IR# JRP.59

Seismic Hazard - Regional Normal Faults

Requesting Organization – Joint Review Panel **Information Request No.: JRP.59**

Subject - Seismic Hazard - Regional Normal Faults

References:

Newfoundland and Labrador Hydro - Lower Churchill Project: GI1170 - Seismicity Analysis. Document no. 722850-GI1170-40ER-0001-00

Wheeler, R.L. 1995. Earthquakes and the cratonward limit of Iapetan faulting in eastern North America, Geology, Feb 1995; 23: 105 - 108

Related Comments / Information Requests:

CEAR # 202 (Natural Resources Canada)

Rationale:

NRCan has indicated that the Proponent did not discuss the potential reactivation of normal faults of the Melville Rift System which is a major fault system of the area. As an example of this:

> *Thus the Geological Survey of Canada (GSC) did not include the Lake Melville area in its delineation of rift-based source zones for the National Building Code seismic hazard maps (Adams and Halchuk, 2003). Rather, in their rift model (R model), this region lies in an Iapetan rift background zone (IRB) that surrounds the more active rifted margin zone of the St. Lawrence system. The activity levels for this zone (IRB) will be compared to those obtained from the alternative source models used in this study in the next section.*

The EIS does not mention that in the R model there is the LAB Seismic Zone just to the east of the Lower Churchill area. Nowhere the impact of this seismic zone is discussed either in terms of its recorded seismicity and the potential reactivation of its faults.

The LAB area was defined by Adams and Basham (1990) on the basis of a magnetic lineament. It is also shown in Wheeler (1995). Adams and Basham (1990; p. 9) state:

> *"The earthquakes extending from Sept Îles across easternmost Quebec and southern Labrador may lie on a strike slip fault related to the St. Lawrence rift system (mapped by Gower et al., 1986).*

This is illustrated in Figure 7 of Adams and Basham (1990). Figure 6 of the same paper shows that the area is in line with the extension of the Cartwright Fault Zone. This is also illustrated in Fig. 6 of Gower et al., 1986. In the latter it is reported that these faults are probably related to Iapetan rifting, the same episode that is the basis for the R model used to derive seismic hazard in the St. Lawrence Valley.

It is important to document the Rift faults in the neighbourhood of the projected dams.

Considering the connection that is made between normal faults and seismic hazard in eastern Canada, the rift faults must be considered and discussed in the hazard analysis.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.59**

Information Requested:

The Proponent is asked to provide information about the seismic zone LAB and its link with rift faults, and assess the implications of this for the Project.

Response:

The report on Earthquake Hazard Analysis, Gull Island and Muskrat Falls Damsites (Part 2), has been revised to discuss the LAB zone and its implications for seismic hazard. Sensitivity calculations have been performed to check that inclusion of the LAB R-model zone of GSC would not significantly affect the calculated hazard. The check showed that, relative to the local model to which it might be compared, the model including LAB produced slightly higher values (about 10 percent) at low frequencies, and slightly lower values (also about 10 percent) at high frequencies. Further discussion of the rift faults has been provided in the revised Part Two, provided in Attachment A.

INFORMATION RESPONSES
LOWER CHURCHILL PROJECT
CEAA REFERENCE NO.07-05-26178

JOINT REVIEW PANEL

Attachment A

Report on Earthquake Hazard Analyses: Gull Island and Muskrat Falls Damsites

IR# JRP.59

October 5, 2009

nalcor energy
LOWER CHURCHILL PROJECT

PART TWO

Report On

Earthquake Hazard Analysis: Gull Island and Muskrat Falls Damsites

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

Revision 3: July, 2009

PART TWO
TABLE OF CONTENTS

PAGE NO.

List of Figures

List of Tables

SUMMARY

A site-specific seismic hazard assessment was performed for the Gull and Muskrat damsites in the Lower Churchill region of Labrador (approximate location 52.5N 61W). The analysis determines the expected earthquake ground motions over a range of probability levels, including 1/1000, 1/2500, 1/5000 and 1/10,000. The ground motions are calculated for "hard rock" site conditions, which in eastern Canada typically have shear-wave velocities > 2000 m/s near the surface. This site condition corresponds to NEHRP A in the standard NEHRP (National Earthquake Hazard Reduction Program) site classification scheme. In the NEHRP classification, NEHRP A sites are those with average shear-wave velocity in the top 30 m >1500 m/s; NEHRP B and C correspond to average shear-wave velocities in the top 30 m of 760-1500 m/s and 360-760 m/s, respectively, while NEHRP D (stiff soil) corresponds to average shear-wave velocities of 180-360 m/s. Soils amplify ground motions, with softer conditions producing greater amplifications, especially at longer periods.

The Muskrat site is founded on hard rock, and thus the seismic hazard calculation results for NEHRP A are directly applicable. The Gull site is located on stiff soil, with likely shear-wave velocities in the top 30 m ranging from 200 m/s to 400 m/s, based on reported blow counts of 15 to 50. It is therefore classed as a NEHRP D site. Generic amplification factors are defined to obtain motions on NEHRP D conditions from the NEHRP A ground-motion results; these are applied to provide the expected ground motions for Gull.

This study derives a range of ground-motion estimates for the 1/10,000 probability level, including evaluation of the impact of the chief sources of uncertainty. Weighted mean-hazard results are provided for a range of probabilities, for both the Muskrat (NEHRP A, Table 3-1) and Gull (NEHRP D, Table 3-2) sites. The results refer to natural seismicity, and do not address the probability of reservoir-induced seismicity. Reservoir-induced seismicity is typically of small-to-moderate magnitude; it may produce large-amplitude accelerations, predominantly at high frequency and of short duration.

The results of the probabilistic analyses can be summarized in simplified terms as follows. At the probability level of 1/10,000, the expected peak ground acceleration (PGA, from natural earthquakes) for the hard rock site conditions (NEHRP A) at Muskrat is approximately 0.09g. For the NEHRP D site at Gull, it is 0.11g. The ground motions at this probability level

(1/10,000) correspond approximately to local earthquakes of **M**5.5 to 6.0 at distances from 30 to 50 km, for frequencies > 2 Hz. At long periods (f<2 Hz), motions correspond to those that would be expected for a major regional earthquake (**M**7.5) about 300 km away, in either the offshore or St. Lawrence seismic zones.

1 INTRODUCTION

This report presents a seismic hazard assessment for the Gull and Muskrat damsites on the Lower Churchill River for annual exceedence probabilities in the range from 1/1000 to 1/10,000. The analysis determines the likelihood of ground motion at the site by considering the magnitudes, rates of occurrence, and locations of earthquakes throughout the region, using the probabilistic 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 consider the effects of major uncertainties on the hazard at Gull and Muskrat, and incorporate new information on seismicity and ground motion relations from the last ten (10) years of data. To include new and more complete information, a range of possible models to describe the seismic setting and ground motions is defined.

The analysis does not include any local information on specific faults or geological structures. Rather it is assumed that there are no such local features that would affect the overall regional hazard estimates; thus an implicit assumption is that there is no evidence of faults that have moved in geologically recent times (last 10,000 years) in the site area. This assumption can be refined at a more detailed analysis stage if warranted in light of site-specific geologic information. For example, if a local fault with recent offset was identified, then this fault would delineate a local fault-based source zone, with geological information on the dates and extent of movement being used to define a recurrence relation for the fault. Microseismic studies of any such identified sources could also be conducted. However, such features are very rare in eastern Canada, and it is thus very unlikely that they will be identified in the site area. The analysis addresses natural seismicity, and does not address the probability of reservoir-induced seismicity.

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 may 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 Gull/Muskrat. 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.

There are two (2) sites of interest covered by this study. The Muskrat site (53.25N 60.77W) is founded on hard rock, and thus seismic hazard calculation results for NEHRP A sites are directly applicable. The Gull site (52.96N 61.42W) is located on stiff soil, with likely shear-wave velocities ranging from 200 m/s to 400 m/s, based on reported blow counts of 15 to 50 (SNC-Lavalin, personal communication, 2007). It is therefore classed as a NEHRP D site. The two (2) sites are located close enough together, within a broad zone of scattered seismicity, that their seismic hazards are equivalent except for the difference in site conditions. In hazard calculations in eastern Canada, NEHRP A is the reference condition, as the ground-motion prediction equations are generally defined for NEHRP A. We perform hazard calculations for NEHRP A conditions for a single intermediate site, location near both sites. These results would apply to facilities at either site, provided they were founded on NEHRP A. They are thus directly applicable to the Muskrat site. To consider the site conditions at Gull, generic amplification factors are defined to obtain motions on NEHRP D conditions from the NEHRP A results; these are applied to provide the expected ground motions for Gull.

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.

The spatial distribution of earthquakes is described by defining seismic source zones (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. In most cases, including this study, the hazard is dominated by contributions from the source zone within which the site is located. The hazard integral sums up the likelihood of earthquakes at all distances within the source zone, assuming that earthquakes are distributed randomly in space across the source zone.

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 (2) types of uncertainty exist:

- random uncertainty due to the physical variability of earthquake processes, and
- 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 (2). 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, 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 (e.g. median, 84^{th} 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 use a sensitivity approach to display the alternative results that are obtained under various alternative input assumptions. We also use a trimmed logic “shrub” to provide weighted mean-hazard UHS results for a range of probabilities, considering the key input uncertainties.

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 and treat the key uncertainties: these are the uncertainty in seismotectonic model for the site source region (which defines uncertainty in activity rates) and the uncertainty in ground-motion relations. For these key parameters, several alternative models are defined and their implications for the UHS at 1/10,000 per annum (p.a.) are determined. A mean-hazard UHS is also provided, for probability levels of 1/1000, 1/2500, 1/5000 and 1/10,000 p.a.

Other sources of uncertainty include those in the maximum magnitude and in the recurrence parameters for a given source zone. However, seismic hazard results are not generally very sensitive to maximum magnitude, over a reasonable range of values, and thus this factor can be neglected in a simplified "logic-shrub" approach. Sensitivity to recurrence rates is implicitly included by considering alternative seismic source zone models that imply different local rates of activity.

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 and PGV.

2.3.1 Seismic Source Models

The first step in the seismic hazard analysis is the definition of seismogenic source zones. Figure 2-1 shows seismicity of the region through the end of 2006, as obtained from the Geological Survey of Canada (www.earthquakescanada.gc.ca). 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:

$$\mathbf{M} = -0.39 + 0.98\ MN$$

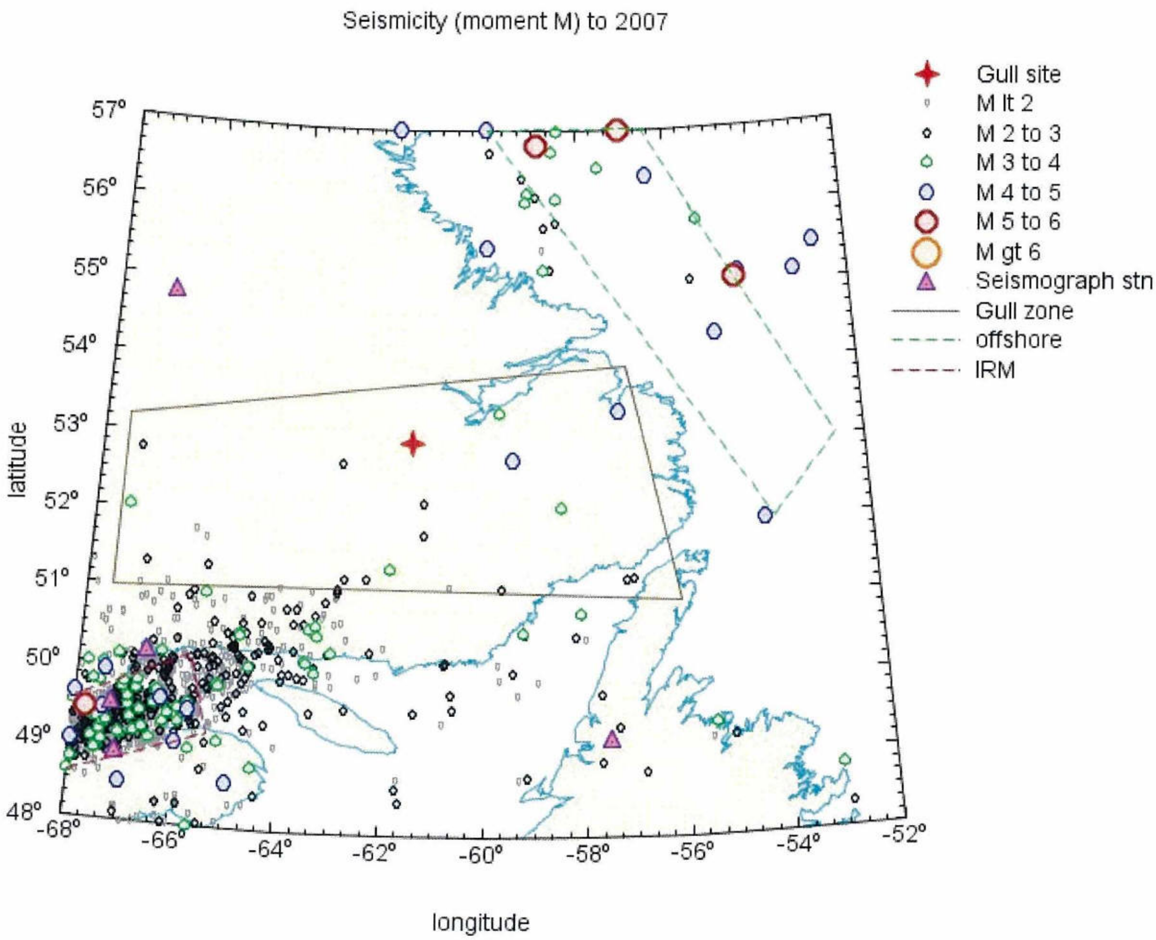
$$\mathbf{M} = 0.800 + 0.838\ ML$$

where ML is local magnitude. 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 Figure 2-1 are plotted in terms of their moment magnitudes.

The Gull/Muskrat site location is in an area of very sparse seismicity, with active regions such as those offshore or in the Lower St. Lawrence being too far distant (300 km) to cause significant hazard, except possibly at long periods (as long-period motions decay slowly). At intermediate-to-high frequencies, the hazard will be dominated by the sparse local seismicity. A source zone that represents this seismicity is defined in Figure 2-1 as the "Gull zone". Note that the map may not provide a balanced pictorial representation of the activity in the site area, as the nearest seismograph stations are >300 km away, and thus the reporting of events will be very incomplete for **M**<3.

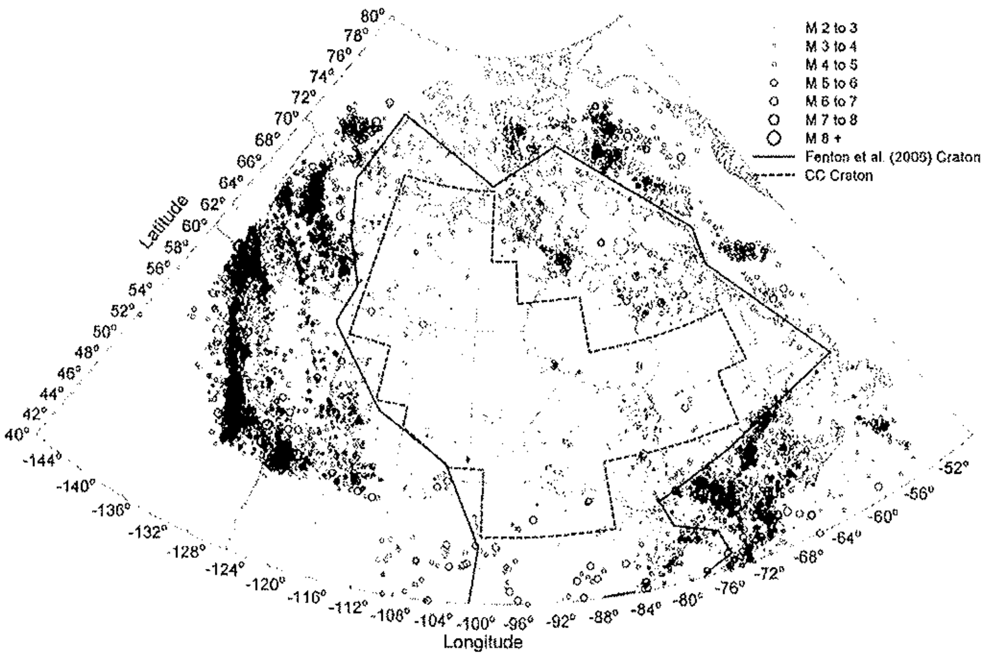
Another problem with defining the local seismicity rates is that they are so low that it is difficult to obtain meaningful statistics from the limited historical record in the area. This difficulty is dealth with by defining an alternative parameterization of the local seismicity rates. Average rates for larger craton areas in North America (NA), as determined by Atkinson and Martens (2007) for the stable North American craton as a whole, should be applicable to the site. As shown in Figure 2-2 (from Atkinson and Martens, 2007), the Gull/Muskat area lies within the NA craton defined by the solid lines, but not within the Central Canada subset defined by the dotted lines. The recurrence rates for the NA craton, normalized to the same area and per annum rate as the Gull zone of Figure 2-1, may thus be used as an alternative definition of local recurrence rates.

Figure 2-1: Recorded Seismicity (M>1) Through 2006



Note: Recorded seismicity in the Gull/Muskrat area, along with the source zones that were used in the analysis. Note that the Offshore and IRM zones are approximate representations of distant hazard, as discussed in the text. Seismicity at low magnitudes in the site area is incompletely reported, as the nearest seismograph station is >300 km away.

Figure 2-2: Definition of the Stable North American Craton (solid line) and the Central Canada Craton (dotted line)



Note: From Atkinson and Martens (2007).

For completeness of the hazard calculations at long periods, a simplified representation of the hazard from distant sources has been included. The sub-sections of the active seismic sources offshore and in the Lower St. Lawrence that come closest to the site area are defined as additional source zones as shown in Figure 2-1. The definition of the recurrence parameters for these and the other sources are discussed in the next section.

The above representation of the source zonation is simplistic, and does not attempt to include local geological factors. Overall, the Lake Melville region includes Iapetan rift faulting features (Gower et al., 1986), which may be relevant to the seismic hazard, as larger events in ENA have typically occurred on such structures (Adams and Halchuk, 2003). The regional faults that bound the Churchill River in this area are features of this type (ie. ancient rift faulting features, approximately 600 million years old). However, the contemporary activity level in this region is notably less than that along other Iapetan rift features in the St. Lawrence and Ottawa values, and its structural relation to those features is unclear. Thus the Geological Survey of Canada (GSC) did not include the Lake Melville area in its delineation of the major rift-based source zones for the National Building Code seismic hazard maps (Adams and Halchuk, 2003). In the GSC rift model (R model), this region lies in an Iapetan rift background zone (IRB) that surrounds the more active rifted margin zone of the St. Lawrence system. The activity levels for this zone (IRB) will be compared to those obtained from the alternative source models used in this study in the next section.

It is noted that in the GSC R-model, the Gull and Muskrat sites lie just to the northwest of the LAB source zone. The LAB zone includes a band of seismicity in the Gulf of St. Lawrence, which starts to the east of the IRM zone, and then trends towards Labrador through the Lake Melville area. The LAB zone follows the trend of Iapetan structures noted by Gower et al. (1986), and passes about 30 km southeast of the Gull and Muskrat sites. The LAB source is not explicitly included in the seismic hazard model for two reasons: (i) the seismicity rates are very uneven in the zone (with the Gulf of St. Lawrence being more active that Labrador); and (ii) part of the LAB zone as defined by the GSC has been included in the Gull zone of Figure 1. However, a sensitivity test was performed to verify that inclusion of the LAB zone, as defined by Adams and Halchuk (2003), would not significantly affect the hazard results. The lack of sensitivity to a possible LAB zone owes to the fact that local seismicity dominates the hazard at high frequencies, while at low frequencies the active zones (IRM and offshore) are more important. Nevertheless, the local faults near the Gull and Muskrat sites should be checked for evidence of geologically-recent activity that might impact the seismic hazard estimates derived herein on the basis of contemporary seismicity.

The two alternative definitions of local source model discussed above (Gull zone and NA craton model) are both assigned a relative weight of 0.5 in the seismic hazard evaluations, reflecting approximately equal credibility based on current information.

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 $\geq$**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 relation obtained for the Gull source zone is shown in Figure 2-3. In developing this relation, 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 were estimated initially as follows, with checking of these levels done based on the magnitude recurrence plot (Figure 2-3) as described below:

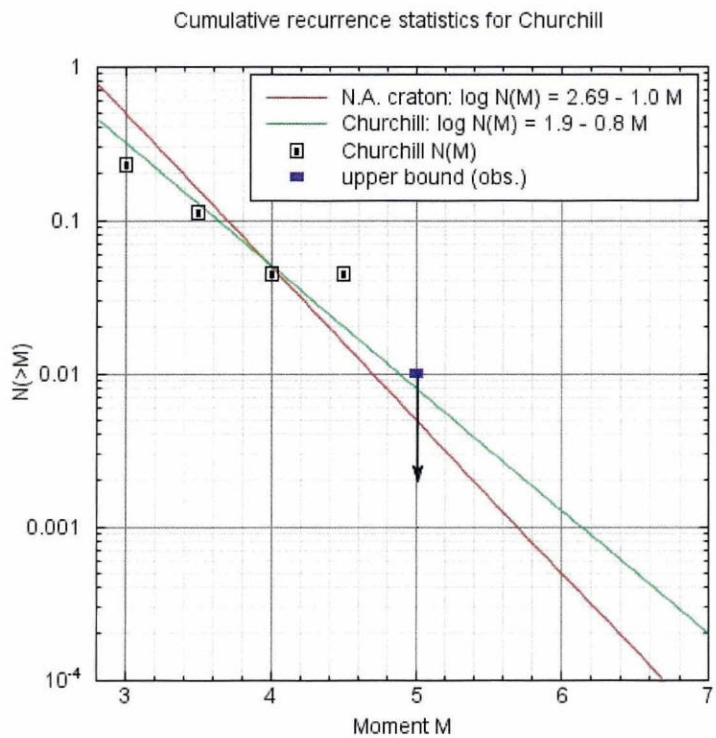
Year to begin statistics for:

M3	M3.5	M4	M4.5	M5	M6
1990	1962	1962	1962	1918	1918

Based on inspection of Figure 2-3, it is possible that the observed catalogue is not complete for **M**3 (since 1990), as these rates appear to be lower than the NA average. On the other hand, the Gull region may have a lower b value (flatter recurrence slope) than the NA average. An upper limit on the local rate of **M**>5 events has been shown on Figure 2-3, based on the fact that no such events have been observed, and any such events should have been reported if they occurred after about 1918. Overall, the rates observed for Gull are fairly consistent with those reported by Atkinson and Martens (2007) for an area of this size within the NA craton. Both of these models are considered to have approximately equal credibility in terms of representing true seismicity rates in the site region.

The rates determined from these zones can be compared to those of the GSC IRB zone discussed in the previous section. According to Adams and Halchuk (2003), the IRB zone has an assigned b value of 0.9, with an expected rate of **M**>5 events of 0.0065, when normalized to the same area as used in the Churchill zone. Comparing this rate and slope to those defined in Figure 2-3, we see they are very similar. In fact, the GSC IRB model lies between the two (2) models used in this study in terms of recurrence rates. Therefore, it is inherently considered by the two (2) selected model representations.

Figure 2-3: Recurrence Relations for Local Source Zone Models Used in the Lower Churchill Area



Note: Symbols and green line show observed rates and assigned relation for the Gull source zone of Figure 1. Red line shows NA craton rate of Atkinson and Martens (2007), normalized to the same area as the Gull zone.

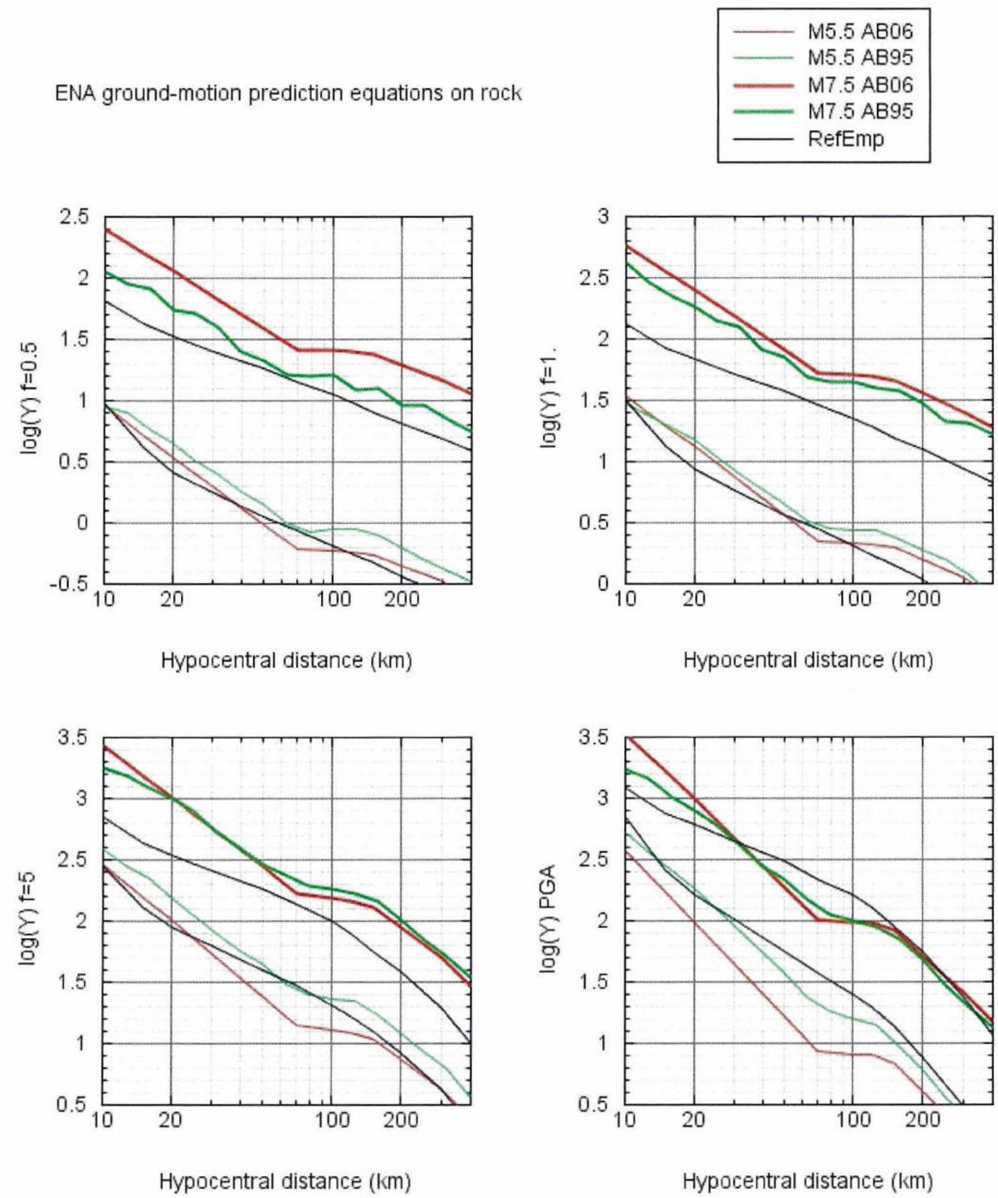
For the distant sources, a simplified representation is used (Figure 2-1), in which the recurrence parameters, normalized for the appropriate area, are as defined by the GSC ECM model for the offshore region, and the GSC IRM model for the Lower St. Lawrence. According to the GSC model, the offshore zones have a slope b = 0.74, with a rate of **M**>5 events of 0.428 p.a., per million square km. The IRM zone has a slope of b= 0.86, with a rate of **M**>5 events of 0.923 p.a., per million square km (Adams and Halchuk, 2003). These rates, normalized for the actual areas defined on Figure 2-1, are adopted for the distant source zones. The source zone model for these distant events is assumed to be the same for both the Gull zone and the NA craton representations of the seismicity. Thus there are two (2) source models considered, each with a weight of 0.5: (i) Gull zone, with distant offshore and IRM sources; (ii) NA craton rate model, with distant offshore and IRM sources.

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. A value of Mx=7.0 is used for the local zone, as this represents an unrifted continental interior. For the offshore and Lower St. Lawrence areas the maximum magnitude is taken as Mx=7.5. 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).

2.3.3 Ground Motion Relations

Ground motions (on hard rock) are given in this analysis by the ground-motion prediction equations (GMPEs) of Atkinson and Boore (2006) for eastern North America (ENA). The equations used provide peak ground acceleration (PGA) and velocity (PGV), as well as response spectra (PSA, 5% damped horizontal component) as a function of moment magnitude and hypocentral distance (Note: the hypocentral distance version of the AB06 equations is used as the events are treated as point sources in the hazard analysis.) To consider sensitivity to ground-motion relations, earlier relations of Atkinson and Boore (1995), as adopted in the 2005 NBCC seismic hazard model are considered, as are alternative Referenced Empirical ground-motion relations (Atkinson, 2007) based on making modifications to ground-motion relations for active tectonic regions in order to accommodate ENA empirical data. The considered suite of ground-motion relations is shown on Figure 2-4 for NEHRP A. Conversion of results to other site conditions (NEHRP D) is discussed in Section 3.

Figure 2-4: Ground-Motion Relations for ENA (Hard Rrock) Considered in this Study



Note: AB06 = Atkinson and Boore (2006). AB95 = Atkinson and Boore (1995). Ref. Emp. = Atkinson (2007) referenced empirical alternative. Shown for M 5.5 and M 7.5 versus hypocentral distance, for PSA at 0.5 Hz, 1 Hz, 5 Hz and PGA.

Note that all relations are for hard-rock sites (NEHRP A) in eastern North America (ENA). 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; 2006). 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 Atkinson and Boore (2006) and Atkinson (2007) relations include more recent information.

The alternative GMPEs are weighted as follows. The Atkinson and Boore (2006) equations are given the largest weight, 0.5, as they are based on the most recent ground motion information and modeling for ENA. The Atkinson (2007) relations by the Referenced Empirical model are given an intermediate weight of 0.3; they incorporate much more recent data from other regions, but their applicability to ENA is less clear than for AB06. The older relations of Atkinson and Boore (1995) are retained for continuity with current GSC seismic hazard estimates, but are given the lowest weight (0.2) as they are now outdated and have been replaced.

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).

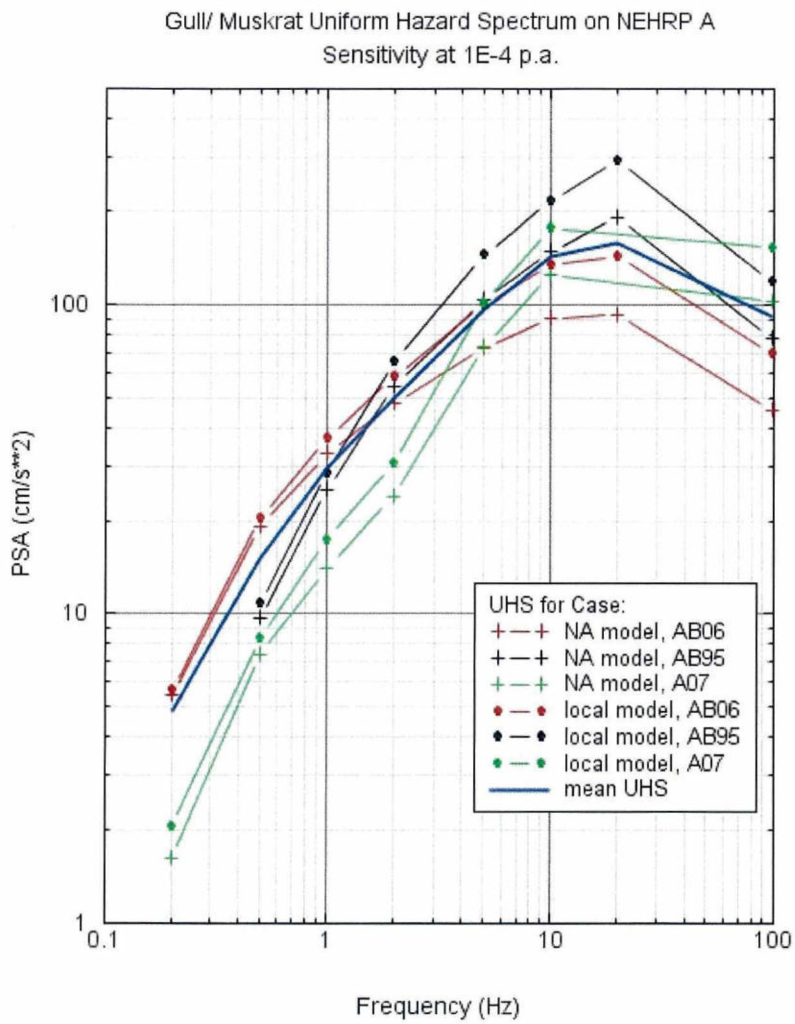
3 RESULTS OF SEISMIC HAZARD ANALYSIS

3.1 MEAN-HAZARD UHS AND SENSITIVITY

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 Figures 3-1 and 3-2. The peak ground acceleration (PGA) is plotted for reference at a frequency of 100 Hz, but the shape of the curve between 20 Hz and 100 Hz is arbitrary (no spectral values were calculated for frequencies above 20 Hz). *(Note: Most ground motion relations available for ENA do not include coefficients for frequencies above 20 or 25 Hz. However, the Atkinson and Boore (2006) equations extend to 40 Hz. Hazard calculations for just this relationship (AB06) can be used to infer that the 40 Hz PSA is, in general, approximately equal to the 20 Hz PSA - within ~10% for probabilities of 1/1000 to 1/10,000 at low-seismicity sites. Thus if values of PSA at frequencies greater than 20 Hz are required, it should be assumed that the 40 Hz PSA is equal to the 20 Hz PSA.)*

The PGA refers to the maximum acceleration of the ground shaking during the seismic event (i.e., 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.

Figure 3-1: UHS at Gull/Muskrat for Annual Probability of 1/10,000

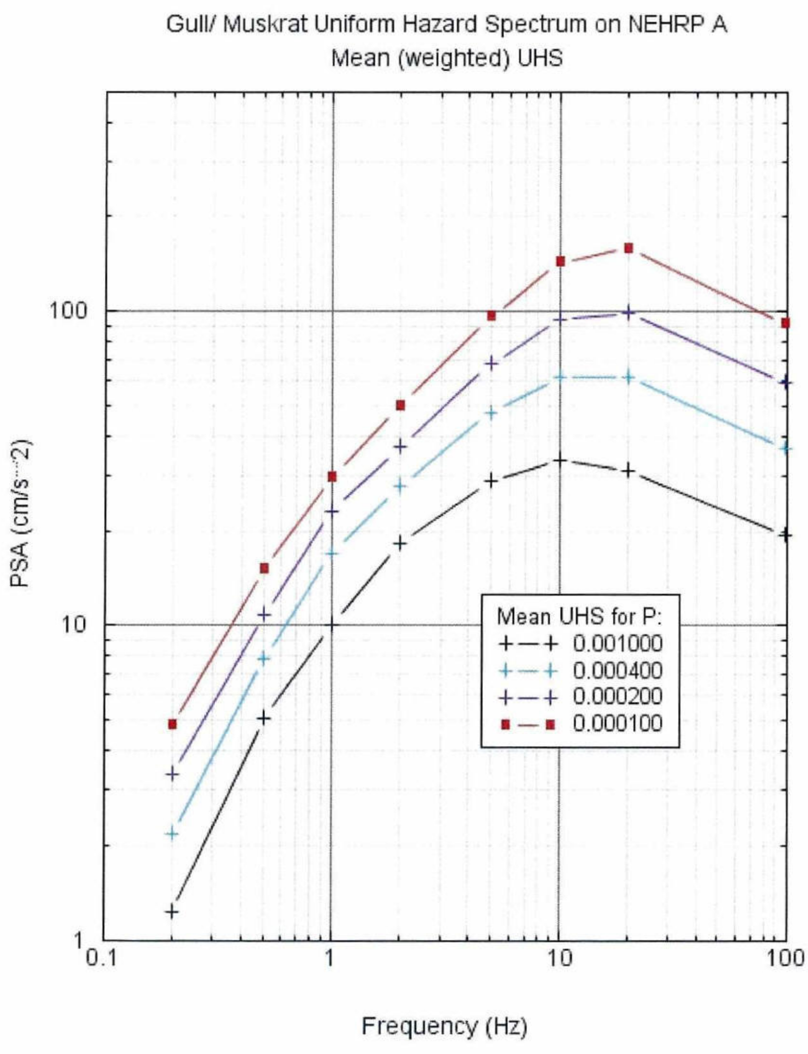


Note: Results for each combination of seismic source model and ground motion model are shown, along with the mean-hazard UHS. All for NEHRP A.

The sensitivity of results to alternative sets of input parameters is shown in Figure 3-1 for the probability level of 1/10,000 per annum (p.a.). The mean-hazard UHS for this probability is also shown. The mean-hazard UHS is obtained by weighting the probabilities of exceedence of each value of ground-motion amplitude by the relative weights provided in Section 2, to provide a weighted-hazard curve. We then interpolate the weighted hazard curve to obtain the mean-hazard UHS for each target probability level. It is noted that there is a wide spread of possible results, with variability of as much as a factor of two (2) about the mean-hazard UHS from the lowest to highest estimates.

Figure 3-2 summarizes the mean-hazard UHS results for all probability levels from 1/1000 to 1/10,000 per annum, for rock sites. These results are listed in Table 3-1.

Figure 3-2: Mean-Hazard UHC for Gull/Muskrat at a Range of Target Probabilities



Note: All for NEHRP A.

Table 3-1: Weighted-Mean-Hazard Ground Motions for Gull/Muskrat

Frequency	0.001	0.0004	0.0002	0.0001
0.2	1.2	2.2	3.4	4.8
0.5	5.1	7.8	10.8	15.1
1	10.1	17.0	23.2	29.7
2	18.2	27.7	37.1	49.7
5	28.8	47.4	67.9	96.0
10	33.4	61.6	93.8	142.9
20	31.2	61.5	98.6	157.9
PGA	19.4	36.8	59.1	92.1
PGV	1.1	1.7	2.3	3.2

Note: For 5% damped horizontal-component PSA, PGA (cm/s^2) and PGV (cm/s), for NEHRP A site conditions, for a range of annual probabilities.

3.2 RESULTS FOR NEHRP D SITE CONDITIONS (GULL SITE)

The seismic hazard results have been obtained for NEHRP A (hard rock) site conditions, as given in Table 3-1. These results apply to the Muskrat damsite, as it is founded on hard rock. The Gull site is founded on stiff soil, with estimated shear-wave velocity of 200 m/s to 400 m/s, as based on blow counts of 15 to 50 (SNC-Lavalin personal communication). This corresponds to NEHRP D class conditions.

To obtain the corresponding ground motions on NEHRP D from the NEHRP A results is a two-step process. First, seismic hazard calculations are performed for one of the models (the NA craton model), using the AB06 ground-motion relations, for both NEHRP A and NEHRP B/C boundary conditions. The AB06 ground-motion relations are available for both of these site conditions (unlike most other relations). A comparison of the B/C to A results is used to assess how much amplification occurs in going from NEHRP A to NEHRP B/C boundary site conditions. Then, the soil amplification equations of Boore and Atkinson (2007) are used to assess the amplification from B/C to NEHRP D (with assigned site shear-wave velocity = 250 m/s and PGA=0.09g). This is the recommended procedure described by Atkinson and Boore (2006). Note that due to the low ground-motion levels involved, soil response is essentially linear, which means the same factors can be applied for all probabilities. The derived factors to amplify NEHRP A motions to obtain the corresponding motions on NEHRP D sites are listed in Table 3-2.

Table 3-2: Amplification Factors

Frequency	Amplification
0.2	2.54
0.5	2.76
1	2.81
2	2.77
5	1.91
10	1.47
20	1.10
PGA	1.23
PGV	2.41

Note: Amplification factors to go from NEHRP A results (hard rock) to NEHRP D results (shear-wave velocity 250 m/s in upper 30 m).

The factors of Table 3-2 were applied to the results of Table 3-1 to obtain motions for NEHRP D site conditions, as provided in Table 3-3. These results are applicable to screening-level analyses at the Gull site. This treatment of soil response at Gull could be refined in future, if site-specific soil profile information becomes available, by inputting rock ground motions as per Table 3-1 (or a compatible time history) into the base of the Gull soil profile.

Table 3-3: Weighted-Mean-Hazard Ground Motions for Gull/Muskrat

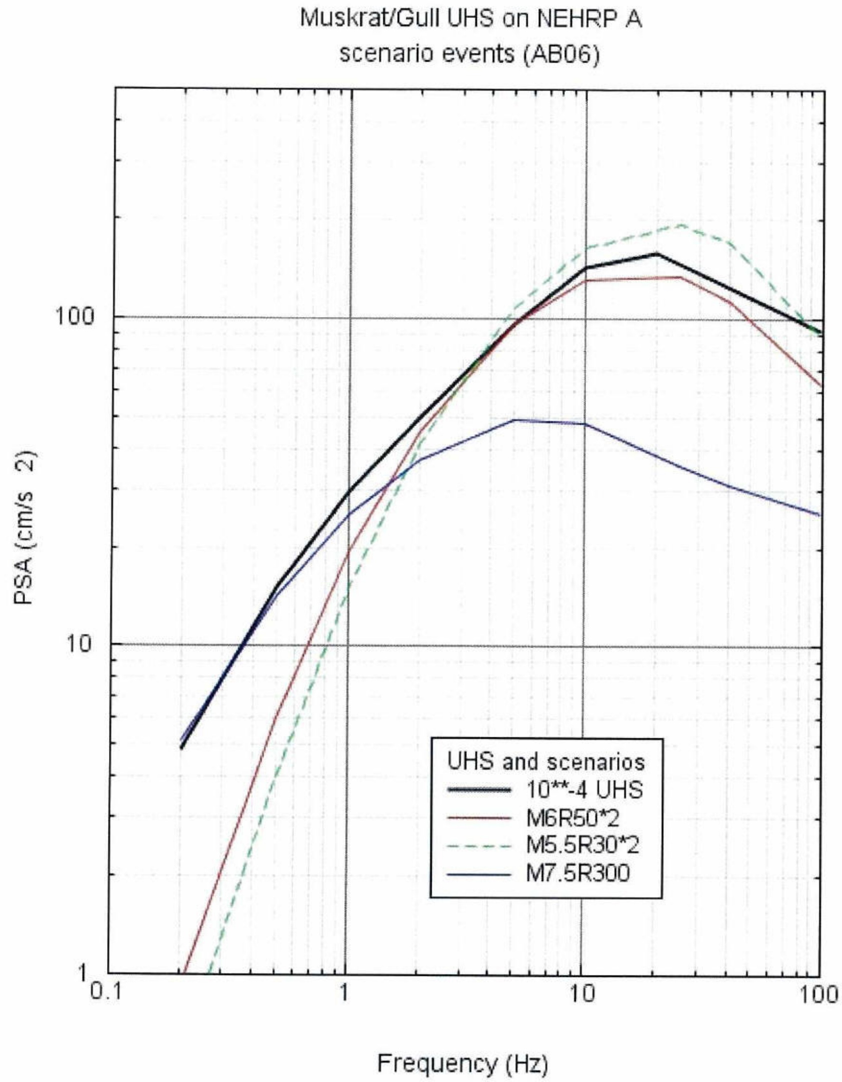
Frequency	0.001	0.0004	0.0002	0.0001
0.2	3.1	5.5	8.6	12.3
0.5	14.0	21.6	29.9	41.5
1	28.3	47.7	65.1	83.4
2	50.4	76.7	102.7	137.6
5	55.0	90.6	129.6	183.4
10	49.1	90.6	137.9	210.1
20	34.4	67.6	108.4	173.6
PGA	23.9	45.2	72.7	113.3
PGV	2.6	4.0	5.6	7.8

Note: For 5% damped horizontal-component PSA, PGA (cm/s^2) and PGV (cm/s), for NEHRP D site conditions, for a range of annual probabilities.

3.3 SCENARIO EARTHQUAKES

To provide insight on what types of events correspond to the UHS at low probabilities, Figure 3-3 compares the mean-hazard UHS at 1/10,000 per annum to the response spectra and PGA predicted by the Atkinson and Boore (2006) ground-motion relations for representative magnitudes and distances. The predictions of the ground motion relations are scaled (by a factor of 2) to represent motions near the median plus one standard deviation of the predictions, for the moderate events. This is appropriate for the comparison as hazard contributions tend to be dominated by events with amplitudes above the median. The UHS at 1/10,000 is approximately matched at low frequencies (<1 Hz) by an event of **M**7.5 at 300 km, corresponding to a large event offshore or in the Lower St. Lawrence. At intermediate-to-high frequencies, the UHS is approximately matched by an event of **M**6 at 50 km or **M**5.5 at 30 km; these would represent rare-but-possible moderate local earthquakes. Such local events could occur on buried crustal faults, most likely at depths of 5 km or greater. As has been noted earlier, the results of this analysis refer to natural seismicity, and do not address the probability of reservoir-induced seismicity (RIS). Thus the scenarios outlined do not include an RIS scenario or its associated ground motions.

Figure 3-3: Comparison of Gull/Muskrat Mean-Hazard UHS for 1/10,000 P.A.



Note: To predicted ground motions for **M**5.5 to 7.5 events according to Atkinson and Boore (2006) ground-motion relations (shown for NEHRP A).

4 REFERENCES

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McGuire, R. (1976). FORTRAN computer program for seismic risk analysis. U.S. Geol. Surv. Open-file Rpt. 76-67.

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5 LIST OF ABBREVIATIONS

CC	Central Canada
ENA	Eastern North America
GMPE	ground-motion prediction equation
GSC	Geological Survey of Canada
IRB	Iapetan rifted background
IRM	Iapetan rifted margin
M	moment magnitude
ML	local magnitude
MN	Nuttli magnitude
NA	North America
NBCC	National Building Code of Canada
NEHRP	National Earthquake Hazard Reduction Program
p.a.	per annum
PGA	peak ground acceleration
PGV	peak ground velocity
PSA	Pseudo-acceleration, 5% damped
RIS	Reservoir induced seismicity
UHS	Uniform hazard spectra

IR# JRP.60

Seismic Hazard - Ground Motions

Requesting Organization – Joint Review Panel **Information Request No.: JRP.60**

Subject - Seismic Hazard - Ground motions

References:

Newfoundland and Labrador Hydro - Lower Churchill Project: GI1170 - Seismicity Analysis. Document no. 722850-GI1170-40ER-0001-00

Related Comments / Information Requests:

CEAR # 202 (Natural Resources Canada)

Rationale:

The EIS indicates that the Gull Island dam is founded on overburden, while the Muskrat Falls dam is founded on rock. NRCan has stated however that the calculations found in the technical documentation submitted to NRCan are for Type "C" soils while calculations of ground motions should be adjusted to reflect the geology at the two sites. No mention is made of this adjustment of ground motions.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.60**

Information Requested:

The Proponent is asked to provide the results of calculations of ground motions for Muskrat Falls in the same manner as they are given for Gull Island, including an appropriate adjustment to reflect the differing geology at each of the two sites.

Response:

The hazard calculations for the Muskrat Falls dam were performed for hard rock (NEHRP A), as the dam is founded on rock. The ground motion relations for Muskrat Falls (NEHRP A) are described in sections 2.3.3 and 3.1 in SNC Lavalin (2009) included as Attachment A to the response to IR# JRP.59.

For the Gull Island dam, which is founded on overburden, the rock motions were amplified for the overburden (NEHRP D), as described in Section 3.2 (Table 3.2) in SNC Lavalin (2009).

Moreover, at Muskrat Falls, the ridge of land located between the north shore of the river and the rock knoll, called the "spur", is classified as a type "D" soil (NEHRP D), based on the data obtained from the 1979 geophysical investigations. This spur was not included in this study; however, the results obtained at Gull Island site are applicable to this area and this will be confirmed during the final design for Muskrat Falls.

The class-C peak ground acceleration (PGA) value at the Gull Island site for a two percent probability of exceedence in 50 years is 0.087 g. Applying the National Building Code site class factors, the corresponding PGA values for Muskrat Falls (on A) and Gull Island (on D) would be 0.061 g and 0.11 g, respectively. For comparison, the values obtained for this probability level from the site-specific analysis are 0.037 g at Muskrat Falls and 0.045 g at Gull Island.

The earthquake hazard analysis carried out during this study indicated the PGA for Gull Island and Muskrat Falls to be 0.11 g and 0.09 g, respectively, for the probability level of 1/10,000 per annum.

Reference:

SNC Lavalin. 2009. Part 2. Report on Earthquake Hazard Analysis: Gull Island and Muskrat Falls Damsites. Revision 3: July, 2009. Report for Lower Churchill Project. St. John's, NL.

IR# JRP.61

Seismic Hazards - Neotectonic Reactivation of Faults

Requesting Organization – Joint Review Panel **Information Request No.: JRP.61**

Subject - Seismic Hazards - Neotectonic Reactivation of Faults

References:

Newfoundland and Labrador Hydro - Lower Churchill Project: GI1170 - Seismicity Analysis. Document no. 722850-GI1170-40ER-0001-00

International Commission on Large Dams (ICOLD), 1998. Neotectonic and dams - Recommendations and case histories, *Bulletin 112*

Related Comments / Information Requests:

CEAR # 202 (Natural Resources Canada)

Rationale:

The Executive Summary states that "There is currently no evidence of seismic activity having occurred at the Lower Churchill sites in recent (geological) times." NRCan indicates that this comment is not warranted by the evidence presented in the EIS.

There is some regional background level of seismic activity (including two events in the 19th century). Evidence of pre-historic events may be found in geological features such as landslides and liquefaction. Unless proven otherwise, the numerous landslides near Muskrat Falls could be related to past seismic activity. See ICOLD (1998) for details on how this should be approached.

There are no signs of neotectonic reactivation of faults (possibly due to the absence of field mapping aimed at this task). No field investigations have been conducted to document possible neotectonic reactivation. LIDAR images are not sufficient to state that no neotectonic activity has taken place. The Proponent should be aware of the Bulletin 112 by ICOLD (1998) and should refer to this document in their examination of neotectonic reactivation of faults.

On page 4-20 the EIS states "Although there is an absence of confirmed active faults by direct field mapping…"

No field mapping was done specifically for this Project. Other mapping was done at a regional scale and was not looking at the neotectonic reactivation.

Part 1 of the Seismicity Analysis Document does not provide much information on possible neotectonic movements. Contrary to the title, there is no discussion of the links between geological structures and seismicity. On page 1-3, it is stated that "These images do not show any particular feature or information of concern about the faults forming the valley of the Churchill River". While reference is made to Natural Resources Canada, NRCan has indicated that they only provided the magnetic and gravimetric information, and not this conclusion. In any case, one can distinguish anomalies that trend parallel to the axis of the Lake Melville Rift Structure.

There is mention that faults were drilled and have clay gouges and closer jointing, which could be indicative of recent fault reactivation. In addition, the LIDAR image (Figure 3.1) shows extensive landslide activity, which could be, unless proven otherwise, the result of regional seismic activity.

The Proponent's conclusion and methodology is rather surprising, however because the vegetation is very dense, it will be very difficult to find any evidence of recent fault movement.

Examination of remote sensing imagery (available for free on Google Earth) reveals many outcrops along some shores of the area.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.61**

Information Requested:

The Proponent is asked to:

a. **provide information to explain whether geologists have looked at the field evidence to support the conclusions reached, or only LIDAR images;**

Response:

Engineering investigation and design of the Project has been ongoing since the 1960s and has included field investigation of the geological conditions at the sites. During 1970 and 1971, a geological investigation was conducted at the Gull Island site and a geological map of the area was developed. The investigation indicated that most faults in the region were ancient and stable and that bedrock is generally competent. A detailed study of the Muskrat Falls site was conducted in 1979 and included geotechnical field investigations and testing. Other work in the area of the Muskrat Falls site, related to the spur and associated pumpwell system, has concluded that the relatively low permeability and fine grained nature of the soils making up the spur are conditions that contribute greatly to the occurrence of landslides along the spur.

The scope of the report provided was to provide a review of recent information and to determine if further investigation was warranted at this stage in the design process. At the time of the site investigations, 2007-2008, the geologists were looking for site evidence of neotectonic movement. No geological structures were found, other than a few discontinuities. The LIDAR images were used to look for evidence to be checked in the field. No evidence was found that could be related to neotectonic movement. Consequently, no further investigation was undertaken. The search was done exclusively at the Gull Island site. With the lack of evidence for the region, no site investigation was judged necessary at Muskrat Falls. However, further analysis will be conducted later the detailed design phase. This additional analysis will include obtaining additional field evidence, if warranted, and will be provided to Natural Resources of Canada.

Reference:

SNC Lavalin. 2009. Part 2. Report on Earthquake Hazard Analysis: Gull Island and Muskrat Falls Damsites. Revision 3: July, 2009. Report for Lower Churchill Project. St. John's, NL.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.61**

Information Requested:

The Proponent is asked to:

b. **provide any information on plans for field studies which should be made to document the regional normal faults of the area with special emphasis on potential neotectonic movement;**

Response:

No further field studies are contemplated, at this time, to document potential neotectonic movements.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.61**

Information Requested:

The Proponent is asked to:

c. **correct the coordinates of Gull site on page 2-4 (they should be 52.96°N -61.42°W / Muskrat Falls 53.25 -60.77); and**

Response:

The coordinates on p. 2-4 of the Earthquake Hazard Analysis (Attachment A of IR# JRP.59) have been corrected in Revision 3 of Part Two.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.61**

Information Requested:

The Proponent is asked to:

d. **review the interpretation of seismic hazard at the site.**

Response:

Using the corrected coordinates the interpretation of seismic hazard at the site has been reviewed. The hazard calculations have been checked and it has been verified that they are not affected.

IR# JRP.62

Seismic Hazard - Reservoir-Triggered Seismicity (RTS)

Requesting Organization – Joint Review Panel **Information Request No.: JRP.62**

Subject - Seismic Hazard - Reservoir-Triggered Seismicity (RTS)

References:

Newfoundland and Labrador Hydro - Lower Churchill Project: GI1170 - Seismicity Analysis. Document no. 722850-GI1170-40ER-0001-00

ICOLD, 2008. Reservoirs and seismicity

Adams, John; Wetmiller, R.J.; Hasegawa, H.S; Drysdale, J.A, 1991. The first surface faulting from a historical intraplate earthquake in North America. Nature (London). 352; 6336, Pages 617- 619. 1991

Related Comments / Information Requests:

CEAR # 202 (Natural Resources Canada)

Rationale:

Page ii of the Seismicity Analysis (referenced above) indicates that "(o)nly a very low percentage of reservoirs are known to have triggered an induced seismic event." However, the EIS does not explain why this possibility should not be considered with respect to this Project. NRCan indicates that dams that exceed 100 m have a higher potential to trigger earthquakes (ICOLD, 2008).

The potential for Reservoir-Triggered Seismicity to occur with a sizable earthquake is an inherently difficult hazard to assess. However, it must be considered because Reservoir-Triggered Seismicity mostly occurs in the near field and at shallow depth; however the possibility of RTS must be considered in the design of the dam and associated structures. NRCan has indicated that the seismic reports present evidence that RTS is possible considering the local structural geology, the history of RTS in the Canadian Shield and the fracturing of some faults, however the application of the Risk Prediction Method is not clearly explained. In general, the report refers to worldwide RTS cases without considering nearby cases in Quebec (5 cases) as potential analogues to Lower Churchill. NRCan states that the author appears to be concerned with the occurrence of RTS, but in fact it is the main shock of the RTS that matters, not so much RTS itself. The seismic map of Figure 4-2 dates back from the 1970s, is out of date, and there are more modern maps on seismic hazards (2 generations).

The inference that "it is unlikely that a significant seismic activity will be triggered, i.e., activity equal or greater than M3 or M4 on the Richter Scale" is not supported by the material presented. These numbers do not relate to anything presented.

A special warning about RTS is presented in one study, but not taken into consideration in the EIS. NRCan has suggested that the Proponent consider the possibility of seismographic (not strong motion) monitoring.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.62**

Information Requested:

The Proponent is asked to provide:

a. **ground motions of a credible Reservoir-Triggered Seismicity main shock computed and compared with the ground motions from the probabilistic hazard calculations;**

Response:

As noted in the EIS, Volume IA, Sections 3.7.4 and 3.7.5, the analysis done for the siting of the generating facilities included consideration of the geology of the area. Stable geology, suitable for the siting of the Project facilities, is present at both sites selected for the generating facilities.

While the exact magnitude and distance of an RTS event is difficult to quantify, most of the energy in the type of RTS event considered in the seismicity study (M5 or less, nearby) would be at frequencies well above the natural frequency of the dams, and would be of short duration. This means that the natural frequency of the dam will not be excited by RTS. The type of modeling requested will be carried out during the detailed design stage of the Project. This is typical for reservoir engineering design and construction projects. Probabilistic hazard calculations will be analyzed in more detail as will all other loads or combination of loads and will be incorporated into final design so that the dam is sited and constructed in a manner that will withstand the likely seismic events in the project area.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.62**

Information Requested:

The Proponent is asked to provide:

b. a reference to the Risk Prediction Method included in the Vladut report so that the method can be properly evaluated; and

Response:

A reference to the Risk Prediction Method included in the Vladut report is as follows:

Vladut Thomas 16th Congress on Large Dams, San Francisco, ICOLD France (1988), "Approaches to the mitigation of reservoir induced seismicity in environmental impact assessment" Question 60, Report 40, pp.637-656.

Requesting Organization – Joint Review Panel **Information Request No.: JRP.62**

Information Requested:

The Proponent is asked to provide:

c. **a discussion of the potential and need for seismographic (not strong motion) monitoring to be undertaken in the Project area prior to construction.**

Response:

As noted by Natural Resources Canada, seismographic (not strong motion) monitoring was recommended in the seismicity study (SNC Lavalin 2009), however, this statement was not included in the EIS. To clarify, Nalcor Energy (Nalcor) will be undertaking seismographic monitoring in the Project area prior to construction, as recommended in the seismicity study. The plan is to install four short period seismographic stations in the Project area to monitor activity and any induced ground motions.

Reference:

SNC Lavalin. 2009. Report on Earthquake Hazard Analysis: Gull Island and Muskrat Falls Damsites. Revision 3: July, 2009. Report for Lower Churchill Project. St. John's, NL.