Probabilistic Seismic Hazard Assessment for Point Lepreau Generating Station

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Abstract

A Probabilistic Seismic Hazard Assessment (PSHA) has been performed for the Point Lepreau Generating Station (PLGS). The objective is to provide characterization of the earthquake ground shaking that will be used to evaluate seismic safety. The assessment is based on the current state of knowledge of the informed scientific and engineering community regarding earthquake hazards in the site region, and includes two primary components—a seismic source model and a ground motion model. This paper provides the methodology and results of the PLGS PSHA. The implications of the updated hazard information for site safety are discussed in a separate paper.

1. Introduction

A site-specific probabilistic seismic hazard assessment (PSHA) was performed by AMEC Environment & Infrastructure, Inc. (AMEC), for the Point Lepreau Generating Station (PLGS) in New Brunswick, Canada [1] in response to seismic safety concerns following the accident at the Fukushima Dai'ichi power plant in Honshu, Japan, caused by the March 11, 2011, Tohoku, Japan, earthquake, and as part of the 2012 Canadian Nuclear Safety Commission decision for renewal of the operating license for the PLGS. The purpose of this assessment is to provide an update of the seismic hazard characterized for the PLGS site based on numerous geologic and seismic hazard studies that have been conducted in the site region since the previous seismic hazard analyses for the site were performed in the 1970s and 1980s (e.g., [2] and [3]). The approach to this assessment was to conduct a site-specific PSHA to characterize ground motion hazard at the site in terms of peak horizontal ground acceleration and response spectral accelerations at selected structural response frequencies (periods) and for a range of probabilities of exceedance appropriate for evaluating seismic safety during the design life of the PLGS.

The PSHA involved compilation of an earthquake catalog for the region surrounding the site and identification and characterization of regional seismic source zones and local seismic sources. The results of paleoseismic studies in the region were incorporated in the seismic source characterization. Ground motion models applicable to the hard rock conditions of southeastern Canada were selected using the most recent published literature and through discussions with experts. Probabilistic hazard analyses were conducted for peak ground acceleration (PGA) and response spectral accelerations (S_a) covering the frequency range of importance to nuclear power plant design and performance.

2. Geologic and Tectonic Setting

Understanding the geology, structure, tectonic setting and seismicity of a region facilitates the identification of potential seismic sources and provides a context for developing tectonic models of crustal deformation that can be used to characterize the seismic potential of individual geologic structures and source zones. The PLGS site is located in the Northern Appalachian Orogen, which extends from the Gulf of St. Lawrence to the Atlantic Ocean, and is an area that has experienced a long and complex geologic and tectonic history. The PLGS site is located on the northwestern edge of the Fundy Basin, one of numerous rift basins of early Mesozoic age on the continental margin of eastern North America. The site is underlain by Triassic bedrock of the Lepreau Formation, consisting primarily of sandstones and conglomerates, with minor thin lenses of shale [4]. The geologically most recent, and unequivocal evidence for major tectonic activity in the region is Late Triassic to Late Jurassic normal faulting along the Atlantic margin related to continental rifting and the subsequent opening of the Atlantic Ocean. However, historical seismicity along the St. Lawrence rift system and in other concentrated zones such as Passamaquoddy Bay, local geologic evidence of Cenozoic reactivation of faults, evidence of paleoseismicity, and geologic and geodetic data are all indicative of regional and local crustal deformation and suggest continuing neotectonic activity, albeit at much lower rates than during the last episode of major tectonic deformation.

3. Seismicity

An earthquake catalog of seismicity from 1568 to 2011 for the region surrounding PLGS was developed for this study. The primary source of data for the project catalog is the Central and Eastern United States Seismic Source Characterization (CEUS SSC) for Nuclear Facilities Project catalog [5] that includes earthquakes from 1568 through the end of 2008. The CEUS SSC catalog is appropriate to use for this project because it merged all the relevant continental, regional, and local catalogs for instrumental and historical earthquakes, and was compiled for a Senior Seismic Hazard Analysis Committee (SSHAC) Level 3 study. Preparation of the catalog involved extensive research of literature on specific earthquakes, use of uniform moment magnitude that is consistent with ground motion models, and formal treatment of uncertainties in estimates of moment magnitude. For the portion of the CEUS SSC catalog that lies within Canada, appropriate regional and local catalogs (i.e., Geological Survey of Canada [GSC] catalogs for events that occurred in Canada) were identified as preferred sources. The CEUS SSC catalog has been supplemented for this study by earthquake data within the bounds of the project catalog for the 2009 through 2011 timeframe that were obtained from the GSC National Earthquake Database [6], the United States Geological

Survey (USGS) National Earthquake Information Center database [7], and the Weston Observatory [8]. Since the end of 2011, no significant earthquakes have occurred in the region surrounding PLGS that would require consideration in the project catalog.

The CEUS SSC earthquake catalog [5] utilizes a uniform moment magnitude estimate, expected moment magnitude (E[**M**]), and includes earthquakes as small as E[**M**] 2.2. The catalog is composed of independent earthquake events with all foreshocks and aftershocks, or dependent events, removed. Assessment of earthquake occurrence rates requires an evaluation of the completeness of the earthquake catalog. For this study the completeness regions and associated completeness periods for each region were adopted from the CEUS SSC model [5].

To the west-southwest of the PLGS site, an increased level of historical seismicity has been recognized in the area of Passamaquoddy Bay (Figure 1). The project earthquake catalog includes 33 earthquakes within this area. The largest earthquakes that have occurred in the Passamaquoddy Bay area are the October 22, 1869, E[**M**] 5.47 earthquake and the March 21, 1904, E[**M**] 5.73 Eastport earthquake [9]. The 1869 event was located approximately 61 km west-southwest of the site based on felt intensities. This earthquake displaced furniture in St. Stephens and glass was reportedly broken in St. John [10]. A study of felt effects for historical earthquakes by [10] indicates that the PLGS site is in an area that experienced an estimated Modified Mercalli Intensity (MMI) of IV to V following the 1869 earthquake. The 1904 Eastport earthquake was located 55 km west-southwest of the PLGS site. Reported damage associated with this event included toppled chimneys and broken windows in the town of St. Stephens, 65 km southwest of the site, and in Calais and Eastport, Maine, and cracked plaster and walls that were found in St. John, 39 km northeast of the site [10]. The PLGS site is located in an area that experienced Rossi-Forel intensity of VI to VII [3], which corresponds to MMI of V to VI [10].

4. Paleoseismicity

Because the record of historical and instrumental seismicity only represents several hundred years of earthquake history in the region, a paleoseismic evaluation was performed by M. Tuttle & Associates [12] for the PLGS site region. The paleoseismic study was performed to help constrain the source area, magnitude, and recurrence times of large regional earthquakes in the late Quaternary (in particular, the past 10–12 kyr [thousand years]) in the region.

Based on the distribution of observed earthquake-induced soil liquefaction features (Figure 1), the preferred interpretation of [12] is that three earthquakes occurred about 1 ka (thousand years ago), 4 ka, and 12 ka in the Passamaquoddy Bay area, centered near the epicenter of the 1904 event, that were responsible for triggering the formation of sand dikes and soft-sediment deformation structures on the Bocabec, Digdeguash, and Magaguadavic Rivers. This suggests a recurrence interval ranging from 1.8 to 4.5 kyr, with an average recurrence time of 3.15 ± 1.35 kyr. The liquefaction potential analysis performed by [12] predicts that earthquakes of M 6.5–7 generated by a source near the epicenter of the 1904 earthquake would produce the distribution of liquefaction features observed, as well as where such features were not observed.

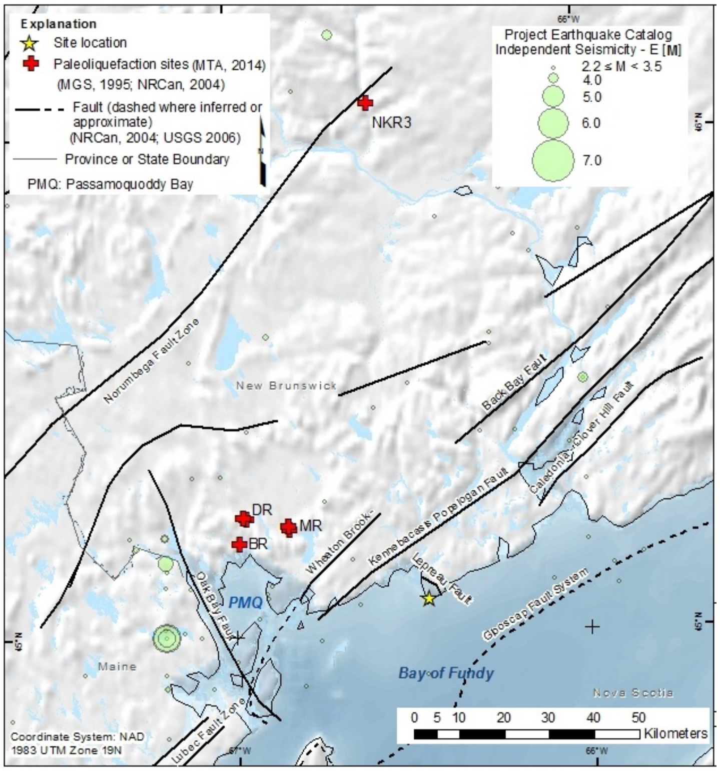

Figure 1. Faults, Seismicity, and Earthquake-Induced Paleoliquefaction Features in the Site Region

The results of the paleoseismic investigations are incorporated in the PSHA through: 1) adjustment of the Passamaquoddy Bay seismicity-based source zone geometry to include the potential locations of the paleoearthquakes; 2) adjustment of maximum magnitude distributions for the seismic source zones within which Passamaquoddy Bay area seismicity and the identified earthquake-induced paleoliquefaction features lie; and 3) adjustment of the probability of Oak Bay fault being seismogenic.

Calculated magnitude-recurrence relationships for the Passamaquoddy Bay seismicity-based source zone (M 6.0 every ~1,000 years, M 6.5 every ~5,000 years, and M 7.0 every ~10,000 years) agree well with recurrence estimates of late Quaternary M 6 to 7 earthquakes based on earthquake-induced paleoliquefaction features (approximately 1,000 to 5,000 years with an average of 3,000 years) [12].

5. Seismic Source Characterization

A key objective of this study is to identify and quantify the uncertainties associated with seismic source characteristics, thus incorporating the current knowledge and uncertainties into the hazard analysis. The uncertainty assessment in this study is performed using a logic tree methodology. The seismic source model developed for this assessment encompasses a region having a radius of more than 300 km surrounding the PLGS site. This region was selected to ensure that all sources, including regional and local aerial source zones and local faults, that could potentially contribute to ground motion hazard at the site are incorporated ino the analysis.

5.1 Regional Seismic Sources

Earthquakes that cannot be attributed to mapped active fault zones are modeled as occurring in areal seismic source zones, shown as polygons on Figures 2 and 3. The size and extent of the areal source zones were delineated based on prominent geologic structures and tectonic provinces and consistent patterns of seismicity. Our model includes two types of seismic source zones: (1) Regional seismotectonic source zones based primarily on geologic and tectonic characteristics (Figure 2); and (2) Seismic source zones based on observed seismicity (Figure 3).

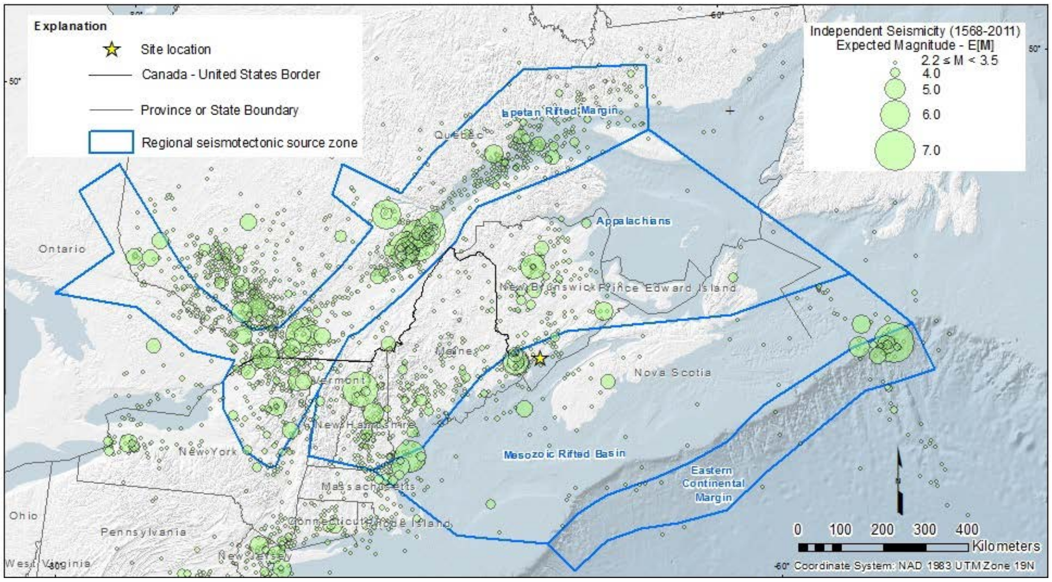

Figure 2. Regional Seismotectonic Source Zones (Alternative A)

A key difference between these methodologies is the degree to which the spatial pattern of observed seismicity (both historical and instrumentally recorded earthquakes) provides an indication of the locations of future seismicity. Because the distribution of seismicity is not uniform within the large regional seismotectonic zones, seismicity was smoothed to evaluate the spatial density variations (clustering) of seismicity within each zone. The methodology used for spatial smoothing of seismicity in the regional seismotectonic source zones is one that smooths the rate of activity within each zone. The regional seismotectonic basis for source zonation is strongly favored (0.8) over the seismicity-based alternative (0.2) because it subdivides the region into zones with more uniform crustal characteristics, as well as taking into account the spatial variability of seismicity within each zone, rather than characterizing the entire zone as having a uniform rate.

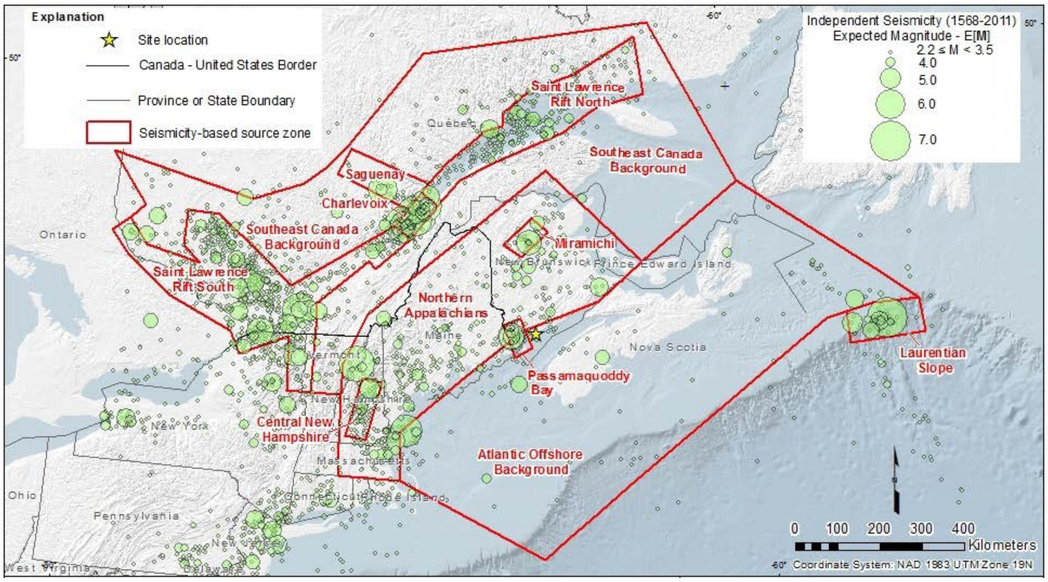

Figure 3. Seismicity-Based Seismic Source Zones

The regional seismotectonic model includes four source zones that extend more than 300 km from the site (Figure 2). These are the Mesozoic Rifted Basin (MRB), Northern Appalachian (APL), Iapetan Rifted Margin (IRM), and Extended Continental Margin (ECM) zones. The geometry of these zones are based on [5], [13], and other geologic maps and publications. Three alternative geometries for these source zones were considered to incorporate the uncertainty of source zone boundaries, especially in the vicinity of the PLGS site (i.e., the MRB/APL boundary).

The seismicity-based source zones modeled in this study generally follow the GSC 5th generation historical seismicity (H2) zones [13]. The seismicity-based source zone model includes 11 crustal areal seismic source zones that cover the region extending at least 300 km from the site as shown on Figure 3. These zones were constructed to encompass areas of relatively uniform seismicity and the rate within each zone, regardless of geographic extent, is characterized as uniform. Two alternative source zone geometries are considered to take into consideration the uncertainty in the boundary of the Northern Appalachians/Atlantic Offshore Background (NAN/AOB) boundary, which is located near the PLGS site (Figure 3); these alternatives are given equal weight in our model. The northeastern boundary of the

Passamaquoddy Bay (PMQ) zone was modified from [13] to include paleoliquefaction features identified by [12].

The primary approach used for assessing the maximum magnitude for a seismic source zone is the Bayesian approach as described in [5], which was based on the approach initially outlined in Johnston et al (1994). For zones that contain the paleoliquefaction features identified by [12], the maximum magnitude distribution was adjusted to account for the paleoearthquakes being the largest observed earthquakes in the zone. The frequency of occurrence of earthquakes associated with a source was computed from the statistics of the earthquake catalog for the source. For source zones, the standard truncated exponential magnitude distribution was used to define the relative frequency of various sizes of earthquakes. Earthquakes in the seismic source zones are modeled as occurring on planar fault sources distributed throughout the source area at a uniform spacing of 5 km for all distant source zones and spacing of 1 km for the Northern Appalachian, Passamaquoddy Bay, and Mesozoic Rifted Basin zones. Orientation and style of faulting of the modeled planar fault sources are based largely on the CEUS SSC model [5], with some modifications based on more local studies. Maximum depth of seismogenic rupture for modeled pseudo faults is based on the seismogenic depth of the crust used in CEUS SSC model [5] with modification to the ECM zone based on the depth of the 1929 Grand Banks earthquake.

5.2 Potential Local Fault Sources

Active faults for this assessment are generally defined as those that have had displacement or seismic activity during the Quaternary period (i.e., 2.6 million years before present [Myr BP] to the present). Several faults within 100 km of the PLGS site were considered in evaluating local seismic sources; however, based on a thorough literature review and conversations with local experts, we found no evidence of faults within 100 km of the site that may unambiguously be considered to be active. Although there is no firm evidence to associate any particular fault with the occurrence of earthquakes in southern New Brunswick [14], several authors have postulated that seismicity in the Passamaquoddy Bay area may be associated with the Oak Bay fault (e.g., [15], [16], [17]). Additionally, seismicity and potential earthquake-induced paleoliquefaction features in the area of the Norumbega fault, suggest that it may have been active in the Quaternary. Faults within 100 km of the site that were considered in our evaluation are the Oak Bay fault, the Glooscap fault system in the Bay of Fundy, the Lepreau fault, and the Norumbega fault (Figure 1). Each of these faults was evaluated for seismogenic potential following the methodology of [18]. “Seismogenic” in this context is defined as capable of generating moderate-to-large earthquakes ($M > 5$) in the present tectonic environment and worthy of being represented as a fault source in the PSHA. The evaluation takes into account the association of the fault with seismicity, seismogenic crustal extent of the fault, whether slip is favourable in the current stress regime, and evidence for multiple episodes of reactivation. The Oak Bay fault was included as a fault source in the PSHA with a 0.47 probability of being seismogenic.

6. Ground Motion Model

A key input to the probabilistic seismic hazard model for the PLGS site, as in most PSHAs, is specification of earthquake ground motions through implementation of ground-motion prediction equations (GMPEs). There are two necessary components of a GMPE. The first is a relationship for the median amplitude (mean log amplitude) of peak ground motions as a function of earthquake magnitude, source-to-site distance, and spectral frequency of interest, as well as other explanatory variables that may be appropriate. The second and equally important component is a relationship for the aleatory variability (random variation) of peak ground motions about the median amplitude. For Central and Eastern North America (CENA), however, recorded strong-motion data is very limited. As a result, the available ground-motion models are primarily based on theoretical/numerical modeling approaches that have been calibrated using comparisons with recorded data from more active regions, in addition to the relatively sparse CENA data.

To address uncertainty in the GMPEs, four alternative GMPEs that have been developed based on different approaches are used in the PSHA. The models utilized were developed to represent ground surface motions on generic CENA hard rock sites. The GMPEs used in this PSHA are: 1) Pezeshk et al. (2011) [19]; 2) Atkinson (2008) [20], with the Atkinson and Boore (2011) [21] revision; 3) Atkinson and Boore (2006) [22], with the Atkinson and Boore (2011) [21] revision; and 4) Silva et al. (2003) [23]. These are a very similar set of GMPEs to those on which the ground motion model being applied to seismic hazard maps for the 2015 edition of the National Building Code of Canada [24] are based. The four GMPEs are given equal weight and are all implemented for hard rock site conditions present at the PLGS site, on which the reactor and other safety elements at the site are founded. The sigma values of [24] are used to incorporate the aleatory variability in ground motion models.

7. PSHA Analysis Approach

The methodology used to conduct a PSHA was developed first by [25] and has undergone substantial development since that time. Current practice is described in detail in several publications, such as [26], [27], [28], [29], [30], and [31]. The basic formulation involves computing the frequency at which a ground motion parameter exceeds a specified level at the site. The procedure for computing the frequency of exceedance involves assessing the following parameters and probability distributions: (1) the frequency of earthquake occurrence; (2) given an earthquake occurrence, the distribution of possible earthquake sizes (magnitudes); (3) given an earthquake of a particular size, the distribution of the possible distances from the site to the rupture; and (4) given an earthquake of a particular size and location, the distribution of possible ground motions at the site. Items (1) and (2) are specified by earthquake recurrence relationships developed for the seismic sources; item (3) is specified by the locations and geometries of the seismic sources relative to the site; and item (4) is specified by ground motion prediction equations.

The site-specific PSHA conducted in this evaluation utilized proprietary in-house seismic hazard codes (software programs) developed by AMEC, and qualified under AMEC's Nuclear Quality Assurance (NQA-1) Program. These programs have also been used for U.S. Nuclear Combined Operating and Licensing (COL) applications, recent design-related evaluations for clients in Canada and worldwide for nuclear facilities, as well as for buildings, dams, oil and gas facilities, mines, and other civil facilities.

8. Results and Conclusions

The results of the PSHA are presented in terms of site-specific uniform hazard response spectra for annual frequencies of exceedance in the range of 10^{-2} to 10^{-5} (equivalent return periods ranging from 100 years to 100,000 years) (Figure 4). Ordinates for these response spectra are given for PGA and over the spectral frequency range of 40–0.25 Hz at a damping ratio of 5 percent. The probabilistic seismic hazard results indicate that the seismic hazard at the PLGS site is dominated by seismic activity in the Passamaquoddy Bay area, which is located approximately 25–30 km west-southwest of the site, and has been the source of earthquakes with magnitudes estimated as large as M 5.7 during the historical period and earthquakes potentially as large as M 7.0 during the late Quaternary based on interpretation of earthquake-induced paleoliquefaction features [12]. The Passamaquoddy Bay seismicity lies within several seismic source zones in the different model alternatives (i.e., the Passamaquoddy Bay zone in the seismicity-based alternative models, and the Mesozoic Rifted Basin [Alternatives A and B] and Northern Appalachian [Alternative C] zones in the regional seismotectonic alternative models). The largest contribution to the hazard is from the Mesozoic Rifted Basin zone in the regional seismotectonic model alternative A. Ground motion values associated with the 10,000-year return period mean total hazard level for spectral frequencies of 1 Hz and 10 Hz are $S_a = 0.12g$ and $S_a = 0.80g$, respectively, and for PGA is 0.58g (Figure 5 illustrates total hazard results for PGA); for the 10,000-year return period median total hazard level, the ground motion values for 1 Hz, 10 Hz, and PGA are, respectively, $S_a = 0.07$ g, $S_a = 0.53$ g, and PGA = 0.34 g.

The regional seismotectonic source zones were found to be the dominant contributors to the hazard. The contribution of individual assessments to the uncertainty for various components in the seismic hazard computation was also examined. The results indicate that alternative geometries of regional seismotectonic source zones are the largest contributors to the uncertainty in seismic hazard at the site. Other significant contributors to uncertainty are the estimation of the b-value of the Gutenberg-Richter magnitude-frequency relationships, selection of the appropriate ground motion models, and the maximum magnitude assessments.

Comparison of peak ground accelerations from this project with other studies conducted for, or applicable to, the PLGS shows that median values for uniform hazard response spectra from the present assessment (mean values are not reported for the previous studies) are similar to those previously reported (e.g., [3] and [32]) Median PGA at the 10,000 year return period hazard level is 0.34 [this study], 0.33 [32], and 0.25-0.43 [3]. The slightly higher PGA values determined for the site in this study are primarily due to incorporation of new data regarding the size and location of earthquakes in the site region, particularly recently identified earthquake-induced paleoliquefaction features in the Passamaquoddy Bay area, and the incorporation of more recent GMPEs.

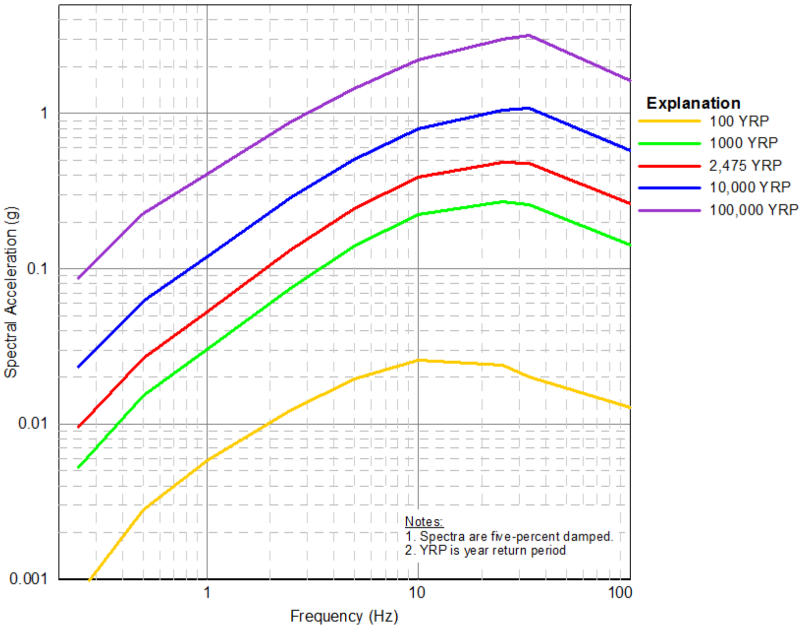

Figure 4. Uniform Hazard Response Spectra Based on Mean Hazard Results.

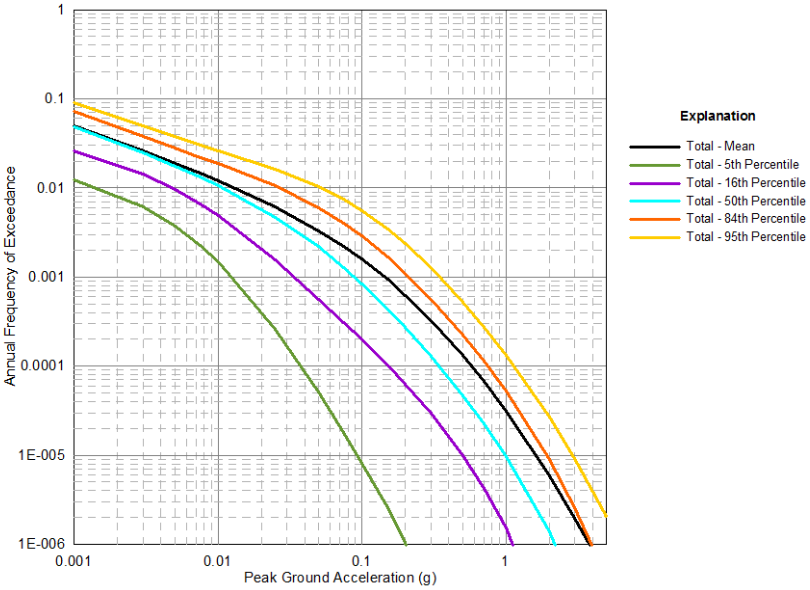

Figure 5. Mean and Fractile Total Hazard Results at Peak Ground Acceleration

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