3D Sedimentary Basin Effects in the Metro Vancouver Area and Its Seismic Hazard Implications: Updates and Validations of the Georgia Basin Velocity Model

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ABSTRACT

A multi-year seismic microzonation mapping project for Metro Vancouver, B.C. is underway to assess and map earthquake shaking (amplification), liquefaction, and landslide hazards. In this study, we used an updated sedimentary Georgia basin velocity model to examine predicted three-dimensional (3D) earthquake ground shaking in Metro Vancouver. Our overall aim is to properly characterize and incorporate earthquake basin effects from the Georgia sedimentary basin into the Metro Vancouver hazard mapping. The Pacific Northwest (Cascadia) Community Velocity Model [1] was first modified in the upper 1 km by [2][3][4] to accurately represent velocities in the Georgia basin. The basin structure can lead to strong lateral variations in peak ground motion, amplification and shaking duration. Depending on source-basin-receiver geometry, the effects may correlate with basin depth and the slope of the basin edges; yet, the basin can also affect peak ground motion and estimated shaking hazard outside the basin. Using the updated Georgia basin velocity model, we simulate strong ground motion within the Georgia Strait area by means of 3D deterministic wave propagation simulations based on the finite difference method. We use the observed ground motions of the December 2015 moment magnitude (**M**) 4.7 Vancouver Island earthquake to validate the updated velocity model. The results of this study are important in understanding the key factors controlling the basin response and its resonance(s) and its impact on seismic hazard assessment for Metro Vancouver.

Keywords: microzonation mapping, basin effects, 3D deterministic earthquake simulation, seismic hazard, velocity model.

INTRODUCTION

Earthquake waves are altered by 3D basin structure by the generation of long-period surface waves from the conversion of incident shear waves at the basin edge and/or walls (e.g. [5]), and by the trapping of shear waves at the basin edge (e.g. [6]). As an example, long-period (~2 s) earthquake ground motion in the soft clay basin of Mexico City during the 1985 Ms 8.1 Michoacán earthquake, more than 300 km distant, was ~14 times higher [7] and lasted nearly three times longer than on firm ground nearby [8]. Large amplification in sedimentary basins may also result from constructive interference of upward propagating shear waves and laterally propagating surface waves from the basin edges (i.e. basin-edge effect; [9][10]).

In deep sedimentary basins, the effects of surface waves need to be taken into account in the design of long-period structures and smaller structures undergoing large nonlinear deformations [11][12]. In the LA basin, for example, late-arriving surface waves ≥ 3 s dominate strong-motion earthquake recordings, and their decay rate is less than for shear waves; hence, general ground-motion prediction equations (GMPEs) underestimate amplitude in the basin by as much as a factor of 3 [11]. Day et al. [12] simulated ground motions of 60 scenario earthquakes in the LA basin to complement the empirical strong-motion dataset for development of the Next Generation of ground-motion Attenuation relations. The depths to Vs of 1.0, 1.5, and 2.5 km/s ($Z_{1.0}$, $Z_{1.5}$, and $Z_{2.5}$, respectively) are proposed as suitable predictors of long-period motion in basins by [12]. Although these added terms improved prediction of long-period motion by GMPEs, ultimately 3D basin effect simulations should be directly incorporated in the generation of seismic hazard maps, as was carried out for Seattle, Washington by [13]. Effort is underway on capturing sedimentary basin amplification into national seismic hazard maps in the US [14].

The area of highest seismic risk in Canada is metropolitan Greater Vancouver, where over 2 million people and critical infrastructure are exposed to seismicity related to the Cascadia subduction zone [15]. Greater Vancouver is underlain by the Georgia basin, a Late-Cretaceous sedimentary basin; surficial Holocene sediments of the Fraser River delta in southern Greater Vancouver compose the upper-most sediments of the basin. The basin thickness increases from north to south with a maximum thickness of 7 (±1) km (depth to velocities of 5.5 km/s) at the SE end of the strait. Amplification of earthquake ground motion here from inevitable future large earthquakes is not only dependent on the 1D soil column and non-linear response of the sediments, but is also dependent on the 3D structure of the Georgia basin. Realistic estimates of earthquake ground motion must account for all of these components. Previous numerical modelling of earthquake response on the Fraser delta has concentrated on the effect of the 1D soil layering, confirming amplification due to the thick accumulations of Holocene deltaic and/or Pleistocene glacial sequences [16][17][18][19][20].

The goal of this study is to use 3D finite-difference numerical modelling to compute long-period (> 2 s) ground motions in the Georgia basin region of B.C. for the 2015 **M** 4.7 Vancouver Island earthquake to quantify effects due to 3D basin structure. The Pacific Northwest 3D velocity model of [1] is the base elastic structure model. We use a modified version of the model in which velocities in the upper 1 km for the Georgia basin region has been updated [2]. Simulated long-period ground motions using this updated 3D velocity model were calibrated using earthquake recordings of the 2001 **M** 6.8 Nisqually, WA, earthquake, the only suitable earthquake recordings at the time. The 2015 **M** 4.7 earthquake was recorded on 19 seismographs and 56 strong-motion instruments in southern B.C. Jackson et al. [21] providing a sufficient ground motion dataset from which to further evaluate accuracy of our 3D long-period waveform simulations. In comparison to the **M** 6.8 Nisqually earthquake, the **M** 4.7 Vancouver Island earthquake has a simpler source-rupture model. Thus, complexities due to source modelling will not propagate to the simulated ground motions and this will enable us to better focus on the basin effects (velocity model). Moreover, considering the deep focus of the Vancouver Island inslab earthquake, ground motions from this earthquake serve as vertical-incident input motions radiating directly into the Georgia basin.

REGIONAL SEISMICITY AND PREVIOUS INSLAB EARTHQUAKES

The 29 Dec. 2015 (11:39 p.m. Pacific Time) **M** 4.7 Vancouver Island inslab earthquake was a normal-faulting event at 60 km depth within the subducting Juan de Fuca (JdF) oceanic plate, whose epicenter (48.62° N, 123.30° W) is located ∼21 km N-NE of Victoria and 71 km S-SW of Vancouver, B.C. [21]. The earthquake was felt to distances of more than 400 km across much of British Columbia's South Coast and parts of Washington State. The preferred faulting plane of the Canadian National Seismograph Network (CNSN) seismic moment tensor solution strikes approximately N–S at 317° with a steep 64° dip and -100° rake. The largest recorded JdF plate earthquakes occurred beneath Puget Sound in 1949 (**M** 7.1), 1965 (**M** 6.5), and 2001 (**M** 6.8), whereas events beneath Georgia Strait have generally been of smaller magnitude (**M** ≤ 5.5).

The 2015 **M** 4.7 Vancouver Island earthquake is note-worthy to the region due to its magnitude and location. It is the fourth recorded inslab earthquake greater than magnitude 4 to have occurred in Georgia Strait (epicenter within 50 km of Victoria). Inslab earthquakes exhibit the greatest frequency of occurrence in Cascadia, more frequent than crustal or interface events. In addition, despite their greater depth, their predicted shaking is stronger than crustal events of the same size. Due to these factors, inslab earthquakes dominate (especially at short-periods) the hazard in southwestern B.C. [22].

DATABASE OF M 4.7 VANCOUVER ISLAND EARTHQUAKE RECORDINGS

The 2015 **M** 4.7 inslab earthquake is a notable well-recorded event due to the increased density of strong-motion instrumentation in southwestern B.C., currently >100 free-field strong-motion stations [21]. This earthquake also generated the first ever borehole earthquake recordings (Fig. 1) obtained at depth in B.C. Figure 1 shows the available CNSN broadband and strong-motion (Internet Accelerometer; IA) stations within the study area (Georgia basin structural model).

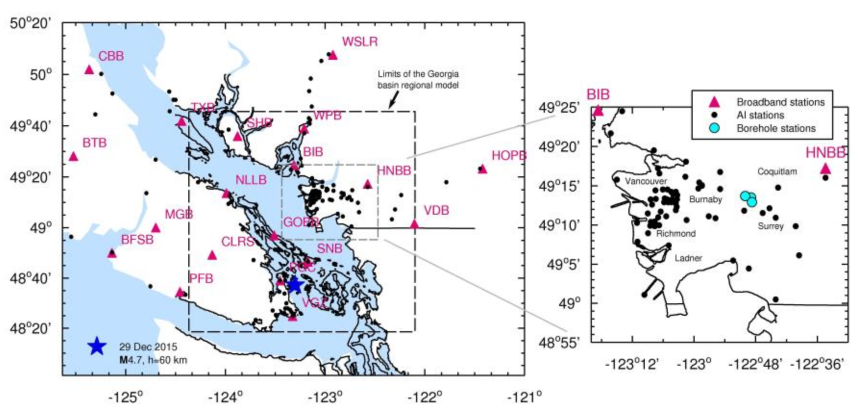

Figure 1. Overview map showing locations of CNSN and IA stations in relation to the Georgia basin velocity model limits (black dashed box) and Greater Vancouver (grey dashed box).

Ground motions from this event are retrieved and processed from all available accelerometer and seismometer stations within 500 km from the epicenter [21]. Strong-motion recordings were obtained from the B.C. Smart Infrastructure Monitoring System (BCSIMS) IA network. Time series are available from 56 strong-motion stations operating within 100 km of the earthquake epicenter. Ground motions at further distances are unlikely to exceed the site background and instrument's noise;

waveforms available at farther distance stations are not considered further here. The 2015 **M** 4.7 earthquake was also recorded by the three downhole arrays at both terminus ends of the Port Mann Bridge (shown with three cyan circles in Fig. 1). Jackson et al. [21] used these strong-motion borehole recordings to examine the variation of earthquake shaking amplitude with depth in the Lower Mainland. They concluded that the recorded motions increase toward the surface and are of similar or higher amplitude than at nearby surface stations. Amplification between top and bottom sensors is a consistent factor of 7–8 in all three arrays over a similar 40–45-m depth interval of Fraser delta sediments. Cross-correlation analysis determines Vs estimates less than 350 m/s consistent with these delta sediments. Assaf et al. [20] perform 1D numerical modeling to compare the theoretical amplification with the observed spectral ratios from borehole recordings from the 2015 earthquake. Studying the acceleration spectral amplitudes at different stations for earthquakes between 1976 and 2015, they were be able to confirm the previously predicted amplification at lower frequencies (< 1 Hz; [16][18]) in Fraser river delta. It has been demonstrated by [19] that at thick delta sites the fundamental frequency could be as low as ∼0.3 Hz (3 seconds).

VELOCITY MODEL (PHYSICAL STRUCTURE MODEL)

The base elastic 3D model is a clipping of the Pacific Northwest 3D velocity model [1], with dimensions of 150 km NS by 180 km EW by 60 km Up-Down and a spatial uniform-grid resolution of 250 m (i.e., 6,480,000 grid cells). The minimum Vs is set to 625 m/s, representative of a Pleistocene glacial (stiff) sediment surface. The Georgia basin is elongate in a NW-SE orientation, with depths of < 3 km NW and < 7 km SE of Greater Vancouver. The upper 1 km of the 3D structure model is revised in the Georgia basin region using recent geologic and geophysical information from a variety of sources [2][3][4]. A non-basin model is generated from the updated 3D basin model by setting the minimum Vp to 5.5 km/s, effectively removing the lowest velocity (basin) sediments. Figure 2 compares the updated basin and non-basin models in the upper 250 m. The basin and non-basin models are identical at 7 km depth.

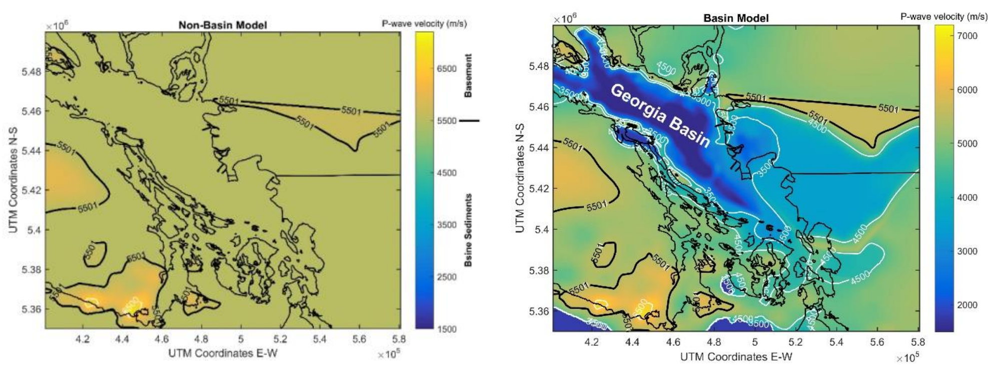

Figure 2. Depth slice(s) of non-basin and the updated basin Vp models from surface to 250 m. Thin black lines are coastlines and thick contours (5.5 km/s) representing the basement of the basin. Modified after Molnar (2011).

As part of the seismic microzonation mapping project for Metro Vancouver, B.C., we are aiming to further update and improve the resolution of the Georgia basin velocity model, specifically within the Metro Vancouver area, by incorporating Vs profiling information, including ~42 seismic array locations, ~1000 microtremor H/V spectral ratio measurements, and ~500 geotechnical reports obtained from local agencies and/or engineering firms. Characterizing Vs layers is of critical importance for recently deposited materials (e.g. alluvial basins), because these materials tend to have the lowest velocities and therefore the greatest potential for seismic (de)amplification, soil non-linearity, and/or liquefaction (pore water pressure dissipation).

M 4.7 RECORDED GROUND-MOTIONS AND EARTHQUAKE SOURCE MODEL

To assess the effects of 3D Georgia basin structure on long-period (> 2 s) ground motion for large scenario earthquakes, numerical 3D finite difference modelling of viscoelastic wave propagation is applied. Shorter period ground motions are not resolved, limited by the grid spacing and minimum Vs chosen for the 3D basin model according to a 5 node per minimum shear wavelength rule-of-thumb commonly used for fourth-order finite-difference schemes. Simulations are calibrated by comparing synthetic waveforms with the three (closest) selected broadband seismograms of the 2015 **M** 4.7 Vancouver Island earthquake.

Figure 3 shows the recorded time-series on broadband seismometers within the study area. Clear P- and S-wave arrivals are observed in the vertical and horizontal components, respectively at the closest stations; lower amplitudes at further stations. Other complexities in the waveforms are due to regional path and local site variations from the source to each station. Figure

4 shows the borehole array recordings. Acceleration time-series are converted to velocity and band-pass filtered. The signals are too weak at $f < 0.5$ Hz.

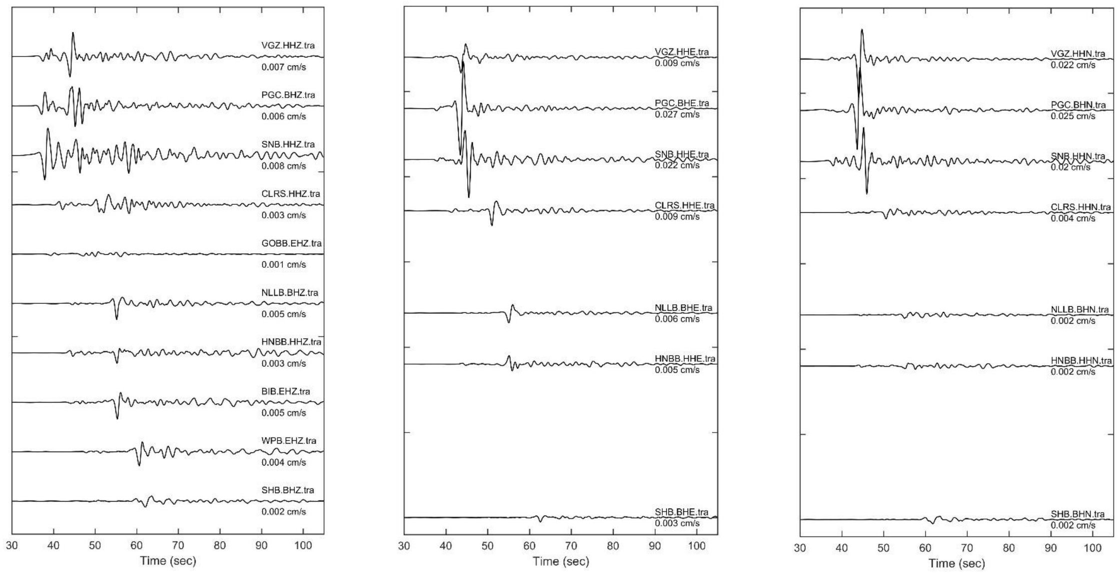

Figure 3. Broadband velocity time-series are low-pass filtered with a corner frequency of 0.5 Hz. Left panel shows the vertical components, and the middle and the right panels show the two horizontal (EW & NS, respectively) components.

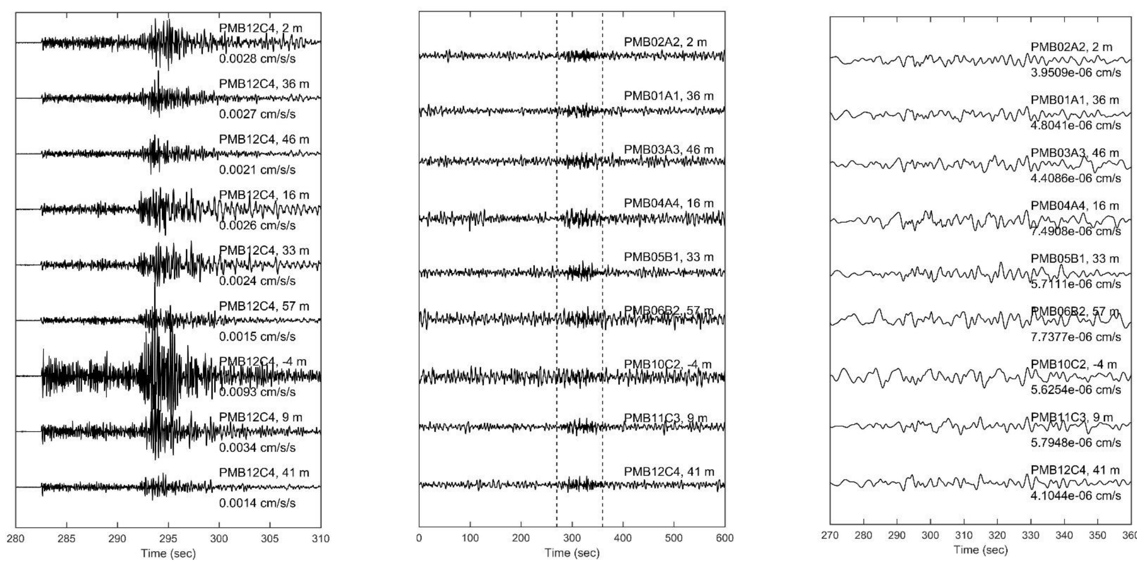

Figure 4. Vertical-comp. acceleration (left) and velocity time-series (middle) from IA stations are band-passed filtered with corners of 0.1 & 0.5 Hz. The right panel shows zoomed-in window (depicted with dashed lines in the middle panel). The name of stations, their depth of recordings, and peak ground velocity (PGV) values are reported on each trace.

It has been shown [21] that the stress parameter of the **M** 4.7 inslab earthquake, if approximated by a Brune source model, is high (~1000 bars). Inslab events are expected to have larger stress parameters in comparison to crustal or subduction zone interplate earthquakes of the same magnitude. A larger depth of faulting logically leads to a higher static stress drop because of the increased shear load on the faults due to an increase in confining pressure [23]. It has also been observed that deeper inslab earthquakes have a significantly smaller area of asperities in comparison to shallower strike-slip earthquakes with the same seismic moment. This difference in rupture area can lead to a 3- to 5-fold increase in stress drop for earthquakes with seismic moments between 1024 (**M** 5.3) and 1028 (~**M** 8.0) dyne.cm [23].

The CMT solution provided by NRCAN is shown in Figure 5. The inversion was done with long-period waveforms. The moment-tensor mechanism of Vancouver Island earthquake is normal faulting with a down-dip-trending T axis which is similar in style to other Cascadia inslab earthquakes [23]. Considering the 2001 Nisqually earthquake [24] as an analogous case to the 2015 Vancouver Island earthquake, the steeply dipping plane (FP2) is the most probable rupture plane. The information for the 1949 and 1965 inslab earthquakes are also provided in Table 1.

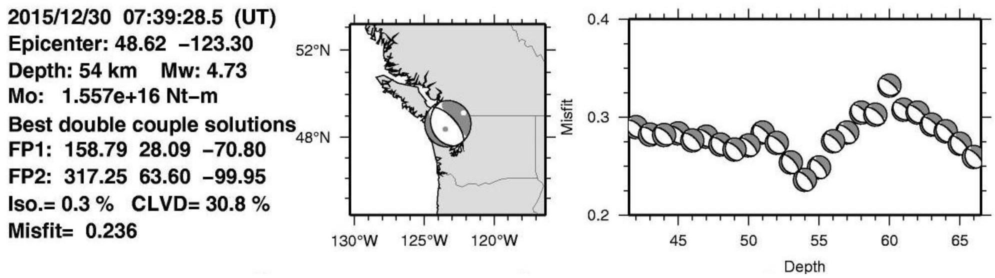

Figure 5. Focal mechanism solution computed based on CNSN broadband data. Best double couple solutions (nodal fault planes) are reported as FP1 and FP2.

Table 1. Inslab earthquake information in the Puget Sound region.

Earthquake	Date	Mag.	Depth (km)	Epicenter lat°, long°	Focal mechanism	References
Olympia, Washington	13 Apr. 1949	7.1	54	47.17°N 122.62°W	strikes EW±15°, dips 45°±15° to the N, and has nearly pure left-lateral slip	[25]
Seattle-Tacoma	29 Apr. 1965	6.6	60	47.38°N 122.31°W	strikes 344° and dips 70° [24]; Dip-slip	[26]
Nisqually	28 Feb. 2001	6.8	56	47.14°N 122.71°W	FP1: 196°/22°/-67° FP2: 351°/68°/-98° (Preferred nodal plane)	[26]

We use a point source approximation to model ground motions from this earthquake. This is a valid assumption considering the depth (centroid depth = 54 km) and size of earthquake. A symmetric cosine moment-rate (source time) function with a total rise time T_{rise} = 1.0 sec is assumed. We set 20 grid points (5 km) as an absorbing boundary conditions [27] – a zone of highly attenuative material [28] – to minimized the reflections from the sides and bottom of the model. For the simulations we consider a focal depth of 50 km, to avoid model edge effects. The 3D elastic equations of motion are solved here using the scheme of [29] with fourth-order accuracy in space and second-order accuracy in time.

RESULTS

In Figure 6, we compare the synthetic ground motions with the broadband recordings (low-pass filtered with a corner of 0.5 Hz) at the three closest stations to the epicenter. The synthetics capture the largest P- and S-wave arrivals and generally agree with later arrivals observed in the seismograms at VGZ and SNB. The fit is less ideal for station PGC which could be due to local site effects, simplicity of the source model considered for simulating ground motions; unmodeled crustal effects due to subsurface heterogeneities and detailed structures in the earth in comparison to the adopted velocity model; and uncertainties in the earthquake location. In general, stations in the basin and its edge (SNB) are expected to have more complex, longer duration waveforms, with phases following the S-waves.

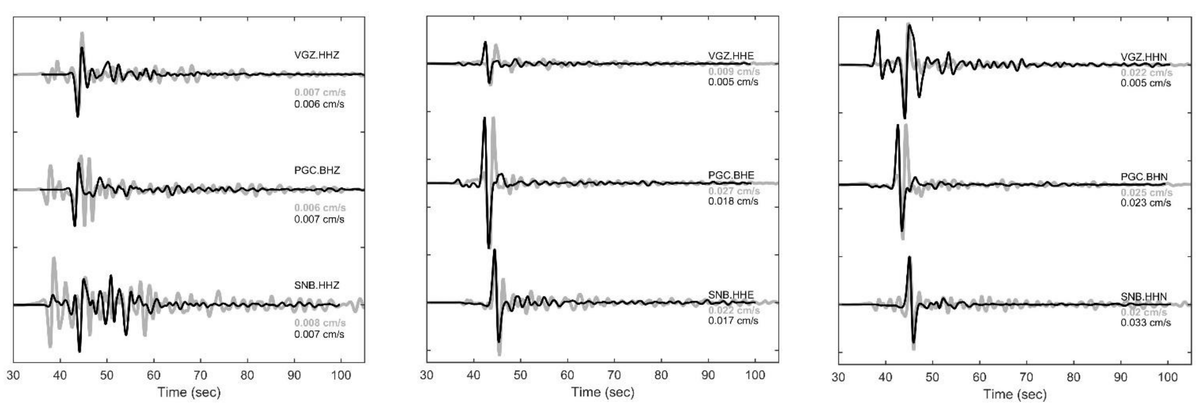

Figure 6. Comparison of empirical **M** *4.7 earthquake recordings (gray lines) and synthetic (black lines) velocity time-series for the 3 closest broadband stations.*

Figure 7 shows simulated PGV maps of the Georgia basin region for the two hor. and ver. directions of motion. For the Georgia basin region, high NS (and EW) ground motions (~0.15 cm/s) occur near the epicenter, possibly due to the source radiation pattern. Predicted ground motions (< 0.5 Hz) in the Georgia basin region, over ~150 km distant, are < 0.03 cm/s.

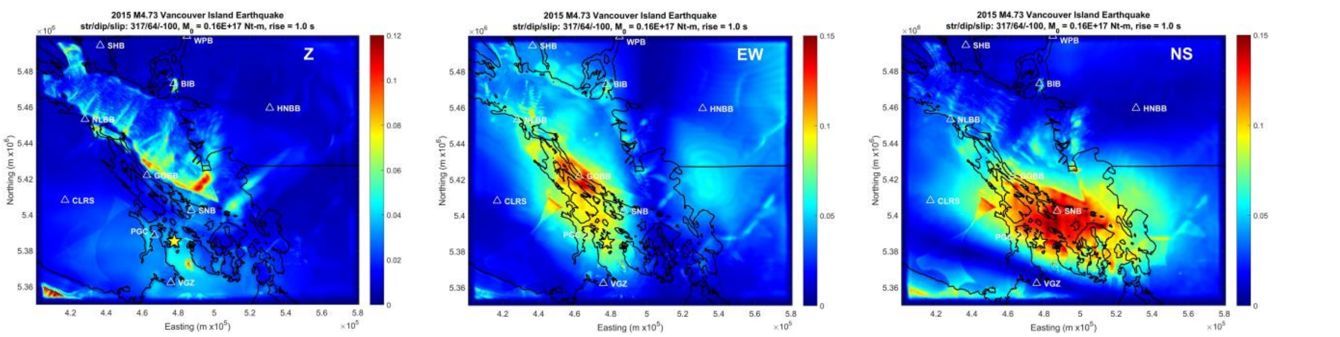

Figure 7. Predicted PGV maps of **M** *4.7 Vancouver Island earthquake for Georgia basin region. Earthquake epicenter is shown by star. White triangles denote locations of selected earthquake recording sites labelled with code names.*

Time-snapshots of peak velocities for ~25 s of the basin model simulation are presented in Figure 8 and Figure 9 to investigate the generation of peak waveform arrivals at a location close to the epicenter. The delay of particular peak arrivals at the surface in comparison to at depth is readily apparent in the cross-section time-snapshots in Figure 8. Similar to the observations in other studies (e.g. [13]), synthetic time-series near the basin edge have relatively simple, short duration signals, whereas stations located over the deepest parts of the basin have more complex, longer duration waveforms. By ~25 s in the simulation, the 3D Georgia basin structure generates and sustains the strongest long-period surface waves, in the deep narrow NW-SE extent of the basin axis (Figure 9). High basin amplifications in Georgia Strait, W and S of the onshore circular high amplification area, are coincident with basin edges in the upper 500-1000 m (Figure 9).

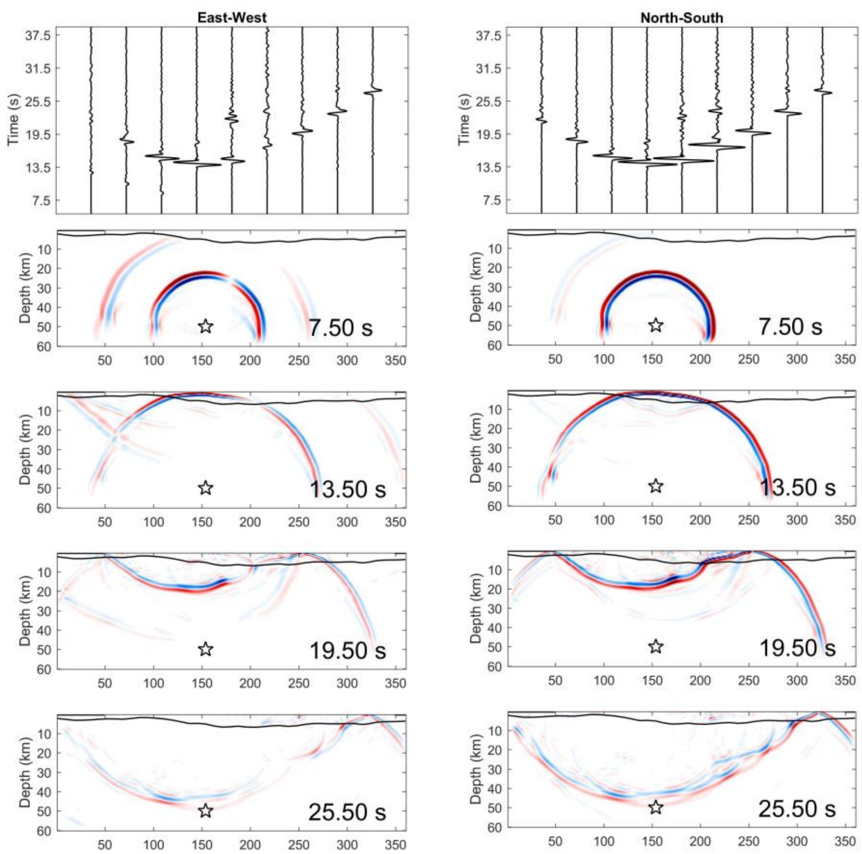

Figure 8. Cross-sectional time-snapshots of simulated EW & NS motions for a Vancouver Island earthquake in the basin model. Star denotes hypocenter, and black line is 5.5 km/s Vp contour (representing base of basin). The synthetic waveform for given locations are shown on the top panel.

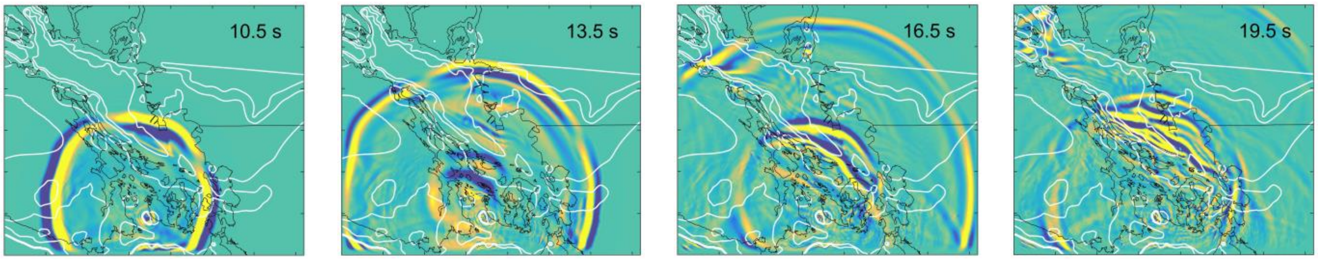

Figure 9. Time-snapshots of simulated ver. motion. Thin white lines are contours of basin V_P model structure at 500 m depth.

CONCLUSIONS

The 2015 **M** 4.7 inslab earthquake was recorded by a relatively dense strong-motion network as well as by surrounding regional seismograph networks. The available recordings of this earthquake provided a significant opportunity to re-evaluate source characteristics and regional attenuation from a moderate magnitude inslab earthquake that originated within the subducting JdF plate, as well as local variations in the shaking related to geology and site effects in southwestern B.C. [21]. In this study, we explore the effects of 3D Georgia basin on the ground motions from the Vancouver Island earthquake. The overall conclusions can be summarized as follow:

- The observed ground motions at stations in the basin and its edge (e.g., SNB) show more complex, longer duration waveforms, with phases following the S-waves.
- The presence of 3D Georgia basin structure has significantly increased the levels and duration of predicted ground shaking.
- The strength of the constructive interference is related to the propagation direction of surface waves generated in the upper 1 km of the 3D basin structure, and depends on the source hypocenter.
- Including the physical structure model could result in more than 10 times larger predicted peak ground motions in comparison the predicted background peak motion ($PGV_{Basin}/PGV_{Non\text{-}Basin}$). The increase in predicted peak motion amplitude is mostly due to later-arriving surface waves present in the basin waveforms.

ACKNOWLEDGMENTS

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