of Atkinson and Adams (2013) used in the development of the Canada national seismic hazard maps.

2. Campbell-Bozorgnia NGA-West2 GMPE

We used the extensively expanded PEER NGA-West2 database (Ancheta et al., 2014) to update our NGA-West1 GMPE for the “average” or RotD50 (Boore, 2010) horizontal components of PGA, PGV, and 5%-damped PSA at 21 periods (T) ranging from 0.01 to 10 s. Our NGA-West1 (Campbell and Bozorgnia, 2008) and NGA-West2 (Campbell and Bozorgnia, 2014) GMPEs are referred to as CB08 and CB14 in the remainder of this paper. In the development of CB14, we applied our own set of selection criteria to the PEER database resulting in the use of 15,521 recordings from 322 earthquakes with moment magnitudes ($\mathbf{M}$) ranging from 3.0 to 7.9 and closest distances to the fault rupture plane (rupture distance, R_{RUP}) ranging from 0 to 500 km (Figure 1). We used 7,208 of the near-source (0–80 km) recordings from 282 worldwide earthquakes to develop our base model, which included a geometric attenuation term, and 8,313 far-source (80–500 km) recordings from 276 earthquakes to develop an anelastic attenuation term.

We modified or added several new terms and predictor variables to CB08, including an additional magnitude scaling term to accommodate trends seen in the new small-magnitude data; a new hanging-wall term based on ground-motion simulations; magnitude-dependent style-of-faulting, hypocentral depth, fault rupture dip, and between-event and within-event aleatory variability terms; and regionally dependent linear shallow site, shallow sediment-depth; and anelastic attenuation terms. A comparison of CB08 with CB14 indicates that these GMPEs generally give similar ground motion estimates for $\mathbf{M} > 5.5$ and R_{RUP} <

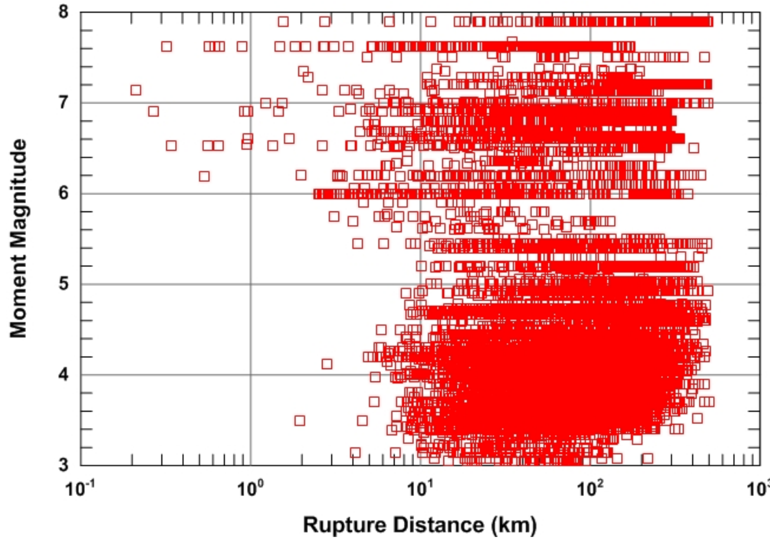

Fig. 1 – Distribution of recordings used in CB14

100 km (Campbell and Bozorgna, 2014). The largest differences are at smaller magnitudes, where the new database allowed us to refine our magnitude- and distance-scaling terms to correct the overestimation observed in CB08. Other significant differences are in the hanging-wall term, where CB14 estimates the highest ground motion near the down-dip edge of the fault rupture plane, and in the style-of-faulting and hypocentral depth terms, where CB14 indicates that strike-slip and reverse faults have statistically similar ground motions.

The natural log RotD50 (average) horizontal component of PGA (g), PGV (cm/s), and PSA (g) is given by the following generalized mixed-effects ground-motion model:

$$\ln Y = f_{mag} + f_{dis} + f_{flt} + f_{hng} + f_{site} + f_{sed} + f_{hyp} + f_{dip} + f_{atn} + \eta_i + \varepsilon_{ij} \quad (1)$$

where Y is the ground-motion intensity measure of interest and the functions (f-terms) model the fixed effects that represent the scaling of ground motion with respect to earthquake magnitude, geometric attenuation, style-of-faulting, hanging-wall geometry, shallow site response, shallow and deep basin response, hypocentral depth, fault dip, and anelastic attenuation, respectively. The random-effects and random-error terms, η_i and ε_{ij}, represent the distributions of the between-event residuals for event i and the within-event residuals for site j of event i, respectively. The between-event and within-event residuals are normally distributed with zero means and standard deviations of τ and ϕ, respectively. The total standard deviation σ is the square-root of the sum-of-squares of τ and ϕ. Because of paper length restrictions, the functional forms of these terms are not presented. Instead, the reader is referred to the detailed documentation of the functional forms given in Campbell and Bozorgnia (2014). CB14 can be used to estimate ground motions for $\mathbf{M}$ = 3.3–7.5 or 8.5 depending on style-of-faulting, R_{RUP} < 300 km, and V_{S30} = 150–1500 m/s, where V_{S30} is the time-average shear-wave velocity in the top 30 m of a site. Companion GMPEs for the vertical component and the vertical-to-horizontal (V/H) ratio are given in Bozorgnia and Campbell, 2015a,b).

3. Atkinson-Adams NBCC2015 GMPE

Atkinson and Adams (2013), hereafter referred to as AA13, used a representative suite of alternative GMPEs and applicable data to guide the selection of a "central" GMPE as well as upper and lower GMPEs that express epistemic uncertainty about this central model. They believe, as proposed in Atkinson et al. (2014), that this approach offers more flexibility in expressing uncertainty in knowledge of the correct median GMPE than a weighted combination of available GMPEs. The representative GMPE approach used in AA13 allows explicit judgments regarding magnitude and distance scaling and the extent to which the selected models satisfy data constraints that are important to the hazard analysis. It also allows control over how both the median GMPEs and their uncertainty behave across regions and event types, ensuring that the epistemic uncertainty is larger in regions with poorer data, for example, regardless of whether alternative published GMPEs are coincidentally similar. The use of a representative suite of models can have significant practical utility, enabling a complex problem to be efficient and transparent by using a minimum number of alternatives for hazard calculations. AA13 admit that there is a large degree of judgment involved in the selection of the central model and its upper and lower branches, and this exerts significant influence on the hazard results. However, such subjective judgments are equally important when using individually weighted GMPEs. AA13 refer to numerous sensitivity tests that are being conducted separately that show the representative three-equation approach that they used produces similar hazard results to the use of multiple GMPEs, provided the same range of epistemic uncertainty is sampled.

AA13 used the following set of principles in the development of a representative suite of GMPEs for western Canada: (1) the median GMPEs should be selected from published (or peer-reviewed) relationships; (2) the GMPEs should be evaluated for a given reference site condition, in this case V_{S30} = 760 m/s representing NEHRP B/C site conditions (BSSC, 2009); (3) the magnitude measure for the GMPEs should be defined as moment magnitude ($\mathbf{M}$); (4) the distance metric for the GMPE should be a finite-fault distance measure, in this case R_{RUP} and the closest distance to the surface projection of the fault rupture plane R_{JB}, or Joyner-Boore distance; (5) epistemic uncertainty in median GMPEs should be modeled by use of alternative relationships; (6) a set of three alternative GMPEs should be used to describe the epistemic uncertainty (a lower, central, and upper branch), with each of the three branches representing an alternative estimate of the median ground motion; (7) the relative performance of the models, and a check on whether they fairly represent epistemic uncertainty, should be assessed by comparing the proposed GMPEs to each other and to available ground-motion data; (8) an initial estimate of epistemic uncertainty should be assessed for each region, then revisited to ensure the epistemic uncertainty across regions is logically consistent and is in agreement with key relevant datasets; and (9) the aleatory variability about the median GMPE, often referred to as sigma, should be treated as a separate model from the median GMPEs and their epistemic uncertainty.

AA13 defined a three-equation suite of GMPEs that is based loosely on the NGA-West1 equations. For application, these equations are presented in the form of tables. They used the GMPE of Boore and Atkinson (2008), as modified to better represent ground motions for moderate-magnitude earthquakes (Atkinson and Boore, 2011), for an unspecified style-of-faulting as the central GMPE, because (in their words) "*these are the simplest, and do not require specification of unknown variables*." This GMPE is referred to as BA08'. They used the other NGA-West1 GMPEs to estimate the epistemic uncertainty bounds on the central model. Figure 2 provides an example of the guidance used to select lower and upper alternatives about the central GMPE to reflect epistemic uncertainty. The NGA-West1 data shown on this figure are adjusted to NEHRP B/C site conditions using the site term in Boore and Atkinson (2008). In this plot, the colored symbols represent the data for events in the range $\mathbf{M}$ = 6.25–6.75, with error bars representing the one-sigma bounds plotted at the middle of the magnitude bin, and the colored lines represent the predictions for $\mathbf{M}$ = 6.5 from BA08' [B&A], Abrahamson and Silva (2008) [A&S], Campbell and Bozorgnia (2008) [C&B], and Chiou and Youngs (2008) [C&Y]. A series of such plots was made to examine the magnitude-distance range that is most important for hazard applications in western Canada. AA13 made a subjective judgment from Figure 2 (and similar figures) that the epistemic uncertainty in the median estimate of ground motion can be reasonably modeled by adding and subtracting 0.1 to 0.15 common log units (i.e., multiplying and dividing by factors of 1.25 to 1.40) from the BA08' GMPE, to give upper and lower alternative median models, respectively. AA13 found that this model encompasses the NGA-West1 GMPEs and most of the data constraints fairly well.

AA13 note that their approach does not imply a preference for the BA08' GMPE and that all of the NGA-West1 models have the same degree of validity. Rather, they note that it is convenient to use BA08', the simplest of the models, as the representative GMPE and use factors about this GMPE to bracket the family of NGA-West1 GMPEs. Looking carefully at GMPE plots for the $\mathbf{M}$ = 6.5–7.5 earthquakes that dominate seismic hazard in western Canada from shallow crustal earthquakes, AA13 found that uncertainty in the central GMPE, considering the alternative GMPEs and the data that constrain them, is of the order of 0.15 common log units (a factor of 1.4). This also takes into account the fact that GMPEs based on global data are being imported to western Canada. AA13 also found that the uncertainty should increase with distance, based on the spread in the NGA-West1 GMPEs, which is also appropriate given that these models combined data from different regions with somewhat different attenuation rates. Based

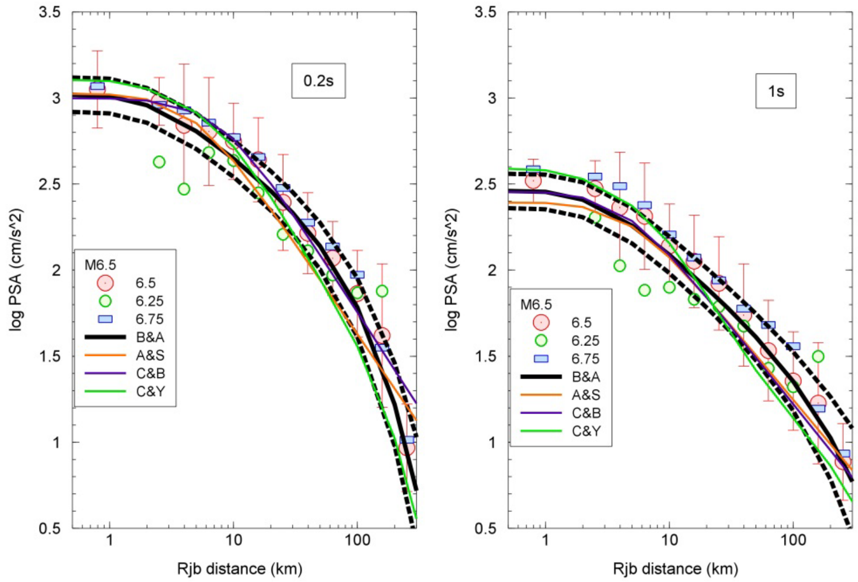

Fig. 2 – Lower, central, and upper GMPEs for an $\mathbf{M}$ = 6.5 crustal event in western Canada proposed by AA13 (after Atkinson and Adams, 2013). Lines and symbols are explained in the text.

on this evaluation, AA13 recommended the following common log factor (delta) to add and subtract from BA08' to model epistemic uncertainty by use of lower and upper alternative GMPEs:

$$\Delta \log Y = \min(0.10 + 0.0007 R_{JB}, 0.3) \tag{2}$$

This "delta" is capped at 0.3 to prevent unreasonably large values at R_{JB} > 280 km. The total uncertainty from the lower to upper limits of the GMPE is about a factor of 2. AA13 recommended weights for the lower, central, and upper alternative GMPEs of 0.25, 0.5 and 0.25, respectively.

4. Comparison of Median Models

The representative median GMPE of BA08' adopted by AA13 uses R_{JB} (Joyner-Boore distance) as the finite-fault distance metric; whereas, CB14 uses R_{RUP}. In order to avoid complicated conversions between these two distance metrics, comparisons between the median GMPEs of AA13 and CB14 are made for an earthquake on a vertical (90°-dipping) strike-slip fault. In this case, differences in these metrics can be taken into account with the simple equation:

$$R_{RUP} = \sqrt{R_{JB}^2 + Z_{TOR}^2}$$

where Z_{TOR} is the depth to the top of the fault rupture plane. All comparisons are made for NEHRP B/C site conditions (V_{S30} = 760 m/s), which is the reference site condition used by AA13. Since the GMPE recommended by AA13 does not include any source, path, or site parameters other than $\mathbf{M}$ and R_{JB}, CB14 is evaluated for default values of Z_{TOR}, Z_{HYP} (hypocentral depth), and $Z_{2.5}$ (depth to the 2.5 km/s shear-wave velocity horizon beneath the site) from equations recommended in Campbell and Bozorgnia (2014). There was no attempt to select values for these parameters that would make the comparisons either better or worse than found by using the default values. Because a vertical fault is assumed, hanging-wall effects are not included. There are a few discrepancies in the comparison that we mention, but do not consider to be important. The first is the use of a strike-slip style-of-faulting to evaluate CB14 when BA08' was evaluated for an unknown style-of-faulting. The second is the use of RotD50 (Boore, 2010) to define the average horizontal component in CB14 when BA08' uses GMRotI50 (Boore et al., 2006) to define this component. These differences amount to only a few percent and are negligible compared to the degree of epistemic uncertainty.

4.1. Attenuation

Figure 3 compares the distance scaling (attenuation) of AA13 and CB14 for two periods (T = 0.2 and 1.0 s) and two magnitudes ($\mathbf{M}$ = 5.0 and 7.0). The dashed lines in these plots are the lower and upper AA13 representative GMPEs. Although CB14 exhibits somewhat stronger attenuation, especially for the larger magnitude, the model falls within the lower and upper bounds of AA13 except for R_{JB} < 7 km for the smaller magnitude. This latter discrepancy is due to differences in the pseudo-depth term, but is not important for probabilistic seismic hazard analysis (PSHA), because of the small magnitudes and short distances where this discrepancy occurs.

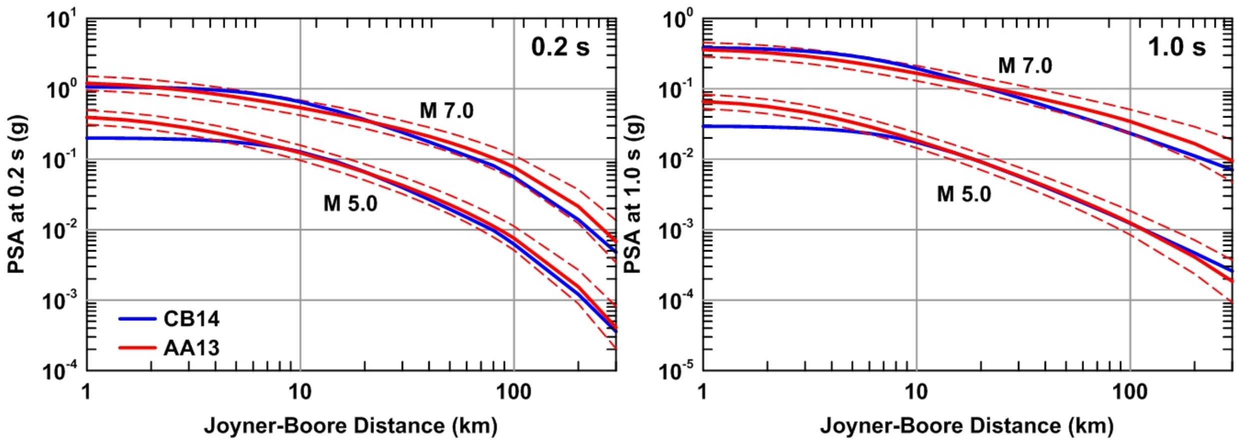

Fig. 3 – Comparison of attenuation between AA13 and CB14

4.2. Magnitude Scaling

Figure 4 compares the magnitude scaling of AA13 and CB14 for two periods (T = 0.2 and 1.0 s) and two distances (R_{JB} = 10 and 50 km). The dashed lines in these plots are the lower and upper AA13 representative GMPEs. Although CB14 exhibits somewhat stronger magnitude scaling at the smaller magnitudes, the predictions fall within the lower and upper bounds of AA13 except for $\mathbf{M}$ < 4.8 and short distances. This latter discrepancy is potentially due to differences in the distance metrics at small magnitudes, where the default value of Z_{TOR} is around 7 km. However, this discrepancy is not important for PSHA, because of the small magnitudes and short distances where it occurs.

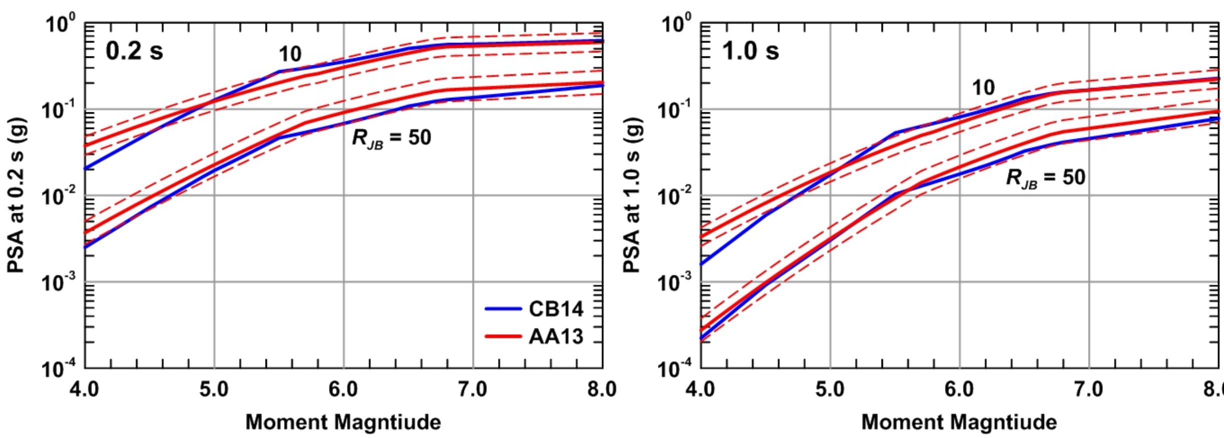

Fig. 4 – Comparison of magnitude scaling between AA13 and CB14

4.3. Response Spectra

Figure 5 compares the predicted response spectra of AA13 and CB14 for two magnitudes ($\mathbf{M}$ = 5.0 and 7.0) and two distances (R_{JB} = 10 and 50 km). The dashed lines in these plots are the lower and upper AA13 representative GMPEs. Generally speaking, the predicted response spectra of CB14 fall within the lower and upper bounds of AA13 over a relatively large range of magnitudes and distances. Although

CB14 exhibits similar spectral amplitudes and shapes at small magnitudes, it has a very different shape at large magnitudes, short distances, and short periods, where it manifests itself as a spectral peak at about T = 0.15 s, similar to that found at small magnitudes, and significantly higher amplitudes below this period. This behavior is different from the other NGA-West2 GMPEs (Gregor et al., 2014). This shape discrepancy is potentially due to a smaller implied value of the site attenuation parameter κ_0 for the NHERP B/C firm-rock site condition being evaluated, which becomes negligible for softer site conditions (Campbell and Bozorgnia, 2014; Gregor et al., 2014). This discrepancy is only important for PSHA at T < 0.2 s (short-period structures) in a high-seismicity region where large magnitudes dominate the hazard.

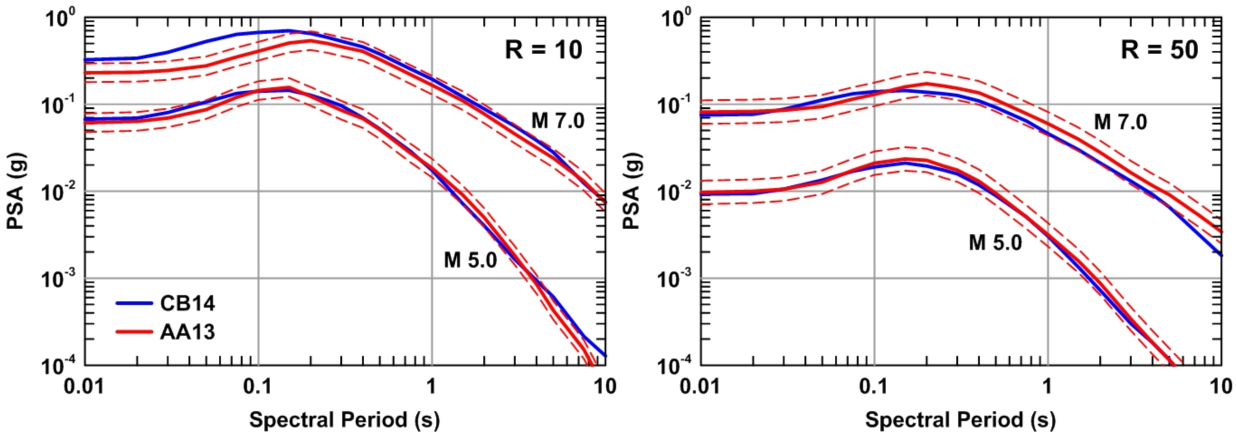

Fig. 5 – Comparison of magnitude scaling between AA13 and CB14

5. Comparison of Aleatory Variability Models

The value of the aleatory standard deviation (sigma) can have a significant impact on the results of a PSHA (Bommer and Abrahamson, 2006). Traditionally, the sigma that is used in PSHA has been based on observed variability of the data about the median GMPE derived from a regression analysis. AA13 suggest that this may not be the appropriate way to define sigma, because what is really needed is the random variability of future events and not the total variability from a regression, which includes factors such as model misfit, variable soil conditions, data errors, among others. These factors all contribute to regression errors, but may not represent natural variability. There is also a potential for double-counting of aleatory variability when epistemic uncertainty in the median equations is included in the PSHA. Atkinson (2011) shows that the actual within-event sigma (ϕ) in ground-motion amplitudes for well-recorded earthquakes is about 0.22 common log units at long periods (T > 1 s), decreasing to about 0.20 units at short periods ($T \leq$ 0.25 s). This implicitly includes variability in site response for a given value of V_{S30}. According to AA13, the NGA-West1 GMPEs indicate that typical values of between-event sigma (τ) decrease from about 0.16 common log units at long periods (T > 1 s) to 0.12 units at short periods ($T \leq$ 0.25 s) and include both intra-regional as well as inter-regional variability (at least for the larger-magnitude global events) in source characteristics.

Based on the values of sigma presented above, AA13 suggested that representative values for the total sigma (σ) that includes both inter-site and inter-regional variability would be about 0.27 common log units (0.62 natural log units) at long periods (T > 1 s), decreasing to 0.23 common log units (0.53 natural log units) at short periods ($T \leq$ 0.25 s). These proposed sigma values are smaller by 8–10% than the corresponding range determined by Boore and Atkinson (2008). AA13 conclude that this is in accord with their view that the assigned aleatory variability should be somewhat less than indicated by regression statistics in order to avoid double-counting of aleatory and epistemic uncertainty.

Figure 6 compares the sigma values recommended by AA13 with those derived by CB14 from mixed-effects regression analysis. Values are shown for $\mathbf{M} \leq$ 4.5 (left panels) and $\mathbf{M} \geq$ 5.5 (right panels) to reflect the magnitude-dependence of the CB14 sigma values, which are constant, but different, for these two magnitude ranges. CB14 recommends using a linear transition between these two magnitude ranges. Magnitude-dependent values of sigma are also supported by three of the other four NGA-West2 GMPEs that incorporated small-magnitude data in their development. The magnitude-independent sigma values in AA13 are substantially smaller than those in CB14 for $\mathbf{M} \leq 4.5$. The agreement is better for $\mathbf{M} \geq 5.5$, although the AA13 values of σ are smaller by more than 10% at some periods. We also note that the AA13 values of ϕ are very similar to the single-site values reported by Rodriguez-Marek et al. (2013), which suggests that they might be somewhat low.

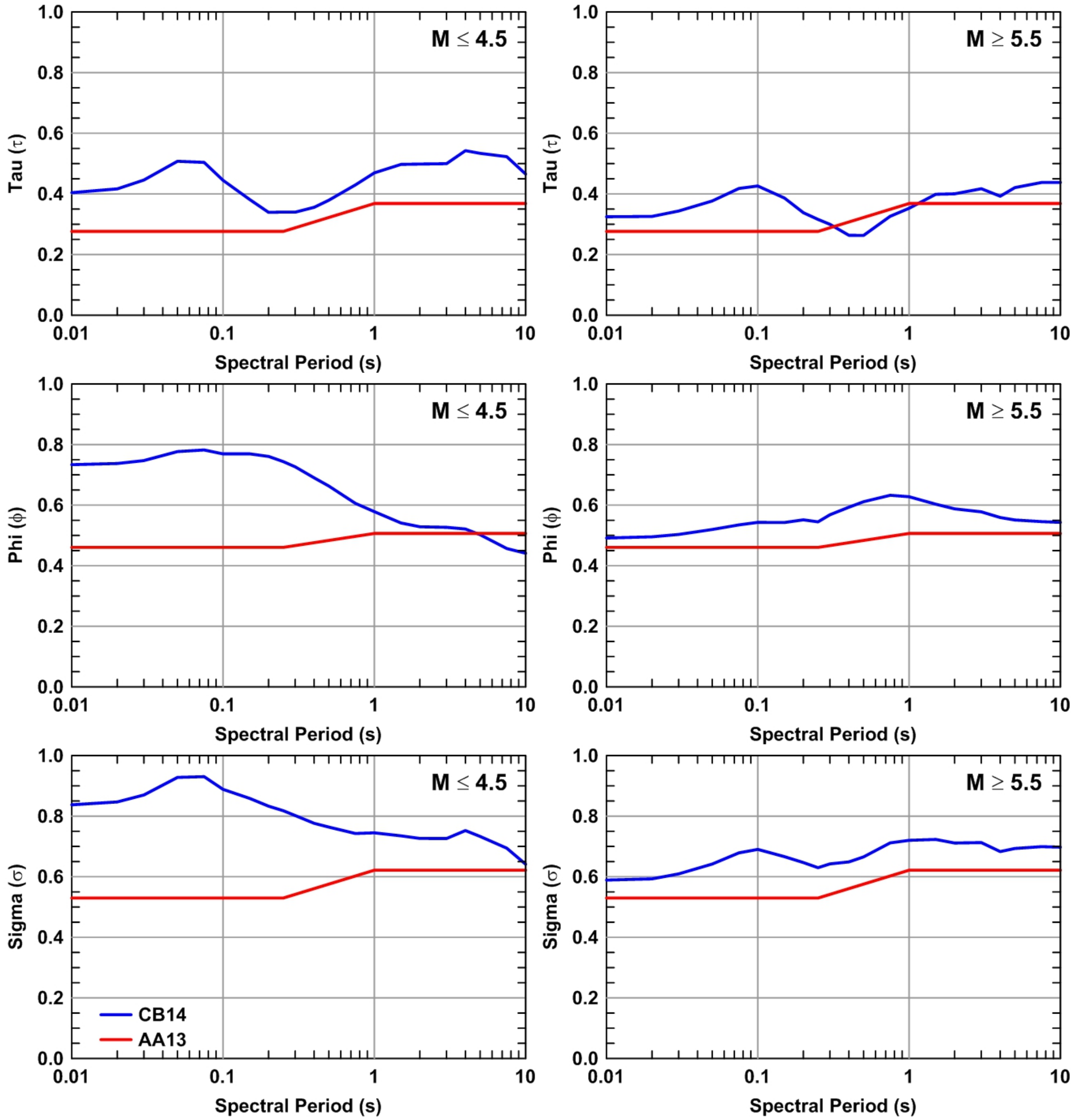

Fig. 6 – Comparison of between-event (tau, τ), within-event (phi, ϕ), and total (sigma, σ) aleatory variability between AA13 and CB14

6. Conclusions

In general, the AA13 GMPEs proposed for use in the new Canada building code (NBCC2015) are consistent with the CB14 NGA-West2 GMPEs. A notable exception is at large magnitudes and short periods, where CB14 is higher. The AA13 aleatory variability is lower than CB14 by a larger amount than originally validated against BA08', which would imply relatively lower hazard. Of course, these comparisons are for only one of the NGA-West2 GMPEs. A more formal validation should be done with all of the GMPEs before any definitive conclusions are made.

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