# ANNEXE A

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## Rapport préliminaire d’étude sismique locale

# EARTHQUAKE HAZARD ANALYSIS:

# RABASKA LNG FACILITIES, QUEBEC

## Preliminary Report

By:
Gail M. Atkinson, Ph.D.
Engineering Seismologist

For:
SNC-Lavalin Inc.
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# RABASKA LNG FACILITIES, QUEBEC

## *Executive Summary*

A site-specific seismic hazard assessment was performed for the proposed LNG terminal site at Rabaska, Quebec. The analysis determines the expected earthquake ground motions over a range of probability levels, including 1/500, 1/1000, 1/2500 and 1/5000. The 1/500 per annum (p.a.) ground motion corresponds to the "Operating Basis Earthquake" (OBE) level in LNG facility codes such as CSA Z276 (Canadian, upcoming 2007 edition), NFPA59A (U.S., 2006 edition) and EN1473 (Europe, upcoming 2007 edition), while the 1/2500 p.a. motions correspond to the "Safe Shutdown Earthquake" (SSE) level in CSA Z276 (2007) and NFPA59A (2006). The SSE level in the EN1473 (2007) is 1/5000 p.a. The choice of probability level for the OBE and SSE is made by the Owner and will meet the requirements of the Canadian code. Additionally, it is my understanding that the Owner intends to apply for the design of LNG tanks the more stringent SSE return period recommended by EN1473. The ground motions are calculated for the site ground-motion conditions of "soft rock" (NEHRP B/C boundary, with shear-wave velocity in the top 30 m of approximately 800 m/s). The emphasis in this study is on deriving the range of estimates, including the impact of the chief sources of uncertainty. Weighted mean-hazard results are also provided (Table 2) for each probability level.

The results can be summarized in simplified terms as follows. At the probability level of 1/2500, the expected peak ground acceleration (PGA) for the soft-rock (B/C) site conditions at Rabaska is approximately 0.45g. For comparison, the acceleration at Rabaska from the national seismic hazard maps produced by the Geological Survey of Canada (2003), for the 1/2500 p.a. probability, is 0.34g (for the GSC reference condition of NERHP C). The ground motions at this probability level (1/2500) correspond approximately to a magnitude 7 earthquake occurring in the Charlevoix seismic zone, at a distance of about 70 km from the site, or a magnitude 6 local earthquake, about 20 km from the site. At the probability level of 1/5000, the expected PGA at Rabaska is approximately 0.64g, corresponding approximately to a magnitude 7 earthquake at about 50 km, or a magnitude 6 earthquake at about 15 km from the site.

## 1 - INTRODUCTION

This report presents a seismic hazard assessment for the site of the proposed LNG terminal facilities at Rabaska, Quebec (46.82N, 71.06W) for annual exceedence probabilities in the range from 1/500 to 1/5000. By comparison, the CSA Z276 guidelines for LNG facilities (upcoming 2007 edition) are expected to refer to ground motions for an Operating Basis Earthquake (OBE) with an annual probability of 1/500 and a Safe Shutdown Earthquake (SSE) with an annual probability of 1/2500; these probability levels (1/500 and 1/2500) match those in the U.S. Standard NFPA59A (2006 edition). The

European code, EN1473 (Europe, upcoming 2007 edition) refers to an OBE probability of 1/500 and an SSE probability of 1/5000. The analysis determines the likelihood of ground motion at the site by considering the magnitudes, rates of occurrence, and locations of earthquakes, using the probabilisitic Cornell-McGuire method. The method is widely used throughout North America and forms the basis for seismic zoning maps in building codes in Canada (Adams and Halchuck, 2003). This assessment represents an update and site-specific refinement of the type of estimate provided in the National Seismic Hazard maps by the Geological Survey of Canada (GSC, Adams and Halchuck, 2003); the results of this study address more specifically the tectonic setting of the Rabaska site, and incorporate new information on seismicity and ground motion relations from the last 10 years of data. To include new and more complete information, a range of possible models to describe the seismic setting is defined.

In analyzing the engineering effects of ground motion, both the amplitude and frequency content of the vibrations are important. Therefore the seismic ground motions are expressed using the response spectrum (PSA(f)), which shows the maximum acceleration that a simple structure would experience as a function of its natural frequency. The response spectrum result is a Uniform Hazard Spectrum (UHS), in which the amplitude for each frequency corresponding to a specified exceedence probability is provided. The peak ground acceleration (PGA) for this probability is also estimated, as is the peak ground velocity (PGV). The frequency associated with the PGA varies, but in general the PGA is associated with high-frequency motions (near 10 Hz); the PGV is associated with motions near 2 Hz. The UHS results of this study are presented in the figures and tables provided in Section 3.

Time histories of ground motion that match the UHS for specified probability levels will be developed in a later phase of the project. The time histories may be derived by modifying real earthquake records that are appropriate for eastern Canadian rock sites, for magnitude-distance ranges that dominate the hazard at Rabaska. The modifications are done to spectrally match the original record to the target UHS through an iterative process of amplitude adjustment in the frequency domain.

# 2 - SEISMIC HAZARD ANALYSIS METHOD

## 2.1 Overview

Seismic hazard analyses in eastern Canada are based on probabilistic concepts which allow incorporation of both geologic interpretations of seismic potential and statistical data regarding the locations and sizes of past earthquakes. The Cornell-McGuire method (Cornell, 1968; McGuire, 1976, 1977, 2004) has proven particularly well-suited to calculate expected ground motions for a wide range of seismic hazard environments, offering flexibility in the consideration of spatial and temporal characteristics of regional earthquake occurrence, and the basic physics of the earthquake process.

In general, it is difficult to correlate seismicity with specific faults. Earthquakes typically occur at depths of 5 to 20 km, on faults that have no surface expression. Furthermore, faults mapped on the surface in eastern Canada were formed hundreds of millions of years ago, and may bear little relation to current seismic activity. Thus there is no clear-cut relationship between observed faults and seismicity. (Note: This is apparent in Figure 2, showing Charlevoix seismicity in comparison to mapped faults.) Geotechnical reports for Rabaska (Terratech, 2006) are consistent with this view. The site geology consists of folded and faulted Paleozoic strata formed approximately 500 million years ago as part of the Appalachian province. During the Taconian Orogeny, the sediments were pushed over the underlying Precambian basement rocks, which lie approximately 4 km below the Paleozoic sediments at the site. Major tectonic activity in the region ceased about 400 million years ago. Investigations by Terratech, using seismic refraction geophysical survey and diamond core drilling, along with two trial excavations, have provided information on the quality of the rock and its overall structure. They conclude that there is no evidence of recent faulting identified in the exposed strata at the site area or in boreholes. For example, the rock core recovered in some boreholes present evidence of faulting, but the rock appears to be healed as indicated by cementing of the fault with secondary minerals such as calcite (Terratech, 2006). It is important to recognize that in this region, the Appalachian rocks are underlain at depth by older Precambrian sequences, in which the seismicity occurs; most seismicity in the Charlevoix seismic source zone occurs between 7 and 15 km below the surface, with earthquakes occurring to depths of up to 30 km (Lamontagne et al., 2000). Thus we would expect modern earthquake-related faulting to occur below the Appalachian rock sequence, rather than within it. Any such faulting would leave little surficial evidence, other than perhaps the disturbance of post-glacial sediments if shaking was sufficiently strong. The examination of post-glacial soils near the site during the trial excavation (which was conducted over a known fault or fold) led to the conclusion that there is no clear evidence that the soil materials were tectonically disturbed (Terratech, 2006).

The spatial distribution of earthquakes is described by defining seismic source zones (faults or areas, which may contain groups of faults) on the basis of seismotectonic interpretations; the earthquake potential of these zones is generally assumed to be uniform. The frequency of earthquake occurrence within each source zone is described by a magnitude recurrence relationship, truncated at an upper magnitude bound, Mx. Earthquake ground motion relations provide the link between the occurrence of earthquakes of various magnitudes and the resulting ground motion levels at any site of interest. The probability of exceeding a specified level of ground motion at a site can then be calculated by integrating hazard contributions over all magnitudes and distances, including all source zones. To obtain ground motion levels or earthquake response spectra for a specified probability, calculations are repeated for a number of ground motion values, for all desired ground motion parameters, and interpolation is used to determine the relationship between ground-motion amplitude and annual probability.

The Cornell-McGuire framework has been well-accepted in all parts of North America. In Canada, it forms the basis for the seismic hazard maps in the National Building Code of Canada (NBCC 1985 and beyond), and is the usual basis for seismic hazard evaluations of all important engineered structures. The results are generally expressed as a Uniform Hazard Spectrum (UHS), in which the amplitude for each frequency corresponding to a specified target probability is provided. The peak ground acceleration (PGA) and velocity (PGV) for the target probability may also be estimated. When time histories of ground-motion are required for use in engineering analyses, these may be derived to be consistent with the expected ground motion characteristics of the UHS for the target probability. The analysis methods used to generate UHS results and time histories are described in more detail by McGuire (2004).

## 2.2 Treatment of Uncertainty

It has long been recognized that seismic hazard analyses are subject to greater uncertainties than those associated with most environmental phenomena. Two types of uncertainty exist:

- random uncertainty due to the physical variability of earthquake processes
- model uncertainty due to incomplete knowledge concerning the processes governing earthquake occurrence and ground motion generation (eg. uncertainties in input parameters to hazard analysis).

The first type of uncertainty is incorporated directly into the Cornell-McGuire analysis framework, and is included in a standard 'best-estimate' seismic hazard result. The second type of uncertainty implies a spread of possible results about those that might be considered a best estimate. This type of uncertainty can cause differences in results, among alternative hypotheses, of factors of more than two. It also implies that, as new information on seismic hazard becomes available (through seismic monitoring and research) hazard estimates may change significantly from those developed at an earlier time.

Seismic hazard analysis procedures have been developed in recent years to formally evaluate the level of model uncertainty (sometimes referred to as epistemic uncertainty) in hazard analyses. A logic tree approach is often used to represent each input parameter by a simple probability distribution, thereby producing a family of possible output hazard curves, with associated weights (McGuire, 2004). Such an approach has been used in hazard analyses for critical engineered structures such as nuclear power plants (eg. Atkinson, 1990), and has also been used in the latest national seismic hazard maps (Adams and Halchuck, 2003). The logic tree approach is simply a way of formalizing consideration of the implications of alternative assumptions. It is most useful in cases where there is a range of competing alternative hypotheses that significantly impact the seismic hazard results. A full logic tree can be used to define the mean hazard and fractiles (eg. median, 84th percentile) expressing confidence in the estimated UHS. Alternatively, a "logic shrub", including the most significant branches of the logic tree, can be used to determine the mean-hazard UHS by weighting the alternatives for each of the key uncertainties (while leaving fixed the parameters that exert only a minor influence on the results). In this preliminary evaluation of hazard, we focus on a sensitivity approach, which displays the alternative results that are obtained under various alternative input assumptions. This approach is most useful to identify the key uncertainties, and determine the appropriate scope for further refinements to the analyses. We also use a trimmed logic "shrub" to provide weighted mean-hazard UHS results for a range of probabilities.

### *2.2.1 Seismic Source Zones*

A relevant aspect of the treatment of uncertainty in the new national seismic hazard maps, produced by the Geological Survey of Canada (GSC), concerns the issue of alternative seismotectonic hypotheses. Two alternative approaches to defining seismic source zones were defined. In one model (the Historical model), it was assumed that future large earthquakes in eastern Canada will be concentrated in zones of very limited spatial extent, in which they have occurred in the recent past (about 200 years of historical earthquake data on the location of large eastern earthquakes). This model implies high hazard in a few local zones, and low hazard elsewhere.

In the second GSC model (the Iapetan Rift model), it was assumed that future large earthquakes in eastern Canada will occur at random in broad source zones of major crustal weakness, as developed during tectonic rifting episodes associated with the Iapetus Ocean. These zones of weakness include the many ancient rift fault structures, formed about 500 to 700 million years ago, that follow the St. Lawrence and Ottawa River valleys. It is believed that future large events in eastern Canada are most likely to occur within these rifted zones (Adams and Basham, 1989). In the 'rift' hazard model, earthquake activity is smoothed over the entire extent of the rifted regions. This results in enhanced ground motion estimates in parts of the zone that have had low seismicity rates within the period of historical record, and reduced ground motion estimates in areas that have had high seismicity. Figure 1 shows the GSC zones for the two models they consider, in relation to regional seismicity (Note: all events were converted to moment magnitude, as discussed later in the report).

In the GSC hazard analysis approach, which they term the robust approach, the higher of the ground motion estimates from these two alternative zonation models is adopted as the mapped ground-motion parameter (Adams and Halchuck, 2003). This captures a significant geologic uncertainty in most of the populated regions of the St. Lawrence Valley and is appropriate for the purposes of the national hazard maps. However, it is not necessarily a "worst case" for all sites, and is actually unconservative for areas of the St. Lawrence that have higher-than-average levels of seismicity, but lie outside the concentrated zone of activity defined for Charlevoix. Thus it is warranted to examine carefully alternative models for Rabaska, in order to accurately assess and understand the seismic hazard setting and its implications. To do this requires defining additional seismic source models that could be applicable to the Rabaska site, expressing a fuller, more site-specific range of interpretations that the limited regional set considered by the GSC. The definition of these alternative source interpretations is standard practice in state-of-the-art seismic hazard analyses.

As shown in Figure 1, the Rabaska site lies about 60 km southwest of the active Charlevoix seismic zone. The Charlevoix zone is anomalously active for an intraplate environment, with 5 earthquakes of M>6 since the mid-1600s, and hundreds of micro-earthquakes recorded there every year (Lamontagne et al., 2000). The earthquakes occur in Precambrian basement, on reactivated Iapetan rift faults that are hidden in the St. Lawrence and its south shore by several kilometers of Appalachian nappes and hundreds of meters of Quaternary sediments. Although the major faults are defined geophysically (from remote sensing techniques), as shown in Figure 2, the seismicity is seen to be diffuse within the crustal volume and not specifically confined to the interpreted major fault structures (Lamontagne et al., 2000). Consequently, there is uncertainty in the geographic extent of the structures that may participate in this active zone. Furthermore, the relevance of the mapped faults and their specific locations (as per Figure 2) to the seismic hazard at the site is questionable. This is an uncertainty that was not evaluated in the GSC model, but is important for site-specific hazard to Rabaska; specifically, we need to address the possibility that the Charlevoix zone may extend to the Rabaska site. This scenario is not likely, but possible. Another uncertainty not evaluated in the GSC models concerns the actual levels of seismicity at Rabaska. It can be seen on Figure 1, from the density of plotted epicenters, that the activity levels in the site area are lower than those near Charlevoix, but higher than those in other areas of the St. Lawrence or Ottawa Valley. Thus the GSC rift model (IRM zone) may tend to underestimate the seismic hazard at Rabaska.

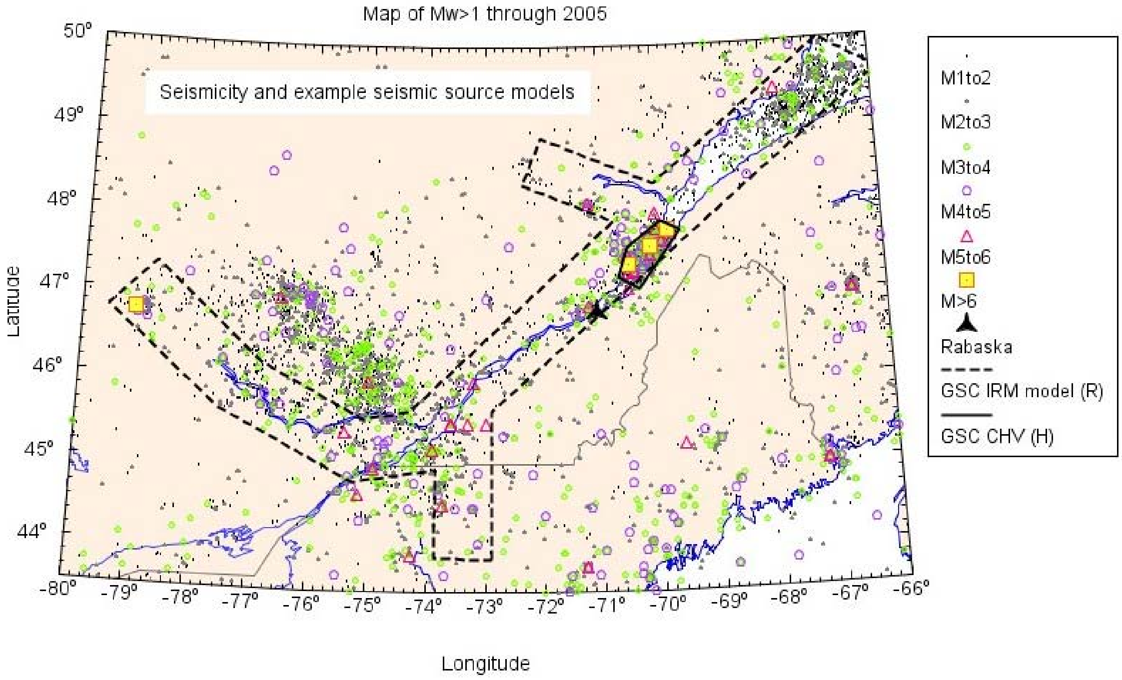

*Figure 1 – Recorded seismicity (***M***>1) through 2005 along the GSC source zone models used in the national seismic hazard maps (dashed black line is IRM rift model, solid black line is Charlevoix zone).*

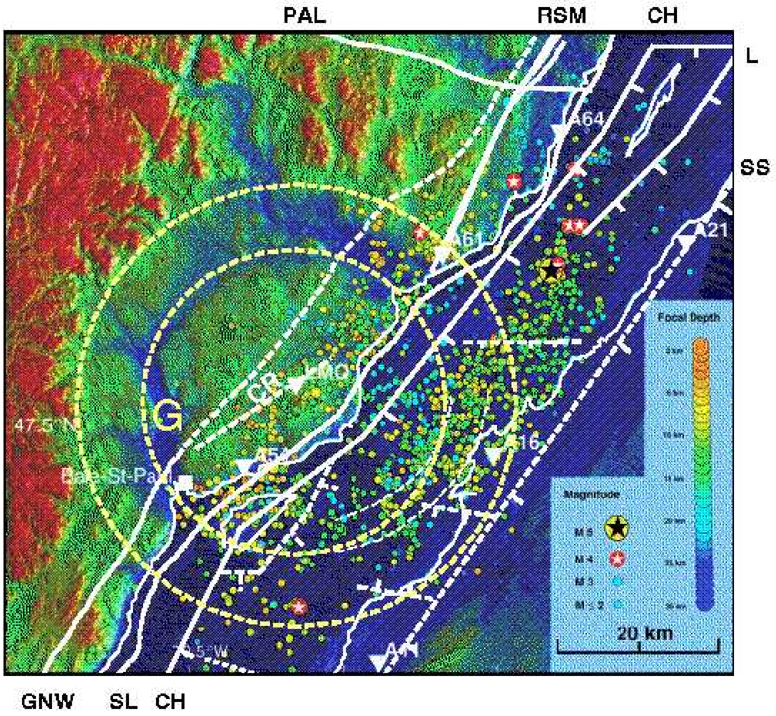

*Figure 2 – Structural model of Charlevoix seismic zone, including faults, seismicity, seismograph stations, and Charlevoix impact crater. PAL=Palissades fault; RSM= Rang St.-Mathilde fault; SL=St.-Laurent fault; CH=Charlevoix fault; L+lievres fault; SS=South shore fault; G=peripheral graben of the impact structure; CR=Crater fault; GNS=Fouffre NW fault. (after Lamontagne et al., 2000).*

To adequately consider the implications of the local seismicity rates, and the uncertainty in the extent of the Charlevoix activity, we define two alternative representations of the seismic zonation for Rabaska. These are shown on Figure 3. The "confined" Rabaska model (Model A), denoted "RAB_c" on Figure 3, is our best estimate of the source zone boundaries based on historical seismicity. It is based on enclosing regions that are spatially homogeneous in their seismicity levels, along the St. Lawrence system of faults. In this model, the local seismicity at Rabaska is not connected to the Charlevoix activity. To test the importance of the actual boundaries used to define the local zone around Rabaska, an alternative version of this basic "confined seismicity model" is drawn, in which a somewhat larger local zone for Rabaska, denoted "RAB_alt" on Figure 3, is considered (Model C). In addition, we consider a less-likely scenario that acknowledges the uncertainty in the actual areal extent of the Charlevoix activity, by defining a broader Charlevoix zone that extends to the site area, denoted "CHV_b" on Figure 3 (Model B). We also consider the extended IRM model of the GSC (Figure 1) as an alternative source model (Model D). For this project, it is not necessary to consider sources of seismicity at greater distances than those covered by these source zones, as they have insignificant impact on hazard at Rabaska. The set of alternative source models that have been defined here provide a more site-specific description of the seismic setting at Rabaska than do the two source zones used in the GSC regional model developed for the national hazard maps, and more fully cover the range of uncertainty in interpretation of hazard for the Rabaska site.

A recommended approach in the use of these alternative models is to weight the probabilities of ground-motion exceedence from the alternative models according to their likelihood of being correct, based on current knowledge. For example, the CHV_b model and the IRM model (models B and D) both have a low likelihood (say 10%) based on historical seismicity patterns. This differs from the GSC “robust” approach, which takes the worst case of a more limited set of models; for a site-specific assessment, the weighted approach is generally accepted as preferred practice.

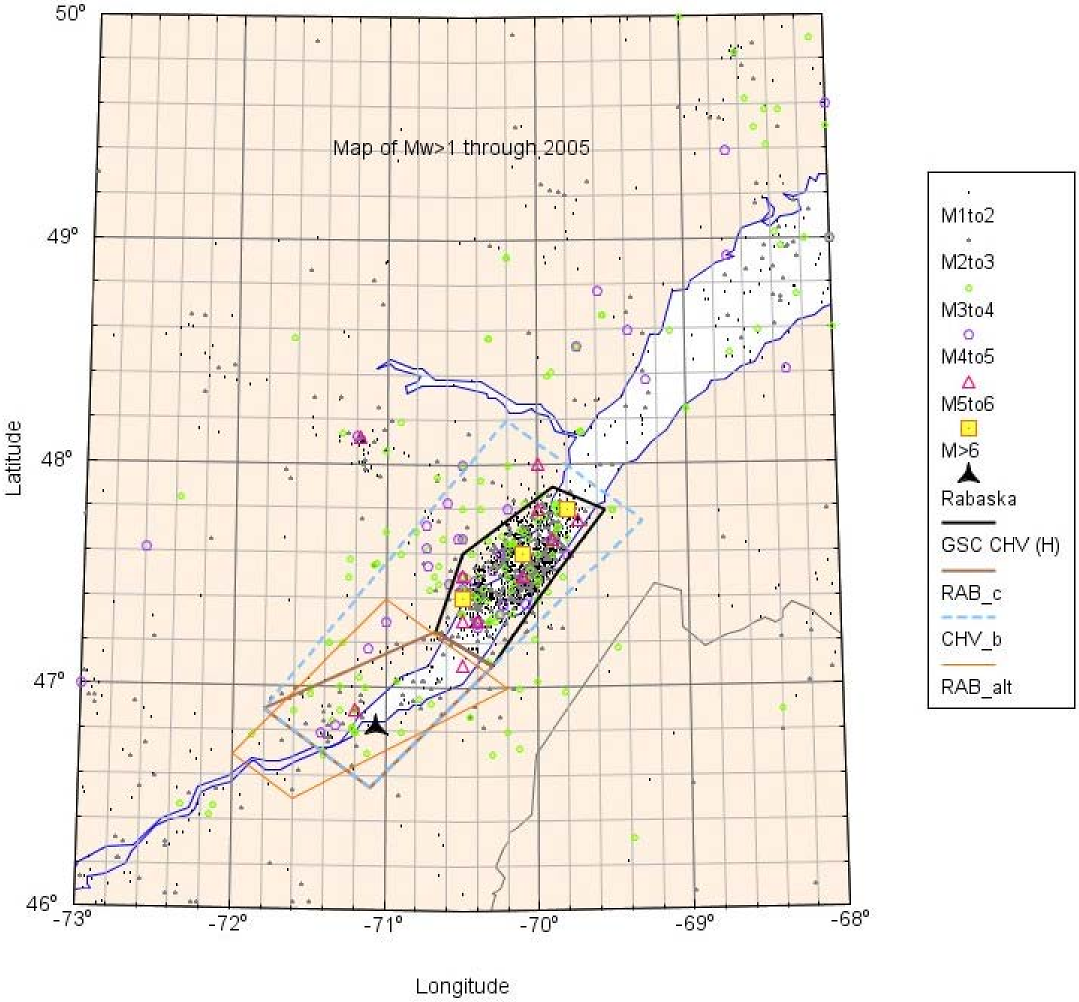

*Figure 3 – Recorded seismicity (**M**>1) through 2005 along with the alternative source zone models defined to represent uncertainty in seismic source zonation. Three combinations are considered: (Model A) (CHV-H + RAB_c); (Model B)) (CHV_b); (Model C)) (CHV-H + RAB_alt).*

### *2.2.2 Ground-Motion Relations*

Uncertainties in the ground motion relations are often the most important uncertainty in a seismic hazard analysis. They are assessed by considering three alternative sets of ground-motion relations. The first is the Atkinson and Boore (1995) relations used in the 2005 national seismic hazard maps. These relations were based on a stochastic point-source model of ground motion, with the parameters calibrated using regional seismographic data. More recent relations are also included. The Hybrid-Empirical relation of Campbell (2003) is used to consider the implications of this ground-motion model, which is based on making suitable modifications to strong-motion relations from other data-rich regions such as California. An updated relation by Atkinson and Boore (2005) is also included; this relation uses a stochastic finite-fault model of ground motions, incorporating new data on attenuation and source parameters that has been gathered in the last 10 years. Figure 4 shows these alternative relations. All relations shown are defined for the horizontal component for hard-rock site conditions (near-surface shear-wave velocity ≥ 2000 m/s), which is the standard reference condition for ground-motion relations in eastern North America (ENA). However, it is known that the average near-surface velocity at Rabaska is about 800 m/s (Terratech, 2006); this corresponds to the boundary between NEHRP B and NEHRP C conditions. Therefore, following the hazard computations for hard rock, all results will be converted to B/C boundary conditions, using a procedure discussed Section 3.2. In the hazard calculations, all relations are converted to use the hypocentral distance measure for consistency with the seismic hazard software. The implications of the alternative relations are displayed to show sensitivity, and they are weighted (assuming equal weights for each) to produce mean-hazard results; this is typical practice to handle uncertainty in the ground-motion relations.

Other sources of uncertainty include those in the maximum magnitude and in the recurrence parameters. The sensitivity to these parameters is less important, as will be shown later in the report.

In summary, the analysis in this report fully incorporates *random variability* in earthquake locations and ground motions. *Model uncertainty* is incorporated by examining the sensitivity of results in order to define the key uncertainties: these are the uncertainty in seismotectonic model for the site source region and the uncertainty in ground-motion relations. For these key parameters, several alternative models are defined and the implications for the UHS at specified probability levels are determined.

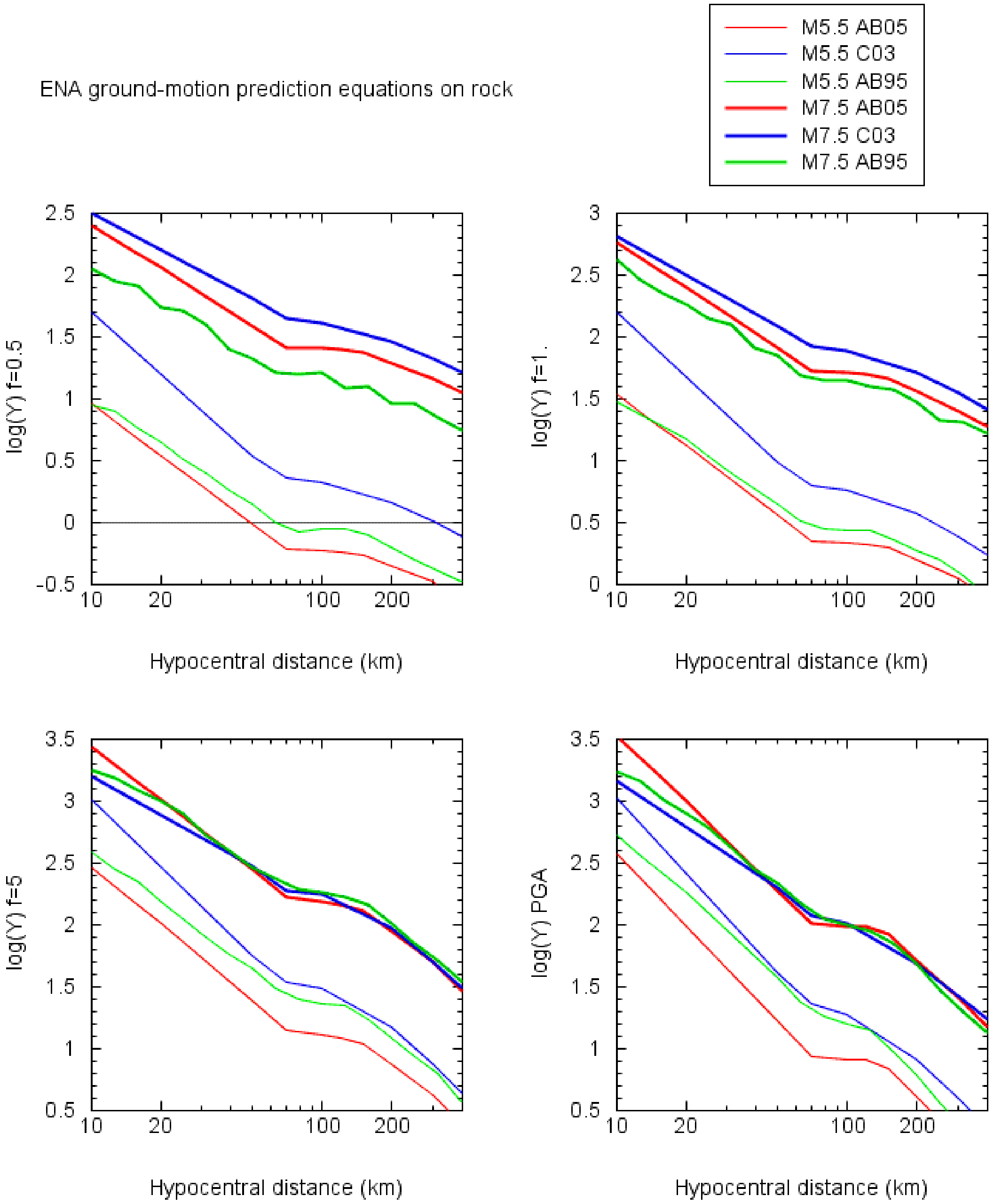

*Figure 4 – Comparison of alternative ground-motion models used in seismic hazard analysis for PSA at f=0.5, 1, 5 Hz, and PGA (AB95=Atkinson and Boore, 1995; C03=Campbell, 2003; AB05=Atkinson and Boore, 2005). All relations converted to hypocentral distance. All for NEHRP A.*

## 2.3 Input Parameters for Seismic Hazard Analysis

The input parameters for the seismic hazard analysis include the seismic source zonation, the magnitude recurrence parameters and maximum earthquake magnitude for each source zone, and the ground motion relations for response spectra at several vibration frequencies and PGA.

### *2.3.1 Seismic source models*

Figure 3 shows the alternative seismic source models, based on clusters of historical seismicity and their uncertainty, along with the regional seismicity data as obtained from the Geological Survey of Canada through 2005 (www.seismo.nrcan.gc.ca). Three combinations are defined in this study: (Model A- confined seismicity) = GSC_H + RAB_c; (Model B – broad seismicity) = CHV_b; and (Model C- alternative confined model) = GSC_H + RAB_alt. We also consider a fourth model (Model D), based on the IRM zone defined by the GSC (Figure 1). The first of these models is preferred based on the historical seismicity and location of rift faults along the St. Lawrence.

The magnitude scale currently used in the GSC catalogue is the Nuttli magnitude scale (MN). The moment magnitude scale, **M**, was used in this study, because the ground motion relations are given in terms of moment magnitude. (Note: moment magnitude is similar to the more familiar "Richter magnitude" that is often used to describe the size of events in California.) For events with no moment magnitude determination, a conversion was made from Nuttli magnitude using the relation of Atkinson and Boore (1995) for ENA, or from local magnitude (for older events for which no MN is available) via an empirical relationship derived from data for southeastern Canada. These relations are:

$$\mathbf{M} = -0.39 + 0.98\ \mathrm{MN}$$
$$\mathbf{M} = 0.800 + 0.838\ \mathrm{ML}$$

For small to moderate events, the moment magnitude tends to be about 0.5 units less than the Nuttli magnitude for the same event. For example, events with MN of 3.5 have a moment magnitude of 3.0. The 2005 Riviere du Loup, Quebec earthquake had an MN of 5.4, and a moment magnitude of **M**5.0. The events of Figures 1 and 3 are plotted in terms of their moment magnitudes. All known events of **M**>1 are plotted, although the catalogue is not complete for the smaller events.

### *2.3.2 Magnitude Recurrence Relations*

Recurrence data, expressing the relative frequency of occurrence of earthquakes within a zone as a function of magnitude, can generally be fit to the Gutenberg-Richter relation:

$$\mathrm{Log}\ N(M) = a - b\,\mathbf{M}$$

where N(M) is the number of events per annum of magnitude ≥**M**, **M** is moment magnitude, and *a* and *b* are the rate and slope of the relation. In most parts of the world, *b* values are in the range from 0.8 to 1., while *a* values vary widely depending on the activity level of the region.

The magnitude recurrence relations obtained for the source zones of Figure 3 are shown in Figures 5 through 7 (Models A to C, respectively). The recurrence relation for the IRM model of the GSC (Model D, Figure 1) is also shown on Figure 6. In developing these relations, uneven completeness of the catalogue was accounted for. This was accomplished by estimating the annual rate for events of different magnitudes separately, using, for each magnitude, seismicity data for the time period for which reporting of those data is complete. These completeness intervals are as follows:

| Region | Year to begin statistics for: | | | | | |
|---|---|---|---|---|---|---|
| | **M**2 | **M**3 | **M**4 | **M**5 | **M**6 | **M**7 |
| St.Lawrence | 1982 | 1920 | 1860 | 1810 | 1810 | 1810 |

Thus the annual rate of **M**3 events is based on just the last few decades, while the annual rate of **M**5 events considers all events from the early 1800's.

The minimum magnitude for the hazard calculations is **M**5.0, as smaller events do not cause damage to well-engineered structures. The maximum magnitude (Mx) is generally assumed to be in the range from **M** 7.0 to 7.5, based on global studies of maximum magnitudes for similar tectonic regions (Johnston, 1996). Johnston noted that 7.0 is the largest magnitude observed globally for unrifted stable continential interior shield regions such as those outside the St. Lawrence Valley. For rifted areas, maximum magnitudes are higher. Results are not very sensitive to this choice, as shown below. A value of Mx=7.5 is chosen for all zones, as they all include Iapetan rift faults. The largest events in eastern Canada have had **M** of about 7.2 (eg. 1929 Grand Banks earthquake); those in the St. Lawrence Valley have not exceeded **M** 7 within the period of historical record (for example, the 1925 Charlevoix earthquake had **M**=6.4; Bent, 1992).

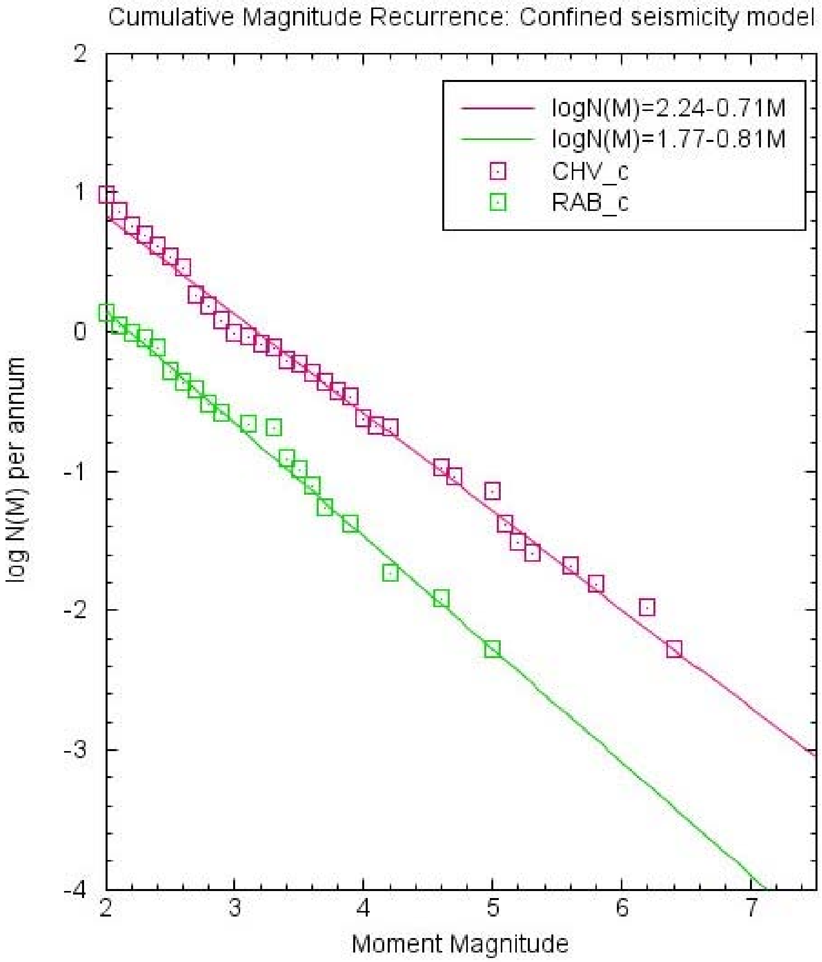

*Figure 5 – Recurrence Relations for Confined Source Zone Model A (CHV_c=Charlevoix, confined; RAB_c=Rabaska, confined).*

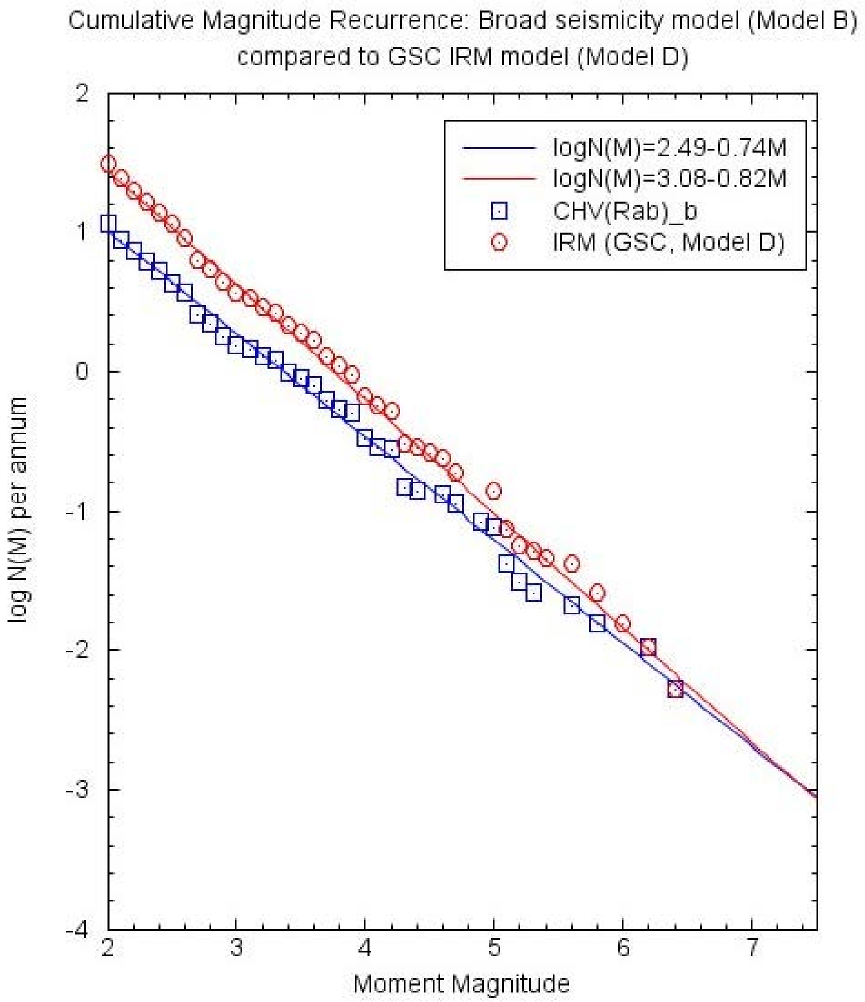

*Figure 6 – Recurrence Relations for Broad Source Zone Model B and the GSC IRM source Model D. (CHV(Rab)_b=Charlevoix, broad)*

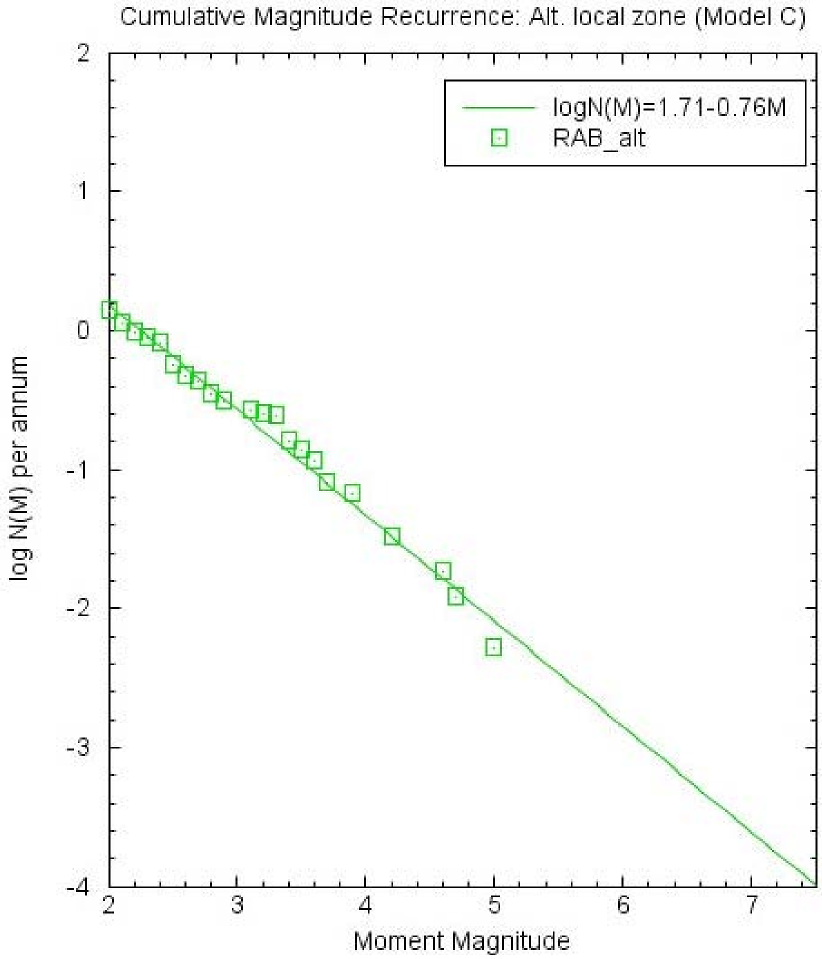

*Figure 7 – Recurrence Relation for alternative local zone RAB_alt used in Confined Model C.*

For each model, the appropriate source geometry as shown in Figure 3 (or 1) is applied, with the associated recurrence relations for each zone of the model, as shown in Figures 5 to 7; contributions to hazard are integrated from **M**=5.0 to **M**=7.5.

### *2.3.3 Ground motion relations*

Three alternative sets of ground motion relations are adopted as described in Section 2.2. These include the Atkinson and Boore (1995) relations, the Campbell (2003) Hybrid Empirical relations, and the Atkinson and Boore (2005) relations; the relations are equally weighted. All relations are for hard-rock sites in eastern North America. All have been converted to equivalent relations for hypocentral distance for consistency with their application in the seismic hazard computations (see EPRI, 2004). They provide PGA, PGV and response spectra (5% damped pseudo-acceleration) for the random horizontal component of motion, on bedrock, as a function of moment magnitude and distance from the earthquake source. These relations have been validated against the eastern ground motion database (Atkinson and Boore, 1995; 2005). The Atkinson and Boore (1995) relations are those adopted in the GSC calculations for the national seismic hazard maps (Adams and Halchuck, 2003), whereas the Campbell (2003) and Atkinson and Boore (2005) relations include more recent information. Random uncertainty in the relations was modeled by a lognormal distribution of ground motion amplitudes about these median relations, with a standard deviation of 0.25 log (base 10) units for high frequencies, increasing to 0.30 units at low frequencies. This random uncertainty is consistent with recent studies (eg. Atkinson and Boore, 1995; EPRI, 2004).

It should be noted that the ground motion relations apply to hard rock sites (eg. shear-wave velocity>2000 m/s). Shear-wave velocity studies at Rabaska suggest an average shear-wave velocity of about 800 m/s in the near-surface (Terratech, 2006). Thus the resulting motions need to be modified from NEHRP A to NEHRP B/C boundary conditions. This modification will be performed on the hard-rock results as described in Section 3.2.

# 3 - RESULTS OF SEISMIC HAZARD ANALYSIS

## 3.1 Sensitivity to Input Assumptions

Using the input parameters given in the previous section, the PGA, PGV and response spectra were computed for a range of probabilities using the Cornell-McGuire method. The values of PGA and PSA (5% damped), for the horizontal component of motion on hard rock for these probabilities are displayed in a number of plots. The UHS is for hard-rock site conditions (shear-wave velocity near surface > 2000 m/s), and will subsequently be modified for the local NEHRP B/C conditions.

The peak ground acceleration (PGA) is plotted for reference at a frequency of 100 Hz, but the shape of the curve between 40 Hz and 100 Hz is arbitrary (no spectral values were calculated for frequencies above 40 Hz). The PGA refers to the maximum acceleration of the ground shaking during the seismic event (ie. the peak amplitude on a free-field record of ground acceleration versus time) – it does not have an actual associated frequency, as the frequency at which the PGA occurs will depend on the earthquake magnitude and distance. The response spectrum shows the maximum acceleration of a damped single-degree-of-freedom oscillator, when subjected to the input record of ground acceleration versus time. Oscillators with a high natural frequency will respond to input ground motions that are rich in high frequency content, while oscillators with low natural frequency will respond more strongly to input ground motions that are rich in low frequency content.

The sensitivity of results to alternative sets of input parameters is shown in Figures 8 to 10, for a probability level of 2% in 50 years (0.0004 per annum); this is the probability level used in the 2005 national seismic hazard maps and specified for the SSE in recent LNG codes (CSA and NFPA). Figure 8 shows the Uniform Hazard Spectrum (UHS) at this probability level for the three alternative ground-motion models, using the Confined seismicity model in each case (Model A); this illustrates sensitivity to the ground-motion relations. Figure 9 shows the UHS for the alternative source zone models, using the AB95 ground-motion relations in all cases (to show sensitivity to source zone model). Figure 10 illustrates the sensitivity of the results to the parameters of the recurrence relations (slope b and rate a of the Gutenberg Richter relation, and maximum magnitude), for the Confined seismicity Model A (AB95 relations). This was evaluated by considering the implications of the following cases, which are considered reasonable given the uncertainty in actual activity rates and in the magnitude conversions used to obtain them: (i) double the calculated rate of **M**≥5 in the local source zone, using a fixed regional b-value (based on GSC IRM model) of 0.8 (Mx=7.5); (ii) use the observed rate of **M**≥5, but with a shallower slope, of b=0.7 (Mx=7.5); (iii) use the best-estimate recurrence parameters, but with Mx=7.0. The results shown on Figures 8 to 10 confirm that the most important parameters are the seismic source zone model and the ground-motion relations. Note that the uncertainty in source model, as indicated in Figure 9, effectively includes uncertainty in the recurrence relations, as the different source models imply different seismicity rates.

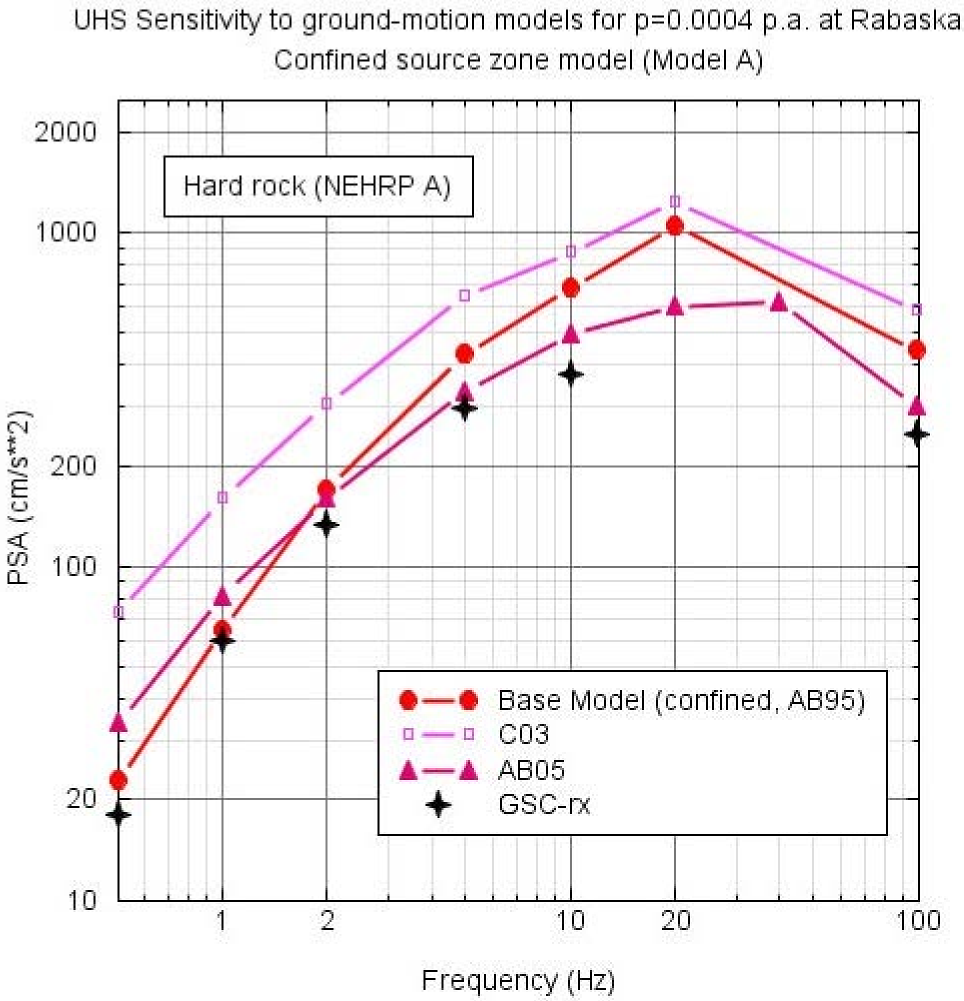

*Figure 8 – Sensitivity of UHS for 2% in 50 year probability to alternative ground-motion relations, assuming the Confined seismicity model (Base Model=Confined AB95, EPRI Hybrid Empirical, Atkinson and Boore, 2005). GSC "robust model" results are also shown. All for NEHRP A.*

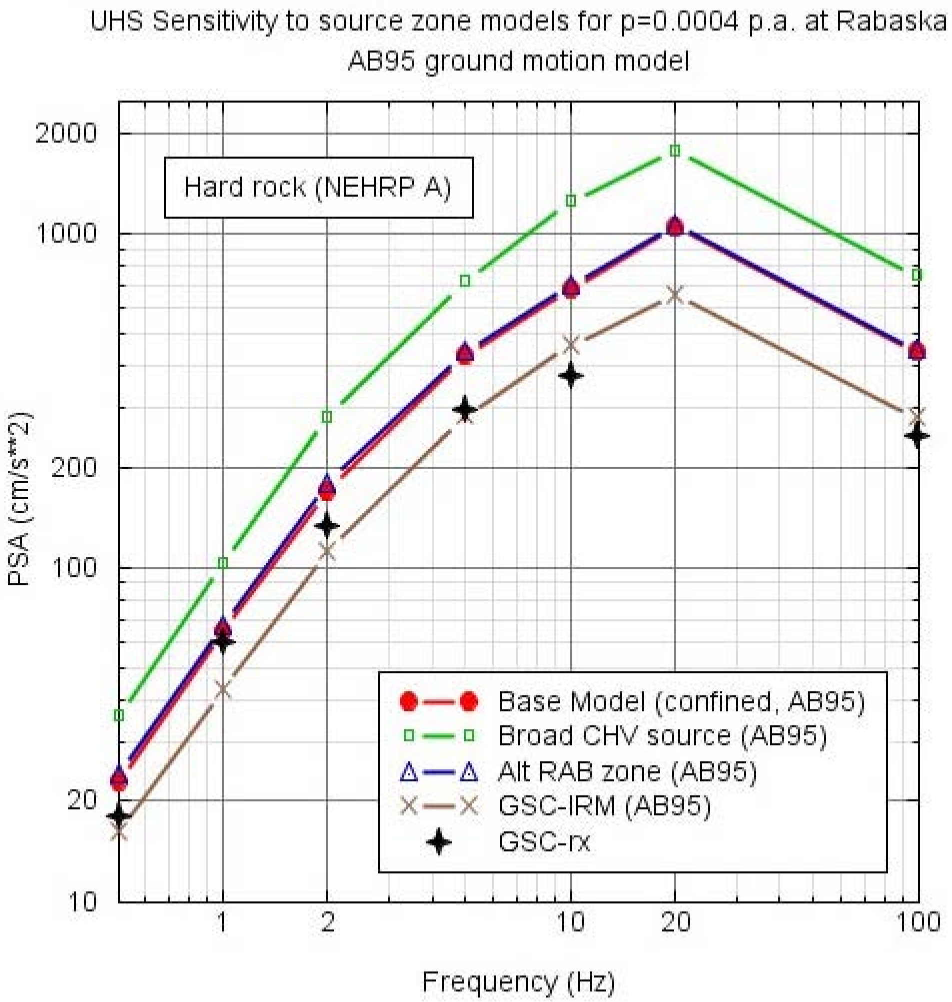

*Figure 9 – Sensitivity of UHS for 2% in 50 year probability to source model (Base Model=Confined Model A with AB95; Broad CHV=Model B; Alt RAB=Model C; GSC-IRM=Model D). GSC "robust model" results from national seismic hazard maps are also shown. All for NEHRP A.*

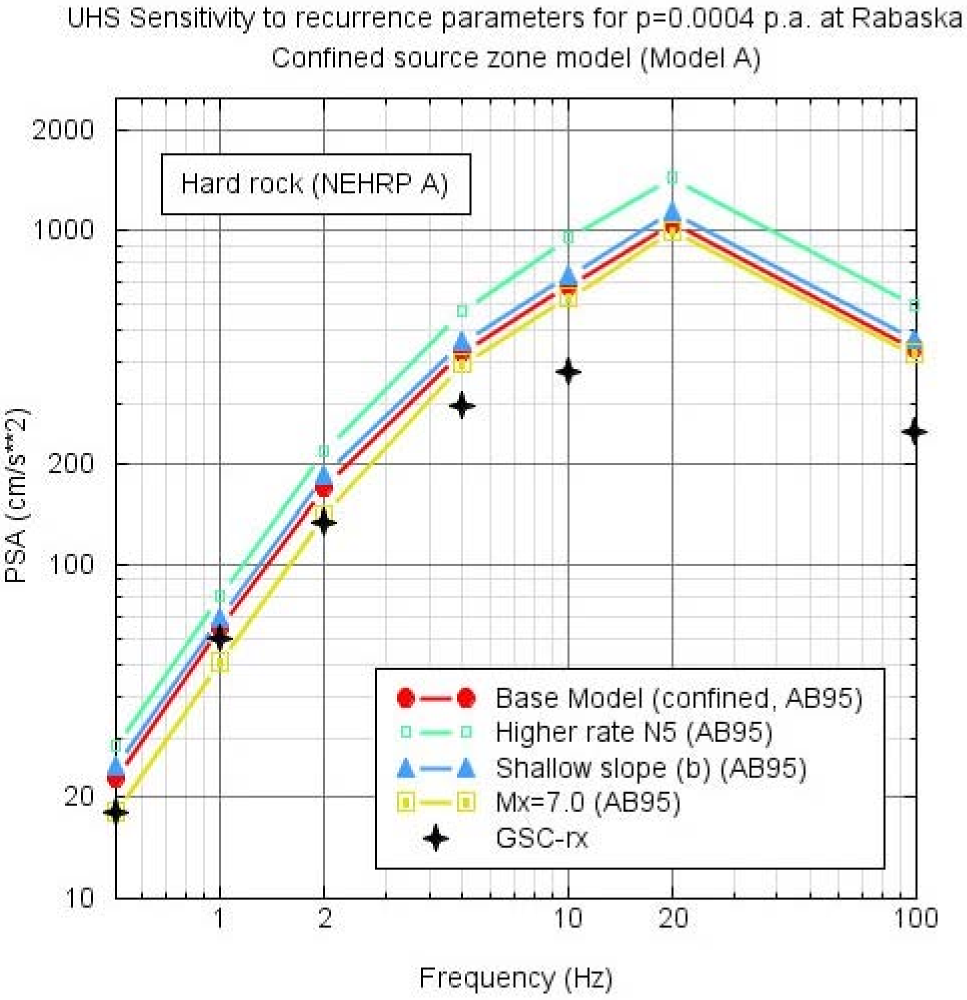

*Figure 10 – Sensitivity of UHS for 2% in 50 year probability to recurrence parameters including maximum magnitude (for Base model A) and seismicity recurrence parameters. GSC "robust model" results are also shown. All for NEHRP A.*

To provide insight on what types of events correspond to the UHS at low probabilities, Figure 11 compares the Model A UHS (for AB95 ground-motion relations) to median+σ response spectra and PGA predicted by the Atkinson and Boore (2005) ground-motion relations. The median+σ is used for the comparison as hazard contributions tend to be dominated by events with amplitudes about one standard deviation above the median. The UHS for an annual probability of 0.0004 (1/2500) is approximately matched at low frequencies by an event of **M**7 at 70 km, corresponding to a large event within the Charlevoix seismic zone. At high frequencies, the UHS is approximately matched by an event of **M**6 at 20 km, corresponding to a moderate local earthquake. This local event could occur on any of the many buried rift faults in the area, most likely at depths of 10 km or greater.

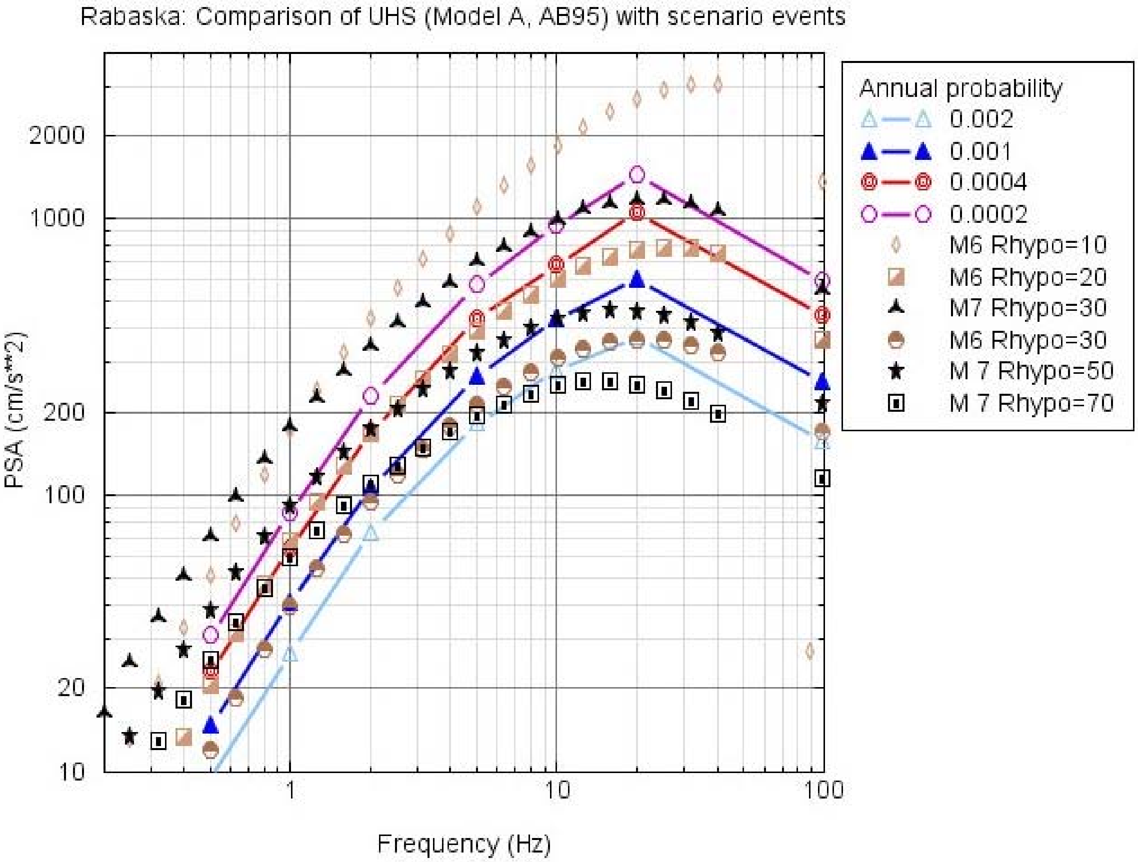

*Figure 11 – Comparison of Rabaska UHS for Model A (AB95) to median plus sigma predicted ground motions for **M**6 to 7 events according to Atkinson and Boore (2005).*

## 3.2 Conversion of Results from NEHRP A to NEHRP B/C

The seismic hazard computations were performed for hard-rock site conditions (NEHRP A, with near-surface shear-wave velocities > 1500 m/s), as most of the ENA ground-motion relations are only available for this site condition. The recent relations of Atkinson and Boore (2005) are provided as separate equations for two site conditions: hard-rock (NEHRP A) and the NEHRP B/C boundary (shear-wave velocity 760 m/s). By taking the ratio of the response spectra for NEHRP B/C to that for NEHRP A, the dependence of the site amplification on magnitude and distance may be evaluated. This is shown in Figure 12. The site amplification has a weak dependence on distance and magnitude, except for PGA, for which the distance dependence is strong. (This is a consequence of the changing frequency content of PGA with distance.)

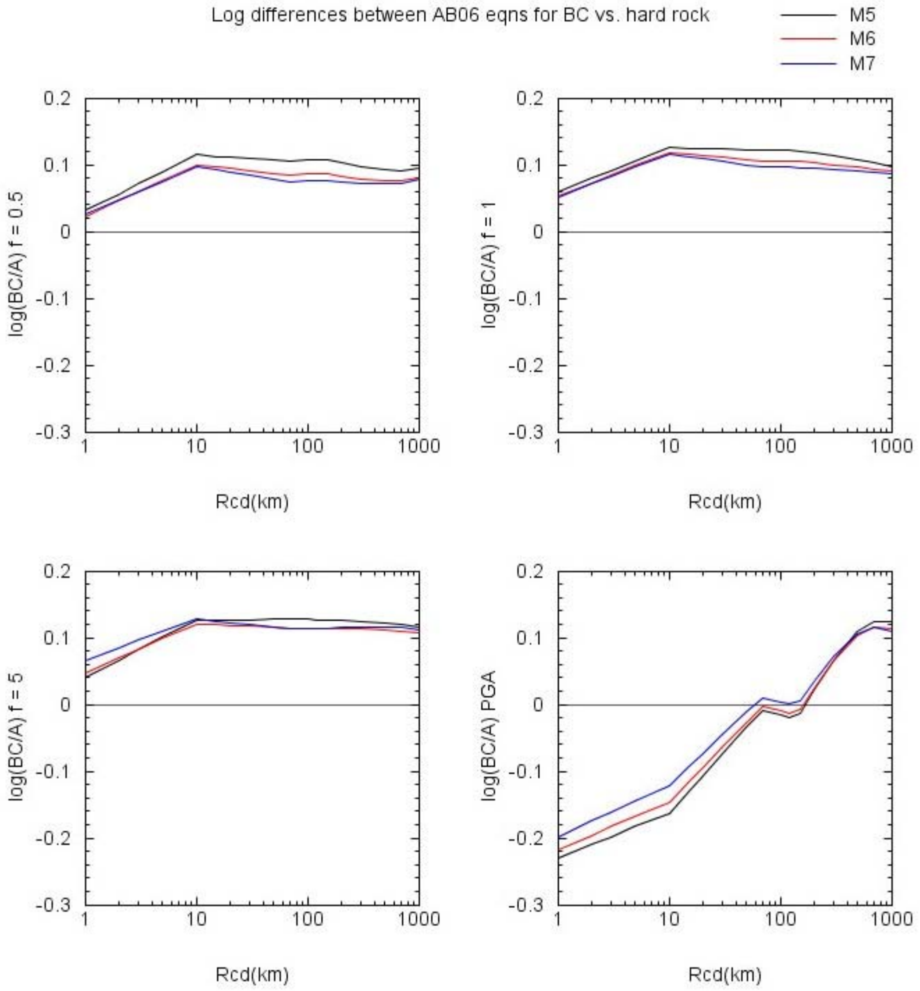

*Figure 12 – Log$_{10}$ of the ratio of predicted ground motions for NEHRP BC boundary (760 m/s) to that for NEHRP A (>1500 m/s), based on Atkinson and Boore (2005). Ratio is shown for frequencies of 0.5, 1 and 5 Hz, and for PGA, for magnitudes 5, 6 and 7, as a function of closest distance to the fault.*

To accurately model the implications of the site amplification, it is best to perform the seismic hazard analysis directly for the site conditions of interest. Since this can only be done for the AB05 relations (as the others are not available for B/C boundary), the following approach is adopted. The hazard is calculated at Rabaska, using Model A and the AB05 ground-motion relations, for both NEHRP A and B/C boundary. We then take the ratio of the calculated UHS ground motion, at several probability levels covering the complete range of interest, to determine the net effect of the site amplification at Rabaska on the UHS. As shown on Figure 13, the amplification factor depends only weakly on the probability of the ground motion. A smoothed curve that is a good representation of the amplification for all probabilities of interest is therefore adopted as the B/C amplification factor (black line on Figure 13). This function results in amplification, by as much as a factor of 1.4, over most frequencies. At very high frequencies (>10 Hz), and for PGA, there is actually a de-amplification (factor<1), due to the high-frequency energy absorption of the softer rock materials in the near surface.

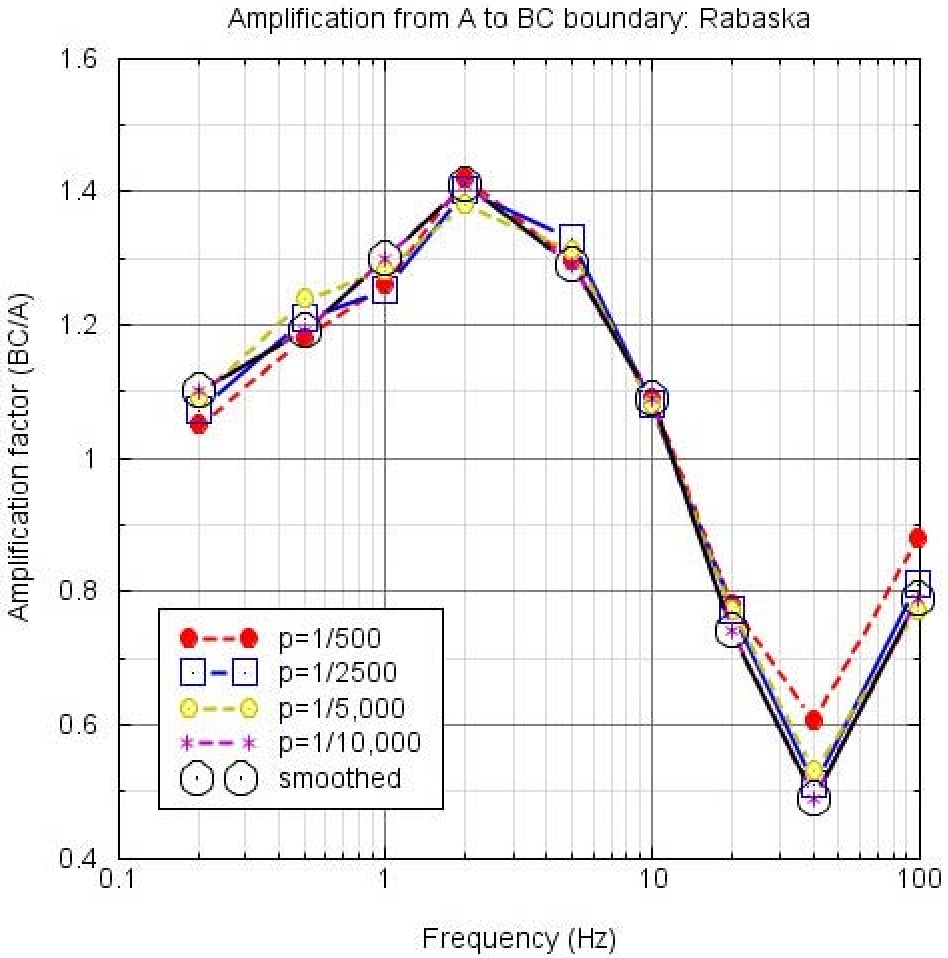

*Figure 13 – Factors to convert hazard results for hard rock (NEHRP A) to results for B/C boundary, as calculated from the ratio of results for the AB05 relations for hard rock to the results for the AB05 relations for B/C boundary (under Model A). The smoothed valued (black dots) are adopted to convert the results for all models, over a wide range of probabilities.*

To provide UHS results for the B/C boundary conditions on which the tanks will be situated, all UHS results computed for NEHRP A are multiplied by the smoothed factors shown in Figure 13, and listed in Table 1. For facilities to be located on soil, the B/C motions need to be further amplified for the overlying soils, based on a site-specific soil response analysis.

*Table 1 – Amplification Factors at Rabaska for UHS ground-motions for B/C boundary, relative to computed results for NEHRP A.*

| Frequency (Hz) | Amplification Factor (BC/A) |
|---|---|
| 0.2 | 1.1 |
| 0.5 | 1.2 |
| 1.0 | 1.3 |
| 2.0 | 1.4 |
| 5.0 | 1.35 |
| 10. | 1.1 |
| 20. | 0.8 |
| 40. | 0.6 |
| PGA | 0.9 |

Figure 14 shows the B/C boundary (soft rock) 1/2500 UHS at Rabaska for the base case estimate (Model A, AB95 ground-motion model), along with the range of estimates that is obtained by taking the minimum and maximum of the UHS values for the 4 source models, and 3 ground-motion models (eg. minimum and maximum values for the 12 cases). The high variability in the range of estimates is similar for other probability levels (eg. 1/1000, 1/5000).

A weighted-mean-hazard result is also shown on Figure 14. This is derived by weighting the probabilities of exceedence of each analyzed ground-motion amplitude across the hazard cases considered, to obtain a weighted-mean-hazard UHS. The weights considered are an interpretation of the relative likelihood of each alternative, as follows:

*Source Models:*

| | |
|---|---|
| Model A (Rabaska confined) | 0.5 |
| Model B (Broad Charlevoix) | 0.1 |
| Model C (Rabaska alternative) | 0.3 |
| Model D (GSC IRM) | 0.1 |

*Ground Motion Models:*

| | |
|---|---|
| Atkinson and Boore (1995) | 0.33 |
| Campbell (2002) | 0.33 |
| Atkinson and Boore (2005) | 0.34 |

Figure 15 shows the corresponding plot for the B/C boundary 1/500 UHS. All of the estimates have been converted to B/C boundary using the factors of Figure 13. Also shown in the GSC estimate for “firm ground” conditions (NEHRP C). Note that while the GSC estimate for Rabaska appears to be very unconservative for hard-rock conditions in relation to the results of this study (Figure 9), when we consider the results for soft rock the discrepancy between this study and the GSC estimate is reduced. This is because the GSC results included a very conservative conversion from NEHRP A to NEHRP C, which counteracts the unconservatism in their source model.

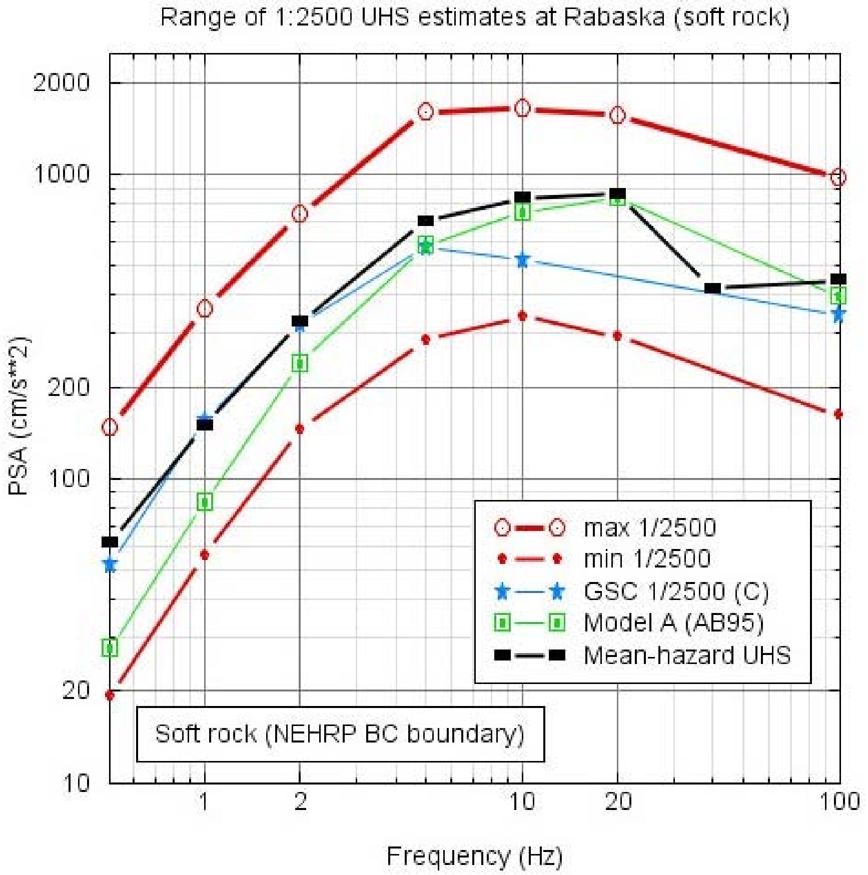

*Figure 14 – UHS at Rabaska converted to B/C boundary conditions, for 1/2500 p.a. Red lines show minimum and maximum estimates from the 3 source models, considering the 3 ground-motion models. Green line shows base-case estimate for Model A, AB95 ground-motion relations. Blue line shows GSC value for NEHRP C. Black line is weighted mean-hazard UHS.*

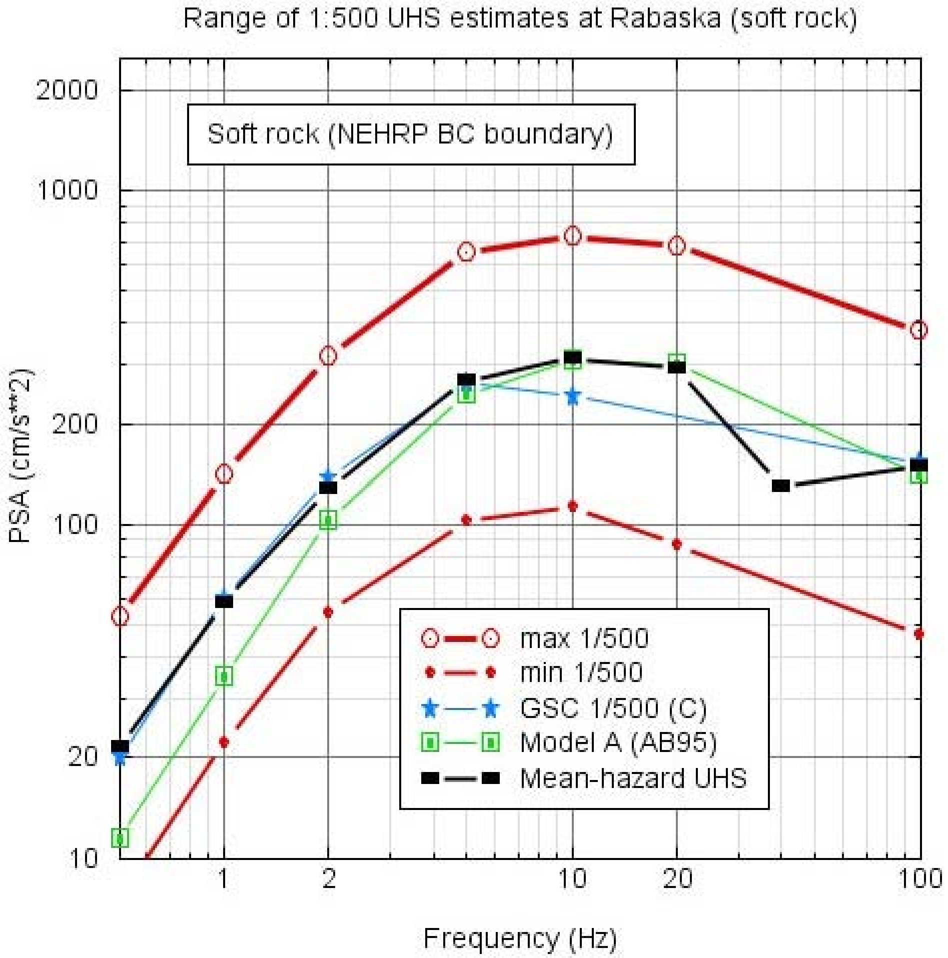

*Figure 15 – UHS at Rabaska converted to B/C boundary conditions, for 1/500 p.a. Red lines show minimum and maximum estimates from the 3 source models, considering the 3 ground-motion models. Green line shows base-case estimate for Model A, AB95 ground-motion relations. Blue line shows GSC value for NEHRP C. Black line is weighted mean-hazard UHS.*

On Figures 14 and 15 it is noted that the range of plausible estimates, considering the full range from minimum to maximum, is very large. It represents more than a factor of two about the mean estimate. As shown earlier, the primary contributors are uncertainty in the seismic source models and in the ground-motion relations. Both the upper and lower end of the range represents combinations that are relatively unlikely, due to the use of a low-likelihood source model (the broadened Charlevoix zone or the IRM model). A better estimate of the most likely motions can be obtained by weighting the various inputs to the models and obtaining weighted-mean-hazard UHS ground motions, as illustrated by the black lines in Figures 14 and 15.

The figures above are provided to illustrate the UHS for two example probability levels: 1/500 and 1/2500. Computations have been performed for a wider range of annual probabilities, including 1/500, 1/1000, 1/2500 and 1/5000. Table 2 provides weighted-mean-hazard UHS ground motions, using the weights provided above, for Rabaska for B/C boundary site conditions, for each of these probability levels.

*Table 2 – Weighted-Mean-Hazard Ground Motions for Rabaska, for 5% damped horizontal-component PSA, PGA (cm/s$^2$) and PGV (cm/s), for B/C boundary site conditions, for a range of annual probabilities*

| **Frequency(Hz)** | **1/500** | **1/1000** | **1/2500** | **1/5000** |
|---:|---:|---:|---:|---:|
| 0.1 | 0.85 | 1.5 | 2.6 | 3.9 |
| 0.2 | 3.1 | 5.5 | 9.4 | 14 |
| 0.5 | 22 | 34 | 61 | 86 |
| 1 | 59 | 88 | 149 | 215 |
| 2 | 127 | 200 | 327 | 472 |
| 5 | 270 | 422 | 702 | 986 |
| 10 | 315 | 499 | 831 | 1222 |
| 20 | 294 | 471 | 858 | 1188 |
| 40 | 130 | 227 | 421 | 665 |
| PGA | 149 | 250 | 446 | 630 |
| PGV | 4.7 | 7.3 | 11.7 | 16.9 |

## 3.3 Vertical Component Motions

The UHS were derived for the horizontal component of motion. For some analyses, the vertical component of motion is also required. The vertical UHS may be obtained by applying the factors (V/H) as listed in Table 3 to the corresponding horizontal-component UHS. These are empirically-derived factors for rock sites in eastern Canada, based on analysis of seismographic data (Siddiqqi and Atkinson, 2002). The V/H factors should be applied to the spectra for B/C boundary conditions.

*Table 3 – Vertical-to-Horizontal component spectral ratio, for ENA rock sites*

| **Frequency(Hz)** | **V/H ratio** |
|:---:|:---:|
| ≤0.5 | 1. |
| 1.0 | 0.88 |
| 2.0 | 0.82 |
| 5.0 | 0.74 |
| ≥10. | 0.71 |
| PGA | 0.71 |

## 3.4 Long-Period Motions

The expected motions for periods as long as 10 seconds (frequency 0.1 Hz) are required for some analyses for the LNG tanks (eg. sloshing is long-period behaviour).

ENA ground-motion relations do not provide predictive equations for periods longer than 5 sec. However, the simulations performed by Atkinson and Boore (2005) for their most recent ENA ground-motion relations considered periods as long as 10 seconds. On Figure 16, the ratio of predicted response spectra for 0.2 Hz (5 sec) to that for 0.1 Hz (10 sec) is plotted for large events, in the magnitude-distance range that dominates the hazard for long-period motions. The ratio is approximately independent of distance, and has only a weak dependence on magnitude in the relevant magnitude range (6.5 to 7.5). The mean $\log_{10}$ ratio is 0.65±0.11 for **M**6.5, decreasing to 0.50±0.19 for **M**7.5. For this study, we take the mean ratio calculated for **M**7 to 7.5 (at ≤100 km), which is 0.56±0.18 in log units, as being the best estimate. Estimated long-period motions can thus be obtained from computed UHS motions at 0.2 Hz by multiplying the 0.2 Hz PSA by the factor 0.275 ($=1/10^{0.56}$). This ratio was used to compute the 0.1 Hz motions provided in Table 2, based on the results for 0.2 Hz.

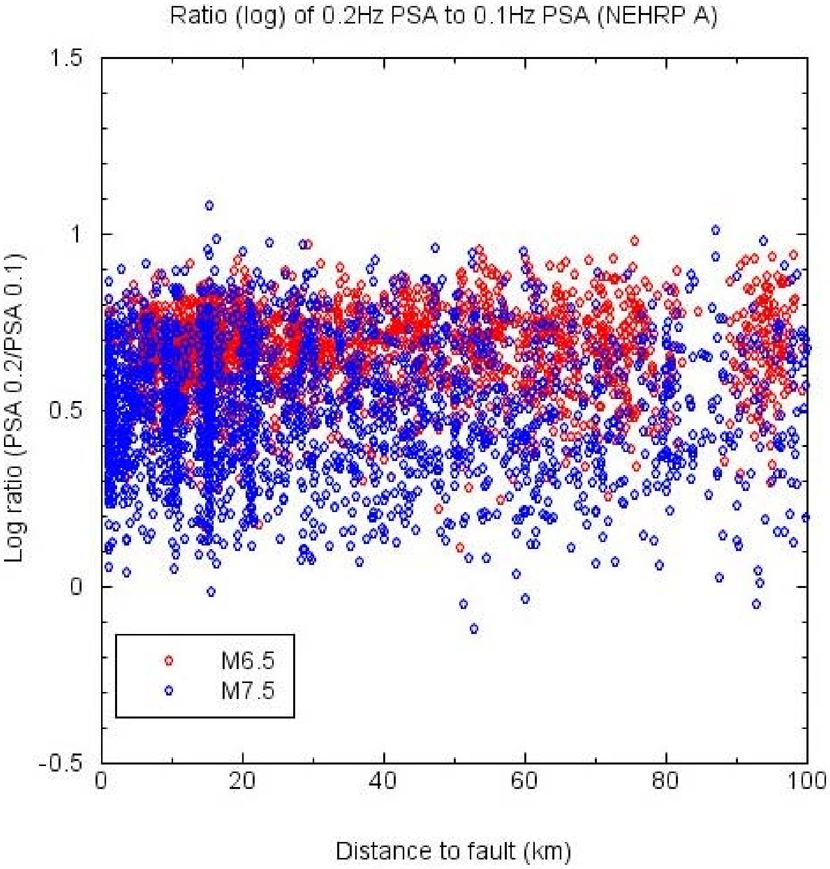

*Figure 16 – Log ratio of PSA for 0.2Hz to PSA for 0.1 Hz, for **M**6.5 to 7.5, based on Atkinson and Boore (2005) simulations for hard rock.*

## 3.5 Results for other damping levels

The UHS results presented in the preceding have been for a damping level of 5% of critical. The corresponding results for other levels of damping may also be required. These may be obtained by multiplying the ground-motion values for 5% damping by the following factors (Table 4); these factors were obtained for rock sites in eastern Canada by Atkinson and Pierre (2004), for frequencies in the range from 0.5 to 20 Hz. For frequencies <0.5 Hz, the 0.5 Hz values are adopted, while for frequencies >20 Hz, the 20 Hz values are adopted.

*Table 4 – Multiplicative factors to convert UHS results for 5% damping to other damping levels (Atkinson and Pierre, 2004).*

| **Frequency(Hz)** | **0.5%** | **1%** | **2%** | **3%** | **7%** | **10%** | **15%** |
|---:|---:|---:|---:|---:|---:|---:|---:|
| ≤0.5 | 1.350 | 1.266 | 1.174 | 1.103 | 0.922 | 0.835 | 0.736 |
| 0.8 | 1.450 | 1.361 | 1.231 | 1.134 | 0.908 | 0.810 | 0.701 |
| 1 | 1.550 | 1.414 | 1.260 | 1.148 | 0.901 | 0.793 | 0.679 |
| 1.3 | 1.675 | 1.469 | 1.289 | 1.163 | 0.894 | 0.777 | 0.657 |
| 2 | 1.800 | 1.576 | 1.332 | 1.187 | 0.880 | 0.758 | 0.627 |
| 3.2 | 1.950 | 1.685 | 1.385 | 1.208 | 0.872 | 0.743 | 0.614 |
| 5 | 2.100 | 1.765 | 1.420 | 1.226 | 0.862 | 0.734 | 0.599 |
| 7.9 | 2.200 | 1.841 | 1.442 | 1.234 | 0.860 | 0.729 | 0.597 |
| 10 | 2.300 | 1.871 | 1.456 | 1.240 | 0.860 | 0.729 | 0.598 |
| 13 | 2.350 | 1.902 | 1.471 | 1.246 | 0.860 | 0.729 | 0.600 |
| ≥20 | 2.400 | 1.950 | 1.485 | 1.249 | 0.858 | 0.730 | 0.606 |

## 3.6 Recommendations and Conclusions

This study has provided a range of estimates for expected ground motions at Rabaska, for a range of probability levels. There is large uncertainty in the estimates due to their sensitivity to the seismic source model and the ground-motion relations. There are two approaches that can be taken to deal with this uncertainty:

1. A logic tree approach can be used to weight the alternative models and obtain a mean-hazard UHS. As there are a limited number of uncertainties that are significant, a simple logic "shrub" based on the 12 alternative cases presented here captures most of the uncertainty. An illustration of this approach is provided in Figures 14 and 15, and the results given in Table 2 reflect this approach. The uncertainties could be defined in more detail to produce a full logic tree, that could be used to provide not just a mean-hazard UHS, but to more fully describe the distribution of results in terms of fractiles: median, 84th percentile, and so on. This would lead to an

improved description of the uncertainty in the results, but would not reduce the overall amount of uncertainty, nor greatly impact the estimate of the mean-hazard UHS.

2. Further work can be undertaken to reduce the uncertainty. The most promising approach for uncertainty reduction is to use paleoseismic investigations to try to determine whether the recurrence rates of large events in the site area (Rabaska zone of Figure 3) are significantly lower than those in the Charlevoix zone (also on Figure 3). Referring to Figure 5, the historical seismicity data implies that there is an order of magnitude difference in the recurrence rates of large events in these two regions. However, due to our uncertainty in the actual areal extent of the Charlevoix seismicity, we have effectively assigned a high uncertainty to this inference. If paleoseismic investigations of post-glacial (last 10,000 years) soils can establish that they have been repeatedly disturbed in the Charlevoix region, but not in the Rabaska region, then we could discount the hypothesis that the Charlevoix zone may extend to the Rabaska area. This would greatly reduce the uncertainty in seismic source modeling.

In an effort to reduce the actual uncertainty in the seismic hazard estimates, by refining our knowledge of the extent of the Charlevoix region of seismicity, an experienced paleoseismologist, Dr. M. Tuttle, has been retained by Rabaska to perform a comparative paleoseismic investigation of the Charlevoix and Rabaska regions. The results of this study are not yet available, but could result in a significant reduction in the UHS motions. Until this work is completed, the actual earthquake hazard analysis is considered preliminary. It will be repeated, and the ground motion values and conclusions revised accordingly, when the paleoseismic investigation results are available.

The final UHS defined for the OBE and SSE (B/C site conditions) may be used as input for modal analyses of structures on soft rock, as the input spectrum for soil response analyses for structures founded on soil, and as the target spectrum for the development of site time histories. Time histories appropriate to ENA soft-rock conditions should be developed considering both short-period and long-period hazard sources.

Table 5 provides a summary of the weighted-mean-hazard results (horizontal component), based on this study, in comparison to the GSC results used in the NBCC national seismic hazard maps (provided for 1/500 and 1/2500 p.a. probabilities). The complete study results for all probabilities are provided in Table 2.

*Table 5 – Rabaska weighted-mean-hazard 5% damped PSA results (cm/s$^2$) for B/C boundary site conditions. NBCC UHS values (NEHRP Class C) at Rabaska are also shown.*

| **Frequency(Hz)** | **NBCC 1/500** | **This study 1/500** | **NBCC 1/2500** | **This study 1/2500** |
|---|---|---|---|---|
| 0.1 | | 0.85 | | 2.6 |
| 0.2 | | 3.1 | | 9.4 |
| 0.5 | 20 | 22 | 51 | 61 |
| 1. | 59 | 59 | 151 | 149 |
| 2 | 133 | 127 | 314 | 327 |
| 5 | 261 | 270 | 565 | 702 |
| 10 | 236 | 315 | 512 | 831 |
| 20 | | 294 | | 858 |
| PGA | 149 | 149 | 337 | 446 |
| PGV | | 4.7 | 15 | 12 |

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