Site-Specific Modifications to the Canadian Fifth-Generation Seismic Hazard Model

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ABSTRACT

The Fifth-generation Seismic Hazard Model developed by Halchuk et al. [1] is an invaluable tool to estimate earthquake ground motions based on probabilistic seismic hazard analysis (PSHA) in Canada. Their model was developed to produce spectral accelerations for a 2,475-year return period to support seismic design for the 2015 National Building Code of Canada (2015NBCC). As such, the Fifth-generation model was created to capture earthquake activity on a national scale, rather than to reflect smaller-scale changes surrounding some sites. When the local seismicity pattern and rate differs from the Fifth-generation model or very long return period values are needed, then changes to the model can provide additional detail on site-specific hazard and the confidence in the site-specific ground motions.

This paper presents a method where modifications can be made to the Fifth-generation model to incorporate the distribution and activity of local earthquakes, using a site in southeastern Canada as an example. Modifications were made to have the greatest effect on total seismic hazard. A new seismic source was created based on historical seismicity from the Seismic Hazard Earthquake Epicentre File (SHEEF2010) of Halchuk et al. [2]. The new source was incorporated into the existing model, and other sources adjusted to maintain earthquake occurrence rates, while avoiding double-counting of earthquakes. To estimate seismic hazard values for the site condition (i.e., soil Site Class A with time-averaged shear-wave velocity in the upper 30 m ($V_{S,30}$) of ~2,000 m/s), the Atkinson et al. [3] ground motion model (GMM) was used to model source-to-site attenuation. Modifications to the Fifth-generation model result in a decrease in total hazard of approximately 4% for a soil Site Class C site condition at the location of this study. The modifications made only modest changes to the total hazard, but better reflect local seismicity trends to provide increased confidence in the results.

Keywords: PSHA, Seismic Hazard, Seismic Hazard Model, Tailings Storage Facility (TSF)

INTRODUCTION

The Fifth-generation Seismic Hazard Model developed by Halchuk et al. [1] is used to estimate earthquake ground motion parameters for the design using 2015NBCC. These ground motions are estimated out to a return period of 2,475 years. This return period is sufficient for standard buildings governed by 2015NBCC, however, design and analysis of structures with higher consequences of failure often require estimation of earthquake ground motions at a longer return period. For example, the Canadian Dam Association (CDA) requires that dams classified as “Very High” or “Extreme” be analyzed for stability under earthquake loadings with return periods exceeding 2,475 years, and up to 10,000 years. In order to estimate ground motions at specific sites for return periods in excess of 2,475 years, the suitability of the Fifth-generation model needs to be closely examined, and the model possibly modified, to reflect better the local seismicity pattern and rate.

This paper presents an example of a site-specific seismic hazard analysis in which the Fifth-generation model was modified for use in a PSHA to estimate earthquake ground motions for return periods up to 10,000 years for a given site condition. The site used in this example is located in southeastern Canada, however, the methods used in implementing the modifications can be applied at sites throughout Canada.

BACKGROUND

The modified seismic source model in this study was developed for the analysis of a tailings storage facility (TSF) located in southeastern Canada (Figure 1). Geophysical testing and review of bedrock cores indicates that the time-averaged shear wave velocity in the upper 30 m ($V_{S,30}$) is about 2,000 m/s at this site.

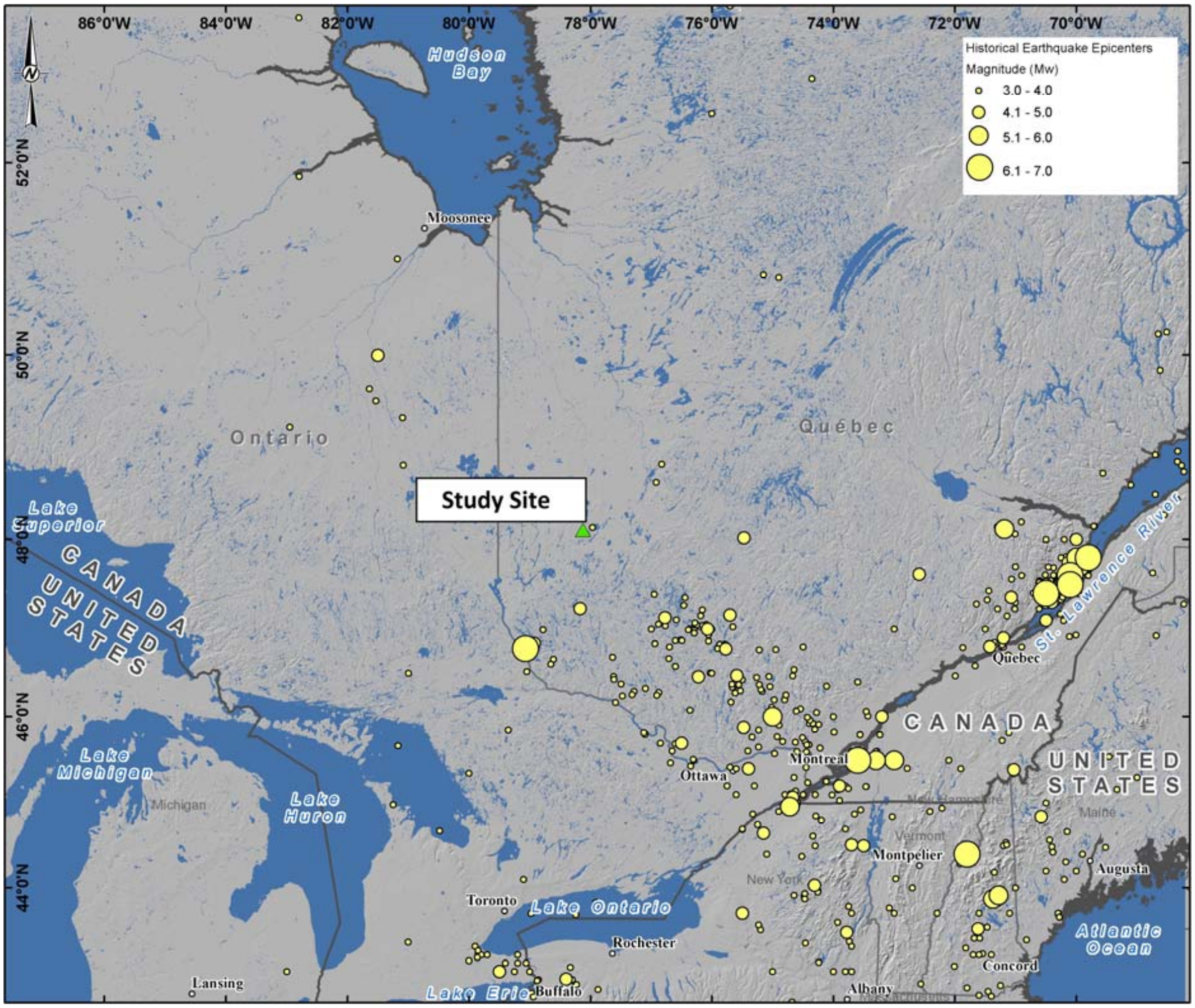


Figure 1. Historical earthquake epicenters from SHEEF2010 surrounding the study site.

SITE-SPECIFIC SEISMIC SOURCE MODEL

In seismic hazard studies, a seismic source model is developed to represent geographically defined seismotectonic regions considered capable of producing moderate to large earthquakes that influence the earthquake ground shaking expected at a site of interest. These sources can be large and small areas of historical earthquake epicenters, tectonic terrains or geophysical regions. Earthquake sources associated with the rupture areas of large historic earthquakes are also considered, where applicable, as are faults where there is evidence of surface displacement during the Late Pleistocene stage of the Pleistocene Epoch (i.e., about the last 130,000 years). A seismic source model is defined in terms of parameters that include: source location, source geometry, faulting mechanisms, maximum earthquake magnitudes, and earthquake recurrence models.

The seismic source model developed here is a site-specific modification to the Fifth-generation model used to develop 2,475-year return period hazard values as the basis for the 2015NBCC. In this study, the Fifth-generation model is modified using historical earthquake epicenters and magnitudes to represent better the earthquake occurrence rates surrounding the study site.

Earthquake Catalog

Development of a site-specific PSHA requires a comprehensive understanding of the spatial and temporal distribution of historical earthquakes for the region surrounding the site of interest. SHEEF2010 developed by Halchuk et al. [2] for the Fifth-generation model was used in this study to develop the site-specific source model. The earthquake catalog includes events with an original catalog magnitude of 2.5 or higher. The estimated moment magnitude (**M**) used in the catalog may be less. SHEEF2010 contains data up to and through the year 2010. Figure 1 shows the location and magnitude of historical earthquakes in SHEEF2010 for southeast Canada.

When developing recurrence parameters for seismic analysis, it is important to understand the time period for which the earthquake catalog is complete. The completeness period of the catalog varies with earthquake magnitude and study area. The procedure outlined in Stepp [4] was used to estimate the completeness period for the portion of the SHEEF2010 catalog located in southeastern Canada, as shown in Figure 1. Available magnitude data were grouped into 0.5 **M** bins, and the completeness evaluated for each bin using the Stepp [4] procedure. Table 1 lists the year of catalog completeness estimated for each magnitude bin of the southeastern portion of SHEEF2010.

Table 1. Year of completeness for each magnitude range used for the subset of the SHEEF2010 catalog used in this study.

Magnitude Range (M)	Catalog Completeness Year
$3.0 \leq \mathbf{M} < 3.5$	1925
$3.5 \leq \mathbf{M} < 4.0$	1900
$4.0 \leq \mathbf{M}$	1860

Canadian National Seismic Source Model

The seismic source model used in this study adopts area sources and parameters from the Fifth-generation model developed by Halchuk et al. [1]. Information for the model was gathered from GSC Open File 7576, downloaded directly from the Natural Resources Canada website [5]. Each seismic source consists of a given area that is assigned a set of parameters to represent the characteristics and rate of recorded earthquakes in that region. Each zone has alternative parameters, along with the relative weighting for each parameter. Parameters are weighted to capture uncertainties in the seismic modeling process.

The Halchuk et al. [1] model is divided into four main components based on location within Canada. This study used only the southeast Canada component of the national seismic source model. This method, however, is applicable to other components of the Canada model. The southeastern Canada component of the fifth-generation model comprises three separate seismic sub-models: the Historical (H2) sub-model, the Regional (R2) sub-model, and the Hybrid (HY) sub-model, as shown in Figure 2. Source parameters in the H2 sub-model are based on historical earthquake locations and magnitudes (e.g., Figure 1). The R2 sub-model was developed using regional geological criteria as the basis for selection of the seismic source parameters, while the HY sub-model was developed using both historical earthquake data and regional geological parameters. In the southeastern Canada component of the Fifth-generation model the individual sub-models are weighted at 0.4, 0.2, and 0.4 for the H2, R2, and HY sub-models, respectively. Halchuk et al. [1] provides additional details on the basis for the development of the seismic sources and their relative weightings.

The Fifth-generation model was implemented in the EZ-FRISK v. 8.0 seismic hazard analysis software. Correct implementation of the model was verified with a trial PSHA using EZ-FRISK and the ground motion model (GMM) look-up tables from Halchuk et al. [1]. The look-up tables are included in the Open File 7576 [1]. The trial PSHA in EZ-FRISK produced similar spectral acceleration values (soil Site Class C) to those from the NBCC2015 online tool [5] for the 2,475-, 975-, and 475-year return periods at the site, and at nearby sites in southeastern Canada. Spectral acceleration values calculated using the EZ-FRISK software and the NBCC2015 online tool [5] varied by up to 3% between PGA and 2-second spectral periods, and up to 11% for spectral periods longer than about 5 seconds. These results confirmed that the Fifth-generation model was implemented appropriately in EZ-FRISK.

Site-Specific Modifications

The Fifth-generation model was developed as a national model to estimate hazard for standard engineered structures across Canada. For this study, modifications were made to the Fifth-generation model to characterize better the seismic setting directly surrounding a study site. Modifications were made based only on the historical earthquake catalog. Modifications were made so they could be integrated into the existing Fifth-generation model. Options for the modifications included adding a new sub-model, modifying existing sources in one or more sub-models, or adding additional sources to one or more sub-models. For this study, an additional source zone – MMS – was developed as part of the H2 model, shown in Figure 3.

Modifying the H2 model was chosen for two main reasons:

1. Characterizing new sources based on historical seismicity is the same approach as used in developing the H2 model.
2. The study site is located within a narrow eastward extension of the H2_SEB source (Figure 2a) of the H2 sub-model. The extension appears to capture a cluster of historical earthquakes surrounding and to the south of the study site that probably better reflect the earthquake activity to the north rather than to the more active areas to the west of the study site.

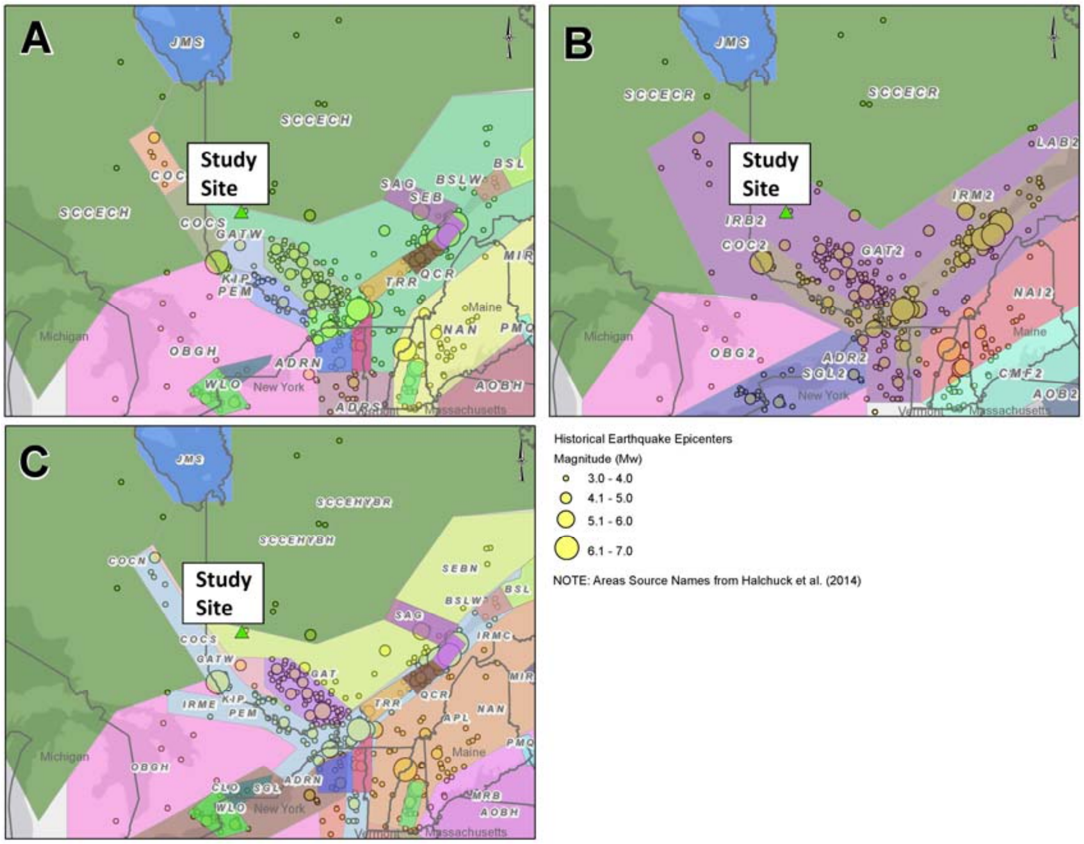


*Figure 2. Area seismic sources in the southeastern Canada component of the Fifth-generation Seismic Hazard Model: A) Historical (H2), B) Regional (R2), C) Hybrid (HY.) Earthquakes **M**≥3 shown for each source zone.*

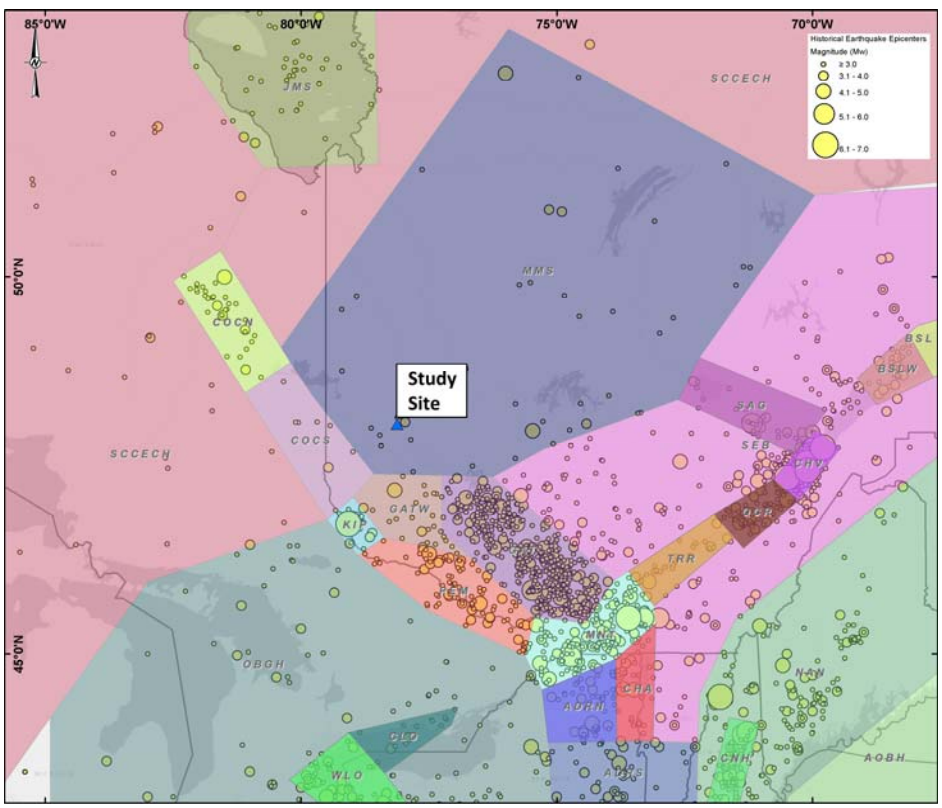


*Figure 3. Earthquakes of **M**≥2.5 and site-specific seismic source zones (H2 model).*

This study developed a new MMS source zone based on the historical seismicity in the SHEEF2010 catalog. The site boundary was created by drawing a boundary around an area of similar earthquake activity. The source zone geometries for the H2_SCCECH and H2_SEB (Figure 3) sources in the Fifth-generation model were then adjusted to retain the recurrence-per-area rate from the original national seismic source model. Figure 3 shows the modified H2 sub-model used in this study.

MMS Source Parameters

There is a limited historical earthquake record to calculate stable earthquake activity rates in much of southeast Canada. In the absence of sufficient data, an assumed *b-value* of 0.8 was used for the modified source zones. This value is recommended by United States Geological Survey (USGS) for modeling shallow crustal seismic sources in CENA [6]. A standard deviation of 0.519 was assigned to the *b-value* for the MMS, which is consistent with nearby sources in the H2 source zone model. The minimum magnitude earthquake considered in this study is an **M**4.8, while the maximum magnitude values used to characterize the MMS source are 7, 7.3, and 7.6 as lower, middle, and upper bounds respectively. These values are consistent with the earthquake record and the rest of the Fifth-generation model. The *a-values* for the MMS were then estimated using the maximum likelihood method of Weichert (1980). The data used was grouped into 0.1 **M** bins for recurrence parameters calculations.

Figure 4a shows a comparison of the modeled seismicity rates to SHEEF2010 historical seismicity used to develop the MMS source zone. The error bars are larger than the upper and lower values used for the modeled seismicity because there is a very limited number of earthquakes available from the historical earthquake catalog. For example, there are no recorded earthquakes over **M**4.5 within the MMS source zone, thus, there are large uncertainties in the earthquake recurrence model and associated earthquake activity rates. The level of uncertainty in earthquake activity is similar for most source zones in this study, and in the Fifth-generation model for southeastern Canada.

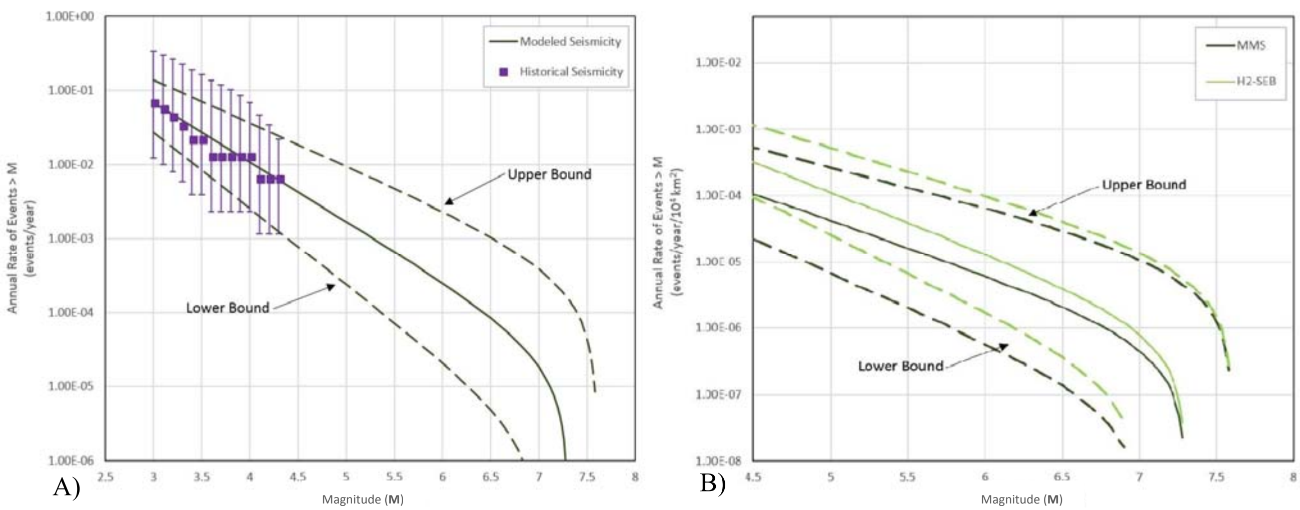


Figure 4. Comparison of A) historical earthquake occurrence and modeled earthquake activity rates for the site-specific MMS source, and B) area normalized earthquake activity rates for MMS and H2_SEB.

Figure 4b shows that the earthquake activity rate for the MMS source, normalized by source area, is slightly lower than that of H2_SEB from the Fifth-generation model. Figure 4b also shows that the range of earthquake activity rate between lower, mean, and upper bound alternatives is slightly larger for the MMS source than for the H2_SEB source. The earthquake activity rate values shown in Figure 4b are normalized to an area of 10^4 km^2 and extended out to extremely low annual rates (i.e., 1 in 10 million years) to aid comparison of the two seismic sources.

GROUND MOTION MODEL (GMM)

The GMM is a key component in seismic hazard analysis. GMMs provide estimates of earthquake ground motions at a site (e.g., PGA and response spectral acceleration ordinates) as function of the earthquake magnitude, source-to-site distance, and local site soil conditions. This study considered two representative GMMs developed for the CENA region. They are the suite of GMMs proposed in Atkinson et al. [3] and Atkinson [7], and the suite of GMMs developed for the NGA-East project [8]. Implementation of the NGA-East GMMs into the software used for this analysis, however, was not feasible due the excessive effort required to incorporate the 13 different GMMs that comprise the suite. The suite of GMMs in Atkinson et al. [3] and Atkinson [7], therefore, was selected for this study.

The selected suite of GMMs presented in Atkinson et al. [3] and Atkinson [7] was developed using recent seismological models for CENA, including those considered in the NGA-East project [8]. The GMMs were also calibrated using seismographic data recorded in southeastern Canada. This suite of GMMs is hereafter referred to as the Atkinson GMMs.

The Atkinson GMMs were developed for a reference hard-rock site condition with $V_{S,30}$ of about 2,000 m/s. The GMMs use earthquake moment magnitude and closest source-to-rupture plane as inputs. In addition to the mean GMM, the Atkinson GMMs also contain upper and lower GMMs to capture epistemic uncertainty. The upper and lower GMMs were defined by capturing the variation in existing GMMs proposed for CENA [7].

The Atkinson GMMs are considered appropriate for this site because the tectonic and geologic conditions at the study site are similar to those for which the GMMs were developed. Moreover, Atkinson [7] shows that the mean GMM as presented in Atkinson et al. [3] provides similar ground motion predictions as those from the NGA-East GMMs for a similar site condition; and the epistemic uncertainty in the Atkinson GMMs is consistent with the spread indicated in the suite of 13 NGA-East GMMs [7].

Following recommendations in Atkinson [7], the mean, upper, and lower GMMs for this study were weighted 0.6, 0.2, and 0.2, respectively.

SITE-SPECIFIC SEISMIC HAZARD ANALYSIS RESULTS

The site-specific seismic hazard analysis for the study site was performed for a site with $V_{S,30}$ of 2,000 m/s, or soil Site Class A in the NBCC2015. Results for the PSHA are best analyzed using the uniform hazard acceleration response spectra (UHRS), as it is typically used for the structural seismic analysis and design of engineered structures. The response spectra are described as uniform (equal) hazard because each spectral acceleration value shown on the response spectrum has the same return period, i.e., an equal probability of exceeding the ground motions at any spectral period [9]. These acceleration response spectra present the accelerations for a range of structural periods of engineering interest.

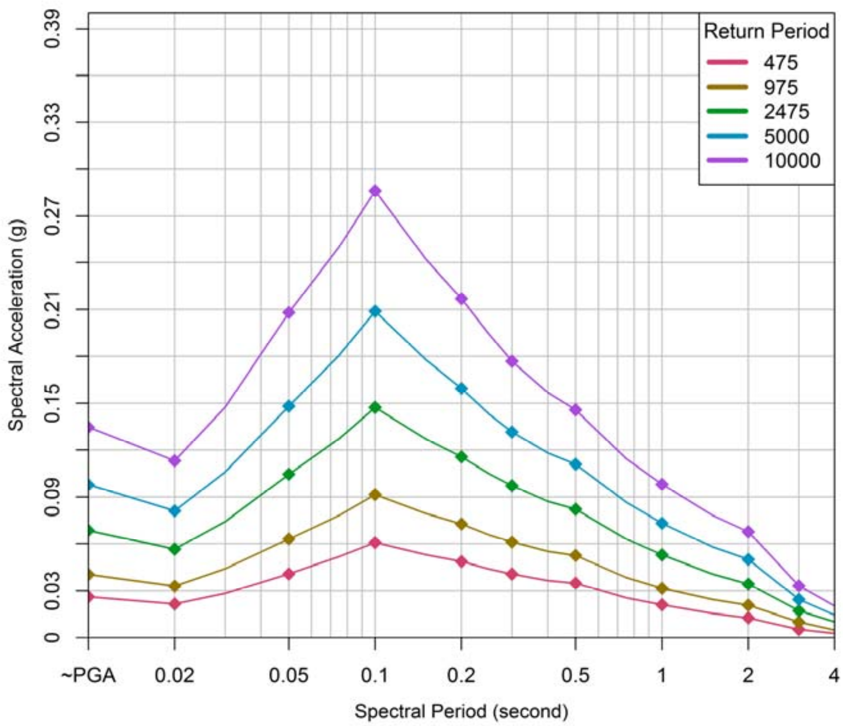


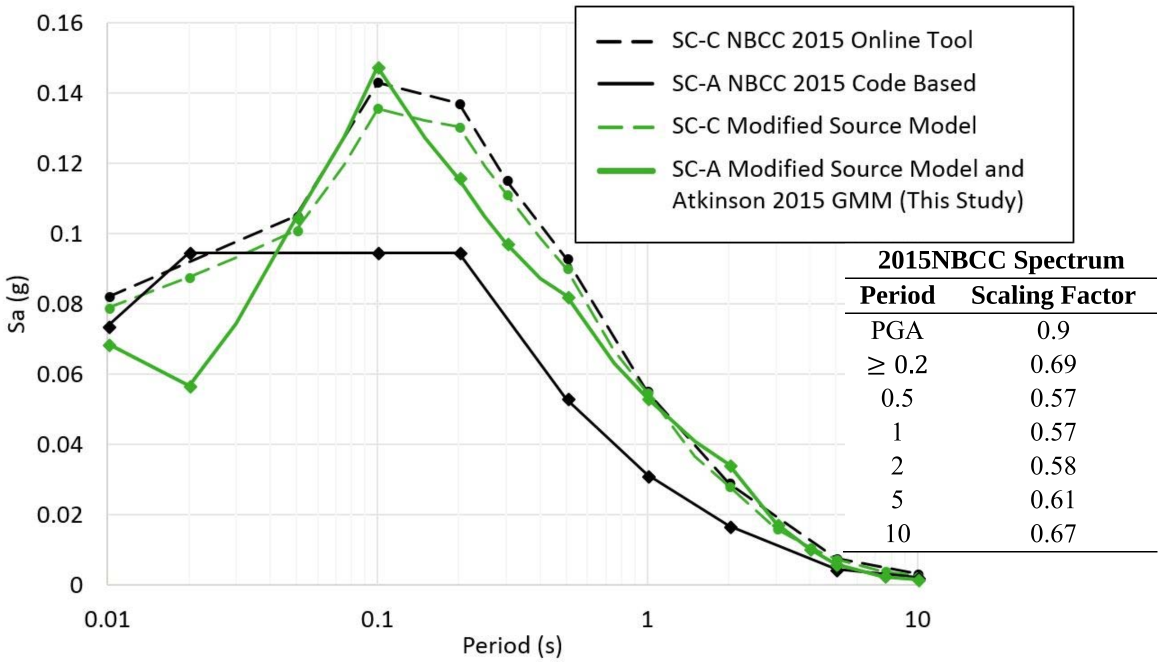
Figure 5. Uniform hazard acceleration response spectra (5% damped) for 475-, 975-, 2,475-, 5,000-, and 10,000-year return periods for a site soil condition of $V_{S,30}$ = 2,000 m/s at the study site.

Figure 5 shows the site-specific, mean, 5%-damped UHRS for the 475-, 975-, 2,475-, 5,000-, and 10,000-year return periods for a $V_{S,30}$ of 2,000 m/s site condition; and for spectral periods from PGA to 4 seconds. The spectral acceleration of 0.01-second period is essentially equivalent to the PGA for a specific magnitude and distance. For each return period, the PGA (0.01-second period) is greater than the spectral acceleration at 0.02-second period. The shape of the response spectrum, in this case, is largely a function of the suite of GMMs used.

For additional details on the full development of the hazard model, please see the companion paper [10].

COMPARISON TO 2015 FIFTH-GENERATION SEISMIC HAZARD MODEL RESULTS

Figure 6 compares acceleration response spectra developed in this study to acceleration response spectra estimated from the Fifth-generation model. All response spectra are based on a 2,475-year return period at the study site. Dashed lines in Figure 6 are the 2,475-year return period UHRS for a soil Site Class C site (very dense soil and soft rock). Site Class C spectral acceleration values were estimated using the GMM look-up tables provided by Halchuk et al. [1] for the Fifth-generation and modified source models, as discussed previously. The solid lines represent the 2,475-year return period acceleration response spectra for an NBCC2015 soil Site Class A (i.e., a hard rock site with a $V_{S,30}$ >1,500 m/s). The response spectrum with a solid black line uses the NBCC2015 code-based soil amplification factors to scale the soil Site Class C response spectrum to a Site Class A (hard rock). The solid green line is a response spectrum calculated using the seismic sources developed for this site-specific study using the Atkinson GMMs with an assumed $V_{S,30}$ of 2,000 m/s (i.e., hard rock).



2015NBCC Spectrum	
Period	**Scaling Factor**
PGA	0.9
≥ 0.2	0.69
0.5	0.57
1	0.57
2	0.58
5	0.61
10	0.67

Figure 6. Comparison of site-specific PSHA results using the modified source model to the Fifth-Generation Seismic Hazard Model for a return period of 2,475 years.

Figure 6 shows that the site-specific acceleration response spectrum is higher than the NBCC2015 code-based response spectrum for a soil Site Class A site for periods from about 0.04 to 6 seconds. The Site Class A code spectrum flattens out between PGA and the 0.2-second spectral period, as is typical for a code-based spectrum used in the seismic analysis and design of standard buildings and related engineered structures. While code-based response spectra are used for building structures, their spectral shape is typically different from the shape of site-specific response spectra.

The differences in spectral shape and amplitude between the NBCC2015 spectrum and the site-specific spectrum as calculated in this study likely results from the use of the Atkinson GMMs. The Atkinson GMMs reflect newer information on the response of hard rock sites in CENA, the NGA-East GMMs, current estimates on ground motion variability, and newer information on site response of Site Class A versus Site Class C [7]. PSHA that use recently developed CENA models, such as the Atkinson and NGA-East GMMs, typically show that the estimated hard rock motions at higher frequencies have increased when compared to the Fifth-generation GMMs that were developed around 2010. This site-specific study and results are in line with current trends and the state of PSHA practice over the last five years.

While these differences appear large in Figure 6, the overall hazard at the study site is low, such that the differences may have limited impact on engineering design.

CONCLUSIONS

As part of local regulations and industry guidelines, certain structures are required to be designed for earthquake ground motions with return periods of up to 10,000 years. The current tool commonly used in practice in Canada, the Fifth-generation Seismic Hazard Model [1], however, is created to estimate seismic ground motions out to 2,475-year return periods for standard structures founded on soil Site Class C sites. In order to estimate ground motions for a longer return periods and for differing site conditions, modifications can be made to the Fifth-generation model to better represent the local site-specific earthquake distribution and activity rate.

In this example, a PSHA was performed for a site in southeastern Canada. Analysis called for estimation of earthquake ground motions with a return period up to 10,000 years, and for a soil Site Class A site condition. For this study an additional seismic source was created and included in the H2 sub-model of the Fifth-generation model for the southeastern Canada region. The additional source was created using historical seismicity records from the SHEEF2010 catalog [2]. The ground motion models used in this study were the Atkinson [3] GMMs that are applicable to soil Site Class A.

Modifications to the Fifth-generation model result in a decrease in total seismic hazard of approximately 4% from the 2015NBCC code-based values for Site Class C site condition at the location of this study. Comparison of the modified and unmodified seismic source models show that the seismic hazard in study site area is very low, and that the modifications made only a small change to the overall hazard. Changing the GMMs and site condition, however, had a much more pronounced effect on the overall hazard.

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