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Review

A Comparison of Return Periods of Design Ground Motions for Dams from Different Agencies and Organizations

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Abstract: The purpose of this paper is to review and compare the criteria of seismic design ground motions and approaches in seismic hazard analysis set forth by various agencies and organizations. A total of 13 agencies and organizations were reviewed including three for non-dam structures. It was found the both the deterministic and probabilistic seismic hazard analysis approaches have been used. Many have combined the two approaches to complement each other. High-consequence dams are designed for a long ground motion return period of approximately 10,000 years, which lies between the design return periods of bridges and nuclear power plants. In contrast to other agencies and organizations, U.S. Bureau of Reclamation dams are not subjected to specific design return periods; they are designed based on risk-informed decisions, which consider the failure probability in relation to the public protection guideline values. In addition, criteria from the Reclamation Design Standards are to be followed in any dam modifications. Based on the findings of this paper, it was deemed that the current Reclamation dam safety decisions and practices are in general agreement with other dam agencies and organizations that also adopt the risk-informed decision process.

Keywords: return period; design earthquake ground motion; dam safety; risk assessment activities; consequences; seismic dam modification; embankment dam

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1. Introduction

The U.S. Bureau of Reclamation (Reclamation) owns and maintains 484 dams in the 17 western United States. The mission of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. The Reclamation Dam Safety Program under the authority of the Safety of Dams Act of 1978, as amended, implements risk management activities to ensure the safe performance of aging dams in its inventory.

As part of its risk assessment activities, Reclamation dams are reviewed and evaluated on a regular basis (e.g., the Comprehensive Review (CR) and the Dam Performance Assessment that alternate every four years) to identify dam safety issues related to normal dam operations and new or updated hydrologic and seismic hazards. The CR includes potential failure modes and risk analyses. If the risk analysis of a dam indicates a sufficiently high probability of failure, actions may be needed to reduce the risk of failure to protect the downstream public. To prioritize dam safety actions, the Reclamation Dam Safety Office (DSO) utilizes the risk-informed decision making framework as outlined in the Public Protection Guidelines [1].

Since many of Reclamation's dams are located in seismically active zones, the probability of a dam failure due to seismic loadings needs to be assessed using the seismic potential failure mode (PFM) and risk analyses. A PFM could be developed for an embankment dam with liquefiable foundation soils, such that, if shaken with strong ground motions, the dam could experience excessive deformation leading to an overtopping failure or an internal erosion failure induced by significant embankment cracking. Case histories on dam damage and deformation induced by strong earthquake shaking (e.g., ref. [2]) are considered when developing the seismic PFM and risk analyses. A required input to the seismic risk analysis is the probability of earthquake loadings. Results from a probabilistic seismic hazard analysis (PSHA) for the dam in question are well suited for the risk analysis. Ground motions with associated return periods (or the reciprocal of the annual exceedance probability) determined from PSHA are used as loading probabilities in the quantitative risk analysis. In addition, the PSHA results are used as a basis to produce ground motion time histories needed for engineering analysis and design.

The Reclamation DSO has supported a research study on the understanding and improvement of earthquake ground motions as it is an integral part of the PFM and risk analyses performed by Reclamation. The findings of this research study could potentially impact future seismic modifications of dams deemed to have high probabilities of failure. As part of the research study, this paper documents the design earthquake ground motions (viz., seismic hazard analysis approaches and design ground motion return periods) adopted by other dam owners, regulators, organizations, and other critical infrastructure industries. The guidelines and criteria from other agencies and organizations are compared to Reclamation's practice, and the differences and similarities are identified.

It should be noted that the comparison presented in this paper is limited to the general approaches of seismic hazard analysis. As such, detailed seismic hazard analysis calculations, source characterization, the treatment of uncertainties, and the determination of specific ground motion parameters are not included. Furthermore, the terminology appeared in this paper are kept as close as possible to how they are presented in the source references. The interpretation and paraphrasing of the source references are kept to a minimum so that the contents of this paper are traceable to the source references. Readers are encouraged to review the source references cited in this paper for additional information and clarification. The target audience of this paper will be, but not limited to, engineers performing nonlinear dynamic analysis and dam safety decision makers. Acronyms and abbreviations used by different agencies and organization are listed in the backmatter of this paper.

2. Review of Guidelines from Different Agencies and Organizations

Guidelines and criteria for seismic design earthquake ground motions from different government agencies and organizations, including Reclamation, are reviewed in this section. A total of 13 agencies and organizations were selected for the review. Note that the review presented herein is not exhaustive. However, 10 agencies and organizations selected are associated with the safety evaluation of dams. Three non-dam agencies and organizations are also included for the purpose of comparing return periods of design ground motions for other types of critical infrastructures with dams.

2.1. Reclamation

Earthquake loadings for analysis of Reclamation embankment dams are described in Chapter 13 of Embankment Dams Design Standards [3]. Reclamation's current dam safety practice is primarily "risk-informed", which means that the decisions are made by considering the annual probability of seismic loading, the likelihood of dam failure given a

particular seismic loading, and the consequences of dam failure in terms of life loss; other considerations may also affect decisions. Therefore, Chapter 13 of the Reclamation Design Standards [3] is intended primarily to support the probabilistic risk analysis. For the design of dam modifications, the standards-based approach is also used in conjunction with the risk-informed approach, where the criteria from other chapters of the Reclamation Design Standards are to be followed (e.g., minimum factors of safety for slope stability analysis [4] and filter and drain design criteria [5]). The three components of the seismic dam safety decision process are shown in Figure 1; seismic loadings are used in the engineering analysis as well as the risk analysis.

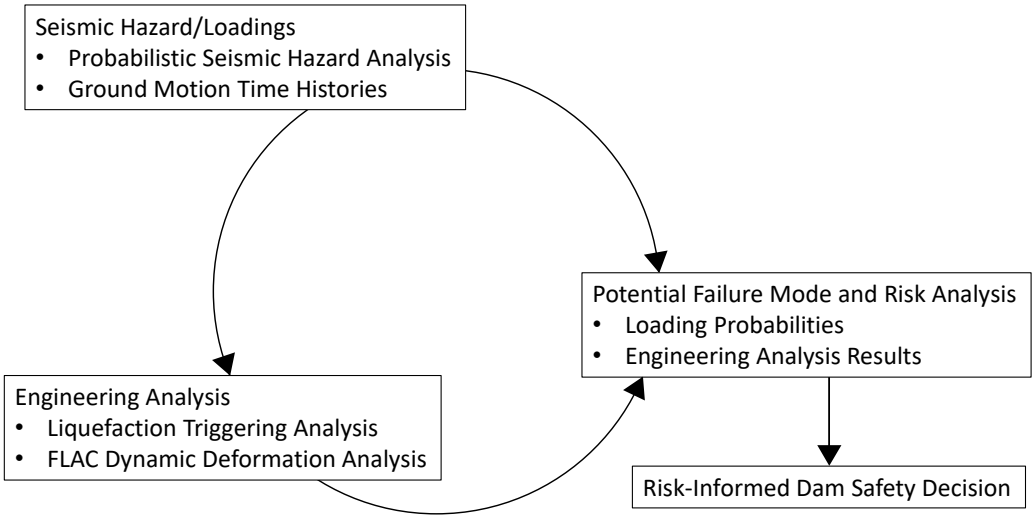

Figure 1. Components leading to a seismic dam safety decision for embankment dams.

Site-specific PSHA is typically performed for all Reclamation dams. PSHA studies generally include the identification and characterization of seismic sources or zones of seismicity, the selection of appropriate ground motion models, the development of hazard curves for peak ground acceleration and spectral acceleration for a suite of spectral periods, and the development of uniform hazard spectra (UHS) for return periods of interest. Seismic hazard curves show the relationship between spectral acceleration and the annual frequency (mean or fractile) that the spectral acceleration is expected to be exceeded. A UHS is associated with a specific annual exceedance frequency (or a return period), and it is a graph of spectral acceleration against the spectral period. A UHS includes the peak ground acceleration, which is the zero-period spectral acceleration. The results of PSHA are used in the development of earthquake ground motion time histories for nonlinear dynamic analysis. One benefit of the PSHA approach is that it combines the contribution from all seismic sources to produce a complete model of the earthquake hazard for the dam site. If the hazard is calculated for a sufficient number of spectral periods, a UHS can be produced by selecting spectral accelerations that correspond to a common return period.

Combining all earthquake sources into a hazard curve obscures the contribution from particular sources, and it may not be clear what magnitude to use in geotechnical analyses (e.g., soil liquefaction analysis). Fortunately, disaggregating the PSHA results allows the distribution of the magnitude and the distance of seismic sources to be determined. The dominating source and magnitude for a particular return period can then be utilized in the soil liquefaction analysis and in developing time histories for nonlinear dynamic analysis.

The deterministic maximum credible earthquake (MCE) approach has been superseded since the 1990s by the probabilistic approach in Reclamation's dam safety practice. For the probabilistic risk analysis, it is necessary to know the annual exceedance prob-

abilities associated with different levels of loading and not just the maximum loadings considered possible at a dam site.

Ground motion time histories are developed utilizing the UHS, where the UHS considers the frequency of occurrence and magnitudes from all earthquake sources in the general area of the dam. The UHS does not represent the actual response spectrum for a particular earthquake. Reclamation design standards [3] recognize that matching the entire UHS would be unnecessarily conservative. Therefore, the design standards state that ground motions for dynamic analysis should not be forced to match the UHS for the full range of natural periods. To avoid unnecessary conservatism, a preferred technique is to use the broadened conditional mean spectrum (CMS) as the target spectrum.

It is not always obvious which period is the most critical for a particular dam, so the preferred practice is to develop several CMSs to represent an UHS, each anchored at different potential critical natural periods (e.g., 0.2 and 1.0 s). The Reclamation practice is to select five or more sets of ground motion records (seeds) for spectral matching each CMS, with each set consisting of two horizontal components and a vertical component (see [3] (Appendix A)). Ground motion seed time histories can be existing strong-motion recordings or computed synthetic records, and the seed time histories are selected with consideration of the type of fault, earthquake magnitude, source distance, and site condition. The scaled or spectrally matched ground motion records may need to be deconvolved so that the shaking can be applied to the base of the numerical model. For risk analysis, the full range of dynamic deformation results are needed and not just the worst case. With nonlinear behavior expected for embankment dams, the most critical period is likely to be longer than the fundamental period of the embankment. Reclamation design standards also suggest that ground motions can be developed for a specific scenario earthquake from a particular fault.

2.2. ICOLD

The International Commission on Large Dams (ICOLD) is a non-regulatory agency that provides standards and guidelines to address dam safety issues. The criteria of acceptable seismic dam performance suggested by ICOLD Bulletin 148 [6] are that (1) there should be no uncontrolled release of water from the reservoir from the shaking of a Safety Evaluation Earthquake (SEE) and (2) there should be no or insignificant damage to the dam and appurtenant structures from the shaking of an Operating Basis Earthquake (OBE). An SEE is the maximum level of ground motion for which the dam should be designed or analyzed. A deterministically evaluated MCE, or the probabilistically evaluated earthquake with a long return period (e.g., 10,000 years), can be considered as an SEE. Deterministically evaluated earthquakes may be more appropriate in locations with relatively frequent earthquakes from known and well-identified sources, for example, near plate boundaries [6]. The OBE shaking results in a functional dam and appurtenant structures, and the damage is minor and easily repairable. It is appropriate for an OBE to have a minimum return period of 145 years (i.e., a 50% probability of not being exceeded in 100 years). The OBE can be considered as an economical criterion and is negotiable, whereas the SEE is a non-negotiable safety criterion for the dam. Depending on the applications, a dam may be analyzed with SEE or both of SEE and OBE loads [6].

Four levels of consequence rating (i.e., low, moderate, high, and extreme ratings) are used to help determine the seismic input parameters. ICOLD consequence is loosely defined as the anticipated impact downstream of a dam failure; for example, socio-economic consequences can be expressed by the number of persons who would need to be evacuated in case of a dam failure. Different countries will need to adapt socio-economic consequences that suit their circumstances [6].

For extreme- or high-consequence dams, the SEE should be estimated at the 84th percentile level if developed by a deterministic approach or have a mean annual exceedance probability (AEP) greater than or equal to 1/10,000 if developed by a probabilistic approach. For moderate-consequence dams, the SEE should be estimated at the 50th to 84th percentile level if developed by a deterministic approach or a mean AEP greater than or equal to 1/3000 if developed by a probabilistic approach. For low-consequence dams, the SEE ground motion parameters should be estimated at the 50th percentile level if developed by a deterministic approach or a mean AEP greater than or equal to 1/1000 if developed by a probabilistic approach. The OBE usually would have a mean AEP of about 1/145 [6].

2.3. FERC

The U.S. Federal Energy Regulatory Commission (FERC) licenses and inspects private, municipal, and state hydroelectric projects in the U.S. The Division of Dam Safety and Inspections of the Office of Energy Projects at the FERC is responsible for the safety of power-generating facilities under its jurisdiction throughout the U.S. To account for the impacts of earthquakes at these facilities, FERC has established seismic design criteria in Chapter 13 of Engineering Guidelines for the evaluation of hydropower projects [7]; this FERC document provides guidelines for estimating seismic parameters and procedures for evaluating deterministic seismic hazard analysis (DSHA) and PSHA.

The FERC guidelines [7] establish requirements of a seismic hazard evaluation at a particular dam site. The guidelines do not provide the definition of an "active" fault based on a specified time criterion but rather emphasizes the importance of key fault parameters, which include the fault slip rate, fault displacement for each fault rupture event, length and area of fault rupture, earthquake size, and earthquake recurrence interval. The guidelines require that a DSHA should always be conducted to obtain the target spectrum for each seismic source that is significant to the site. In a DSHA, the median (50th percentile) of intensity measure (e.g., spectral acceleration or peak ground acceleration) distribution from the empirical ground motion model (or attenuation relationship) is used when the seismic source has a relatively low degree of activity (i.e., faults with slip rates, SR $\leq$ 0.3 mm/year), and the 84th percentile value is used when the seismic sources have relatively high slip rates (i.e., faults with slip rates, SR $\geq$ 0.9 mm/year). For a slip rate value between 0.3 and 0.9 mm/year, the fraction of standard error term (ε) as a function of slip rate can be estimated and then be used to calculate the corresponding percentile. The maximum magnitude on each source, hence the MCE, is used for selecting the earthquake ground motions. For a background seismic zone (i.e., a possible seismic source not associated with any known fault), the distance from the site to such sources is typically assigned as a depth below the site that varies from 5 to 15 km, depending on the data from instrumental seismicity, and the maximum moment magnitude is typically M = 6 ½ $\pm$ ¼.

When sufficient information for the seismic sources is available, a PSHA may be completed to supplement the deterministic evaluation [7]. A PSHA should be used to generate the hazard curves, UHS, quantify the hazard contributions contribution by source, and the deaggregation plots. Results from the PSHA can be used to inform the methods of engineering analyses and selection of design parameters. FERC describes the U.S. Geological Survey (USGS) Unified Hazard Tool [8] as a valuable tool for comparison purposes; however, FERC notes that the results from the tool should not be used in lieu of site-specific seismic hazard evaluation since the USGS values do not represent the necessary site-specific loadings. FERC states that the return periods of 475 years (i.e., 10 percent in 50 years) and 2475 years (i.e., 2 percent in 50 years) should be obtained and compared to those from the PSHA. If significant differences exist between the site-specific results and the USGS hazard values (e.g., in hazard curves

and magnitude–distance deaggregation data), possible causes for these differences should be explained and documented. In addition, if a PSHA is conducted, the UHS should be decomposed into two or more CMSs to provide more realistic expected spectral shapes. Analyses and design should be based on site-specific seismic hazard results and not the USGS hazard values.

Examples of PSHA are provided in the FERC guidelines [7]. In one of the examples, the UHSs for different return periods for a site are compared to the MCE response spectra of a fault source associated with a magnitude and a distance for the same site; the example comparison is shown in Figure 2. In the example comparison, the short spectral periods of the 84th percentile MCE (i.e., red dashed curve) is close to the UHS at a return period of about 700 years, and the long spectral period is close to the UHS at a return period of 2000 years. Note that although both DHSA and PSHA are presented in Figure 2, it is not clear which approach was chosen by FERC and how they are used in the design and analysis of this example project.

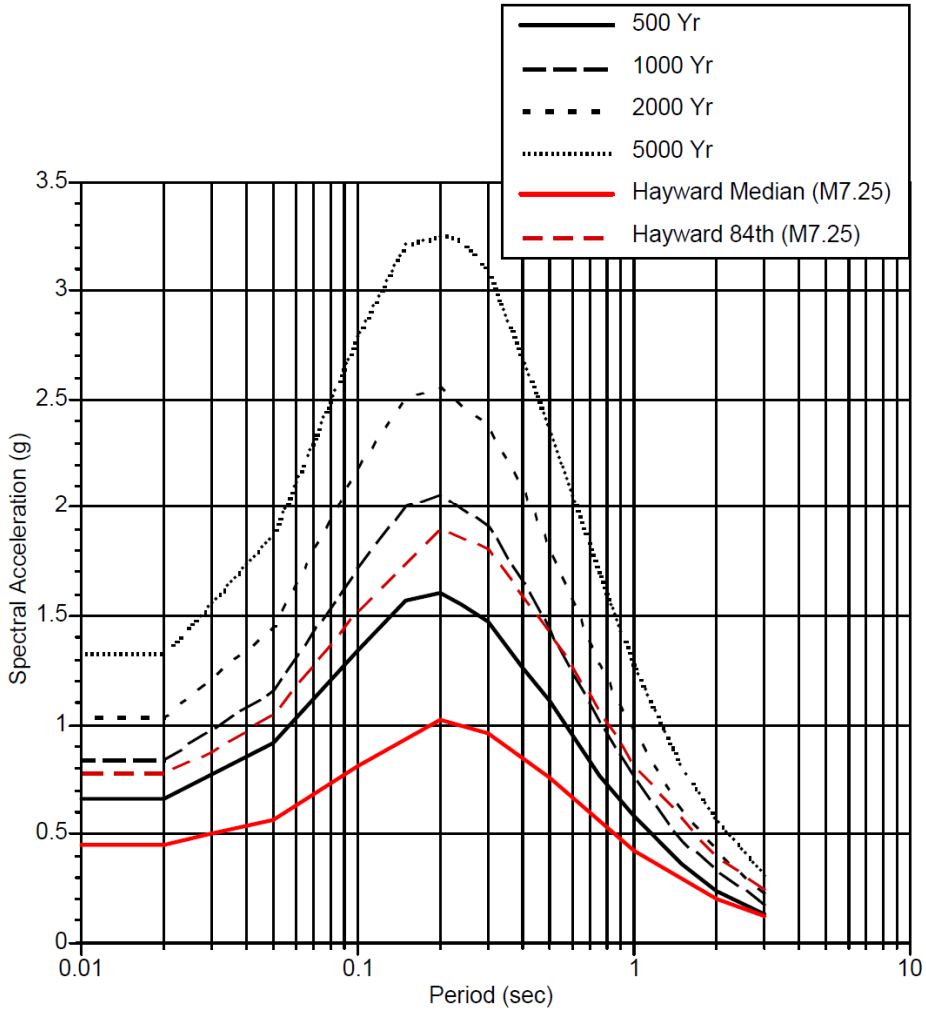

Figure 2. Comparison UHS (black curves) and deterministic MCE spectra (red curves) of an example site (following [7]).

The FERC guidelines [7] indicates that a UHS does not represent the spectrum of any single event. It is common to find that short-period (e.g., <0.2 s) ground motions are controlled by nearby moderate magnitude earthquakes, whereas long-period (e.g., >1 s) ground motions are more likely controlled by distant large magnitude earthquakes. A reason for using a UHS rather than using multiple spectra for the individual earthquake scenarios is to reduce the number of analyses required; however, such a practice is discouraged by the guidelines.

Instead, a suite of realistic spectra for scenario earthquakes should be developed using procedures suggested in the FERC guidelines [7]. The spectrum with the expected spectral shape for a scenario earthquake is computed as the "expected scenario earthquake spectrum" or commonly known as the CMS. From the "seed" time histories, ground motion time histories for engineering design and evaluation can be developed by the spectral matching procedure that matches the expected scenario spectrum. The FERC guidelines [7] recommend at least seven ground motion time histories for each scenario spectrum.

FERC is transitioning to a risk-informed dam safety evaluation from the existing standards-based (deterministic) guidelines. The FERC Risk-Informed Decision Making (RIDM) Guidelines [9] was published in 2016, and many pilot studies have been performed by the FERC licensees following the RIDM guidelines since its publication [10]. The RIDM guidelines divide the dam safety risk analyses into four levels: (1) screening level, (2) periodic, (3) semi-quantitative, and (4) quantitative [9]. In general, complexity and effort increase with ascending risk analysis levels. Since 2021, FERC requires its licensees to perform a Level 2 risk analysis as part of a comprehensive assessment. As outlined in the RIDM guidelines [9], the development of PSHA curves along with the previously developed MCE are needed for semi-quantitative risk analyses (Level 3) and quantitative risk analyses (Level 4). For Levels 1 and 2 risk analyses, the collection of seismic hazard data and geologic studies are performed for the regional area with a radius of greater than 100 km from the site. For Levels 2 and 3 risk analyses, the data are collected at a distance of 15 to 100 km from the site. The data collected for Levels 3 and 4 risk analyses are site-specific, and the area covered is less than 15 km from the site; the site-specific data can be applied to seismic retrofit and design for new dams [11].

2.4. USACE

The U.S. Army Corps of Engineers (USACE) operates and maintains approximately 740 dams and associated structures nationwide. The requirements for the seismic evaluation, analysis, and design of civil works projects by the USACE are documented in Engineer Regulation (ER) 1110-2-1806 [12]. The requirements are applicable to seismic design for new and existing civil works project features (e.g., hydraulic structures such as dams and levees). A USACE civil works project is assigned one of the two project feature types (i.e., Non-Critical and Critical) based on a project-specific assessment of consequences, as outlined in Table 1. A Non-Critical project feature has no direct loss of life and causes no disruption of project feature services or has minimal property losses during or immediately following an earthquake. A Critical project feature constitutes failure or damage due to an earthquake that could result in a direct loss of life and cause a disruption of lifeline facilities. The property losses due to the failure of a Critical project feature are described as "major to extensive."

In addition, seismic ground motion hazard regions are classified into low, moderate, and high categories based on the peak ground acceleration (PGA) [12]. The PGA should be determined using the average small-strain shear wave velocity in the upper 30 m (100 feet) (V_{s30}) of the site profile, free-field conditions, and an earthquake ground motion return period of 975 years. Low seismic ground motion hazard regions are associated with a PGA that is less than or equal to 0.1 g (PGA $\leq$ 0.1 g). Moderate seismic ground motion hazard regions have a PGA between 0.1 g and 0.2 g (0.1 g < PGA < 0.2 g). High seismic ground motion hazard regions have a PGA that is equal to or greater than 0.2 g (PGA $\geq$ 0.2 g).

Table 1. Consequence-based project feature classification (following [12]).

Project Feature Type [1]	Direct Loss of Life [2]	Disruption or Loss of Project Feature Service or Functionality; Loss of Service or Access for Lifeline Facilities [3]	Property Losses [4]	Adverse Environmental Impacts [5]
Non-Critical	None expected	None or damage is cosmetic or rapidly repairable	Minimal	Minimal damage
Critical	None expected to probable or likely (one or more)	Probable or likely	Major to extensive	Major to extensive damage [6]

[1] Categories are based on project feature performance. Project performance could be impacted by performance of a single or multiple individual project feature within a project or system. [2] Loss of life potential is based on failure or inundation mapping of the area downstream of the dam or within the leveed area. In some cases, inundation mapping may also include upstream areas. [3] Indirect threats to life caused by the interruption of lifeline or other facility services because of project failure or operation loss (such as direct loss of [or access to] critical medical facilities, safe water supply). [4] Direct economic impact of property damages, project facilities, downstream property, and property within the leveed or upstream area, and indirect economic impact because of loss of project services (such as inundation impact on navigation industry because of the loss of a dam and navigation pool, impact on a community of the loss of water or power supply). [5] Adverse environmental impacts caused by the project feature failure or loss of water supply for environmental purpose, beyond what would normally be expected for the magnitude flood event if the project did not exist. [6] In some cases, major to extensive damage may require extensive mitigation and, in some cases, it may be difficult or impossible to mitigate the environmental damage.

Earthquake ground motions and the associated performance requirements for the evaluation, analysis, and design of consequence-based civil works project features are presented in Table 2. Two levels of ground motion are considered. One is the operating basis earthquake ground motion (OBE-GM), and the other one is the maximum design earthquake ground motion (MDE-GM). The performance requirement associated with OBE-GM is that the project feature functions with little or no damage and without an interruption of function. The MDE-GM is the maximum level of ground motion for which a project feature is designed or evaluated, and the associated performance requirement is that the project feature performs without a loss of life or catastrophic failure (such as an uncontrolled release of a reservoir). However, the MDE-GM could result in severe damage to the project feature, property losses, or adverse environmental impacts. Note that in developing the MDE-GM for critical project features, the maximum credible earthquake ground motion (MCE-GM) is also considered. The MCE-GM is defined as the largest earthquake ground motion that can reasonably be expected to generate by a specific source, zone, or scenario and is based on the seismological and geological characterization of both nearby and more distant potentially active seismic sources [12]. Note that the definitions of the OBE-GM and MDE-GM are the same as the OBE and SEE adopted by ICOLD [6], respectively.

Site seismic ground motion hazard classification will be used to determine the analysis methods. The appropriate level of complexity in analysis methods will depend on the phase of the design or assessment, project feature-specific conditions, project feature criticality, and structure type. Advanced analysis methods (such as the response spectrum analysis, ground motion time series analysis, and nonlinear seismic analyses) must be performed in the final design or evaluation of Critical project features in high seismic ground motion hazard regions. For Critical project features in moderate seismic ground motion hazard regions, analysis methods must be based on project feature-specific considerations. For Non-Critical project features in all seismic ground motion hazard regions, a higher level of analysis can be adopted, if reasonably justified. Advanced analyses may be beneficial for designing Non-Critical project features in all seismic ground motion hazard regions and Critical project features in low seismic ground motion hazard regions. Furthermore, for Critical project features, evaluations are required for aftershock events and fault rupture displacements within 30 km (~19 miles) from the project feature site [12].

Table 2. Criteria for seismic design ground motions (following [12]).

Project Feature Type	Minimum Earthquake Return Period for OBE-GM [1]	Earthquake Return Period for MDE-GM
Non-Critical	145-year return period [2]	975-year return period
Critical	475-year return period [3]	Greater [4] of the following: (1) 2475-year return period [5,6] (2) MCE-GM (84th percentile values from ground motion models for source slip rate, SR $\geq$ 0.9 mm/year, median or 50th percentile values for SR $\leq$ 0.3 mm/year, and interpolation for SR values between 0.3 mm/year and 0.9 mm/year

[1] Earthquake return periods are based on 50 years of new project feature service life or additional 50 years of service life for an existing project feature. [2] A higher earthquake return period for OBE-GM, such as a 225-year return period, can be used for a Non-Critical project feature based on the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair. [3] A higher earthquake return period for OBE-GM, such as a 975-year return period, can be used for a Critical project feature based on the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair. [4] If the 84th percentile MCE-GM (irrespective of slip rates) is lower than the 2475-year return period GM in a low seismic ground motion hazard region, the 84th percentile MCE-GM can be considered for MDE-GM of the Critical project feature based on the significance of the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair. However, the selected MCE-GM value cannot be lowered below 90 percent of the 2475-year return period GM. [5] A higher earthquake return period for MDE-GM (such as 5000 or 10,000 years) can be used for a Critical project feature based on the consequences, project feature functionality, project feature service life, and/or post-earthquake response and repair. [6] In regions where mapped seismic sources are not available for MCE-GM determination, a minimum earthquake return period of 2475 years will be used for MDE-GM.

The USACE has adopted a risk-informed approach for new designs and/or modifications to dams and levees [12]. Risk-informed design and evaluation will be performed using the risk assessment process. Dam features are required to meet the performance objectives provided in Table 2 in conjunction with tolerable risk guidelines, as outlined in ER 1110-2-1156 [13]. The full range of probabilistic earthquake hazards and ground motions must be developed considering the seismologic and geologic conditions, tolerable risk guidelines, and project feature type. The OBE-GM and MDE-GM are two earthquake ground motions out of a full range of earthquake ground motion levels that must be evaluated as part of the risk-informed design and evaluation process. The scope of the risk assessment can be scaled to the project's feature size, complexity, site ground motion hazards, criticality, and consequences of a project feature [12].

2.5. NRCS

The U.S. Department of Agriculture, Natural Resources Conservation Service (NRCS) published a Technical Release (TR) [14] to provide design procedures and the minimum requirements for the planning and construction of local government and conservation district earth dams. According to the TR, the effects of earthquake loading need to be considered for all dams. The level of investigation and analysis will depend on the potential consequences of the dam failure, the seismicity of the site, individual site characteristics that influence the performance of the dam under earthquake loading, and the anticipated analysis and design methods.

Three levels of consequence from a seismic failure are described in the NRCS TR [14]. The "low consequence" is associated with dams in rural or agricultural areas, and a failure may result in damage to farm buildings, agricultural land, or country roads. The "significant consequence" of a seismic failure may include damage to isolated homes and main highways and the interruption of the service of relatively important public utilities. The "high consequence" of a seismic failure may cause a loss of life or serious damages to

homes, industrial and commercial buildings, important public utilities, and main highways or railroads.

Both the MDE and OBE are considered in the NRCS TR [14]. In a design, the dam needs to withstand the level of earthquake shaking resulting from the MDE without the release of water from the reservoir. On the other hand, an OBE would result in damages limited to the extent that the dam retains partial function prior to repair of the dam. The OBE is the critical ground motions for the evaluation of a post-earthquake scenario; in a design, the dam needs to withstand OBE shaking and have the capability to pass the principal spillway flood without failure. The development of MDE is a function of the consequence of a seismic failure, as indicated in Table 3. The OBE is to be developed based on the hazard potential classification of a seismic failure as shown in Table 4. The values of annual probability of exceedance in Tables 3 and 4 are minimum values. Note that the definitions of MDE and OBE are the same as the SEE and OBE adopted by the ICOLD [6], respectively.

Table 3. Minimum annual probability of exceedance of peak ground acceleration (PGA) for maximum design earthquake (MDE) loading (following [14]).

Consequence of a Seismic Failure	Annual Probability of Exceedance of PGA	Return Period (Years)	Approximate Probability of Exceedance in 50 Years
Low consequence	1×10^{-3}	1000	5%
Significant consequence	4×10^{-4}	2500	2%
High consequence	1×10^{-4}	10,000	0.5%

Table 4. Minimum annual probability of exceedance of peak ground acceleration for operating basis earthquake (OBE) loading (following [14]).

Hazard Potential Classification of Dam	Annual Probability of Exceedance of PGA	Return Period (Years)	Approximate Probability of Exceedance in 50 Years
Low hazard potential	-	-	-
Significant hazard potential	4×10^{-3}	250	20%
High hazard potential	2×10^{-3}	500	10%

Site-specific seismic hazard assessments can be performed using either the DSHA or PSHA [14]. For high hazard potential dams that use the DSHA, the selection of seismic parameters should be based on the mean plus one standard deviation (i.e., 84th percentile level) results. The documentation of the site-specific study should include a comparison of the proposed earthquake loading and those from the most recent version of the USGS Unified Hazard Tool [8] and the rationale for the selection.

2.6. CDA

The Canadian Dam Association (CDA), a non-regulatory organization, published the Dam Safety Guidelines [15] and a separate companion series of Technical Bulletins [16] to outline processes and criteria for the management and analysis of dam safety projects in Canada. As recommended by the guidelines [15], the seismic design criteria should be based on a site-specific seismic hazard evaluation, in which a PSHA is typically performed to obtain the earthquake ground motion parameters. Damage to dams and their appurtenant structures can result from seismic hazards such as (1) shaking caused by an earthquake, (2) liquefaction, settlement, cracking, or displacements induced by the shaking, or (3) surface rupture along the fault that caused the earthquake. Earthquake design ground

motion (EDGM), characterized by the required seismic design parameters at the dam site, would need to be developed for use in the seismic response analysis of the dam and its appurtenant structures.

The EDGM needs to consider the desired level of safety and should be selected based on the consequences of a dam failure. The dam classification as a function of the consequences is defined in Table 5. The suggested AEP associated with a dam classification is summarized in Table 6, where the probability levels are established by considering the expected consequences of a dam failure. The required performance of a dam and its appurtenant structures when subjected to the EDGM is that a catastrophic failure such as the uncontrolled release of reservoir water does not occur; however, severe damage or economic loss may be tolerated from the EDGM [16]. Note that the definition of EDGM is the same as the SEE adopted by the ICOLD [6].

Table 5. Dam classification from CDA Dam Safety Guidelines (following [15]).

Dam Class	Population at Risk (PAR) [1]	Incremental Losses		
		Loss of Life [2]	Environmental and Cultural Values	Infrastructure and Economics
Low	None	0	• Minimal short-term loss • No long-term loss	• Low economic losses; area contains limited infrastructure or services
Significant	Temporary only	Unspecified	• No significant loss or deterioration of fish or wildlife habitat • Loss of marginal habitat only • Restoration or compensation in kind highly possible	• Losses to recreational facilities, seasonal workplaces, and infrequently used transportation routes
High	Permanent	10 or fewer	• Significant loss or deterioration of important fish or wildlife habitat • Restoration or compensation in kind highly possible	• High economic losses affecting infrastructures, public transportation, and commercial facilities
Very high	Permanent	100 or fewer	• Significant loss or deterioration of critical fish or wildlife habitat • Restoration or compensation in kind possible but impractical	• Very high economic losses affecting important infrastructure or services (e.g., highway, industrial facility, storage facilities for dangerous substances)
Extreme	Permanent	More than 100	• Major loss of critical fish or wildlife habitat • Restoration or compensation in kind impossible	• Extreme losses affecting critical infrastructure or services (e.g., hospital, major industrial complex, major storage facilities for dangerous substances)

[1] Definitions for population at risk: None—There is no identifiable population at risk, so there is no possibility of loss of life other than through unforeseeable misadventure. Temporary—People are only temporarily in the dam-breach inundation zone (e.g., seasonal cottage use, passing through on transportation routes, participating in recreational actives). Permanent—The population at risk is ordinarily located in the dam-breach inundation zone (e.g., as permanent residents); three consequence classes (high, very high, extreme) are proposed to allow for more detailed estimates of potential loss of life (to assist in decision-making if the appropriate analysis is carried out). [2] Implications for loss of life: Unspecified—The appropriate level of safety required at a dam where people are temporarily at risk depends on the number of people, the exposure time, the nature of their activity, and other conditions. A higher class could be appropriate, depending on the requirements. However, the design flood requirement, for example, might not be higher if the temporary population is not likely to be present during the flood season.

Table 6. Suggested earthquake design ground motion (EDGM) levels (following [16]).

Dam Class	Annual Exceedance Probability (AEP) of Earthquake Design Ground Motion (EDGM) [1]
Low	1/500
Significant	1/1000
High	1/2500
Very high	1/5000 [2]
Extreme	1/10,000 [2]

[1] AEP levels for EDGM are to be used for mean rather than median estimates of the hazard. [2] The EDGM value must be justified to demonstrate conformance to societal norms of acceptable risk. Justification can be provided with the help of failure modes analysis focused on the particular modes that can contribute to failure initiated by a seismic event. If the justification cannot be provided, the EDGM should be 1/10,000.

Although the seismic hazard assessment in Canada is generally based on PSHA as most of the seismically active areas in Canada lack direct correlation with well-defined active or likely active faults, DSHA is not precluded if sufficient seismotectonic information is available [15]. DSHA can be used to validate the rationale and hypothesis adopted in the PSHA, while the PSHA can be used to ensure that the DSHA is probable. In most cases, the use of both approaches is considered beneficial [16].

According to the Technical Bulletin [16], the acceleration time history records selected to reflect the magnitude, distance, and site condition should be modified so that their response spectra are compatible in amplitude with the design ground motion levels. Table 7 summarizes the recommended practices for time history record selection. As indicated in Table 7, multiple time history records should be selected, typically a suite of 3 to 7, depending on the project.

Table 7. Recommendations for selection of time history records (following [16]).

General	• Multiple records should be selected (3 to 7, depending on the project). • Records should be free-field rock outcrop motions.
Tectonics and geological conditions	• Records should be from similar tectonics setting and source mechanism, e.g., plate boundary region, continental interior, subduction zone, or modified appropriate to achieve such similarity.
Earthquake and ground motion parameters [1]	• Magnitude should be similar to that of design scenario(s), typically within about $\pm$0.5 M. • Distance should be similar to that of design scenario(s) typically within $\pm$50%. • A suite of response spectrum shapes that collectively match the target response spectrum. • Spectral acceleration, Sa, corresponding to the fundamental vibration mode of structures should be similar to the target Sa at that period, typically within a factor of 2.
Time history scaling	• Simple uniform scaling is preferred, rather than spectrum matching scaling in time or frequency domain. However, spectrum match is appropriate, under many circumstances. • Simple uniform scaling at the spectra response period of most significance should be less than a factor of 2.

[1] It may be necessary to relax some of these recommended criteria to obtain a sufficient number of suitable records.

2.7. ANCOLD

Guidelines on the selection of seismic ground motions resulting from earthquakes for existing and new dams in Australia are provided by the Australian National Committee on Large Dams (ANCOLD) [17]. Although ANCOLD is a non-regulatory organization, guidelines produced by ANCOLD are referenced by jurisdictions across Australia. The guidelines cover water supply dams, tailings dams, retarding basins, and appurtenant structures. The seismic design criteria are based on the consequences of a dam failure. The ANCOLD guidelines [18] define the consequences of dam failure as the outcome or result of a dam failure in terms of the loss of life and damage to property and/or services, as well as environmental damage. The ground motion parameters are selected using the "Consequence Categories", which is a seven-tier category system (i.e., very low, low, significant, high C, high B, high A, and extreme) based on the potential effects of dam failure on the general community. Specifically, the categories are based on the severity level of the potential damage and loss, in conjunction with either the population at risk (PAR) or potential loss of life (PLL). The severity levels for various impact types are summarized in Table 8. The ANCOLD guidelines [18] define the PAR as "all those persons who would be directly exposed to flood waters assuming they took no action to evacuate" and the PLL as "the number of potential fatalities what would result from a dam failure". Tables 9 and 10 summarize the consequence category assessments using the PAR and PLL analyses, respectively. Methods for assessing PLL include RCEM, UK RARS, HEC-LifeSim, HEC-FIA, and LSM [19].

Table 8. Severity levels for various impact and damage types (following [20]).

Damage Type	Minor	Medium	Major	Catastrophic
Infrastructure (dam, houses, commerce, farms, community)	<$10 M	$10 M–$100 M	$100 M–$1 B	>$1 B
Business importance	Some restriction	Significant impact	Severe to crippling	Business dissolution, bankruptcy
Public health	<100 people affected	100–1000 people affected	<1000 people affected for more than one month	>10,000 people affected for over one year
Social dislocation	<100 person [months] or <20 business months	100–1000 person months or 20–2000 business months	>1000 person months or >200 business months	>10,000 person months or numerous business failures
Impact area	<1 km^2	<5 km^2	<20 km^2	>20 km^2
Impact duration	<1 year	<5 years	<20 years	>20 years
Impact on natural environment	Damage limited to items of low conservation value (e.g., degraded or cleared land, ephemeral streams, non-endangered flora and fauna). Remediation possible.	Significant effects on rural land and local flora and fauna. Limited effects on: A. Item(s) of local and state natural heritage. B. Native flora and fauna within forestry, aquatic and conservation reserves, or recognized habitat corridors, wetlands or fish breeding areas.	Extensive rural effects. Significant effects on river system and areas A and B. Limited effects on: C. Item(s) of National or World natural heritage. D. Native flora and fauna within national parks, recognized wilderness areas, Ramsar wetlands and nationally protected aquatic reserves. Remediation difficult.	Extensively affects areas A and B. Significantly affects areas C and D. Remediation involves significantly altered ecosystems.

Table 9. Consequence category of a dam based on population at risk (PAR) (following [18]).

Population at Risk	Severity of Damage and Loss			
	Minor	**Medium**	**Major**	**Catastrophic**
<1	Very Low	Low	Significant	High C
≥1 to 10	Significant [2]	Significant [2]	High C	High B
>10 to 100	High C	High C	High B	High A
>100 to 1000	Note [1]	High B	High A	Extreme
>1000		Note [1]	Extreme	Extreme

[1] With a PAR in excess of 100, it is unlikely Damage will be minor. Similarly with a PAR in excess of 1000, it is unlikely Damage will be classified as Medium. [2] Change to "High C" where there is the potential of one or more lives being lost.

Table 10. Consequence category of a dam based on potential loss of life (PLL) (following [18]).

Potential Loss of Life (PLL)	Severity of Damage and Loss			
	Minor	**Medium**	**Major**	**Catastrophic**
<0.1	Very Low	Low	Significant	High C
≥0.1 to 1	Significant	Significant	High C	High B
>1 to 5		High C	High B	High A
>5 to 50	Note [1]	High A	High A	Extreme
>50		Note [1]	Extreme	Extreme

[1] With a PLL equal to or greater than one (1), it is unlikely Damage will be minor. Similarly with a PLL in excess of 50, it is unlikely Damage will be classified as Medium.

The ANCOLD guidelines [17] adopted the same levels of ground motions for dam design and assessment as those defined in the ICOLD [6]. The two levels are the OBE and the SEE. The OBE is the level of ground motion at the dam site for which only minor damage is acceptable. The dam should remain functional, and damage from the earthquake shaking not exceeding the OBE should be easily repairable. The SEE is the maximum level of ground motion for which the dam should be designed or analyzed; damage can be accepted but there should be no uncontrolled release of water from the reservoir.

The assessment of design seismic ground motions can be performed using the deterministic analysis approach or the risk-based analysis approach according to the ANCOLD guidelines [17]. The deterministic analysis approach requires the selection of the OBE and SEE. Dam safety criteria of factor of safety and deformation are to be met so that there is a low likelihood of dam failure given the SEE loading. In the deterministic analysis approach, design ground motions at the dam site are defined in probabilistic terms and by ground motion resulting from the MCE on the active faults in the vicinity of the dam. The selection of design seismic ground motion for the OBE and SEE using the deterministic analysis approach is summarized in Table 11. The risk-based analysis approach requires an assessment of the seismic ground motions at the dam site up to and beyond the SEE for use in risk analyses. For high and extreme consequence category dams, the ANCOLD guidelines [17] prefer the risk-based analysis approach to the deterministic analysis approach. For significant and low consequence category dams, deterministic approaches will usually be adequate.

Table 11. Seismic design ground motions from deterministic analysis approach (following [17]).

Dam Consequence Category	**Operating Basis Earthquake (OBE)** [1]	**Safety Evaluation Earthquake (SEE)** [2,8]
Extreme Consequence Category Dams	Commonly 1 in 475 AEP up to 1 in 1000 AEP	The greater of: Ground motion from the MCE on known active faults [3] or Probabilistic ground motion Extreme: 1 in 10,000 AEP [4]
High A, B and C Consequence Category Dams	Commonly 1 in 475 AEP up to 1 in 1000 AEP	Probabilistic ground motion [5,6,7]: High A: 1 in 10,000 AEP High B: 1 in 5000 AEP High C: 1 in 2000 AEP
Significant Consequence Category Dams	Commonly 1 in 475 AEP	Probabilistic ground motion [5,6]: 1 in 1000 AEP
Low Consequence Category Dams	Commonly 1 in 475 AEP	Probabilistic ground motion [5,6]: 1 in 1000 AEP

[1] To be determined by the owner and other stakeholders in consultation with the consultant. [2] The design of the dam should be such that there will be a low likelihood of the dam failing given the SEE. [3] Active faults are as defined in the ANCOLD [17]. Use the 85th percentile of the hazard from the deterministic MCE. This represents the standard deviation of the random variability about the best estimate of the hazard level from that single earthquake scenario. [4] 85th fractile. This is required so that the design is more likely to have a sufficiently low likelihood of failure given the SEE, than if the median loading was used. [5] Median, 50th fractile. [6] For high B, high C, significant, and low consequence category dams, if the structure is susceptible to liquefaction or has components that will fail at ground motions only a little greater than those presented in this table, check the design for the critical ground motion and assess the adequacy of the design using risk assessment methods. [7] Adoption of these SEE criteria for high B and high C consequence category dams may, in some particular cases, not provide an acceptable level of risk in accordance with ANCOLD risk management guidelines. It is therefore recommended that some level of risk assessment should be undertaken in these cases before adopting the AEP stated in the table. If it cannot be demonstrated that an acceptable level of risk would be achieved, an AEP of 1 in 10,000 should be adopted. [8] Post closure, tailings dams should be designed in accordance with the ANCOLD guidelines on tailings dams.

For time history analyses, both horizontal and vertical components of ground motion should be included in the time history accelerograms. At least five scaled records are commonly necessary for the design of new dams or upgrades of existing dams to demonstrate a robust design. Accelerograms are to be adjusted using the amplitude scaling or spectral matching procedures so the resulting response spectra would approximately match the design response spectrum over the range of frequencies equivalent to the range of natural frequencies of interest for the dam [17].

2.8. NZSOLD

The New Zealand Society on Large Dams (NZSOLD), a non-governmental organization, publishes dam safety guidelines to be considered during the investigation, design, construction, commissioning, assessment, rehabilitation, and operation of large dams in New Zealand. The seismic hazard and earthquake loads need to be considered in the dam safety planning and evaluation process. As indicated in the NZSOLD guidelines [21], a dam is classified according to its Potential Impact Classification (PIC), which is a function of the consequences due to a hypothetical dam breach (i.e., an uncontrolled release of the stored water). The methodology for evaluating the PIC is similar to the Consequence Category used by ANCOLD [18]. Table 12 summarizes the PIC in relation to the PAR, the potential loss of life, and the assessed damage level; the damage levels are based on the severity of damages to community buildings, historical or cultural sites, critical or major infrastructure and natural environment as a result of the dam breach. Criteria for assessing the damage levels can be found in the NZSOLD guidelines [21]. The PIC and the performance criteria are used when conducting seismic hazard studies of a dam.

Table 12. Determination of Potential Impact Classification (PIC) (following [21]).

Assessed Damage Level	Population at Risk (PAR)				Potential Loss of Life
	0	0 to 10	11 to 100	100+	
Catastrophic	High	High	High	High	No persons
	N/A [1]	High	High	High	One person
	N/A [1]	High	High	High	Two or more persons
Major	Medium	Medium	High	High	No persons
	N/A [1]	Medium	High	High	One person
	N/A [1]	High	High	High	Two or more persons
Moderate	Low	Low	Medium	Medium	No persons
	N/A [1]	Medium	Medium	Medium	One person
	N/A [1]	High	High	High	Two or more persons
Minimal	Low	Low	Low	Low	No persons
	N/A [1]	Medium	Medium	Medium	One person
	N/A [1]	High	High	High	Two or more persons

[1] Not applicable. Population at risk is zero; therefore, no potential loss of life.

The NZSOLD dam safety guidelines recommend that dams and appurtenant structures should be designed to meet appropriate performance criteria. The natural hazard loading conditions and potential failure modes of a dam should be identified; the design needs to include a thorough evaluation of dam safety risks and the measures to control the risks. The seismic performance criteria for the design and analysis of dams include two levels of earthquakes, which are the SEE and OBE. The performance requirement for the SEE is that there is no uncontrolled release of the impounded contents when the dam is subjected to the seismic load imposed by the SEE; damage to the dam may have occurred. The performance requirement for the OBE is that the dam and appurtenant structures remain functional and that the resulting damage is minor and easily repairable [21]. Note that the definitions of SEE and OBE are the same as those adopted by the ICOLD [6].

The AEP of the OBE design ground motions presented in the NZSOLD guidelines is about 1 in 150 regardless of the PIC; however, as noted by the guidelines, some owners may choose to adopt a higher standard (e.g., an AEP of 1 in 500) to reflect the importance of the structure. Values of AEP for the SEE performance criterion are summarized in Table 13, which are related to the different levels of PIC and the potential loss of life. The SEE ground motion parameters can be determined using either the deterministic approach or the probabilistic approach; however, the probabilistic approach is favored by many seismic hazard experts because it provides a uniform basis for evaluating the hazard and yields more consistent results. Probabilistic methods that consider background sources are suited for dams located away from known active faults. A deterministic approach is used when active faults are located nearby, as it represents a specific earthquake scenario; the deterministic approach can sometimes result in higher or lower design ground motion estimates compared to probabilistic methods. Determining whether a probabilistic or deterministic approach is more appropriate for a given dam site would require judgment [21].

Table 13. Recommended performance criteria for low, medium and high PIC dams (following [21]).

Performance Criteria	Potential Impact Classification (PIC)		
	Low	**Medium**	**High**
Operating Basis Earthquake (OBE)	1 in 150 AEP [1] regardless of PIC		
Safety Evaluation Earthquake (SEE) [3]	50th percentile level for the MCE ground motion [2] if developed by a deterministic approach, and if developed by a probabilistic approach then at least a 1 in 500 AEP ground motion but need not exceed the 1 in 1000 AEP ground motion.	50th percentile level for the MCE ground motion for incremental Potential Loss of Life of 0 and 84th percentile level for incremental Potential Loss of Life of 1 if developed by a deterministic approach and need not exceed the 1 in 2500 AEP ground motion developed by a probabilistic approach.	84th percentile level for the MCE ground motion if developed by a deterministic approach and need not exceed the 1 in 5000 AEP ground motion for incremental Potential Loss of Life of 0 or 1 and 1 in 10,000 AEP ground motion for incremental Potential Loss of Life of 2 or more developed by a probabilistic approach.

[1] AEP is annual exceedance probability. [2] MCE is maximum credible earthquake. [3] Recommendations on SEE design loads are further discussed in [21].

The PAR, PLL, and other consequences of failure should be considered when determining the appropriate levels of SEE ground motion. The SEE ground motion for low PIC dams is estimated from the 50th percentile of MCE ground motion when based on a deterministic approach. Alternatively, when based on the probabilistic approach, the minimum AEP ground motion used should be at least 1 in 500 AEP but not exceed the 1 in 1000 AEP ground motion. For medium PIC dams, the SEE ground motion should be estimated from the 50th percentile of the MCE ground motion for zero (0) incremental potential loss of life and the 84th percentile level for one (1) incremental potential loss of life if developed using the deterministic approach; if the probabilistic approach is used, the SEE ground motion should not exceed the 1 in 2500 AEP ground motion. For the case of high PIC dams, SEE ground motion should be estimated at the 84th percentile of MCE ground motion when developed by a deterministic approach, and if the probabilistic approach is used, the mean 1 in 5000 AEP ground motion need not be exceeded for an incremental potential loss of life of less than or equal to one (1), and the mean 1 in 10,000 AEP ground motion need not be exceeded for incremental potential loss of life equal to or greater than two (2) [21].

For low PIC dams, detailed site-specific seismic hazard studies are not required. For medium PIC dams, published data can generally be used to obtain probabilistic estimates of seismic hazard for design and analysis. For medium PIC dams with embankment fills or foundations that could soften when subjected to strong earthquake ground motions and for high PIC dams, a site-specific seismic hazard assessment should be completed using both deterministic and probabilistic analyses. Depending on the analysis method, the design ground motions for the OBE and SEE should include response spectra and possibly acceleration time histories. For embankment dams that are expected to behave nonlinearly, both horizontal and vertical components of ground motion need to be developed with damping rate in the range of 5% to 20%. The time history records developed from actual earthquakes should have similar magnitude and distance from the source as those anticipated at the dam site. The minimum number of time histories that should be considered is three, and the performance should be assessed based on the maximum response of the three ground motions [21].

2.9. India CWC

The Central Water Commission (CWC) Dam Safety Organization of the Indian Government performs a coordinative and advisory role for the state governments and dam owners in India. As a non-regulatory agency, the CWC has published a series of guidelines and manuals under the Dam Rehabilitation and Improvement Project to provide guidance related to dam safety design and analysis. The design earthquakes, target spectra, and selection of ground motions are addressed in the Manual for Assessing Structural Safety of Existing Dams [22].

According to the manual, two performance levels of ground motion are to be considered in the seismic design of new dams and the safety evaluation of existing dams, and they are the OBE and MDE ground motions. Both the OBE and MDE ground motions are to be determined by PSHA. At the OBE level of ground shaking, the dam and appurtenant structures should experience little or no damage and continue to function without interruption. At the MDE level of ground shaking, there should be no catastrophic failure, such as the uncontrolled release of the impounded water, although significant damage or economic losses may be tolerated [22].

The return periods of the OBE ground motion are 144 and 500 years for concrete dams and embankment dams, respectively. Return periods of MDE ground motion for concrete dams are based on the consequences of the dam failure, criticality of project function, and turnaround time to restore the facility to be operational after the earthquake event. The three categories of consequences of a dam failure are low, moderate, and high. For concrete dams, the MDE ground motion return periods associated with the low, moderate, and high consequence categories are 1000, 3000, and 10,000 years, respectively, whereas the MDE ground motion return period for embankment dams is just 10,000 years [22]. Note that the OBE and MDE ground motion return periods for concrete dams are the same as those presented in the ICOLD guidelines [6].

The three categories of consequences of failure described above are not explained in detail in the CWC manual [22]. However, categories of consequences of failure that match the design earthquakes described above are found in the CWC Guidelines for Classifying the Hazard Potential of Dams [23]. These consequence categories, which are based on the population at risk and economic losses, are summarized in Table 14. In addition to the three categories of consequences of failure, Table 14 also shows a "Very high" category, which is perceived by the authors to be the same as the "High" category for the purpose of developing design earthquake ground motion. The "High" and "Very high" categories are not differentiated in the CWC manual. Note that the CWC guidelines [23] also present a new hazard potential classification system utilizing a consequences-based approach. Since the newly proposed hazard potential classes do not seem to match the categories of consequences of failure for the design earthquakes described in the CWC manual, they are not presented in this study.

As suggested by the CWC manual [22], ground motion records can be developed using either the amplitude scaling method or the spectral matching method. Furthermore, the CWC manual prefers the amplitude scaling as it preserves the natural variability in the ground motion records. Similar to the building profession, CWC manual recommends 11 ground motion records for performing nonlinear response history analysis of concrete dams. Note that the number of ground motion records for performing the dynamic analysis of embankment dams is not specified in the CWC manual.

Table 14. Consequence categories for dams (following [23]).

Consequence Category	Potential Incremental Consequences of Failure	
	Population at Risk	**Economic and Social**
Very high	>100,000	Very high economic losses affecting infrastructure, public and commercial facilities in inundation area. Typically includes destruction of or extensive damage to large residential areas, concentrated commercial land uses, highways, railways, power lines and other utilities.
High	Between 10,000 and 100,000	Substantial economic losses affecting infrastructure, public and commercial facilities in inundation area. Typically includes destruction of or extensive damage to concentrated commercial land uses, highways, railways, power lines and other utilities. Scattered residences may be destroyed or severely damaged.
Moderate	Between 2000 and 10,000	Moderate to low economic losses to limited infrastructure, public and commercial activities.
Low	<2000	Minimal economic losses typically limited to owners' property. Virtually no potential for future development of other land uses within foreseeable future.

2.10. California DSOD

The California Department of Water Resources, the Division of Safety of Dams (DSOD), a regulatory agency, oversees the design, construction, and maintenance of its jurisdictional dams. The Safety of Dams Inspection and Reevaluation Protocols [24] provide seismic hazard assessment protocols for evaluating the dynamic stability of California DSOD dams. The protocols are used by the California DSOD staff when performing independent analyses of all proposed designs and reevaluations, and the results are compared to those submitted by the dam owners and their consulting engineers for concurrence.

California DSOD protocols [24] set forth the design ground motion for a dam safety reevaluation as well as the minimum earthquake required. The deterministic approach is adopted by the California DSOD for selecting an appropriate level of SEE. Table 15 summarizes various SEE loading levels based on the hazard potential classification (or consequence of dam failure) and the fault slip rate. The hazard potential classifications (i.e., low, significant, and high classification levels) are the same as those from the Federal Guidelines for Dam Safety published by the U.S. Federal Emergency Management Agency (FEMA) [25]. However, California DSOD subdivided the high hazard potential classification into "high" and "extremely high". In addition to the loss of at least one human life, which is the definition of the high hazard potential classification, a failure of a dam that has the extremely high hazard potential classification would result in an inundation area with a PAR of 1000 or more persons or result in an inundation of facilities or infrastructure that poses a significant threat to public safety as determined by the California DSOD on a case-by-case basis.

Table 15. Deterministic level of design for safety evaluation earthquake (SEE) (following [24]).

Hazard Class	Slip Rate			
	Very High 9 mm/yr or Greater	**High 8.9 to 1.1 mm/yr**	**Moderate 1.0 to 0.1 mm/yr**	**Low Less Than 0.1 mm/yr**
Extremely High	84th	84th	67th to 84th	50th to 84th
High	84th	84th	50th to 84th	50th to 84th
Significant	67th to 84th	50th to 84th	50th to 67th	50th
Low	50th	50th	50th	50th

The California DSOD protocols [24] use deterministic methods to develop site-specific ground motions. Ground motion parameters at the median, median plus ½ of the standard deviation, or median plus one standard deviation (i.e., 50th, 67th, or 84th percentiles, respectively) are determined from ground motion prediction equations appropriate for California. All dams under California DSOD jurisdiction are analyzed for at least the expected 50th percentile ground motion parameters associated with a maximum magnitude earthquake at the closest distance to the controlling fault from the dam site. Dams that have significant, high, and extremely high hazard potential classifications need to be evaluated and designed to target values greater than 50th percentile, and 84th percentile is normally the highest level used by the California DSOD (see Table 15).

The selection of the appropriate percentile level is informed by a site-specific PSHA. The return period for California DSOD design loads typically exceeds 1000 years [26]. California DSOD protocols [24] provide examples of the loading probability for seismic analyses. For instance, dams near active faults may be designed using an 84th percentile ground motion because lower levels of ground motion have a return period less than 1000 years. On the other hand, a similar dam in areas of low seismic activity (e.g., Sierra Nevada Range) could be designed using a 50th or 67th percentile ground motion because the return period is on the order of 5000 years or greater. In addition, when performing nonlinear dynamic analyses for geotechnical reevaluation, the California DSOD protocols require a minimum of three sets of ground motion time histories spectrally matched to the MCE level to determine the average response from the nonlinear deformation analyses.

The California DSOD protocols [24] also provide a minimum earthquake standard for sites in areas of low seismic activity and unrecognized seismic sources (e.g., the western slope of the Sierra Nevada, the Central Valley, and southeastern California). The PGA of the minimum earthquake is within the range of 0.15 to 0.25 g. Specifically, when reevaluating existing dams, a minimum earthquake PGA of 0.15 g should be used. Revaluations of major dam modifications should use a minimum earthquake PGA of 0.2 g. Reevaluations of high-consequence projects should use a minimum earthquake PGA of 0.25 g.

2.11. ASCE

The intents of building standards are to mitigate the collapse of buildings and loss of life, and their use is generally not appropriate for dam applications [7]. This section, which is related to the seismic design and analysis of buildings, is included for comparison purposes.

The American Society of Civil Engineers Standard (ASCE) [27] uses the term Risk-Targeted Maximum Considered Earthquake (MCE_R), which represents ground motion intensity (e.g., 0.2 s and 1.0 s spectral response acceleration) with a certain probability of exceedance in a given time period (i.e., a uniform risk of building collapse with 1% in 50-year probability). In a building design, the design ground motion intensity is usually based on an intensity of 2/3 of the MCE_R. The two objectives of building standards are to (1) achieve a performance level of "life safety" (i.e., a building that has suffered from significant damage and may not be able to be occupied until after repairs are made) if the building site experiences a ground motion intensity equal to the design ground motion intensity of 2/3 MCE_R and (2) to achieve a performance level of "collapse prevention" (i.e., a building is on the verge of collapse) if the building site experiences a ground motion intensity equal to the MCE_R [28]. As required by the building standards, the site-specific MCE_R spectral response acceleration at any period should be taken as the lesser of the spectral response accelerations from the probabilistic ground motions and the deterministic ground motions [27].

A nonlinear response history analysis can be performed to demonstrate a structure's ability to resist the MCE_R shaking. Ground motion time histories for the analysis can be developed based on the site-specific target response spectra. A suite of no less than 11 ground

motions is required for each target spectrum. Ground motions are selected to be consistent with the magnitudes, source characteristics, fault distance, and site conditions controlling the target spectrum. Ground motion modification can either be amplitude-scaled or spectrally matched [27].

When performing geotechnical analyses (e.g., potential for liquefaction), the ground motion is to be determined based on the maximum considered earthquake with geometric mean (MCE_G) peak ground acceleration, which is different from MCE_R. In ASCE standards after 2009, MCE_R spectral response acceleration parameters were derived for the "maximum direction shaking" and are risk-based rather than hazard-based. However, to ensure consistency between the peak ground acceleration and the basis of the simplified empirical field procedure for estimating liquefaction potential, MCE_G peak ground acceleration (PGA_M) should be used [27].

Note that the maximum considered earthquake (MCE) with a uniform hazard level of 2% in 50-year probability (i.e., a return period of 2475 years) in the earlier building standards ASCE 7-05 [29] has been replaced with the MCE_R in the recent building standards, which have adopted a uniform risk of collapse of 1% in 50-year probability. The change from MCE to MCE_R has resulted in only a slight increase or decrease in design ground motions on a regional basis [30]. To be able to compare the building hazard level to uniform hazard return periods of design ground motions from other dam agencies and organizations, the MCE return period of 2475 years from ASCE 7-05 is selected for the comparison.

2.12. AASHTO

Similarly to building standards, the specifications for seismic bridge design are generally not appropriate for dam applications as the seismic responses of bridges and consequences of a bridge failure are different from dams. This section is included for comparison purposes.

The specifications for the seismic bridge design adopted by the state departments of transportation in the U.S. are published by the American Association of State Highway and Transportation Officials (AASHTO) [31]. The AASHTO guide specifications require that bridges are to be designed for the life safety performance objective using, at a minimum, the limit state of incipient bridge column collapse at a targeted risk of approximately 1.5 percent in 75 years. Life safety for the design event is to be taken to imply that the bridge has a low probability of collapse but may suffer significant damage and that significant disruption to service is possible. Partial or complete replacement may be required. The risk-targeted approach results in a uniform risk of reaching the design limit state across the U.S. [31].

The seismic design ground motions are characterized using a risk-targeted acceleration response spectrum. A site-specific, risk-targeted seismic hazard analysis should be considered if the bridge is considered to be "critical" or "recovery". A "critical" or "recovery" bridge is required to be open to all traffic once inspected after the design earthquake and usable by emergency vehicles and for security, defense, economic, or secondary life safety purposes immediately after the design earthquake. The site-specific hazard analysis can be conducted using either PSHA or DSHA [31].

Response spectrum compatible time series of acceleration should be developed from representative recorded earthquake motions. The recorded acceleration time series should be scaled to the approximate level of the risk-targeted design response spectrum in the period range of significance. At least three response spectrum compatible acceleration time series should be used for representing the design earthquake when conducting dynamic ground response analyses or the nonlinear inelastic modeling of bridges. If a minimum of seven scaled or matched earthquake records is used, the design actions may be taken as the mean response calculated [31].

Note that the design ground motions used in the current guide specifications [31] are based on a risk-targeted approach, which differs from the previous edition of guide specifi-

cations [32]. The previous edition adopted uniform-hazard design ground motions with a seven percent probability of exceedance in 75 years, which is approximately equivalent to a 1000-year return period. Comparisons of the risk-targeted ground motion and the uniform hazard ground motion in terms of PGA were made in the current guide specifications, and the results show that the risk-targeted PGA is within ±15 percent of the uniform-hazard PGA for the 17 city locations across the U.S. [31]. Since the risk-targeted PGAs are not substantially different from uniform hazard PGAs, the uniform hazard design ground motion with a 1000-year return period from the previous edition of guide specifications is used for comparison with other dam agencies and organizations.

2.13. USNRC

Similarly to buildings and bridges, the seismic design of nuclear power plants is generally not appropriate for dam applications as the seismic responses of nuclear power plants and consequences of failure are different from dams. This section is included for comparison purposes.

The U.S. Nuclear Regulatory Commission (USNRC) was established by the U.S. Energy Reorganization Act in 1974, and as an independent regulatory agency, it is responsible to ensure that the requirements of Title 10 of the Code of Federal Regulations (CFR) are met for the development and regulation of the use of nuclear materials and facilities in the U.S. The general seismic design criteria and the development of the design-basis ground motion (or the safe shutdown earthquake, SSE, ground motion) are governed by three Title 10 CFRs. Nuclear power plants (NPPs) licensed prior to January 1997 need to comply with the requirements of 10 CFR Appendix A to Part 100 (Seismic and Geologic Siting Criteria for Nuclear Power Plants) [33], and those licensed after January 1997 must comply with the requirements of 10 CFR Part 100.23 (Geologic and Seismic Siting Criteria) [34] and 10 CFR Appendix S to Part 50 (Earthquake Engineering Criteria for Nuclear Power Plants) [35]. The purpose of these criteria is to ensure that a nuclear power plant can be constructed and operated at the proposed site without undue risk to the health and safety of the public.

The 10 CFR Appendix A to Part 100 [33] defines the SSE as an earthquake that produces the maximum vibratory ground motion for which certain structures, systems, and components (SSCs) are designed to remain functional. Also defined in the criteria is the OBE, which could reasonably be expected to affect the plant site during the operating life of the plant; it is an earthquake that produces the vibratory ground motion for which those features of the NPP necessary for continued operation are designed to remain functional.

As described in the 10 CFR Appendix S to Part 50 [35], the horizontal component of the SSE ground motion in the free-field at the foundation level of the structures must be from an appropriate response spectrum with a peak ground acceleration of at least 0.1 g. Furthermore, if vibratory ground motion exceeds that of the OBE ground motion, the NPP must shutdown for inspection. Prior to resuming operations, it must demonstrate that no functional damage has occurred to features necessary for continued operation. The OBE ground motion must be set to one of the two required choices: (1) one-third or less of the SSE where an explicit analysis of design is not required or (2) a value greater than one-third of the SSE where an analysis and design must be performed for the OBE to demonstrate that the applicable stress, strain, and deformation limits of the SSC are satisfied. Both the SSE and OBE ground motions are characterized by ground motion response spectra.

The USNRC Regulatory Guide (RG) 1.208 [36] presents the general process to determine performance-based ground motion response spectra, which includes (1) site- and region-specific geological, seismological, geophysical, and geotechnical investigations, (2) a PSHA, (3) a site response analysis to incorporate the effects of local geology and topography, and (4) the selection of appropriate performance goals and methodology. The "determinis-

tic" approach has been replaced with the "probabilistic" analysis, which examines how all seismic sources and earthquake types can affect a site [37].

The performance-based approach employs Target Performance Goal (P_F), Probability Ratio (R_P), and Hazard Exceedance Probability (H_D) criteria to ensure that nuclear power plants can withstand the effects of earthquake with a desired performance. The Hazard Exceedance Probability is calculated as follows:

$$H_D = R_P \times P_F, \tag{1}$$

The RG 1.208 assigns $P_F = 1 \times 10^{-5}$ and $R_P = 10$, which results in $H_D = 1 \times 10^{-4}$. The P_F value of 1×10^{-5} is equivalent to the mean annual probability of exceedance (frequency) of the onset of significant inelastic deformation (FOSID), which is the minimum structural damage state with the overall seismic response being essentially elastic [36].

The performance-based ground motion response spectra (GMRS) are obtained by scaling the site-specific mean uniform hazard response spectra (UHRS) by a design factor (DF) as follows:

$$\text{Performance-based GMRS} = (\text{Site-specific UHRS}) \times \text{DF}, \tag{2}$$

where the site-specific UHRS has a mean annual probability of exceedance of 1×10^{-4}. The design factor is found as follows:

$$\text{DF} = \max\left[1.0,\ 0.6(A_R)^{0.8}\right], \tag{3}$$

where A_R is the ground motion ratio of spectral accelerations, frequency by frequency, from a seismic hazard curve corresponding to a 10-fold reduction in hazard exceedance frequency. Mathematically, A_R is found as follows:

$$A_R = \frac{\text{Site-specific mean } 1 \times 10^{-5} \text{ UHRS}}{\text{Site-specific mean } 1 \times 10^{-4} \text{ UHRS}}. \tag{4}$$

The value of A_R should not be greater than 4.2 [36]. As an example, a performance-based GMRS determined from the site-specific mean UHRS of 1×10^{-4} and 1×10^{-5} is depicted in Figure 3. Using the method described above, the performance-based GMRS achieves the FOSID target performance goal of 1×10^{-5}, and the performance-based GMRS is considered as the design response spectra for the SSE.

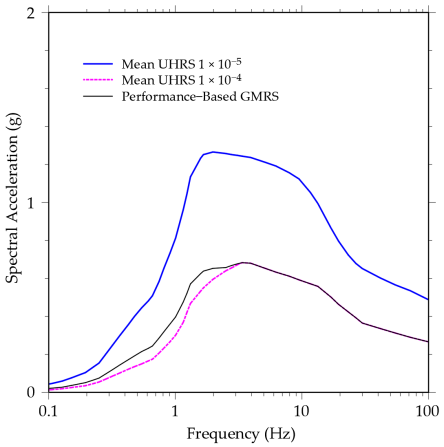

Figure 3. Determination of performance-based ground motion response spectrum from site-specific uniform hazard response spectra (UHRS) (following [36]).

3. General Observations

The return periods of design earthquake ground motions adopted by various agencies and organizations are compared graphically in Figures 4 and 5 for dams and non-dam structures, respectively. The bars in these figures show the range of the return period of design earthquake ground motions at various classifications of dam failure consequence; a bar with an open end on one side shows no limit on the return period on that side, and a single line represents a single return period. Note that agencies and organizations that utilize the risk-inform decision making process have bars with open ends indicating the unbound return period used in the risk assessment.

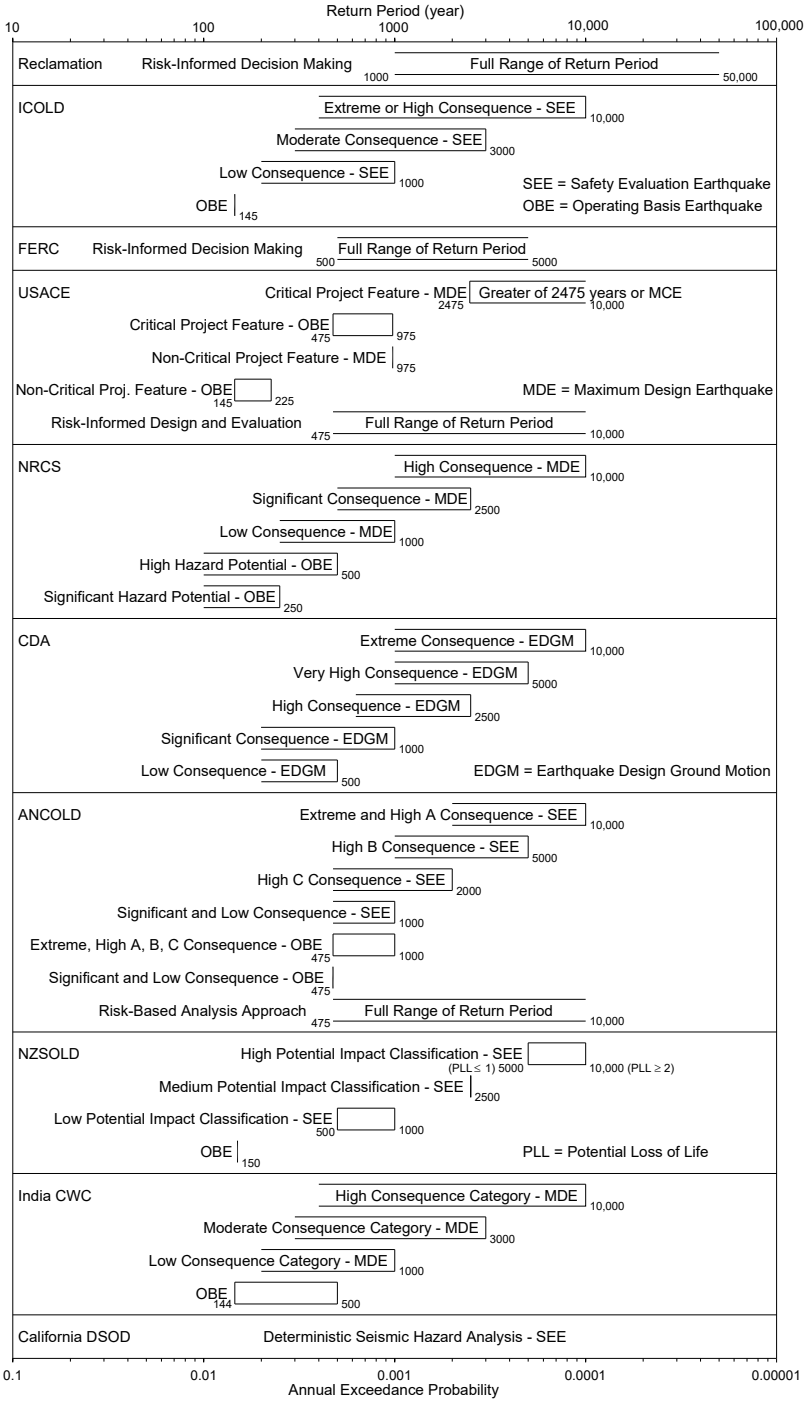

Figure 4. Comparison of return periods of seismic design ground motions for dams from various agencies and organizations (return period range indicated by horizontal bar; bar with open end on one side shows no limit on the return period on that side; single line represents single return period).

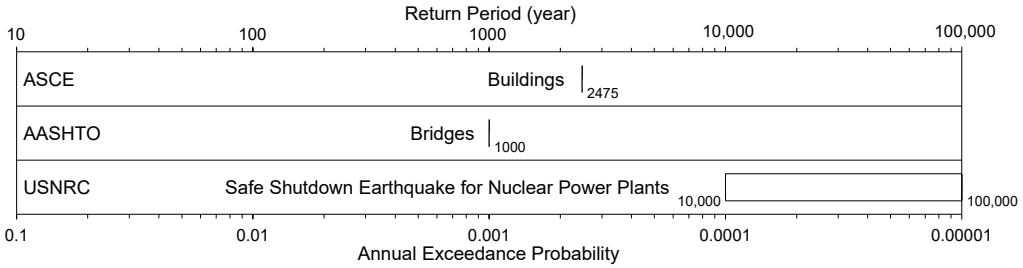

Figure 5. Comparison of return periods of seismic design ground motions for non-dam structures from various agencies and organizations (return period range indicated by horizontal bar; single line represents single return period).

General observations noted from this review are listed as follows:

- Reclamation uses the probabilistic approach solely, and the approach is suited for risk assessment activities such as potential failure mode and risk analyses.
- When performing a risk-informed analysis of dams, agencies utilizing PSHA to develop ground motions do not specify an upper bound return period on the seismic loading. A full range of earthquake ground motion levels are considered. Note that the term "risk-based" analysis used by the CDA, ANCOLD, and NZSOLD has the same meaning as the "risk-informed" analysis used by Reclamation, FERC, and USACE, which is to address dam safety risk assessment activities.
- The use of the maximum credible earthquake (MCE) for the design and reevaluation of dams is still prevalent in many agencies except Reclamation. High-consequence dams are typically assigned 84th percentile MCEs, and low-consequence dams are typically assigned 50th percentile MCEs.
- Both the deterministic and the probabilistic approaches are used when defining the maximum design earthquake (MDE), also known as the safety evaluation earthquake (SEE), ground motions for critical project features or high-consequence dams. Criteria from USACE and ANCOLD require that the greater ground motion of the deterministic approach or the probabilistic approach be selected as the MDE (or SEE) ground motion.
- When the risk-informed analysis approach is not used, the upper bound of the return period for MDE (or SEE) seismic design ground motions of dams from various agencies and organizations appears to be about 10,000 years.
- The return period for operation basis earthquake (OBE) design ground motions from various agencies and organizations ranges from 144 years to about 500 years.
- Reclamation does not utilize the MDE (or SEE) and OBE, since Reclamation does not have explicit performance criteria, at the time of writing. Reclamation evaluates performance implicitly through the risk assessment, and the design ground motions are selected based on meeting the requirements of the public protection guidelines [1].
- The OBE is generally used as a threshold to initiate post-earthquake dam inspections. Although the OBE is not used by Reclamation, a guideline was developed by Reclamation for conducting post-earthquake dam inspections [38]. Dams judged to be more susceptible to earthquake damage require an inspection if the peak ground acceleration (PGA) exceeds 0.05 g, and well-built dams require an inspection if the PGA exceeds 0.1 g.
- Nuclear power plants are subjected to the longest design ground motion return period (i.e., up to 100,000 years) compared to those of dams, buildings, and bridges.
- The design ground motion return period of dams (about 10,000 years) is between those of bridges (about 1000 year) and nuclear power plants (about 10,000 to 100,000 years).

- Time histories for numerical analysis are typically spectral matched to the conditional mean spectrum and not the uniform hazard spectrum except for nuclear power plants, for which the entire uniform hazard spectrum is matched.
- For the numerical analysis of dams, the number of sets of time histories at the period of interest for each earthquake return period (or each expected scenario spectrum) ranges from three to seven.

4. Remarks

Reclamation dams are not subjected to specific design ground motion return periods compared to the ones required or recommended by other agencies and organizations; Reclamation seismic designs are based on risk-informed decisions, which is a function of failure probability in relation to the public protection guideline values [1]. For example, a Reclamation embankment dam in California was recently designed and modified for a ground motion return period of about 20,000 years in order to reduce the risk of a potential seismic failure to an acceptable level (i.e., below the public protection guideline values). Based on the findings of this paper, it was deemed that the current Reclamation dam safety decision and practice are in general agreement with other dam agencies and organizations that also adopt the risk-informed decision process, and the design ground motions used in dam modifications can be slightly more conservative than other agencies and organizations. At the time of writing, the design ground motion return periods for Reclamation dams vary on a case-by-case basis. Also, at the time of writing, Reclamation is planning on implementing explicit seismic performance criteria for future dam designs.

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Abbreviations

The following abbreviations are used in this manuscript:

AASHTO	American Association of State Highway and Transportation Officials
AEP	Annual exceedance probability
ANCOLD	Australian National Committee on Large Dams
ASCE	American Society of Civil Engineers
CDA	Canadian Dam Association
CFR	U.S. Code of Federal Regulations (per USNRC)
CMS	Conditional mean spectrum
CR	Comprehensive Review (per Reclamation)
CWC	Central Water Commission of India
DF	Design factor (per USNRC)
DSHA	Deterministic seismic hazard analysis
DSO	Dam Safety Office (per Reclamation)
DSOD	California Division of Safety of Dams

EDGM	Earthquake design ground motion (per CDA)
ER	Engineer regulation (per USACE)
FEMA	U.S. Federal Emergency Management Agency
FERC	U.S. Federal Energy Regulatory Commission
FOSID	Frequency of onset of significant inelastic deformation (per USNRC)
GMRS	Ground motion response spectrum (per USNRC)
ICOLD	International Commission on Large Dams
MCE	Maximum credible earthquake
MCE	Maximum considered earthquake (per ASCE)
MCE_G	Maximum considered earthquake with geometric mean PGA (per ASCE)
MCE_R	Risk-targeted maximum considered earthquake (per ASCE)
MCE-GM	Maximum credible earthquake ground motion (per USACE)
MDE	Maximum design earthquake (per USACE and NRCS)
MDE-GM	Maximum design earthquake ground motion (per USACE)
NPP	Nuclear power plant (per USNRC)
NRCS	U.S. Natural Resources Conservation Service
NZSOLD	New Zealand Society on Large Dams
OBE	Operating basis earthquake
OBE-GM	Operating basis earthquake ground motion (per USACE)
PAR	Population at risk
PFM	Potential failure mode
PGA	Peak ground acceleration
PGA_M	Site-specific MCE_G peak ground acceleration (per ASCE)
PIC	Potential Impact Classification (per NZSOLD)
PLL	Potential loss of life (per ANCOLD)
PSHA	Probabilistic seismic hazard analysis
RG	Regulatory guide (per USNRC)
RIDM	Risk-informed decision making (per FERC)
SEE	Safety evaluation earthquake (per ICOLD, ANCOLD, NZSOLD, and DSOD)
SSCs	Structures, systems, and components (per USNRC)
SSE	Safe shutdown earthquake (per USNRC)
TR	Technical release (per NRCS)
UHRS	Uniform hazard response spectrum (per USNRC)
UHS	Uniform hazard spectrum
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
USNRC	U.S. Nuclear Regulatory Commission

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