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Capturing Uncertainties in Maximum Credible Earthquake Peak Ground Acceleration Estimates from the Cascadia Subduction Zone

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ABSTRACT

We develop a logic-tree approach to capture uncertainties associated with a maximum credible earthquake (MCE) at an example site in northern Vancouver Island, British Columbia. The uncertainties incorporated into the MCE analyses are those associated with the potential fault rupture length and depth for a segmented and unsegmented Cascadia Subduction Zone (CSZ) plate interface fault. Incorporating these uncertainties results in a range of estimates for the MCE magnitude. We then apply three equally weighted NGA-Sub ground motion models to calculate a weighted 84th-percentile peak ground acceleration (PGA) for the example site with a V_{S30} of 760 m/s. The weighted PGA of 0.59 g incorporates uncertainties associated with the MCE source parameters as well as those associated with the ground motion models.

The approach captures additional uncertainties associated with the MCE source as well as the ground motion models. Use of a logic tree approach with weighted uncertainties promotes greater transparency in the selection of MCE scenarios. Our goal is to increase confidence in deterministic ground motions where they are still used to assess seismic performance of critical structures.

Keywords: Cascadia Subduction Zone, Maximum Credible Earthquake, NGA-Sub, Logic Tree, Uncertainty Estimation.

INTRODUCTION

Assessment of the seismic safety of critical structures, such as water and tailings storage dams, is a major concern for design engineers and regulators worldwide. In Canada, existing local, national, and international codes, and guidelines (e.g., British Columbia Health, Safety and Reclamation Code for Mine, Canadian Dam Association, International Commission on Large Dams, Global Industry Standard on Tailings Management) permit ground motions associated with a maximum credible earthquake (MCE) for seismic analysis and design of these critical structures. The MCE ground motions are based on single-event earthquake scenarios to represent "the largest reasonably conceivable earthquake that is considered possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework" [1]. The scenarios are typically selected by experienced seismotectonic specialists. The calculated MCE ground motions do not have an associated likelihood (i.e., annual exceedance probability [AEP] or probability of exceedance in a specified time) and cannot not readily be associated with a particular AEP, exceedance probability or return period.

While MCE ground motions can be used to assess the seismic stability and safety of critical structures, their use is not without limitations. The MCE scenarios are judgement-based, and analyses typically only incorporate uncertainties related to the one or more empirical source-to-site attenuation ground motion models (GMM). The selection of appropriate MCE scenarios by specialists should also account for uncertainties associated with the characteristics of the earthquake source, such as the length of the fault rupture, the rupture depth, and the estimated maximum earthquake magnitude. Understanding and judging the significance of these uncertainties is crucial for developing MCE ground motion estimates suitable for the assessment of the performance of critical structures during earthquakes.

This paper offers a revised approach to the understanding and incorporation of some of the uncertainties associated with MCE ground motions. We propose a simplified logic-tree approach as a framework to capture uncertainties associated with the MCE ground motions. The approach highlights the importance of capturing uncertainties associated with the earthquake source as well as the GMMs. Our goal for this example analysis is to encourage transparency among practitioners to document the uncertainties considered when selecting deterministic MCE scenarios. The approach described offers a simple method to improve MCE ground motion estimates.

We use estimates of the 84^{th}-percentile horizontal peak ground acceleration (PGA) for a site in northern Vancouver Island to illustrate the approach. We selected this site because it is in one of the most seismically active regions of Canada, has an historical record of large earthquakes, and has a reasonable scientific consensus for the uncertainties associated with the principal large earthquake sources that define the MCE scenario.

TECTONIC SETTING OF NORTHERN VANCOUVER ISLAND

We selected this example site on Vancouver Island because it is close to the boundary between the Pacific and the North America tectonic plates. Figure 1 shows the general tectonic map of the region [2], [3]. As shown in Figure 1, there are several microplates associated with this part of the plate boundary, including from north to south the Explorer, Juan de Fuca, and Gorda plates. These smaller microplates are remnants from the breakup of the much larger Farallon plate that has now been largely subducted beneath western North America [4].

The present-day subduction zone in the region is the Cascadia Subduction Zone (CSZ) where the Juan de Fuca plate, Explorer plate, and Gorda plate subduct beneath the North American plate. These plates have a general northeast direction of convergence with respect to North America. The seismically active subduction zone extends about 1,200 km from northern California to British Columbia [2]. The CSZ can produce earthquakes in the moment magnitude (**M**) 9 range. For example, the last great CSZ earthquake was an estimated **M**9.0 in January of 1700 [5].

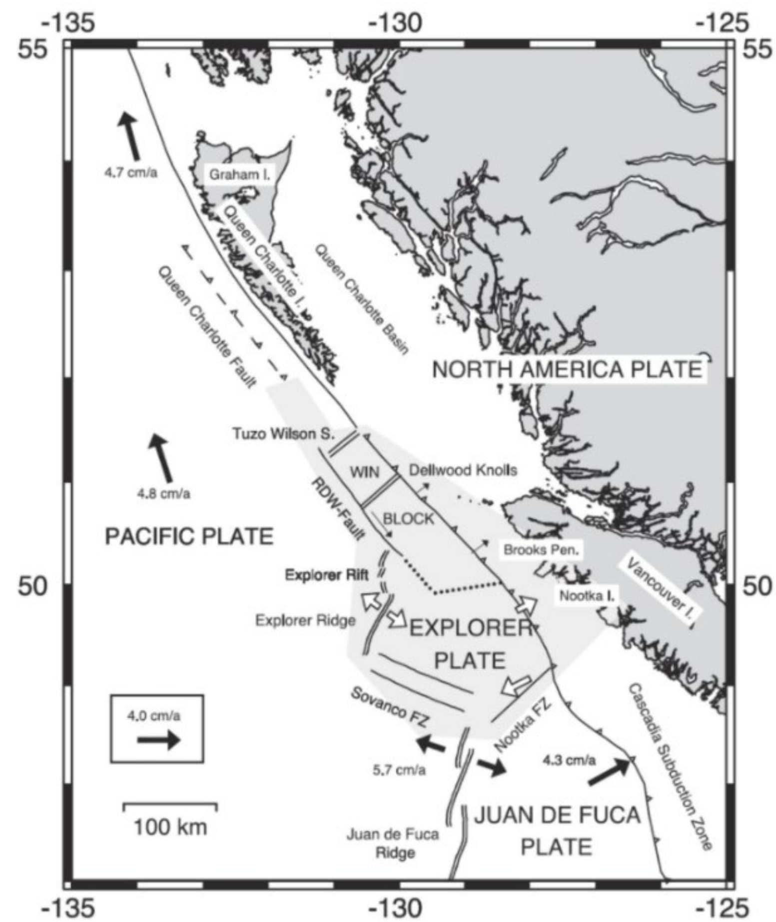

Figure 1. General plate tectonic map of northern Vancouver Island and southwest British Columbia (after [1]).

The northern boundary of the CSZ is relatively uncertain. Some studies (e.g., [6]) considered the Nootka fault, which separates the Explorer and Juan de Fuca subducted slabs, as the northern boundary; and some (e.g., [7], [8]) considered the Brooks Peninsula as the northern boundary.

The North America-Pacific plate boundary to the northwest of the CSZ becomes a major transform plate boundary marked by the Queen Charlotte fault zone (QCFZ) and associated structures. A fault associated with the QCF, but not the main fault, was the source of the **M**7.8 Haida Gwaii earthquake in 2012 [9].

EXISITNG HAZARD STUDIES

The northern end of the CSZ, QCFZ and associated faults likely presents the highest earthquake hazard in western Canada, and perhaps in all of Canada. The expected hazard is high because of the relatively high tectonic plate velocities, relatively high fault slip rates, historical and instrumental earthquake activity rates, and historical earthquakes up to **M**9. Accordingly, earthquake hazard assessments in this region need to model accurately the earthquake sources to develop reliable estimates of ground motions.

The Geological Survey of Canada developed the 6th-Generation Seismic Hazard Model of Canada in 2020 [6]. The CSZ interface fault as modelled by [6] has three earthquake sources—the Cascadia plate interface source, Explorer plate interface source, and the Winona source. The northern boundary of the Cascadia interface source is at the Nootka fault.

The 2018 National Seismic Hazard Maps (NSHM) prepared by the US Geological Survey [7] also modelled the CSZ and related structures offshore of Vancouver Island. The CSZ interface source included alternative rupture scenarios, down-dip depths, and maximum earthquake magnitudes in [8]. The three maximum rupture depths limits were:

- *Upper Limit*: Located at the midpoint of the 1 cm/year interface fault locking contour and its fully locked region (approximate depths at 10 to 24 km)
- *Middle Point*: Located at the 1 cm/year interface fault locking contour (approximate depths 12 to 29 km)
- *Lower Limit*: Located at the up-dip limit of the nonvolcanic tremor zone (approximate depths 26 to 38 km).

These depths and the full, along-strike length of the CSZ were used to calculate the likely range of maximum earthquake magnitudes for the CSZ interface fault. Table 1 lists the range of maximum magnitude alternatives for each down-dip depth alternative above. The earthquake magnitude estimates assume that the northern boundary of the extent of CSZ interface source rupture terminates at the Nootka fault (Figure 1).

Table 1. Maximum Earthquake Magnitude Alternatives from [9].

Down-dip Depth Alternative	Maximum Magnitude Alternatives (M)		
	Upper	Preferred	Lower
Bottom	9.35	9.02	8.86
Middle	9.13	8.83	8.70
Top	9.02	8.73	8.62

In 2012, BC Hydro commissioned a comprehensive probabilistic seismic hazard analysis (PSHA) to quantify earthquake ground motions for their many dam sites throughout British Columbia and western Alberta [8]. The PSHA considered alternative northern edges for the rupture of the CSZ interface source. The northern alternative was the northern edge of the Explorer plate below the Brooks Peninsula in northern Vancouver Island. In this alternative, the Explorer plate is seismogenic and capable of rupturing with the Juan de Fuca plate to the south. The southern alternative was that rupture only to the Nootka fault (Figure 1). The northern and southern alternative rupture extents had 0.9 and 0.1 weights, respectively [10]. The probability that an **M**9 or larger event ruptured both the Cascadia interface and the Explorer Plate has a 0.5 weight; i.e., half of the great earthquakes involved rupture of the Explorer plate AND the Juan de Fuca plate; and half of the great earthquakes ruptured only the Juan de Fuca section of the CSZ interface.

These major probabilistic studies identified and captured the principal uncertainties in the along-strike and down dip extents of CSZ rupture, and the range of possible earthquake maximum magnitudes (Table 1).

DETERMINISTIC SEISMIC HAZARD ANALYSIS

Deterministic seismic hazard analysis (DSHA) uses discrete, earthquakes to estimate ground motions at a site. DSHA requires identification and characterization of the major seismic sources to identify the largest earthquake that will produce the strongest ground motions at the site. Typically, the MCE has a single assumed magnitude with a hypocenter at the closest approach of the seismic source to the site of interest. Site ground motions are calculated for the selected MCE magnitude, source-to-site distance, applicable GMM(s), and site ground conditions. The DSHA results are typically median and/or 84th-percentile acceleration estimates. The use of median or 84^{th}-percentile depends on the perceived failure-consequence of the structure under analysis. In some cases, the average fault slip rate and maximum earthquake magnitude are also used to select median or 84^{th}-percentile accelerations.

Analysis Approach

We undertook a DSHA for the example site using an approach that captures more uncertainties than in a typical DSHA. The approach incorporates three equally weighted Next Generation Attenuation Subduction (NGA-Sub, see further discussion below) GMMs to calculate the weighted median and 84th-percentile peak ground acceleration (PGA) for a time-averaged shear-wave velocity in the 30 m below the ground or reference surface (V_{S30}) of 760 m/s. We considered not only uncertainties in GMMs by using multiple alternative ground motion models (GMMs) as in a typical DSHA, but also alternative fault rupture lengths and down-dip extents using a logic tree approach to capture alternatives in these two additional parameters.

Earthquake Scenario Development

Figure 2 shows the logic tree that includes the alternative earthquake source parameters and weights for the segmented/unsegmented rupture lengths, the down-dip rupture extents, and the associated uncertainty in maximum earthquake magnitude. The "unsegmented" rupture scenario is when the Explorer plate interface fault ruptures with the Juan de Fuca plate interface. The "segmented" rupture scenario is when the Explorer and the Juan de Fuca plate interfaces rupture separately.

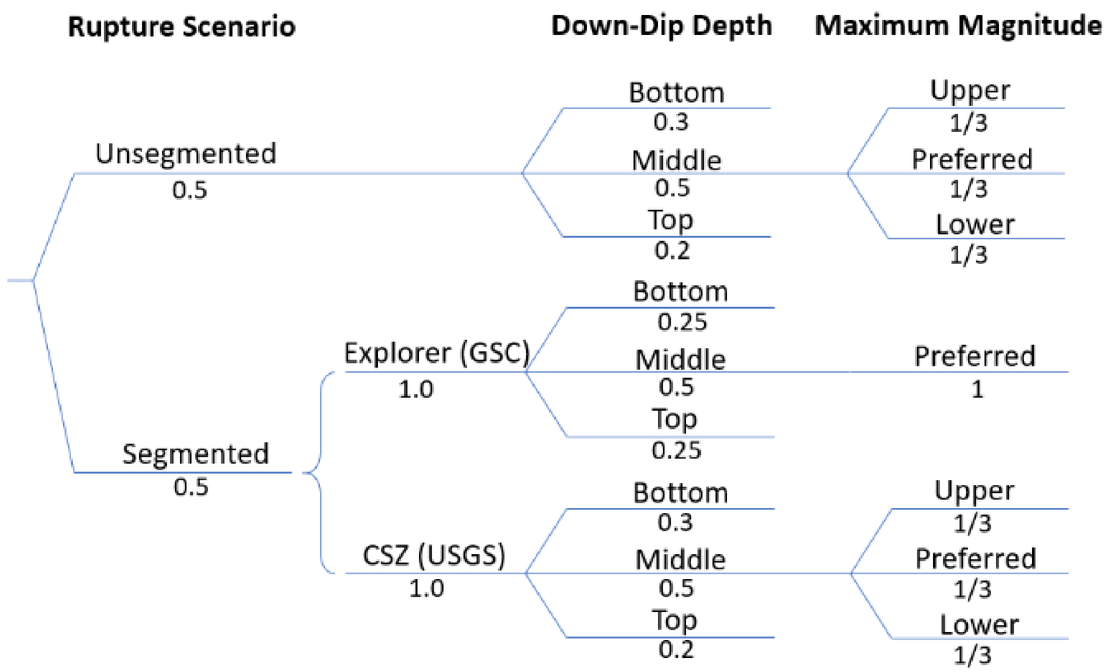

Figure 2. Earthquake scenario logic tree

For the unsegmented scenario, we applied the alternative down-dip depths and maximum earthquake magnitudes as specified in [7] and listed in Table 1. Although the rupture length of the unsegmented scenario is about 80 km longer than that of the CSZ interface sources in [9], the additional length results in a less than 10% increase of the total rupture length and only a small increment in the calculated earthquake maximum magnitudes. We consider this small increment is already included in the uncertainty in the maximum earthquake magnitudes listed in Table 1. For the segmented scenario, we included the Explorer plate interface fault source from [7] and the CSZ interface sources [9].

The PGA estimated for the example site is, therefore, the weighted average of the unsegmented PGA and the segmented PGA estimates. The unsegmented PGA estimate is the weighted average of PGAs of earthquake scenarios for alternative down-dip depths and maximum earthquake magnitudes. The segmented PGA estimate is the greater of the weighted-average PGAs for the Explorer plate interface source or the CSZ interface source.

Ground Motion Models

Ground motion modeling is a key component of any seismic hazard analysis. Typically, a suite of empirical ground motion models (GMM) is used to estimate the source-to-site attenuation of earthquake ground motions at horizontal PGA and at other spectral periods (usually 5%-damped). GMMs are typically selected based on the similarity between the tectonic and geologic conditions surrounding the site and those where the earthquake motions were recorded and used to derive the GMMs.

This study considered three GMMs:

- A GMM developed in [10]) that was an update of the model from [9] and is the BC Hydro subduction GMM using the ground motion dataset developed for the NGA-Sub project
- A GMM published by [11] that is an NGA-Sub GMM with regional adjustment factors for the CSZ
- A GMM developed by [12] that is an NGA-Sub GMM with regional adjustment factors for the CSZ

Developers of these GMMs used the NGA-Sub dataset of recorded strong ground motions and adjusted for application to the CSZ. We consider the three GMMs are equally valid among the available GMMs. Accordingly, we equally weighted these GMMs for PGA calculations.

DETERMINSITIC HAZARD RESULTS

Table 2 lists the 84th-percentile PGA values calculated for the three interface sources from the GSC model [9], one interface source from the USGS model [10], and the unsegmented source defined in this study. Table 2 also lists the weighted average of PGAs for the unsegmented source and the greater of two segmented sources as shown in Figure 2. The uncertainty-weighted MCE PGA is 0.57 g—the average of weighted-average PGAs from the three equally weighted GMMs.

Table 2. Calculated 84th-percentile PGAs for Example Site in Northern Vancouver Island

Seismic Source [reference]	**Maximum Earthquake Magnitude (M)**	**Rupture Distance (km)**	**PGA (g)**		
			Ref. [10]	**Ref [12]**	**Ref. [13]**
CSZ [6]	9.15	143-145-150[1]	0.231	0.118	0.225
Explorer [6]	8.5-8-7.6[2]	62	0.429	0.250	0.328
Winona [6]	7.7	76.5	0.241	0.132	0.189
CSZ [8]	Refer to Table 1	126-126-129[1]	0.265	0.134	0.241
Unsegmented	Refer to Table 1	42	0.952	0.596	0.838
	Weighted Average PGA		0.690	0.423	0.583
	Maximum Credible Earthquake PGA		0.57		

Notes:

1. Rupture distances for the bottom, middle and top down-dip depth alternatives.
2. Maximum magnitudes for the bottom, middle and top down-dip depth alternatives.

We identified the 2,475-year return period PGA (i.e., 2% probability of exceedance in 50 years) from the 2020 NBCC online calculator (2020 National Building Code of Canada Seismic Hazard Tool (nrcan.gc.ca)) for the example site. The estimated PGA is 0.36 g for a 2020 NBCC soil Site Class B site condition (i.e., V_{S30} of 760 m/s). This result suggests that the estimated weighted MCE PGA of 0.57 g has an annual exceedance probability (AEP) less than about 1/5000 (i.e., return period of more than 5,000 years). The estimate of likely return period or AEP for the MCE PGA estimate is only very approximate. The 2020 NBCC online hazard tool uses the GSC seismic source model [7], but with a different suite of GMMs and other logic tree parameters when compared to this simplified deterministic approach. Deterministic PGAs should not be compared to those completed using probabilistic analysis. While this analysis applies a weighted approach to selection of the MCE PGA, the PSHA approach is much more robust as it considers a much wider range of earthquake magnitudes and distances and associated uncertainties.

CONCLUSION

We develop a logic-tree approach to capture uncertainties associated with the potential fault rupture length and depth for a segmented and unsegmented Cascadia Subduction Zone (CSZ) at an example site in northern Vancouver Island, British Columbia. Incorporating source parameters uncertainties in addition to those from empirical GMMs into the MCE analyses results in a range of estimates for the MCE magnitude for the example site with a V_{S30} of 760 m/s. The weighted PGA of 0.57

g has an annual exceedance probability (AEP) less than about 1/5000 has when compared to the 1/2,475 AEP PGA of 0.36 g provided from the 2020 NBCC online hazard tool for the same site with a soil Site Class B designation, although the 2020 NBCC hazard model uses a different suite of GMMs and other logic tree parameters when compared to this simplified deterministic approach. We consider the advantage of the approach is that the need to incorporate source parameter uncertainties in a weighted MCE ground motion requires greater transparency in the selection and weighting source parameter uncertainties. As MCE uncertainties are evaluated and documented there can be increased confidence in the ground motions applied in seismic performance assessment.

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