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QUANTIFYING BASIN AMPLIFICATION IN SOUTHWEST BC FROM SIMULATED M9 CASCADIA SUBDUCTION ZONE EARTHQUAKES

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Abstract

Southwest British Columbia has the potential to experience large-magnitude earthquakes generated by the Cascadia Subduction Zone. Buildings in Metro Vancouver are particularly vulnerable to these earthquakes because the region lies above the Georgia sedimentary basin, which can amplify the intensity of earthquake ground motions. Studies of recorded ground motions and simulations have shown that deep sedimentary basins can greatly increase the intensity of earthquake ground motions at medium and long periods. Earthquake design provisions in Canada neglect basin amplification and the consequences of accounting for these effects are uncertain. By leveraging physics-based simulations of a suite of M9 Cascadia Subduction Zone earthquake scenarios, this paper develops site-specific and period-dependent basin amplification factors throughout Metro Vancouver. The M9 simulations, which explicitly account for basin amplification, are benchmarked against ground motion models (GMMs), i.e. BC Hydro, which neglect such effects. The results indicate that for sites outside the basin, the empirical and simulated seismic hazard estimates are consistent. However, for sites within the basin and periods in the range of 1 to 4 s, GMMs significantly underestimate the hazard. The simulated M9 ground motions are also benchmarked against probabilistic estimates of the hazard from the 2015 National Building Code of Canada. Four different hazard levels are considered: 2%, 5%, 10% and 40% probability of exceedance in 50 years. At sites within the Georgia basin, the M9 simulations, which have a return period of approximately 500 years, far exceed the 10% in 50-year probabilistic estimates of the hazard. The proposed basin amplification factors vary across the region as a function of basin depth, reaching values as high as 9.2 at a 2 s period. The proposed factors are intended for use in design until basin amplification is explicitly considered within Canada’s national seismic hazard model.

Keywords: Cascadia Subduction Zone; M9 Simulated ground motions; Basin effects; Basin Amplification Factor.

1. Introduction

The Cascadia Subduction Zone (CSZ) megathrust fault lies in the Pacific Northwest region stretching almost 1000 km from Northern Vancouver Island to Northern California. The last known rupture of the CSZ was in 1700 giving rise to a magnitude (M) ~9 earthquake [1] that produced tremendous shaking and a huge tsunami that swept across the Pacific. Despite evidence of 13 past large M 8-9 earthquakes in the Cascadia subduction zone (i.e. native oral histories and paleoseismic records) [2], there are no quantitative observations of the ground shaking during these events. How the Cascadia subduction zone will rupture in an inevitable future megathrust earthquake and the influential variability in ground shaking is largely unknown.

A recent study estimated a 14% probability of rupture of the CSZ in the next 50 years [3]. Accuracy of predicted earthquake ground motions depends on properly accounting for the earthquake fault rupture, travel path, and local site conditions. Current Ground Motion Models (GMMs) provides earthquake shaking estimates based on past observations of earthquake magnitude, epicentral or rupture distance, and local site conditions. These empirical models are insufficient to describe the expected ground motions for a future Cascadia megathrust event because the unique geological conditions of the Cascadia subduction zone and its dynamic rupture characteristics prevent direct comparison between a future Cascadia earthquake and past observations in other parts of the world (Chile, Japan, etc.). With advancements in computing, full 3D wave propagation simulations are usurping the use of GMMs for earthquake shaking prediction, especially for medium to long period structures [2]. For instance, Frankel et al. [4] produced 30 sets of broadband synthetic seismograms for M9 CSZ earthquakes by combining synthetic seismograms derived from 3D finite-difference simulations (≥1 s) with finite-source stochastic synthetics (< 1 s). These three-dimensional simulations, which considered a variety of rupture parameters to determine the range of expected ground motions, were used in this study. This model by Frankel et al. [4] was shown to accurately reproduce ground motions from the 2003 M8.3 Tokachi-oki [5] and 2010 M8.8 Maule, Chile [6] earthquakes.

Metro Vancouver lies above the Georgia sedimentary basin. Past studies have shown that recorded motions have spectral accelerations that are larger in deep sedimentary basins than in surrounding locations [7–10]. The effects of deep sedimentary basins on ground motion characteristics have also been observed in physics-based simulations of earthquake ground motions [4,11–14]. In Canada, currently enforced seismic design provisions, i.e. National Building Code of Canada 2015 (NBCC 2015) [15], do not explicitly account for these effects. Frankel et al.'s [4] M9 CSZ simulations used a three-dimensional velocity model [16], which characterizes the geological profile of the region, and thereby explicitly accounts for basin effects. As a result, these M9 simulations enable studying the impact of the Georgia sedimentary basin on spectral accelerations.

This paper evaluates and benchmarks a suite of physics-based simulation of a M9 CSZ earthquakes in Metro Vancouver, which explicitly account for basin amplification, against GMMs, i.e. BC Hydro [17], which neglect such effects. The M9 simulations are also benchmarked against probabilistic estimates of the hazard from the NBCC 2015, namely the 2%, 5%, 10% and 40% in 50 year hazard levels. The evaluations are carried out in strategic locations within and outside of the Georgia basin to quantify the expected effects of the basin on ground motion amplification. Since the current framework of the NBCC 2015 does not account for basin amplification, a period dependent and site-specific basin amplification factor is formulated. The proposed factors are intended to enable explicit consideration of these effects within Canada's national seismic hazard model for interface source contributions, and associated seismic design provisions.

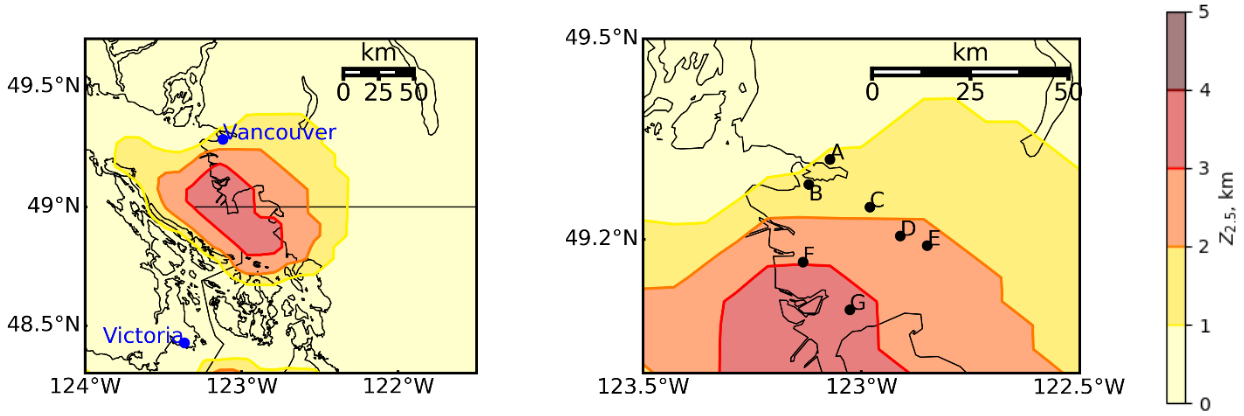
2. Simulations of M9 CSZ Earthquake and Georgia Sedimentary Basin

To understand the impact of a megathrust CSZ earthquake in the Pacific Northwest region, a collaborative group of researchers from the United States Geological Survey (USGS) and University of Washington (UW) created a suite of 30 physics based simulated M9 CSZ ground motions [4]. Each of the 30 scenarios accounts for variations in hypocenter location, extent of the rupture plane and rupture direction. The simulated ground motions were generated using a finite-difference method, for periods greater than 1 s, by utilizing a three-dimensional velocity model [16]. The geology profile of the Georgia sedimentary basin, as developed by Molnar et al. [18], was integrated into the velocity model [16]. Therefore, the effects of basin amplification due to the Georgia basin are explicitly accounted for within this suite of simulated M9 CSZ earthquakes. For periods less than 1 s, a stochastic procedure was implemented to generate the ground motions assuming constant geological profile [19]. Therefore, the impacts of the basin on the ground motion is not considered for periods below 1 s. The simulated motions were generated with an assumption of a constant time-averaged 30 m shear-wave velocity (V_{s30}) equal to 600 m/s. Hence, these ground motion simulations are appropriate for dense soils consistent with NEHRP Site Class C (360 m/s < V_{s30} < 760 m/s) [20], but may under-predict shaking in softer sites, and over-predict shaking in stiffer sites.

The Georgia sedimentary basin in southwest British Columbia is one in a series of basins in the Pacific Northwest region [21]. Based on recorded motions in other regions with similar sedimentary basins, it is expected that the ground motions in Metro Vancouver will be amplified due to the presence of Georgia basin. The amplifications are likely to occur in the medium to long period range and can have adverse consequences on seismic performance of structures, particularly with periods of 1 to 5 s. Previous studies have estimated average (period independent) basin amplification factors in the Georgia basin of 4.1 and 3.1 for shallow earthquakes and deep earthquakes, respectively [18, 22]. Numerous study have proposed depth to soils with a shear wave velocity of 1.0, 1.5 and 2.5 km/s, represented as $Z_{1.0}$, $Z_{1.5}$ and $Z_{2.5}$, as a proxy for deep sedimentary basin depths [23]. However, recent studies recommend the use of $Z_{2.5}$ for computing basin amplification in the Pacific Northwest as sites with a shallow $Z_{1.0}$ value can still have a deep $Z_{2.5}$ value [24]. Fig. 1a shows the variations in $Z_{2.5}$ in southwest British Columbia, with maximum $Z_{2.5}$ values of approximately 4 km, as assumed in Stephenson et al.'s velocity model [16], used to develop the M9 CSZ simulations. It can be inferred from Fig. 1a that Victoria is outside the basin with a $Z_{2.5}$ value of 0.06 km, whereas cities within Metro Vancouver have a range of basin depths. As a result, seven different sites were strategically selected considering their high concentration of building infrastructure, i.e. major urban centers, and a variety of basin depths. Table 1 summarizes the selected locations and their corresponding latitude, longitude, $Z_{1.0}$ and $Z_{2.5}$, as well as the labels used to locate these sites in Fig. 1b and additional maps discussed later.

Table 1 – $Z_{1.0}$ and $Z_{2.5}$ values for the selected locations within Metro Vancouver.

Locations	Labels	Latitude (°)	Longitude (°)	$Z_{1.0}$ (m)	$Z_{2.5}$ (km)
Victoria	REF-A	48.43	-123.36	0	0.06
West Vancouver	REF-B	49.33	-123.16	119.57	0.67
North Vancouver	A	49.32	-123.07	128.79	1.18
Vancouver	B	49.28	-123.12	132.81	1.22
Burnaby	C	49.25	-122.98	144.92	1.74
New Westminster	D	49.21	-122.91	150.15	2.23
Surrey	E	49.19	-122.85	149.58	2.23
Richmond	F	49.17	-123.13	168.97	3.22
Delta	G	49.09	-123.03	163.19	3.27



(a) (b)

Fig. 1. Variations of $Z_{2.5}$ in (a) southwest British Columbia and (b) Metro Vancouver with selected locations including North Vancouver (A), Vancouver (B), Burnaby (C), New Westminster (D), Surrey (E), Richmond (F) and Delta (G). Adapted from [25].

3. Benchmarking of M9 CSZ Simulated Ground Motions

In its design provisions, the NBCC 2015 uses a site-specific 5% damped elastic spectrum with a 2% probability of exceedance in 50 years, i.e. a 2475 year return period, to characterize seismic demands for building design. The response spectrum is primarily derived from probabilistic seismic hazard analysis. Canada's national seismic hazard model [26] includes a range of GMMs for different earthquake sources, e.g. BC Hydro [17] for subduction earthquakes. To quantify deep basin amplification on ground motion shaking, the response spectrum of the suite of simulated M9 CSZ earthquakes are benchmarked against the estimates of the BC Hydro GMM for the same set of rupture scenarios. Fig. 2a-2i provide a comparison of the average of the geomean spectra for the suite of M9 simulations against corresponding BC Hydro estimates. These spectra are shown for each of the sites, presented in Table 1. Additionally, Uniform Hazard Spectra (UHS) with a 2%, 5%, 10% and 40% probability of exceedance in 50 years, as derived from Canada's national seismic hazard model [26] are also provided to benchmark the M9 CSZ earthquake scenarios against probabilistic estimates of the hazard.

As seen in Fig. 2a, for sites outside of the Georgia basin, i.e. Victoria, the M9 simulations and BC Hydro predictions match well. However, just outside of the basin edge and for sites within the basin, the simulated M9 spectra are significantly higher than the corresponding BC Hydro estimates, particularly in the 1 to 5 s period range. As observed in Fig. 2c-2i, the ratio of the M9 to BC Hydro spectral accelerations in the 1 to 5 s period range strongly correlates with $Z_{2.5}$. At sites with lower $Z_{2.5}$ values, i.e., 1.18 km in North Vancouver, this ratio is around 2.7 at 2 s period. At sites with higher $Z_{2.5}$, i.e., 3.26 km in Delta, the ratio is around 6.2 at the same period.

For locations within the basin with a $Z_{2.5}$ in the range of 1 to 2 km, e.g. Vancouver, simulated M9 spectral accelerations for periods in the range of 1 to 3 s are consistent with the NBCC 2015 probabilistic seismic hazard estimates with a 975-year return period. For locations within the basin with a $Z_{2.5}$ in the range of 3 to 4, e.g. Richmond, M9 estimates exceed the 2475-year return period probabilistic estimate of the hazard. The NBCC 2015 UHS represents contributions to the hazard from all seismic sources in the region, i.e. crustal, intraslab and interface. Therefore, the M9 CSZ earthquake spectra, which has an estimated 500-year return period [27], should fall below the 10% in 50-year probabilistic estimate of the hazard. While this observation holds outside of the basin, i.e. Victoria, due to basin amplification, the M9 spectra for sites within the basin far exceed this hazard level.

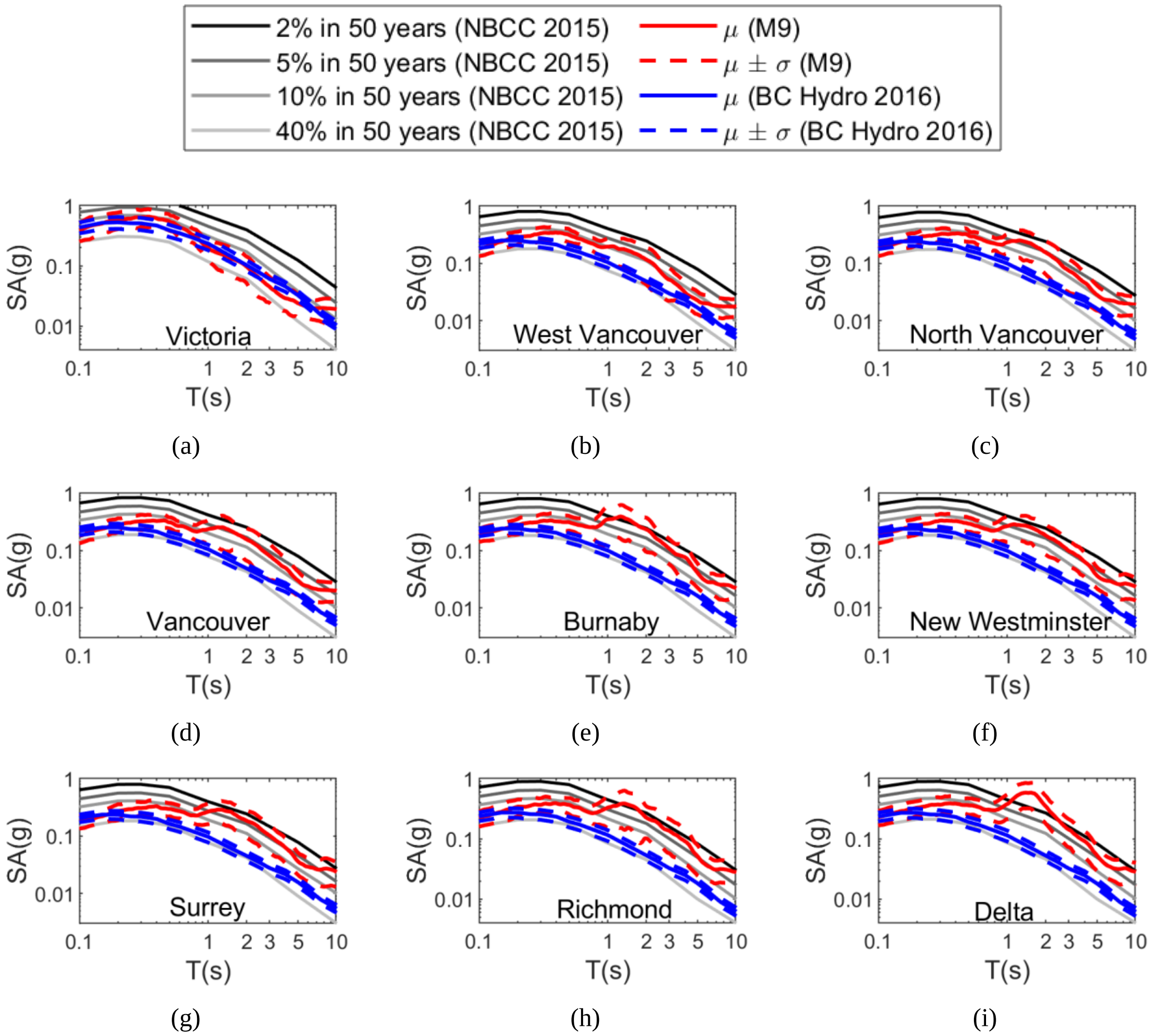


Fig. 2. Average response spectra of simulated M9 CSZ earthquake ground motions, BC Hydro estimates and NBCC 2015 probabilistic estimates of the hazard with 2%, 5% 10% and 40% probability of exceedance in 50 years in (a) Victoria, (b) West Vancouver, (c) North Vancouver, (d) Vancouver (e) Burnaby, (f) New Westminster, (g) Surrey, (h) Richmond and (i) Delta. Adapted from [25].

4. Spectral Acceleration Basin Amplification Factors

In order to accurately quantify the effects of deep basins on ground motion shaking, we utilize a site-specific and period-dependent spectral acceleration basin amplification factor, BAF_T^i. For each rupture scenario, site and period, the ratio of the spectral acceleration predicted by the M9 simulations to BC Hydro predictions is computed. This value is then normalized by the same ratio computed at a reference site outside the basin, i.e. Victoria and West Vancouver. The resulting BAF_T^i is the geometric mean of individual basin amplification factors calculated for each rupture scenario. This basin amplification factor, defined in Eq. (1), can be used in current design provisions to amplify design spectral accelerations as a proxy to account for basin effects.

$$BAF_T^i = \prod_{x=1}^{n} \left(\left(\frac{SA_{M9}^i(T)}{SA_{GMM}^i(T)} \right) \Big/ \left(\frac{SA_{M9}^{ref}(T)}{SA_{GMM}^{ref}(T)} \right) \right)^{\frac{1}{n}} \tag{1}$$

where, BAF_T^i is the basin amplification factor at a site i and period T, $SA_{M9}^i(T)$ is the spectral acceleration of the simulated M9 ground motion at period T for a particular rupture scenario, and $SSA_{GMM}^i(T)$ is the BC Hydro prediction of spectral acceleration at period T for the same rupture scenario. $SA_{M9}^{ref}(T)$ and $SA_{GMM}^{ref}(T)$ represent the same parameters, but calculated at the reference sites outside the basin, and n is the number of rupture scenarios. Fig. 4a and 4b show the BAF_T^i at the sites of interest, listed in Table 1, within Metro Vancouver for a period range of 0.5 to 10 s, considering both Victoria ($Z_{2.5}$ = 0.06 km) and West Vancouver ($Z_{2.5}$ = 0.67 km) as reference sites. The geospatial variation of BAF_T^i is illustrated in Fig. 5a and 5b. $BAFs$ are highest in the period range of 1 to 5 s, and remain fairly constant from periods of 5 to 10 s. Amplification factors are highest in Delta, where the Georgia basin has a $Z_{2.5}$ value of 3.27 km, reaching values of 9.2 at a period of 2 s.

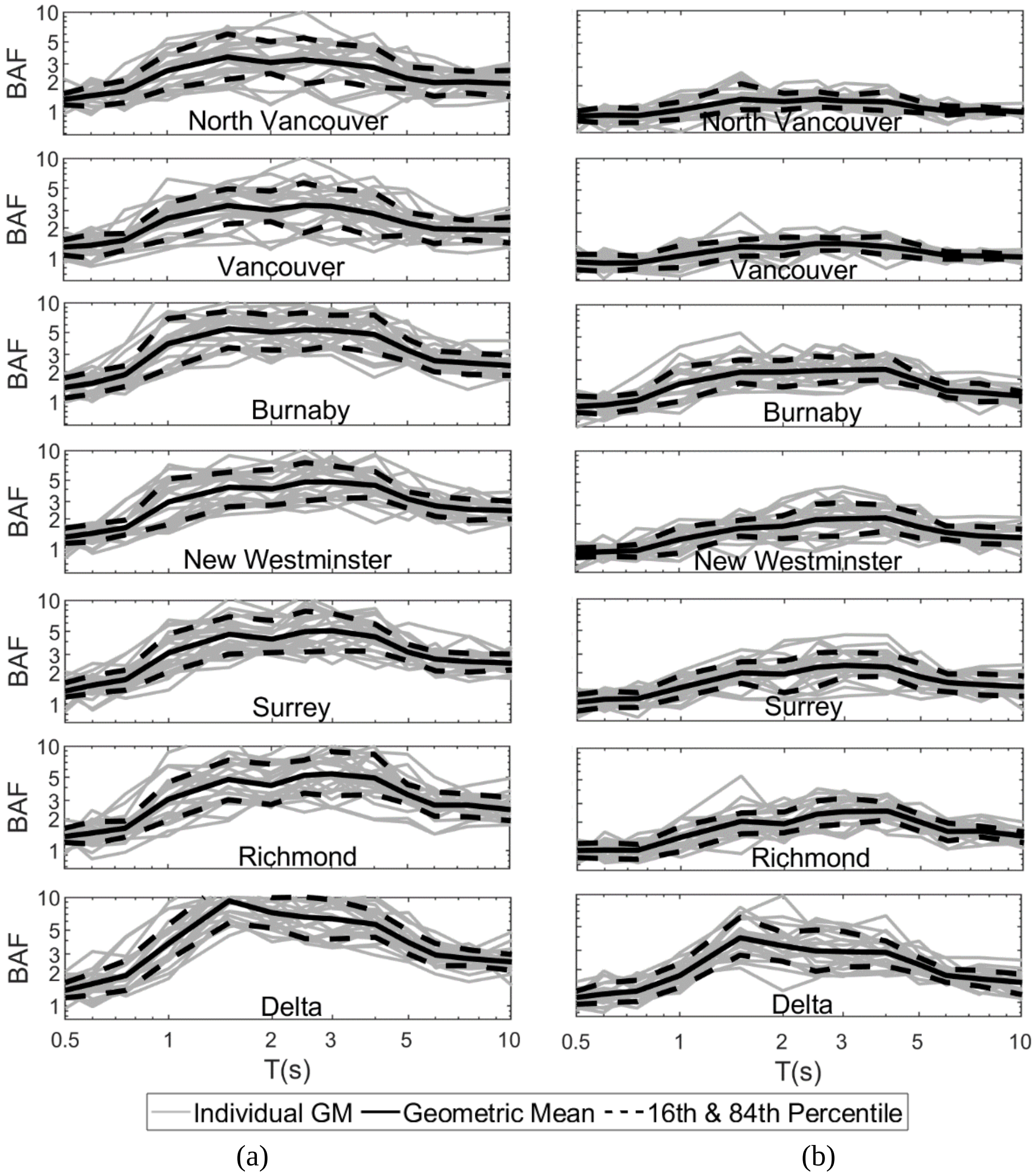
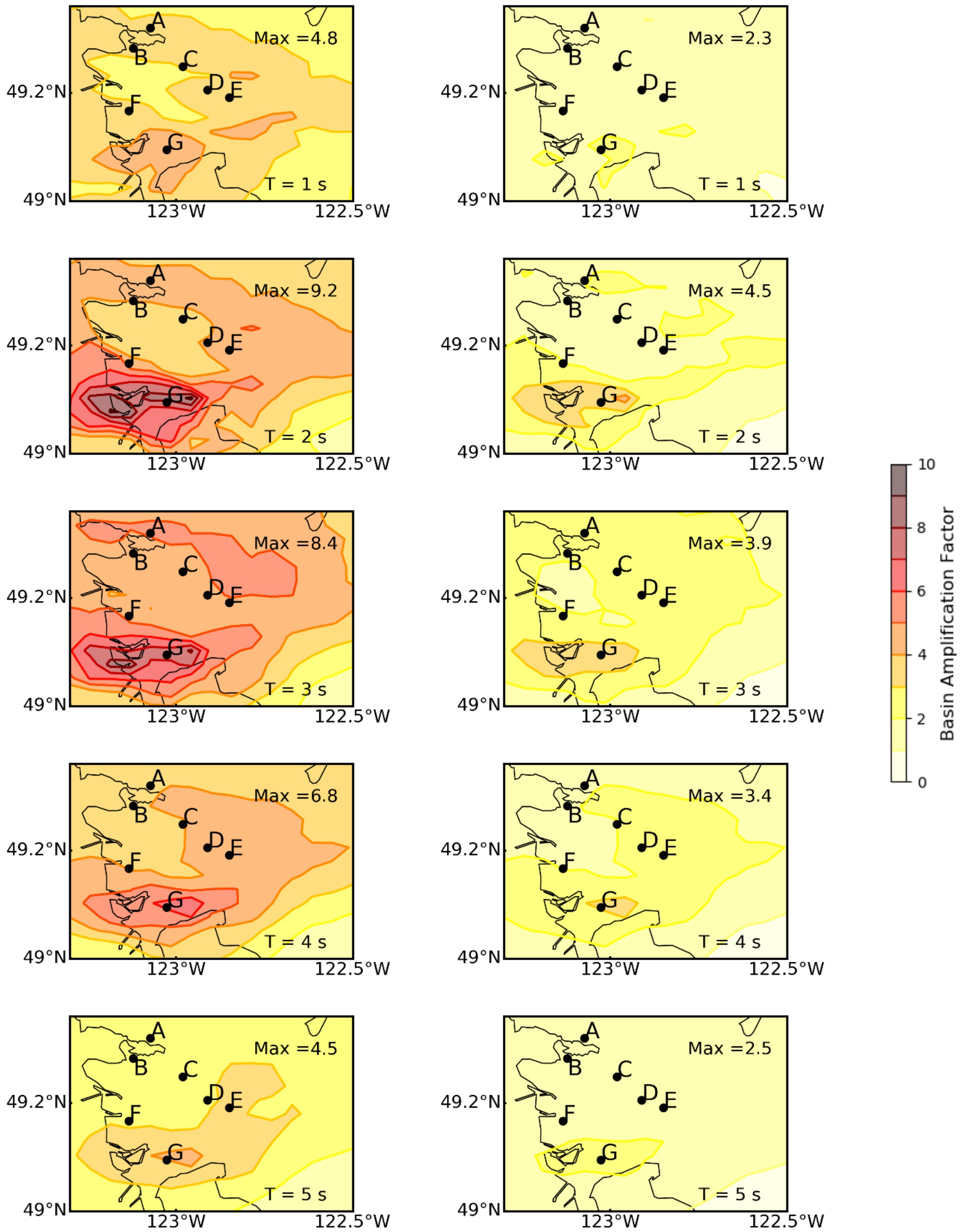


Fig. 4: Spectral Acceleration Basin Amplification Factor (BAF) for selected locations in Metro Vancouver with (a) Victoria and (b) West Vancouver as reference sites. Adapted from [25].



(a) (b)

Fig. 5. Geospatial variation of Basin Amplification Factor (*BAF*) within Metro Vancouver (annotated with the maximum BAF in the region at the upper-right corner and period at lower-right corner) for periods of 1, 2, 3, 4 and 5 s with (a) Victoria and (b) West Vancouver as reference sites. Adapted from [25].

The amplifications computed in this study are substantially higher than those predicted for crustal earthquakes by Campbell and Bozorgnia [8]. In the latter GMM [8] for crustal sources, the basin amplification is equal to 1.0 for $Z_{2.5}$ ranging from 1 to 3 km. However, if this relationship were applied to the subduction sources and the Georgia basin, it would considerably underestimate the effects of basin amplification as illustrated in Figure 5. Studies that used the M9 simulations to estimate basin amplification in the Seattle basin [19, 24] also found that the Campbell and Bozorgnia [8] basin term underestimated amplification of spectral accelerations. Frankel et al. [4] showed that amplification factors from the M9 simulations and ground motion recordings (from earthquakes with similar depths and azimuths as a megathrust event) yielded consistent amplification factors that were significantly higher than those predicted by Campbell and Bozorgnia [8]. These differences are partly attributed to some of the basin amplification being absorbed in the V_{S30} term in NGA-West2, which would not apply to the Seattle basin or the Georgia basin because V_{S30} is similar for sites inside and outside the basin [24].

As seen Fig. 4 and 5, BAF is sensitive to the choice of reference site, primarily due to the differences in $Z_{2.5}$ between Victoria (0.06 km) and West Vancouver (0.67 km), but possibly also due to the influence of basin-edge effects affecting the West Vancouver site [22]. For instance, Delta has a BAF of around 9.2 at 2 s period with Victoria as a reference site. However, the BAF is around 4.5 at the same period with West Vancouver as a reference site. In a recent USGS report [24], it is noted that in order to develop site-specific basin terms using three-dimensional simulations or observations and a reference GMM, a reference $Z_{2.5}$ or shear wave velocity profile, V_S, from the GMM dataset is required. While this information is not currently available, a reference $Z_{2.5}$ and V_S profile of the BC Hydro GMM will permit a more appropriate selection of a reference site to quantify basin amplification in Metro Vancouver.

Currently enforced basin amplification factors in the city of Seattle [28] for performance-based seismic design projects, require amplification factors of 1 to 2 for periods in the range 0 to 2 s, and amplification factors of 2 for periods greater than 2 s. These observations are derived from the selection of a reference site immediately outside the basin. Similar basin amplification factors are reported in this study when using a reference site immediately outside the basin, i.e. West Vancouver.

5. Conclusion

By leveraging a suite of physics-based simulations of M9 CSZ earthquakes, this study highlights that Canada's current national seismic hazard model, adopted by the NBCC 2015, underestimates expected ground motion shaking in Metro Vancouver because it does not explicitly consider amplification effects from the Georgia sedimentary basin. To address this issue, site-specific and period-dependent basin amplification factors are proposed throughout the Metro Vancouver region.

The results shows that basin amplification factors correlate with $Z_{2.5}$, a proxy commonly used for basin depth. The study also illustrates how the choice of reference site can significantly influence the anticipated basin amplification. Out of the seven locations selected in this study, Delta has the highestBAF, with a value of 9.2 at a 2 s period with Victoria as the reference site, and 4.5 at the same period with West Vancouver as the reference site.

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