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# Site-Specific Seismic Analysis for Concrete Gravity Dams: A Case Study from Ontario

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## ABSTRACT

Seismic design of ordinary building structures in Canada typically involves choosing appropriate spectral acceleration values from the National Building Code of Canada (NBCC). This design approach, however, is not applicable to dams because they typically behave differently under seismic loads, have very short periods of vibration and may have higher consequences from partial damage or failure.

The Canadian Dam Association Dam Safety Guidelines and the Lake and Rivers Improvement Act, indicate that dam structures in Ontario shall be assessed using site-specific probabilistic seismic hazard analyses that account for the local ground conditions, and the earthquake ground motions that act on the structure.

J.L. Richards and Associates Limited (JLR) carried out a dam stability analysis of the West Nipissing Power Generation dams located in Sturgeon Falls, Ontario, a region of low historical earthquake activity and hazard. Based on the "Very High" Hazard Potential Classification of the dams, the design earthquake requires a 5,000-year return period ground motion for seismic analysis and design. During preliminary analysis, the dams were analyzed using the Equivalent Static Force Procedure outlined in the NBCC to find that the earthquake load cases govern the design of these dams.

To validate the seismic values used in the analysis, JLR, in collaboration with Golder Associates Ltd. (Golder), carried out a site-specific seismic hazard study for the dams. In this study, a site-specific uniform hazard acceleration response spectrum (UHRS) was developed for the site with a $V_{s,30}$ of 1812 m/s. Synthetic and actual acceleration time-history records were scaled to match the site-specific UHRS. Based on the site-specific seismic study, we found that extrapolating ground motions from the 2015 NBCC provided unconservative estimates of spectral accelerations at this site. In addition, engineering uncertainties were minimized and decisions on dam stabilization retrofits validated by using a more comprehensive and site-specific analysis.

Keywords: Site-Specific Seismic Hazard Assessment, Time-History Analysis, Concrete Gravity Dams

## INTRODUCTION

The process for the seismic design and analysis of dams differs from the procedures outlined in the National Building Code of Canada (NBCC) [1], and other similar codes. These codes are typically referred to when completing seismic analyses of structures in Canada. Buildings in Canada are designed for different importance levels (e.g. low, normal, high, or post-disaster) depending on their use and occupancy while dams are designed based on their Dam Class or Hazard Potential Classification (HPC) depending on the potential losses (in terms of life safety, property, environment and heritage value), should a dam failure occur. This is outlined in the Dam Safety Guidelines published by the Canadian Dam Association (CDA Guidelines) [2].

Common buildings and structures are seismically designed for ground motions with a return period of 2475 years (2% probability of exceedance in 50 years). Factors are then applied to the seismic acceleration values (published in the NBCC 2015) to account for the importance level of the structure. For dams, the return period used for seismic design depends on the Dam Class, or HPC, and may vary quite significantly from dam to dam. In the CDA Guidelines [2], dams with a "Low" Dam Class are designed for ground motions with a return period 100 years (probability of exceedance of 39.5% in 50 years) and dams with an "Extreme" Dam Class are designed for a ground motions with a return period of 10,000 years (probability of exceedance of 0.5% in 50 years). Spectral values for Canadian cities with return periods above or below 2475 years can be obtained or extrapolated from the Seismic Hazard Calculator published on National Resources Canada's (NRCan's) website [3].

While it is fairly standard practice to use ground motion values from the NBCC [1] or extrapolated values from NRCan [3] for preliminary analysis of dams, these ground motions are not suitable for detailed design of concrete gravity dams. The CDA Guidelines [2] and the Lake and Rivers Improvement Act (LRIA) [4] administered by the Ontario Ministry of Natural Resources and Forestry (OMNRF), indicate that dam structures in Ontario shall be assessed using site-specific probabilistic seismic hazard analyses that account for the local ground conditions and the earthquake ground motions that act on the structure. The site-specific requirement is to account for sources of uncertainty in the tectonic setting and local site factors that are not accounted for in the NBCC seismic hazard values.

In order to apply the above principles in the stability analysis of the existing West Nipissing Power Generation Power Dam and Spill Dam located in Sturgeon Falls, Ontario, a probabilistic seismic hazard assessment (PSHA) was completed to develop a site-specific acceleration response spectrum. Acceleration time-history earthquake records were then selected and scaled to match the site-specific response spectrum for future use in the dynamic analysis of the dam structures.

## LITERATURE REVIEW

In Ontario, the design and analysis of dams is carried out in accordance with the CDA Guidelines [2], the LRIA [4] and application of established engineering principles. While guidance for the seismic design of dams is provided in the documents noted above, there is very little information provided within these documents on the appropriate seismic methodology to be used. As such, the NBCC 2015 Structural Commentaries [5] are often used as a reference to gain an understanding of seismic principles. The following section provide a brief overview of the seismic procedures and principles outlined in the documents referenced above.

### Canadian Dam Association Dam Safety Guidelines (2013)

The CDA Guidelines [2] provide guidance on the analysis and assessment of dams. For analysis of dams under seismic loading, a traditional standards-based approach is recommended. This approach involves determining the dam classification, and choosing the annual exceedance probability (AEP) for earthquakes based on that Dam Class. Table 1 below shows the AEP and percent chance of occurrence recommended for dams based on their Dam Class.

*Table 1. Earthquake Hazards Standards-Based Assessment (CDA Guidelines [2])*

| Dam Class | Annual Exceedance Probability | Percent Chance of Occurrence |
|---|---|---|
| Low | 1/100 | 39.5% in 50 years |
| Significant | Between 1/100 and 1/1,000 | Between 39.5% in 50 years and 4.9% in 50 years |
| High | 1/2475 | 2% in 50 years |
| Very High | ½ between 1/2475 and 1/10,000 or MCE | ½ between 2% in 50 years and 0.5% in 50 years |
| Extreme | 1/10,000 or MCE | 0.5% in 50 years |

The CDA Guidelines [2] also indicate that the use of seismic zoning maps published in the NBCC [1] are for common buildings only and they are not applicable to dam design. CDA notes that the use of NBCC seismic values may be unconservative for remote sites (where most dams are located). Mean hazard values are also recommended for dam design and the pre-2015 NBCC [1] values represent median hazard values (the 2015 NBCC now provides mean values). It is further noted that the seismic loading on dams is dependent on the intensity of the ground shaking at the site, and solely the earthquake magnitude.

Based on the above, the CDA Guidelines [2] recommend that a site-specific seismic hazard assessment is carried out in order to develop the Earthquake Design Ground Motion (EDGM) parameters. The EDGM parameters must be developed based on the consequences of dam failure (i.e. annual exceedance probability is based on the Dam Class), local and regional tectonic information, and statistical analysis of historic earthquakes in the region. The seismic hazard must consider the contribution of various magnitude earthquakes and their distances to the site.

### Lake and Rivers Improvement Act (2011)

Direction on seismic design is provided in the LRIA [4] under the *Technical Bulletin for Seismic Hazard Criteria, Assessment and Considerations*. The bulletin provides similar direction to the CDA Guidelines [2], and clearly states that the earthquake ground motions at dam sites are to be developed by carrying out a site-specific seismic assessment. The bulletin also provides a flowchart showing the process used in evaluating the seismic safety of a dam. Figure 1 below is a summarized version of the chart provided in the LRIA bulletin.

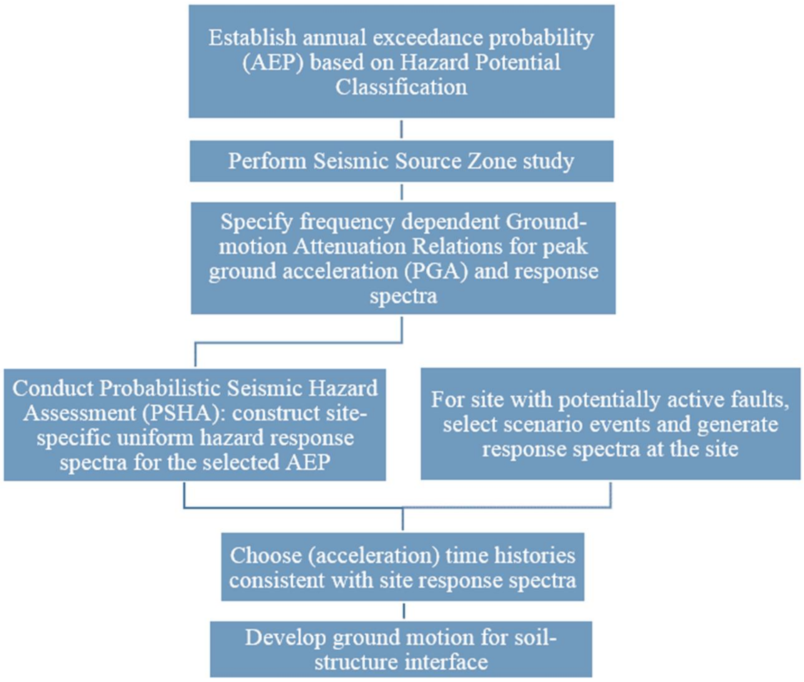



*Figure 1. LRIA Process to assess seismic safety of a dam [4]*

Similar to the CDA Guidelines [2], the LRIA [4] indicates that the peak ground acceleration (PGA) and pseudo-spectra acceleration (PSA) provided in the NBCC are not applicable to dams. The lack of applicability is because the established probability of exceedance used for seismic design of buildings (i.e. 2% in 50 years), and the need to extrapolate seismic values for lower probability design of dams does not consider the ground motion characteristics necessary to establish the design earthquake scenarios for analyses of dams.

Determination of the annual exceedance probability for the design earthquake is based on the Hazard Potential Classification (HPC) of the dam as outlined in Table 2 below. The HPC is similar to the Dam Class used in the CDA Guidelines [2]. The associated annual exceedance probabilities are also similar, but differ slightly for life safety, property, and environmental considerations.

*Table 2. Earthquake Annual Exceedance Probability (LRIA [4])*

| **HPC** | **Earthquake Design Ground Motion (Annual Exceedance Probability)** | | | |
|---|---|---|---|---|
| | **Life Safety** | | **Property and Environment** | **Cultural - Built** |
| Low | 500 year | | | |
| Significant | 500 year to 1,000 year | | | |
| High | 10 or fewer | 2,500 year | 1,000 year to 2,500 year | 1,000 year |
| Very High | 11 to 100<br>More than 100 | 5,000 year<br>10,000 year | 2,500 year to 10,000 year | |

**Seismic Method in National Building Code of Canada and Commentaries**

The National Building Code of Canada (NBCC) [1] and the NBCC 2015 Structural Commentaries [5] provide very clear guidance on seismic design and analysis of new and existing structures. The seismic data tabulated in the NBCC provides spectral values for cities and towns throughout Canada for a return period of 2475 years. For seismic design of buildings, there is a well-established method to calculate the acceleration response spectrum based on the published values, and the Site Class of the soil. Load factors are then applied to the calculated values based on the intended used and occupancy of the building.

The NBCC [1] considers an upper plateau for the spectral response accelerations used in design that is equal to the spectral acceleration for a period of 0.2 s (commonly denoted as S(0.2)). In other words, spectral response accelerations for periods less than or equal to 0.2 s are specified to be equal to S(0.2) for building designed in accordance with the NBCC. This is deemed unconservative in some cases. For example, in Toronto the spectral acceleration value a 0.2 s is only 83% of the spectral acceleration value at 0.1 s. However, limiting the value to S(0.2) is deemed acceptable for buildings, as the period may lengthen when structural damage occurs, and there is significant reserve strength in short period structures.

The NBCC [1] describes various methods that may be used for seismic analysis. The commentaries provide direction on the numerical integration linear time history method that is recommended in the CDA Guidelines [2] and LRIA [4] for dam design. Specifically, the method for the selection and scaling of time-history earthquake records is described. Some key points outlined in the selection and scaling of time-history records outlined in the NBCC Commentaries [5] include the following:

- The design response spectrum for periods less than 0.5 s should be developed in order to include the short-period range;
- For ground motion selection and scaling, the period range of interest should be a function of the natural period of the structure;
- The response spectra of the selected ground motions should have similar spectral shapes to those of the target response spectrum;
- No more than two records from the same earthquake event should be selected;
- The minimum number of ground motions selected should be 11; and
- Each ground motion should be scaled such that its response spectrum equals or exceeds the target response spectrum (on average) over the period range of interest. Scale factors less than 0.2 or larger than 4.0 should be avoided, and scale factors beyond these limits may indicate that the ground motion is not compatible.

## OBJECTIVE OF SEISMIC STUDY

A dam stability analysis was carried out on the West Nipissing Power Generation (WNPG) Power Dam and Spill Dam located in Sturgeon Falls, Ontario. For the preliminary analysis, spectral accelerations were extrapolated from NRCan's Seismic Calculator [3] and analyzed using the Equivalent Static Force Procedure (ESFP) outlined in the NBCC [1]. Based on this preliminary stability analysis, it was determined that the earthquake load cases are the governing load cases for these dams.

Based on the CDA Guidelines [2] and LRIA [4], extrapolating seismic values from the NBCC [1] and using the values for seismic analysis of dams is not suitable. Based on the LRIA [4], the dams have a "Very High" Hazard Potential Classification (HPC), resulting in a design earthquake with a 5,000-year return period (1 in 5,000 AEP). In addition, the dams have a very short natural period of vibration (below 0.2 s) and the short period accelerations need to be considered.

In order to validate the seismic values and carry-out a more detailed and accurate seismic analysis, a site-specific uniform hazard acceleration response spectrum (UHRS) was developed for the site, The UHRS was used to select earthquake acceleration time-history records and scale them to match the UHRS. The results of this study are described below.

## RESULTS OF SEISMIC HAZARD STUDY

The seismic hazard study was carried out by Golder Associates Ltd. (Golder) and J.L. Richards and Associates Limited (JLR). The study was divided into two phases; (1) development of the 5,000 year return period UHRS for the WNPG Site, and (2) selection and scaling of time-history values to match the site-specific UHRS.

### Probabilistic Seismic Hazard Analysis and Development of Uniform Hazard Response Spectrum

A PSHA was carried out by Golder to estimate the likelihood of exceeding a certain measure of ground motion. Earthquake activity rates were defined for seismic sources surrounding the site, including uncertainties. The total earthquake ground motion hazard at the site was calculated as the sum of the ground motions from all possible earthquakes from all seismic sources.

As part of the PSHA, a seismic source model was developed to define potential sources of moderate to large magnitude ground motions for the site. Each source in the seismic source model was defined based on location, source geometry, faulting mechanism (e.g. normal, strike-slip), maximum earthquake magnitude, probability of existence, and earthquake recurrence parameters. For the WNPG site, all seismic sources are assumed to have earthquakes occurring on reverse faults, and all significant seismic sources are located within a 300 km radius of the site.

The site is located on hard rock with a measured average shear wave velocity in the upper 30 m ($V_{s,30}$) of 1812 m/s evaluated by interpretation of multichannel analysis of surface waves (MASW). Earthquake ground motions were estimated based on the ground motion models (GMMs), used by the United States Geological Survey (USGS) for the central and eastern United States in the 2014 US National Seismic Hazard Model (USGS 2014) [6]. The USGS (2014) [6] GMM weighting factors were adjusted.

Following the definition of the seismic sources and weighing of the GMMs, the seismic hazard analysis was performed using EZ-FRISK 8.00 [7]. From this, the 5,000 year return period (5% damping) UHRS was developed for the site, taking into account site-specific soil conditions (i.e. $V_{s,30}$ of 1812 m/s). Figure 2 below shows the site-specific 5,000 year return period UHRS developed for the WNPG site.

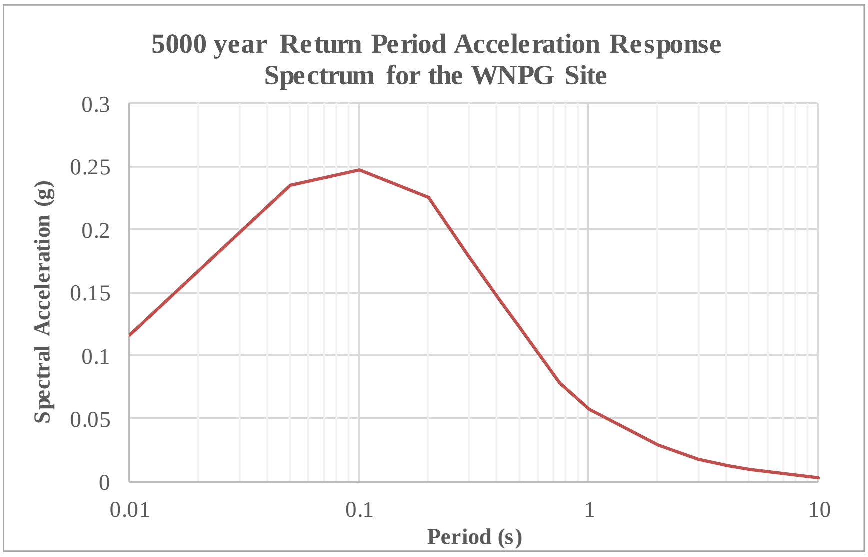



*Figure 2: 5,000 year return period UHRS*

**Selection and Scaling of Time-History Records**

JLR selected and scaled 11 earthquake acceleration time-history records. These acceleration records were scaled for future dynamic analysis of the WNPG dam structures. JLR selected seven (7) simulated and four (4) real records for the time-history analysis of the dam structures. The selection of the time-histories is discussed below.

**Simulated Earthquake Records**

The simulated records are chosen from the Atkinson Directory of Simulated Response Histories for Sites in Eastern and Western Canada [8]. The acceleration response spectra for the simulated records were compared to the target response spectrum developed by Golder (as shown in Figure 2). The comparison is made over the period range of interest (0.2T to 1.5T, where T is the natural period of vibration of the structure). These time-history records were developed for future use in the analysis of dams and other structures (e.g. retaining walls) that must be designed in accordance with the CDA Guidelines [2] and the LRIA [4]. Because these structures have a low natural period, the period range of interest used to scale the earthquake records was taken as 0.04 s to 0.3 s. Table 3 lists summary information from the simulated records chosen for the analysis of short period structures at the WNPG site.

*Table 3. Simulated Earthquake Records (Atkinson Directory [8])*

| Record | Fault distance (km) | Azimuth | # | Scale Factor |
|---|---|---|---|---|
| 1– East 6a2 | 26.3<br>26.3 | 177.6<br>177.6 | 20<br>21 | 0.81 |
| 2– East 6a2 | 30.7<br>30.7 | 147.1<br>147.1 | 41<br>42 | 0.99 |
| 3– East 7a2 | 50.3<br>50.3 | 255.4<br>255.4 | 4<br>6 | 0.86 |
| 4– East 7a2 | 50.3<br>50.3 | 174.8<br>174.8 | 10<br>12 | 0.88 |
| 5– East 7a2 | 50.3<br>50.3 | 257.7<br>257.7 | 14<br>15 | 0.83 |
| 6– East 7a2 | 51.9<br>51.9 | 318.8<br>318.8 | 19<br>20 | 0.91 |
| 7– East 7a2 | 47.8<br>47.8 | 328.4<br>328.4 | 28<br>30 | 0.91 |

***Real Earthquake Records***

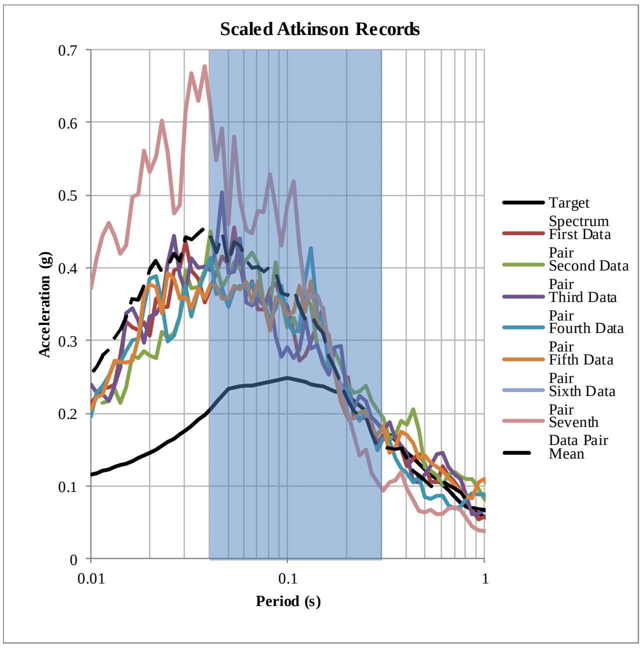
The real earthquake records for this study were taken from the Pacific Earthquake Engineering Research (PEER) database [9]. This database contains recorded earthquake acceleration time-histories from around the world. Actual records were selected using the same selection methods as used to select simulated records. Table 4 below lists key parameters for the four best matches to the site-specific target spectrum for the WNPG site.

*Table 4. Real Earthquake Records (PEER Database [9])*

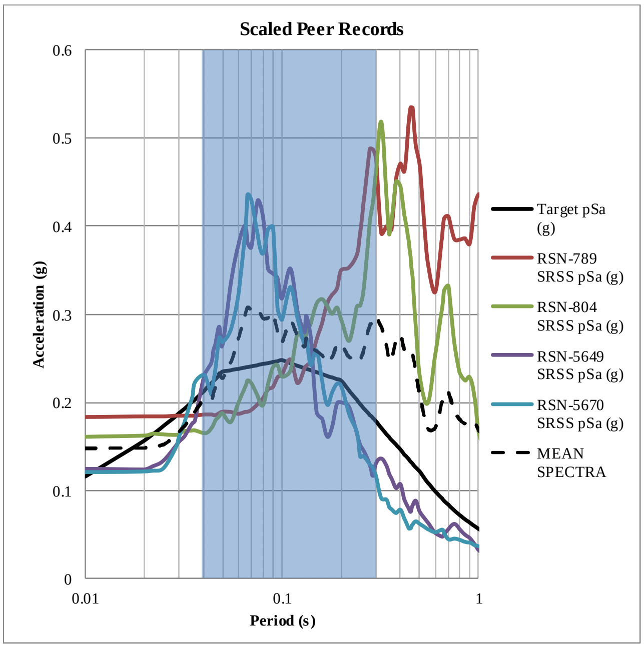
| Record Seq. # | D5-75[1](s) | D5-95[2](s) | Event | Year | Station | Magnitude | Mechanism | Rjb[3] (km) | Rrup[4] (km) | $V_{s,30}$[5] (m/s) | Scale Factor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 789 | 5.1 | 10.6 | Loma Prieta | 1989 | Point Bonita | 6.93 | Reverse Oblique | 83.37 | 83.45 | 1315.92 | 1.79 |
| 804 | 5.3 | 12.1 | Loma Prieta | 1989 | So. San Francisco, Sierra Pt. | 6.93 | Reverse Oblique | 63.03 | 63.15 | 1020.62 | 1.36 |
| 5649 | 15.3 | 25.7 | Iwate, Japan | 2008 | IWTH17 | 6.9 | Reverse | 72.44 | 72.44 | 1269.78 | 1.45 |
| 5670 | 12.7 | 20.2 | Iwate, Japan | 2008 | MYG011 | 6.9 | Reverse | 82.93 | 82.93 | 1423.8 | 1.18 |

[1]D5-75 denotes the time (or duration) needed to build up between 5 and 75 percent of the total Arias intensity (measure of the strength of a ground motion).
[2]D5-95 denotes the time (or duration) needed to build up between 5 and 95 percent of the total Arias intensity.
[3]Rjb denotes Joyner-Boore distance (shortest distance from a site to the surface projection of the rupture surface).
[4]Rrup denotes the distance to rupture plane.
[5]$V_{s,30}$ denotes the average shear wave velocity in the upper 30 m.

The earthquake acceleration time-history records were scaled to match the site-specific UHRS developed by Golder over the period range of interest. The scaled UHRS for the simulated (Atkinson [8]) records and real (PEER [9]) records are graphically shown in Figure 3 below. Records were scaled such that the average acceleration of all the records are greater than or equal to the acceleration provided in the site-specific UHRS for the WNPG site. The scaling method is described in “Earthquake Time Histories Compatible with the 2005 NBCC Uniform Hazard Spectrum” [10].




*(a)*




*(b)*

*Figure 3. (a) Scaled Simulated (Atkinson) Records, (b) Scaled Real (Peer) Records*

## DISCUSSION

By carrying out a PSHA, a site-specific UHRS was developed for the WNPG dam site. The UHRS indicates high spectral accelerations at short periods of vibration with the maximum spectral acceleration at a period of 0.1 s. We note that that the time-history values selected and scaled by JLR are generally conservative for short period structures. As such, the selected records could be further refined to lower the mean spectrum at short periods. Prior to detailed finite element modeling (FEM) and time-history seismic analysis of dam structures at the site, JLR will review real records from the United States Nuclear Regulatory Commission (USNRC) to determine if there are records within this database that result in a better match and reduce the overly conservative scaled values.

JLR developed spectral values for the WNPG site by plotting the 475 year and 2475 year return period spectral values on a log-log scale. These plots were developed as a basis to compare the UHRS developed for the WNPG site to the spectral values obtained from the NRCan website [3]. Based on the very high hazard potential classification of the WNPG Power Dam, the earthquake design ground motion must have a return period of 5,000 years (or a probability of exceedance of 1% in 50 years) in accordance with the LRIA [4]. Prior to measuring the $V_{s,30}$ from the MASW at the site, the dam was assumed to be founded on NBCC soil Site Class B site conditions. As such, the response spectrum developed for the assumed soil Site Class B was used for the preliminary seismic analysis. The MASW interpretation indicated a $V_{s,30}$ of 1812 m/s, equivalent to NBCC soil Site Class A site condition. Figure 4 shows a comparison of the NBCC extrapolated values for 5,000 year return period earthquake accelerations for both NBCC soil Site Class A and B and the 5,000-year return period UHRS developed from the site-specific PSHA.

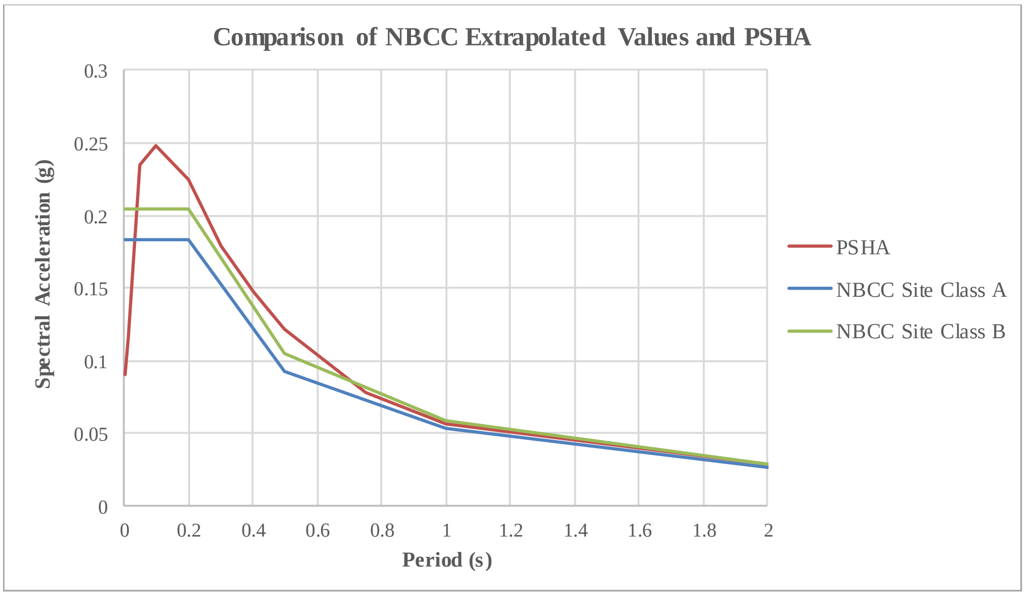



*Figure 4: Comparison of NBCC Extrapolated Values and PSHA*

Based on the comparison, the NBCC [1] extrapolated values are unconservative, especially in the short period range where site-specific spectral acceleration values are 135% higher than the extrapolated NBCC values for Site Class A at a period of 0.1 s. Because concrete gravity dams have a short period of vibration (generally less than 0.1 s), the spectral acceleration values at short periods of vibration must be well understood and defined to support robust seismic analysis. Accordingly, the upper plateau of the response spectrum (S(0.2)) applied in ordinary buildings' seismic design is not acceptable for dam seismic analysis and design because is caps spectral acceleration values for shorter period structures.

We note also that NBCC response spectra are based on single degree of freedom (SDOF), constant stiffness, and lumped mass systems with assumed 5% damping. These assumptions do not align well for concrete gravity dams that have variable stiffness, distributed mass, and damping in the range of 5% to 10%. Given these differences, we concluded that it is not appropriate to apply the simplified NBCC seismic analysis methods to seismic analysis of concrete gravity dams.

## SUMMARY AND CONCLUSIONS

A preliminary seismic analysis of the Power Dam and Spill Dam at the WNPG site was undertaken using methods from the 2015 NBCC [1]. Based on the analysis, we determined that the earthquake load cases govern the loads for the dams. For the more detailed analysis, a site-specific PSHA was undertaken in accordance with the CDA Guidelines [2] and LRIA [4]. From the PSHA, a site-specific UHRS was developed for the site for a return period of 5,000 years and acceleration time-history records were scaled to match the site-specific UHRS for use in the FEM models of the dam structures. The FEM results will be used to make decisions on dam stabilization retrofits, and for detailed design.

The principal conclusions for this study are that:

- The maximum spectral accelerations for the WNPG site occur at a periods below 0.2 s. This conclusion differs from the response spectrum developed from the NBCC where the maximum spectral acceleration is equal to S(0.2) for periods less than or equal to 0.2 s.
- Extrapolation of spectral values from the NBCC for low probability design, yield spectral values that are less than those developed by carrying out a site-specific PSHA. Using NBCC values for preliminary analysis resulted in unconservative estimates of the design earthquake ground motions for the WNPG site.
- Spectral accelerations for low period structures should not be assumed to be equal to the spectral acceleration value at a period of 0.2s (S(0.2)). Sites, such as the WNPG site located in Sturgeon Falls, Ontario may have peak spectral accelerations at periods below 0.2 s. These short periods should not be ignored for very stiff structures with short natural periods of vibration.
- For structures with a natural period less than 0.1 s, the decline in acceleration values may be beneficial and hence provide a more cost-effective solution to dam owners for seismic design or retrofit. This decrease in acceleration is ignored in the NBCC design because the natural period of ordinary building structures undergoing damage in a seismic event will likely lengthen such that structures with extreme short periods would begin to climb this curve and attract higher accelerations. Conversely, for dam structures period lengthening does not occur because structural damage is limited in the design for water tightness.

We conclude that a site-specific PSHA can minimize the uncertainty in seismic design of structures, especially those that are not characteristic of typical buildings in Canada. Developing site-specific seismic parameters allows engineers to make sound decisions on the requirements for seismic retrofits in critical structures such a dams.

**ACKNOWLEDGMENTS**

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**REFERENCES**

[1] National Research Council Canada. (2017). *National Building Code of Canada 2015*. Retrieved from http://www.nrc-cnrc.gc.ca

[2] Canadian Dam Association. (2013). *Dam Safety Guidelines 2007 (2013 edition)*. Retrieved from https://www.cda.ca

[3] Natural Resources Canada. (2016). *Seismic Design Tools for Engineers.* Retrieved from http://www.earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/index-en.php

[4] Ministry of Natural Resources and Forestry (2011). *Seismic Hazard Criteria, Assessment and Considerations Technical Bulletin*. Retrieved from https://www.ontario.ca/page/seismic-hazard-criteria-assessment-and-considerations.

[5] National Research Council Canada. (2017). *User's Guide – NBC 2015 Structural Commentaries (Part 4 of Division B*). Retrieved from http://www.nrc-cnrc.gc.ca

[6] United States Geological Survey. (2014). *The 2014 United States National Seismic Hazard Model*. Retrieved from https://pubs.er.usgs.gov/publication/70184229

[7] Fugro USA Land Inc. (2018). EZ-FRISK Software v.8.00b. Software for Earthquake Ground Motion Estimation. Fugro USA Land, Inc., Walnut Creek, CA, USA. http://www.ez-frisk.com

[8] Atkinson, G.M. (2005). 2005 National Building Code of Canada Time History Directory. University of Western Ontario, London, ON, Canada. https://www.seismotoolbox.ca/NBCC2005.html.

[9] University of California. (2013). PEER Ground Motion Database: Pacific Earthquake Engineering Research Center. University of California, Berkeley, CA, USA. https://ngawest2.berkeley.edu/site

[10] Atkinson, G.M. (2009). "Earthquake time histories compatible with 2005 National Building Code of Canada uniform hazard spectrum". *Canadian Journal of Civil Engineering*, 36, 991-1000.uhrs