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LOW PROBABILITY GROUND MOTIONS FOR A PROPOSED DAM SITE IN NORTHEASTERN BC

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ABSTRACT: The proposed dam site is located east of the Northern Rocky Mountain Trench and cordilleran deformation front in a region of relatively low seismicity. The region east of the site has been relatively quiet without any significant natural earthquakes until 2001, when a M5.4 Dawson Creek occurred approximately 70 km southeast of the site. This earthquake changed the potential for moderate to large earthquakes east of the deformation front. However, no active fault is known to exist nor have they been mapped. The local earthquakes are dominated by relatively small magnitude induced earthquakes due to oil and gas activities in the region. Alternative source zone models were developed to capture the epistemic uncertainties in the hazard due to the natural and induced earthquakes. A probabilistic approach with a logic tree to treat epistemic uncertainties was used to estimate low probability ground motions. As the site is influenced by both Western and Eastern North American type sources, a suite of ground motions prediction equations representative of both conditions were used. The estimated 1/10,000 Annual Exceedance Probability (AEP) Peak Ground Acceleration (PGA) for the site is 0.23 g.

1. Introduction

The site is located in the northeastern British Columbia in a region of relatively low seismicity. However, a magnitude M5.4 Dawson Creek earthquake occurred approximately 70 km southeast of the site on April 14, 2001. This is the largest historical earthquake to have occurred in this area and it changed somewhat the perception about the natural seismicity near the site, which is located east of the Cordilleran deformation front close to Fort St. John, BC. The site is also close to the oil and gas fields located around the Fort St. John and there have been induced seismic activities in this area. Locally, the induced seismic activity dominates, especially after 1984, when fluid injection was used to enhance the recovery of oil/gas. A site-specific probabilistic seismic hazard assessment was conducted to derive ground motions with 1/10,000 Annual Exceedance Probability (AEP). In the assessment, the seismic hazard at the site due to both natural and induced seismicity was considered. Uncertainties in the assessment are also addressed quantitatively to obtain reliable estimates of low probability ground motions. The study presented in this paper was conducted to determine preliminary estimate of ground motions, which could be used in the early stages of the design of a proposed dam.

2. Tectonics and Earthquakes

The proposed dam site is located in the Northeastern British Columbia and east of Southern Cordillera. The southern Canadian Cordillera, which is the Cordillera region seaward of the Rocky Mountain Trench, extending from the Canada/United States border in the south to the British Columbia/Yukon border in the north is a region of relatively low seismic activity compared with the northern Canadian Cordillera. The magnitudes of notable large events to occur in the southern Cordillera ranged between M5.4 and M6. Most of the seismic activity in the region is due to natural seismicity. However, there are regions where induced earthquake activity has been attributed to hydrocarbon extraction and associated high-pressure water injection.

Northern Rocky Mountain Trench (NRMT) Fault strike slip system is one of the major faults in the area of interest. North of 54N, the trench follows a trace of a large right lateral strike slip fault. This fault had at least 450 km of dextral displacement since the mid-Cretaceous. It was considered to have been active from the pre mid-Cretaceous to the Eocene or Oligocene time. South of the Walter Creek Fault, which is linked to the NRMT had about 60 km of right lateral strike slip. The McLeod lake fault, which was considered a splay of NRMT was considered to have been active during Paleocene to Eocene time. West of the NRMT are several groups of associated transcurrent faults including Pinchi, Thibert and Ktcho faults, which occur along the eastern margin of the Intermontane Belt.

Earthquake catalogue were obtained from Geological Survey of Canada (GSC), Ottawa and Pacific Geoscience Center (PGC), Sydney with data from 1700 to December 2007. While the PGC catalogue had all the events converted to moment magnitude scale, the data obtained from the GSC, Ottawa (SHEEF catalog) had a mixture of magnitude scales. The events in the SHEEF catalog were converted to moment magnitude.

Figure 1 shows the earthquakes that occurred between 1985 and 2007 within about 100 km from the site obtained from the Earthquakes Canada. There are two clusters of activity within 100 km of site. One is located in the Fort St. John area just north of the site and the other is located about 70-100 km northwest of the site. All the events in the first cluster were recorded after 1984, and had a maximum magnitude of 4.3. The events in the second cluster were recorded after 2001, and had a maximum magnitude of 3.2. On April 14, 2001, a magnitude 5.4 Earthquake occurred approximately 70 km southeast of the site at depth 15 km.

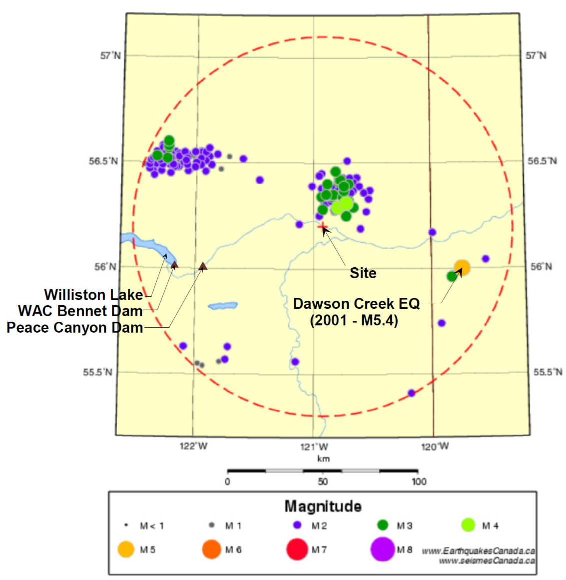

Fig. 1 - Epicenters of Earthquakes within 100 km from the Site between 1985-2007.

3. Induced Seismicity Near Fort St. John Area

Activities by humans that have resulted in the stimulation of earthquakes include: injection of fluid into rocks at depths; extraction of fluids from subsurface formations; impoundment of reservoirs behind high dams; detonation of large underground explosions; and opening of underground cavities for mining. The intense oil and gas activity in the Fort St. John area and the induced seismicity associated with it is of interest to seismic hazard assessment at the site. The Fort St. John area in the northeastern BC is a major oil and gas producing area in BC. The first gas discovery was made in this area in the early 1950s and the first oil well was drilled in the mid 1970s. However, significant oil production and enhanced recovery by injection of fluid did not occur until the 1980s. A few years later, increased seismic activity was observed in this area, which was previously considered as a region of very low seismicity. This activity appears to continue until the present time and earthquakes with magnitude as high as 4.3 were recorded in this Fort St. John area. There were no earthquakes either recorded or felt in this area prior to 1984. The seismographic network established in the 1960s in Western Canada would have permitted the recording of at least moderate-magnitude earthquakes, though the detection capabilities for small events improved in the 1980s.

Horner et al. (1994) studied the earthquakes that occurred in this area between 1984 and 1993, and showed that there is both spatial and temporal correlation between these earthquakes and the process of oil extraction and the associated high-pressure water injection. They also noted that the injection pressure of about 25 MPa used during this period was perhaps high enough to induce failure on favorably oriented pre-existing faults. Horner et al. (1994) noted that there was abundant evidence for faults in the Peace River Arch (PRA) region where these oil and gas fields were located and this PRA region had been tectonically active since at least the Proterozic. The May 22, 1994 Mw4.3, earthquake, which occurred 10 km northeast of Fort St. John, was considered induced (Horner et al., 1994). This earthquake was felt in the area bounded by Fort St. John, Charlie Lake, North Pine and Cecil Lake and is the largest recorded earthquake near Fort St, John. The March 8, 1970 M_N4.6, Snipe Lake earthquake, which occurred in the Rocky Mountain House area located southeast of Fort St. John, is the largest induced earthquake ever recorded in that region. Although this earthquake was considered to be induced by the oil and gas extraction in the Rock Mountain House area (Milne, 1970), there was insufficient data to make a definitive conclusion. On May 28, 2012, a 4.5 magnitude earthquake occurred at 9 km southeast of the site at focal depth of 3 km. This earthquake is slightly larger earthquake than the 1994 magnitude 4.3 earthquake, which occurred 17 km north of the site.

Reservoir induced seismicity at the site of this 60 m high dam was considered remote as the reservoir filling at the WAC Bennet dam (183 m high), Peace Canyon Dam and Mica Dam did not cause any earthquakes.

4. Probabilistic Seismic Hazard Assessment

The quantification of the probabilistic seismic hazard at the site is estimated using the well-known Cornell-McGuire approach. They consist of defining seismic sources, either areal or linear faults; definition of the earthquake frequency within each source zone; definition of the attenuation of ground shaking relationship for earthquakes in the area, and, finally, numerical summation of the contributions of all earthquake magnitudes at all distances from the site from each source. The computer program EZ-Frisk (Risk Engineering Inc., 2008) was used in this project to perform the calculations in the last step.

Two types of uncertainties associated with the seismic hazard were considered in the analyses, namely the aleatory uncertainty and the epistemic uncertainty. The aleatory uncertainty or the random uncertainty is due to the physical variability of the earthquake processes such as the randomness of the location of the earthquakes and the scatter in the earthquake ground motions. This uncertainty is readily incorporated within the Cornell-McGuire analysis framework by integrating over the statistical distribution in the ground motion relations and by considering the randomness in earthquake location. The epistemic uncertainty or the professional uncertainty is due to incomplete understanding the physical models governing the earthquake occurrence and ground motion generation. The epistemic uncertainty was considered in the analyses following a logic tree approach.

4.1. Seismic Source Zone Models

The uncertainties in the source zone model and the ground motion relations are the key parameters that can significantly affect the seismic hazard estimates. Two alternative source zone models, referenced as Model 1 and 2, were developed to capture the regional seismicity and the local seismicity, respectively. The induced earthquakes are treated in two different ways, consistent with the two views expressed in the next section, during the development of our source zones. In Model 1, the area with induced activity was included as part of broad zone without separating it from natural seismicity in the surrounding areas. In Model 2, this area was separated from the rest of the area surrounding it and treated as a separate source zone.

4.1.1. Modelling Induced Seismicity

One argument related to oil and gas production or injection related seismicity is that the earthquake events are the result of pre-existing stress and fault conditions. These earthquakes are considered to be triggered, not caused, by oil and gas extraction activity, and the earthquakes would be expected to occur naturally at some point in the future, had they not been triggered. If the seismicity was observed long enough, the induced earthquakes should be expected to blend into the overall activity rates for the region. These events therefore form part of the hazard, and the influence of the oil and gas activity is to alter the timing of these events, rather than their overall long-term rates. To accommodate this view, the region of induced seismicity can be included within a large source zone, since the observed increased rates of activity could occur naturally at other locations.

Another view is that events that have been induced by oil and gas activity are not part of the natural seismicity rates, since the combination of in-situ stresses and geological structure was not sufficient to cause the earthquakes in the absence of the hydrocarbon extraction. Proponents of this view may argue that these induced events should not be included in the recurrence statistics for the purposes of calculating earthquake hazard. However, the cause of the earthquakes is immaterial if these events are capable of causing damage. Thus, an alternative approach is to treat the region of induced activity as a separate source zone. The induced activity can be excluded from the calculations of activity rates in larger, regional source zones where it would bias the statistics for the entire zone upward, but the hazard from the region of induced activity would still be included in the hazard model.

4.1.2. Source Zone Models 1

Source zone Model 1 was developed to capture the regional seismicity and it was modified from Geological Survey of Canada's model for Western Canad (Adams and Halchuck, 2003); it was subdivided into three models: Model 1a, 1b and 1c. Figures 2, 3 and 4 show the proposed source zone Models 1a, 1b and 1c, respectively, and the historical seismicity.

<u>Model 1a</u>: In this model, the northern and southern rocky mountain trenches are represented by zone RMT and the adjacent fold and thrust belt is represented by zone FTB. The eastern boundary of FTB is drawn along the cordilleran deformation front. Activity east and north of FTB zone is captured into zones EDF and NDF, respectively. The site is located within the EDF zone. Model 1a assumes that the seismic activity within the region is controlled by the known tectonic features and the activity is confined to their apparent boundaries.

<u>Model 1b</u>: This model is a slight variation of Model 1a. In this model, the site is brought into zone FTB', which is wider than the FTB zone in Model 1a, and it encompasses the apparent cordilleran deformation front. The adjacent zone is modified into EDF' in Model 1b. Model 1b is based on both geological controls and historical seismic activity, which can be observed east of the cordilleran deformation front.

<u>Model 1c</u>: This model is a slight variation of alternative Model 1b. In this model, the source zones RMT, FTB' and FHL' are brought into a single zone RFT, which captures the seismic activity at Rocky Mountain Trench, fold and thrust belt and Flat Head Lake. This model assumes that the pockets of observed seismic activity in this area can occur anywhere within the zone RFT. Prediction of seismic hazard at the site using this model will likely be conservative.

4.1.3. Source Zone Models 2

Source zone Model 2 was proposed to capture the local seismicity. It was subdivided into four models: Models 2a, 2a', 2b and 2b'. Figures 5 and 6 show the Models 2a/2a' and 2b/2b' respectively, together with historical seismic activity in this area. Figure 7 shows the source zone boundary used for SJS in Model 2a and SJB in Model 2b. The source zone boundaries used for SJS' in Model 2a' and SJB' in Model 2b' are the same as those for SJS and SJB, respectively. In these models, only the focal depth is different.

The primary purpose of Model 2 and its sub-models is to capture:(1) the cluster of seismic activity observed just north of the site in the Fort St. John area at about 20 km and northwest of the site at about 80-100 km; (2) induced seismic activity associated with the oil and gas fields; (3) moderate magnitude tectonic earthquakes such as the 2001 M5.4 Dawson creek earthquake, which may occur east of the deformation front close to the site; and (4) any reservoir induced earthquakes, for which the induced seismicity near the site may be considered an analogue.

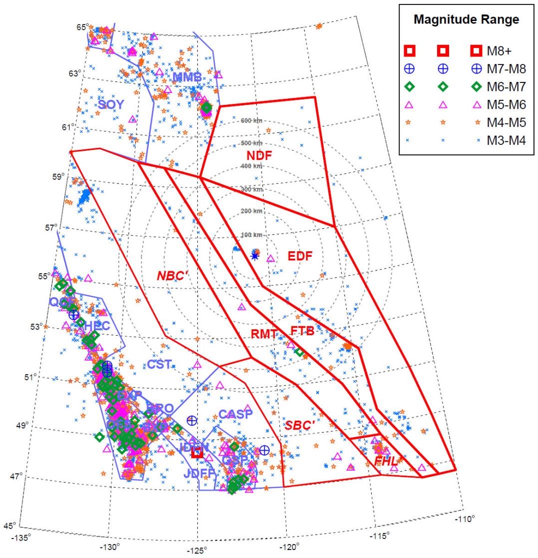

Fig. 2 - Model 1a and Earthquakes

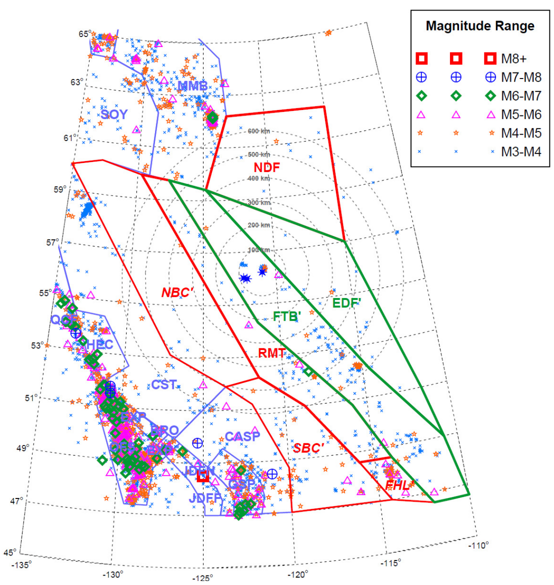

Fig. 3 - Model 1b and Earthquakes

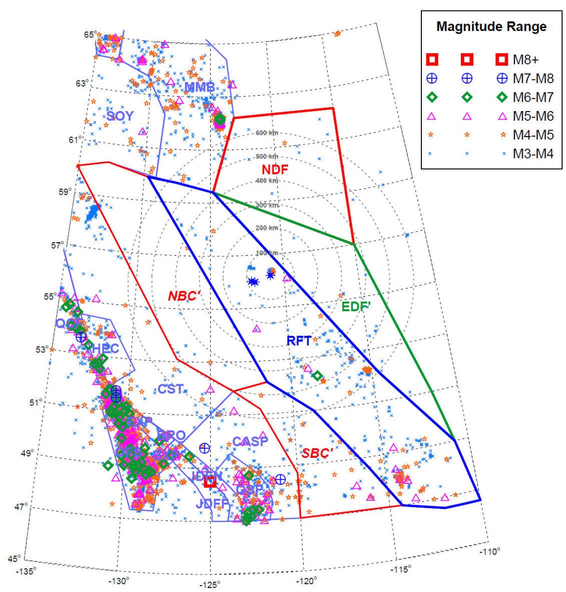

Fig. 4 - Model 1c and Earthquakes

Model 2a: SJS zone in Model 2a was drawn encompassing the site, cluster of seismic activity observed just north of the site in the Fort St. John area and the oil and gas fields in this area. The depth of this zone was taken as 5 km and is considered appropriate for the induced seismic activity. Note in this model, the source zone NFT1' excludes seismic activity within the zone SJS. Model 2a': The source zone boundaries for Models 2a and 2a' are the same. The only difference is the depth of the source zone SJS, which was taken as 10 km in Model 2a' and renamed as SJS'. This variation was introduced to consider the fact that a tectonic earthquake such as the 2001 Dawson Creek earthquake, which occurred at about 15 km depth, may occur at depths deeper than 5 km.

Model 2b: Zone SJB in Model 2b was drawn encompassing the site, cluster of seismic activity observed just north of the site and north west of the site at about 80-100 km, the locations of the 2001 Dawson Creek earthquake and the reservoirs of WAC Bennett Dam and Peace Canyon Dam. Similar to SJS, the depth of this zone was also taken as 5 km. In this model also, the source zone NFT2' excludes seismic activity within the zone SJB. Model 2b': The source zone boundaries for Model 2b' are the same as those for Model 2b and the only difference is the depth of source zone SJB, which was taken as 10 km and renamed as SJB'.

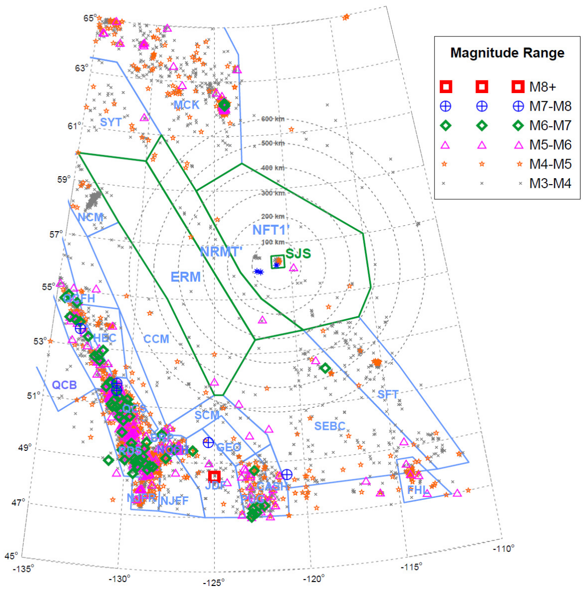

Fig. 5 – Model 2a and Earthquakes

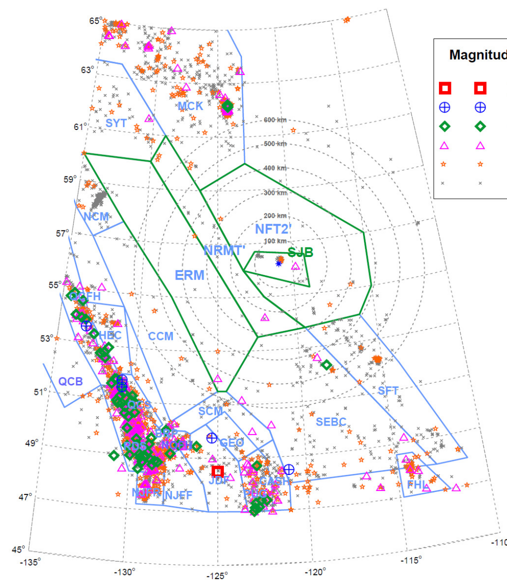

Fig. 6 – Model 2b and Earthquakes

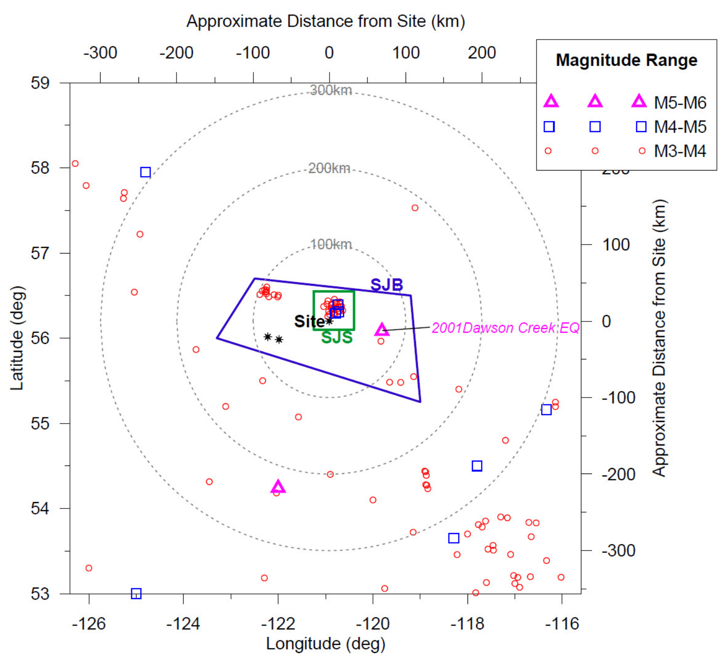

Fig. 7 – Zone SJS in Model 2a and SJB in Model 2b

4.2. Magnitude Recurrence Relationships

The earthquake recurrence (M-R) within each source zone was assumed to follow the well-known Gutenberg-Richter relationship. The Gutenberg–Richter parameters for each source zone are determined by plotting the logarithm of the number of events per year against earthquake magnitude. These relationships are dependent on the reliability of the earthquake records in an area. Prior to calculating the magnitude-recurrence relationships for each of the source zones, earthquake data were removed from the database for periods where the data were incomplete within a given magnitude range. This prevents bias in the computation of per annum activity rates at each magnitude level. Exponential curve fitting was generally used for the source zones to develop the M-R relationships, and they were truncated at the maximum magnitude values selected for the zones.

Figure 8 and 9 show the M-R relationships for the pertinent source zones in the Models 1 and 2. Exponential curve fitting was used for all source zones and the relationships were truncated at the "best" estimate value of the maximum magnitudes.

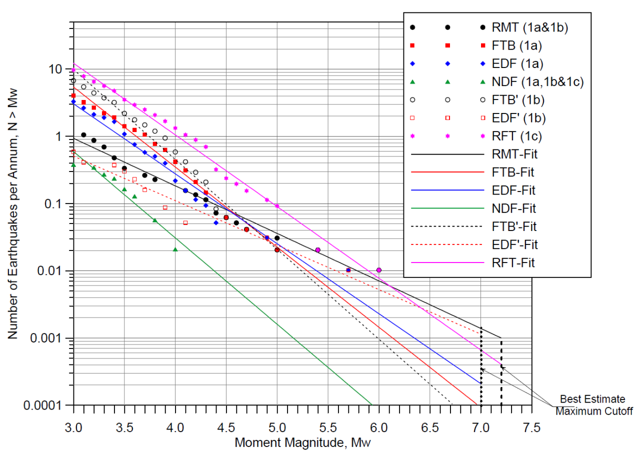

Fig. 8 – M-R Relationships for Model 1 Zones

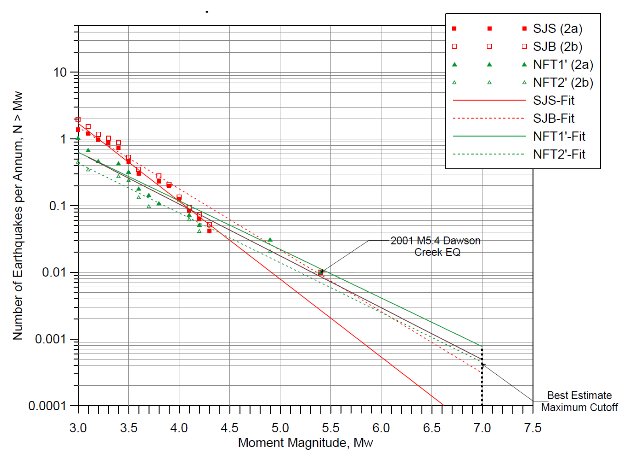

Fig. 9 – M-R Relationships for Model 2 zones

4.3. Maximum and Minimum Magnitudes

It is generally accepted that the low magnitude earthquakes below a certain threshold value are incapable of causing damage to engineered structures and thus should not be considered. A minimum magnitude of 5.0 was used. Maximum magnitude is the possible maximum magnitude of earthquake that may occur within a zone. Three possible values called the best, upper and lower bound values were used for each zone. The best estimate for zones surrounding the site was taken as 7.0 except for zones RMT, RFT and FHL' for which a slightly higher magnitude of 7.2 was used. For zones located east of the deformation front, noticeably the zones SJS and SJB, were assigned 7.0, 6.8 and 7.5 as the best, lower and upper bound estimates. Johnston et al. (1994) and Fenton et al (2006) concluded that 7.0 is the approximate maximum magnitude that occurs in unrifted stable continental cratons throughout the world, and would therefore be the lowest maximum magnitude that should be considered for any continental source zone. Adams and Atkinson (2003) noted best estimates of maximum magnitude are 7.0 for the stable continental shield, and 7.0-7.8 for zones of weakness within the continent. Typical upper and lower bounds are 0.3 units higher and lower than best estimates. Ebel and Kafka (1991) note that because earthquake activity in the region cannot be identified with specific faults and geologic features, geologic arguments cannot be used to further constrain the maximum magnitude that can be expected in a region.

4.4. Ground Motion Prediction Equations

In probabilistic seismic hazard analyses, the ground motion variability, which is usually described by a lognormal distribution, has significant impact on the computed hazard. The standard deviation of the log normal distribution is typically used to characterize the aleatory uncertainty or the random uncertainty in the ground motions. Abrahamson (2006), who studied the truncation of lognormal distribution of ground motion relations, concluded that using an untruncated lognormal distribution in probabilistic seismic hazard analyses is appropriate for ground motion values that are below the physical limits of the underlying rock or soils.

The low probability hazard at the site is dominated by relatively shallow crustal earthquakes, which may occur east and west of the limit of the Cordilleran deformation. Therefore, a set of four GMPEs was used:

Boore and Atkinson (2008) and Campbell and Bozorgnia (2008): These recent empirical ground motion relations take advantage of the global database of records for shallow earthquakes in active tectonic regions and considered appropriate for the shallow crustal sources in the Western North America (WNA). These were developed as a part of PEER-NGA (Pacific Earthquake Engineering Research Center-Next Generation Attenuation) project and they approximately span the range of results for moderate events at close distances at short periods, and large events at longer distances at longer periods. These events are expected to dominate the hazard at the site;

Atkinson (2005): This relationship was based on modifying an empirically-calibrated stochastic model of California relations to be appropriate for British Columbia rock site conditions, which differ from those in California. This equation is the only equation that actually examines British Columbia ground motion data and considers typical site conditions in BC;

Atkinson and Boore (2006): This equation was developed for predicting ground motions in Eastern North America (ENA).

As numerous GMPEs are currently available and newer GMPEs are continuously developed, Bommer et al. (2010) developed a ten point criteria as a basis for selecting GMPEs for the seismic hazard analyses. They identified eight GMPEs from more than 150 as passing all their ten selection criteria. Except for Atkinson (2005), other three equations were in the list identified by Bommer et al. (2010). The reference site condition for the analyses was taken as NEHRP Site B/C boundary, which is defined as having a time-averaged shear wave velocity of 760 m/s in the top 30 m.

4.5. Logic Tree

Figure 10 shows the logic tree used in the analyses to handle the epistemic uncertainty and the corresponding weightings. The uncertainties in the source zone models, maximum magnitudes and GMPEs were considered. Alternative branches in the logic tree were assigned subjective weights based on the rationale explained earlier.

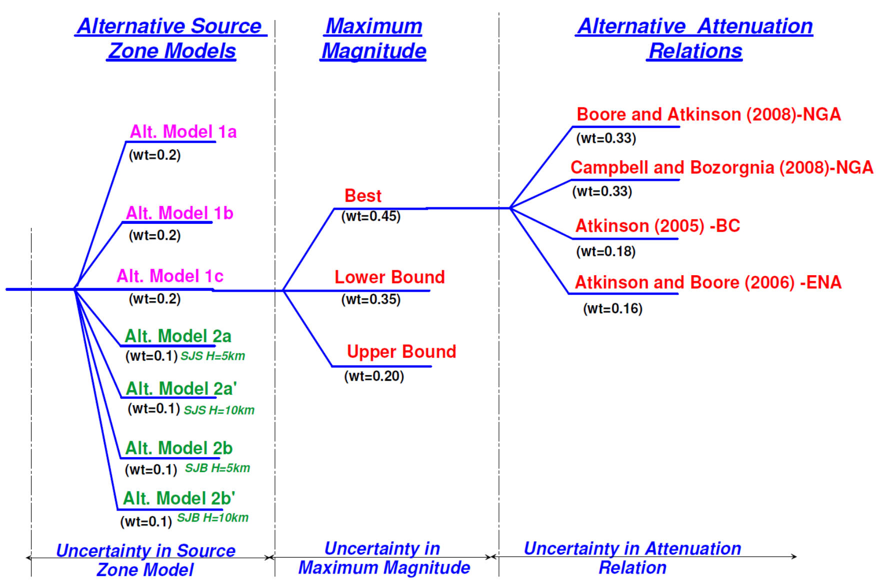

Fig. 10 – Logic Tree

4.6. Results

Figure 11 shows the annual probability of exceedance versus PGAs corresponding to mean, median, 16th and 84th percentiles. Figure 12 shows the corresponding Uniform Hazard Response Spectra (UHRS) for ground motions with 1/10,000 AEP. Figures 13 and 14 show the individual results for the source zone Models 1 and 2, respectively.

The 1/10,000 AEP mean, median and 84th percentile PGA values are 0.23 g, 0.12 g and 0.29 g, respectively. As evident from Figures 13 and 14, the 1/10,000 AEP ground motions predicted by “regional” Model 1 and its sub-models are significantly lower than those predicted by the “local” Model 2 and its sub-models (2a, 2a’, 2b and 2b’). The hazard contribution from the Model 2, which was assigned 40% weight, dominates the hazard at the site. Among sub-models for Model 1, the ground motions from Model 1c are greater than those predicted by Models 1a and 1b as expected. Among sub-models for Model 2, the ground motions predicted by the Models 2a/2a’ are greater than those predicted by Models 2b/2b’, which are much bigger in size than the models 2a/2a’. Smaller focal depth 5 km used in Models 2a/2b apparently lead to greater ground motions than by Models 2a’/2b’ for which 10 km was used. Among the GMPEs, Atkinson and Boore (2006) consistently predicted greater motions compared to the others, as expected due to the lower attenuation and higher stress drops that are applicable to ENA.

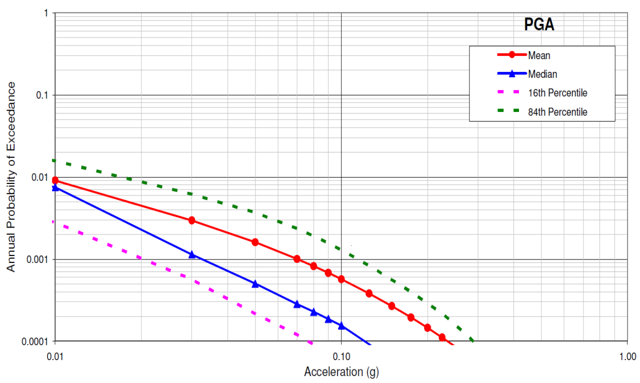

Fig. 11– Probability of Exceedance versus PGA

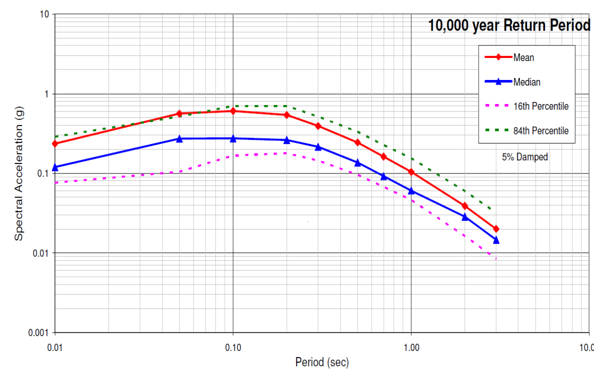

Fig. 12 – 1/10,000 AEP UHRS

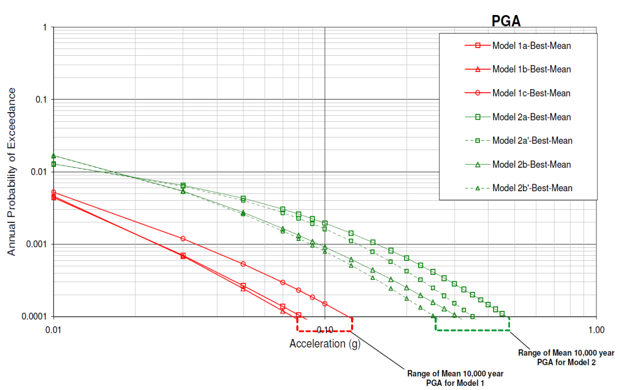

Fig. 13– Probability of Exceedance versus PGA for Each Model

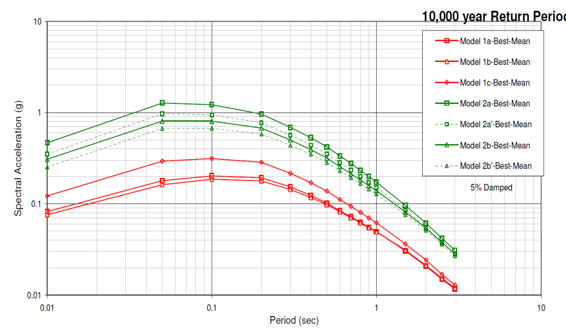

Fig. 14 – 1/10,000 AEP UHRS for Each Model

5. Summary and Conclusions

A site specific seismic hazard assessment was performed for a dam site in northeastern, BC to derive ground motion parameters corresponding to 1/10,000 AEP. The site is located east of the Northern Rocky Mountain Trench and cordilleran deformation front in a region of relatively low seismicity. The region east of the site has been relatively quiet without any significant natural earthquakes until 2001, when a M5.4

Dawson Creek occurred approximately 70 km southeast of the site. This earthquake changed the potential for moderate to large earthquakes east of the deformation front. However, no active fault is known to exist nor have they been mapped. The local earthquakes close to the site are dominated by relatively small magnitude induced earthquakes due to oil and gas activities in the region. Seismic hazard at the site due to both induced and natural seismicity were considered in a probabilistic seismic hazard analysis to derive ground motions with 1/10,000 AEP. Owing to the uncertainties in the model and model parameters, several alternative models and model parameters were considered using a logic tree approach. As the site is influenced by both Western and Eastern North American type sources, a suite of GMPEs representative of both conditions were used. The 1/10,000 AEP PGA for the site is 0.23 g.

6. Acknowledgements

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