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A CONSISTENT CROSS-BORDER SEISMIC HAZARD MODEL FOR LOSS ESTIMATION AND RISK MANAGEMENT IN CANADA

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ABSTRACT: We describe a seismic hazard model that seamlessly integrates national seismic hazard models for the conterminous U.S and Canada to provide earthquake risk managers the latest seismic hazard science and technology for the cross-border region. The model uses (1) spatially varying gridded seismicity for the major metropolitan areas of southeastern Canada, (2) a comprehensive probabilistic model for the Cascadia subduction system that includes the possibility of giant (M9) earthquakes similar to the 2011 Tohoku-oki earthquake in Japan, (3) updated ground motion prediction equations (GMPEs) for eastern and western North America, and (4) a soil-based attenuation (SBA) methodology to avoid bias in the conversion of earthquake motions from rock to soil where the majority of exposure is sited. NEHRP site conditions were mapped for all of Canada from existing regional geological data with refined large-scale soil mapping for major metropolitan areas where detailed soil information was available.

1. Introduction

A fundamental tool for modern portfolio seismic risk management in the insurance industry is the stochastic earthquake event set, which is typically derived from a probabilistic seismic hazard assessment (PSHA) model. The stochastic event set is a geographically referenced set of earthquake scenarios, each defined by an earthquake magnitude, recurrence frequency, and ground motion “footprint,” that appropriately represent the median hazard, epistemic uncertainty, and aleatory variability represented by a PSHA model. It allows the estimation of portfolio damage and losses from earthquakes over a wide range of loss exceedance probabilities or return periods, where the return period is the reciprocal of the annual probability of exceedance.

This purpose is quite different from the usual engineering use of a PSHA model whose intent is to create national seismic hazard maps (NSHMs) in which amplitudes of selected ground motion intensity measures for a specified return period are used to specify codified seismic design requirements. Because government-based NSHM models are widely regarded as incorporating the best available scientific knowledge concerning the seismic hazard for a given region or country, especially by the insurance industry, they are commonly used to develop national stochastic event sets. Reinsurance companies are often interested in estimates of economic damage or insured losses to a portfolio of sites that span international borders, so it is important that the hazard across these borders be consistent and unbiased in order for these companies to manage their risk properly. This is the motivation for developing the consistent Canada-U.S. cross-border hazard model described in this paper and in Thenhaus et al. (2015).

2. Previous Cross-Border Hazard Investigations

Halchuk and Adams (1999) compared a preliminary version of the fourth generation seismic hazard model of Canada (Adams et al., 1995, 1999) with the 1996 version of the U.S. national seismic hazard model (Frankel et al., 1996) after correcting for differences in reference soil conditions between the two studies. They found ground motion values for cities in similar tectonic environments on either side of the border to agree within 50%. They concluded that the disagreement in hazard contours across the border was caused by differences in the definition of source zones, choice of ground motion prediction equations (GMPEs), and the treatment of the Cascadia subduction zone. They proposed smoothing the ground motion values for a given level of hazard using a ramp function over a transition zone defined by a 100 km region on either side of the border. Although this approach might be appropriate for engineering applications at single sites and a limited number of probability levels, it cannot be used to assess hazard and risk to a portfolio of properties where single events can impact multiple sites on both sides of the border.

3. Seismic Source Characterization Model

The principle sources of the seismic hazard data used in this study to develop our seismic source characterization (SSC) model are the fourth generation NSHM model of Canada (Adams and Halchuk, 2003; Halchuk and Adams, 2008) developed by the Geological Survey of Canada (GSC) and the 2008 U.S. NSHM model (Petersen et al., 2008), with updates through 2009 (S. Harmsen, personal communication), developed by the U.S. Geological Survey (USGS). Both national models were developed to serve as the basis for prescribing building-code engineering seismic design criteria in their respective countries. However, approaches to accomplishing this purpose differ between the two governmental organizations, as summarized below.

In Canada, a primary part of the epistemic uncertainty is explicitly modeled using multiple Euclidean source geometries and historical seismicity rates, which GSC calls the Historical (“H”), Regional (“R”), and Floor (“F”) models, combined with a deterministic Cascadia subduction zone megathrust (“C”) model. The H-model uses Euclidean (area) source zones to define spatial clusters of historical shallow crustal earthquakes and intermediate-depth Wadati-Benioff (intraslab) earthquakes on the premise that future earthquakes will likely occur in the vicinity of past earthquakes (e.g., Kafka and Levin 2000). On the other hand, the R-model uses larger Euclidean source zones to distribute the historical earthquakes along regional structural geologic trends on the premise that future earthquakes of similar maximum magnitude cannot be excluded from areas of similar geological setting based on lower historical recurrence rates alone. The F-model provides a minimum hazard in the low seismicity region of central Canada. For building-code purposes, the largest ground motion from the four models was used in a conservative “robust” approach of estimating the hazard at a given location. The Queen Charlotte fault that forms the strike-slip boundary between the Pacific and North American plates north of the Cascadia subduction zone was the only shallow crustal fault that was included in the model. Additional details are provided in Adams and Halchuk (2003).

In the U.S., crustal faults control the hazard in large parts of the western U.S. away from the Cascadia subduction zone and spatially smoothed historical seismicity defines the hazard elsewhere. By using smoothed seismicity, the dilemma of uncertain boundary choices on seismic source definitions in regions where causative geological structures are unknown is avoided in the USGS PSHA methodology. Although this approach is also consistent with the observations of Kafka and Levin (2000), it differs somewhat from the area-source zonation methodology used by the GSC for the H-model and differs significantly from the GSC’s R-model. The smoothed seismicity approach uses a kernel smoothing method to assess earthquake frequency in regions of unknown causative faults (Frankel, 1995) with maximum magnitudes defined on the basis of regional tectonics (e.g., Wheeler and Frankel, 2000). Crustal faults in the Puget Sound region contribute to the hazard at long return periods; otherwise, the hazard is dominated by the smoothed seismicity associated with the Cascadia subduction zone Wadati-Benioff (intraslab) and megathrust interface events. The Cascadia subduction zone megathrust was modeled using a full probabilistic representation of possible rupture scenarios on the subduction interface. Primary sources of epistemic uncertainty are incorporated through a logic-tree methodology that assigns probabilities or likelihoods to alternative modeling choices. Additional details are provided in Petersen et al. (2008) and Field et al. (2009).

A major challenge of this study was to merge the two national models in order to provide a consistent and unbiased cross-border view of seismic hazard along the southern boundary of Canada with the U.S., considering the different approaches used in each country to quantify the seismic hazard for use in the building codes. We chose to use the U.S. NSHM model as our primary source of seismic hazard data when possible, even in Canada, because it uses more current science and technology than the Canadian fourth generation NSHM model. The choice of using the USGS hazard model as the primary model, while not necessarily supported by the GSC, served to provide spatial and methodological continuity with our existing stochastic event set for the conterminous U.S.

Merging of the two models was accomplished by developing a "transition region" that provided a smooth transition between the GSC and USGS source zonation and earthquake recurrence models. Within this region, represented by the hachured area in Figure 1, the smoothed seismicity from the USGS model was averaged with the area-source seismicity from the GSC H-model on a 0.1° by 0.1° grid. The GSC H-model was used for this purpose because it more closely represents the historical seismicity of Canada, making it similar to the smoothed seismicity approach used by the USGS. The GSC H-model was used exclusively north of the transition region. The USGS smoothed seismicity and crustal fault models were used exclusively south of the transition region. The USGS probabilistic fault-rupture model for the Cascadia subduction zone, with its full logic-tree representation of uncertainty, was used in place of the GSC deterministic model to estimate the seismic hazard in British Columbia. More detail regarding the modification of the GSC seismic hazard model is provided in the regional discussions presented in the next sections.

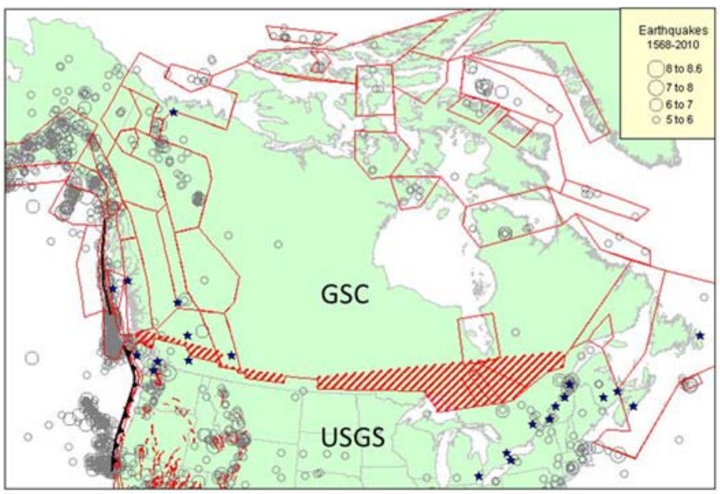

Fig. 1 – Canada-U.S. seismic source model. Red boundaries are Euclidean area-source zones from the GSC H-model. Red hachures are transition regions between the GSC Canada and USGS U.S. models. Stars indicate the locations of Canadian cities used to compare seismic hazard estimates between our model and the GSC model.

3.1. Southeastern Canada

Approximately 70 percent of the population of Canada is concentrated in southeastern Canada, along and near the international border extending from Windsor, Ontario (across the border from Detroit, Michigan) to Quebec City, and includes the cities of Toronto, Montreal, and Ottawa. Although part of the Stable Continental Region (SCR) of central and eastern North America (CENA), this area has experienced no less than 15 moment magnitude (**M**) 5.0 to 7.2 earthquakes since 1663 (Lamontagne et al., 2008). These events are located within the failed rifts that formed during the initial opening of the Atlantic Ocean basin. Active faults responsible for these damaging earthquakes remain unknown and the seismic hazard has been estimated by the GSC using the larger ground motions from the H-model and R-model (Adams and Halchuk, 2003).

To be consistent with both the historical seismicity and the USGS PSHA methodology (Petersen et al., 2008) that we previously applied in the northeastern U.S. in our U.S. seismic hazard model, we used the

USGS smoothed seismicity model to characterize earthquake sources in this region. The USGS smoothed seismicity extended to 50° N latitude, well north of the border in this region as shown in Figure 1. Therefore, the seismic hazard is dominated by the USGS NSHM model for the population centers located along the Saint Lawrence Seaway.

3.2. Southwestern Canada

The metropolitan area of Vancouver in southwestern Canada, British Columbia, is the third most populous area in Canada and home to 2.3 million people (Statistics Canada, 2011 Census). The metropolitan area of Victoria, at the southeastern tip of Vancouver Island, has a population of 344,600 (Statistics Canada, 2011 Census). These metro areas are exposed to potentially severe ground motion hazard from earthquakes of up to M 9.0 ± 0.2 (Petersen et al. 2008) along the Cascadia megathrust fault zone (Figure 1). They are also subject to hazard from intermediate-depth Wadati-Benioff zone (intraslab) earthquakes that occur within the subducted Juan de Fuca plate and to earthquakes occurring within the shallow crust.

The Cascadia megathrust extends approximately 1,000 km from offshore of central Vancouver Island to Cape Mendocino, California. The entire megathrust last ruptured in 1700 in a giant **M** 9 earthquake and tsunami (e.g., Satake et al., 1996). We replaced the deterministic M 8.2 model used by the GSC to characterize this megathrust (Adams and Halchuk, 2003) with the probabilistic model used by the USGS in order to allow for the occurrence of **M** 9 earthquakes (Petersen et al., 2008). We note that the GSC is planning to revise its model of the Cascadia megathrust in the fifth generation seismic hazard model of Canada (Adams, 2011). Our probabilistic model considers characteristic earthquakes of **M** 8.8, 9.0 and 9.2 that rupture the entire megathrust fault zone. The likelihood of these magnitudes is 0.2, 0.6 and 0.2, respectively. The average recurrence interval for one of these characteristic events is around 500 years as determined from paleoseismic and other investigations (e.g., Atwater and Hemphill-Haley, 1997; Petersen et al., 2002, 2008). Consistent with insurance industry practice, our model incorporates an assessment of the time-dependent probability of a future giant earthquake by Petersen et al. (2008) that is based on a Brownian Passage Time probability distribution (Matthews et al., 2002) with a mean recurrence interval of 500 years, an aperiodocity parameter of 0.5, and a date for the last earthquake of January 1700 (Satake et al., 1996).. The characteristic earthquake rupture model is assigned a weight of 0.67. An alternative model of **M** 8.0–8.7 floating earthquake ruptures along the megathrust interface is assigned a weight of 0.33 (Petersen et al., 2008). The recurrence rates of these events are constrained to be consistent with an average recurrence interval of 500 years at any location along the coast to be consistent with paleoseismic data.

Wadati-Benioff earthquakes occurring within the subducted Juan de Fuca plate are modeled by the USGS smoothed seismicity model at a depth of 50 km beneath Puget Sound and the Georgia Strait (Petersen et al., 2008). Similarly, shallow crustal earthquakes are modeled as smoothed seismicity in the southern-most part of this region transitioning to the GSC area-source model to the north (Figure 1). The metropolitan areas of Vancouver and Victoria are within this southern-most region and, therefore, their seismic hazard is controlled by the USGS smoothed seismicity and Cascadia subduction zone megathrust models.

The Queen Charlotte fault zone is the only shallow crustal fault in our Canada hazard model. The fault extends northward from offshore of Haida Gwaii (formerly known as the Queen Charlotte Islands) to the Fairweather fault of southeastern Alaska and accommodates right-lateral displacement between the Pacific and North American plates (Rohr et al., 2000). An **M** 8.1 earthquake in 1949 ruptured a 500 km long segment of the fault causing damage in Prince Rupert. This event is the largest shallow crustal earthquake in Canadian history (Lamontagne et al., 2008). Another earthquake of **M** 7.7 occurred on this fault zone in the same region in 2012. Although the region impacted by the Queen Charlotte fault is sparsely populated, we include it in our model for completeness.

3.3. Central Interior and Northern Canada

Although relatively sparsely populated, Canadian provinces and territories in the central interior and north are home to a wealth of economic assets related to the extraction of natural resources. Seismicity of this region is low as is typical of an SCR, except in some peripheral areas, such as the Labrador Sea, where crustal rebound from the last glaciation causes an increased level of earthquake activity. Increased activity also occurs in the mountain ranges of the western Northwest Territories and Yukon. A rare sequence of **M** 6.6 and 6.9 earthquakes in this region occurred in the Nahanni Range of the Northwest Territories on 5 October and 12 December 1985 (Wetmiller et al., 1988; Lamontagne et al., 2008).

Being located north of our transition zone, we model this region using Euclidean area source zones of the GSC H-model, which model the peripheral seismic zones of this region and the low seismic activity of central interior of Canada as a large area of background seismicity. Adams and Halchuk (2003) found that area-normalized earthquake frequencies for the North American SCR were somewhat lower than SCR's globally and that frequencies for central Canada were lower still, which could possibly be due to incomplete earthquake reporting in remote regions. Following the GSC methodology, we incorporated a weighted average of the three different frequency estimates with the global and North America SCR frequencies each weighted 0.4 and the frequency specific to the central interior of Canada given a lower weight of 0.2 due to possible bias from incomplete earthquake reporting. Unlike the GSC, we did not adopt the "floor" F-model minimum ground motion values used in the low seismicity regions for purposes of conservative seismic design. In our opinion, this non-probabilistic approach to conservative hazard assessment gives a biased view of hazard and is inappropriate for purposes of loss estimation and risk management. The weighted SCR frequency was also applied in a region of the Canadian Rocky Mountains where the GSC found too little earthquake data available to establish reliable earthquake recurrence frequencies and, instead, applied the F-model.

Although recurrence frequencies in the Canadian central interior region are low, the percentage difference in terms of frequencies can be quite high between the USGS smoothed seismicity model and GSC H-model for individual locations within the transition region. These differences notwithstanding, we provide a smooth transition between the background recurrence rates of the northern Great Plains of the central U.S. and the background recurrence rates of the central interior of Canada using the transition regions shown by the red hachured zones in Figure 1. As indicated in Figure 1, this procedure was also used in southern British Columbia, albeit over a narrower transition region.

4. Ground Motion Prediction Equations

We used the same set of GMPEs and weights adopted by the USGS in the 2008 U.S. NSHM model (Petersen et al., 2008). We refer the reader to the USGS report for a description of these GMPEs and the weights assigned to them. Four sets of GMPEs were used to estimate ground motions in the four tectonic regions of Canada and the U.S. Seven GMPEs were used in the SCR of CENA where ground motion attenuation is relatively low. Three GMPEs were used in the active shallow crustal region of western North America (WNA) where ground motion attenuation is relatively high. Three GMPEs were used for the megathrust interface sources of the Cascadia subduction zone, and three GMPEs were used for the Wadati-Benioff intraslab sources. Multiple GMPEs were implemented for each tectonic region to capture epistemic uncertainty among the different ground motion models. All four sets are the same as those used in our U.S. stochastic event set, which extends their application uniformly across the international border thereby assisting the elimination of the cross-border hazard discrepancy.

5. Reference Site Condition

GMPEs are typically evaluated for a reference site shear wave velocity for purposes of the hazard calculation to facilitate hazard comparisons between sites and allow site-specific conditions to be applied during design. For site conditions other than the reference site condition, the ground-shaking amplitude must be adjusted using a site amplification factor. In North America, it has been standard practice for decades that ground motions for national seismic hazard maps (NSHMs) that form the bases of engineering seismic design code criteria be computed for some type of a referenced rock site condition, whether firm rock, soft rock or a boundary condition between rock types. Unfortunately, this practice requires large site amplification factors to adjust to soil site conditions. This procedure is counterintuitive considering that, (1) most of the risk exposure in the form of insured properties is located on soil and not rock, and (2) most of the strong ground motion recordings used in development of the GMPEs are from soil sites. In addition, some GMPEs used to create past NSHMs were not wholly based on strong motion records from rock recording sites, but were found to contain some records from soil-like sites. This only became known through the regional mapping of V_{s30} throughout California (Wills et al., 2000). The mismatched site conditions caused an upward bias in the referenced rock ground motion amplitudes displayed in the NSHMs. The multi-year PEER NGA project (Power et al., 2008) corrected these biases in development of the new NGA set of GMPE's. However, the bias remains if referenced rock NGA GMPEs are used in conjunction with the previously established U.S. National Earthquake Hazard Reduction Program (NEHRP) site amplification factors that are still in use and recommended by the Building Seismic Safety Council (BSSC, 2009; Huang et al., 2010). When using the rock-based approach, this bias in the site amplification factors tends to underestimate amplitudes for soil sites by up to 20% or more depending on the actual soil type and return period of the probabilistic calculation.

We address this issue by using a soil-based attenuation approach (SBA), which we have used in seismic hazard models over the last decade. In this approach, ground motion amplitudes are calculated on a firm soil reference site class using the GMPEs. The NEHRP site amplification factors recommended by the BSSC are then renormalized to this site class so that no amplitude modifications are required for firm soil sites. The renormalized site amplification factors to firm soil are given in Table 1 for spectral acceleration (PSA) at return periods of 0.3 s and 1.0 s.

SBA is intuitively appealing since the vast majority of strong ground motion recordings are on soil sites and the majority of loss exposures are on soil sites as well. For example, extensive metropolitan areas have developed on alluvial basins for the simple reason of topography and the ease of access and construction. Seattle, Washington and Los Angeles, California are prime examples among many other cities that could be listed.

Table 1 - NEHRP site amplification factors renormalized to firm soil.

NEHRP Site Class	V_{S30}(m/s)	PSA Site Factors	
		0.3 s	1.0 s
A (hard rock)	1830	0.5 – 0.9	0.3 – 0.5
AB	1500	0.6 – 1.0	0.4 – 0.6
B (rock)	1130	0.6 – 1.0	0.4 – 0.7
BC	760	0.7 – 1.0	0.5 – 0.8
C (soft rock)	560	0.8 – 1.0	0.7 – 0.9
CD	360	0.9 – 1.0	0.8 – 0.9
D (firm soil)	270	1.0 – 1.0	1.0 – 1.0
DE	180	1.0 – 1.3	1.2 – 1.3
E (soft soil)	150	1.0 – 1.6	1.5 – 1.6

We note that SBA does not remove the hazard bias in the NEHRP site amplification factors but simply shifts the majority of the bias to rock sites, which tend to be somewhat over-estimated by the method. We are willing to make this trade-off in exchange for reduced bias and uncertainty for the majority of exposure located on soil sites. In addition, the entire issue of the "hazard bias" was evaluated in a 2008-2013 PEER NGA-West 2 study (Stewart and Seyhan, 2013), in which the revised NEHRP site factors are being evaluated by the Building Seismic Safety Council for inclusion in the next edition of the NEHRP seismic design provisions.

6. Site Conditions Maps

Site amplification factors vary geographically according to the mapped classification of site conditions. NEHRP site classification maps were only available for the city of Victoria at the time of our study was completed. For five other metropolitan centers, NEHRP site conditions maps were developed from large-scale geologic maps using the methodology described by Wills et al., (2000). These cities are Vancouver, Toronto, Ottawa, Montreal and Quebec. As an example, the derived maps for Montreal and Toronto are shown in Figure 2.

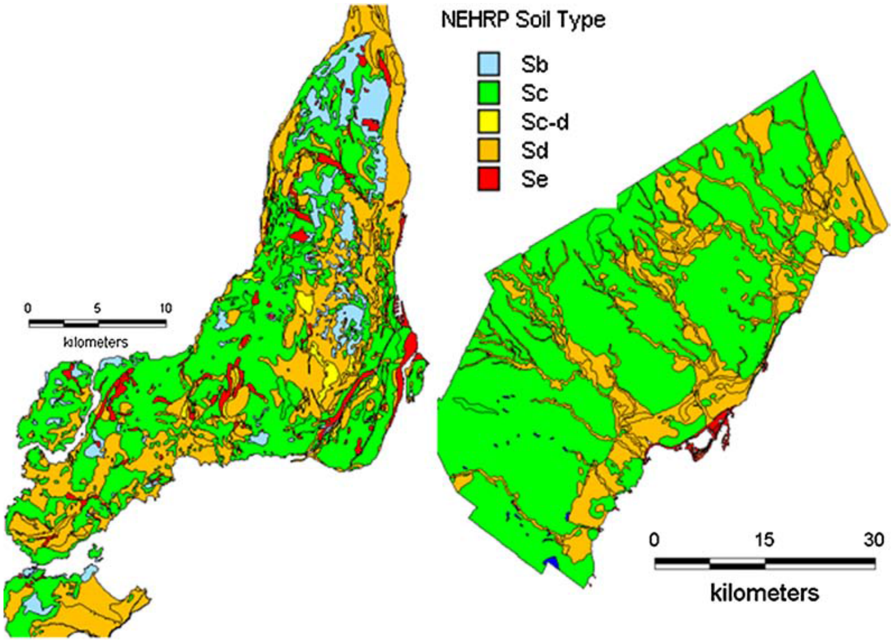

Fig. 2 - Examples of derived site conditions maps of Montreal (left) and Toronto (right).

Site conditions for the remainder of Canada were derived from the map of surficial geology of Canada by Fulton (1995). Differences were juxtaposed across the international border due to different map resolutions and geologic unit descriptions in each country. However, these differences in site conditions translated to differences in ground motion amplitudes of around 10% or less.

7. Hazard Results

The probabilistic ground motion hazard values in this study for both the U.S. and Canada were calculated using the open-source software OpenSHA (Field et al., 2003). Hazard maps were computed for PSA 0.3 s and 1.0 s periods for use with multi-parameter structure vulnerability equations to arrive at probabilistic estimates of economic loss from earthquakes. Figure 3 shows these hazard maps as a fraction of gravity (g) on NEHRP Class D (firm soil) for PSA 1.0 s and return periods of 500 and 2500 years. The figures graphically demonstrate achievement of the primary goal of the project, which was to provide consistent and unbiased cross-border seismic hazard estimates across all return periods.

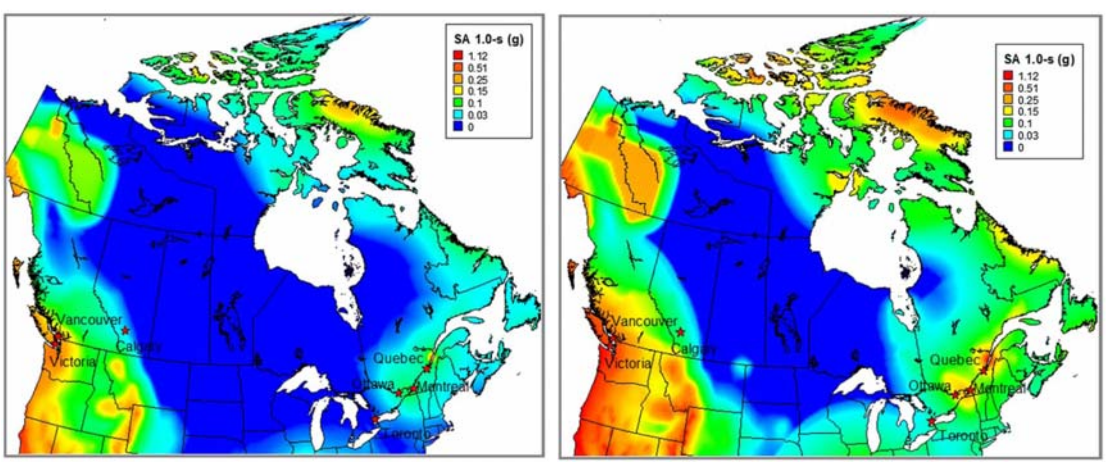

Fig. 3 - Cross-border hazard map for Canada and the U.S. showing the distribution of 500-year (left) and 2,500-year (right) SA 1.0 s on NEHRP Class D (firm) soil.

Figure 4 shows hazard-curve comparisons for PSA at 1.0 s period between the GSC hazard results for the H-model (Adams and Halchuk, 2003; Halchuk and Adams, 2008) and the results of this study for the cities of Toronto and Montreal. Both hazard curves represent NEHRP site class D site conditions. For purposes of comparison, the GSC ground motions were converted from NEHRP C to NEHRP D site conditions using the modified NEHRP site factors recommended for use in CENA by Hwang et al. (1997). These results show good agreement between the two models. The results of the GSC R-model at return periods of 475-year and 2,475-year return periods are higher than either of the hazard models, as was the intent of the GSC in order to incorporate conservatism in the Canada building code. In addition, GSC fifth generation seismic hazard values at the 2,475-year return period that are currently proposed for a 2015 revision of the Canada building code (Halchuk et al., 2014) are shown for comparison purposes. The GSC 2014 proposed values agree to within 10-percent of the results of this study.

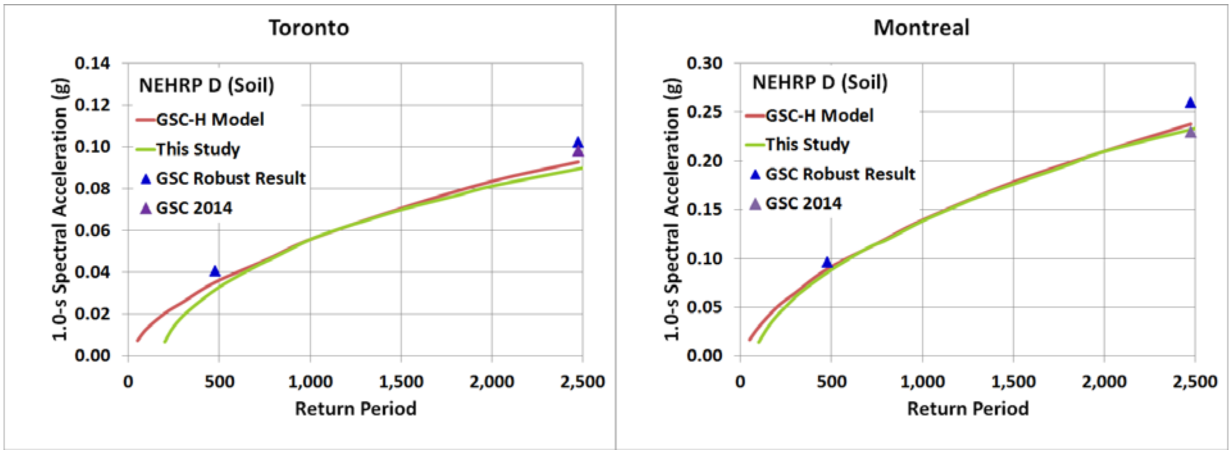

Fig. 4 - Hazard curve comparisons for Toronto and Montreal for the results of this project, the GSC H-model and the GSC "robust result" that is currently used in the building code of Canada, and the GSC proposed 2014 values for use in a 2015 revision of the national building code.

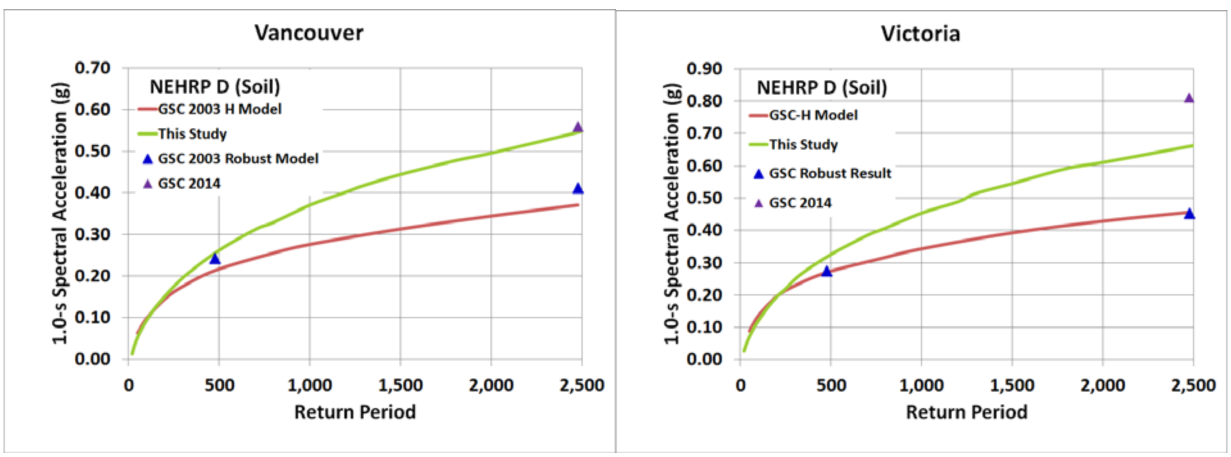

Fig. 5 - As in Figure 4 for the cities of Vancouver and Victoria.

Figure 5 shows the same hazard curve comparisons as in Figure 4 only for the west coast cities of Vancouver and Victoria, British Columbia. The contrast in results between the GSC H-model and the results of this study is pronounced with the results of this study significantly higher at return periods greater than about 250 years. The higher and steeper hazard curves from our cross-border model are due to our use of both a probabilistic Cascadia subduction source model and a newer set of subduction zone GMPEs as opposed to the GSC **M** 8.2 deterministic model for this subduction system (Adams and Halchuk, 2003). The higher results of the probabilistic model suggest that the GSC fourth generation "robust results" for these locations was perhaps not as robust as originally intended. However, the GSC proposed 2014 values for use in a 2015 revision of the national building code completely compensate for this previous discrepancy. The GSC 2014 proposed value at Vancouver is in good agreement with the result of this study whereas the proposed value at Victoria is somewhat higher.

8. Conclusions

Institutional national seismic hazard maps and related products intended for building code applications seldom directly serve the diverse needs of the risk management community. Many times judgments by organizations involved in the code process are influenced by the need to develop conservative seismic hazard products for the goal of life-safety that is stipulated in codes. Approaches to accomplishing this goal are often different in neighboring countries. This study serves as a case study in the transformation of national seismic hazard models intended for building code applications in Canada and the U.S. to solve the problem of inconsistent seismic hazard methodologies, and resulting inconsistent ground motion hazard estimates, across the international border. By applying the latest seismic hazard methodology in major Canadian metropolitan areas near the border and seamlessly integrating the two national models in other regions, a unified cross-border seismic hazard model was created for use by risk managers to achieve consistent estimates of loss from earthquakes that affect both countries. In accomplishing this goal, biases in the officially recommended use of the NEHRP soil amplification factors for building code applications were addressed to minimize as much as possible their impact on financial estimates of earthquake losses.

9. Acknowledgements

We thank John Adams and Stephen Halchuk for providing the GSC source files for the fourth generation seismic hazard maps of Canada and their assistance with its implementation. We similarly thank Mark Petersen and Stephen Harmsen for providing the USGS source files for the 2008 update of the U.S. national seismic hazard maps and their assistance with its implementation.

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