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LONG-PERIOD RESPONSE SPECTRA OF LARGE SCENARIO EARTHQUAKES IN BRITISH COLUMBIA

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ABSTRACT: Numerical simulation of large scenario earthquakes is at the forefront of seismic hazard analysis, with the potential to replace use of ground-motion prediction equations (GMPEs) in future. Three-dimensional finite-difference numerical simulation of earthquake wave propagation has been used to predict long-period (≥ 2 s) ground motions of potential large scenario earthquakes in British Columbia: a M9 Cascadia subduction zone mega-thrust earthquake, M6.8 deep earthquakes in the subducting oceanic plate, and M6.8 shallow earthquakes in the over-riding continental plate. New proposed ground motion prediction equations (GMPEs) of the 5th generation national seismic hazard model, intended for use in the 2015 National Building Code of Canada, provide peak ground acceleration, velocity, and spectral acceleration up to 10 seconds. This paper presents the first comparison of long-period response spectra predicted from GMPEs and 3D earthquake rupture simulations for potential large earthquakes in British Columbia.

1. Introduction

Probabilistic seismic hazard analysis (PSHA), which considers all potential earthquake sources for a given time period, relies on attenuation relations or ground-motion prediction equations (GMPE) to predict earthquake ground motions. GMPEs provide the amplitude of shaking as a function of earthquake source magnitude and/or fault type, source-to-site distance, and amplification factors based on geological conditions. Development, calibration, and validation of GMPEs are therefore important to seismic hazard analysis.

GMPEs are developed by fitting an analytical expression to empirical earthquake data. Synthetic ground motions are generally used if empirical data is lacking in a region (e.g., Eastern Canada). Empirical data has a variety of shortcomings; for example, sparse data in the near-field for large magnitudes, and difficulty in capturing source waveform patterns (e.g., velocity pulses, complex geometry faults, surface or buried faults). Physics-based simulations of earthquake rupture produce synthetic data that captures shortcomings of empirical data. Inclusion of synthetic data augments or extends empirical ground motion datasets from which to develop the GMPE.

Physics-based simulations of earthquake rupture have been performed for large scenario earthquakes in the tectonic setting of the Cascadia subduction zone (Figure 1). Olsen et al. (2008) simulated north-to-south rupture of the ~1200 km long Cascadia subduction thrust fault; the source radiation pattern is the 2004 M9.1 Sumatra earthquake rupture. Molnar et al. (2014a, b) simulated M6.8 scenario earthquakes within 100 km of Greater Vancouver that occur either in the subducting Juan de Fuca plate (average ~50 km depth) or the overriding crust of the North America plate (average ~8 km depth). All simulations were performed using a 3D numerical viscoelastic wave propagation code with a maximum resolvable frequency of ≤ 0.5 Hz (≥ 2 s period). Currently, all synthetic ground motions predicted from 3D earthquake rupture models in British Columbia are long-period (≥ 2 s) ground motions.

This paper compares long-period earthquake ground motions predicted at twelve sites in Greater Vancouver, British Columbia, via two different methods: (1) the proposed central GMPEs of the 5th generation national seismic hazard model (Atkinson & Adams, 2013), and (2) physics-based 3D numerical wave propagation simulations of earthquake source models initiated within a 3D geological volume (mesh).

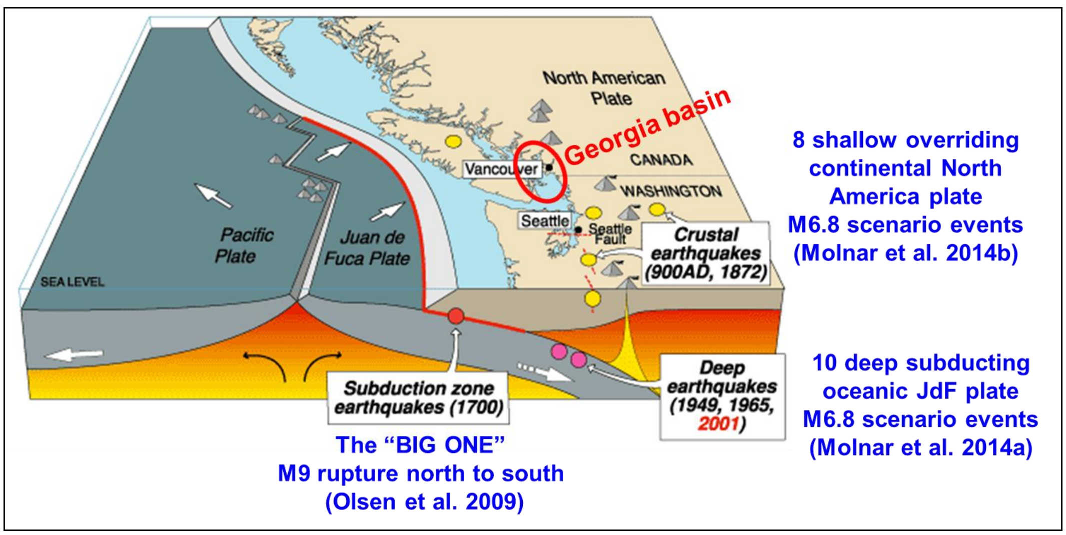

Figure 1. – Cartoon depicts three types of earthquake sources associated with the Cascadia subduction zone. Labels (in blue) reference long-period ground motion simulation studies.

2. Ground Motion Prediction Methods

2.1. Ground Motion Prediction Equations

Earthquake ground-motion amplification due to underlying ground (geologic) conditions is accounted for in the proposed GMPEs for both deep inslab and shallow crustal earthquakes by a site condition parameter. The site condition is represented by the harmonic mean shear-wave velocity in the upper 30 metres (known as v_{S30}); the reference site condition is the B/C site class boundary or a v_{S30} of 760 m/s. Table 1 lists details of the proposed central GMPE parameters used in this study.

The proposed central GMPE of the 5th generation seismic hazard model for western crustal earthquakes (Atkinson and Adams, 2013) is the PEER-NGA West GMPE of Boore and Atkinson (2008) that has been modified for moderate magnitudes (Atkinson and Boore, 2011).

The proposed central GMPE for western subduction inslab earthquakes (Atkinson and Adams, 2013) is the Zhao et al. (2006) GMPE, after adjustment for Cascadia site conditions. In general, a class C site (v_{S30} of 760 m/s) represents both soft shallow soil sites (e.g., Japan sites) and stiff thick soil sites (e.g., Vancouver, British Columbia). However, soft shallow soils at Japan sites amplify ground motions at short periods (~0.1-0.2 s), whereas stiff thick soils at Vancouver sites will amplify ground motions at longer periods.

Table 1 – GMPE parameter values used in this study.

	Shallow Crustal Earthquakes	**Deep Inslab Earthquakes**
GMPE	Atkinson & Boore (2011)	Zhao et al. (2006) including adjustment for Cascadia site conditions
Source Depth	10 km	50 km
Fault Type	"unspecified" fault mechanism	N/A
$\mathbf{v_{S30}}$	760 m/s (B/C site class conditions)	760 m/s (B/C site class conditions)

2.2. 3D Numerical Wave Propagation Simulations

Long-period earthquake ground motions in southwestern British Columbia were computed using 3D numerical finite-difference viscoelastic wave propagation (Olsen, 1994) for M6.8 deep inslab scenario earthquakes (Molnar et al. 2014a) and M6.8 shallow crustal scenario earthquakes (Molnar et al. 2014b). Ten M6.8 deep inslab scenario earthquakes were simulated using the rupture pattern of the 2001 M6.8 Nisqually, Washington, earthquake (Molnar et al. 2014a). Eight M6.8 shallow crustal scenario earthquakes were simulated using the earthquake rupture pattern of the 1994 M6.7 blind-thrust Northridge, California, earthquake (Molnar et al. 2014b). The average depth of the deep and shallow scenario earthquakes are ~50 km and ~8 km, respectively.

Two different physical-structure models of the subsurface 3D geological volume were used (Figure 2): a nonbasin model representative of hard rock ground conditions (minimum v_S set to 2200 m/s), and a basin model representative of the Georgia basin sedimentary rock and glaciated sediments (minimum v_S set to 625 m/s). The physical-structure models are represented by a uniform 250-m cubic mesh. Hence, the minimum NBCC site class (v_{S30}) of the nonbasin and basin models are class A and class C, respectively. The maximum resolvable frequency is ≤ 0.5 Hz or periods ≥ 2 s.

In this study, the two north-south and east-west horizontal components of simulated earthquake motion at the surface of the 3D geological model are extracted at twelve locations along a north-south profile across the Georgia basin (Figure 2): two sites in Vancouver, three sites across Richmond, two sites across Ladner, two sites outside (north and south) of the basin, two sites at the steep basin edges (pink squares) and a deep and narrow basin site (red square). Waveforms are extracted in the same 12 locations of the nonbasin model; however, the use of "basin" to describe some of the locations does not apply in this case. Pseudo-spectral acceleration (PSA) response spectra are computed from the synthetic horizontal-component velocity waveforms extracted at the 12 locations. The average epicentral distance (R_{epi}) for the scenario earthquakes at the 12 sites of investigation is ~60 km (range of 6-125 km).

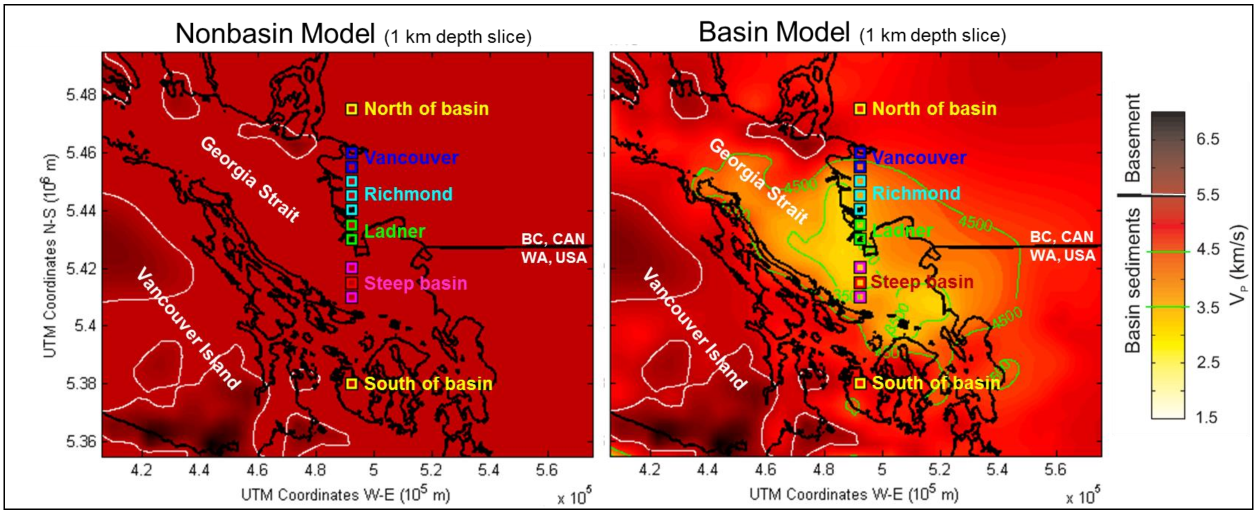

Figure 2. – Horizontal 1-km depth slices of the nonbasin and Georgia basin models; coastline and international border shown by black lines. Locations of extracted synthetic waveforms shown by colored squares.

3. Comparison of GMPE and 3D Simulation Synthetic Data

3.1. Deep Inslab Scenario Earthquakes

Figures 3 and 4 show pseudo-acceleration response spectra from basin and nonbasin model simulations (colours correspond to locations in Fig. 2) in comparison to proposed central GMPE estimates (shown by black lines for different R_{epi}) of the 5th generation national seismic hazard model for logarithmic and linear scales, respectively. The upper and lower GMPE estimate at the closest and furthest considered epicentral distances are included in this study (dashed lines in Figs. 3 to 6) to provide uncertainty bounds.

The maximum predicted PSA for deep inslab M6.8 earthquakes is < 0.04 g and < 0.015 g for basin and nonbasin models, respectively, at long (≥ 2 s) periods; the average basin amplification is a factor of ~3 (Molnar et al. 2014a). The smooth double-peak shape of the numerical long-period response spectra (Fig. 5 in particular) is related to the double-pulse earthquake source model (Molnar et al. 2014a). The amplitude variation of the numerical long-period motions is relatively consistent at all 12 locations with varying geological and/or basin conditions (depicted by varying colours); the observed amplitude variation is related to varying distance of the 10 scenario earthquakes (R_{epi} of 6-125 km). Numerical solutions of the nonbasin model simulations are generally lower than the proposed central GMPE (comparison of site class A vs. class B/C conditions, respectively), whereas numerical solutions of the basin model simulations are in better agreement with the proposed central GMPE. Basin model simulations at sites outside of the basin (yellow lines in top right plot of Figs. 3 & 4) are generally lower than the proposed central GMPE as expected (comparison of site class A vs. class B/C conditions, respectively).

Overall, the observed increase in predicted ground motions for M6.8 deep inslab scenario earthquakes due to the presence of the 3D Georgia basin (basin model vs. nonbasin model) is encapsulated within the uncertainty bounds of the proposed GMPEs at periods ≤ ~4 s, but not at longer periods (≥ ~4 s).

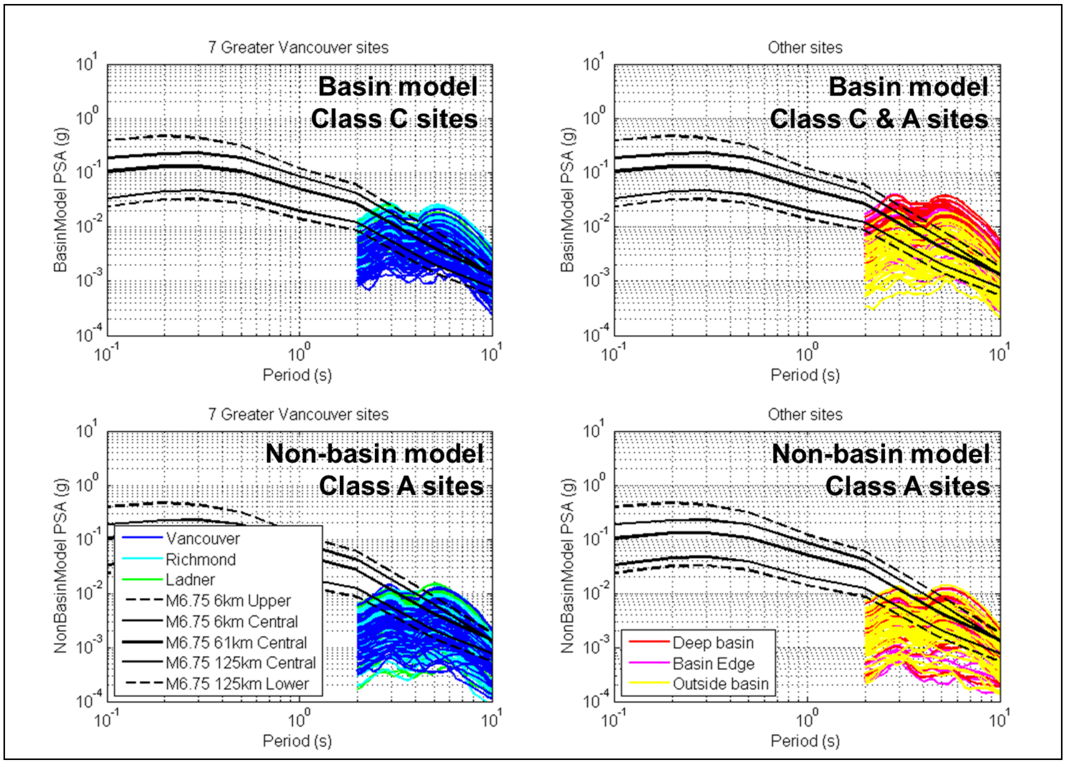

Figure 3. – Response spectra for deep inslab M6.8 earthquakes (logarithmic scale).

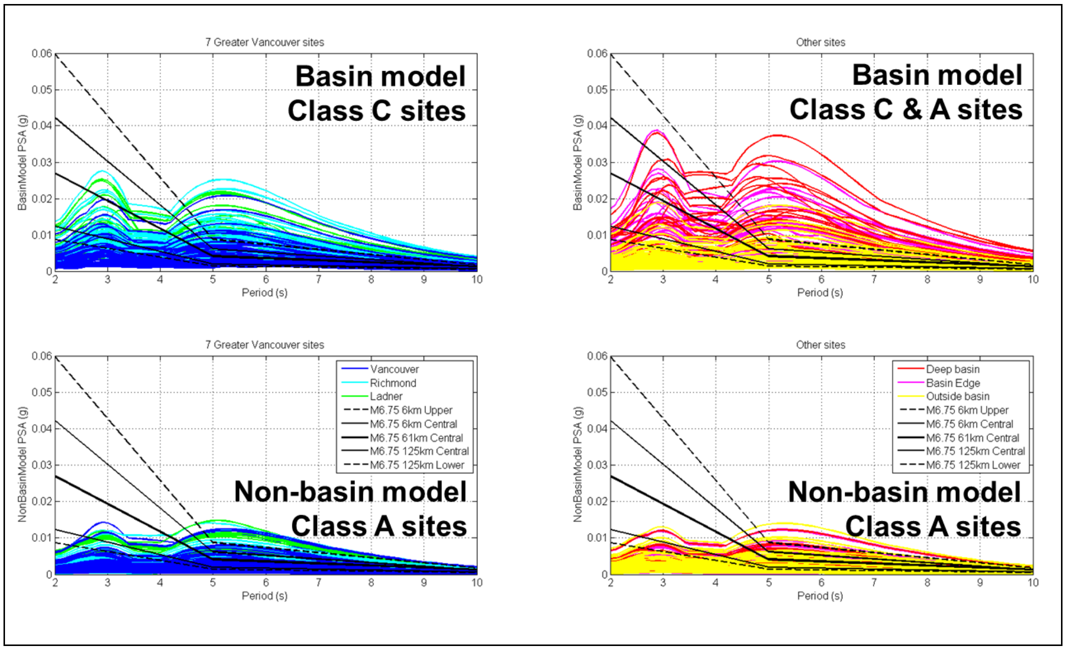

Figure 4. – Response spectra for deep inslab M6.8 earthquakes (linear scale).

3.2. Shallow Crustal Scenario Earthquakes

Figures 5 and 6 show pseudo-acceleration response spectra from basin and nonbasin model simulations (colours correspond to locations in Fig. 2) in comparison to proposed central GMPE estimates (shown by black lines for different R_{epi}) for logarithmic and linear scales, respectively.

The maximum predicted PSA for shallow crustal M6.8 scenario earthquakes is generally < 0.3 g and < 0.05 g for basin and nonbasin models, respectively, at long (≥ 2 s) periods; the average basin amplification is a factor of ~4 (Molnar et al. 2014b). The shape of the numerical long-period response spectra (Fig. 5 in particular) is related to the complex earthquake source model (Molnar et al. 2014b). The amplitude variation of the numerical long-period motions is relatively consistent at all 12 locations with varying geological and/or basin conditions (depicted by varying colours); the observed amplitude variation is related to varying distance of the 8 scenario earthquakes (R_{epi} of 6-125 km). The amplitude variation is similar amongst the 12 sites for both deep and shallow scenarios; however, higher amplitudes are predicted for shallow M6.8 earthquakes, as expected. In contrast to the deep inslab results, numerical solutions of the nonbasin model simulations are in general agreement with the proposed central GMPE, whereas numerical solutions of the basin model simulations are generally higher. Basin model simulations at sites outside of the basin (yellow lines in top right plot of Figs. 5 & 6) are in general agreement with the proposed central GMPE.

Overall, the observed increase in predicted ground motions for M6.8 shallow crustal earthquakes due to the presence of the 3D Georgia basin (basin model vs. nonbasin model) is not encapsulated by the uncertainty bounds of the proposed GMPEs at all periods investigated (2-10 s).

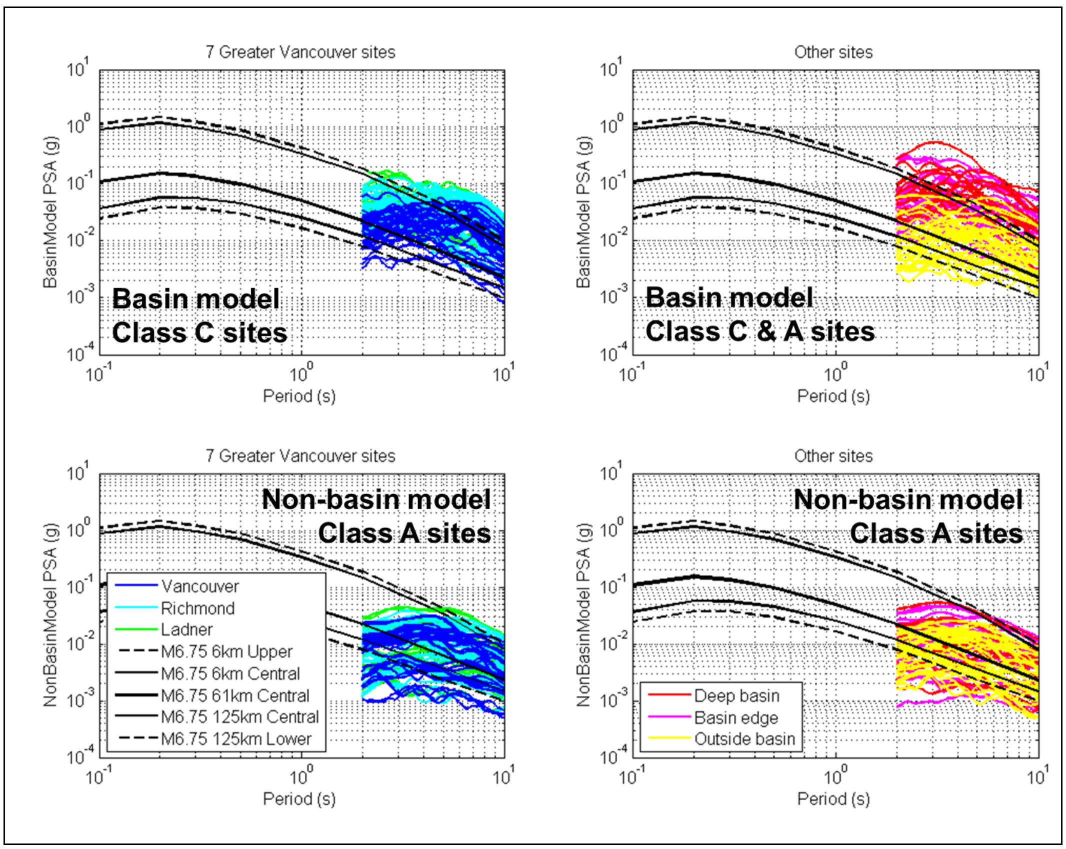

Figure 5. – Response spectra for shallow crustal M6.8 earthquakes (logarithmic scale).

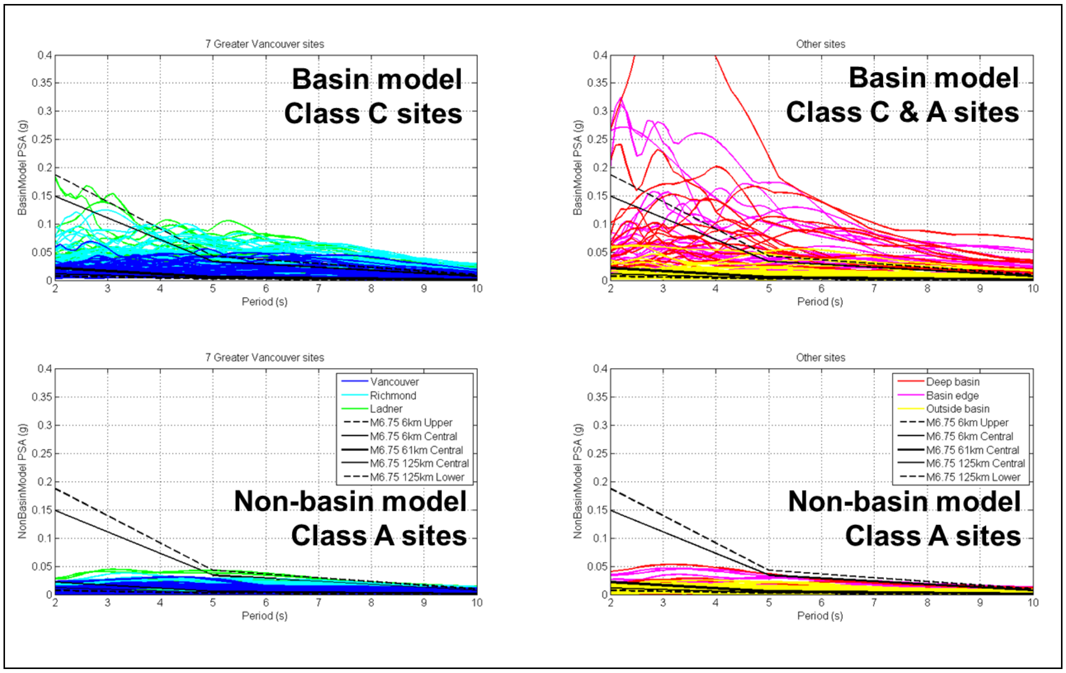

Figure 6. – Response spectra for shallow crustal M6.8 earthquakes (linear scale).

4. Summary

This paper presents comparison of long-period response spectra predicted by proposed ground motion prediction equations of the 5th generation national seismic hazard model (intended for adoption in the 2015 NBCC) and 3D earthquake rupture simulations for potential large earthquakes in British Columbia. Molnar et al. (2014a, b) demonstrated earthquake ground-motion amplification due to the 3D Georgia sedimentary basin at sites in Greater Vancouver for future large earthquakes; an average factor increase of 3-4 between basin-model and nonbasin-model 3D earthquake rupture simulations. This is the first opportunity to examine if the long-period (≥ 2 s) ground motion amplification resulting from the 3D Georgia sedimentary basin underlying Greater Vancouver is encapsulated by the proposed GMPEs of the 5th generation national seismic hazard model. Molnar et al. (2014a, b) determined that GMPEs with basin-sediment adjustment terms ($Z_{1.0}$ or $Z_{1.5}$) may be the most suitable for sites in the 3D Georgia sedimentary basin region.

The uncertainty bounds of the proposed GMPEs for M6.8 deep inslab earthquakes does encapsulate basin-amplified ground motions at periods of 2-4 s; Atkinson applies a site response correction term for long period response in British Columbia compared to sites in Japan. However, at periods ≥ 4 s, basin-amplified ground motions are not encapsulated by the proposed GMPEs for large inslab earthquakes. The uncertainty bounds of the proposed GMPEs for M6.8 shallow crustal earthquakes do not encapsulate basin-amplified ground motions at all periods investigated (2-10 s). Hence, it may be necessary to include 3D basin-sediment correction terms to the proposed GMPEs for sites in Greater Vancouver.

5. Acknowledgements

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6. References

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