Ground-motion models for the 6th Generation Seismic Hazard Model of Canada

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ABSTRACT

The 6th Generation seismic hazard model of Canada is being developed to generate seismic design values for the 2020 National Building Code of Canada (NBCC2020). Ground-motion models (GMMs) from the Next Generation Attenuation (NGA)-West 2 and NGA-East programs are used, and epistemic uncertainty in ground-motion models is captured through the use of a classical weighted logic tree framework. For the first time in Canada, seismic hazard is computed directly on primary (e.g. A-E) seismic site classes from their time-averaged shear wave velocities in the upper 30 m of the crust (V_{S30}). This approach simplifies the way end users will determine seismic design values for a given location and site class, while having other technical advantages such as capturing epistemic uncertainty in site amplification models. It will remove the need for separate site amplification look-up tables in the building code, enabling users to simply supply their location and site class to determine seismic design values. In general, the new ground-motion models predict higher hazard in most Canadian localities due to a variable combination of changes in median ground motions, site amplification and aleatory uncertainty.

Keywords: National Building Code, PSHA, ground-motion models, site amplification

INTRODUCTION

The 6th Generation seismic hazard model for Canada, proposed for use in the 2020 National Building Code of Canada (NBCC2020), generates seismic ground motions using a multiple ground-motion model (GMM) logic tree approach rather than the three-branch representative suite used for the 5th Generation model (used in NBCC2015) [1]. The new approach was used because the suite did not allow for GMM-specific site amplification [e.g., 2] and aleatory uncertainty (sigma) models. Additionally, for the 5th Generation model the amplification factors from a single GMM for active crust were assumed to hold for all models, and there was no epistemic uncertainty captured to represent the variability between sigma models.

This document summarizes the GMMs selected, including their sigma and site amplification terms, and compares them with the 5th Generation GMMs. For the 6th Generation model, GMMs were mostly used as implemented within the v3.2 OpenQuake engine [3], with some necessary modifications as discussed below. Short- (0.2 s) and long-period (2.0 s) spectral accelerations are used to illustrate the changes for scenario events that are typical contributors to seismic hazard; the changes may differ for other scenarios.

GMM SELECTION

This section describes the GMMs of the 6th Generation model and compares them with the GMMs of the 5th Generation model using scenario events. The 6th Generation GMMs and their approximate ranges of applicability are shown in Table 1.

Table 1. Ground motion models for each tectonic regime in the 6th Generation model (references provided in text).

Tectonic Regime	GMM	Weight	V_{s30} (m/s)	PGV	T_{Max} (s)	Cascadia Factor
Subduction Inslab	Aea15	0.25	E - B	N	10	N
	Zea06	0.25	E - A	N	5	Y
	AB03	0.25	E - B	N	3	Y
	Gea05	0.25	B	Y	5	N
Subduction Interface	Aea15	0.25	E - B	N	10	N
	Zea06	0.25	E - A	N	5	Y
	GA14	0.25	E - B	Y	9	Y
	AM09	0.25	B/C	N	5	N
Active Crust	ASK14	0.25	180 - 1500	Y	10	N
	BSSA14	0.25	150 - 1500	Y	10	N
	CB14	0.25	150 - 1500	Y	10	N
	CY14	0.25	180 - 1500	Y	10	N
Stable Crust	NGA-East-13	0.5	3000	Y	10	N/A
	AA13	0.5	B/C	Y	10	N/A

Subduction GMMs (Inslab and Interface)

The majority of the subduction GMMs for the 6th Generation model are similar to those considered by Atkinson and Adams, 2013 (AA13, [1]) when the three-branch suite for the 5th Generation model was derived (Figure 1). For inslab events, the GMMs of Abrahamson et al., 2016 (Aea15, [4]), Zhao et al., 2006 (Zea06, [5]), Atkinson and Boore, 2003 (AB03, [6]) and García et al., 2005 (Gea05, [7]) are used with equal weights. The Cascadia factor in Table 1 identifies GMMs which are largely derived from, or intended for, Japan. These were adjusted with a Cascadia factor to account for differences in site conditions following the method and advice of Atkinson and Adams [1]. The Gea05 GMM, developed for inslab earthquakes in central Mexico, was included within the logic tree because it was found to perform well against recorded ground-motions from moderate to large-magnitude earthquakes recorded in Cascadia (Brillon, pers. comm., 2016). The effect of using all four GMMs in a logic tree is a small increase in mean ground motions at short periods, relative to the 5th Generation model, but a decrease at long periods owing to the smaller predictions of Aea15 and AB03.

For interface events, the GMMs of Aea15, Zea06, Ghofrani and Atkinson, 2014 (GA14, [8]) and Atkinson and Macias, 2009 (AM09, [9]) are used. These four GMMs are the same GMMs weighted in AA13 to produce the central relationship. However, it is important to note the 6th Generation model weighs all four of the GMMs equally whereas AA13 gave a weight of 0.5 to AM09 for their central GMM. Equal weighting is used in the 6th Generation model from the standpoint that each GMM is no more likely as the others to represent the actual ground motions from future events. In general, the weighted mean of the four GMMs is comparable to that of AA13 at short and intermediate periods but smaller at longer periods ($T > 2$ s) owing to the lower weight on AM09 which predicted larger ground motions at long periods [1].

NBCC2020 requires the definition of response spectral ordinates for oscillation periods out to 10 seconds. When a GMM did not contain the required long period information, extrapolation was performed using the corresponding ratio from Aea15 (which is defined to 10 s) for the same magnitude, distance and site. This was required for GMMs with a T_{Max} of less than 10 s in Table 1. Similarly, peak ground velocity (PGV) was only defined for one of the GMMs within each of the subduction tectonic regimes (Gea05 and GA14). As such, PGV was estimated for the other GMMs using empirical correlation factors developed between Sa(0.5) and PGV predictions from Boore et al., 2014 (BSSA14, [10]) for inslab GMMs and similarly from correlations between Sa(2.0) and PGV of GA14 for interface GMMs [11].

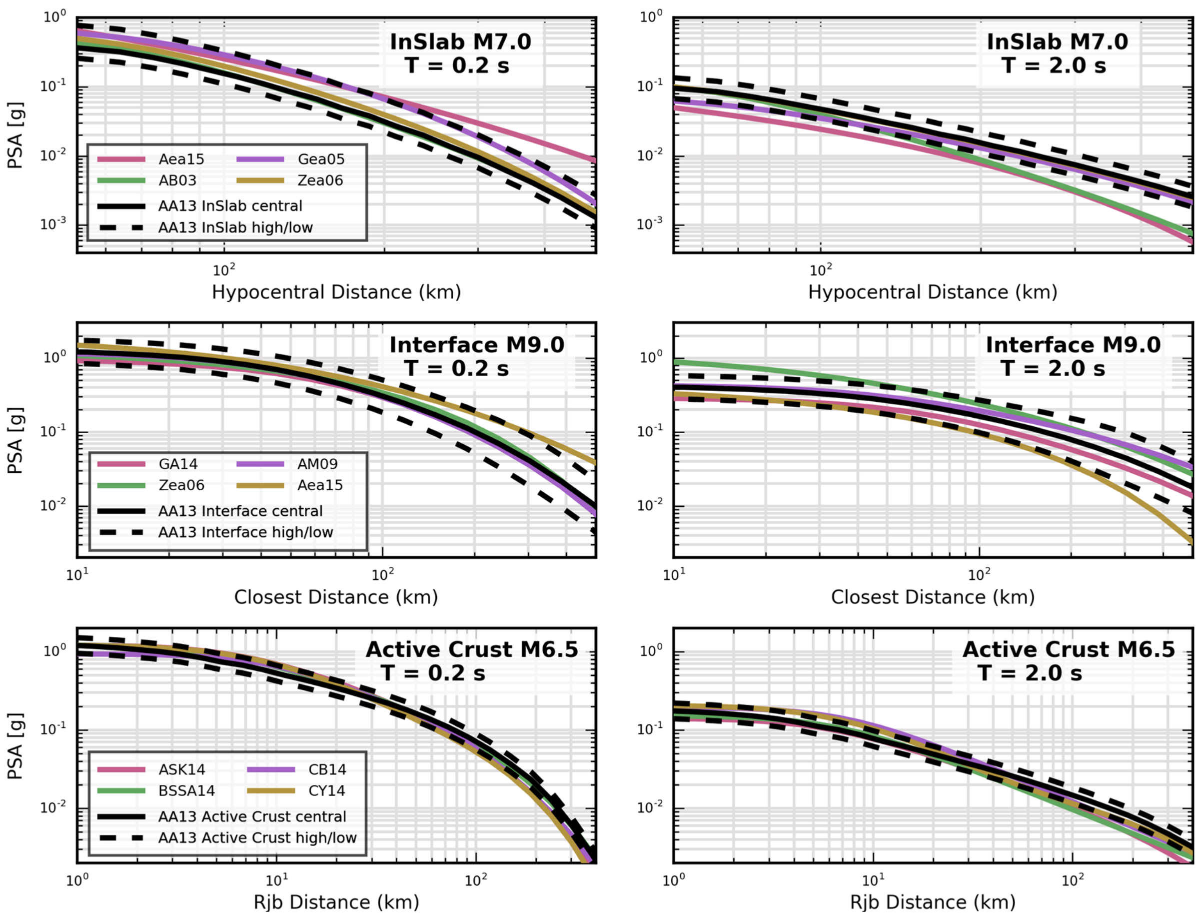

Figure 1. GMMs at V_{S30} = 450 m/s (Site Class C) for the western tectonic regimes.

Western Active Crust GMMs

In the 5th Generation model, AA13 for active crustal earthquakes of the Cordillera [12] was derived largely from consideration of the NGA-West1 GMMs whereby the central GMM was that of BA08 [13] with the others being used to estimate the bounds of the high and low branches. One issue with using the full NGA-West1 relations was the number of fault/source parameters required (many of which are unknown). The 5th Generation model used ASCII tables to define the ground motions, so these additional rupture parameters (e.g., style of faulting, depth to top of rupture) had to be provided *a priori*. By adopting the OpenQuake engine for the 6th Generation model, synthetic pseudo-ruptures can be used, negating the need to define rupture parameters *a priori*. These rupture parameters are not any better known for western Canada, but by modelling a series of possible ruptures in OpenQuake it is possible to sample a range of these parameters thus including a measure of epistemic uncertainty consistent with the degree of understanding of the earthquake rupture process.

For the 6th Generation active crust model, the following NGA-West2 GMMs were adopted with equal weights: Abrahamson et al., 2014 (ASK14, [14]), BSSA14, Campbell and Bozorgnia, 2014 (CB14, [15]) and Chiou and Youngs, 2014 (CY14, [16]). For the active crust scenario presented in Figure 1, AA13 appears to predict lower T = 2.0 s motions at distances less than 30 km, and predicts larger accelerations at larger distances, relative to NGA-West2. The amount of epistemic uncertainty in the 6th Generation active crust GMMs is less than AA13 (Figure 1) and may be underestimating the true uncertainty [17], although the modelling of multiple scenarios (e.g., rupture styles, hypocentral depths) in the 6th Generation model adds some additional uncertainty to that implied by the scenario in Figure 1.

Eastern Stable Crust GMMs

For the “stable” crust of eastern, central and Arctic Canada (east of the Cordillera, [12]), the 6th Generation model equally weights a) the AA13 GMMs used for the 5th Generation model, and b) the 13 NGA-East GMMs (NGA-East-13, [18]). The NGA-East project represents a major advance in the field of ground-motion modelling, but its GMMs were not final when needed for the NBCC2020 schedule, and have not been scrutinized by the wider seismological community. The intent of the 50/50 weight is to move towards the hazard that might be generated by full adoption the final NGA-East GMMs in the future. Although the 13 preliminary GMMs [18] were used, they give similar mean hazard to the 17 near-final GMMs (Peter Powers, USGS, pers. comm.). Figure 2 compares the predicted ground motions for the AA13 and NGA-East-13 GMMs at Site Class C. The weighted mean ± 1 standard deviation of NGA-East-13 is also shown (dashed pink lines) so as to be able to back-compare to AA13 which used the standard deviation of five GMMs to define the low and high branches. For many hazard-important scenarios, the amount of epistemic uncertainty in NGA-East-13 relative to AA13 has increased, particularly for short periods, large distances and large magnitudes. However, for certain scenarios the amount of epistemic uncertainty is comparable or even smaller than AA13 (e.g., Figure 2 at T = 2.0 s for distances < 100 km). It is also apparent that more of the NGA-East-13 GMMs lie above the central AA13 relation than below (compare green and black lines in Figure 2) which will increase mean ground motions and thus hazard. For example, at Site Class C the weighted mean of the individual GMMs increased by roughly 30–40% from the 5th to the 6th Generation model for the mean magnitude and distance deaggregation values for Montreal (M6.5 at 30 km for T = 0.2 s and M7.0 at 70 km for 2.0 s). Note that NGA-East-13 was developed for a V_{S30} of 3000 m/s and in order to calculate the hazard at Site Class C, a site term has been added (discussed in a later section).

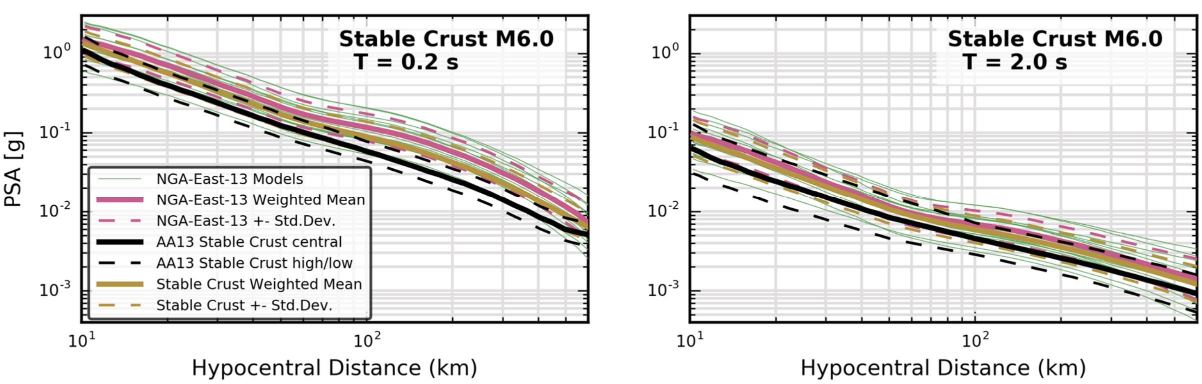

Figure 2. GMM at V_{S30} = 450 m/s (Site Class C) for the stable crust region: NGA-East-13 and AA13 Stable Crust. The weighted mean (and ± 1 standard deviation) for the NGA-East-13 and combined AA13 and NGA-East-13 suites is shown in pink and olive, respectively. NGA-East-13 GMMs were converted to hypocentral distance for comparison in this figure only.

ALEATORY UNCERTAINTY (SIGMA)

The aleatory uncertainty is considered to be the uncertainty associated with the inherent randomness of future events that cannot be reduced by the collection of additional information. For the 5th Generation model, the sigma model of AA13 was used for all tectonic regimes. It was based on estimates of within- and between-event variability of well-recorded events in active tectonic regimes [1]. Similar to the decision to sample multiple published GMMs, the 6th Generation model samples various sigma models by using the sigma model published within each GMM. These in general are sigma models based on the misfit between the GMM and the considered dataset (i.e., from regression statistics). The use of GMM-specific sigmas in the 6th Generation model captures the epistemic uncertainty between sigma models within the logic-tree framework. There is one exception to using the published sigma model of each GMM, and that is with NGA-East-13 models where the AA13 sigma model is retained. Goulet et al. [18] provides a complex sigma model for NGA-East-13, the chief feature being a large sigma for NGA-East's 3000 m/s rock. However, in our view, the use of data adjusted from poorly-known non-rock site conditions appears to have contributed to that larger sigma. In light of this consideration, and the already large epistemic uncertainty (Figure 2), the AA13 sigma model was retained for stable crust. The 6th Generation sigma models can be seen in Figure 3.

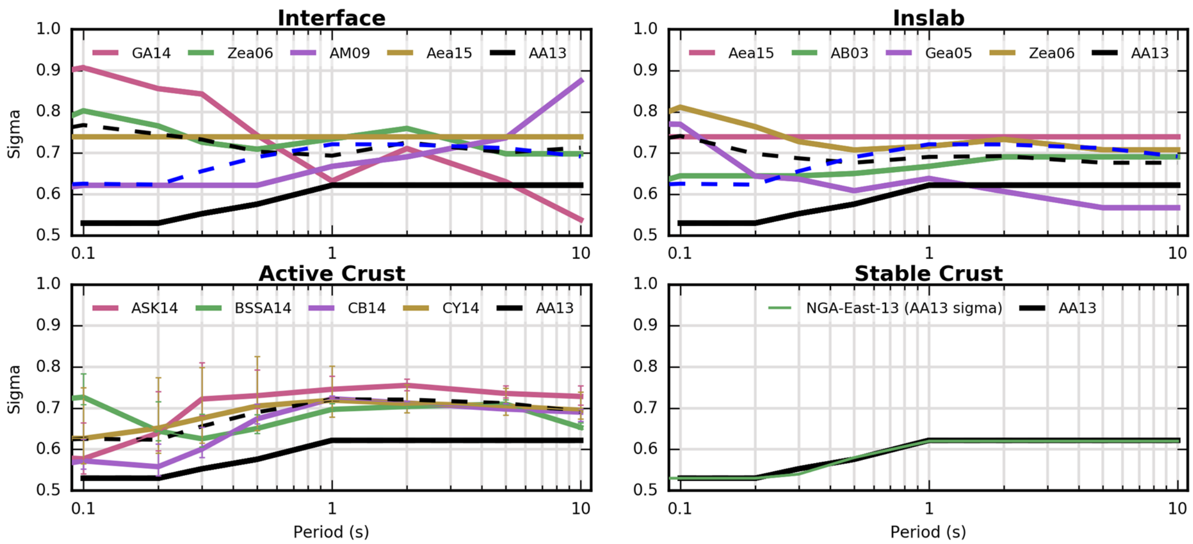

Figure 3. Sigma models for the 6th generation GMMs. Dashed black: mean sigma of the GMMs used. Dashed blue: mean sigma of active crust models for comparison. As the active crust sigma model varies as a function of rupture and site parameters, bars are used to show a representative range of values.

For many localities in the west the change in median ground motions from the GMM (at Site Class C) is not the major driver for the changes in hazard. The 6th Generation GMMs generally fall within the range of epistemic uncertainty of AA13 for many hazard-controlling scenarios; see, for example, Figure 1. This is not surprising considering that AA13 used the spread in the same GMMs (e.g., Zea06) or earlier-iterations (NGA-West1) to guide the bounds of the three-branch representation. Often the larger driver for the increase in median ground motions is the updated sigma model, whereby the average sigma model increased by 0.1 to 0.25 ln units (Figure 3). The increase in sigma is best illustrated by the relative changes in the active crust region; sigma for the 5th Generation model was estimated using the NGA-West1 dataset and there is a general increase in the estimate of sigma in the updated NGA-West2 GMMs. For the inslab and interface sources the average sigma models are comparable to the average active crust (i.e., NGA-West2) models at longer periods ($T \gtrsim 0.4$ s), but are larger at shorter periods (especially for interface GMMs).

The largest contributor to short-period hazard in the Vancouver region are ~M7 inslab earthquakes [19]. As an example of the effect of the updated sigma models on hazard at $T = 0.2$ s, using just the median relations of the 6th Generation inslab GMMs resulted in similar 2% in 50 year hazard to the 5th Generation model (at Site Class C). However, including the 6th Generation sigma model resulted in an overall 30% increase in hazard. While the amount of aleatory uncertainty has increased, there has been a compensating overall decrease in epistemic uncertainty (compare the spread of AA13 versus 6th Generation GMMs in Figure 1).

For eastern Canada, the balance between epistemic and aleatory uncertainty is reversed compared to the west, as the 5th Generation sigma model was retained while the epistemic uncertainty has increased through the adoption of the NGA-East-13 relations (Figure 2). For the east, the increase in hazard for Site Class C is due to the changes in median ground motions, rather than changes in sigma.

SITE AMPLIFICATION

The above discussion of ground motion changes at Site Class C (V_{S30} = 450 m/s) implicitly includes some effects of site amplification because the reference V_{S30} value of the GMMs is 760 – 1100 m/s for the west and 760 m/s (AA13) and 3000 m/s (NGA-East-13) for the east. Amplification factors ($F(T)$) used in NBCC2015 were derived from the active crust GMM of BA08 [13] for $V_{S30} \leq 760$ m/s and from the 2000-to-760 conversion factor of AA13 [1] (calculated from the stable crust GMM of Atkinson and Boore, 2006, [20]) for V_{S30} > 760 m/s). The factors are a function of period and the probabilistic PGA hazard at class C and provide practitioners with a means of transforming the hazard spectra for Site Class C to their desired site class. While simple to implement, there are several issues caused by this approach. Firstly, the probabilistic estimate of PGA will tend to overestimate the amount of non-linearity, as it tends to be larger than the scenario event PGA which governs the degree of non-linearity of individual events. Moreover, it is inappropriate to use the probabilistic hazard of one intensity measure (e.g., PGA) to estimate the degree of non-linearity of a different intensity measure, as their probabilistic hazard values may be dominated by very different events (e.g., 10 s spectral acceleration in Vancouver is dominated by Cascadia interface sources, but the PGA is largely from inslab sources [19]). The second issue with the approach is the use of a single amplification model, as there is considerable variation in published models, even for the same tectonic regime, and this epistemic uncertainty needs to be included.

For these reasons, hazard was calculated directly for each site class and multiple site-amplification models were sampled when possible. If a GMM contained a pre-existing site term in its original parameterization, then that site term was used, as this ensured that it was appropriate for that particular GMM. However, some of the GMMs did not have site terms or their site terms were not applicable at all site classes. Different strategies were used for the west and east to deal with these issues. In both regions, hazard was calculated for V_{S30} values representative of each site class. These values are referred to as $\bar{A}$, $\bar{B}$, $\bar{C}$, $\bar{D}$, $\bar{E}$ and represent V_{S30} values of 1600 m/s, 1100 m/s, 450 m/s, 250 m/s and 160 m/s, respectively, as prescribed in the Commentary of NBCC2015. The value of $\bar{E}$ was increased from the NBCC2015 value of 115 m/s and the lower limit of Site Class E was increased to 140 m/s. This change is proposed for NBCC2020, as it was recognized that few GMM site functions are calibrated for values of $V_{S30} \lesssim 150$ m/s.

West Site Amplification

The empirical site term of Seyhan and Stewart, 2014 (SS14, [21]) was adopted for two of the twelve western GMMs (Inslab: Gea05, and Interface: AM09) that lacked a native site term. SS14 is also the site term of BSSA14 [10]. While SS14 was developed from NGA-West2 data for active crustal GMMs, it is considered a reasonable estimate of site amplification for subduction GMMs that lack a site term.

For Site Class A, there is very little data from western hard rock sites to constrain the amplification models of the adopted GMMs in the west. As such, a lower cap on the amplification factor at Site Class A was implemented. Where it was reasonable, the chosen lower cap was the 2000-to-760 factor for V_{s30} = 2000 m/s of AA13. While this factor was derived for GMMs in the eastern (stable crust) region, it was developed for hard rock observations. However, at $\bar{B}$, the site-terms of many of the western GMMs predict larger deamplification (relative to 760 m/s) than the AA13 factor does at $\bar{A}$. If the $\bar{A}$ site term of the GMM was forced to the AA13 factor (relative to 760 m/s) it would, in general, result in an increase in the ground motions for Site Class A relative to B which is considered to be unreasonable (with exception of at very short-periods). Thus, for a given period, the $\bar{A}$ amplification factor was calculated by interpolating between 760 m/s and 2000 m/s where the amplification factor for 2000 m/s was set to the higher of a) the GMM prediction at 2000 m/s and b) the lower of (1) the 2000-to-760 amplification factor of AA13, and (2) the $\bar{B}$ amplification factor for the particular GMM (Figure 4).

For Site Classes D and E the mean 6th Generation site factors for inslab and interface GMMs (dashed blue lines in Figure 4) are roughly the same as the 2015 factors (black line), but are considerably larger than the 2015 factors for active crust. The 2015 factors are from an NGA-West1 GMM [13] and the site amplification models of NGA-West2 vary more rapidly with V_{S30} (active crust in Figure 4). Recall that $\bar{E}$ was increased from 115 to 160 m/s; while the amplification factors are similar for the same V_{S30} for subduction sources, the mean linear amplification factor to be applied for Class E is lower in the 6th Generation model. For Site Classes A and B, the 6th Generation site factors are smaller (more deamplification) than the 2015 factors.

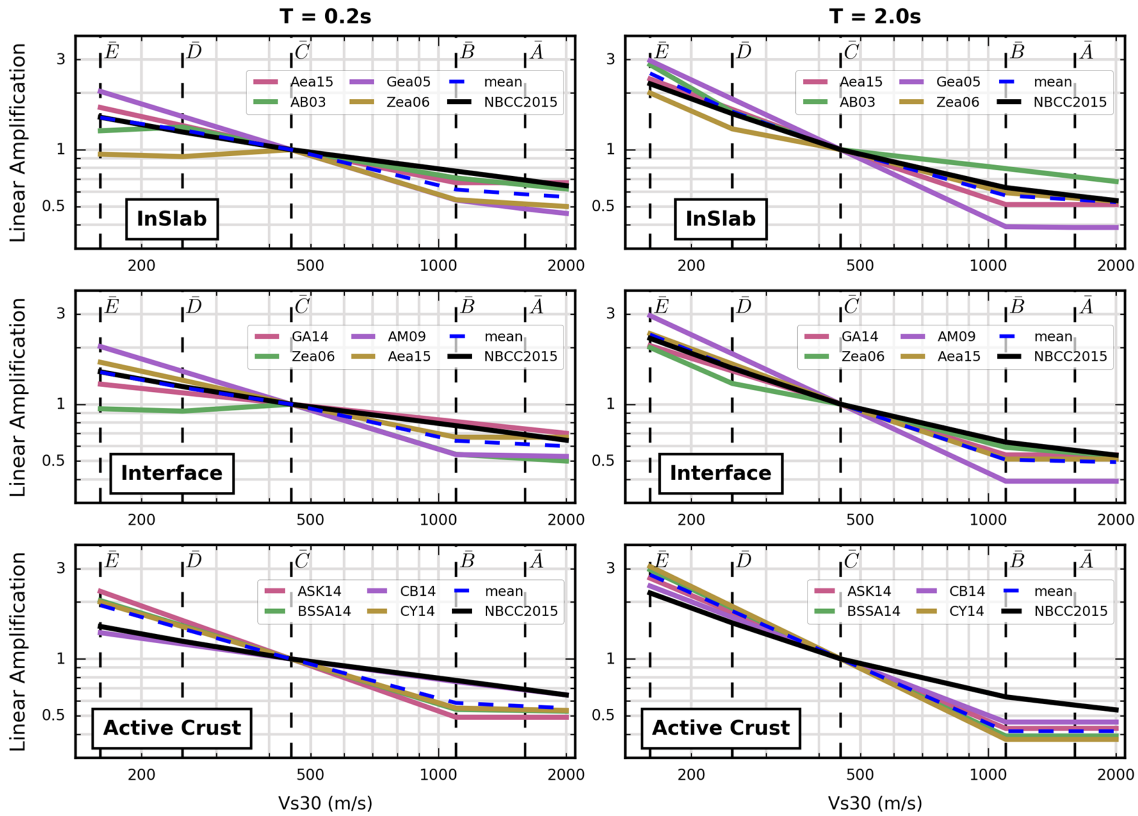

Figure 4. Linear amplification with respect to 450 m/s for western GMMs at T = 0.2 s (left column) and 2.0 s (right column).

East Site Amplification

The GMMs adopted for stable crust sources do not have native site terms and so site terms needed to be selected for the 6th Generation model. For the AA13 GMMs it was reasonable to use the NBCC2015 amplification factors as described above. The NGA-East-13 suite of GMMs is for a reference condition of 3000 m/s and there are few published site amplification models relative to a 3000 m/s reference. The selected site model for the NGA-East-13 GMMs is the larger of a) a continuous function based on the NBCC2015 amplification factors and extended to 3000 m/s using Boore and Campbell, 2017 [22] and b) the L1 model of Harmon, et al. [23] with modification to the non-linear term as recommended to the USGS [24]. The chosen linear amplification factors for the NGA-East-13 model (relative to V_{S30} = 3000 m/s) and for AA13 (relative to V_{S30} = 2000 m/s) can be seen in Figure 5.

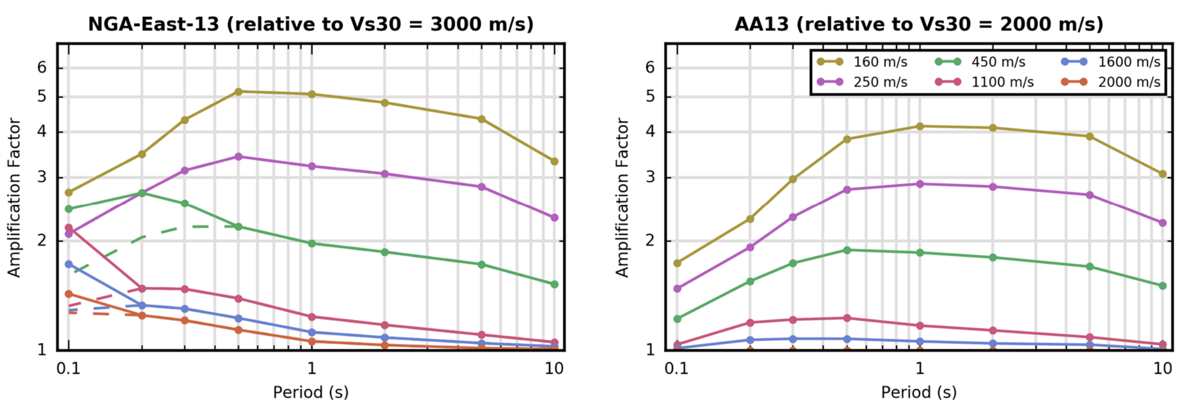

Figure 5. Linear amplification factors for stable crust GMMs. Left: NGA-East-13 GMMs (relative to V_{s30} = 3000 m/s); dashed lines indicate periods at which the function derived from NBCC2015 amplification factors is less than the L1 model of Harmon et al. [23]; Right: AA13 (relative to V_{s30} = 2000 m/s).

The larger of two models is used for NGA-East-13 due to large observed differences between amplification factors for sites with velocity profiles characterized as either gradational or impedance [22]. A gradational site has a shear wave velocity profile that gradually increases with depth. A large portion of the western GMMs have site terms that are intended for and/or largely derived from observations from gradational sites (e.g., NGA-West2, [25]). For sites of this type, the site terms tend to be broadband and increase with decreasing V_{S30} (e.g., SS14 [21]). On the other hand, impedance-type sites are characterized by velocity profiles with a strong impedance contrast as a result of soil over hard rock. Sites of this type often have strong resonance resulting in peaked amplification around the site period [e.g., 22, 26, 27]. Moreover, the scaling of amplification with V_{S30} for impedance sites is weak as it is not the ideal predictive variable for amplification; in these cases site period or soil depth may be a better predictor for the site response [e.g., 23, 26, 27]. While impedance type sites are common in eastern Canada, either type of site (gradational or sharp contrast) can exist for the same V_{S30}. As such, two amplification models are used in order to capture features from the two types; the NBCC2015-like model is more representative of a gradational site and the L1 model [23] which includes considerations for impedance sites such as could be derived from a V_{S30}–only model [23]. The effects of resonance are not fully addressed, as site period (or similar proxy) is not a predictive variable in the 6th Generation model (or NBCC2020). The amplification values are still below what has been observed from resonance effects at the site period [e.g., 28].

Site-specific amplification factors

In order to compare the 6th Generation and NBCC2015 amplification factors, comparable $F(T)$ values from the 6th Generation model were calculated for representative localities. The mean 2%/50 hazard was calculated for a representative suite of localities across Canada at all site classes (e.g., for Vancouver, see Figure 5 of [12]), and divided by the hazard at Site Class C. The NBCC2015 factors are also shown for reference, but recall that V_{S30} for Site Class E has changed from 115 m/s to 160 m/s. It is also important to note that while the comparison below is relative to Site Class C, there is no longer a reference site class for the 6th Generation model and the calculation is performed only as a comparison.

Prior discussions of site amplification focused on the linear portion of amplification. However, at Site Classes D and E (and to a lesser extent at C) non-linear effects will exist in regions of high hazard. Non-linear effects are considered within the GMMs and are typically calculated with respect to the amplitude of a short-period measure (e.g., PGA) on rock. Therefore, at Site Classes D and E site amplification (relative to C) is dependent on the strength of the input motion (as was also the case in NBCC2015). However, as a result of using multiple site-terms within each tectonic regime, the effective amplification factor relative to a reference site condition changes depending on the relative contribution of each of the GMMs to the mean hazard, resulting in different amplification factors for different sites, even for the same PGA.

Figure 6 illustrates the variability in site amplification, most strongly seen in the west, which is due to epistemic uncertainty (i.e., different site terms for the same tectonic region) and to differences in site amplification between tectonic regions. The offset in the linear domain (< 0.1g) represents the average difference between the linear portions of the site terms (observable in Figures 4 and 5) while the slope represents the amount of non-linear deamplification of Site Classes D and E relative to Site Class C. Site Class C also contains non-linear deamplification, as predicted by the site terms of the GMMs, so that the curves in Figure 6 are flatter than if they were relative to rock or hard rock (a typical reference for non-linear deamplification). Also, recall that the amplification factors in NBCC2015 are a function of the probabilistic PGA, which tends to overestimate non-linear effects.

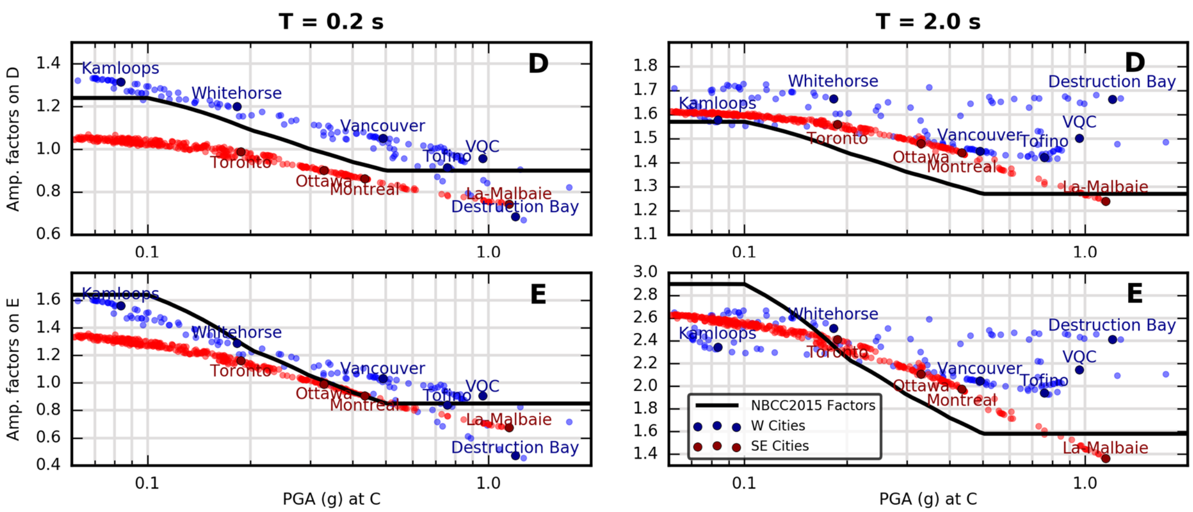

Figure 6. Site amplification (hazard on D or E divided by hazard on C) as a function of PGA for select western and south-eastern localities (VQC= Village of Queen Charlotte).

There are two significant differences with respect to NBCC2015: there is less non-linear behavior (flatter trends, especially at long periods in regions dominated by active crust GMMs, e.g., Destruction Bay, Yukon); and the 0.1-0.5 g limits used in NBCC2015 did not sample the full range of non-linear behavior. These limits, in effect, conservatively capped the amount of non-linear deamplification at a PGA of 0.5 g. Also, at T = 0.2 s the SE locality data has substantially smaller linear amplification (e.g., ~1 for Site Class D) as the difference between Site Class C and D (or E) is small due to the inclusion of the L1 amplification model [23] which increases short-period amplification at Site Class C (see Figure 5). Two trends are also observable for the western cities. This is due to overall differences in site terms between active crust (i.e., NGA-West2) and subduction GMMs (e.g., less non-linearity at long periods). Some cities like Queen Charlotte, where subduction and active crust GMMs both contribute significantly, fall somewhere between.

Another manner in which to present the results is to plot amplified hazard curves (AHCs), which are plots of seismic hazard versus V_{S30} at a given site. While a specific site has a defined V_{S30}, AHCs are useful because they depict how one can expect hazard to vary with V_{S30} for a city where the Site Class can vary from E to A. Figure 7 illustrates example AHCs for Vancouver and Montreal. It is evident that mean hazard is a smooth function of V_{S30}, but is not always monotonic due to non-linearity and site-period effects.

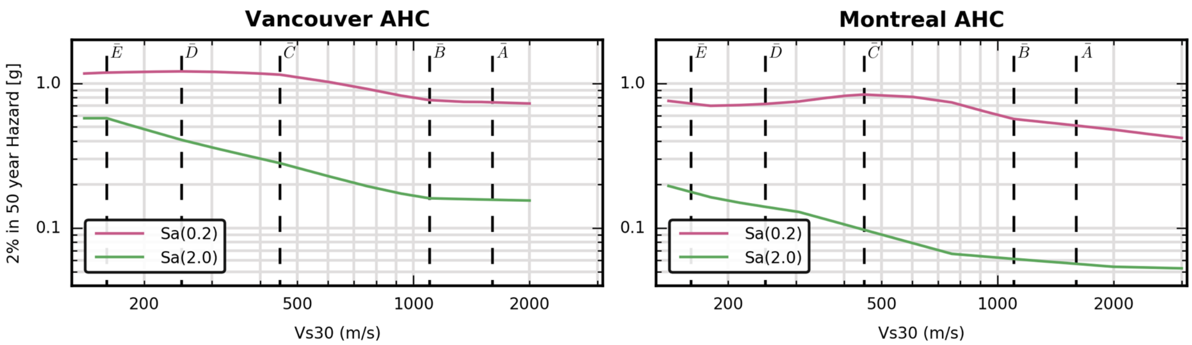

Figure 7. Amplified hazard curves (AHCs) for Vancouver and Montreal.

The adopted site terms represent the response to assumed or average site profiles, as present in the ground motion records used in the development of the GMMs. However, site specific analysis should be considered for sites of importance or where the local geology is expected to produce amplification factors different from the ones presented.

CONCLUSIONS

For most localities in Canada, the 2% in 50-year hazard has increased for all intensity measures in the 6th Generation model. While changes to the source models [12] account for some regional and localized changes (e.g., additional Cascadia interface events, and addition of the Leech River and Devil's Mountain fault systems), for many regions the changes in the GMMs are the major driver for the increase. This is especially true for eastern Canada where there has been no change to the source models. The interplay between changes in median ground motions, aleatory and epistemic uncertainty and site amplification is complex, but several conclusions can be made. In the west, while median ground motions have changed variably there has been an overall increase in the aleatory uncertainty which increases the hazard. For the east, hazard has increased from the inclusion of the NGA-East-13 relations and an updated site amplification model which have increased median ground motions and their epistemic range. For all localities, a large driver for the changes in hazard is due to uncertainties in site characterization. In the east, the uncertainty in site characterization is reflected both in the choice of the site amplification models, and in the median values of the GMMs. In the west, the increase in aleatory uncertainty is, in part, due to the use of global models where data from many regions has been combined and inadequate site characterization has resulted in larger variability. A key research endeavour for the 7th Generation model will be to improve the manner in which site amplification is modelled and how it is included within aleatory and epistemic uncertainty (e.g., [29]).

For the 6th Generation model, hazard is calculated and provided directly for each site class. As such, implied site factors depend on the site in question as the site models differ between GMMs and tectonic regions. This approach simplifies the way end users will determine seismic design values for a given location and site class. It will also remove the need for separate site amplification look-up tables in the building code, enabling users to simply supply their location and site class to determine seismic design values. The 6th Generation model represents a significant step forward for hazard calculation in Canada and the adopted GMMs are being recommended for the calculation of seismic hazard to be used with NBCC2020.

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REFERENCES

[1] Atkinson, GM, Adams, J (2013): Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps, *Can. J. Civ. Eng.*, **40**, 988–998, doi: 10.1139/cjce-2012-0544.

[2] Dowling, J, Finn, WDL, Ventura, CE, Bebamzadeh, A, Fairhurst, M (2016): An alternative approach to site factors for NBCC 2015, *Can. J. Civ. Eng.*, **43**, 1017–1024, doi: 10.1139/cjce-2015-05.

[3] Pagani, M, Monelli, D, Weatherill, G, Danciu, L, Crowley, H, Silva, V, Henshaw, P, Butler, R, Nastasi, M, Panzeri, L, Simionato, M, Vigano, D (2014): OpenQuake Engine: An open hazard (and risk) software for the Global Earthquake Model, *Seism. Res. Lett.*, **85** (3), 692–702.

[4] Abrahamson, N, Gregor, N, Addo, K (2016): BC Hydro ground motion prediction equations for subduction earthquakes, *Earthq. Spectra*, **32** (1), 23-44, doi: 10.1193/051712EQS188MR.

[5] Zhao, JX, Zhang, J, Asano, A, Ohno, Y, Oouchi, T, Takahashi, T, Ogawa, H, Irikura, K, Thio, HK, Somerville, PG, Fukushima, Y, Fukushima, Y (2006): Attenuation relations of strong ground motion in Japan using site classification based on predominant period, *Bull. Seism. Soc. Am.*, **96** (3), 898–913, doi: 10.1785/0120050122.

[6] Atkinson, GM, Boore, DM (2003): Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions, *Bull. Seism. Soc. Am.*, **93** (4), 1703-1729, doi: 10.1785/0120020156.

[7] García, D, Singh, SK, Herráiz, M, Ordaz, M, Pacheco, JF (2005): Inslab earthquakes of central Mexico: Peak ground-motion parameters and response spectra, *Bull. Seism. Soc. Am.*, **95** (6), 2272–2282, doi: 10.1785/0120050072.

[8] Ghofrani, H, Atkinson, GM (2014): Ground-motion prediction equations for interface earthquakes of M7 to M9 based on empirical data from Japan, *Bull. Earthq. Eng.*, **12**, 549–571, doi: 10.1007/s10518-013-9533-5.

[9] Atkinson, GM, Macias, M (2009): Predicted ground motions for great interface earthquakes in the Cascadia subduction zone, *Bull. Seism. Soc. Am.*, **99** (3), 1552–1578, doi: 10.1785/0120080147.

[11] Boore, DM, Stewart, JP, Seyhan, E, Atkinson, GM (2014): NGA-West 2 equations for predicting PGA, PGV, and 5%-damped PSA for shallow crustal earthquakes, *Earthq. Spectra*, **30** (3), 1057-1085, doi: 10.1193/070113EQS184M.

[11] Kolaj, M., Allen, T., and Adams J., (2019): Modifications to ground motion models as used in the 6th generation seismic hazard model of Canada, *Geological Survey of Canada Open File*, in preparation.

[12] Adams, J, Allen, T, Halchuk, S, and Kolaj M (2019): Canada's 6th Generation Seismic Hazard Model, as Prepared for the 2020 National Building Code of Canada, *12th Canadian Conference on Earthquake Engineering*, Quebec City, Canada, paper 192-Mkvp-139

[13] Boore, DM, Atkinson, GM (2008): Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, *Earthq. Spectra*, **24** (1), 99–138,

[14] Abrahamson, NA, Silva, WJ, Kamai, R (2014): Summary of the ASK14 ground motion relation for active crustal regions, *Earthq. Spectra*, **30** (3), 1025–1055, doi: 10.1193/070913EQS198M.

[15] Campbell, KW, Bozorgnia, Y (2014): NGA-West2 ground motion model for the average horizontal components of PGA, PGV, and 5% damped linear acceleration response spectra, *Earthq. Spectra*, **30** (3), 1087-1115

[16] Chiou, BS-J, Youngs, RR (2014): Update of the Chiou and Youngs NGA model for the average horizontal component of peak ground motion and response spectra, *Earthq. Spectra*, **30** (3), 1117–1153, doi: 10.1193/072813EQS219M.

[17] Atik, AL, Youngs, RY, (2014): Epistemic Uncertainty for NGA-West2 Models, *Earthq. Spectra*, **30** (3), 1301-1318.

[18] Goulet, CA, Bozorgnia, Y, Kuehn, N, Al Atik, L, Youngs, RR, Graves, RW, Atkinson, GM (2017): PEER 2017/03 - NGA-East ground-motion models for the U.S. Geological Survey National Seismic Hazard Maps, in, *PEER Report No. 2017/03*, pp. 180.

[19] Rogers, G, Halchuk, S, Adams, J, Allen, T (2015): 5th Generation (2015) seismic hazard model for southwest British Columbia, *11th Canadian Conference on Earthquake Engineering*, Victoria, Canada, Paper 94198.

[20] Atkinson, GM, Boore, DM (2006): Earthquake ground-motion prediction equations for eastern North America, *Bull. Seism. Soc. Am.*, **96**, 2181-2205, doi: 10.1785/0120050245.

[21] Seyhan, E, Stewart, JP (2014): Semi-empirical nonlinear site amplification from NGA-West 2 data and simulations, *Earthq. Spectra*, **30** (3), 1241–1256, doi: 10.1193/063013EQS181M.

[22] Boore, DM, Campbell, KW (2017): Adjusting central and eastern North America ground-motion intensity measures between sites with different reference-rock site conditions, *Bull. Seism. Soc. Am.*, **107** (1), 132–148.

[23] Harmon, J, Hashash, YMA, Stewart, JP, Rathje, EM, Campbell, KW, Silva, WJ, Ilhan, O (2019): Site amplification functions for central and eastern North America - Part II: Modular simulation-based models, *Earthq. Spectra* (in Press).

[24] Petersen, MD, Shumway AM, Powers, PM, Mueller, CS, Moschetti, MP, Frankel, AD, Rezaeian, S, McNamara, DE, Hoover, SM, Luco, N, Boyd, OS, Rukstales, KS, Jaiswal, KS, Thompson, EM, Clayton, B, Field, EH, Zeng, Y (2018): Preliminary 2018 Update of the U.S. National Seismic Hazard Model: Overview of Model, Changes, and Implications, *USGS report for public comment*, 1-47.

[25] Kamai, R, Abrahamson, NA, Silva, WJ, (2016): VS30 in the NGA GMPEs: Regional Differences and Suggested Practice. *Earthq. Spectra*, **32** (4), 2083-2108.

[26] Braganza, S, Atkinson, GM, Ghofrani, H, Hassani, B, Chouinard, L, Rosset, P, Motazedian, D, Hunter, J (2016): Modeling site amplification in eastern Canada on a regional scale, *Seism. Res. Lett.*, **87** (4), 1008-1021.

[27] Hassani, B, Atkinson GM (2018): Site-effects model for central and eastern North America based on peak frequency and average shear-wave velocity, *Bull. Seism. Soc. Am.*, **108** (1), 338-350, doi:10.1785/0120170061

[28] Khaheshi Banab K, Kolaj M, Motazedian D, Sivathayalan S, Hunter J, Crow H, Pugin A, Brooks G. Pyne M (2012): Seismic site response analysis for Ottawa, Canada: A comprehensive study using measurements and numerical simulations, *Bull. Seism. Soc. Am.*, **102**, 1976-1993.

[29] Atkinson, GM (2018): The interface between empirical and simulation-based ground-motion models, *Pure and Applied Geophysics*, **30**, 1-13.