EARTHQUAKE HAZARD ANALYSIS:

GROS-CACOUNA, QUEBEC

FOR SANDWELL ENGINEERING INC.

Final Report

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For:
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SEISMIC HAZARD ANALYSIS:
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Executive Summary

A site-specific seismic hazard assessment was performed for the proposed LNG terminal site at Gros-Cacouna, Quebec. The analysis determines the expected earthquake ground motions over a range of probability levels including:

(i) 1/475 per annum (p.a.), corresponding to the "Operating Basis Earthquake" (OBE) level in LNG facility codes such as CSA Z276 (Canadian, 2007 edition) and NFPA59A (U.S., 2005 edition).

(ii) 1/2475 p.a., corresponding to the "Safe Shutdown Earthquake" (SSE) level in CSA Z276 (2007) and NFPA59A (2005).

Ground motions at even lower probability levels are also derived.

The results are summarized in simplified terms in the following table. For comparison, the acceleration at Gros-Cacouna from the national seismic hazard maps produced by the Geological Survey of Canada (2003), for the 1/2475 p.a. probability, is also shown. The ground motions as the SSE probability level (1/2475) correspond approximately to a magnitude 7 earthquake occurring in the nearby Charlevoix seismic zone, at a distance of about 30 km from the site.

Probability (p.a.)	Peak Ground Acceleration (cm/s^2)	Approximate design magnitude	Approximate design distance (km)
1/475	231	6	25
1/2475	545	7	30
1/5000	735	7	25
1/2475 GSC study	441		

1 - INTRODUCTION

This report presents a seismic hazard assessment for the site of the proposed LNG terminal facilities at Gros-Cacouna, Quebec (47.93N, 69.52W) for annual exceedence probabilities in the range from 1/475 to 1/10,000. 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 1/475 and a Safe Shutdown Earthquake (SSE) with an annual probability of 1/2475; these probability levels (1/475 and 1/2475) match those in the U.S. Standard NFPA59A (2005 edition). 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 Gros-Cacouna site, and incorporate new information on seismicity and ground motion relations from the last 10 years of data.

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. The frequency associated with the PGA varies, but in general the PGA is associated with high-frequency motions (near 10 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 are presented in Section 4. These time histories are modified real earthquake records that are appropriate for eastern Canadian rock sites, for magnitude-distance ranges that dominate the hazard at Gros-Cacouna. 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. The records are provided in electronic format.

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 Gros-Cacouna (Journeaux Bedard and Associates, 2005) are consistent with this view. The site geology consists of massive well-cemented Cambrian sandstones formed approximately 500 million years ago as part of the Appalachian province; there is no evidence of recent faulting identified in the exposed rock slopes at the site area or in boreholes. Specifically, the geotechnical reports indicate that the boreholes reveal tight fractures without evidence to suggest that they originate from fault movements; rather the movement appears to be a result of regional folding of the rock over geological time scales, as supported by the lack of any large seams filled with fault gauge in the cores (Journeaux Bedard and Associates, 2005). 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 depth of up to 30 km (Lamontagne et al., 2000).

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).

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 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 rifted regions. This results in enhanced ground motion estimates in parts of the zone that have not experienced large earthquakes within the period of historical record, and reduced ground motion estimates in areas that have had such events.

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 the populated regions of the St. Lawrence Valley and is appropriate for the purposes of the national hazard maps. However, it is warranted to examine carefully alternative models for Gros-Cacouna, in order to accurately assess and understand the seismic hazard setting and its implications. As shown in Figure 1, the Gros-Cacouna site lies about 20 km northeast 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 Gros-Cacouna.

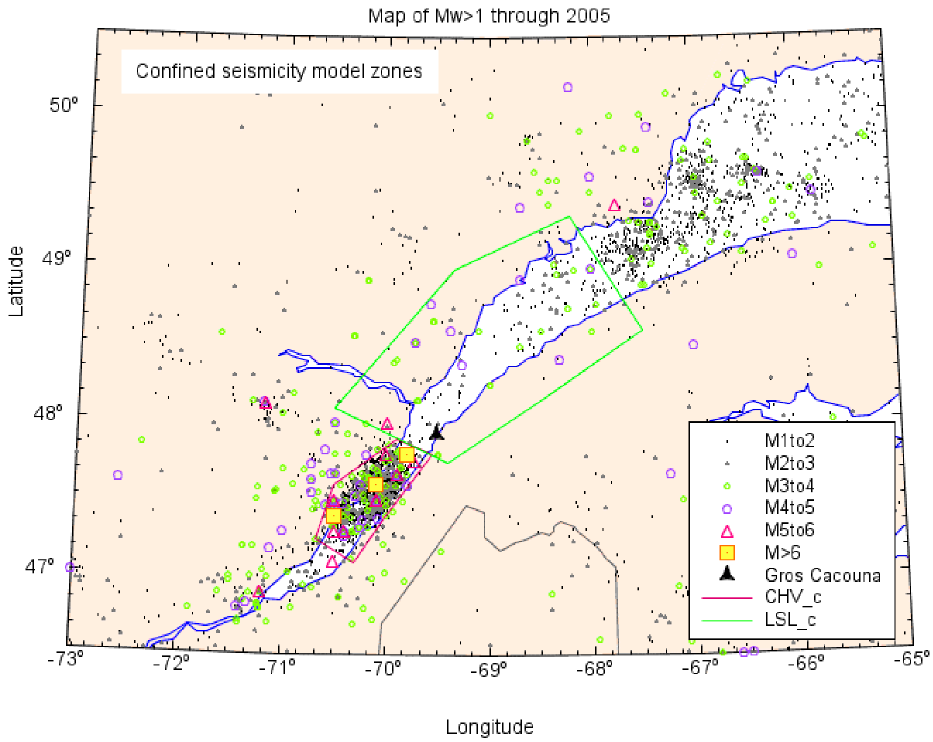

*Figure 1 – Recorded seismicity (**M**>1)through 2005 along with the preferred seismic source zone model (Confined source model)*

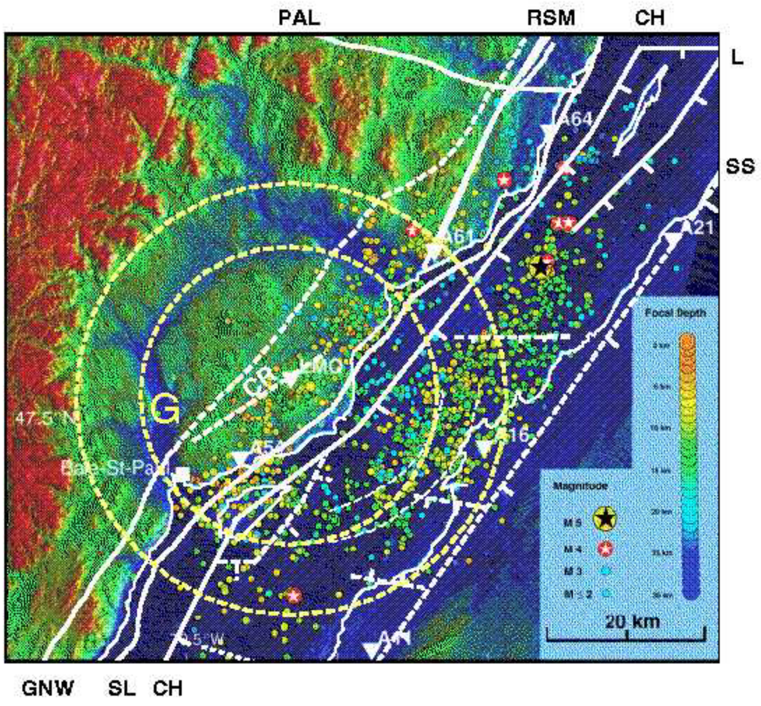

Figure 2 – Structural model of Charlevoix seismic zone, including faults, seismicity, seismograph stations, and Charlevoix impact crater. PAL=Palissades fault; RSM= Rang St.-Mathilde fault; SL=St.-Laurent fault; CH=Charlevoix fault; L+lievres fault; SS=South shore fault; G=peripheral graben of the impact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

The Confined seismicity model of Figure 1 is our best estimate of the source zone boundaries based on historical seismicity. However, to acknowledge the uncertainty in the actual areal extent of the source zones, an alternative model is defined with a broader Charlevoix zone that extends to the site area, as shown in Figure 3. This model also uses a broader definition of the seismicity in the Lower St. Lawrence region to the northeast of the site. Relative weights of 0.9 (confined model) and 0.1 (broad model) are assigned to indicate the relative likelihood of these models. This differs from the GSC "robust" approach that takes a worst case of models; for a site-specific assessment, the weighted approach is generally accepted as preferred practice. Both models include a background rate of seismicity that is applied to those areas outside the defined source zones, to represent the surrounding low-level seismicity; this seismicity does not have a significant effect on the site hazard.

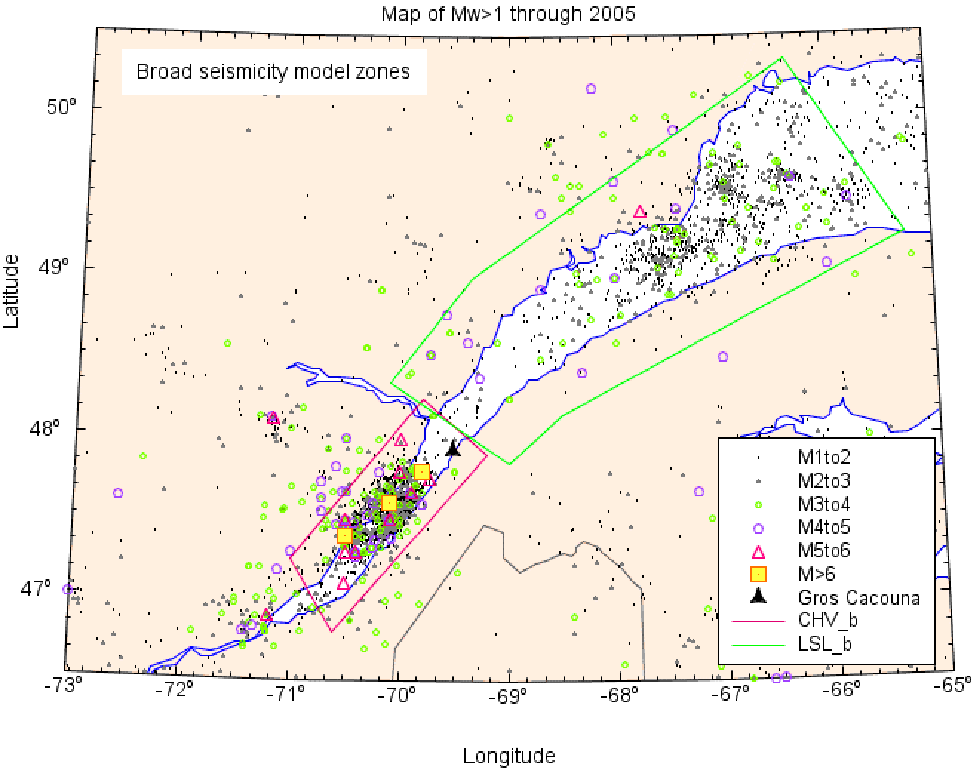

*Figure 3 – Recorded seismicity (**M**>1) through 2005 along with the alternative source zone model (Broad source zones) defined to represent uncertainty in the extent of the active Charlevoix seismic source zone.*

Uncertainties in the ground motion relations are also important. 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 are defined for hard-rock site conditions (near-surface shear-wave velocity ≥ 2000 m/s). In the hazard calculations, all relations are converted to use the hypocentral distance measure for consistency with the seismic hazard software. The alternative relations are equally weighted (0.333 each) in the hazard calculations, to reflect a lack of strong preference for any one of the models; this is typical practice to handle uncertainty in the ground-motion relations. Other sources of uncertainty, such as those in the maximum magnitude, are less important to the results and are only treated in initial sensitivity studies, as described below.

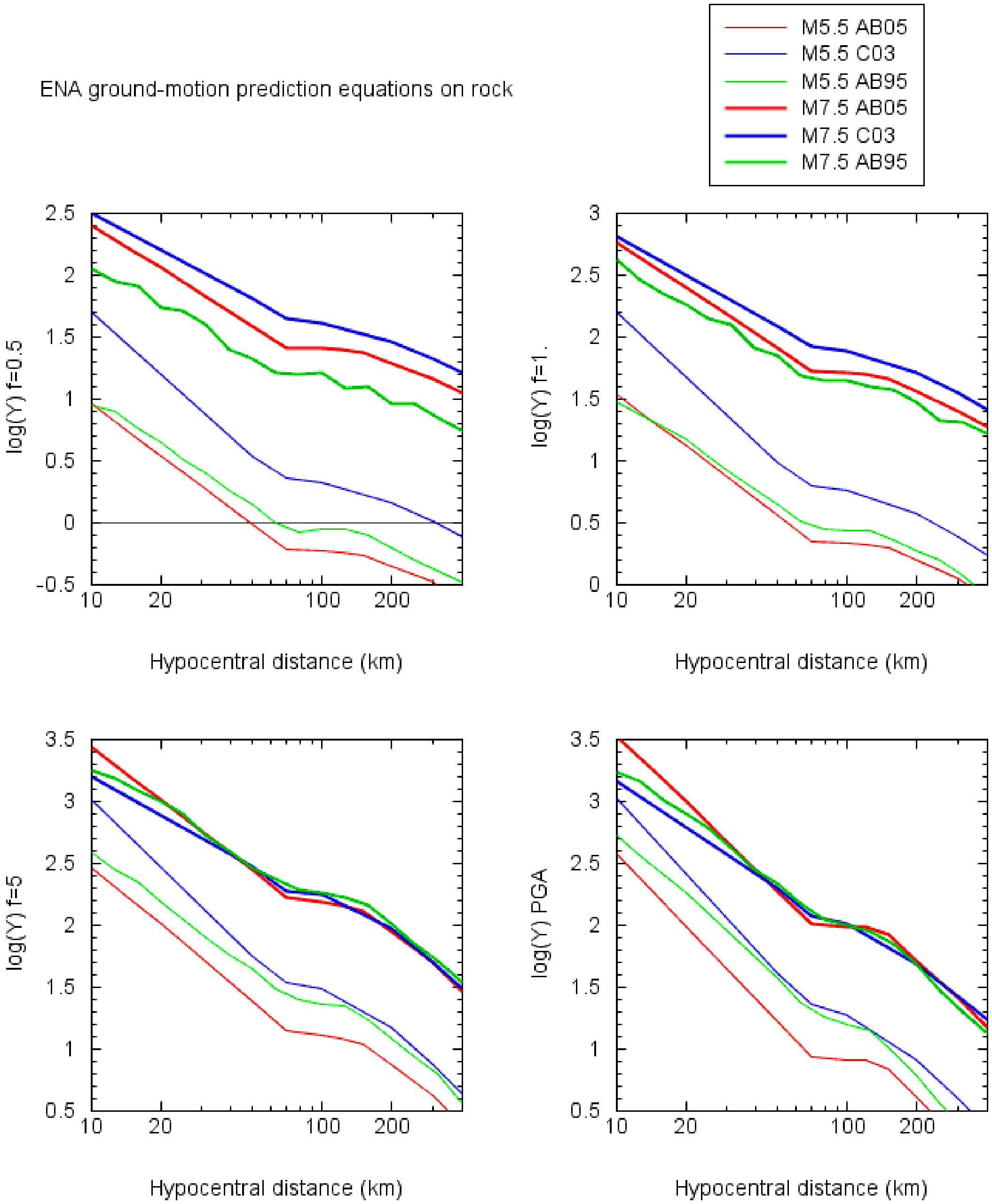

Figure 4 – Comparison of alternative ground-motion models used in seismic hazard analysis for PSA at f=0.5, 1, 5 Hz, and PGA (AB95=Atkinson and Boore, 1995; C03=Campbell, 2003; AB05=Atkinson and Boore, 2005). All relations converted to hypocentral distance.

In summary, the analysis in this report fully incorporates *random variability* in earthquake locations and ground motions. *Model uncertainty* is incorporated by first examining the sensitivity of results in order to define the key uncertainties: these are the uncertainty in seismotectonic model for the site source region (extent of Charlevoix zone), and the uncertainty in ground-motion relations. For these key parameters, several alternative models are defined and the probabilistic hazard results are weighted to define the UHS at specified probability levels. (Note: this involves taking a weighted average of the probability of exceedence calculated for a series of ground-motion amplitudes, then interpolating to find the expected ground-motion for a specified probability.) This provides a mean hazard result; the GSC hazard maps, by comparison, provide a median result, which is slightly less conservative. For site-specific analyses, the mean-hazard UHS is generally preferred as it is the expected value, and better accommodates the influence of major uncertainties on the seismic hazard result.

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 1 shows the preferred seismic source model, based on clusters of historical seismicity, along with the regional seismicity data as obtained from the Geological Survey of Canada through 2005 (www.seismo.nrcan.gc.ca). Figure 3 shows the alternative model in which slightly broader source zones are used to accommodate uncertainty in the actual extent of the source zones. These models are weighted 0.90 and 0.10, respectively. The magnitude scale 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 via Nuttli magnitude, using an empirical relation determined from regional seismicity data. These relations are:

$$\mathbf{M} = -0.39 + 0.98\ \mathrm{MN}$$
$$\mathbf{M} = 2.6 - 0.33\ \mathrm{ML} + 0.13\ \mathrm{ML}^2$$

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:

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

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 Figures 1 and 3 are shown in Figures 5 and 6, respectively. 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:					
	M2	**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).

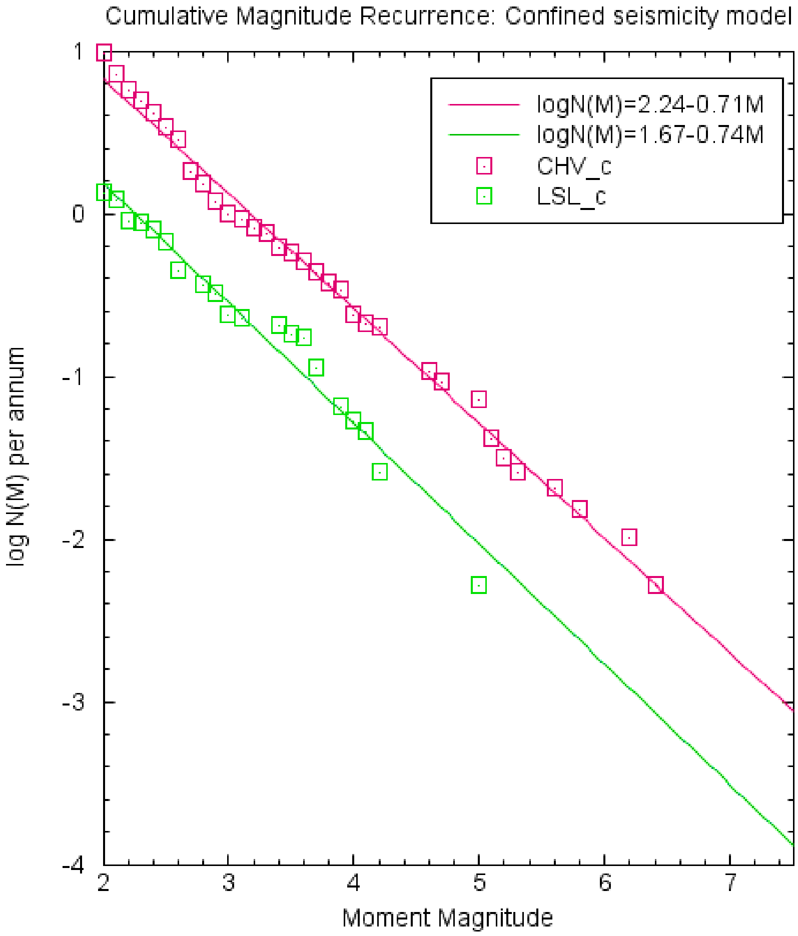

Figure 5 – Recurrence Relations for Confined Source Zone model (CHV_c=Charlevoix, confined; LSL_c=Lower St. Lawrence, confined).

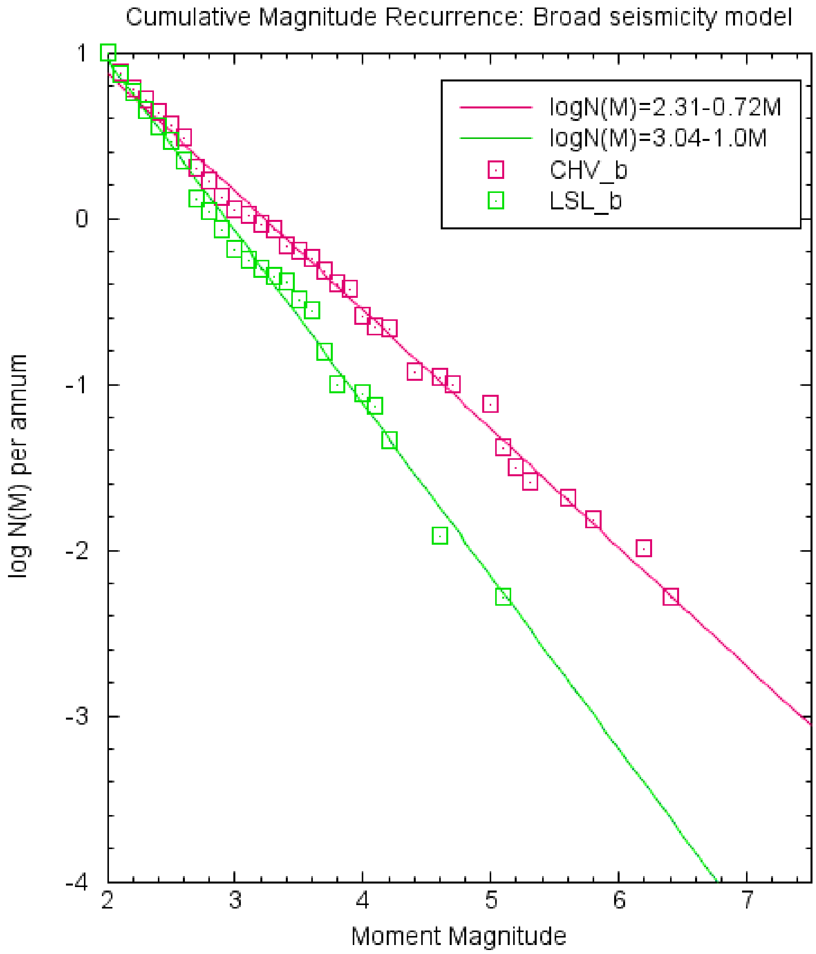

Figure 6 – Recurrence Relations for Broad Source Zone model. (CHV_b=Charlevoix, broad; LSL_b=Lower St. Lawrence, broad)

For each model, the appropriate source geometry as shown in Figure 1 or 3 is applied, with the associated recurrence relations for each zone of the model, as shown in Figures 5 and 6; 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 Gros-Cacouna suggest an average shear-wave velocity of >2400 m/s in the top 15 m (Geophysique Sigma Inc., 2006), supporting this classification. The resulting motions need to be amplified to account for soil response for any structures not founded on hard rock.

The sensitivity of results to alternative sets of input parameters is shown in Figure 7, 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. The plot shows the Uniform Hazard Spectrum (UHS) at this probability level for the two alternative source zone models, using the AB95 ground-motion relations in both cases. The UHS are shown for the 3 alternative ground-motion relations, using the Confined seismicity model in each case. Also shown are the UHS results using a lower maximum magnitude (7.0), for the Confined seismicity model (AB95 relations). The sensitivity to the parameters of the recurrence relations (slope b and rate a of the Gutenberg Richter relation) is examined by considering, for the Confined seismicity model (AB95 relations), two alternative sets of recurrence relations; a steep recurrence relation with a slope of 1.0, with double the best-estimate rate for **M**≥5 events, and a shallow recurrence relation with a slope of 0.6, with half of the best-estimate rate for **M**≥5 events. These results confirm that the most important parameters are the seismic source zone model and the ground-motion relations. Accordingly, the uncertainty in these inputs will be treated formally in the hazard analysis to determine the mean-hazard UHS, while the other uncertainties are not considered further.

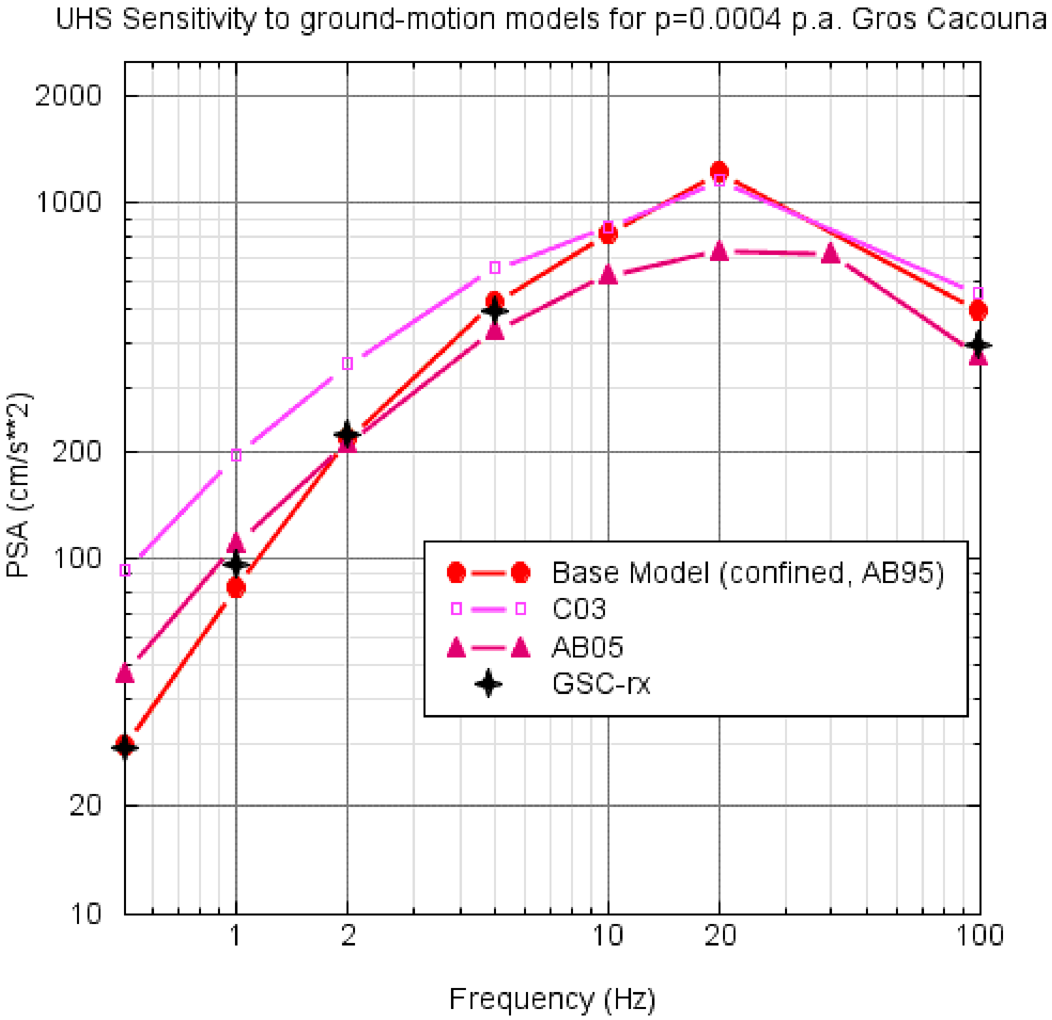

Figure 7 – Sensitivity of UHS for 2% in 50 year probability to alternative ground-motion relations, assuming the Confined seismicity model (Base Model=Confined AB95, EPRI Hybrid Empirical, Atkinson and Boore, 2005). GSC "robust model" results are also shown.

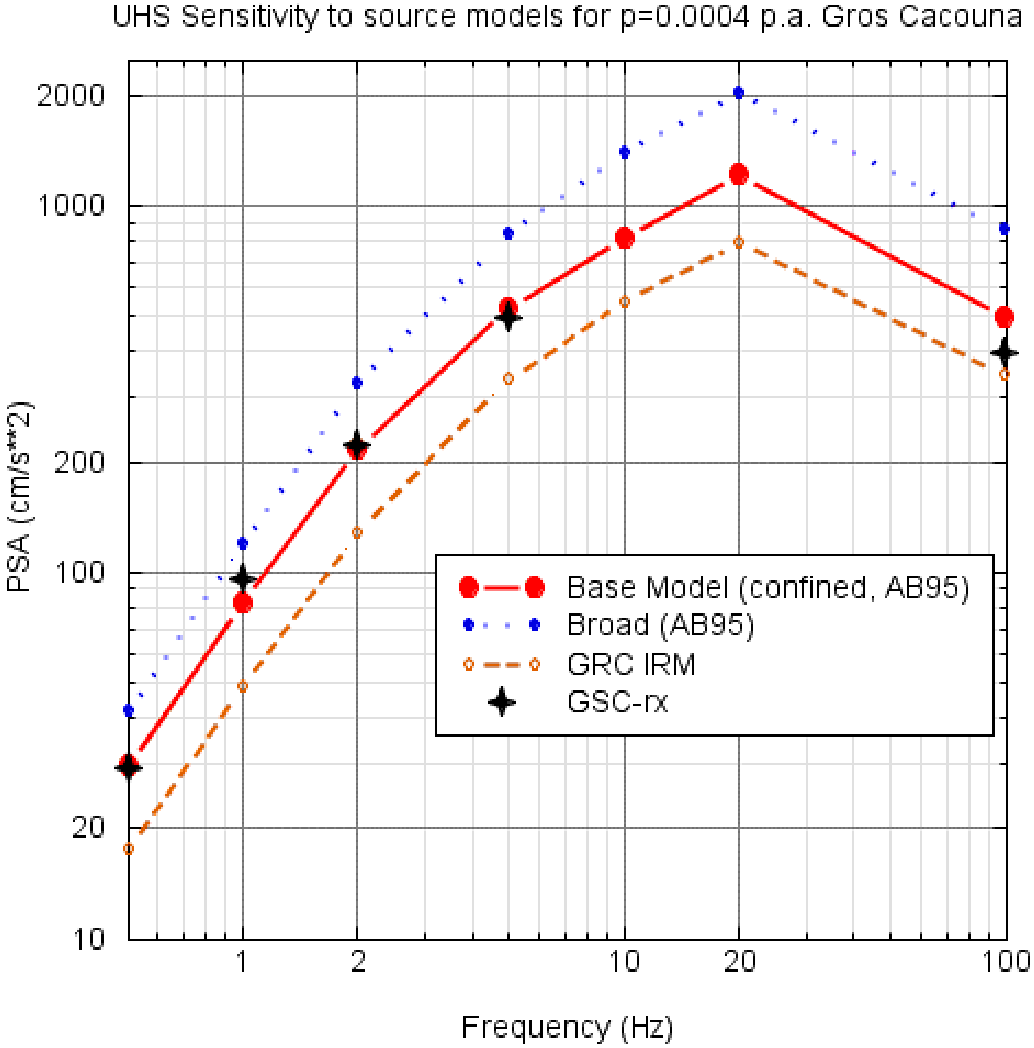

Figure 8 – Sensitivity of UHS for 2% in 50 year probability to source model (Base Model=Confined AB95, Broad model with AB95). GSC "robust model" results are also shown. Results for the GSC IRM (extended rift) model are shown for comparison only, but would underestimate actual seismicity levels at the site.

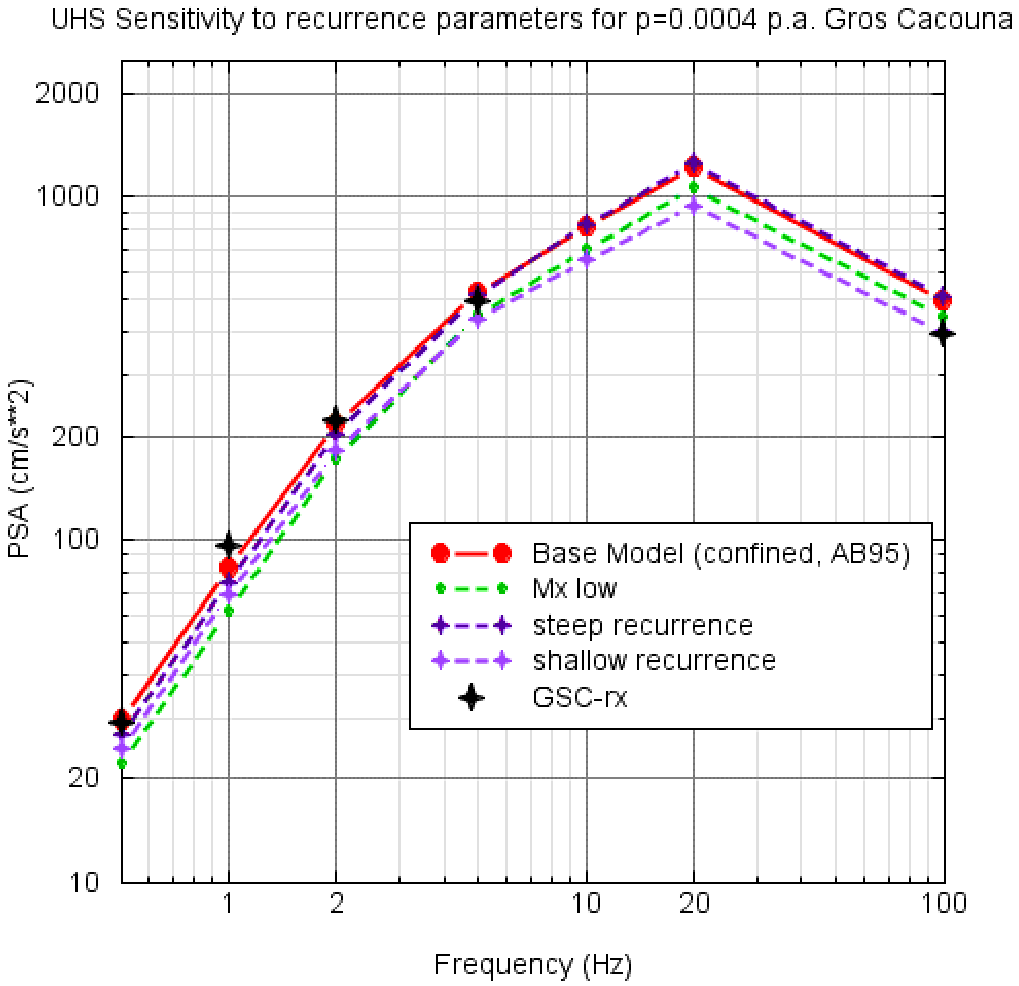

Figure 9 – Sensitivity of UHS for 2% in 50 year probability to recurrence parameters including maximum magnitude (Mx low = 7.0, for Base model) and seismicity recurrence parameters (steep, shallow, for Base Model). Base Model=Confined AB95. GSC "robust model" results are also shown.

3 - RESULTS OF SEISMIC HAZARD ANALYSIS

Using the input parameters given in the previous section, the PGA and response spectra were computed for a range of probabilities using the Cornell-McGuire method. The 'weighted' values of PGA, PGV and PSA (5% damped), for the horizontal component of motion on hard rock for these probabilities are given in Table 1 (PGA and PSA in cm/s^2, PGV in cm/s). Figure 10 shows the mean UHS for selected probabilities. The weights used in deriving the mean UHS are 0.9 and 0.1 for the Confined and Broad seismic source models, respectively, and 0.333 for each of the 3 alternative ground motion models. 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 UHS is for hard-rock site conditions (shear-wave velocity near surface > 2000 m/s), and should be amplified for site response for application to any structure not founded on bedrock.

Table 1 – Mean seismic hazard results for Gros-Cacouna. 5% damped horizontal-component PSA (cm/s^2)

Frequency	0.002 p.a.	0.001	0.0004	0.0002	0.0001
0.2	4	6	11	17	23
0.5	24	39	64	90	126
1.0	60	89	150	201	269
2.0	126	184	287	402	510
5.0	273	408	602	807	1082
10.0	405	562	867	1203	1503
20.0	512	743	1213	1562	2011
40.0	306	485	825	1228	1668
PGV	5	8	12	18	23
PGA	232	353	545	735	992

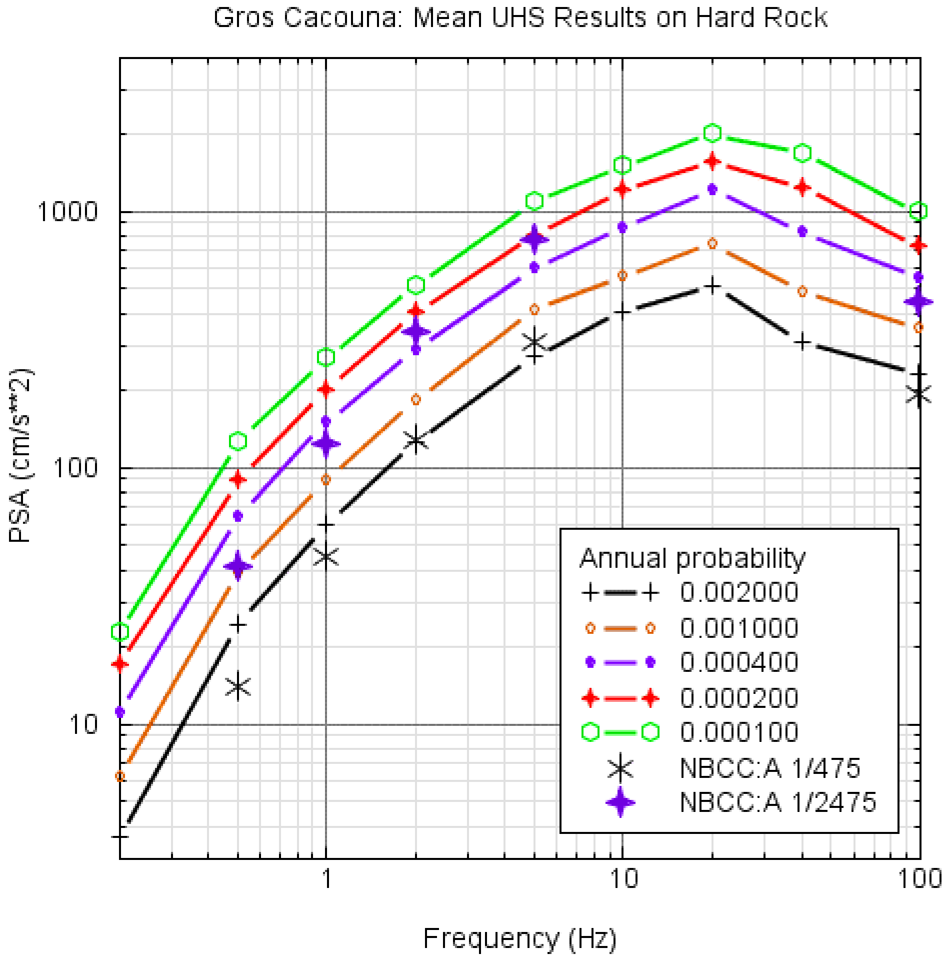

Figure 10 – Mean Uniform Hazard Spectrum (5% damped horizontal component pseudo-acceleration on hard rock) for Gros-Cacouna.

It is noted on Figure 10 that the calculated mean UHS for 1/475 and 1/2475 p.a. probability are quite close to the corresponding median values as obtained for Class A (hard rock) sites from the 2005 NBCC. This comparison is presented in Table 2. In order to make the comparison for equivalent site conditions, the NEHRP Class C values provided in the code were converted to equivalent values for Class A sites as prescribed in the NBCC. Observed differences can be attributed to several factors: (i) this study uses more recent seismicity and ground-motion relations; (ii) this study uses a mean spectrum, while GSC uses a median spectrum; and (iii) the GSC study did not include all of the key uncertainties that affect hazard at Gros-Cacouna, in particular uncertainty in the geographical extent of the active Charlevoix seismicity cluster. The inclusion of the Campbell (2003) ground-motion relations in this study acts to increase the estimates at lower frequencies relative to the NBCC values, while the PGA in this study tends to be increased by the consideration of uncertainty in the boundaries of the Charlevoix source zone.

Table 2 – Comparison of NBCC UHS values (Class A) at Gros-Cacouna to results of this study (in cm/s^2)

Frequency(Hz)	NBCC 1/475	This study 1/475	NBCC 1/2475	This study 1/2475
0.5	14	24	41	64
1.	45	60	124	150
2	127	125	340	287
5	307	273	770	601
PGA	193	231	441	545

To provide insight on what types of events correspond to the UHS at low probabilities, Figure 11 compares the weighted (mean) UHS 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 probabilities in the range of 1/2500 to 1/10, 000 are approximately matched by the motions for an event of **M**7 at a distance of about 25 to 40 km (with lower probabilities corresponding to slightly nearer distances); this corresponds to a large event occurring in the Charlevoix seismic zone. At moderate probabilities, near 1/500, the UHS is similar to that expected for events of about **M**6, at distances >20 km.

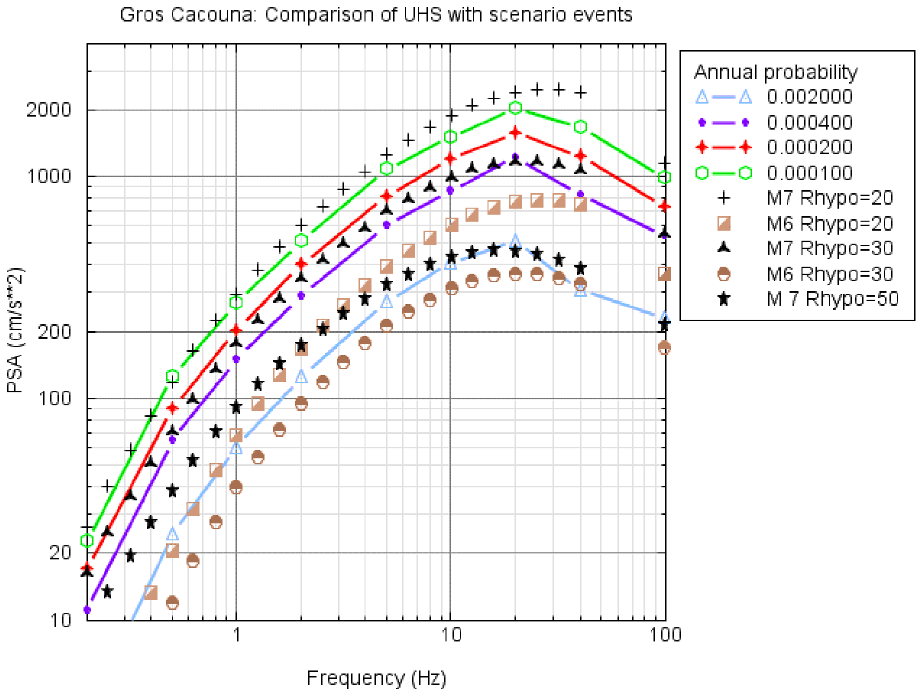

*Figure 11 – Comparison of Gros-Cacouna UHS to median plus sigma predicted ground motions for **M**6 to 7 events according to Atkinson and Boore (2005).*

4 - TIME HISTORIES TO MATCH UHS

Time histories that are appropriate input motions on bedrock for analysis of engineered structures at Gros-Cacouna are required to match 3 probability levels: 0.002, 0.0004, and 0.0002 per annum, corresponding to return periods of 500, 2500 and 5000 years. Figure 12 shows the target UHS for the time histories (5% damped pseudo acceleration on rock). The UHS were derived for the horizontal component of motion as described in the previous section. For some analyses, the vertical component of motion is also required. The vertical target UHS were derived by applying the factors (V/H) as listed in Table 3 to the corresponding horizontal-component UHS. These are empirically-derived factors for hard rock sites in eastern Canada, based on analysis of seismographic data (Siddiqqi and Atkinson, 2002).

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

To obtain time histories that match these target spectra, a technique known as "spectral matching" (McGuire et al., 2002; see also COSMOS, Technical Meeting 2005 http://www.cosmos-eq.org/TS2005.htm) was used. The technique modifies real earthquake records that are in the appropriate magnitude-distance range for the hazard that dominates the target UHS, such that they accurately match the target UHS. A catalogue of input records appropriate for rock sites in eastern North America (ENA) has been compiled by McGuire et al. (2002); these are comprised of ENA records plus some modified rock-like records from more active regions. These records are input to an algorithm that modifies them in the spectral domain by enhancing amplitudes at some frequencies while suppressing amplitudes at others, such that the spectral content of the modified record matches the target UHS. A key advantage of this technique is that the phase characteristics of the record are not modified, and thus it retains the character of the original earthquake time history.

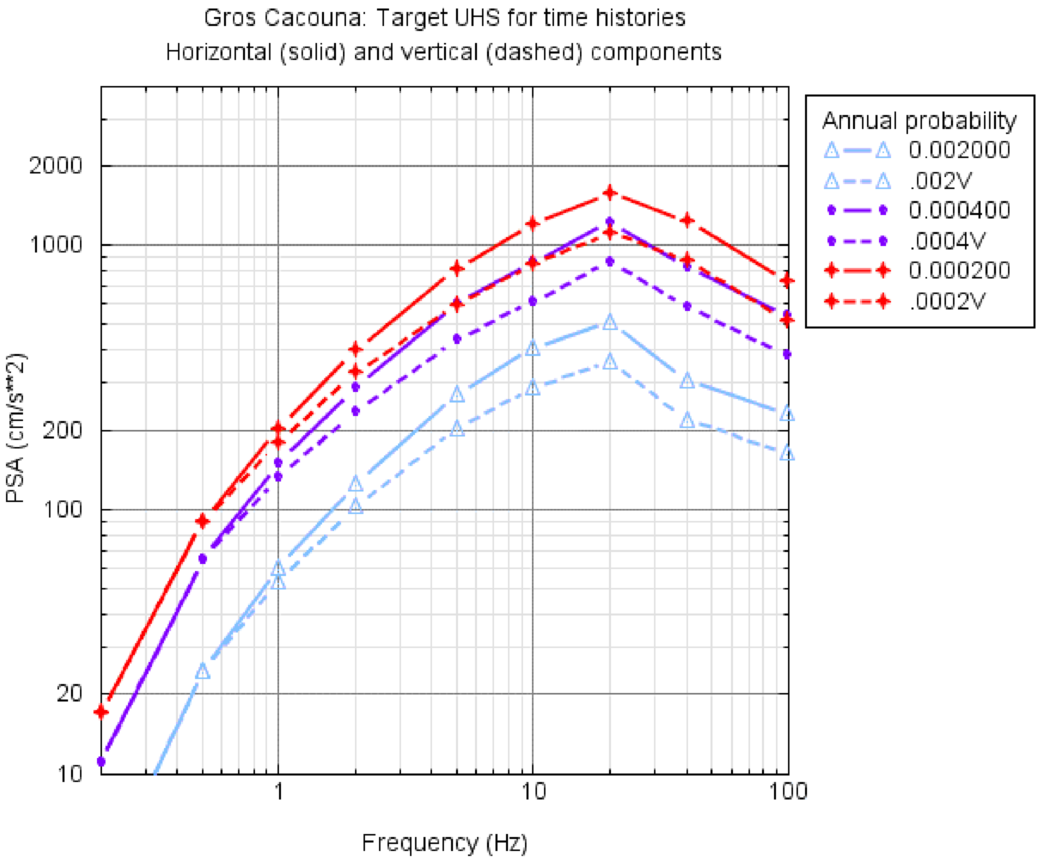

Figure 12 – Target UHS for horizontal (solid lines) and vertical-component (dashed lines) time histories, for probabilities of 0.002, 0.0004 and 0.0002 per annum.

The records selected for modification, obtained from the catalogue of McGuire et al. (2002), are as listed in Table 4.

For each record, there are 2 horizontal components plus a vertical component. Each horizontal component is modified to match the target horizontal-component UHS, while the vertical component is modified to match the corresponding target vertical-component UHS. Thus there are 3 components for each record. For each probability, 3 records are used, for a total of 27 components (3 components * 3 records * 3 probabilities). Because the target UHS for the 0.0002 and 0.0004 p.a. probability levels are quite similar (just a modest shift in amplitude), the same input records are used for both (**M**~7 at moderate distance); for the 0.002 p.a. level, a smaller event size (**M**~6) is selected. The procedure used to obtain the modified time histories comprises the following steps.

1. Take the Fourier transform (FFT) of the input selected record, FA(input). Also compute its response spectrum, PSA(input).

2. Compare PSA(input) to the UHS PSA, PSA(targ), for the selected probability level (as function of frequency).
3. Multiply the Fourier amplitude spectrum FA(input) by the ratio [PSA(targ)/PSA(input)] at each frequency (leaves phase unchanged).
4. Reverse FFT to get a modified time history.
5. Iterate steps 1 to 4 a few times, since PSA does not equal FA (correction is approximate, but will converge in a few iterations). Acceptance criteria for a match are <5% of points having a discrepancy of >25% in spectral amplitude, over the frequency range from 0.2 to 30 Hz.
6. Baseline correct the modified record.

Table 4 – Time History Files to Match UHS

p(UHS) Target	**Earthquake**	**Mom. M**	**Dist (km)**	**Station**	**Comp.**	**Filename (output)**
0.002	Saguenay	5.8	52	S16	H1	Mod1125S16L.AT2
0.002	Saguenay	5.8	52	S16	H2	Mod1126S16T.AT2
0.002	Saguenay	5.8	52	S16	V	Mod1126S16V.AT2
0.002	Saguenay	5.8	70	S17	H1	Mod1125S17L.AT2
0.002	Saguenay	5.8	70	S17	H2	Mod1126S17T.AT2
0.002	Saguenay	5.8	70	S17	V	Mod1126S17V.AT2
0.002	WhittierNarrows	6.0	12	GRV	H1	ModWN87GRVH1.AT
0.002	WhittierNarrows	6.0	12	GRV	H2	ModWN87GRVH2.AT
0.002	WhittierNarrows	6.0	12	GRV	V	ModWN87GRVV.AT2
0.0004	Duzce	7.1	35	MDR	H1	ModDUZCEH1.AT2
0.0004	Duzce	7.1	35	MDR	H2	ModDUZCEH2.AT2
0.0004	Duzce	7.1	35	MDR	V	ModDUZCEV.AT2
0.0004	Nahanni	6.8	16	S3	H1	ModNAH-H1.AT2
0.0004	Nahanni	6.8	16	S3	H2	ModNAH-H2.AT2
0.0004	Nahanni	6.8	16	S3	V	ModNAH-V.AT2
0.0004	Landers	7.3	42	29P	H1	ModLAN-H1.AT2
0.0004	Landers	7.3	42	29P	H2	ModLAN-H2.AT2
0.0004	Landers	7.3	42	29P	V	ModLAN-V.AT2
0.0002	Duzce	7.1	35	MDR	H1	ModDUZCEH1b.AT2
0.0002	Duzce	7.1	35	MDR	H2	ModDUZCEH2b.AT2
0.0002	Duzce	7.1	35	MDR	V	ModDUZCEVb.AT2
0.0002	Nahanni	6.8	16	S3	H1	ModNAH-H1b.AT2
0.0002	Nahanni	6.8	16	S3	H2	ModNAH-H2b.AT2
0.0002	Nahanni	6.8	16	S3	V	ModNAH-Vb.AT2
0.0002	Landers	7.3	42	29P	H1	ModLAN-H1b.AT2
0.0002	Landers	7.3	42	29P	H2	ModLAN-H2b.AT2
0.0002	Landers	7.3	42	29P	V	ModLAN-Vb.AT2

Example time histories (for the Saguenay earthquake at station S16) are shown for one of the components for the 0.002 p.a. probability in Figure 13 (both input and modified records), while Figure 14 shows the response spectra of the modified time histories for all 3 components. Note that for the Saguenay records the frequency content below about 1 Hz cannot be recovered due to long-period noise problems with the original digitized records; this is considered acceptable since the low-frequency motions at this probability level are not significant (only the higher frequencies are of interest in this case). The frequency range is not an issue for the other records, which are usable from 0.2 to 40 Hz. Figure 15 shows example time series for one of the components for the 0.0002 p.a. probability level (both input and modified records), while Figure 16 shows the response spectra of the modified time histories for all 3 components. All time series are provided in electronic format within the file groscacounaTH.zip. Table 4 indicates which records are to be applied to which probability and component. The records are for bedrock motions (vs~2000 m/s). For any structures on soil, or for soil response studies, the records should be considered as bedrock input at the base of the soil layer.

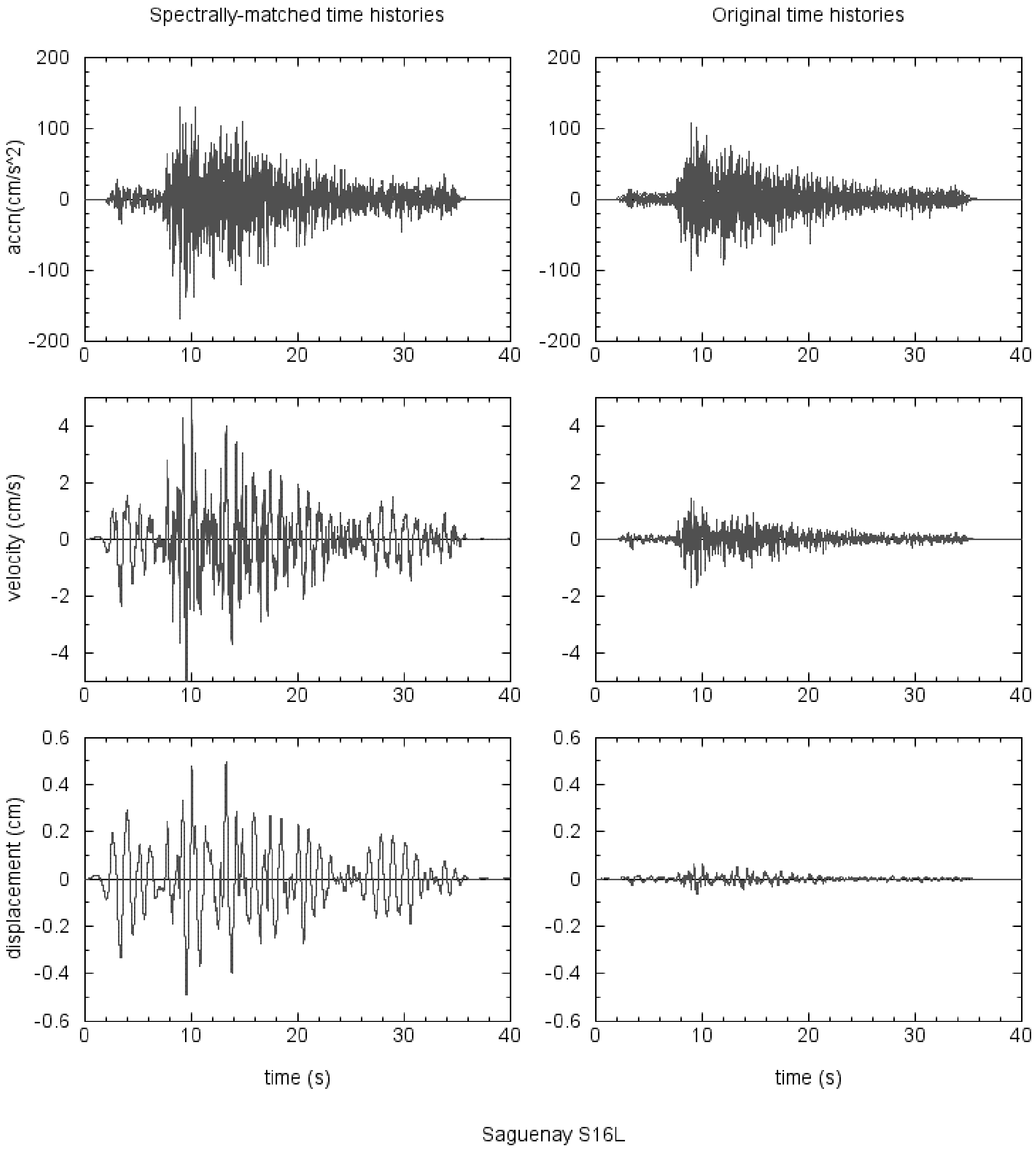

*Figure 13 – Example output and original time histories, Saguenay **M**5.8 earthquake at 52 km (S16), matched to UHS at 0.002 per annum (1/500).*

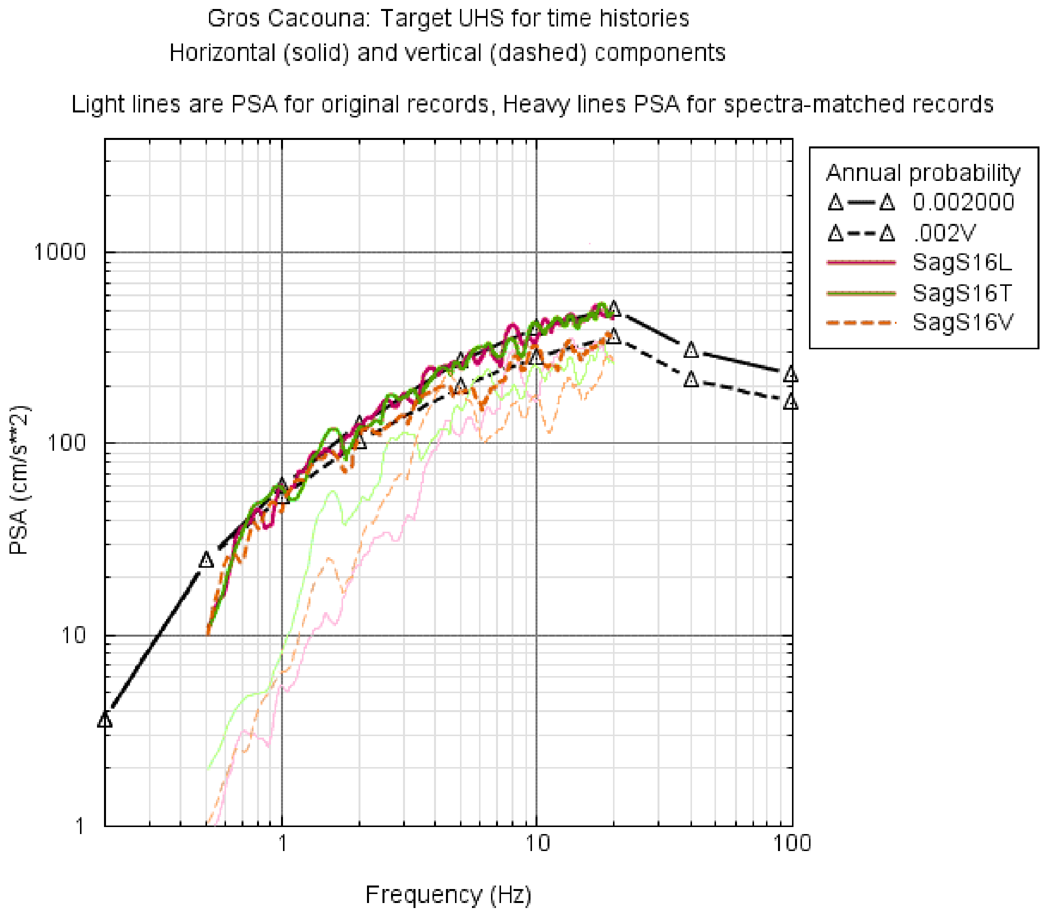

*Figure 14 – Comparison of PSA for Saguenay **M**5.8 earthquake at 52 km (S16),for original (light lines) and spectrally-matched (heavy lines) records, with target UHS at 0.002 per annum (1/500). Both horizontal components and the vertical component are shown.*

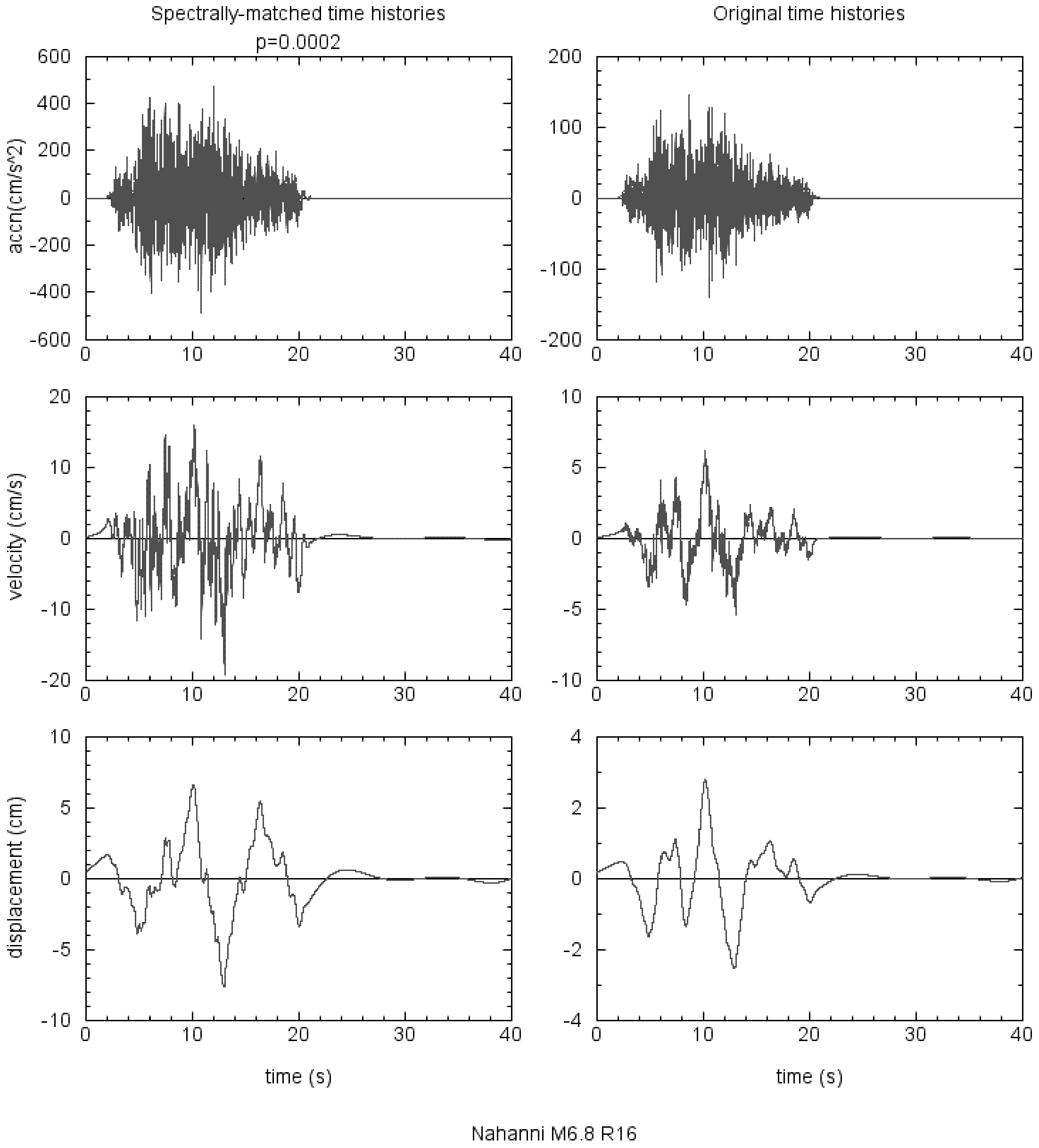

Figure 15 - Example output and original time histories, Nahanni ***M6****.8 earthquake at 16 km (S3), matched to UHS at 0.0002 per annum (1/5000).*

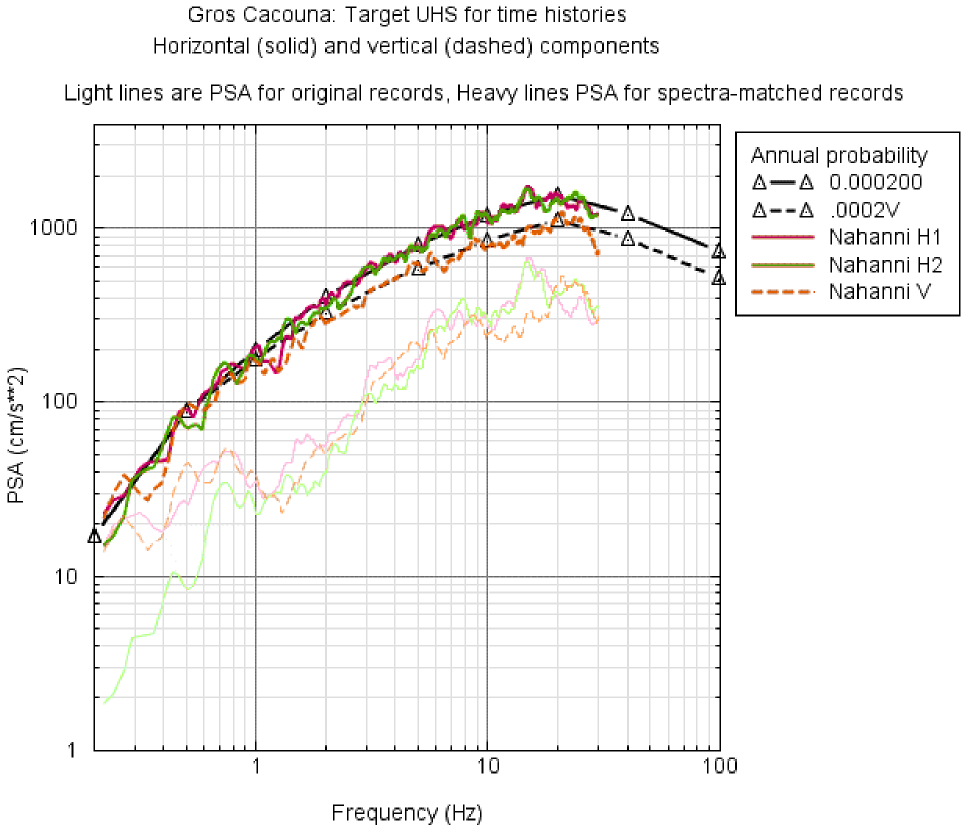

*Figure 16 – Comparison of PSA for Nahanni **M6**.8 earthquake at 16 km (S3),for original (light lines) and spectrally-matched (heavy lines) records, with target UHS at 0.0002 per annum (1/5000). Both horizontal components and the vertical component are shown.*

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