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SITE-SPECIFIC SEISMIC HAZARD ANALYSIS FOR LIQUEFIED NATURAL GAS FACILITY—A CASE STUDY IN WESTERN CANADA

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ABSTRACT: This paper summarizes a site-specific seismic hazard analysis completed for a liquefied natural gas (LNG) facility to comply with Canadian Standards Association Z276-11 with 2014 update—Production, Storage and Handling of LNG. We developed a site-specific seismic source model based on the 2010 Canadian National Hazard seismic source model, but with two site-specific refinements: 1) the Cascadia subduction zone was modelled as both a fault and area source; and 2) different ground motion predicting equations (GMPE) and their relative weightings. Spectral accelerations from PSHA generally agree with the median ground motions from the 2010 Canada National Hazard model; whereas the spectral accelerations for PGA and 2-second structural periods are lower than the mean spectral accelerations from the 2010 model. The relatively lower earthquake ground motions probably result from our incorporation of a more up-to-date understanding of the regional and site geology, and application of more recent GMPEs. This case study demonstrates the need for site-specific seismic hazard analysis for infrastructure with high failure consequences.

1. Introduction

Reliable estimates of earthquake loading are a critical input for the stability analysis and design of major engineered infrastructure, particularly offshore structures. These important facilities are often long-lived, important resources where the consequences of failure can be extreme for both the environment and economic performance.

This paper presents an example of how site-specific seismic analysis is applied to a liquefied natural gas (LNG) facility to meet the requirements of the Canadian national standard for the production, storage and handling of LNG—Canadian Standards Association (CSA) Z276-11 with 2014 update. The purpose of the seismic hazard analysis parts of CSA Z276-11 is to provide earthquake ground motion estimates to support structural design.

The proposed LNG facility is located in coastal western Canada—a region of moderate earthquake occurrence and seismic hazard. The site-specific PSHA evaluates the geological, geotechnical and seismic conditions around the site and provides the earthquake ground motion estimates required by the standard.

2. Seismic Design Requirements

Canada has a national standard for the production, storage and handling of LNG – Canadian Standards Association (CSA) Z276-11 (with 2014 update). The standard requires a site-specific SHA for LNG tanks and their associated systems. CSA Z276-11 requires the development of site-specific response spectra for earthquake ground motions from three earthquakes:

- The operating basis earthquake (OBE)
- The safe shutdown earthquake (SSE)
- The aftershock level earthquake (ALE)

In CSA Z276-11 the SSE is defined as the mean acceleration response spectra having a 2% probability of being exceeded in 50 years (i.e. 2,475-year return period). The OBE is the mean acceleration response spectra having a 10% probability of exceedance in 50 years (i.e. 475-year return period). The ALE is half of the SSE.

3. Regional Geology and Tectonic Setting

Quaternary tectonics and historical seismicity of the region are the two elements used to characterize seismic sources for the study site. These are discussed further below.

Coastal British Columbia is located near the tectonically active western boundary of the North American, Pacific and Juan de Fuca/Explorer plates. The boundary zone consists of three contrasting segments:

- A southern segment is an active subduction zone, along which slabs of oceanic lithosphere of the Juan de Fuca plate, and its recent offshoot the Explorer plate, sink northeastward under the overriding continental lithosphere of the North American plate of southern British Columbia and adjacent Washington, Oregon and Northern California, USA. Relative plate convergent rates (North America fixed) range from about 20 to 46 (millimeters per year, mm/yr).
- A central segment that extends northward into the Gulf of Alaska from just south of the Queen Charlotte Islands that contains the Queen Charlotte and Fairweather dextral transform faults. These faults accommodate northwestward or northward movement of the Pacific plate relative to the North American plate of about 50 to 55 mm/yr. Contemporary earthquake locations and activity rates suggest that the Queen Charlotte Fault (QCF) system is also continuous with the Denali-Chatham Strait fault system. This northward connection, however, remains unclear because the Denali-Chatham Strait fault system lacks major and even small earthquakes to confirm the fault continuity.
- A northern segment that comprises the Aleutian Trench and the Chugach-St. Elias faults where the Pacific plate and the Yakutat "block" slide under the Aleutian Islands and the Wrangell Mountains, respectively.

The Yakutat block is an “allochthonous terrane”—an internally consistent, fault-bounded package of rocks that has no geological connection to the surrounding rock units. The Yakutat block comprises Cenozoic- and Mesozoic-age clastic sediments carried northward into the Gulf of Alaska on the Pacific Plate, and are now colliding with and becoming accreted to the North American Plate.

Bedrock geology in this part of western Canada comprises mostly calc-alkaline volcanic rocks and quartz diorite intrusive rocks. The calc-alkaline volcanic rocks are part of the Nicola Group of geologic formations that consist of layered volcanic rocks and interbedded sedimentary rocks deposited during the Triassic Period more than 200 million years ago. The quartz diorite intrusive rocks belong to the Coast Plutonic Complex, and they comprise predominantly igneous rocks with minor inclusions of volcanic and/or sedimentary rocks. Throughout most of this region, unconsolidated deposits such as glacial till, marine clays and glacial outwash sediments mantle these basement and bedrock units. Like most valley sites in coastal British Columbia, the site is located on a low-relief floodplain with alluvial/deltaic deposits extend to depths of 100 m or more. Quaternary sediments are gravel, sand and silt, with many silty and some clayey horizons.

4. Historical Seismicity and Earthquake Catalog

Fereidoni et al. (2012) have compiled the Canadian Composite Seismicity Catalog (CCSC) that contains felt and instrumental earthquake records for all of Canada. The CCSC is considered complete up to the end of 2010. The CCSC is based primarily on the Seismic Hazard Epicentre File (SHEEF) compiled for the 2005 Canada National Hazard Maps. We developed a project earthquake catalog for the study site by supplementing the CCSC with earthquakes recorded up to early 2014. Earthquake catalog sources were two major online earthquake catalogs in North America, including National earthquake database (NEDB) maintained by Natural Resources Canada (NRCAN) and United States Geological Survey Comprehensive Catalog (ComCat).

Both automatic and manual procedures were used to remove duplicate entries in the combined catalog. A common magnitude scale (M) was assigned for each earthquake record using either direct reports from the source catalog or conversion from other magnitude scales using the methods used to develop the CCSC catalog.

Upon the removal of duplicates and conversion to a common magnitude scale, the remaining earthquake catalog records were declustered following algorithms proposed by Reasenberg (1985). Figure 1 shows the epicentres of earthquakes ($M \geq 4.0$) for the declustered catalog.

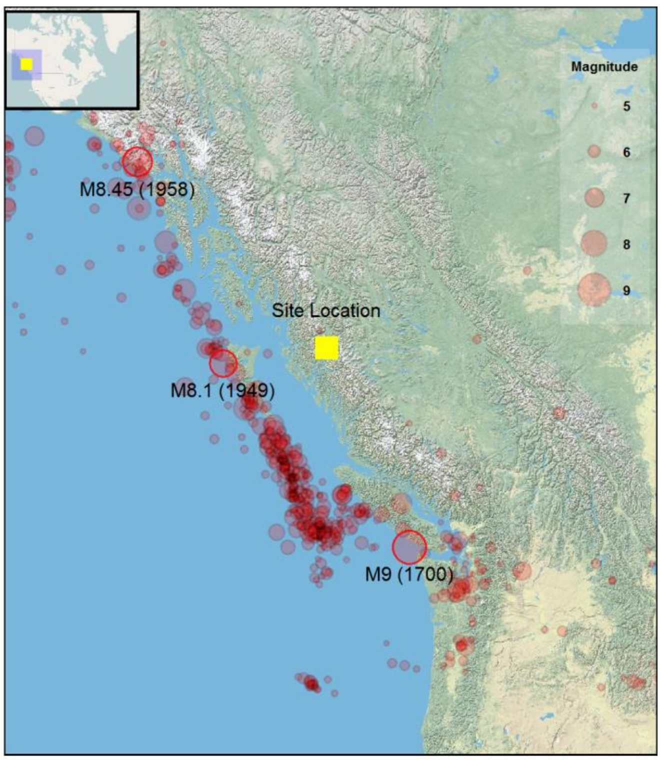

Fig. 1 – Historical Seismicity

5. Site-Specific Seismic Source Model

We developed a site-specific seismic source model to represent specific seismotectonic regions capable of producing moderate to large earthquakes that influence the earthquake ground shaking expected at the site(s) of interest. A seismic source model defines all the known active and potentially active seismic sources that can contribute to the earthquake ground motions at the site(s). We consider earthquake sources associated with the rupture areas of large historic earthquakes, where applicable, where there is evidence of fault displacement during the Holocene Epoch (last 11,700 years).

The seismic source model developed for the study site includes nine areal sources and two fault sources used in the PSHA, and one Cascadia subduction interface source used in the DSHA. Figure 2 shows the seismic sources used in this study.

5.1. Crustal Areal Sources

Horner and Rogers (H and R) at the Geological Survey of Canada (GSC) developed the H and R models for western Canada as part of the Fourth Generation Seismic Hazard Maps of Canada (Adams and Halchuk 2003). According to Adams and Halchuk (2003), the two models reflect experts' understanding of the seismotectonics that cause the distribution and frequency of historical earthquakes.

Our initial analyses indicate that the R source model result in higher ground motions at the study site, and in turn, the areal sources in this study were developed primarily based on the "R model" defined in 2005 Canada Hazard Model. We have, however, made minor adjustments to those areal sources expected to be primary contributors to the ground motions at the study site.

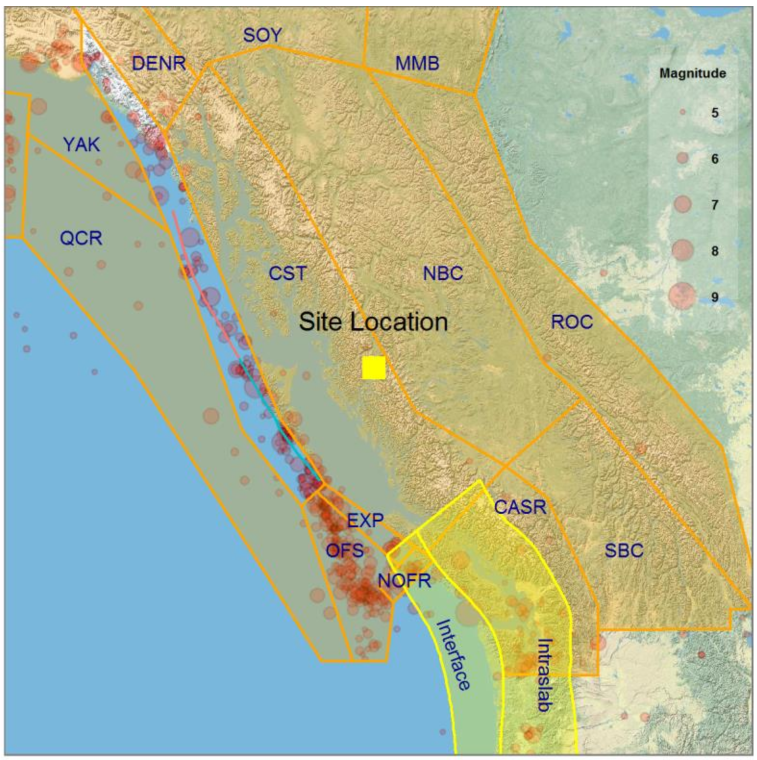

Fig. 2 – Seismic Source Model

The primary contributor to the study site is the Coastal area source (CST) in which the study site is located. We made two main changes to the original CST of the R Model. First, we combined the CST with the Hecate Strait area source that covers most of the Haida Gwaii Island (formerly Queen Charlotte Island). Similarity in the geological and tectonic settings of these two areal sources warranted their combination. Furthermore, there is no known geological structure along the boundary between these two sources. Second, we moved the western boundary of the combined CST eastward to avoid clusters of earthquakes associated with the QCF. The distribution by depth of earthquakes shows that the majority of earthquakes in the CST have a recorded shallow depth (0 to 5 km) or deeper at about 16 to 20 km. Most earthquakes located on the QCF have recorded depths of less than 20 km.

We modelled the Cascadia area source with the seismicity at shallow depths in the Cascadia subduction zone. The boundary of the Cascadia area source was determined based on the Cascadia subduction zone geometry of Hayes et al. (2012). In addition, another area source, the Queen Charlotte Border (QCB), was defined to represent earthquakes offshore and to the east of the QCF.

We assigned a preferred fault style to each of the areal sources based on the present-day tectonics. The areal sources, e.g., CST, east to the Pacific-North American plate boundary were assigned with reverse faulting because the North America plate is shows contractional strains from earthquake focal mechanisms and plate tectonic models. The area sources such as QCB west to the boundary are assumed to have mostly strike-slip fault displacements.

5.2. Queen Charlotte Fault

The QCF marks the major transpressive boundary between the Pacific and North American plates from northern Vancouver Island to northern British Columbia. It extends more than 350 km from a southerly triple junction with the Explorer, North American and Pacific plates, to the southern extent of the Denali and Fairweather faults of Alaska and the. Estimated average fault slip rates are about 45 to 51 mm/yr (DeMets et al. 2010).

The QCF has been the site of at least four large earthquakes in the last hundred years: an M 7 in 1929, an M 8.1 in 1949 (Canada's largest recorded earthquake since the 1700 Cascadia earthquake) an M 7.3 in 1970, and the M 7.7 Haida Gwaii earthquake on October 27, 2012 (Szeliga 2013).

We represented the QCF in the seismic source model as two seismically independent segments based the frequency and distribution of large earthquakes over the last 100 years along the length of the fault.

5.3. Cascadia Subduction Zone

The Cascadia subduction zone extends about 1,200 km from Vancouver Island in British Columbia to Cape Mendocino in California. Hyndman and Rogers (2010) provide a detailed description of the Cascadia subduction zone, including evidence of past great earthquakes and estimates of contemporary seismic hazard.

To comply with the CSA Z276-11 Standard, the Cascadia subduction zone source ground motions were evaluated using deterministic methods, and the 84th-percentile spectral accelerations at the periods of interest were calculated. The NRCC's User Guide—NBC 2010: Structural Commentaries, Annex J—recommends a maximum credible earthquake (MCE) of M 8.2. More recent research (e.g., Hyndman and Rogers 2010), however, indicates that the January 1700 earthquake was about M 9. We considered, therefore, that for this study an M 9 earthquake better reflects the best estimate for an MCE at the Cascadia subduction zone. Our calculation of deterministic hazard used an M 9 rather than M 8.2 MCE value.

The geometry of the Cascadia subduction interface source was adopted from Hayes et al. (2012). For this study, we assumed that the coseismic rupture of the Juan de Fuca-North American plate interface extended from the upper episodic tremor zone below the base of the transition zone at about 30 km depth to the sea floor (Hyndman and Rogers 2000). The greater of the deterministic 84th-percentile earthquake response spectrum for the Cascadia subduction zone or the mean-hazard probabilistic ground motion with 2,475-year return interval at each period of interest becomes the SSE design earthquake spectra according to CSA Z276-11.

5.4. Earthquake Recurrence Parameters

Table 1 lists the main parameters of the seismic sources used in this PSHA. These source parameters include the sense of fault displacement, maximum earthquake magnitude, and earthquake recurrence parameters. The earthquake activity rate represents the number of earthquakes each year greater than a minimum earthquake magnitude occurring on the areal source.

6. Ground Motion Characterization Model

A ground motion prediction equation (GMPE) is a key component to estimate earthquake ground motions in seismic hazard analysis. We selected the GMPEs for this study based on the similarity of the tectonic and geologic conditions at the study site to the regions where the earthquakes were recorded and use to develop the GMPEs.

6.1. Ground Motion Prediction Equations for Crustal Areal Sources and Fault Sources

Four Next Generation Attenuation (NGA-West2) models, including Abrahamson, Silva and Kamai 2014 (ASK14), Boore, Stewart, Seyhan and Atkinson 2014 (BSSA14), Campbell and Bozorgnia 2014 (CB144) and Chiou and Youngs 2014 (CY14), were used to model earthquake ground motion attenuation for the areal and fault sources. Each model was used with equal weighting in this SHA. The NGA-West2 models have been developed for active tectonic regions based on earthquake strong ground motion data recorded at active plate boundaries, particularly California, USA. The NGA-West2 GMPEs were developed in a systematic process using improved strong ground motion recordings, consideration of the soil condition at the ground-motion recording stations, near-source saturation effects, and basin effects. The NGA-West2 models represent further development of the NGA models employed globally to model the source-to-site attenuation of earthquake ground motions triggered by fault sources.

Because the NGA models were developed in a joint effort with interactions and exchanges of ideas, the models cannot be considered as truly independent. The GMPE developers recommended incorporation of an additional epistemic uncertainty to the median ground motion estimation. Al Atik and Youngs (2013) proposed a simplified model of epistemic uncertainty for probabilistic seismic hazard analysis. We implemented Al Atik and Youngs (2013) model and included additional epistemic uncertainty for NGA-West2 models.

Table 1 – Recurrence parameters for seismic sources.

Seismic source	Faulting style	Closest Distance to the Site (km)	Minimum magnitude	Maximum magnitude	Average Slip Rate (mm/year)	Mean annual activity rate (M>=4.75)	b-value
Queen Charlotte I (QCFI)	Strike-slip	280	4.75	8.1	45	--	0.728
Queen Charlotte II (QCFII)	Strike-slip	340	4.75	8.1	45	--	0.716
Coastal (CST)	Reverse	0[1]	4.75	7.4	--	0.28	0.84

[1]The study site is located in the Coastal area source (CST).

6.2. Ground Motion Prediction Equations for Subduction Sources

For subduction interface sources, we applied four alternative GMPEs, Abrahamson et al. (2015), Atkinson and Macias (2009), Ghofrani and Atkinson (2013) and Zhao et al. (2006). Following the recommendations from Atkinson and Adams (2013), we give a 50% weight to the GMPE of Atkinson and Macias (2009), 20% weight to that of Abrahamson et al. (2015), 20% weight to the GMPE of Ghofrani and Atkinson (2013), and a lesser weight of 10% to the GMPE developed by Zhao et al. (2006). Atkinson and Macias (2009) has a high weight because it was developed specifically for attenuation of earthquakes occurring at the Cascadia subduction zone. A relatively higher weight was given to Abrahamson et al. (2015) and Ghofrani and Atkinson (2013) because they were developed recently, and they included the new information from the well-recorded 2011 M 9 Tohoku earthquake.

Site correction factors were also applied to the GMPEs based predominantly on Japan data, including those of Zhao et al. (2006) and Ghofrani and Atkinson (2013). These factors are as recommended by Atkinson and Adams (2013) to account for specific Cascadia subduction zone site conditions. The modification is needed because the majority of sites in the Cascadia region are different from those in Japan where soils are usually much deeper. Site conditions in the Cascadia region, in general, result in greater amplification at longer periods, but less at short periods.

7. Seismic Hazard Analysis Results

This section presents the results of the PSHA for the study site for a reference rock site with an assumed average shear wave velocity for the upper 30 m of soil column (Vs30) of 750 m/s.

The hazard curves illustrate the variations in horizontal peak ground acceleration (PGA) and spectral accelerations as a function of the annual exceedance probability (AEP). The AEP is the reciprocal of the return period. Figure 3 (left) shows 5%-damped hazard curves developed for the PGA for return periods ranging from 10 to 10,000 years.

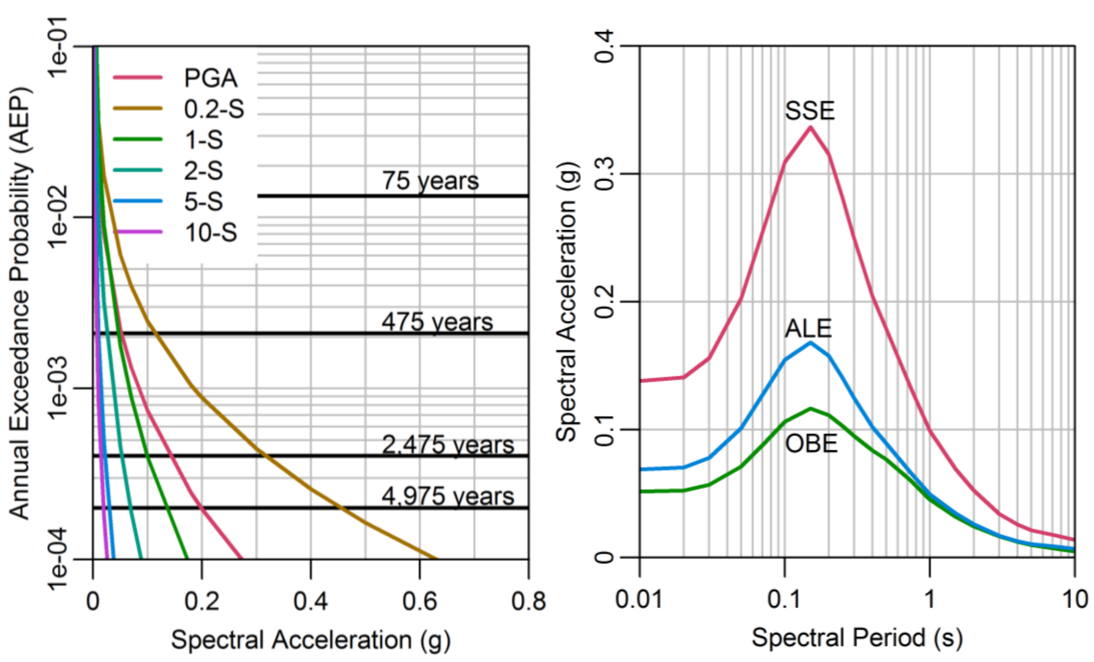

Fig. 3 – Seismic hazard analysis results including hazard curves (left) and uniform hazard spectra (right)

7.1. Design Earthquake Response Spectra

Figure 3 (right) shows the 5%-damped uniform hazard, site-specific horizontal acceleration response spectra for the OBE, SSE, and ALE. The design-level horizontal acceleration response spectrum for the SSE is the greater of the mean-hazard probabilistic ground motion with 2,475-year return period or the deterministic 84^{th}-percentile response spectrum for the Cascadia subduction zone. An M 9.0 MCE at a distance of about 400 km generates the deterministic ground motions.

7.2. Hazard Deaggregation

Figure 4 shows the deaggregation results for the SSE return period, for PGA and 1-second spectral accelerations; and for the reference soil site. The deaggregation results show that major contributors to the SSE PGA are moderate-magnitude earthquakes (M 5.0 to 6.0) at close distances (within 40 km).

For 1.0-second spectral period, large earthquakes at greater distances become the dominant sources of the earthquake ground motions at the study site. The peak in Figure 4 (right) at the distance of about 280 km corresponds to the contribution from the first QCF segment; the peak at the distance of about 340 km is contributed primarily by earthquakes on the second QCF segment. The deaggregation results for the OBE return period show a similar trend. The primary contributor to the earthquake hazard are moderate-magnitude earthquakes (M 5.0 to 6.0) at close distances (within 40 km) and large magnitude earthquakes (M 8.0 to 8.5) on the QCF segments (about 280 km and 340 km away, respectively) for PGA, and large-magnitude earthquakes (M 8.0 to 8.5) from the QCF for the 1.0-second spectral acceleration.

7.3. Comparison with Existing Studies

Figure 5 compares our analysis results with ground motions from the 2010 Canadian National Hazard Maps. The mean PGAs and spectral accelerations from this study for stiff soil condition (site class C with Vs30 ranging from 360 to 750 m/s), in general, agree well with the median ground motions from the 2010 Canada hazard maps. The mean PGA and 2-second spectral acceleration values are slightly smaller than the mean values from the 2010 maps. The relatively smaller earthquake ground motions probably result from our incorporation of most up-to-date understanding about the regional and site geology, and recent GMPEs.

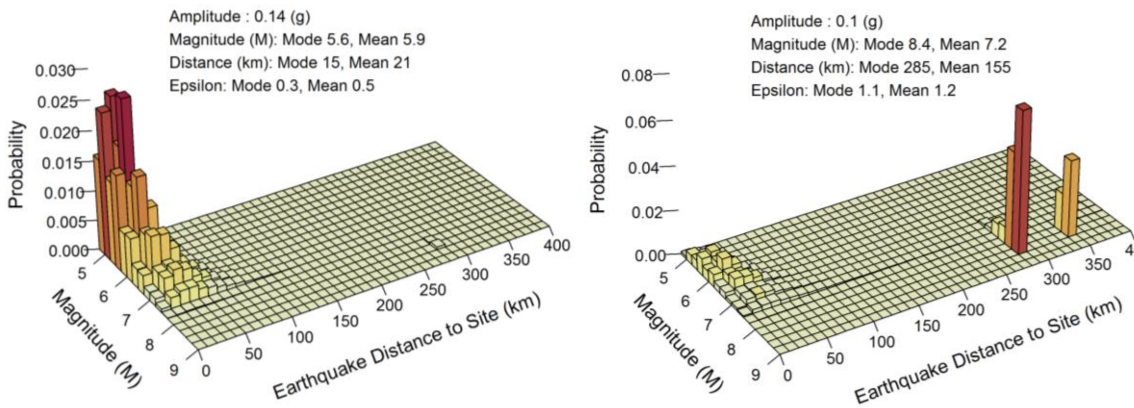

Fig. 4 – Seismic hazard deaggregation results for SSE for PGA (left) and 1-second (right)

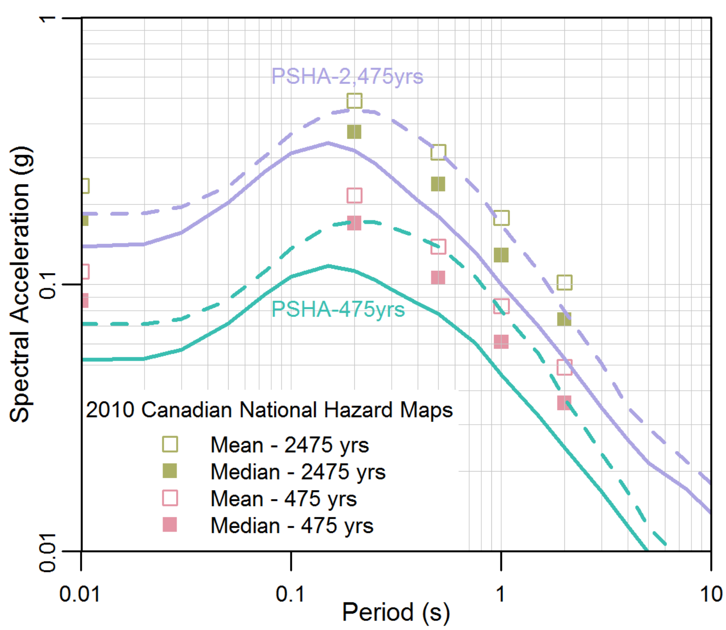

Fig. 5 – Comparison with 2010 Canadian National Hazard Maps (Dashed Lines for Site Condition B/C Boundary, Vs30 = 750m/s and Solid Lines for Site Condition C/D Boundary, Vs30 = 360 m/s)

8. Summary and Concluding Remarks

The historical earthquake record and the present-day regional tectonic setting within about 500 km are used to develop a site-specific seismic hazard model to meet the requirements of CSA Z276-11. The model contains nine areal sources, two fault sources and one Cascadia subduction source. The areal and fault sources are based on the R model in the 2005 Canada Hazard Model that has been adjusted from an updated project earthquake catalog and more recent geological studies.

The derived spectral accelerations from the site-specific PSHA generally agree with the median ground motions from the 2010 Canada National Hazard model; whereas the PGA and 2-second spectral accelerations are slightly lower than the mean spectral accelerations from the 2010 model. The relatively lower earthquake ground motions probably result from our incorporation of most up-to-date understanding about the regional and site geology, and recent GMPEs. LNG tanks and associated systems typically have a long structural fundamental period. It is important, therefore, to characterize the sources of large earthquakes such as the Queen Charlotte fault (QCF) and Cascadia subduction zone because they can potentially contribute to the long-period ground motions at the site. The site-specific study improves the confidence level for the estimated earthquake ground motions needed for the seismic analysis and design of infrastructure with high failure consequences.

9. Acknowledgements

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