Site-Specific Earthquake Ground Motions in Southwest Quebec, Canada

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ABSTRACT

This paper presents a case study using probabilistic seismic hazard analysis (PSHA) to support earthquake engineering analysis for sites in southwestern Quebec, Canada. The seismic source model is based on the Fifth Generation Seismic Hazard Model but incorporates site-specific modifications to account for the local distribution of historical earthquake epicenters. Recent ground motion models (GMM) and geological analysis are used to develop ground motions for a hard rock site condition with a time-averaged shear-wave velocity in the upper 30 m ($V_{S,30}$) of about 2000 m/s. Through a logic-tree approach, epistemic uncertainty is accommodated for the historical source sub-model, earthquake recurrence parameters, maximum earthquake magnitude, hypocentral depth, and GMM variability. PSHA results confirm that the hazard is relatively low, with mean peak ground acceleration (PGA) values of 0.06 g and 0.12 g for 1 in 2,475 and 1 in 10,000 annual exceedance probabilities (AEP), respectively. Hazard deaggregations show that the main seismic hazard sources are large-magnitude earthquakes (**M** ≥7.0) at moderate source-to-site distances (100 to 160 km), and moderate-magnitude earthquakes (**M**5.0 to **M**6.0) at closer source-to-site distances (0 to 40 km). The site-specific, 5%-damped, 1 in 2,475 AEP uniform hazard response spectrum (UHRS) for a hard rock site (Site Class A, $V_{S,30}$ >1500 m/s) is similar in amplitude to the 2015 National Building Code of Canada (NBCC) soil Site Class C response spectrum at spectral periods longer than about 0.05 seconds. Differences in spectrum shape and amplitude at shorter spectral periods likely arise from the use of GMMs different than those adopted for the 2015 NBCC hazard maps.

Keywords: PSHA, hard rock, uncertainty, hazard deaggregation, response spectrum

INTRODUCTION

Mining-related developments continue to be important to regional development in southwestern Quebec, Canada. Because mining developments often require the construction and closure of mine waste facilities that persist long after mine closure, it is important that these critical facilities can withstand earthquake loads with low annual exceedance probabilities (AEP) or long return periods. It is common practice to use earthquake ground motions developed for the Canadian Fifth Generation Seismic Hazard Model developed by Halchuk et al. [1] and its earlier generations for the seismic analysis and design of critical mining facilities in this part of Canada. However, guidance from the Canadian Dam Association (CDA) *Dam Safety Guidelines 2007* (2013 edition [2]), 2014 CDA Technical Bulletin: *Application of Dam Safety Guidelines to Mining Dams* [3], and international earthquake geotechnical engineering practice is to develop earthquake ground motions for critical infrastructure from site-specific hazard assessment rather than from extrapolations of regional or national hazard models developed for building codes.

Site-specific seismic hazard assessment can, however, be challenging due to the uncertainties in location, size, rate of occurrence, and the resulting shaking intensity of future earthquakes in often complex or uncertain local ground conditions. For southwestern Quebec, Canada, the generally low historical earthquake recurrence rates and limited instrumental data increase the uncertainty level of the seismic hazard estimates needed for the seismic design of critical facilities because earthquake ground motion estimates are subject to both aleatory variability and epistemic uncertainty.

This study reports the results of a site-specific probabilistic seismic hazard analysis (PSHA) completed for a site near Rouyn-Noranda in southwestern Quebec. Starting with the seismic source model for the southeastern component of the Fifth Generation Seismic Hazard Model developed by Halchuk et al. [1], we modify the local source model to account for the seismotectonic setting and historical earthquake record within about 300 km of the site. We use recent ground motion models (GMM) for typical local bedrock site conditions to develop site-specific horizontal acceleration uniform hazard response spectra (UHRS) for low AEPs or long return periods. Epistemic uncertainties in the seismic source model parameters and GMMs are captured through a logic tree approach. The site-specific results are then compared to the 2015 Fifth Generation

Seismic Hazard Maps developed for the 2015 National Building Code of Canada (NBCC2015 [4]). The major sources of uncertainty in the site-specific seismic hazard are also analyzed and discussed.

SEISMOTECTONIC SETTING

Regional Geological Setting

The Rouyn-Noranda region of southwestern Quebec is located in a region of the Canadian Shield that is part of the larger North American Craton. The Canadian Shield is inferred to have formed from the collision of Archean-age microcontinents during the Paleoproterozoic (2.5 to 1.6 billion years ago). The collision of these microcontinents initiated volcanic activity to form volcanic arcs that accreted to and intruded into the existing Archean tectonic plates. These microcontinents combined to form the ancient continent of Laurentia through major tectonic events that resulted in zones of faulted, folded and metamorphosed sedimentary and igneous rocks (Whitmeyer and Karlstrom [5]), including major zones of polymetallic mineralization that are the focus of the past and ongoing mining activities.

Figure 1 shows the locations of the major geological provinces and sub-provinces in southwestern Quebec. The boundary between the Abitibi and Pontiac sub-provinces of the Superior Province is marked by a major structural complex of the east-west striking Cadillac-Larder Lake fault zone. This regional bedrock fault and associated structures shown in Figure 1 is often associated with the polymetallic mineralization. While three historical earthquake epicenters are located within the wider Cadillac-Larder Lake fault zone (Figure 1), earthquakes are typically absent in most parts of the fault zone. The nature of the fault zone rocks, their present-day tectonic setting within the Canadian Shield, a lack of geomorphic evidence for past surface fault rupture, and general absence of historical earthquake epicenters all suggest that the Cadillac-Larder Lake fault zone and other major fault zones within the wider region are not seismogenic.

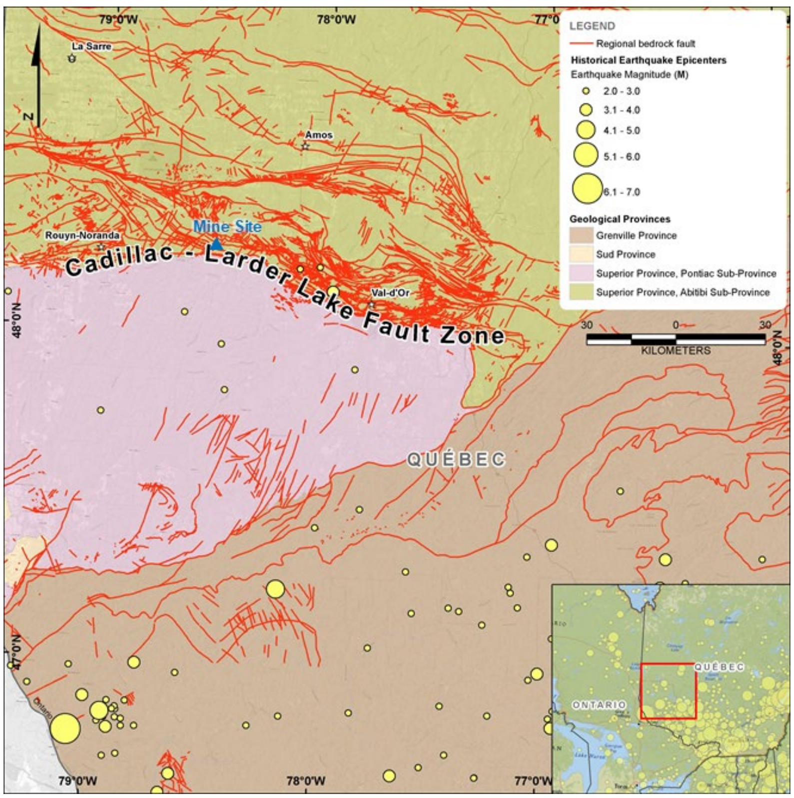


Figure 1. Major geological provinces, mapped basement faults and historical earthquake epicenters in southwestern Quebec.

Site Ground Condition

An important consideration for a site-specific seismic hazard assessment is the nature of rock or soil conditions at the site under review. For earthquake ground motion predictions, the typical proxy for site ground condition is the time-averaged shear-wave velocity (V_S) in the upper 30 m of the soil/rock column (i.e., $V_{S,30}$) as many GMMs scale with the $V_{S,30}$ value.

Direct measurements of V_S for the full extent of the upper 30 m of bedrock are generally absent. This study assumed a $V_{S,30}$ of about 2,000 m/s for bedrock at the site based on the available information about the bedrock geology and rock quality as follows: (1) bedrock units are very old (i.e. about 2.7 billion years), moderately to strongly metamorphosed, and only surficially weathered because of the recent (i.e., less than about 15,000 years ago) glacial erosion; (2) bedrock units are typically steeply dipping at angles of 70° to 80° and cut by high-strain zones that represent zones of plastic deformation; (3) bedrock units are very strong, only slightly weathered and not strongly jointed or faulted (e.g., Mercier-Langevin et al. [6]), but are strongly foliated (i.e., metamorphosed) with well-developed schistosity; (4) physical descriptions of the bedrocks indicate they have a $V_{S,30}$ value that can reasonably be expected to be more than 1,500 m/s; (5) RQD measurements of the bedrock units suggested Vs values of between 1,500 to 2,100 m/s based on Vs and Rock Quality Designation (RQD) correlation of Biringen and Davie [7], although the scatter in their data is high; and (6) experience with some measured V_S values ranging from 1,800 to 2,100 m/s in similar rocks at other sites in this region. By estimating a $V_{S,30}$ of about 2,000 m/s, the GMMs developed for the Central and Eastern North America (CENA) can be readily used (Atkinson [8]; see section "Ground Motion Models (GMM)").

SEISMIC HAZARD ANALYSIS

Probabilistic Seismic Hazard Analysis (PSHA)

PSHA is used to estimate the likelihood that a specified level of an earthquake ground motion parameter will be exceeded during a specific time period. The likelihood of exceedance is determined based on the probability of occurrence of any earthquake of any size (within lower and upper bounds) at any location, and the rate at which ground motions attenuate while traveling from the source to the site. The PSHA approach used for this study follows the Cornell-McGuire framework (Cornell [9]; McGuire [10, 11]). The calculations are carried out using the commercial software EZ-FRISK v.8.00 licensed by Risk Engineering [12].

Seismic Source Model

A seismic source model defines known active and potentially active seismogenic sources that can contribute to the earthquake ground motions at the site under review. Seismogenic sources associated with the rupture areas of large historical earthquakes are considered, where applicable, as are faults where there is evidence of surface displacement during the Quaternary Period (about the last 2.6 million years). Where evidence of a seismic source is equivocal, alternative or representative weighted scenarios can be incorporated to account for the uncertainty. A seismic source model is commonly characterized in terms of parameters that include: source location, source geometry, faulting mechanism, maximum earthquake magnitude, probability of activity, and earthquake recurrence model.

The seismic source model developed for this study is based on the southeastern component of the Canadian Fifth Generation Seismic Hazard Model (Halchuk et al. [1]) and the historical earthquake catalog from the Seismic Hazard Earthquake Epicenter File (SHEEF2010) of Halchuk et al. [13]. The national seismic hazard model is used to develop the 1 in 2,475 AEP hazard values for the NBCC2015. Site-specific modifications are made to its Historical (H2) sub-model using the distribution of historical earthquake epicenters in the SHEEF2010 to represent better the earthquake occurrence rate in this part of Quebec. Details on these site-specific modifications to develop the site-specific seismic source model can be referred to a companion paper by Rossiter et al. [14].

Ground Motion Models (GMM)

GMMs provide estimates of earthquake ground motions (e.g. peak ground acceleration (PGA) and spectral acceleration) at a site as functions of earthquake magnitude, source-to-site distance, site ground condition, and other factors. This study used the suite of GMMs proposed in Atkinson [8] and Atkinson [15] and refers them to as the "Atkinson GMMs" in this paper hereafter. The Atkinson GMMs were developed using recent seismological models for CENA, including those considered in the NGA-East project (Goulet et al., [16]). The GMMs were also calibrated using seismographic data recorded in southeastern Canada. The reference site condition of the Atkinson GMMs is a hard rock site represented with a $V_{S,30}$ of "about 2,000 m/s". Inputs to the GMMs include moment earthquake magnitude (**M**) and closest source-to-rupture plane distance, with an assumed focal depth of 10 km. Aleatory variability in the Atkinson GMMs was modeled by a log-normal distribution with a standard deviation of 0.23 $\log_{10}$ units for high frequencies, increasing to 0.27 $\log_{10}$ units at low frequencies for the reference-rock site condition. This aleatory variability is consistent with other studies (e.g., Atkinson and Adams [17]). In addition to the mean GMM, the Atkinson GMMs also contain upper and lower GMMs to capture the epistemic uncertainty. The upper and lower GMMs were defined by capturing the variations in existing GMMs proposed for CENA (Atkinson [15]). The epistemic uncertainty in the Atkinson GMMs combined epistemic uncertainty for crustal events in western North America (WNA) and additional epistemic uncertainty for CENA as described in Atkinson and Adams [17].

The Atkinson GMMs are appropriate for this site because the tectonic and geologic conditions surrounding the site are similar to those for which the GMMs were developed. Moreover, Atkinson [15] showed that the mean GMM provided similar ground motion predictions as those by the suite of 13 NGA-East GMMs for a similar site condition. The epistemic uncertainty was also indicated to be consistent with that in the suite of NGA-East GMMs.

Logic Tree

A logic-tree approach was used to parameterize the epistemic uncertainty by considering alternative input parameters to the PSHA model (Abrahamson [18]). Figure 2 shows the logic tree developed in this study. Alternatives and weightings for seismic source sub-models, earthquake recurrence parameters (i.e. a- and b-values in Gutenberg and Richter [19]), maximum earthquake magnitude, and hypocentral depth as adopted from Halchuk et al. [1]. Weightings for the mean, upper, and lower GMMs follow the recommendations in Atkinson [15].

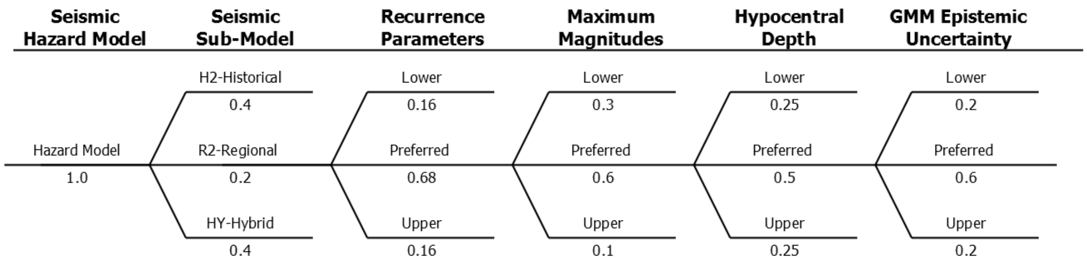


Figure 2. Logic tree for PSHA.

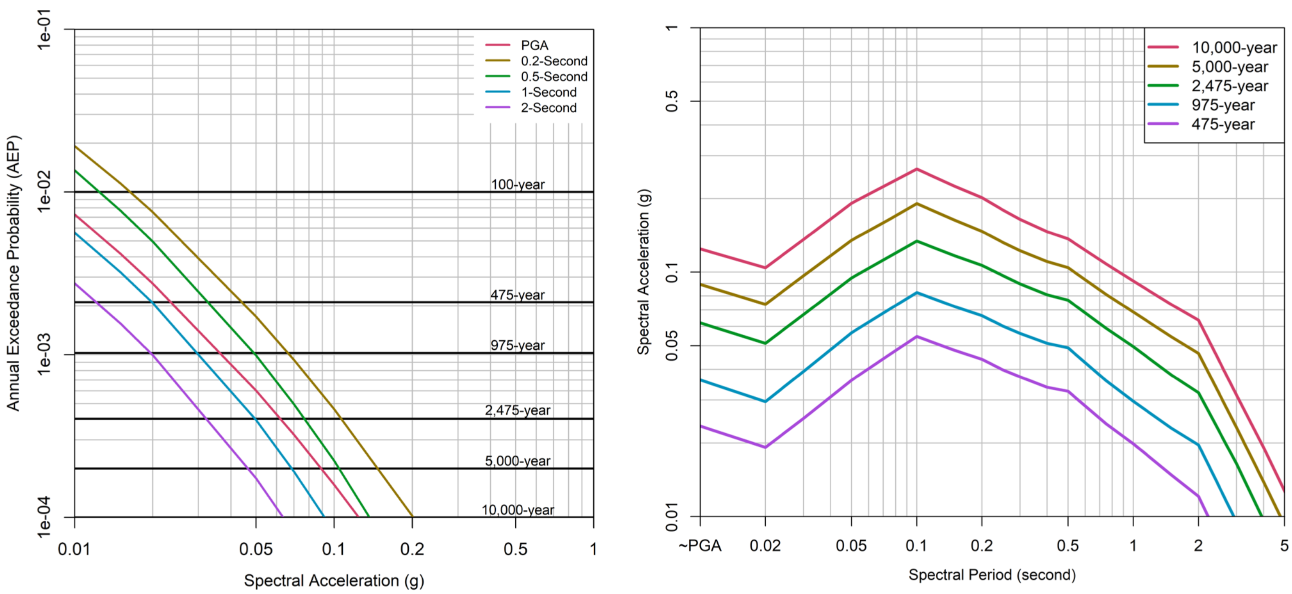
The minimum earthquake magnitude used in the PSHA is **M**4.8 as in Halchuk et al. [1]. Earthquakes with lower magnitudes are generally considered incapable of developing long-duration ground motions and are, therefore, of limited engineering significance to modern engineered structures.

PSHA RESULTS

Hazard Curves and Uniform Hazard Response Spectra (UHRS)

Mean hazard curves (5%-damped) for horizontal PGA and several other spectral periods for a $V_{S,30}$ of 2,000 m/s are presented in Figure 3(a). The hazard curves illustrate the variation in spectral accelerations (Sa) as a function of the AEP or its reciprocal, return period. The difference between slopes of the hazard curves for different spectral periods reflects the difference in earthquake scenarios that control the ground motions at the site.

Figure 3(b) shows 5%-damped, mean horizontal acceleration UHRS for AEPS of 1 in 475, 1 in 975, 1 in 2,475, 1 in 5,000, and 1 in 10,000. The spectral acceleration at 0.01-second spectral period is essentially equivalent to PGA. The UHRS is described as uniform hazard because each Sa value shown on a response spectrum has the same AEP, i.e., an equal probability of being exceeded, at any spectral period. The UHRS provides the Sa for a range of structure periods of engineering interest from PGA up to 5 seconds. The figure indicates that the peak response occurs at a period of about 0.1 seconds. The shape of the response spectrum, in this case, is largely a function of the GMMs (Atkinson [8]) used, not of the contributing seismic sources. PGA values are 0.02 g, 0.04 g, 0.06 g, 0.09 g, and 0.12 g for five AEPs ranging from 1 in 475 to 1 in 10,000.



(a) (b)

Figure 3. 5%-damped, (a) mean hazard curve, (b) mean horizontal acceleration uniform hazard response spectra.

Magnitude-Distance Hazard Deaggregation

The estimated seismic hazard is deaggregated to assess the joint distributions of earthquake magnitude and distance that are the most significant contributors. We calculate the fractional contributions from various combinations of earthquake magnitude and source-to-site distance for all the identified site-specific seismic sources to the Sa amplitude at a given spectral period and an AEP of interest. Figure 4 presents the deaggregation results for the 1 in 2,475 AEP PGA, 0.2-second Sa, and 1-second Sa. Fractional contribution as a function of magnitude and distance is illustrated using two-dimensional magnitude-distance bins in the figure. Each bin defines the range over which the fractional contribution to the hazard is calculated.

The results indicate a bi-modal distribution to the PGA. While the major contributing sources to the PGA are large-magnitude earthquakes (**M** ≥7.0) at moderate distances (100 to 160 km) from the site, a smaller but still significant contribution comes from moderate-magnitude earthquakes (**M**5.0 to 6.0) at close distances (0 to 40 km). As the spectral period increases from 0.01-second (PGA) to 1-second, relative contribution from the lower earthquake mode (i.e. about **M**5.3) decreases, and the higher earthquake mode (i.e. about **M**7.0) at greater distances become the dominant contributing sources to the hazard. In the figure, the large contribution shown at a distance of 490 km from the site for the 1-second Sa represents the cumulative contributions from all earthquakes at a distance of 480 km or greater, rather than from a single magnitude-distance pair.

At a site that has the bi- or multi-modal distributed deaggregation results, mean earthquake magnitude is usually not the primary contributing earthquake scenario but rather the average of several earthquake magnitude modes. Also, according to the generally accepted standard in earthquake geotechnical engineering practice, the higher modal earthquake magnitude is selected as the design earthquake magnitude.

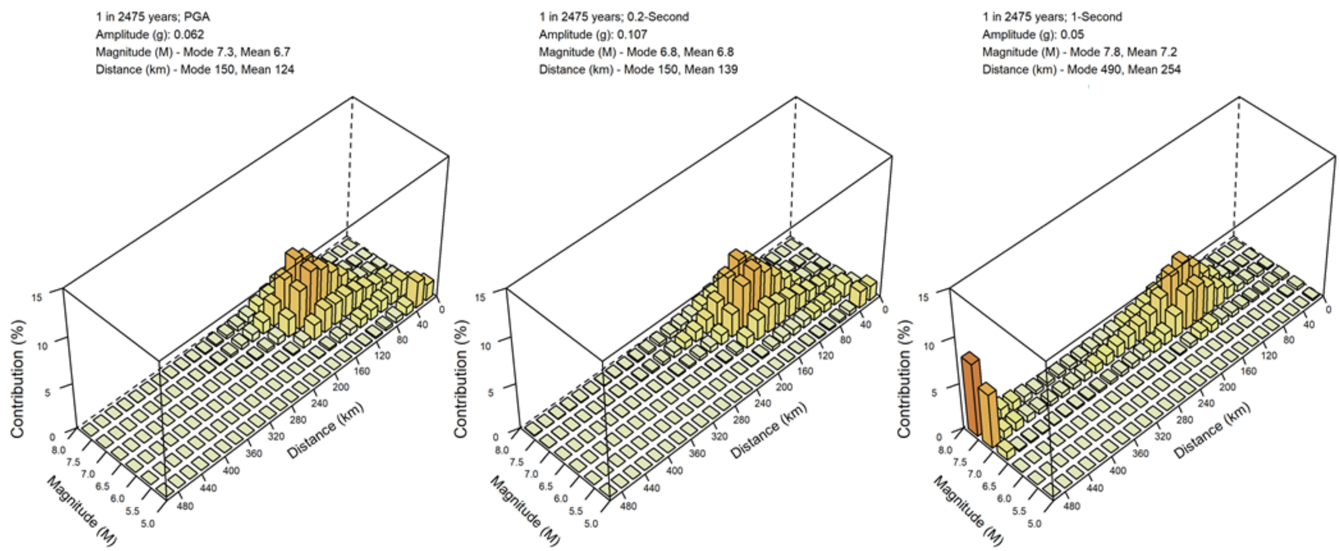
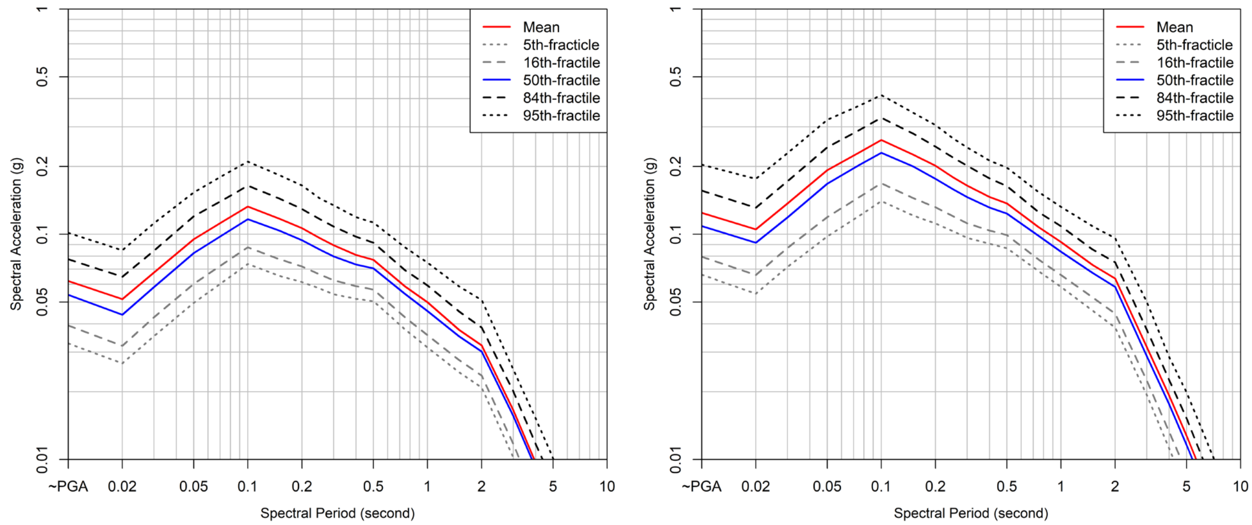


Figure 4. Magnitude-distance deaggregation for the 1 in 2,475 AEP hazard at selected spectral periods.

Uncertainty and Sensitivity of Hazard

Uncertainties in this site-specific PSHA are estimated using hazard fractiles. The 5th-, 16th-, 50th-(median), 84th-, and 95th-fractiles are calculated by post-processing the outputs from EZ-FRISK v.8.00. For a specific AEP, 90% variability in the estimated seismic hazard arises from uncertainties and is constrained by the 5th-fractile and 95th-fractile. Figure 5 presents the uncertainties associated with the mean hazard for the 5%-damped horizontal acceleration UHRS for AEPs of 1 in 2,475 and 1 in 10,000. For example, while the mean PGA is 0.06 g for an AEP of 1 in 2,475, the PGA ranges from about 0.03 g to 0.10 g for the 5th- and 95th-fractiles, respectively (Figure 5a). For an AEP of 1 in 10,000, the PGA ranges from about 0.07 g to 0.20 g within the 5th- to 95th-fractile range with the mean PGA at about 0.12 g (Figure 5b).

The ratio of 95th-fractile to 5th-percentile is a good indicator of the uncertainty level in the probabilistic hazard. For a typical seismically active region, the expected 95th-fractile to 5th-fractile ratio for PGA is about 2.0. At sites in southwest Quebec, the average 95th-fractile to 5th-fractile ratio for PGA over various AEPs is about 3.1. Fractiles results, therefore, indicate a relatively higher uncertainty level than in the regions with much higher rates of observed seismicity. This estimated uncertainty level is typical for PSHA studies in low or low-to-moderate seismicity regions. Even though the mean ground motion is usually adopted for engineering purposes, the quantification of uncertainty associated with the mean can support engineering judgement in earthquake geotechnical engineering analysis and risk assessment.



(a) (b)

Figure 5. 5%-damped, horizontal acceleration UHRS of the mean, 5th-, 16th-, 50th-, 84th-, and 95th-fractiles for (a) 1 in 2,475 AEP, (b) 1 in 10,000 AEP.

To further illustrate the uncertainties in the predicted mean hazard, sensitivity of ground motions to the uncertainties in the input parameters of our PSHA model can be estimated by considering all the alternatives of each parameter. For an individual parameter, the sensitivity is assessed by selecting a node in the logic tree (Figure 2), giving one branch a weight of unity (1) and the others a weight of zero (0), calculating mean hazard, and then repeating this process for all branches at the same node.

Figure 6 shows "tornado plots" that demonstrate the sensitivity of the 1 in 2,475 AEP PGA, 0.2-second, and 1-second Sa values to uncertainties in both the seismic source model and GMMs. Each point in the figure represents a 1 in 2,475 AEP hazard value calculated for one logic tree branch. For example, there are three alternative branches for the GMMs used in the model (i.e. the mean, upper, and lower Atkinson GMMs), which corresponds to the three points at the "GMM" node. The broader the scatter between the "hazard" points at the same node, the higher the sensitivity of ground motions to uncertainties in the corresponding model input. At this site, and likely other sites in southwest Quebec, Sa values are sensitive principally to uncertainties in the earthquake recurrence parameters and the GMMs. Because of the low historical earthquake activity in the region surrounding the site, the high uncertainty is driven by the lack of available earthquake data that is needed to constrain the recurrence parameters. Variation of the sensitivity with spectral periods is a function of the period-dependent coefficients of the GMMs, the controlling earthquake magnitudes and their activity rates. In Figure 6, there is apparently less sensitivity to recurrence parameters and GMMs at 1 second than at PGA and 0.2 second. However, because the 1-second mean Sa value is lower, the percentage sensitivity (i.e., maximum range divided by the mean value) is very similar for each spectral period shown.

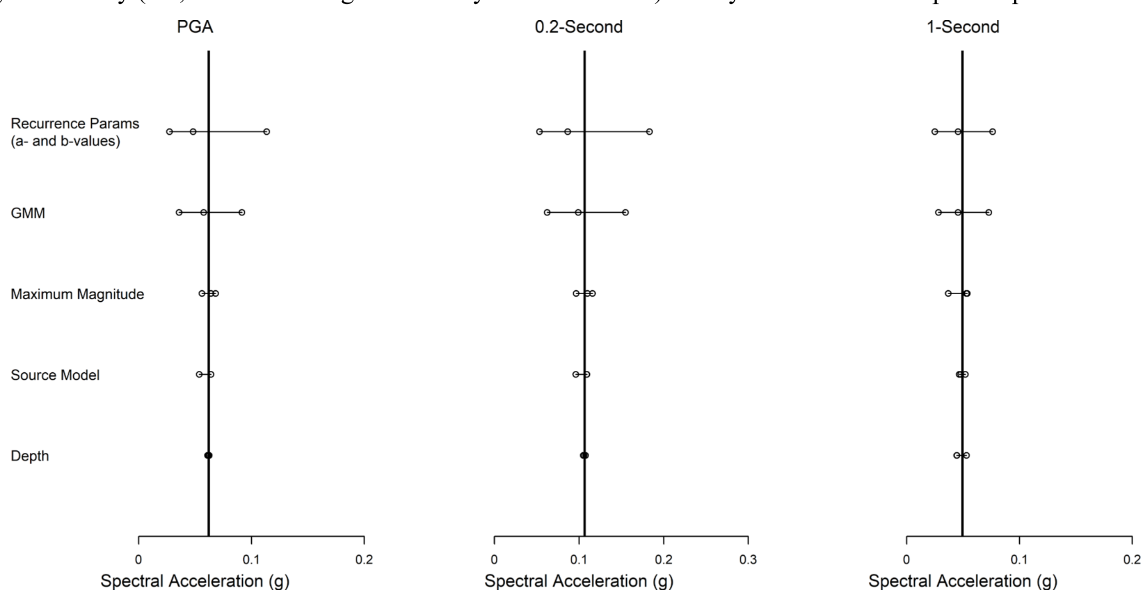
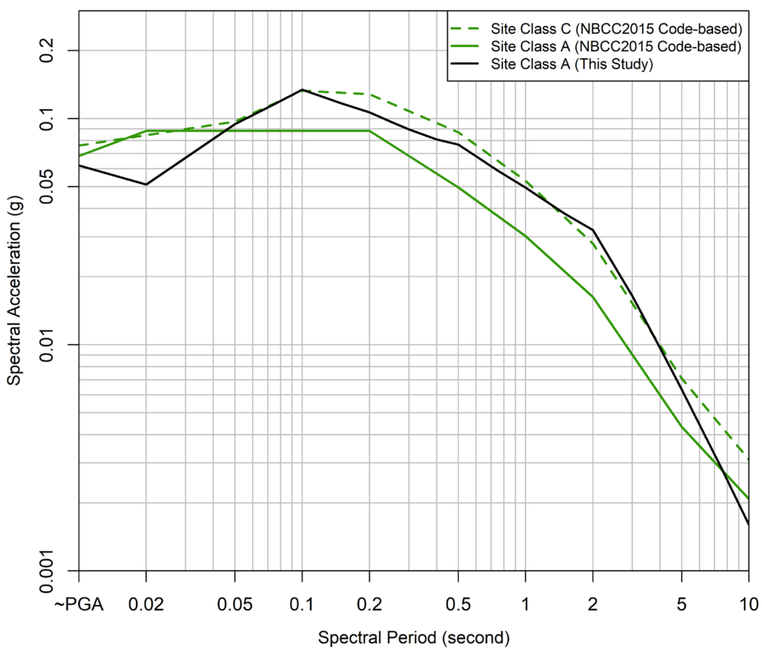


Figure 6. Tornado plots for an AEP of 1 in 2,475 at selected spectral periods.

COMPARISON TO 2015 FIFTH GENERATION SEISMIC HAZARD MAPS OF CANADA

Figure 8 shows a comparison between a site-specific mean horizontal acceleration UHRS (5%-damped) from this study to that calculated using the 2015 Fifth Generation Seismic Hazard Maps of Canada [2] for an AEP of 1 in 2,475. The dashed line in the figure represents the NBCC2015 code-based UHRS (5%-damped) for a soil Site Class C. The green solid line is the UHRS (5%-damped) for soil Site Class A calculated by scaling the soil Site Class C spectrum using the NBCC2015 code-based site amplification factors or coefficients [20] as listed in Figure 8. Based on CSA [20], for spectral periods PGA < $T \leq 0.2$ s, spectral acceleration values Sa(T) = max($\boldsymbol{F}$(0.2)Sa(0.2), $\boldsymbol{F}$(0.5)Sa(0.5)). The hard-rock site condition (i.e. $V_{S,30}$ of 2,000 m/s) considered in this study is equivalent to soil Site Class A in the NBCC2015.

Comparisons show that the UHRS in this study is higher than the NBCC2015 code-based spectrum for soil Site Class A at spectral periods ranging from about 0.05 to 7 seconds while the PGA values are similar. The NBCC2015 Site Class A code-based spectrum has a truncated section between PGA and the 0.2-second spectral period, as is typical when applying code-based site amplification factors or coefficients to a response spectrum for seismic analysis and design of buildings and other standard structures. The response spectrum truncation, however, does not reflect the complete response spectrum. When considering the uncertainty level shown previously (Figure 5(a)), Sa amplitudes on the NBCC2015 soil Site Class A spectrum generally fall within the range of uncertainty assessed for the 1 in 2,475 AEP UHRS in this study. Our UHRS is very similar in amplitude to the NBCC2015 code-based spectrum for soil Site Class C at spectral periods longer than about 0.05 seconds. These differences in spectrum shape and amplitude between the NBCC2015 code-based spectrum and that calculated from this site-specific PSHA are likely because of the use of Atkinson GMMs (Atkinson [8]) in this study and site amplification factors. While differences appear large in Figure 8, we note that the overall hazard is low.



Site Amplification Factor *F* (Site Class C to Site Class A)	
Period (s)	***F***
PGA	0.90
≤ 0.2	Varying
0.2	0.69
0.5	0.57
1	0.57
2	0.58
5	0.61
10	0.67

Figure 7. Comparison the UHRS (5%-damped) result to NBCC2015 code-based spectrum for an AEP of 1 in 2,475.

CONCLUSIONS

A site-specific PSHA study for a $V_{S,30}$ of 2,000 m/s site near Rouyn-Noranda in southwestern Quebec, Canada confirms the relatively low hazard level with amplitudes of mean horizontal PGA for the AEPs of 1 in 2,475 and 1 in 10,000 at 0.06 g and 0.12 g, respectively. Hazard values were estimated using a modified national seismic hazard model (Halchuk et al. [1]; Rossiter et al. [14]), suite of GMMs from Atkinson [8], and logic-tree-based incorporation of epistemic uncertainties in the hazard model inputs. Hazard deaggregations indicate that the main seismic hazard sources are moderate to distant (100 to 160 km from the site), large-magnitude earthquakes (**M** ≥7.0), and moderate-magnitude earthquakes (**M**5.0 to 6.0) close (within 40 km) to the site. Uncertainty analysis indicates a high level of uncertainty associated with the mean hazards. Specifically, the average ratio of 95^{th}-fractile to 5^{th}-fractile for PGA at this site is about 3.1, which is higher than 1.5 times that typically expected in seismically active regions. Major sources of uncertainty are a lack of historical earthquake data due to low seismicity in this region, and uncertainties associated with the Atkinson GMMs. At a 1 in 2,475-year AEP (2,745-year return period), the site-specific UHRS (5%-damped) is very similar to the NBCC2015 seismic hazard response spectrum for a soil Site Class C site.

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