Seismic Hazard Criteria, Assessment and Considerations

Technical Bulletin

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The Lakes and Rivers Improvement Act (LRIA) provides the Minister of Natural Resources with the legislative authority to govern the design, construction, operation, maintenance and safety of dams in Ontario. The Lakes and Rivers Improvement Act Administrative Guide and supporting technical bulletins have been prepared to provide direction to Ministry of Natural Resources staff responsible for application review and approval and guidance to applicants who are seeking approval under Section 14, 16 and 17.2 of the LRIA. All technical bulletins in this series must be read in conjunction with the overarching Lakes and Rivers Improvement Act Administrative Guide (2011).

Seismic Hazard Criteria, Assessment and Considerations

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1.0 General

This technical bulletin has been prepared to provide direction to Ministry of Natural Resources (MNR) staff and guidance to dam owners in the identification of seismic design criteria for dams and is to be used when considering applications for approval under Section 14, 16, and 17.2 of the Lakes and Rivers Improvement Act (LRIA).

The standards and criteria outlined within this technical bulletin are intended to apply to dams (including the control structure and all appurtenant facilities) that hold back water in a river, lake, pond or stream to raise the water level, create a reservoir to control flooding or divert the flow of water; and are not intended to apply to other works subject to LRIA approval such as water crossings, channelizations, enclosures, pipelines and cables.

The seismic design criteria for assessing the seismic safety of a given dam structure or facility are to be based on a site-specific seismic hazard evaluation earthquake ground motion parameters and are typically ascertained by conducting a probabilistic seismic hazard evaluation with or without consideration of scenario events where known active faults are identified.

The selected seismic loading criteria follow a traditional standards-based approach to dam safety assessment. Based on this approach, the extent, level of detail, contents and follow-up for a seismic evaluation depend on the hazard potential of dam failure or mis-operation.

This technical bulletin must be read in conjunction with the Lakes and Rivers Improvement Act Administrative Guide and the Ministry of Natural Resource's Classification and Inflow Design Flood Criteria Technical Bulletin.

2.0 Scope and General Outline

To estimate earthquake ground motion parameters at a particular site, it is necessary to incorporate the appropriate geologic and seismologic input and to utilize the most relevant available procedures for estimating these parameters.

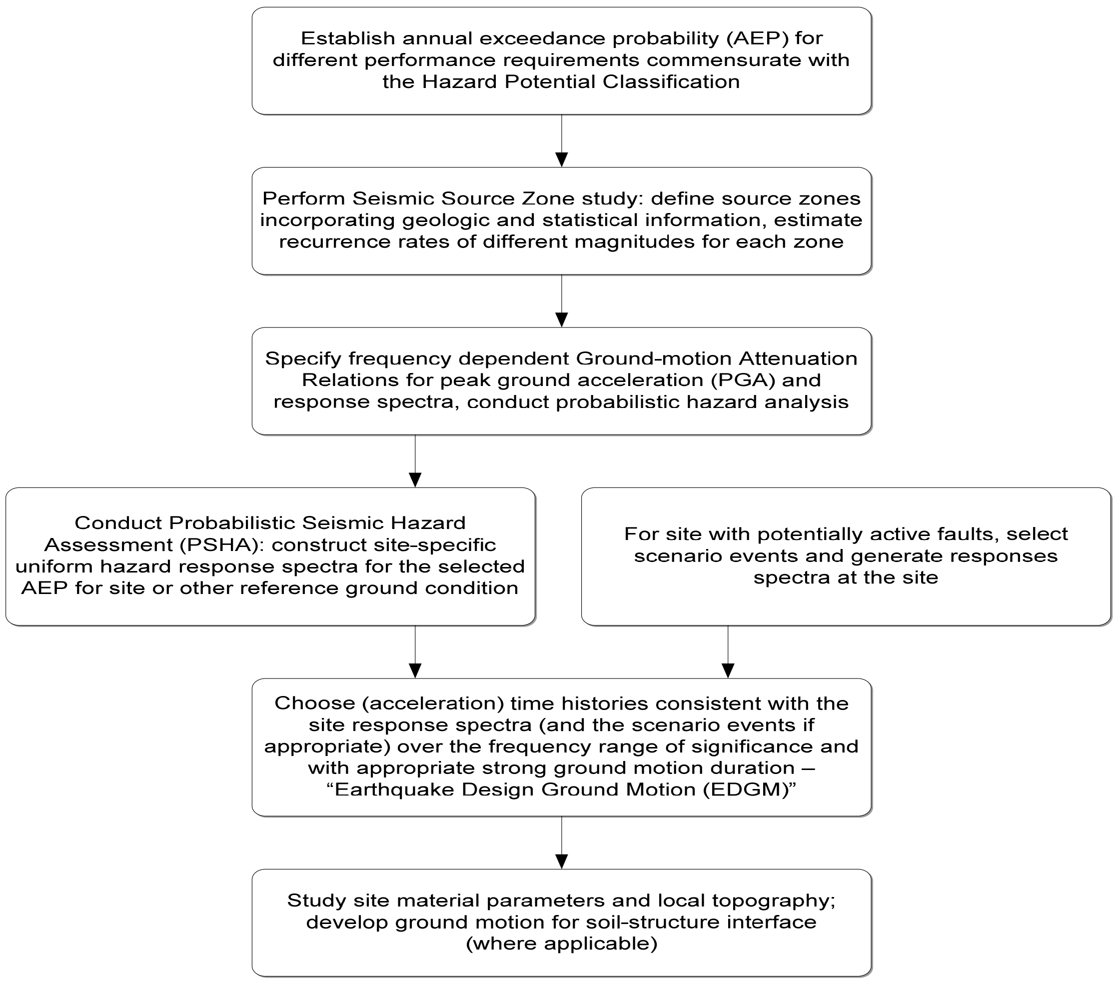
Seismic hazard evaluation is a developing science and is, to a large extent, based upon experience and judgment of qualified specialists.

This technical bulletin outlines the general approach for developing site-specific response spectra of ground motions. The methodology primarily involves the probabilistic evaluation (supplemented by a deterministic "scenario test" under limited cases) performed by appropriate specialists.

The basic procedures used to conduct a site specific seismic assessment involve an appropriate seismic hazard model which is able to incorporate both seismicity and geological information, coupled with an analytical method.

Figure 1 illustrates a typical overall process to assess the seismic safety of a dam.

Figure 1 - Probabilistic Seismic Hazard Assessment



3.0 Determination of Seismic Evaluation Requirements

3.1 Earthquake Hazard and Losses

Earthquake hazard assessment is an integral part of dam safety assessment, especially for dams located in seismic zones. Extreme and rare earthquakes may occur randomly in time and space. These events could cause partial damage or collapse of dams. The losses associated with the partial damage and collapse may be small or large depending on the geographic condition, environment, infrastructure, and number of people exposed to the damage or collapse of the dam. The losses may increase as the earthquake intensity increases. The seismic evaluation requirements should consider both the expected losses of given earthquake intensities and the probabilities of those intensities occurring or being exceeded during specified time intervals.

The determination of seismic loading or seismic events for designing new or evaluating existing dams should be carried out based on sound engineering and scientific principles and judgment of qualified specialists. The seismic hazard assessment should be based on both geotechnical information and a statistical analysis of earthquakes experienced near the site, taking into account all potential seismic sources capable of contributing significantly to the seismic hazard at that site. It should consider the geological zone where seismic occurrence is possible, the observed or potential seismic occurrence rate, the magnitude of seismic events, the transmission of the seismic waves, and the impact of the waves on structures of interest.

The application of probabilistic analysis is an integral part of seismic hazard assessment (Cornell 1968). For example, a current seismic hazard model and set of hazard maps of Canada was developed by the Geological Survey of Canada (Adams and Halchuk, 2003) for the 2005 edition of the National Building Code of Canada (NBCC 2005). The detailed information provided in NBCC 2005 consists of peak ground acceleration (PGA) and pseudo-spectra acceleration (PSA) for various Canadian sites for a median probability of exceedance of 2% in 50 years (i.e. median annual probability of exceedance of about $4x10^{-4}$). However, it must be noted that the national hazard results generated for the NBCC 2005 were based on Canada-wide reference ground condition and are specifically provided for seismic design of common buildings only. The probability level (2% in 50 years) was selected to achieve uniform reliability across the country for building design given the range of resistance factors embedded in limit design approach (e.g. the inclusion of R0 factors to reflect actual building performance). On the other hand, the probability levels appropriate for dam design are to be established taking into account the expected losses of failure in case it occurs. Furthermore, the ground motions for the NBCC 2005 represent only the median (i.e. 50th percentile) hazard value, as compared with the mean hazard value recommended for typical seismic hazard computations for dam design. In view of the above reasons, NBCC 2005 hazard values may not be appropriate for dam projects. As a result, it is essential to conduct a site specific seismic hazard evaluation especially for low probability design.

3.2 Terminology

Dams shall meet, at least, a specified seismic ground motion level (design earthquake). However, there is no consistency in terminology for designating the various earthquake scenarios that are used in defining the levels of earthquake excitations for which dams and their appurtenant structures should be designed or evaluated. Terms such as Maximum Design Earthquake (MDE), Maximum Credible Earthquake (MCE), Safety Evaluation Earthquake (SSE), and “Maximum Potential Earthquake” are used in various jurisdictions.

Damage to dams and their appurtenant facilities is often the result from ground motion induced at the dam site by an earthquake located at some distance from the dam. Therefore, in addition to earthquake magnitude, the ground motion characteristics are necessary to fully characterize the design earthquake scenarios for engineering evaluation of a dam.

Consequently, it is essential to prescribe specific guidelines defining ground motions for assessing dam structures. To reflect this concept, a definition of a “new” term, by the Canadian Dam Safety Association, Earthquake Design Ground Motion (EDGM) is introduced as follows:

> **Earthquake Design Ground Motion**
> EDGM is the level of earthquake ground motions at the location of the dam for which a dam structure is designed and evaluated.

For the design and management of dams under seismic excitations, the performance requirement is that the dam structures subjected to the EDGM should perform without catastrophic failure, such as uncontrolled release of a reservoir, although severe damage to the dam or economic loss may occur. For the standards based approach, dam safety assessment normally takes into consideration of appropriate load and resistance factors.

3.3 Design Earthquake Criteria

The seismic hazard analysis at the site determines the intensity of the seismic loads that might affect the dam. In general, most other international standards use dam hazard classification to determine the seismic load levels to be used for safety evaluation of the dam. The parameter(s) defining the seismic loading for checking dam safety depends on the selected analysis method such as the time history, response spectrum, pseudo-static, etc, and on the required performance levels. Further, because upgrading existing dams to a revised performance standard could be more costly than construction of new dams, the seismic loadings for checking designs and for rehabilitating existing dams deserve extra careful considerations.

The Hazard Potential Classification (HPC) is to be used together with the prescribed performance levels in selecting the required seismic loading criteria. Design earthquakes for various HPCs are presented in Table 1 below.

Table 1 - Design Earthquake Criteria

Hazard Potential Classification	Earthquake Design Ground Motion (annual exceedance probability)		
	Life Safety	Property and Environment	Cultural – Built Heritage
Low	500 year		

Moderate	500 to 1000 year			
High	10 or fewer	2,500 year	1,000 to 2,500 year	1,000 year
Very High	11 to 100	5,000 year	2,500 to 10,000 year	
	More than 100	10,000 year		

Notes:

1. The AEP levels are to be used for the “mean” rather than the “median” estimates. The mean is the expected value given the epistemic uncertainties and, for typical seismic hazard computations in Canada, the mean hazard value typically lies between the 65^{th} and 75^{th} percentiles of the hazard distribution. The median is at the 50^{th} percentile.
2. Generally, a seismic hazard evaluation will not be required for Low or Moderate HPC dams unless specifically requested by the Minister with supporting rationale.

3.4 Factors Influencing the Selection of Seismic Evaluation Requirements

The basic seismic loads for the design of new dams or for the safety evaluation of existing structures are derived from the EDGM parameters.

The primary requirement for the earthquake-resistant design of dams is to protect public safety, environment, life and property. Hence most dams must be capable of resisting the strong ground motions considered appropriate to achieve this performance at the dam site without uncontrolled release of the water impounded in the reservoir.

Factors governing the level of effort required for a seismic safety evaluation include:

1. Severity of seismic hazard at the dam site;
2. Type of dam;
3. Functional requirements;
4. Failure modes;
5. Potential hazard for the dam and reservoir; and
6. The HPC of the dam

The design and evaluation of hydraulic structures for earthquake loading must be based on appropriate criteria that reflect both the desired level of safety and the nature of the design and evaluation procedures.

4.0 Seismic Hazard Evaluations

4.1 General Approach

The purpose of a seismic hazard evaluation is to arrive at the EDGM at the site for use in assessing its facilities under seismic loading conditions. Selection of the EDGM should be based on the dam's HPC according to Table 1 above. The seismic parameters used to define the EDGM should be derived by a site-specific probabilistic seismic hazard assessment conducted by qualified specialists at regular time intervals for dams and associated facilities. It often requires close collaboration of an interdisciplinary team that includes technical experts in seismology, geology, material and geotechnical, and structural engineering. The team is responsible for establishing the seismic design requirements, planning and executing the seismological investigations and evaluating the analytical results.

The EDGM is to be described in terms of amplitude levels, frequency content and duration of ground motion, including time histories that characterize the EDGM. The EDGM should be selected to be representative of mean or best estimate ground motions for the target probability level. Investigations to determine the EDGM should include all of the following aspects.

4.2 Identification of Earthquake Sources

Earthquake sources in the region and in the vicinity of the site that can produce seismic ground motion at levels significant to the design of dam structures should be identified. This identification of earthquake sources should be based on the earthquake history of the region, including the lowest magnitude earthquakes detected by modern seismograph networks, in addition to all known historical and paleoseismic events, and on tectonic and geologic interpretation of the sources and causes of the earthquake activity. Where applicable, the potential or significant earthquake activity along local or regional faults, during the life of the dam facilities, should be considered.

4.3 Earthquake Occurrence Rates

Each potential earthquake source should be characterized in terms of the occurrence rates of earthquakes, as a function of magnitude, and constraints on the upper magnitude bound. Note that historical seismicity does not generally provide constraints on the upper magnitude bound due to the relatively short historical record relative to fault behaviour, which may be measured in thousands of years. Paleoseismic information or other geologic data, or information from equivalent regions elsewhere in the world, may provide constraints on long-term fault behaviour and maximum magnitudes.

4.4 Regional Ground Motion Relations

Appropriate regional relations, that specify the earthquake ground motion parameters, their attenuation with distance, their scaling with magnitude, and random variability, should be defined at all frequencies relevant to the design of the dam facilities. If no relations are available for the region of interest, the choice of relations from other similar regions, and their modification if necessary for the site area, should be justified using available regional seismological data. The site condition to which the regional ground motion relations apply should be clearly documented, as it will be required in the evaluation of site effects.

4.5 Probabilistic Seismic Hazard Assessment Methodology

A probabilistic seismic hazard assessment (PSHA) quantifies numerically, at the dam site, the contributions to the seismic motion of all sources and magnitudes within the affected region. The basic procedures are described by McGuire (2004), EERI Committee on Seismic Risk (1989), the U.S. National Research Council Panel on Seismic Hazard Analysis (1988), Reiter (1990), and SSHAC (1997). Seismic hazard analysis procedures should incorporate both seismicity and geologic information. The probability of exceeding specified ground motion amplitude at a site can be computed by integration of hazard contributions over all magnitudes and distances, for all source zones, according to total probability theorem. To obtain ground motion levels or earthquake response spectra for a desired probability, calculations are performed for a number of ground motion amplitudes, and interpolation is used to find the ground motions associated with the chosen probability level.

5.0 Selection of Seismic Evaluation Parameters

The parameters required to characterize the seismic loads for engineering evaluation of a dam will depend on the type of dam, the possible failure modes or performance requirements of the dam, and the methods used to analyze the dam. In particular, different performance based design considerations and analysis methods are required for either concrete or embankment dams. For concrete dams where the primary concerns are sliding and overturning stability, uplift or cracking under seismic loads, peak or peak effective ground motion parameters, response spectra or acceleration time histories are typically used as ground motion parameters for the assessment. However, for embankment dams where the primary concerns are slope stability or excessive deformations, leading to slumping, loss of freeboard or cracking of embankment, not only the intensity of the ground motions but also the duration of the shaking are important to the evaluation of seismic performance (Tang et al. 2004).

Thus, for most types of analyses the key ground motion parameters are: earthquake magnitude and distance, peak ground motion parameters, acceleration response spectra, and foundation fault displacement (if applicable). These parameters represent the EDGM for a structure under consideration, and can be determined using Probabilistic Seismic Hazard Assessment (PSHA).

In general, given the difficulty of reliably correlating seismicity with specific geologic features across most of Canada, a deterministic seismic hazard assessment (DSHA) is only used in limited cases where active faults are well defined, such as in the case of assessing potential Cascadia subduction earthquake scenarios. Guidelines for selection of seismic evaluation parameters based on DSHA approach can be found in ICOLD Bulletin No. 72 (1989), FERC (2005), and USCOLD (1999).

Glossary of Terms

Active Fault: A fault, reasonably identified and located, known to have produced historical earthquakes or showing geologic evidence of Holocene (11,000 years) displacements and which, because of its present tectonic setting, can undergo movement during the anticipated life of manmade structure.

Intensity (of earthquake): In earthquake engineering, intensity is represented by a numerical index describing the effects of an earthquake on man made structures or other features of the earth surface. The assignment of intensity values is subjective and is influenced by the quality of construction, the ground surface conditions, and the individual perception of the observer. Different intensity scales are used in various countries. The Modified Mercalli scale is the most widely used in North America. For the purpose of hazard and risk-based engineering design, intensity is better expressed in terms of a measure of the earthquake ground motion, such as PGA or the pseudo-acceleration spectral ordinate for the fundamental natural period of the system of interest.

Magnitude (of earthquake): A measure of the relative size of earthquakes related to their strain energy released, based on the displacement amplitude and period of the seismic waves and the distance from the earthquake epicentre.

Seismic Hazard: Any physical phenomenon (e.g. ground shaking, ground failure) associated with an earthquake that may produce adverse effects on human activities. In the context of a probabilistic ground motion analysis, hazard refers to the probability of exceedance certain amplitude of ground motion.

Seismic Waves: Group of elastic surface or body waves (seismic energy) propagating within the earth crust, set up by a transient disturbance of the elastic equilibrium of a portion of the earth crust due to fault rupture or tectonic movement.

Seismicity: The occurrence of earthquakes in space and time.

List of Acronyms

DHSA	Deterministic Seismic Hazard Assessment
EDGM	Earthquake Design Ground Motion
HPC	Hazard Potential Classification
LRIA	Lakes and Rivers Improvement Act
MDE	Maximum Design Earthquake
MNR	Ministry of Natural Resources
NBCC	National Building Code of Canada
PGA	Peak Ground Acceleration
PSA	Pseudo-Spectra Acceleration
PSHA	Probabilistic Seismic Hazard Assessment

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