A Consistent Cross-Border Seismic Hazard Model for Loss Estimation and Risk Management in Canada

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SUMMARY:
A new seismic hazard model for Canada 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 Canadian region. The new 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 (**M**9) 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.

Keywords: Canada, U.S., seismic hazard, risk

1. INTRODUCTION

We first introduced an earthquake loss-estimation model for Canada in 1996. However, a long standing issue in cross-border earthquake risk management for large Canadian and U.S. metropolitan areas has been the inconsistent methodologies used to quantify seismic hazard at the national level for each country. Seismic source characterizations and resulting ground motions for the two countries are different across the international border. Regardless of these differences, however, the fact remains that economic loss from a major earthquake in near-border areas will severely affect both countries. Informed decisions by risk managers in regard to widespread property portfolios require a consistent view of the earthquake hazard and risk for areas both north and south of the international border. To achieve this goal, we have implemented a modified version of the Geological Survey of Canada's (GSC) fourth generation seismic hazard model of Canada that incorporates anticipated features of its next (fifth) generation seismic hazard model for Canada. This implementation serves as a case study on the transformation of an institutional national building code product into a modern tool for earthquake risk management.

2. PRINCIPLE DATA SOURCES

The principle sources of seismic hazard data for this investigation were the fourth generation national seismic hazard model of Canada (Adams and Halchuk, 2003; Halchuk and Adams 2008) and the latest U.S. national seismic hazard model by the U.S. Geological Survey (USGS; Petersen et al., 2008; with updates through 2009; Harmsen, USGS, personal communication). Both national models are developed to serve as the basis for building code engineering seismic design criteria in their respective countries. However, approaches to accomplishing their purpose differ. In Canada, a primary part of the epistemic uncertainty is explicitly modeled using multiple Euclidean (area) source geometries (historical, regional, floor) and a deterministic model for the Cascadia subduction zone megathrust. The highest resulting point values from any of these models then defines the shaking hazard for building code purposes. In the U.S., spatial smoothing of historical seismicity defines the hazard over large central and eastern regions and primary sources of epistemic uncertainty are incorporated through a logic-tree methodology that uses probabilities of alternative modeling choices being correct. A challenge of this investigation was to merge the two models in order to provide a consistent cross-border view of North America seismic hazard considering the different approaches to quantifying the seismic hazard for building code purposes.

3. SOUTHEASTERN CANADA

Approximately 70 percent of the population of Canada is concentrated in southeastern Canada, along and near the international border extending from Windsor (across the border from Detroit) to Quebec, including the cities of Toronto, Montreal and Ottawa. Although part of the Stable Continental Region (SCR) of eastern North America, this area has experienced no less than 15 moment magnitude (**M**) 5.0 to 7.2 earthquakes since the year 1663 (Lamontagne et al., 2008). Active faults responsible for these damaging earthquakes remain unknown and the seismic hazard is estimated by the CGS using two alternative seismic source models (Adams and Halchuk, 2003). The Historical ("H") model uses Euclidean source geometries to define spatial clusters of historical earthquakes on the premise that future earthquakes will likely tend to occur in the vicinity of past earthquakes (e.g., Kafka and Levin, 2000). On the other hand, the Regional ("R") model uses larger Euclidean source geometries to distribute the historical earthquakes along regional structural geologic trends on the premise that future earthquakes of similar maximum magnitude cannot be excluded from occurring in areas of similar geological setting based on lower historical frequency alone.

The dilemma of uncertain boundary choices to seismic source definitions in regions where causative geological structures are unknown is avoided through the more objective use of a geographic counting grid that uses a Gaussian distribution with a 50 km smoothing radius to account for uncertainty in historical earthquake locations (Frankel, 1995). Maximum earthquake magnitudes used to truncate the Gutenberg-Richter magnitude-frequency distributions in each grid cell are defined on regional tectonic bases (e.g., Wheeler and Frankel 2000). The regional distribution of earthquake recurrence frequencies from this method was used to characterize the earthquake hazard throughout southeastern Canada and was found to be generally comparable to the CGS "H" seismic source model. The method is also consistent with the USQuake™ hazard methodology that we previously applied in the northeastern U.S. south of the international border (Figure 1).

4. SOUTHWESTERN CANADA

The city of Vancouver in southwestern Canada, British Columbia, is the third most populous metropolitan area in Canada and home to 2.3 million people. The city of Victoria, at the southeastern tip of Vancouver Island, has a population of 344,600. These metro areas are exposed to potentially severe ground motion hazard from earthquakes of up to **M** 9.0±0.2

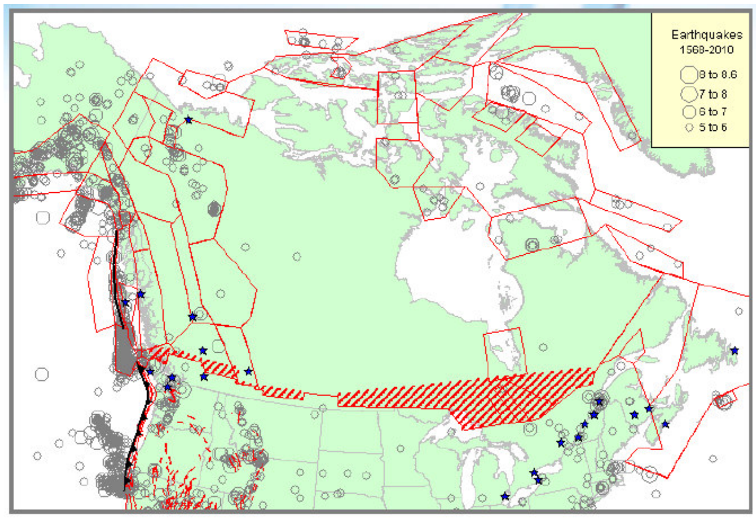

Figure 1. Canadian seismic source model. Red boundaries are Euclidean zones from the CGS "H" model, Red hachures are transition regions between the Canadian and U.S. models. Finite fault rupture models for the Queen Charlotte fault and Cascadia subduction zone megathrust are shown off the west coast. Stars indicate selected urban locations.

(Petersen et al., 2008) along the Cascadia megathrust fault zone (Figure 1), as well as deeper Wadati-Benioff zone earthquakes that occur within the subducted Juan de Fuca plate, and random earthquakes occurring in the shallow crust.

The Cascadia megathrust fault extends approximately 1,200 km from offshore of central Vancouver Island to Cape Mendocino, California. The probabilistic model for the fault used here is from Petersen, et al. (2008) which includes a time-dependent rupture probability model based on a Brownian Passage Time model with a standard deviation of 0.5 considering that the last earthquake occurred in January, 1700 (Satake et al., 2003). This probabilistic model considers scenario ruptures of **M**8.8, **M**9.0 and **M**9.2 earthquakes that fill the megathrust fault zone and are weighted 0.2, 0.6 and 0.6, respectively. The average recurrence interval for this event is 500 years as determined from paleoseismological investigations. The scenario rupture model is given a weight of 0.67. A second model of **M**8.0-8.7 floating earthquake ruptures along the fault zone is weighted 0.33 with recurrence frequency constrained to be 500 years on average at any site along the coast to represent the paleoseismological data obtained in the region. Wadati-Benioff earthquakes occurring in the subducted Juan de Fuca plate are modeled as spatially-smoothed seismicity at a depth of 50 km beneath Puget Sound and the Georgia Strait.

The Queen Charlotte fault zone is the second finite fault modeled in the Canadian region. The fault extends northward from offshore of Queen Charlotte Island to the Fairweather fault of southeastern Alaska and accommodates approximately 6 cm/yr right-lateral displacement between the Pacific and North America plates. An **M**8.1 earthquake on August 22, 1949 that ruptured a 500 km segment of the fault causing damage in Port Rupert is the largest earthquake in Canadian history (Lamontagne et al., 2008).

5. CENTRAL INTERIOR AND NORTHERN CANADA

Although relatively sparsely populated, Canadian provinces of the central interior and north are home to a wealth of economic assets related to the extraction of natural resources including hydrocarbons, metals, minerals, and diamonds. The fishing industry supports many coastal communities. Seismicity of this region is low and 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 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 October 5 and December 12, 1985 (Lamontagne et al., 2008).

Euclidean sources define the peripheral seismic zones of this region and the low seismic activity of central interior Canada is modeled as a large area of background seismicity. Adams and Halchuk (2003) found that area-normalized earthquake frequencies for the North America 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 CGS methodology, we have 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 central interior Canada given a lower weight of 0.2 due to possible bias from incomplete earthquake reporting. Unlike the CGS methodology, however, which computed a "floor" hazard value to be used in the low seismicity regions for purposes of conservative seismic design, we have not imposed such a "floor" value for the purposes of loss estimation and risk management. The weighted SCR frequency was also applied in a region of the Canadian Rocky Mountains where CGS found to little earthquake data available to establish reliable earthquake recurrence frequencies.

Although occurrence frequencies in the Canadian central interior region are low, the percentage difference in frequencies can be quite high between the USQuake™ and CGS "H" models on a point-by-point basis where the two models overlap. In order to provide a smooth transition between the background occurrence frequencies of the northern Great Plains of the central U.S. and the background occurrence frequency of earthquakes in the central interior of Canada, we averaged the two sets of frequencies on a 0.1-degree grid over the region of model overlap for the purpose of smoothing out differences over a transitional area rather than having abrupt frequency changes across a fixed boundary. These transitional areas are shown by the red hachures in Figure 1. As indicated in Figure 1, this procedure was also used in southern British Columbia, albeit over a smaller distance of model overlap.

6. GROUND MOTION PREDICTION EQUATIONS

Ground motion prediction equations (GMPEs) describe the geographic distribution of ground shaking intensity given the physical characteristics of an earthquake including its magnitude, location, rupture geometry, and slip mechanism among other parameters. Three sets of GMPEs were used to determine ground shaking amplitudes for the different tectonic regimes of Canada. One set applies to central and eastern Canada where ground motion attenuation is relatively low. A second set applies to western Canada where ground motion attenuation is relatively high, as in California, and a third set is applied to the subduction sources of Cascadia. Multiple GMPEs for each region were implemented for the purpose of the capturing epistemic uncertainty among the different ground motion models. All three sets are the same as used in the 2010 version of USQuake™ which therefore extends their application consistently across the international border and throughout North America.

Seven GMPEs were modeled in central and eastern Canada with varying weights (Frankel et al., 1996; Toro et al., 1997, as modified by Toro, 2002 for finite faulting; Silva et al., 2002;

Campbell, 2003, 2004; Tavakoli and Pezeshk, 2005; Atkinson and Boore, 2006, 2007, using both 140-bar and 200-bar stress drops. In western Canada, three equally weighted GMPEs developed as part of the PEER Next Generation Atteunation (NGE) project (Power, et al., 2008) were used (Boore and Atkinson, 2008; Campbell and Bozorgnia, 2008; Chiou and Youngs, 2008. In the Cascadia subduction zone, megathrust ruptures were modeled using the plate interface GMPEs of Youngs et al. (1997), Atkinson and Boore (2003, 2008) and Zhao et al. (2006) with varying weights. Intraplate earthquakes of the subducted Juan de Fuca plate slab beneath Georgia Strait and Puget Sound were modeled using the intraslab GMPEs of Youngs et al. (1997) and the global and Cascadia-specific forms of Atkinson and Boore (2003, 2008) with varying weights.

7. REFERENCE SITE CONDITION

As a proxy for "site condition", the functional forms of all of the GMPEs implicitly assume a specific shear-wave velocity for a site at which the ground motion amplitude is to be calculated. If actual site conditions vary from this reference site condition, the output amplitude must be adjusted using a site amplification factor. In North America, it has been standard practice for decades for the national seismic hazard maps (NSHMs) that form the bases of engineering seismic design code criteria to be computed for a reference 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 sites, 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 (Willis et al., 2000). The mismatched site conditions caused an upward bias in the rock-referenced ground motion amplitudes displayed in the NSHMs. The multi-year PEER NGA project (Power et al., 2008) corrected these biases in the new NGA GMPE's. However, the bias remains if rock-referenced 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., 2009). 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 have addressed this issue by using a soil-based attenuation approach (SBA), which has also been the basis for our 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 are given in Table 1 for response-spectral accelerations (SA) with periods of 0.3 s and 1.0 s.

It should be realized 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 over-estimated by the method. This trade-off is made 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" is currently being evaluated in a 2010-2013 "NGA-West 2" study funded in part by the California Earthquake Authority.

NEHRP Site Class	V_{S30} (m/sec)	Site Factor 0.3 s	Site Factor 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

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

8. 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. For five other metropolitan centers, NEHRP site conditions maps were developed from large-scale geologic maps using the methodology described by Willis 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.

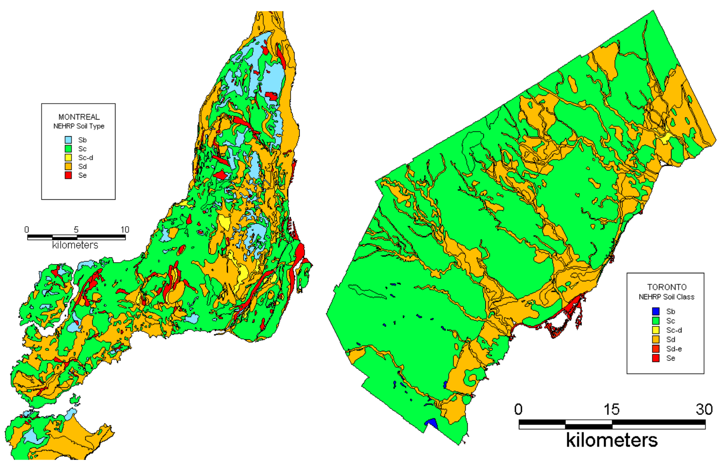

Figure 2. Examples of derived site conditions maps of Montreal (left) and Toronto (right)

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 no more than 10%.

9. HAZARD MAPS

The probabilistic ground motion hazard values for both the U.S. and Canada were calculated using the open-source software OpenSHA (Field et al., 2003). Hazard maps were computed for

SA 0.3 s and 1.0 s periods for use with multi-parameter structural vulnerability equations to arrive at probabilistic estimates of economic loss from earthquakes. These hazard results are shown as a fraction of gravity (g) on NEHRP Class D (firm) soil in Figures 3 and 4 for SA 1.0 s and return periods of 500 and 2500 years. The figures graphically demonstrate achievement of the primary goal of the model, which was to provide consistent cross-border seismic hazard estimates across all return periods.

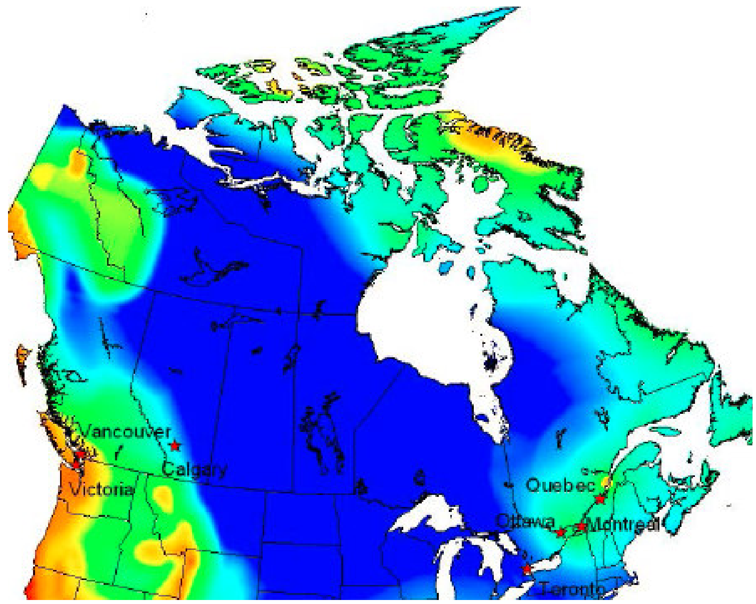

Figure 3. Cross-border hazard map for Canada and the U.S. showing the distribution of 500-year SA 1.0 s on NEHRP Class D (firm) soil.

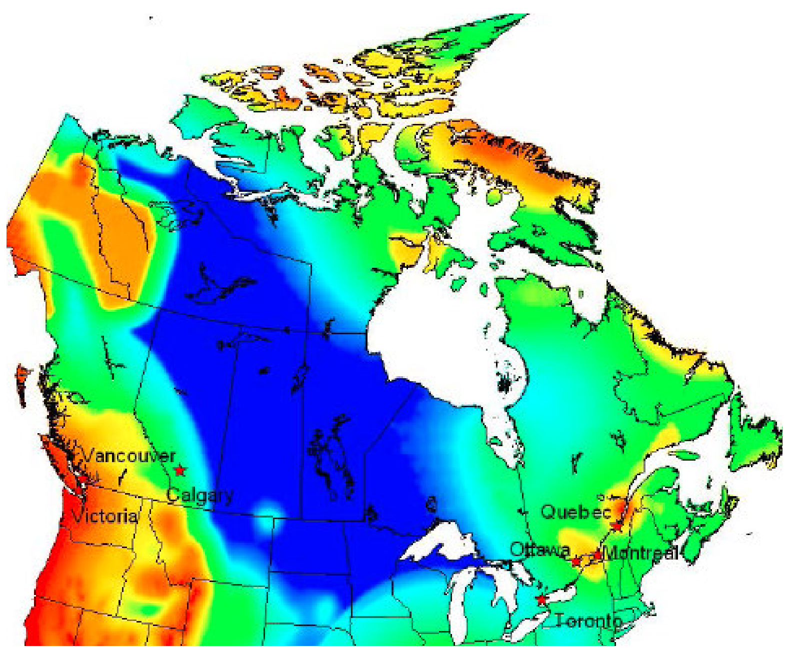

Figure 4. As in Figure 3 for a return period of 2,500 years.

Figure 5 shows hazard curve comparisons between CGS hazard results for their historic model (GSC-H; Adams and Halchuk, 2003) and the results of this study (WCE 3.16) for the eastern cities of Toronto and Montreal on NEHRP Class D (firm) soil. These results show good agreement between the two models with the model from this investigation giving somewhat lower ground motion hazard at return periods less than about 500 years. The CGS "robust" result at return periods of 475 and 2,475 years are higher than either of the hazard models, as intended by CGS for conservative building code applications.

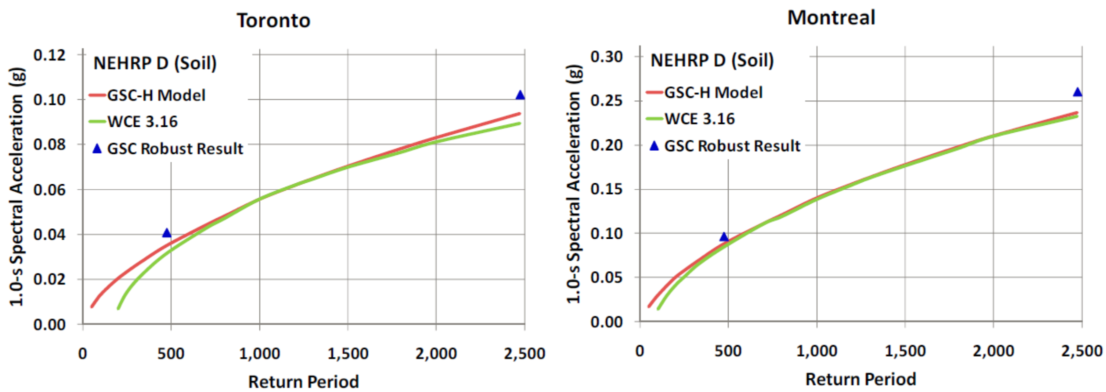

Figure 5. Hazard curve comparisons for Toronto and Montreal for the results of this study (WCE 3.16), the CGS H-model and the CGS "robust" result that is used in the Canadian building code.

Figure 6 shows the same hazard curve comparisons as in Figure 5 for the west coast cities of Vancouver and Victoria, British Columbia. The contrast in results between the CGS H-model and the model from this study (WCE 3.16) is pronounced with this study's model being significantly higher at return periods greater than about 250 years. The higher and steeper WCE 3.16 hazard curves are due to both the inclusion of a probabilistic Cascadia subduction source model and newer subduction zone GMPEs as opposed to the CGS' **M**8.2 deterministic model for this subduction system (Adams and Halchuk, 2003). The higher results of the probabilistic model suggest that the CGS "robust" results for these locations may not be as robust as was originally intended.

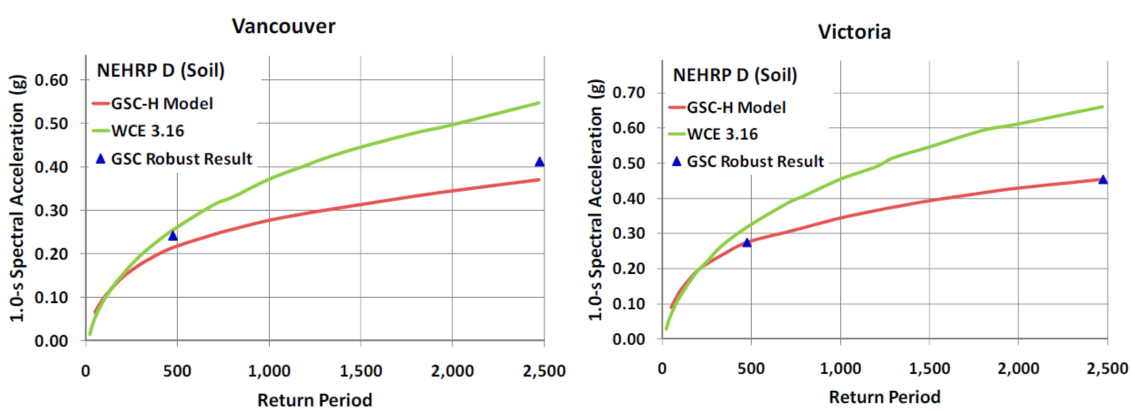

Figure 6. As in Figure 5 for the cities of Vancouver and Victoria.

10. CONCLUSION

Institutional national seismic hazard maps and related products intended for building code applications seldom, if ever, directly serve the diverse needs of the risk management community. Many times judgments by panels or 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 project 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 estimation 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.

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