Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 245

IMPACT OF RECENT DEVELOPMENTS IN GROUND MOTION PREDICTION EQUATIONS ON PROBABLE GROUND MOTIONS FOR CANADIAN CITIES

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ABSTRACT

Since development of the NBCC 2005-2010 seismic hazard model in the mid-1990s, the number of recorded ground motions around the world has increased by orders of magnitude, and ground-motion prediction equations (GMPEs) have changed accordingly – sometimes dramatically so. The general impact of newer GMPEs on seismic hazard estimates for Vancouver, Toronto and Montreal is assessed using a sensitivity analysis. Newer GMPEs may have a profound influence on seismic hazard estimates. In eastern Canada, significant reductions may be warranted in short-period Uniform Hazard Spectra for firm-ground sites. Updated seismic hazard assessments are required to fully quantify the impact of new GMPEs on seismic design parameters for major Canadian cities.

Introduction

A key component of the Canadian Seismic Risk Network (CSRN) is the evaluation of probable ground motions for Canadian cities. Realistic assessments of probable earthquake motions are required for input to testing and analysis of structures to identify seismic deficiencies – and are hence a prerequisite for effective assessment of seismic risk. The estimation of probable ground motions within the CSRN has two phases. To date, suites of ground-motion acceleration records (sometimes called "time histories") have been simulated that are compatible with the 2005-2010 National Building Code of Canada (NBCC 2005, 2010) Uniform Hazard Spectra (UHS at 2% in 50 year probability) for selected cities (Atkinson 2009). Simulated accelerograms are a flexible complement to scaled or modified real accelerograms, providing earthquake records having the expected amplitudes and spectral content for the types of earthquakes that contribute most strongly to hazard. These accelerograms may be used in generic nonlinear dynamic analyses or experimental testing to assess the vulnerability of structures in the context of the current building code requirements.

It is also important to look towards future trends in order to refine our knowledge of the seismic hazards, and thus the second phase of the CSRN research will develop updated seismic hazard analyses for Canadian cities, incorporating new knowledge in seismicity, tectonics, ground motions, and site amplification effects. Accelerograms may then be matched to either current or updated spectra. Updated hazard estimates are needed, because the current NBCC (2010) seismic hazard maps actually date back to the mid 1990s in terms of the input model and parameters, and there have been significant advances in available data and knowledge since that time. For example, the recurrence models are based on seismicity and magnitude information to 1991, while the adopted ground-motion prediction equations (GMPEs) are based on relations

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available as of 1997 (see Adams and Halchuk 2003; Adams and Atkinson 2003). The GMPEs are particularly important. They specify the peak ground motions and response spectral ordinates as a function of earthquake magnitude and distance. For most applications, the seismic hazard results, expressed as response spectral ordinates having a fixed (i.e. uniform hazard) probability of exceedence (UHS), are more sensitive to the adopted GMPEs than to any other input parameter. Since development of the NBCC 2005-2010 seismic hazard model, the number of recorded ground motions around the world has increased by orders of magnitude, and GMPEs have changed accordingly – sometimes dramatically so. In this paper, I perform a preliminary evaluation of the impact of new GMPEs on seismic hazard analyses. The focus is on the NBCC 2010 seismic hazard estimates for firm-ground sites (Class C) for Vancouver, Montreal and Toronto. Recent GMPEs are reviewed, and their relative impact on seismic hazard estimates is assessed using a sensitivity approach.

Recent Ground Motion Prediction Equations

In western North America, most modern seismic hazard applications, including the 2008 national seismic hazard maps produced by the U.S. Geological Survey (Petersen et al. 2008), use the recent PEER-NGA GMPEs for shallow crustal events (see Power et. al. 2008 and references therein). By contrast, the NBCC 2005-2010 maps used the earlier relations of Boore et al. (1997) (BJF97), modified at distances beyond 100 km by inclusion of an anelastic attenuation term suggested by Atkinson (see Adams and Halchuk, 2003 for details). Fig. 1 shows the differences between the newer NGA equations and the modified BJF97 relations; to illustrate the new equations, I plot the Boore and Atkinson (2008) NGA equations (BA08) that update BJF97, as well as the median of all of the NGA equation sets (see Power et al. 2008 and references therein). The 5% damped pseudo-acceleration (PSA) is shown for natural vibration frequencies of 1 and 5 Hz; these are the approximate frequency ranges of interest for 10 and 2-storey buildings, respectively. The main observation from Fig. 1 is that the new GMPEs estimate lower ground-motion amplitudes from large events nearby, particularly for low frequencies. This reflects new knowledge of saturation effects that has been gained from the wealth of new data on ground motions from crustal earthquakes, gathered in the last 10 to 20 years. I view all of the NGA equations as being of equal merit for application to western Canada. They are all based on a rich global database for moment magnitude (**M**)>5.5; nevertheless, all suffer from significant uncertainty in their applicability to the glaciated site conditions of western Canada, as well as in their reliability for small-to-moderate magnitudes (**M**<6) (Atkinson and Morrison, 2009; Chiou et al., 2010). For preliminary evaluation purposes the BA08 equations are convenient due to their simplicity.

For subduction earthquakes, there are significantly-improved GMPEs available for both in-slab and interface events, those of Zhao et al. (2006) being one good example. These newer relations are based on more than ten times as many records as were available to Youngs et al. (1997) (Y97), whose relations were used in NBCC 2005-2010. Figure 2 illustrates the implications of the new GMPEs for in-slab events of **M** 6.0 to 7.5 on C sites. The newer in-slab GMPEs show stronger scaling with magnitude in comparison to the Y97 equations, with larger motions predicted for large in-slab events near the epicenter (fault distances of 50 to 60 km). However, it is noteworthy that the in-slab equations of Atkinson and Boore (2003) (AB03) feature higher motions at high frequencies in Japan than in Cascadia, due to differences in typical profiles of C-class sites in the two regions. Shallow soils over rock in Japan tend to amplify high frequencies; this was evidenced by direct comparisons of in-slab motions for the well-recorded **M**6.7 in-slab earthquakes of 2003 in Cascadia (Nisqually earthquake) and Japan (Geiyo earthquake) (Atkinson and Casey, 2003). The Zhao et al. (2006) in-slab equations are based entirely on data from Japan. The Zhao equations agree well with the AB03 equations for Japan (especially at larger magnitudes), but are significantly higher than the AB03 equations for Cascadia at high frequencies. It is likely that the Zhao equations are an over-estimate of high-frequency motions for in-slab events in Cascadia, due to the Japanese site conditions. Furthermore, the AB03 equations have been shown to agree well with the Nisqually, 2003 ground-motion database. Thus for preliminary evaluations of the impact of newer GMPEs on seismic hazard estimates in Vancouver, the AB03 equations are probably more appropriate. An interesting observation is that in-slab events appear to scale much more strongly with magnitude than do crustal earthquakes (compare to BA08 scaling, for example, shown at larger distances on Fig. 2), particularly at high frequencies.

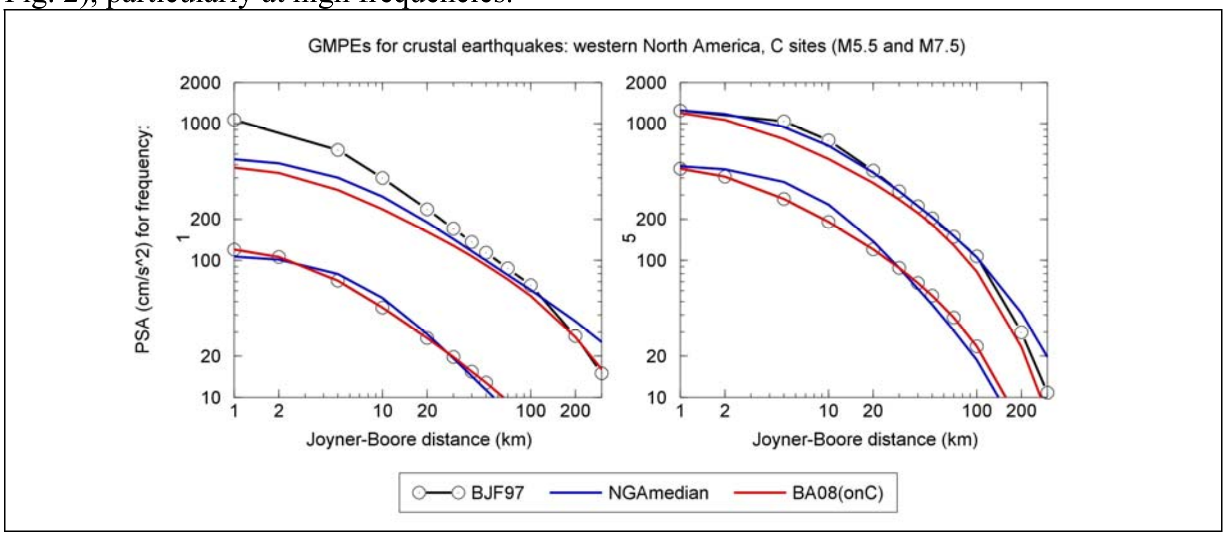

Figure 1. GMPEs for crustal earthquakes in western North America, on C sites, **M**5.5 and 7.5.

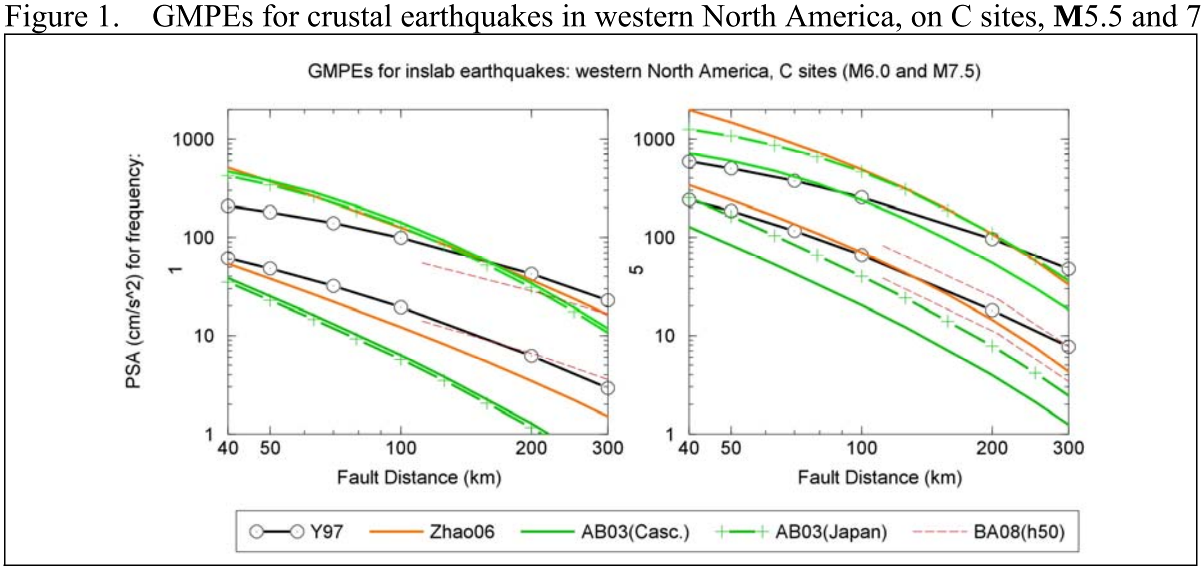

Figure 2. GMPEs for in-slab earthquakes of **M**6.0 and 7.5 on C sites. Y97 used in NBCC2010. Newer AB03 GMPEs for Cascadia and Japan are shown, along with Zhao et al. (2006) equations for Japan. BA08 crustal GMPEs also shown (at depth of 50 km).

For interface events, only the largest magnitudes are important, as interface events would occur offshore at considerable distance, and are best represented by a characteristic-type earthquake model (there is currently no moderate seismicity on the interface). Figure 3 compares the Youngs et al. (1997) interface equations, as used in NBCC2005-2010, to newer empirical equations of Zhao et al. (2006) for Japan, and to hybrid equations specifically for Cascadia by Atkinson and Macias (2009) (AM09), which are based on a combination of empirical and simulated data. The Zhao et al. (2006) interface equations are very similar to those of Atkinson and Macias (2009), considering that the observed differences at higher frequencies can be attributed to the Japanese shallow-soil site conditions, which cause high-frequency motions in Japan to exceed those expected for typical C-class sites in Cascadia by nearly a factor of two (as discussed above and shown in Fig. 2). Both the Zhao et al. and AM09 equations predict significantly higher amplitudes at distances <50 km (offshore) than do the Y97 or AB03 equations, but steeper attenuation. I now believe, based on better data, that the attenuation rates in AB03 for interface events are too slow; they were likely biased by the inclusion in AB03 of interface data from Mexico, which is not representative of behavior in other regions. I use the AM09 equations for preliminary evaluation of the impact of new interface subduction equations on hazard estimates in Vancouver. Interestingly, at distance near 100 km, where most of Cascadia's major cities (including Vancouver) are located, the estimates of Y97, AB03 and AM09 are all fairly similar, and thus the choice may not be critical.

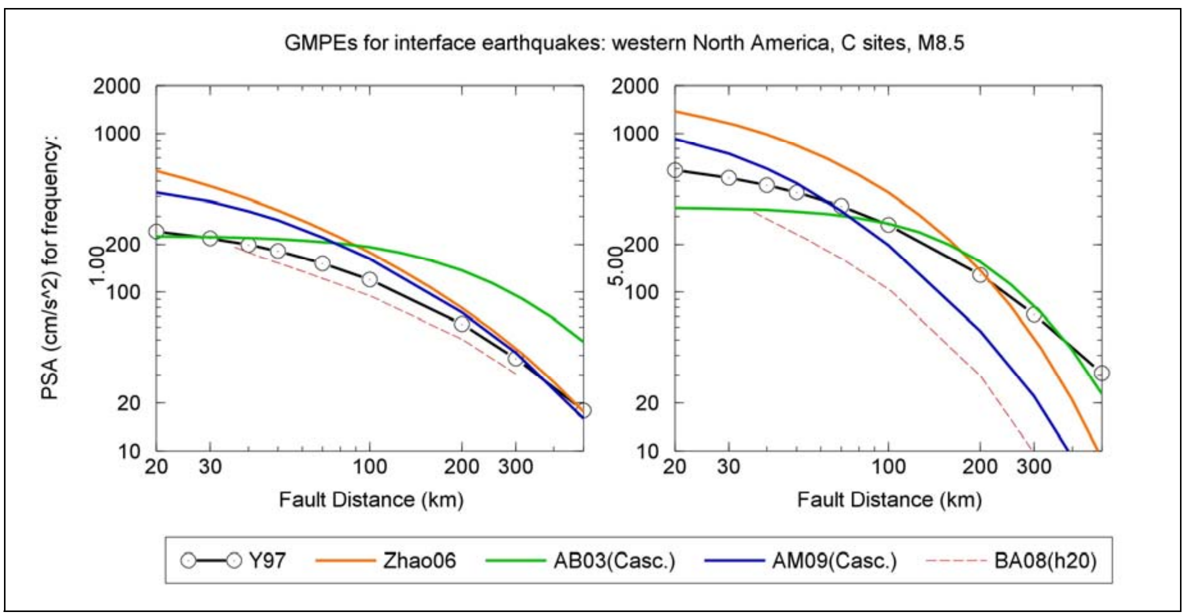

Figure 3. GMPEs for interface earthquakes of **M**8.5 (C sites). Y97 used in NBCC2010, AB03(Casc.) includes Cascadia factors. BA08 for crustal earthquakes shown for reference.

In eastern North America (ENA), there have been significant developments in both the methodology and databases for GMPEs. Consequently, Atkinson and Boore (2006) (AB06) updated their previous GMPEs (Atkinson and Boore 1995, AB95), which had formed the basis of NBCC 2005-2010. There have also been new hybrid empirical models proposed for ENA, by Campbell (2008) and Pezeshk et al. (2009). The Campbell and Pezeshk models are currently under revision. Figure 4 shows the implications of the new ENA GMPEs; only the AB06 equations have been finalized in print, but both the Campbell and Pezeshk equations are useful comparisons from alternative methodologies. Note the tendency of all the newer equations to predict reduced amplitudes at high-frequencies, relative to AB95, especially for larger magnitudes; this trend is particularly pronounced in the AB06 model. Overall, the newer models are less different from each other than were previous models (eg. see the 12 models discussed by EPRI, 2004). In particular, it is encouraging that the newer models agree best with each other in the magnitude-distance ranges where data are most abundant, and suggest greater epistemic uncertainty at large magnitudes and close distances, where constraining data are sparse.

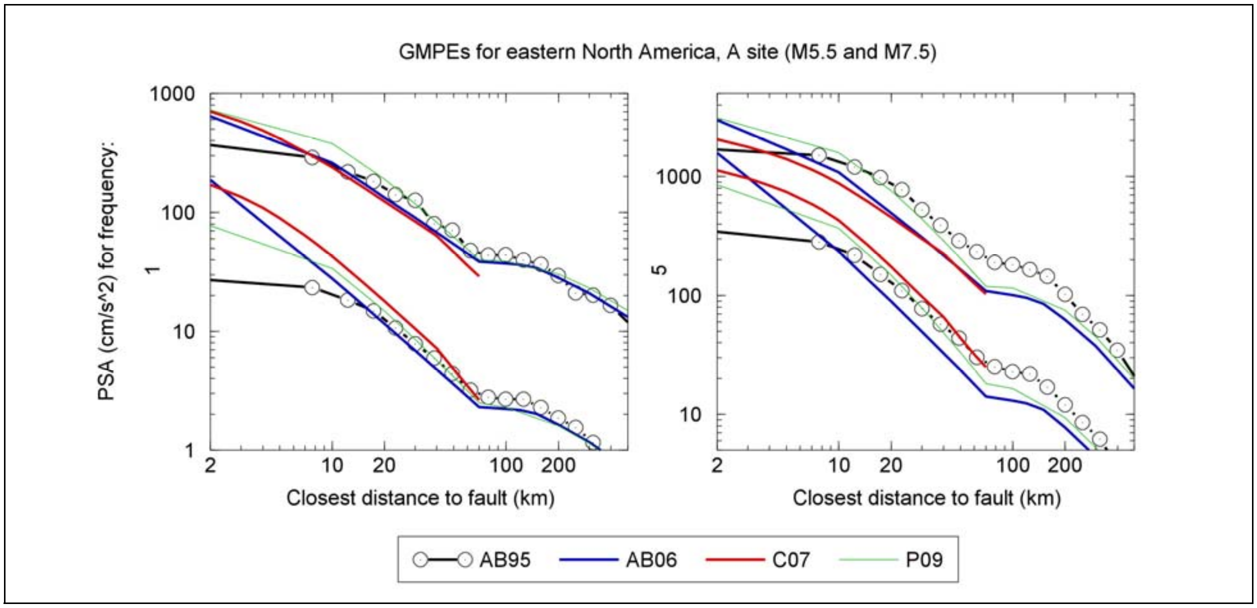

Figure 4. GMPEs for hard-rock sites (vs>2000 m/s) in ENA. AB95 model used in NBCC2010 (assumed hypocenter at 10 km depth); C07=Campbell (2008); P09=Pezeshk et al. (2009).

Impact of GMPEs on Seismic Hazard Estimates

Seismic hazard analyses in Canada are based on probabilistic concepts which allow incorporation of both geologic interpretations of seismic potential and statistical data regarding the locations and sizes of past earthquakes. The Cornell-McGuire method (Cornell, 1968; McGuire, 1976, 2004) has proven particularly well-suited to calculate expected ground motions for a wide range of seismic hazard environments, and forms the basis for the seismic hazard maps in the NBCC (Adams and Halchuk 2003; Adams and Atkinson 2003). The results are generally expressed as a Uniform Hazard Spectrum (UHS), in which the amplitude for each frequency corresponding to a specified target probability is provided. In the Cornell-McGuire method, the spatial distribution of earthquakes is described by defining seismic source zones (faults or areas, which may contain groups of faults) on the basis of seismotectonic interpretations; the earthquake potential of these zones is generally assumed to be uniform. The frequency of earthquake occurrence within each source zone is described by a magnitude recurrence relationship, truncated at an upper magnitude bound, Mx. Ground-motion prediction equations (GMPEs) provide the link between the occurrence of earthquakes of various magnitudes and the resulting ground motion levels at any site of interest. The probability of exceeding a specified level of ground motion at a site can then be calculated by integrating hazard contributions over all magnitudes and distances, including all source zones. To obtain ground motion levels or earthquake response spectra for a specified probability, calculations are repeated for a number of ground motion values, for all desired ground motion parameters, and interpolation is used to determine the relationship between ground-motion amplitude and annual probability.

In this study, the Cornell-McGuire method is implemented to approximately reproduce the NBCC 2010 UHS, which are median-hazard ground motions defined for a probability of 2% in 50 years on Class C sites. The NBCC 2010 model incorporates random variability, and partially incorporates the effects of epistemic uncertainty through the use of a limited-branch logic tree approach (see Adams and Halchuk 2003 for details). To facilitate analysis of the effects of changes to the GMPEs on seismic hazard results, I determined an equivalent model to match the median-hazard UHS from the national seismic hazard maps (as provided by J. Adams and S. Halchuk, Geological Survey of Canada). To do this, I defined a single large areal source zone having the same density of earthquakes at the **M** 5 level as the NBCC 2010 model (from Adams and Halchuk 2003), for the source in which (or above which) the site is located, and the same recurrence slope (b-value). The source zone is arbitrarily defined as a square 1000 km by 1000 km (area of 10^6 km^2), with the site located in the centre; the size is unimportant as the seismicity levels are normalized on a per unit area basis, with most hazard contributions coming from within 100 km. The aleatory uncertainty (sigma) on all GMPEs is assumed to be given by a simple model where sigma=0.30 log10 units at low frequencies (≤0.5 Hz), and smoothly decreases to 0.25 at high frequencies (≥5 Hz). I perform the seismic hazard integration for the best-estimate GMPE used in the NBCC 2010 for the zone, making small adjustments to the normalized rate of **M**5 earthquakes and the b-value as needed until the median NBCC 2010 UHS is approximately matched by the "NBCC 2010 equivalent" model (to within about 10% over the frequency range of interest). This simple approach works well because seismic hazard is dominated by contributions from the source zone in which the site is located.

The most important changes anticipated in updated seismic hazard estimates for Canadian cities over the next few years are those due to newer GMPEs. The GMPEs tend to change significantly over a time span of years to decades, while the basic seismicity parameters that control earthquake rates do not change much (Atkinson 2004). Thus we can gain a very good appreciation of the overall effects of upcoming trends in seismic hazard assessment by changing just the GMPEs in the "NBCC 2010 equivalent" model. This exercise, conducted for Vancouver, Montreal and Toronto, is also a useful way of evaluating, from a sensitivity perspective, the effects of uncertainty in GMPEs on seismic hazard results. However it should be stressed that this evaluation points only to general trends and their likely magnitude. A full evaluation needs to account for epistemic uncertainty in all parameters, including the GMPEs. Epistemic uncertainty in GMPEs has traditionally been handled by defining several alternative GMPEs and assigning them weights (eg. as in the U.S. national seismic hazard maps by Petersen et al., 2008). However, this is not a rigorous approach to defining the actual uncertainty over the magnitudes and distances that are relevant to hazard. A better approach would be to make synchronized use of both the alternative GMPEs and the data that they purport to characterize to devise a better representation of epistemic uncertainty (Atkinson, 2010; see also Douglas, 2010).

Definition of the NBCC 2010 equivalent model

For Montreal and Toronto, only crustal earthquakes need be considered, and thus there is only one source zone to define (for each city); the GMPE for the "NBCC 2010 equivalent" model is the AB95 relation. The GMPE for the NBCC 2010 equivalent model is defined to be the same as that used in the NBCC 2010 calculations. For Vancouver, there are hazard contributions in the NBCC 2010 model from both crustal and in-slab earthquakes; thus two zones are defined, one for crustal events, and an underlying matching zone for the in-slab events. The GMPEs for these zones are the BJF97 and Y97 relations, respectively. The hazard integration is performed from **M**5 to **M**7.5 for all source zones. The derived "NBCC 2010 equivalent model" provides UHS values within about 10% of the actual UHS values from NBCC 2010, as calculated by the Geological Survey of Canada. The values of N≥5 (annual rate of earthquakes of **M**≥5) and b (slope of the plot of log(10) N(≥**M**) versus **M**) for each city are as follows, for a zone with area 10^6 km^2: (i) Vancouver (crustal) N5=1.12 , b=0.74 ;(inslab) N5=2.57 , b=0.52 ; (ii) Montreal N5=0.50 ,b=0.85 ; (iii) Toronto N5=0.045 ,b=0.70.

Results

I explore the impact of new GMPEs by updating these equations in the "NBCC 2010 equivalent" model, leaving all other parameters the same. This allows an evaluation of the impact of new knowledge of ground motions on seismic hazard estimates, and points towards the likely trends that will emerge as seismic hazard analyses for Canadian cities are updated over the next few years. Due to space and scope limitations here, I use only a single set of newer GMPEs from those presented above (for each source zone); the approach is thus a preliminary sensitivity analysis only. Future work will evaluate the effects of the full range of alternative newer GMPEs more thoroughly, including treatment of the important issue of their epistemic uncertainty. For consistency, all equations selected are for the B/C boundary site condition (vs_{30}=760 m/s). For Toronto and Montreal, I change the AB95 GMPE model to the updated model of AB06. For Vancouver, I update the BJF97 GMPE for crustal earthquakes to the BA08 NGA relationship, while the in-slab GMPE is updated from Y97 to AB03 (Cascadia). The AB03 in-slab equations are not available for B/C conditions; I thus convert from C (vs_{30}=550 m/s) to B/C(vs_{30}=760 m/s) using the factors of Boore and Atkinson (2008), assuming linear response. All other input parameters of the seismic hazard calculation model are retained at the values used for the "NBCC 2010 equivalent" model.

The sensitivity on the 2%/50 year UHS values to these updates in the GMPEs is shown on Figure 5 (all UHS plotted for B/C conditions). (Note the UHS is "capped" at a uniform value for periods <0.2 s, as per the NBCC formulation; the PGA is plotted for reference at an arbitrary period of 0.02s). For Vancouver, the effect of new GMPEs is relatively minor, with a modest reduction in the UHS at short periods, and a modest increase at long periods. The hazard contributions are dominated by the expected ground motions from in-slab events, at all periods. Thus consideration of the appropriate GMPEs for these events is of critical importance for future seismic hazard estimates in Vancouver. An additional factor to consider is that new seismic hazard models should include the hazard contributions from great Cascadia interface events directly in the hazard integration, effectively increasing the net rate of large earthquakes considered in the model. To illustrate the possible effect of this change, I added the Cascadia interface source as a characteristic earthquake model, with a frequency of 1/350 years for **M**7.5 events to 1/1000 years for **M**9 events, using the Cascadia interface GMPE of Atkinson and Macias (2009). For calculation purposes the source is placed at a closest-distance to Vancouver of 145 km. The results indicate that adding this additional source does not significantly affect the UHS shown in Figure 5. The hazard contributions are still dominated by in-slab earthquakes, and thus the expected ground motions do not change perceptibly. The Cascadia source is too far away to have much impact on the expected ground motions in Vancouver on firm sites. Of course, this does not mean that the hazard from such events is inconsequential – only that it cannot properly be assessed by looking just at maximum ground-motion amplitudes on firm sites. Furthermore, the relative importance of different event types may change upon a fuller consideration of epistemic uncertainty. Goda et al. (2010) provide a more complete treatment of updated seismic hazard estimates in Vancouver and the possible influence of the Cascadia subduction source.

In Toronto and Montreal, the effects of updating GMPEs could be dramatic. Figure 5 indicates that updating from AB95 to AB06 would decrease short-period UHS values by about a factor of two, while effects at longer periods are minimal. The reasons for dramatic reductions at high frequencies are two-fold. First, the AB06 GMPEs predict significantly lower high-frequency ground motions than AB95. This tendency would be mitigated by also including, in a fuller uncertainty analysis, other recent GMPEs that feature a more modest high-frequency reduction (eg. Campbell, 2008 or Pezeshk et al., 2009). Second, the NBCC 2010 model implicitly includes large amplification factors in converting the AB95 equations for hard rock to equivalent values for C sites; the applied "Reference Ground Condition" factor at 5 Hz, used to obtain the C-class UHS from the A-class calculations, is a factor of 1.94 (Adams and Halchuk, 2003). More recent models do not predict such large amplifications from A to C; this is partially due to newer methodology, and partially due to inclusion of the effects of nonlinearity. For example, the BA06 model would implicitly predict an amplification factor of approximately 1.35 from A to C at 5 Hz. Differences in the amplification models from rock to firm soil thus account for nearly half of the observed reductions in predicted UHS values for Montreal and Toronto at high frequencies. It should be emphasized that Figure 5 is presented to show sensitivity to newer GMPEs, not to suggest final values that will be obtained by newer seismic hazard studies, nor to recommend any particular GMPEs. The main point is that newer GMPEs in ENA are likely to suggest lower UHS values at high frequencies than the 2010 NBCC values. There could be significant economic implications for seismic design for building code applications. Therefore, a full and careful update of seismic hazard estimates, considering new GMPEs, other new information, and their uncertainties, should be conducted as a high priority.

Conclusions

Seismic hazard estimates for Canada's major cities need to be updated from the UHS values provided in NBCC2005-2010, which have their genesis in a 1995 seismic hazard model. In particular, new GMPEs have significant implications for UHS values. This is particularly true in the east, where newer GMPEs suggest that short-period UHS values at 2% in 50 years for firm-ground (C) sites might be dramatically reduced. It should be emphasized that this study provides only a general guide to the direction and magnitude of upcoming changes that should be expected in future national seismic hazard maps and site-specific assessments for Canadian cities. The results presented constitute a sensitivity study, focused just on ground-motion equations, rather than a full seismic hazard analysis. Actual seismic hazard models for such applications will be more complex, including a host of new GMPEs, rather than just representative examples, and also including other changes and uncertainties. Thus the final results of updated seismic hazard estimates for Canadian cities may differ significantly from those presented here.

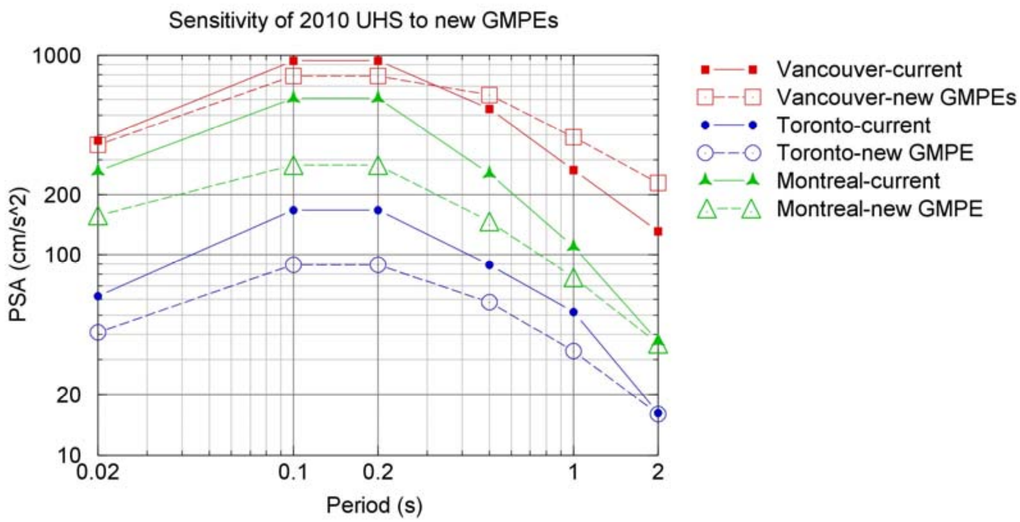

Figure 5. Illustration of sensitivity of UHS to new GMPEs; comparison shows current (NBCC 2010) UHS and re-calculated values using new GMPEs. All UHS for B/C site conditions.

Acknowledgments

CSRN is funded by the Natural Sciences and Engineering Research Council of Canada.

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