Ground Motion Prediction Equations for Application to the 2015 Canadian National Seismic Hazard Maps

Can. J. Civ. Eng. Revised April 2013

Gail M. Atkinson[1] and John Adams[2]
(1. Western University, London, gmatkinson@aol.com;
2. Geological Survey of Canada, jadams@nrcan.gc.ca)

Abstract

Ground-motion prediction equations (GMPEs) and their epistemic uncertainty are a key input to seismic hazard assessments, because the GMPEs specify the expected ground-shaking amplitudes as a function of magnitude and distance. We describe a simple and efficient approach to the definition of GMPEs and their epistemic uncertainty for use in seismic hazard mapping in Canada. The approach defines a lower, central, and upper GMPE for each type of event (eastern crustal, western crustal, interface, inslab, offshore) that contributes to the hazard, by considering alternative published GMPEs and data that may be used to constrain these model choices. The proposed model is being applied in trial seismic hazard maps for Canada, for consideration in the 2015 edition of the National Building Code of Canada (NBCC2015).

Introduction

This paper summarizes a model for specifying ground-motion prediction equations (GMPEs) and their epistemic uncertainty, as proposed for use in new national seismic hazard maps of Canada currently under development by the Geological Survey of Canada (Adams, 2011). The GMPEs, giving median ground motion amplitudes as a function of magnitude and distance, are a key component of the seismic hazard maps in terms of their impact on results. Thus the choice of the GMPEs for input to the seismic hazard mapping program is very important. Equally important is the range of alternative models used to capture epistemic uncertainty in the median predicted ground motions for a given magnitude and distance, expressing a subjective evaluation of the limitations of our current knowledge. This range has important implications for the calculated ground-motion values which are intended for use in

NBCC2015. The method used here may be generally applicable for national seismic hazard maps (where a large number of possible GMPEs need to be represented by a few alternatives to reduce computational time) or for site-specific-seismic hazard analyses where simple weighted combinations of available GMPEs are judged to be inadequate to capture the epistemic uncertainty.

The recommendations contained herein were prepared for use in new national seismic hazard maps, being developed at the Geological Survey of Canada, based on ongoing discussions within the seismic hazard working group of the Canadian Standing Committee on Earthquake Design (members of this development group are listed in the Acknowledgements). Further documentation, including many exploratory plots and additional details, can be found in Atkinson (2012).

This study was motivated by the need to update the GMPEs used in the last national seismic hazard maps (see Adams and Halchuk, 2003; these GMPEs included Boore et al., 1997, Youngs et al., 1997 and Atkinson and Boore, 1995) to reflect the last 15 years of developments in the ground-motion field. During this time period, the databases on which GMPEs are based have grown many-fold, and thus the changes in knowledge have been significant.

We overview the GMPEs proposed for use in eastern Canada (crustal events), for crustal earthquakes in western Canada, for earthquakes offshore of western Canada, and for the two types of subduction zone earthquakes in southwestern British Columbia (B.C.) , those within the subducted slab (inslab) and those great earthquakes on the plate interface. The median GMPEs and alternatives to them are discussed separately from the issue of the appropriate 'sigma' (standard deviation about the median), which follows the discussion of the median equations. It is noted that the proposed model will be implemented for trial hazard map calculations, and the sensitivity of those calculations to alternative approaches to modeling GMPEs and their epistemic uncertainty will also be investigated; those investigations will be reported in a separate study.

As a prelude to the principles below, we note that epistemic uncertainty in median GMPEs has often been modeled by the use of alternative equations (typically those derived by various authors), with model weights being used to represent the relative confidence in each alternative. However, this is not necessarily the best way to model epistemic uncertainty in GMPEs (see Bommer and Scherbaum, 2008;

Atkinson, 2011). To the extent feasible, we prefer to use the alternative GMPEs and applicable data to guide the choice of a representative or "central" GMPE, and to define representative (upper and lower) GMPEs that express uncertainty about the central GMPE. We believe this approach offers more flexibility in expressing uncertainty in knowledge of the correct median GMPE than any weighted combination of the available GMPEs. We note that a similar approach was used for eastern ground motions in NBCC2005 and 2010 (Atkinson, 1995) while a simplified approach following the same general philosophy was used for the western crustal ground motions (see Adams and Halchuk, 2003).

The use of representative GMPEs rather than a weighted combination of alternative GMPEs is undoubtedly the most controversial aspect of the GMPE models we propose herein. This has been a hotly-debated topic at recent workshops and conferences (e.g. 2012 U.S. Geological Survey workshops on the 2014 hazard maps in the U.S., and 2012 workshops on specific industry projects), and there is no clear consensus. Different approaches have different advantages and disadvantages. Proponents of the alternative GMPE approach argue that use of multiple models with alternative functional forms is required in order to properly capture uncertainties in form as well as amplitudes, whereas the use of the representative GMPE approach involves arbitrary judgments concerning the best central model and its uncertainty. On the other hand, the representative equation approach employed here allows explicit judgments to be exercised regarding magnitude and distance scaling and the extent to which the selected models will satisfy data constraints that are important to the project; moreover, it allows control over how both the median GMPEs and their uncertainty will behave across regions and event types. Thus we can ensure that the epistemic uncertainty is larger in regions with poorer data, for example, regardless of whether alternative published GMPEs coincidentally happen to be similar. Furthermore, the representative GMPE approach has flexibility to accommodate important points that cannot be properly handled with the weighted-alternative GMPE approach. For example, many GMPEs are appropriate for some but not all of the magnitude-distance ranges needed, and are therefore not reasonable for general application (e.g. only two of four recent crustal GMPEs from the PEER-NGA suite are suitable for small-to-moderate magnitudes, and at regional distances needed for hazard calculations in western Canada). Finally, the representative equation approach has significant practical utility, enabling a complex problem to be represented by a minimum number of branches for hazard calculations, which is efficient and transparent. Admittedly, there is a large degree of judgment exercised regarding 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 the alternative-GMPE approach, as the selection and weighting of alternative models is also a process based on subjective judgment. Ultimately, it is important to document the rationale for the approach taken, which is provided herein. Furthermore, we note we have performed numerous sensitivity tests to show that the GMPE approach we have taken produces similar results to the weighted-alternative GMPE approach, if the utilized information on available GMPE choices is treated consistently; it is the GMPE models and weights that are important, not the mechanics of how they are treated. These sensitivity tests are described in Atkinson (2012, Appendix B).

The underlying principles for the GMPEs that are proposed herein are as follows:

1. Median GMPEs should be selected from published (or peer-reviewed) equations.
2. The GMPEs will be given for a reference site condition (V_{s30}=760 m/s, where V_{s30} is the time-averaged shear-wave velocity in the top 30 m). Models not available for B/C will be converted to an equivalent model for B/C.
3. The magnitude measure for the GMPEs is moment magnitude (**M**), and the GMPEs will be used with a revised Canadian earthquake catalog where various local magnitude values have all been converted to estimated **M**.
4. A variety of distance metrics may be used in the GMPEs. Point-source metrics may include R_{epi} (epicentral distance) and R_{hypo} (hypocentral distance). Corresponding fault-distance metrics are R_{jb} (Joyner-Boore distance, based on distance to surface projection of rupture plane), and R_{cd} (closest distance to fault rupture surface), respectively. Fault-distance metrics may be converted to an equivalent point-source metric in the hazard software when needed (the need is software dependent); examples of such conversions are provided by Atkinson and Goda (2011) and Atkinson (2012).
5. Epistemic uncertainty in median GMPEs will be modeled by the use of alternative equations, as discussed above.
6. It is proposed for logistical convenience that a set of three alternative-weighted GMPEs will be used to describe the epistemic uncertainty; this includes a "lower", "central" and "upper" GMPE, where each of the three is an alternative estimate of the median ground-motion amplitudes. Each alternative is given a specified weight for use in the hazard calculation (within logic tree enumeration or Monte Carlo simulation software).

7. The relative performance of the models, and a check on whether they fairly represent epistemic uncertainty, may be assessed by comparing the proposed GMPEs to each other, and to available ground-motion data adjusted to the B/C site condition, as appropriate.
8. We make an initial estimate of epistemic uncertainty for each GMPE type or region, then revisit the epistemic uncertainty across regions to ensure overall logical consistency, as well as agreement with key relevant datasets.
9. The random (or aleatory) variability about the median GMPE, often referred to as sigma, is treated as a separate issue from the specification of the median GMPEs and their epistemic uncertainty. Note that the discussion of aleatory uncertainty ("sigma") follows the discussion of the epistemic uncertainty.

Western crustal GMPEs

A common assumption made for crustal earthquakes in B.C. is that their ground motions will be well represented by GMPEs for other active tectonic regions, such as California. Atkinson (2005) looked at this issue and concluded that, overall, observations of B.C. crustal earthquakes might be modeled (with some conservatism) using typical WNA crustal equations, if differences in predominant site conditions of the seismographs are accounted for – in particular the fact that much of B.C. has been glaciated while California has not. Our use of B/C as a reference site condition, however, means no conversion of GMPEs already defined in B/C will be required.

The suite of GMPEs currently favoured for crustal events in active tectonic regimes is the PEER-NGA equations (Power et al., 2008 and the references therein), due to its extensive and high-quality database (especially at the near-source distances important to hazard) from diverse active regions worldwide. (Note: the PEER-NGA equations are being updated in 2012-2013, but the new equations are not yet available.) A few challenges arise in using the PEER-NGA equations, some logistical and some scientific:

(1) many of them involve a level of detail in the parameter specifications that goes beyond what is available/reasonable for western Canada, leaving many parameters to be defined by default "guesses";

(2) it is known that these GMPEs tend to over-estimate motions from events of **M**<5.75 (Atkinson and Morrison, 2009; Chiou et al., 2010; Bommer et al. 2007; Cotton et al., 2008; Atkinson and Boore, 2011), but only two of the equations (BA08 and Chiou and Youngs) have published corrections for this effect (Chiou et al., 2010; Atkinson and Boore, 2011) – which can be important in low-to-moderate seismicity regions of B.C.;

(3) The GMPEs agree "too closely" with each other, and thus probably don't actually convey the true epistemic uncertainty in median values (Abrahamson et al., 2008; Atkinson, 2011).

To overcome these challenges, we define a three-equation suite that is based loosely on the PEER-NGA equations. We use the modified (for moderate-magnitude) BA08' equations (Atkinson and Boore, 2011) for "unspecified" fault mechanism as the central GMPE, as these are the simplest, and do not require specification of unknown variables. We use the other PEER-NGA equations to estimate the uncertainty bounds on these central equations. Figure 1 provides an example of the guidance for lower and upper alternatives to be defined about the central equation to reflect epistemic uncertainty; in this plot, the alternative equations of Boore and Atkinson, Abrahamson and Silva, Campbell and Bozorgnia, and Chiou and Youngs are plotted for PSA at several periods, for **M**=6.5, all for B/C conditions. To put the equations in an empirical perspective, the PEER-NGA data (also converted to B/C conditions, as per Boore and Atkinson, 2008) are plotted in magnitude bins 0.5 units in width, and in distance bins 0.4 log units in width. For the central magnitude value (e.g. 6.5), the mean and standard deviation of the log amplitudes within the bin is plotted. For magnitude bins 0.25 units less or greater than the central value, the means are plotted (without standard deviations, to avoid clutter); the magnitude bins have a 50% overlap. A series of such plots was made to examine the magnitude-distance range that is most important for hazard applications in western Canada. As noted in Abrahamson et al. (2008), the PEER-NGA equations are all fairly similar, and all are reasonably (though not perfectly) constrained by the data. A subjective judgment from Figure 1 (and similar figures) is that the epistemic uncertainty in median equations can be reasonably modeled by adding and subtracting 0.1 to 0.15 units log(10) (25% to 40%) from the BA08' equations, to give lower and upper alternative equations, respectively. This would encompass the PEER-NGA equations and most of the data constraints fairly well.

It should be noted that use of this approach does not imply a preference for the BA08' equations – all of the PEER-NGA equations have the same degree of validity. Rather, it is a convenience of application that the PEER-NGA results may be encapsulated by taking BA08', the simplest of the models, as representative, and using factors about it to bracket the family of GMPEs.

Looking carefully at GMPE plots for western crustal events (such as those shown in Atkinson (2012)) in both log and linear scale, for the **M**=6.5 to 7.5 earthquakes that dominate seismic hazard in western Canada, it appears that uncertainty in the central GMPE, considering the alternative GMPEs and the data that constrain them, is of the order of 0.15 log units (factor of 1.4). This also takes some account of the fact that we are importing a global GMPE to western Canada. Furthermore, it appears that the uncertainty should grow with distance, based on the spread in the PEER-NGA equations; this is also appropriate given that the NGA equations combined data from different regions, having somewhat different attenuation rates. The following log factor (delta) is recommended to add/subtract from BA08' to express epistemic uncertainty through lower and upper alternative relations (this is the uncertainty plotted in Figure 1).

delta (crustal) = min (0.10+0.0007 R_{jb}, 0.3) (log10 units)

Delta is "capped" at 0.3 log units (distance ~280 km, at the edge of the plot) to prevent unreasonably large values at greater distances. Note that the resulting total uncertainty from the lower to upper GMPE is about a factor of 2 for the western crustal events. The factor of 2 should be considered a minimum uncertainty for other event types, because the western crustal GMPEs are the most-widely studied, and best-constrained by data. Recommended weights for the lower, central and upper alternatives for the western crustal events are 0.25, 0.5 and 0.25, respectively.

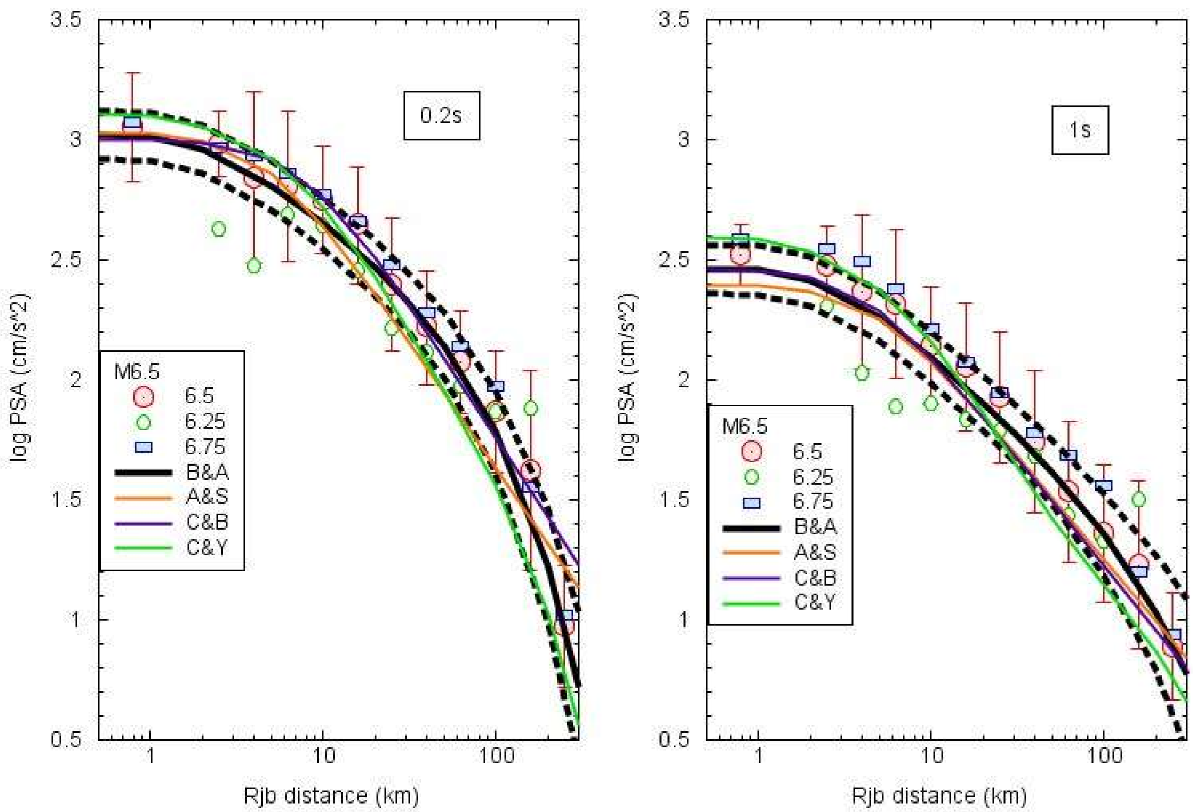

Figure 1 – Proposed lower, central and upper GMPEs, for ***M****6.5 crustal events in western Canada. Solid black line is central equation (BA08'); dashed black lines are lower and upper equations, obtained by adding and subtracting delta from the central equation. Solid lines show other PEER-NGA equations. Symbols show means of the log amplitudes for various 0.5 unit magnitude bins; error bars show standard deviation for the M6.5 magnitude bin.*

Offshore crustal events

Atkinson (2005) examined differences in ground motion source and attenuation properties for different classes of events in B.C., and found that, relative to B.C. crustal onshore events: (i) those along the west coast of Vancouver Island (just offshore) showed similar apparent source properties but steeper attenuation; and (ii) the events far off-shore in oceanic crust have much lower apparent source amplitudes, but a similar apparent attenuation. As the offshore events are not major hazard sources, we can treat these characteristics in the following approximate manner for seismic hazard analysis.

For the events along the west coast of Vancouver Island – within 50 km of land – we use the crustal GMPEs. The use of crustal GMPEs will be conservative, as the actual attenuation for these events may be somewhat steeper. For offshore events (>50 km offshore), we follow the recommendation of Atkinson (2005) that the motions be approximated by using crustal GMPEs (and their associated weights), but with a reduction of 0.5 moment magnitude units. Thus if the actual moment magnitude of an offshore event is 7.0, we predict its ground motions using **M**=6.5. This is consistent with the observation (Ristau et al., 2003, 2005) that moment magnitudes are larger than the commonly-used Local magnitude (ML) of the catalogue. Specifically, Ristau et al. report that **M** = ML + 0.7 for offshore events; we do not expect an exact equivalence between the **M**-ML discrepancy and the size of the adjustment needed to **M**, because log PSA does not scale with magnitude in a 1:1 manner.

Western subduction inslab GMPEs

Figure 2 compares several proposed GMPEs for subduction-zone inslab events of **M**=7, including the Atkinson and Boore (2003) (AB03) GMPE for inslab events (average of rock and C values are plotted to represent B/C conditions; Cascadia factor used), the Zhao et al. (2006) inslab GMPEs for Japan (site class SC I, which is similar to B/C), the Goda and Atkinson (2009) GMPEs for deep events (>30 km) in Japan, and the median inslab GMPE as developed by Abrahamson et al. (2013) (also referred to as the "BC Hydro GMPE model"). The classic Youngs et al. (1997) GMPEs (used in the 2005 and 2010 hazard maps) are also shown for reference. Note that the attenuation rate given by the Y97 relations is relatively gentle, as it was pegged to match that for interface events (due to lack of inslab data at the time the equations were developed). There appear to be large discrepancies between the alternative equations, but this is at least partly due to very different site conditions amongst the datasets employed, even for the same value of V_{s30}, as discussed in the next section.

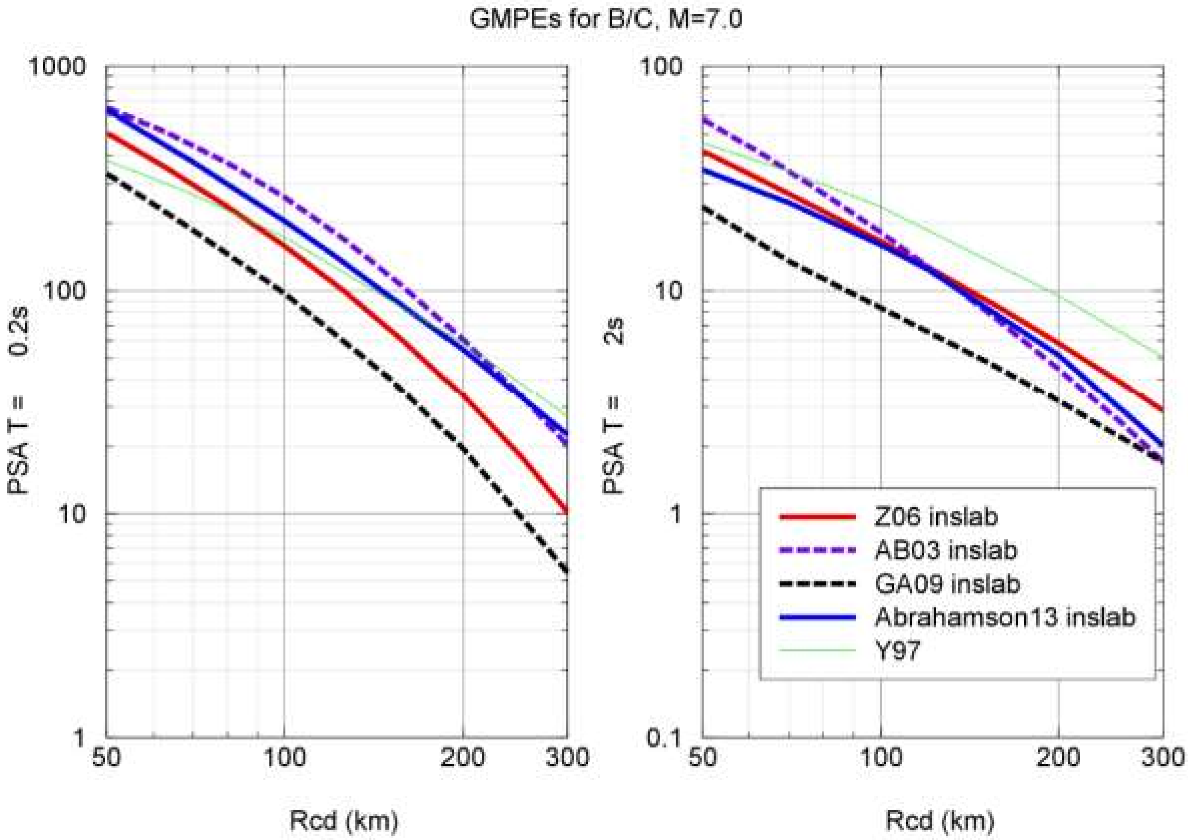

*Figure 2: Comparison of alternative inslab GMPEs for **M**7 on B/C site: AB03 (Cascadia), Z06 (Japan), GA09 (Japan) and Abrahamson et al., 2013 (global). Y97(inslab) shown for reference. GMPEs are given in cm/s^2.*

Modifications of GMPEs for inslab (and interface) to account for Cascadia site conditions

Most of the recent global GMPEs for inslab and interface events are dominated by Japanese data, because Japanese data are the most plentiful. It is known that shallow site conditions in Japan result in amplification of short-period motions relative to long-period motions that is not captured by the use of V_{s30} or site class. Specifically, a NEHRP C site (V_{s30} ~550 m/s) in Japan is typically a soft shallow soil site (<20 m in depth) overlying much harder rock; this is markedly different from the more gradational profiles typical of Californian recording sites. Detailed analyses of the 2011 **M**9 Tohoku ground motions (Ghofrani et al., 2013) have shown that site amplifications in Japan for such sites are commonly a factor of 5 or more at periods of 0.1-0.2 seconds. By contrast, site conditions in the much of the

Cascadia region are quite different (deeper soils), with more amplification at longer periods, but less at short periods. It is reasonable and prudent to adjust the GMPEs based on Japanese data to account for this factor.

A simple and transparent adjustment can be made based on the study by Atkinson and Casey (2003), which compared motions from two **M**6.8 inslab earthquakes, the Nisqually, Washington and Geiyo, Japan events, and showed that there is a period-dependent difference between the two that can be attributed to different typical site conditions, within the same site class. An important point to recall from the Atkinson and Casey study is that they also showed that the attenuation rates for inslab events are similar for Japan and Cascadia – thus the Japan-based GMPEs are appropriate for southwestern B.C. if suitable adjustments for site effects are made.

Atkinson and Casey showed that the discrepancies between the Geiyo and Nisqually motions disappear if we remove the expected regional site effects, computed from quarter-wavelength calculations for generic regional profiles for a given site class for the Nisqually event (factors in Table 2 of their paper). Thus to "convert" a Japan GMPE for Class C to an appropriate equivalent for Cascadia Class C, we multiply the predicted motions by a factor that is the ratio of (Cascadia NEHRP C/Japan NEHRP C).

An alternative approach is to use regional correction factors determined by regression analysis, such as those given by Atkinson and Boore (2003). Their Table 3 shows regional factors for Japan and Cascadia, which can be used to compute the ratio Cascadia/Japan, analogous to that computed by Atkinson and Casey. The difference is that the Atkinson and Boore factors were based on empirical data results (for Cascadia and Japan relative to the global average GMPEs), rather than computations for idealized soil profiles. Table 1 compares the factors suggested for the ratio Cascadia/Japan by these two alternative approaches; they are in good agreement with each other at most periods. It is proposed to use the average of the two results, shown as "Recommended" in Table 1 (both multiplicative and $\log_{10}$ factors shown). Linear interpolation in log-log space can be used for intermediate periods. The recommended soil correction factor damps motions for T<0.4s and amplifies motions for T>0.4s. Note that: (i) the amplification for PGV is assumed to be the same as that for T=0.4s; and (ii) the amplification factor is assumed to return to unity at very long periods.

Table 1 – Factors to convert Japanese GMPEs to Cascadia GMPEs, for the same value of V_{s30}.

Period (s)	Atkinson&Casey (2003)	Atkinson&Boore (2003)	Recommended Cascadia Multiplicative Factor (log units)
10			1.00 (0.000)
5			1.10 (0.040)
3		1.23	1.20 (0.079)
2	1.47	1.55	1.51 (0.179)
1	1.08	1.00	1.04 (0.017)
0.4	1.16	0.83	1.00 (0.000)
0.3			0.81 (-0.091)
0.2	0.71	0.50	0.60 (-0.222)
0.1	0.53	0.35	0.44 (-0.357)
0.04		0.35	0.44 (-0.357)
PGA		0.45	0.50 (-0.301)
PGV			1.00 (0.000)

The site correction factors of Table 1 should be applied to both inslab and interface GMPEs that are based predominantly on Japanese data, in order to obtain corresponding GMPEs for Cascadia. We determined that when this is done, the inslab GMPEs of AB03, Z06 and GA09 become very similar at short periods (0.1s and PGA) – the adjustment for regional site conditions brings them into close agreement. In the following discussion, we have removed regional site effects in our comparisons of GMPEs and data.

It is unclear whether regional site corrections should be applied to the Abrahamson et al. (2013) GMPEs, as they included a broad mix of regions in their database. They looked at the issue of regionalization by evaluating average event residuals by region, and considered these regional terms in the evaluation of epistemic uncertainty. Overall, they did not report recommendations for region-based adjustments to their global model. However, they noted that the Cascadia region had significantly low average residuals at short periods relative to their global model; this finding is consistent with Table 1. We have plotted the global result of Abrahamson et al. (2013) when showing their GMPE for comparison, because they did not specifically recommend a modification for Cascadia. However, it may be noted that if their average regional event terms for Cascadia were applied, their GMPE would be reduced by about 0.17 log units at short periods (0.2 s to PGA).

We propose to use the Z06 GMPEs as the central GMPE, after adjustment for Cascadia site conditions, with the other equations being used to guide the choice of an epistemic uncertainty band about it. We assign an initial distance-independent uncertainty of 0.15 log units to represent lower and upper equations. This uncertainty is about the same as for Cascadia crustal earthquakes on average, and less than that proposed (below) for interface events. We modify the upper representative equation based on consideration of relevant data, as described in the following.

We evaluate how well the proposed suite represents relevant ground-motion data in Figure 3. The included data for the Cascadia region data are from the 2001 **M**6.8 Nisqually earthquake (inslab event, depth=50km). These data, taken from Atkinson and Boore (2003), are adjusted to B/C site conditions, using the conversions of Boore and Atkinson (2008) with an assumed Vs30 of 450 m/s for C and 250 m/s for D. We supplement the Cascadia data by considering also data from the **M**6.8 Geiyo event in Japan (also an inslab event at depth=50km), with the amplitudes adjusted to B/C conditions using the factors in Table 1. Figure 3 shows the lower, central and upper GMPE equations proposed for inslab events of **M**6.8 on B/C (at a focal depth of 50 km) in comparison to relevant data, and also to the proposed central GMPE of Abrahamson et al. (2013). The upper equation of our proposed suite was increased by a factor of 1.5 at periods ≤0.2s (including PGA), because we noted that the data at short periods tended to be larger than those predicted by our initial proposed suite. (Note: the proposed multiplicative factor on the upper curve tapers from 1.5 to 1.0 as the period increases from 0.2s to 1s.) The revised upper GMPE curve (after increase by the factor of 1.5) is in reasonable agreement with Abrahamson et al. (2013). At intermediate periods (1 s) our central GMPE is very similar to that of Abrahamson et al. (2013). At long periods our central GMPE is larger than that of Abrahamson et al. (2013), but in reasonable agreement with the relevant data. In view of the data comparison in Figure 3, the proposed weights for the lower, central and upper GMPE branches are 0.25, 0.5, 0.25 for periods≥1s, respectively. For periods≤0.2s (including PGA), the corresponding weights are 0.2, 0.4, 0.4, with a transition of weights taking place between 1 and 0.2s (e.g. for 0.5s use 0.25, 0.4, 0.35).

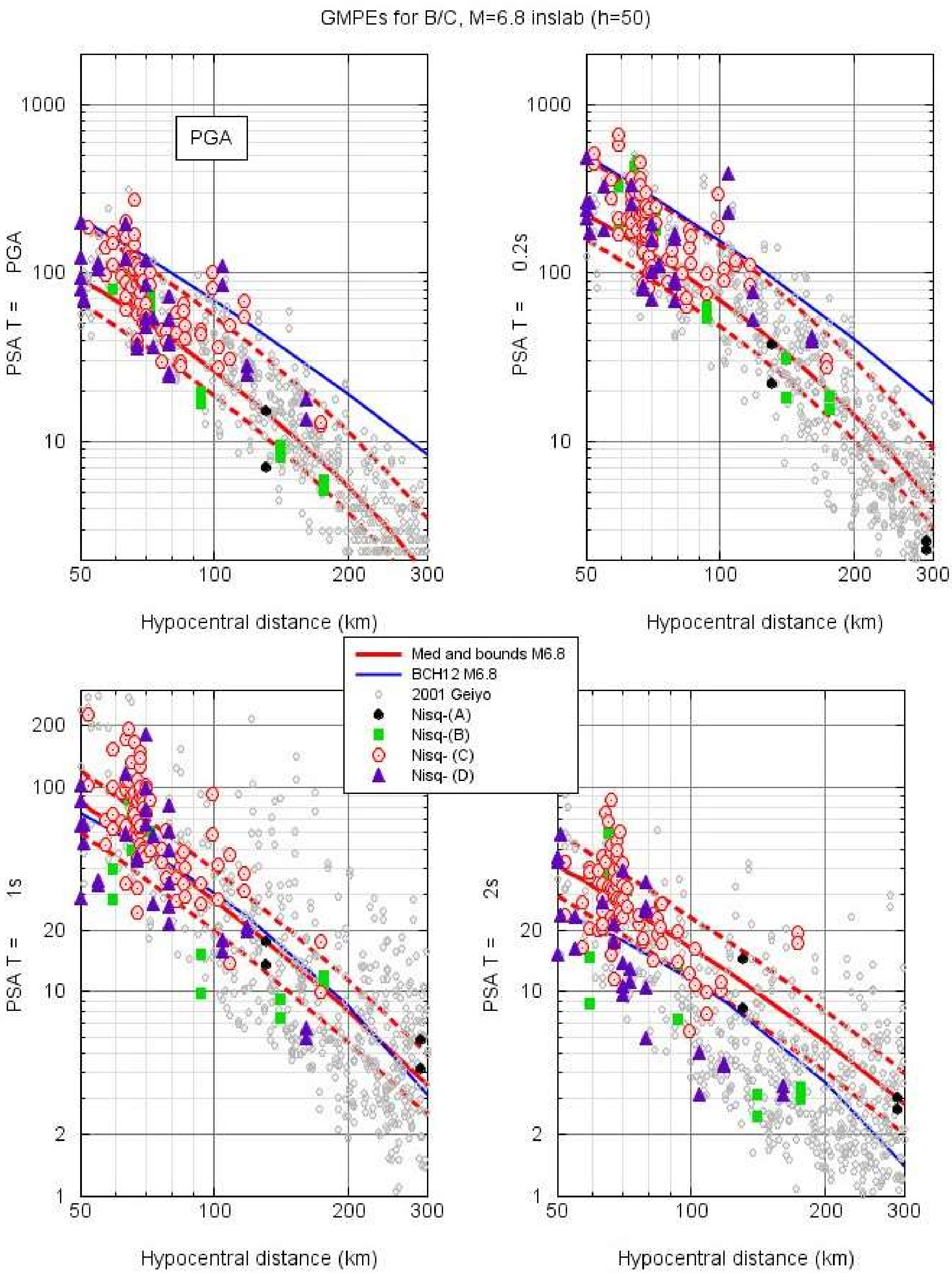

Figure 3 –Proposed lower, central and upper inslab GMPEs (in cm/s²) based on Zhao et al., 2006 (red lines) and central GMPE of Abrahamson et al., 2013 (blue line) for M=6.8 inslab events, in comparison

*to data from **M**6.8 events in Cascadia (Nisqually) and Japan (Geiyo). GMPEs for B/C site condition; all data adjusted to B/C as discussed in text.*

Western subduction interface GMPEs

For interface events, both empirical and simulation-based GMPEs may be used to model the expected Cascadia mega-thrust motions. Zhao et al. (2006), Abrahamson et al. (2013) and Ghofrani and Atkinson (2013) provide empirical GMPEs for interface events, while Gregor et al. (2002) and Atkinson and Macias (2009) both use a simulation-based model to derive GMPEs from stochastic finite-fault simulations. The methodology used by Gregor et al. and Atkinson & Macias is similar, but the Atkinson and Macias (2009) GMPE is calibrated based on larger, more recent interface events (the **M**8.1 Tokachi-Oki event), and is developed for the reference condition of B/C boundary (the Gregor et al. equations are given for “rock” or “soil”, but the specified rock Vs30 is only 363m/s, which is significantly softer than B/C). The use of simulations is important for Cascadia subduction events due to the lack of recorded data for the expected type of event (**M**>8.5 with Cascadia attenuation).

An important factor to consider in selecting GMPEs for great interface earthquakes in Cascadia is new information from the 2011 **M**9 Tohoku earthquake, which was very well recorded. This is the type of event, and approximate magnitude, expected for future great earthquakes on the Cascadia subduction zone. The motions from Tohoku were very large, especially at short periods. This was partly due to pronounced site response effects (Ghofrani et al., 2013), similar to those already discussed. Figure 4 compares the **M**9 Tohoku data, corrected to B/C site conditions (from Ghofrani and Atkinson, 2013) to several candidate GMPEs (for B/C). The empirical GMPE of Ghofrani and Atkinson (2013) included the Tohoku data directly in the regression, whereas the Abrahamson et al. (2013) GMPE used a global database, then subsequently tuned the GMPE following the occurrence of the Tohoku event. It should be kept in mind that the Tohoku data from distances >150 km are all from back-arc sites, which is why the attenuation for Tohoku at larger distances is quite steep (see Ghofrani and Atkinson, 2011). In Cascadia, a gentler attenuation is expected to apply for cities in southwestern B.C., which lie in the fore-arc region. We have not proposed a back-arc correction for sites east of the Cascade volcanic sequence in B.C., because no studies of this effect in B.C. have been performed, and it is not clear that the effect in B.C. is as pronounced as that in Japan. Neglecting this potential effect is a source of conservatism in the ground motions estimated for a Cascadia event in the interior regions of B.C.

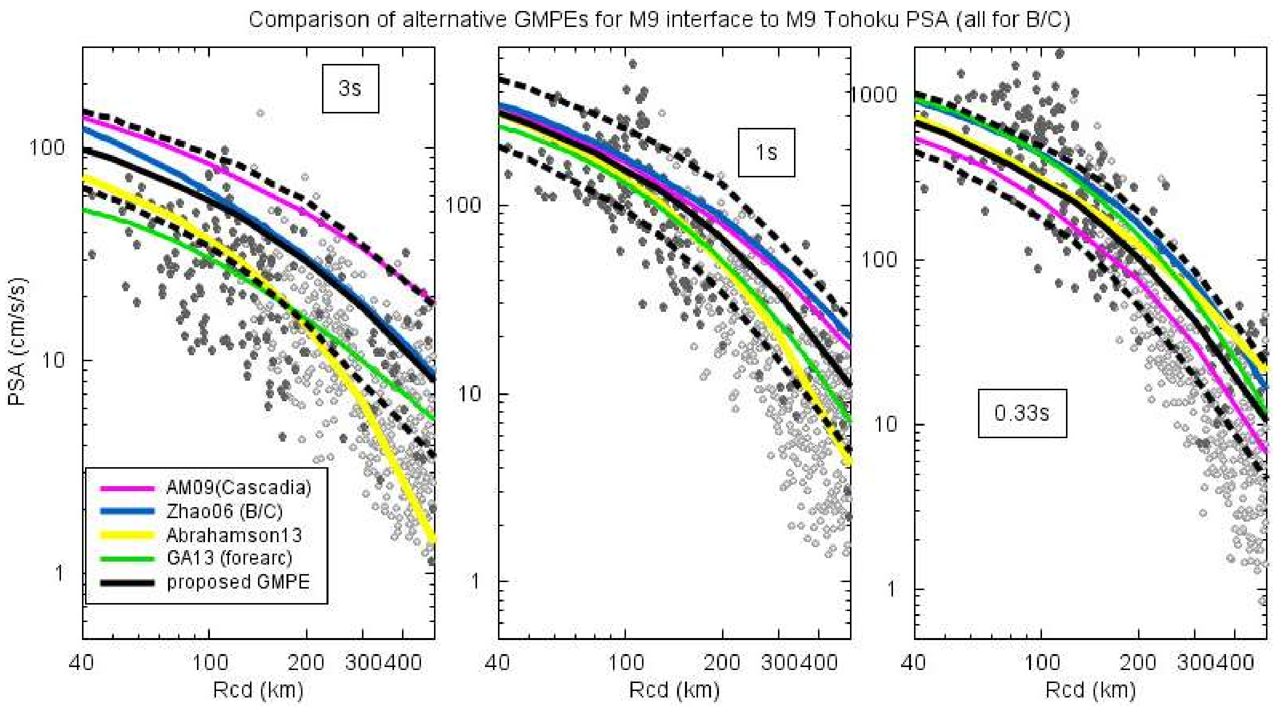

Figure 4 – Interface GMPEs in cm/s^2 *for 3, 1 and 0.33 s for* ***M****=9, in comparison to data for the* ***M****9 Tohoku PSA data (Ghofrani and Atkinson, 2013), all for* V_{s30}*=760m/s; dark symbols are forearc data, light circles are backarc data. Zhao et al. (2006)GMPE is corrected to B/C from C assuming C corresponds to Vs30~450 m/s. Abrahamson et al. (2013) is plotted for fore-arc sites. AM09 (Atkinson and Macias, 2009) is based on simulations for Cascadia; the central GMPE, based on a weighted combination of the three candidate GMPEs as described in the text, is shown (heavy black line) along with lower and upper representative equations that display our estimate of its epistemic uncertainty (dashed black lines).*

Figure 4 shows that the simulation-based GMPE of AM09 predicts significantly-higher motions at long periods, and lesser motions at short periods relative to the other equations and to the Tohoku data. We place significant weight on the AM09 equation as it is a simulation-based model that is specific to Cascadia site and attenuation conditions, but calibrated using Japanese ground-motion records. It agrees reasonably well with the Tohoku motions at intermediate periods, after considering the differences between fore-arc and back-arc attenuation. However, we note that the AM09 GMPE is conservative relative to the Tohoku data and to the alternative GMPEs at long periods (3s plot in Fig. 4). We are not certain whether the AM09 GMPE is indeed an over-estimate, or whether the Tohoku data may not have been representative of a "typical" M9 interface event. The Tohoku event was a complex multiple event, that was comprised of multiple ruptures, whose sum made up its total moment. We also note that the AM09 GMPE tends to be low relative to the Abrahamson et al. (2013) and Ghofrani and Atkinson (2013) GMPEs at short periods (≤0.2s).

In view of these considerations, the preferred central GMPE for interface events is developed by taking a weighted average of the candidate GMPE motions for forearc regions, giving 50% weight to the simulation-based GMPE motions of Atkinson and Macias (2009), with the remaining weight to empirical GMPEs. We give 20% weight to Abrahamson et al. (2013), 20% weight to Ghofrani and Atkinson (2013), and a lesser weight of 10% to Zhao et al. (2006) (noting that the Zhao et al. model does not consider the more recent Tohoku data). Because the Ghofrani and Atkinson (2013) and Zhao et al. (2006) models were based exclusively on Japanese data, they were corrected to Cascadia site conditions by applying the Japan-to-Cascadia factors as given in Table 1 before combining with the Atkinson and Macias (2009) Cascadia model and the Abrahamson et al. (2013) global model. Note that this is the central-model GMPE that is plotted in Figure 4 (i.e. as constructed from the weighted average of the log amplitudes).

It is proposed that the uncertainty in GMPEs for interface events should grow with distance, as was the case for the crustal GMPEs. However, the overall uncertainty should exceed that for crustal events. We have no ground-motion information specific to Cascadia on the motions from this type of event, and therefore the uncertainty must be larger than that for crustal events. We propose uncertainty bounds with which to construct lower and upper GMPE curves (relative to the central GMPE of AM09) as:

$$\text{delta (interface)} = \min(\,(0.15+0.0007\ \text{Rcd}),\ 0.35) \qquad (\log_{10} \text{ units})$$

This will provide a factor of 2.8 in amplitude scaling from the lower to the upper GMPE, at 100 km (growing to a factor of 5.2 at 300 km). The uncertainty will be 0.05 log units larger than that for crustal events in the west. Recommended weights for the lower, central and upper GMPEs are 0.25, 0.5 and 0.25, respectively.

Eastern GMPEs (crustal)

The definition of appropriate GMPEs for eastern North America (ENA) is challenging due to the lack of relevant data in the magnitude-distance range of most interest. We propose to use GMPEs of several different types (differing classes of approaches) that have been developed for ENA within the last decade, as an initial estimate of the epistemic uncertainty. The proposed GMPEs are summarized below (in reverse chronological order of publication); we include only relations that are useable over the entire magnitude/distance range of needed for seismic hazard map computations (**M**4.8 to 8 at distances to 600 km).

PZT11: Pezeshk, Zhandieh and Tavakoli, 2011

The PZT11 GMPE is based on the hybrid empirical approach developed by Campbell (2003), but uses an updated model for both the ENA parameters and the reference equations from western North America (WNA). The idea is that a stochastic point-source model is used to derive adjustment factors for WNA GMPEs, based on differences in model inputs between ENA and WNA. The parameter values are simple and well-motivated.

The PZT11 GMPE is specified for hard-rock site conditions, so must be converted to B/C site conditions. PZT11 used the Atkinson and Boore (2006) (AB06) values of amplification and kappa for ENA hard rock (~2000m/s), and the corresponding values from Boore and Joyner (1997) for WNA rock (~600m/s), in their model to derive correction factors from WNA to ENA. This follows the approach to amplification factors used by AB06, and therefore we can use conversion factors from A to B/C based on AB06 to predict the corresponding B/C motions for the PZT11 model (from their hard-rock GMPE values).

Under this approach, constant values (in log10 units) can be added to the hard-rock predictions (for $\log_{10}$(PSA)) of PZT11 to get equivalent predictions for B/C, as given in Table 2. The conversions were derived by plotting the differences (in $\log_{10}$ units) between the predictions of AB06 on B/C and those on

A, and noting they are insensitive to magnitude. The factors listed are for **M**=6, but would be only about 0.02 units lower for **M**=5, or 0.02 units higher for **M**=7; this is trivial given other uncertainties. The factors are also insensitive to distance, except for very short periods (<0.03s) and PGA; a distance-dependent factor is given for PGA (which can also be used for 0.025s PSA). The distance variable in PZT11 is closest distance to the fault (R_{cd}).

Table 2 – Conversion factors in log10 units from A to B/C site conditions for PZT11 GMPE

PSA:period(s)	A to B/C
5	0.06
2	0.09
1	0.11
0.5	0.14
0.33	0.14
0.2	0.12
0.1	0.03
0.05	-0.1
PGV	0.09
PGA*	-0.3+0.15log(Repi)

* PGA value may also be used for PSA at T≤0.025s.

AB06': Atkinson and Boore, 2006 (as revised in Atkinson and Boore, 2011)

The AB06' GMPE model is based on a stochastic finite-fault approach, which is a simulation approach that uses a seismological model, with key parameters calibrated based on ENA ground-motion data. It is one of a very small number of recent published ENA GMPEs that includes both a comprehensive model and a comprehensive comparison of the model against ENA data. Coefficients are provided for both B/C and hard-rock conditions, so we can use the B/C version directly. The equations were updated (Atkinson and Boore, 2011) to agree better with moderate-magnitude ground-motion amplitude data, and with WNA-scaling of motions with magnitude. The updated version is referred to as AB06'.

The distance variable in AB06' is R_{cd}. Care should be taken in converting to R_{cd} from hypocentral distance as the AB06 model does not build in distance-saturation effects, but instead relies on keeping the fault a reasonable distance away (i.e. the assumption of a buried fault) to avoid this problem. Atkinson and Boore (2011) recommend using a minimum depth to the top of the rupture (Z_{tor}) that depends on magnitude, in order to place minimum constraints on the value of R_{cd} that is associated with near-epicentre distances and hence ensure distance-saturation of near-fault amplitudes. These minimum values for R_{cd} should be applied following the conversion, if necessary. (e.g. R_{cd} is the value given by the conversion equations from R_{hypo}, but constrained such that $R_{cd}(min) = Z_{tor} = 21 - 2.5$ **M** **;** in other words, if the calculated value of R_{cd} is less than (21-2.5**M**), we use (21-2.5**M**) in its place.) Note this minimum value decreases from $R_{cd}(min)$= 8.5 km at **M**5 to $R_{cd}(min)$ = 2.3 km at **M**7.5.

A08': Atkinson, 2008 (as revised in Atkinson and Boore, 2011)

The A08' GMPE is based on a referenced empirical approach, which is similar in concept to the hybrid empirical approach, but uses ENA data directly to derive adjustment factors to WNA GMPEs. It is a useful inclusion from the point of view of epistemic uncertainty as it suggests a smoother attenuation function than do model-based approaches (like AB06' and PZT11). Coefficients are provided for B/C conditions. The distance metric is closest distance to the surface projection of the rupture (R_{jb}). This model was recently updated by Atkinson and Boore (2011) to use modified BA08' GMPEs for WNA (see sections below) as the reference; these modifications account for recent moderate-magnitude observations in both ENA and WNA. The modified version is referred to as A08'.

SGD02S: Silva, Gregor and Daragh, 2002, Single-corner (variable stress)

This GMPE has never been formally published (except on the authors' website) but has been very widely used; it is recommended for consideration for this reason, as an 'industry-standard' stochastic point-source model (in which stress drop decreases with magnitude to mimic WNA saturation effects). It is given for hard-rock conditions, so must be converted to B/C; the conversion factors of Table 2 can be used for this purpose, as the amplification model employed by the authors is very similar to that of AB06. The distance variable is $R_{jb.}$

SGD02D: Silva, Gregor and Daragh, 2002, Double-corner (with saturation)

This is another variant of the SGD02 model, in which a double-corner stochastic point-source model is used in the simulations, to consider epistemic uncertainty in source. As for the SGD02S model, it needs to be converted to B/C, and the distance metric is R_{jb}.

We implement the five ENA GMPEs by defining a suite of three relationships for the ground motions, for each magnitude-distance-period, that express the geometric mean and its standard deviation (where the geometric mean is the arithmetic average of the five log values of the median ground motions from the alternative relations).The mean and mean ± one standard deviation define the central, lower and upper curves. A conversion from the distance metric of each GMPE to epicentral distance is made using a simple approximation, assuming ENA fault dimensions, as a point-source metric is required for the hazard calculations (see Appendix A of Atkinson 2012 for details). We smooth the standard deviation using a triangular 3-point weighted smoothing, to avoid "pinching" of the lower and upper bounding relations at certain distances where the five estimates fortuitously happen to lie close together. The sets of GMPEs are implemented in a table format in the hazard software, so that no "fitting" to the values is required (the table in log PSA vs. log distance is interpolated to find the value corresponding to any **M**, distance and period); the tables are available on the author's website (www.seismotoolbox.ca).

Figure 5 shows the central GMPE from the five candidate relations, along with the corresponding lower and upper GMPEs. The Atkinson and Boore (1995) equations, used in the NBCC (2005, 2010) maps, are shown for reference (converted to B/C). The epistemic uncertainty obtained using this procedure varies with magnitude, distance and period, with a typical average value being 0.17 $\log_{10}$ units (factor of 1.5).

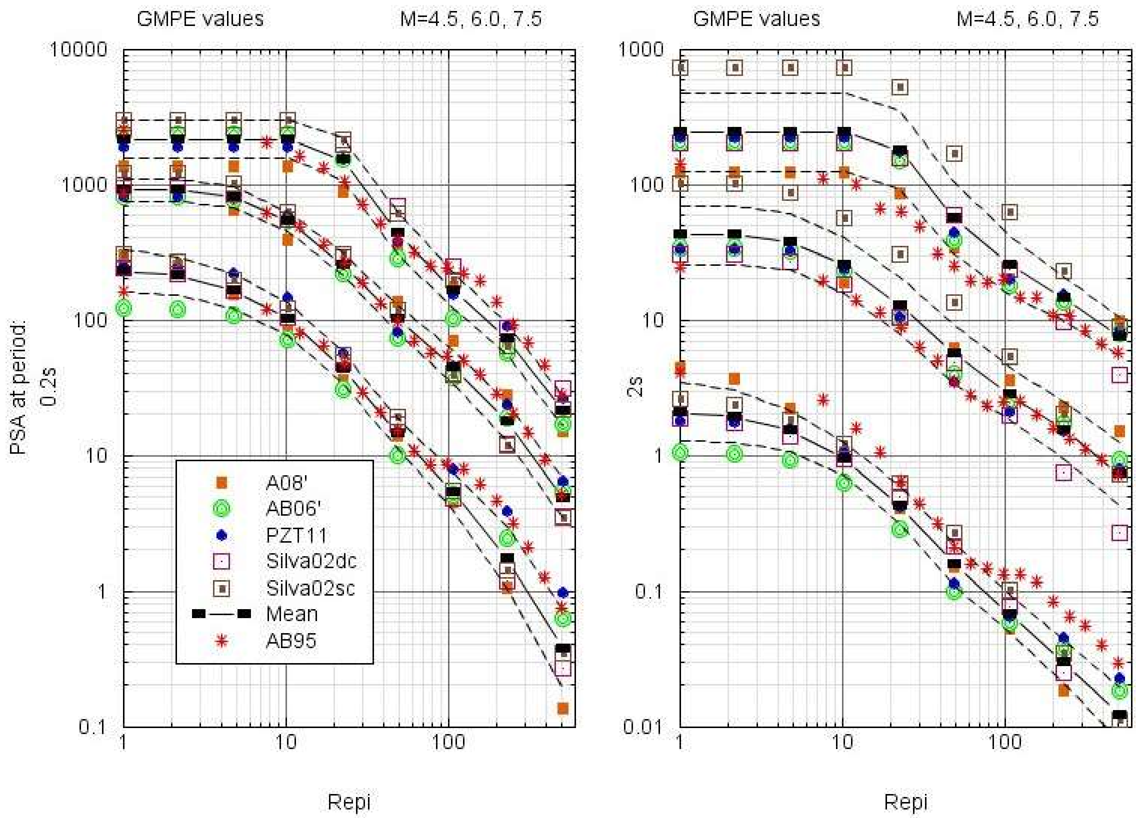

*Figure 5: PSA values in cm/s² at 0.2s and 2s (for **M**=4.5, 6.0, 7.5) for five ENA GMPEs versus epicentral distance, along with geometric mean values (black squares), proposed central GMPE (solid black line), and relations giving mean±standard deviation (dashed black lines). Red asterisks show values from the AB95 equations, which were used in the 2005, 2010 NBCC maps.*

In Figure 6, the standard deviation of the median GMPE predictions for the east is plotted versus distance for **M** 4.5, 6.0 and 7.5, for 2s and 0.2s. Generally, the implied uncertainty from the standard deviation of the GMPEs is larger than the value adopted for western crustal GMPEs, but not always. Overall, the impression is that the eastern GMPEs should carry larger epistemic uncertainty, in comparison to the western crustal equations. Furthermore, in the east the ground motions are most constrained by data and studies at regional distances, and should be considered most uncertain at close distances, due to the paucity of relevant near-source observational data. This pattern of uncertainty behavior with distance is different than that for the west. This suggests that additional uncertainty should be provided, above that given by the standard deviation of log amplitudes about the central GMPE. We add an additional epistemic uncertainty to modify the GMPE+std and GMPE-std equations for the east, having greatest effect at close distances. The uncertainty (log units to add to GMPE+std, and subtract from GMPE-std) is:

delta (ENA GMPE+std, GMPE-std) = max((0.1 – 0.001 Repi), 0.0)

This will increase the epistemic uncertainty above that given by the standard deviation of the geometric mean of the eastern GMPEs by 0.1 (factor of 1.26) at close distances, such that its typical value would be ~0.2 for short periods and 0.35 for long periods. It would leave the uncertainty unchanged for R_{epi}>100 km. The average value (over all magnitudes and periods) is shown in Figure 6, in comparison to the western crustal uncertainty. The recommended weights for the lower, central and upper alternatives are 0.25, 0.5 and 0.25, respectively.

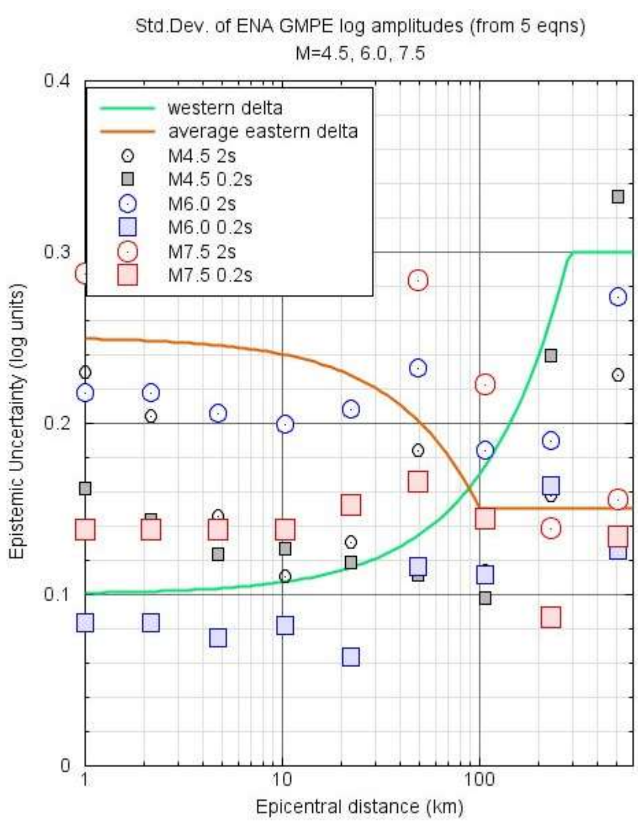

Figure 6 – Standard deviation (in log units) of mean of 5 eastern GMPEs by magnitude and distance for 2s and 0.2 Hz (symbols). Recommended eastern epistemic uncertainty adds 0.1 to these plotted values at close distances (reducing to no additional uncertainty for R_{epi}>100km). Green line shows recommended epistemic uncertainty for western crustal events. Orange line shows general behaviour of the eastern epistemic uncertainty.

Comparison of GMPEs across regions

It is useful to compare the GMPEs to each other across regions. Figure 7 plots the response spectra, for B/C conditions, for **M**7 events at epicentral distances of approximately 10 and 100 km. This plot is indicative of the size of events that contribute to hazard across a broad range of periods for typical Canadian seismic hazard mapping applications. To facilitate comparisons, we have calculated the weighted mean of the GMPE suite for each event type, which is what is shown in Figure 7. This shows that the event types are all scaling in a similar way with period, though there are some significant differences in amplitude levels. At short periods, eastern events show larger amplitudes than western crustal events, as we would expect based on the observations for events in the east, which are typically modeled by higher stress drops. The amplitudes expected for subduction interface events are generally similar to those for crustal events, at least at the **M**7 level. Inslab events have lower amplitudes at short epicentral distances, because they are actually further away, due to their focal depths (~50 km); however, at epicentral distances for which the focal depth effect is less important, the relatively-large amplitudes for inslab events at short periods become more apparent.

We examined plots such as those shown on Figure 7 for a range of magnitudes, but for brevity have shown only one example here. Inspection of such plots gives us confidence that the GMPEs are internally-consistent in the way they behave when compared across regions.

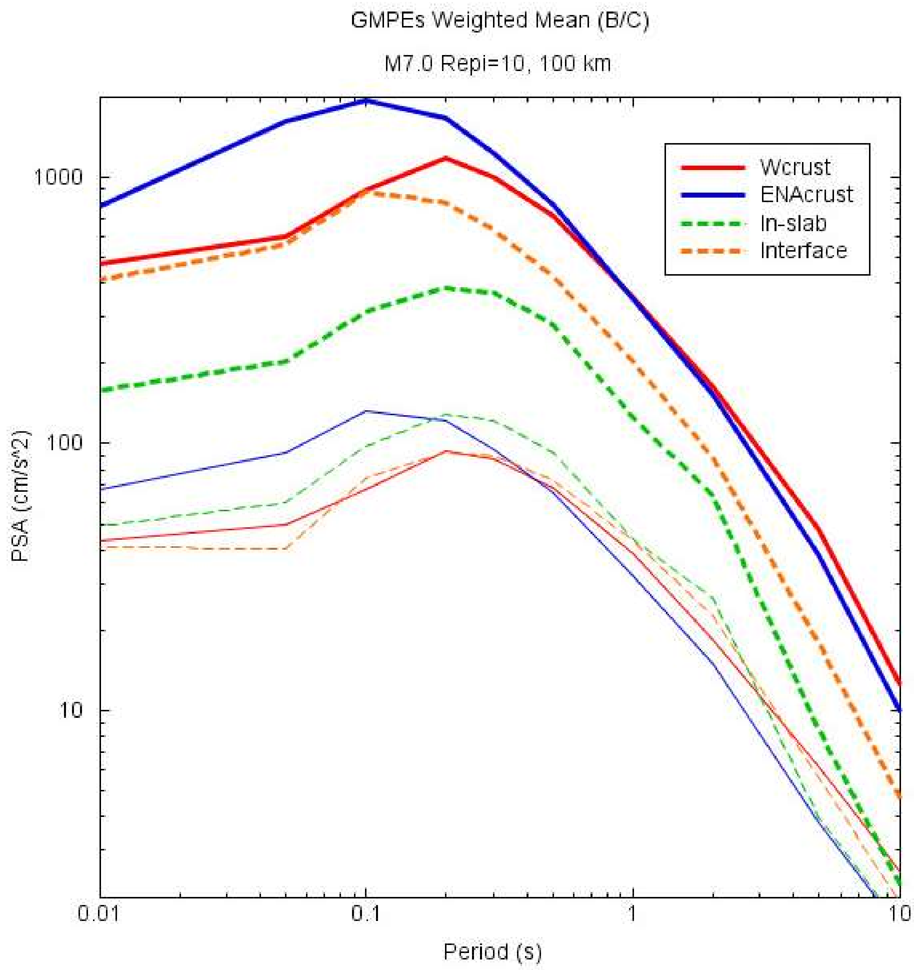

Figure 7 – Response spectrum in cm/s² for M7 events at epicentral distances of 10 (heavy lines), 100 km (light lines), for four different event types, for B/C conditions.

Aleatory Variability in GMPEs (Sigma)

The value of sigma (aleatory variability, or random scatter of observations about a GMPE) to be associated with the GMPEs is an important parameter. Traditionally, sigma was assigned based on observed variability about the regression equation (statistics of misfit to the equations). More recently, it has been realized that this may not be the appropriate way to define sigma, as what we are trying to capture is natural variability in future events, as opposed to total variability in regression - which includes factors such as model misfits, variable soil conditions, data errors and so on. These factors all contribute to reported values for regression statistics, but are not representative of actual physical variability. There is also potential for some double-counting of aleatory uncertainty when epistemic uncertainty in the median equations is included in the hazard analysis. These issues have been discussed in papers by Anderson and Brune (1999), Anderson et al. (2000), Abrahamson and Bommer (2005), Atkinson (2006, 2011) and Strasser et al., (2009). Atkinson (2011) shows that actual variability in amplitudes within well-recorded events is about 0.22 log(10) units at long periods (>1s), decreasing to about 0.20 units at short periods (≤0.25s). This includes just the within-event variability, and also implicitly includes variability in site conditions for a given value of V_{s30} (due to differing soil depths, etc.). Based on the PEER-NGA equations, typical inter-event variability values decrease from about 0.16 to 0.12 units over the same period range; note that the inter-event variability includes any regional variability in source characteristics, in addition to actual event-to-event variability within a specific region. Considering these values, representative values for a multi-site sigma would be about 0.27 log(10) units at long periods (≥1s), decreasing to 0.23 units at short periods (≤.25s); note that single-station sigma values (Atkinson, 2006, 2013) would be lower. The representative values are obtained from the inter-event and intra-event components using the standard square-root-sum-of-squares rule. It is proposed that these sigma values be applied to all event types and regions, as there is no definitive evidence that sigma varies with region (see Atkinson, 2013), and sigma is best defined for western crustal events. The proposed sigma values are slightly smaller than the corresponding range of 0.25 (short period) to 0.30 (long period) quoted by Boore and Atkinson (2008) based on their regression results; this is in accord with our view that the assigned aleatory uncertainty should be less than indicated by regression statistics to avoid double-counting of aleatory and epistemic uncertainty.

Conclusion

This study has suggested suites of lower, central and upper GMPEs for each type of event for use in seismic hazard mapping in Canada. The use of the 3 sets of GMPEs is a simple and efficient way to represent epistemic uncertainty in GMPEs. The implications of this approach, including comparisons with more traditional approaches such as using a variety of alternative published GMPEs without modification, are explored in separate investigations. To date, these investigations have shown that the three-equation approach is equivalent to the use of multiple GMPEs, provided the same range of epistemic uncertainty is sampled.

Acknowledgements

We have benefited from discussions with the ground-motion modeling group of the Canadian Standing Committee on Earthquake Design, including in particular Garry Rogers, Tuna Onur, Liam Finn and Adrian Wightman. Karen Assatourians provided computational assistance. The review comments of Paul Somerville on our GMPE choices are gratefully acknowledged, along with constructive reviews from Trevor Allen and two anonymous reviewers. The first author's research is supported by the National Sciences and Engineering Research Council.

References

Abrahamson, N. and J. Bommer (2005). Probability and uncertainty in seismic hazard analysis. Earthquake Spectra, **21**, 603-608.

Abrahamson, N., G. Atkinson, D. Boore, Y. Bozorgnia, K. Campbell, B. Chiou, I. Idriss, W. Silva and R. Youngs (2008). Comparison of the NGA Ground-Motion Relations. Earthquake Spectra, **24**, 45-66.

Abrahamson, N., N. Gregor and K. Addo (2013). B.C. Hydro Ground Motion Prediction Equations for Subduction Earthquakes. Earthquake Spectra, submitted.

Adams, J. (2011). Seismic Hazard Maps for the National Building Code of Canada. Canadian Society of Civil Engineers General Conference - Ottawa, Ontario June 14-17, 2011, paper JHS-1-1.

Adams, J. and S. Halchuk (2003). Fourth generation seismic hazard maps of Canada: Values for over 650 Canadian localities intended for the 2005 National Building Code of Canada, Geological Survey of Canada Open File 4459, 155 pp.

Anderson, J. and J. Brune (1999). Methodology for using precarious rocks in Nevada to test seismic hazard models. Bull. Seism. Soc. Am., **89**, 456-467.

Anderson, J., J. Brune, R. Anooshehpoor and S. Ni (2000). New ground motion data and concepts in seismic hazard analysis. Current Science, **79**, 1278-1290.

Atkinson, G. (1995). Ground motion relations for use in eastern hazard analysis. In Proceedings, 7th Canadian Conference on Earthquake Engineering, Montreal, June 1995, p. 1001-1008.

Atkinson, G. (2005). Ground motions for earthquakes in southwestern British Columbia and northwestern Washington: crustal, inslab, and offshore events, *Bull. Seism. Soc. Am.* **95**, 1027-1044.

Atkinson, G. (2006). Single-station sigma. Bull. Seism. Soc. Am., **96**, 446-455.

Atkinson, G. M. (2008). Ground-motion prediction equations for eastern North America from a referenced empirical approach: implications for epistemic uncertainty, *Bull. Seism. Soc. Am.* **98**, 1304-1318.

Atkinson, G. (2011). An empirical perspective on uncertainty in earthquake ground motions. Can.J.Civil Eng., **38**,1-14. DOI:10.1139/l10-120.

Atkinson, G. (2012) White paper on development of ground-motion prediction equations for Canadian National Seismic Hazard Maps. www.seismotoolbox.ca (Misc. Resources). Nov. 2012.

Atkinson, G. (2013). Empirical evaluation of aleatory and epistemic uncertainty in eastern ground motions. Seism. Res. L., **84**, 130-138.

Atkinson, G., and D. Boore (1995). New ground motion relations for eastern North America. Bull. Seism. Soc. Am., **85**, 17-30.

Atkinson, G. M., and D. M. Boore (2003). Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions, *Bull. Seism. Soc. Am.* **93**, 1703-1729.

Atkinson, G. M., and D. M. Boore (2006). Earthquake ground-motion prediction equations for eastern North America, *Bull. Seism. Soc. Am.* **96**, 2181-2205.

Atkinson, G. and D. Boore (2011). Modifications to existing ground-motion prediction equations in light of new data. Bull. Seism. Soc. Am., **101**, 1121-1135.

Atkinson, G. M., and R. Casey (2003). A comparison of ground motions from the 2001 **M** 6.8 inslab earthquakes in Cascadia and Japan, *Bull. Seism. Soc. Am.* **93**, 1823-1831.

Atkinson, G. and K. Goda (2011). Effects of seismicity models and new ground motion prediction equations on seismic hazard assessment for four Canadian cities. Bull. Seism. Soc. Am., **101**, in press.

Atkinson, G. M., and M. Macias (2009). Predicted ground motions for great interface earthquakes in the Cascadia subduction zone, *Bull. Seism. Soc. Am.* **99**, 1552-1578.

Atkinson, G. and M. Morrison (2009). Regional variability in ground motion amplitudes along the west coast of North America. Bull. Seism. Soc. Am., **99**, 2393-2409.

Bommer, J., N. Abrahamson, F. Strasser, A. Pecker, P. Bard, H. Bungum, F. Cotton, D. Fah, F. Sabetta, F. Scherbaum and J. Studer (2004). The challenge of defining upper bounds on earthquake ground motions. Seism. Res. L., **75**, 82-95.

Bommer, J., P. Stafford, J. Alarcon and S. Akkar (2007). The influence of magnitude range on empirical ground-motion prediction. Bull. Seism. Soc. Am., **97**, 2152-2170.

Bommer, J. and F. Scherbaum (2008). The use and misuse of logic trees in probabilistic seismic hazard analysis. Earthquake Spectra, **24**, 997-1009.

Boore, D. and G. Atkinson (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped SA at spectral periods between 0.01s and 10.0 s. Earthquake Spectra, **24**, 99-138.

Boore, D. and W. Joyner (1997). Site amplifications for generic rock sites. Bull. Seism. Soc. Am., **87**, 327-341.

Boore, D. W. Joyner and T. Fumal (1997). Equations for estimating horizontal response spectra and peak acceleration from western North American earthquakes: A summary of recent work. Seism. Res. L., **68**, 128-153.

Campbell, K. W. (2003). Prediction of strong ground motion using the hybrid empirical method and its use in the development of ground-motion (attenuation) relations in eastern North America, *Bull. Seism. Soc. Am.* **93**, 1012-1033.

Chiou, B., R. Youngs, N. Abrahamson and K. Addo (2010). Ground motion model for small-to-moderate shallow crustal earthquakes in California and its implications for regionalization of ground motion prediction models. Earthquake Spectra, **26**, 907-926.

Cotton, F., G. Pousse, F. Bonilla, and F. Scherbaum (2008). On the Discrepancy of Recent European Ground-Motion Observations and Predictions from Empirical Models: Analysis of KiK-net Accelerometric Data and Point-Sources Stochastic Simulations, *Bulletin of the Seismological Society of America,* ***98***(5), 2244-2261.

Ghofrani, H. and G. Atkinson (2011). Fore-arc versus back-arc attenuation of earthquake ground motion. Bull. Seism. Soc. Am., **101**, 3032-3045.

Ghofrani, H. and G. Atkinson (2013). Ground-motion prediction equations for interface earthquakes of M7 to 9 in Japan based on empirical data. Bull. Earthq. Eng., submitted.

Ghofrani, H., G. Atkinson and K. Goda (2013). Implications of the 2011 M9.0 Tohoku Japan earthquake for the treatment of site effects in large earthquakes. Bull. Earthq. Eng., in press.

Goda, K., and G. M. Atkinson (2009). Probabilistic characterization of spatially correlated response spectra for earthquakes in Japan, *Bull. Seism. Soc. Am.* **99**, 3003-3020.

Goda, K., H. Hong and G. Atkinson (2010). Impact of using updated information on seismic hazard in Western Canada. Can. J. Civil Eng., **37**, 562-575.

Gregor, N. , W. Silva, I. Wong, and R. Youngs (2002). Ground-motion attenuation relationships for Cascadia subduction zone megathrust earthquakes based on a stochastic finite-fault model, *Bull. Seism. Soc. Am.* **92**, 1923-1932.

Pezeshk, S., A. Zandieh and B. Tavakoli (2011). Ground-motion prediction equations for eastern North America from a hybrid empirical method. Bull. Seism. Soc. Am., in review.

Power, M., Chiou, B., Abrahamson, N, Y. Bozorgnia, T. Shantz and Roblee, C. (2008). An overview of the NGA project. Earthquake Spectra, **24**, 3-21.

Ristau, J., G. Rogers, and J. Cassidy (2003). Moment magnitude-local magnitude calibration for earthquakes off Canada's west coast, *Bull. Seism. Soc. Am.* **93**, 2296- 2300.

Ristau, J., G. Rogers, and J. Cassidy (2005). Moment magnitude-local magnitude calibration for earthquakes in western Canada, *Bull. Seism. Soc. Am.* **95**, 1994-2000.

Scherbaum, F., J. Schmedes, and F. Cotton (2004). On the conversion of source-to-site distance measures for extended earthquake source models, *Bull. Seism. Soc. Am.* **94**, 1053-1069.

Silva, W. J., N. J. Gregor, and R. Darragh (2002). *Development of regional hard rock attenuation relations for central and eastern North America*, Technical Report, Pacific Engineering and Analysis, El Cerrito, CA. www.pacificengineering.org.

Somerville, P., N. Collins, N. Abrahamson, R. Graves and C. Saikia (2002). Ground motion attenuation relations for the central and eastern United States. Report to U.S. Geological Survey (NEHRP).

Strasser, F., N. Abrahamson and J. Bommer (2009). Sigma: Issues, insights and challenges. Seism. Res. L., **80**, 40-56.

Youngs, R. R., S. J. Chiou, W. J. Silva, and J. R. Humphrey (1997). Strong ground motion attenuation relationships for subduction zone earthquakes, *Seism. Res. Lett.* **68**, 58-73.

Zhao, J. , J. Zhang, A. Asano, Y. Ohno, T. Oouchi, T. Takahashi, H. Ogawa, K. Irikura, H. Thio, P. G. Somerville, Y. Fukushima, and Y. Fukushima (2006). Attenuation relations of strong ground motion in Japan using site classification based on predominant period, *Bull. Seism. Soc. Am.* **96**, 898-913.