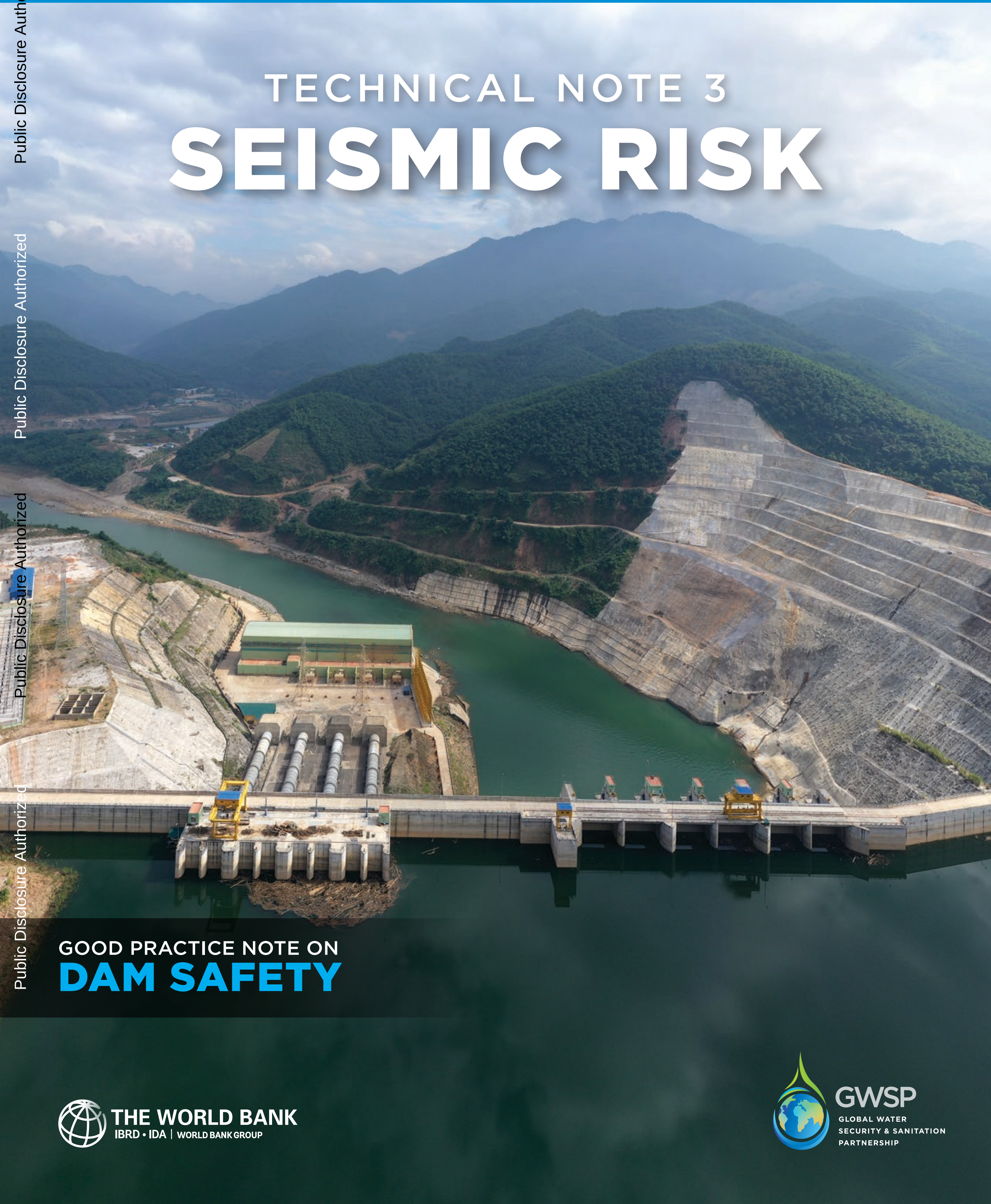
SAFETY OF DAMS AND DOWNSTREAM COMMUNITIES

TECHNICAL NOTE 3

SEISMIC RISK



GOOD PRACTICE NOTE ON
DAM SAFETY

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

GWSP
GLOBAL WATER SECURITY & SANITATION PARTNERSHIP

About the Water Global Practice

Launched in 2014, the World Bank Group's Water Global Practice brings together financing, knowledge, and implementation in one platform. By combining the Bank's global knowledge with country investments, this model generates more firepower for transformational solutions to help countries grow sustainably.

Please visit us at www.worldbank.org/water or follow us on Twitter at @WorldBankWater.

About GWSP

This publication received the support of the Global Water Security & Sanitation Partnership (GWSP). GWSP is a multidonor trust fund administered by the World Bank's Water Global Practice and supported by Austria's Federal Ministry of Finance, the Bill & Melinda Gates Foundation, Denmark's Ministry of Foreign Affairs, the Netherlands' Ministry of Foreign Affairs, the Swedish International Development Cooperation Agency, Switzerland's State Secretariat for Economic Affairs, the Swiss Agency for Development and Cooperation, and the U.S. Agency for International Development.

Please visit us at www.worldbank.org/gwsp or follow us on Twitter #gwsp.

TECHNICAL NOTE 3
SEISMIC RISK

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

This Technical Note on Seismic Risk is a supplementary document to the Good Practice Note on Dam Safety. Please cite the work as follows: World Bank. 2021. "Good Practice Note on Dam Safety - Technical Note 3: Seismic Risk." World Bank, Washington, DC.

Cover photo: Trung Son hydropower dam (Vietnam) © Trung Son Hydropower Company Limited.
Cover design: Bill Pragluski, Critical Stages LLC.

Technical Note 3: Seismic Risk

Contents

Introduction

The importance of ensuring that dam structures can withstand earthquakes has been recognized and practiced for many years. The technical capability of the dam engineering industry in the seismic design of dam structures has increased considerably since the 1980-90s.

Dams designed using modern seismic engineering principles that are well constructed have performed well during earthquakes, with only modest damage. Older dams that have suffered damage from earthquakes are likely to have been subjected to poor construction or maintenance, or they lack modern defensive design measures to prevent failure.

Seismic hazard varies around the world (see Annex A: Global Seismic Hazard Map). Some countries experience major earthquakes frequently, whereas other countries have hardly ever experienced one. Seismic hazard is significant in the Himalayas, northern India, Pakistan, central Asia, parts of China, Taiwan, Japan, Indonesia, Papua New Guinea, the Philippines, South Pacific, New Zealand, western North and South America, Turkey, and southern Europe. These countries are often located near crustal plate boundaries and regularly experience earthquakes greater than magnitude (M) 5. Earthquake shaking has relatively less significance as a design load in northern and western Europe, Africa (except near the Rift Valley areas), Australia, and central/eastern North and South America, which are at some distance from high seismic zones. Correspondingly, countries in these regions have less understanding and preparedness for earthquakes because they lack recent firsthand experience of earthquakes.

The earthquake magnitude in this Note refers to the moment magnitude scale (denoted as a single M for magnitude, but sometimes noted more specifically as Mw compared to other scales) which is a measure of an earthquake's magnitude or an estimate of earthquake size based on its seismic moment.

The moment is a physical quantity proportional to the slip on the fault multiplied by the area (length x width) of the fault surface that slips, indicating the level of the total energy released by the earthquake. The moment magnitude can be estimated based on monitoring data by seismograms using a standard formula. A whole number increase in magnitude represents an increase in released energy of around 32 times. A magnitude increase of two whole numbers represents an increase in released energy of 1,000 times.[1]

The effect of strong earthquake shaking of the structure is likely to be the principal consideration for the seismic design of dams. Nevertheless, associated effects that might also occur from the earthquake, such as upstream landslides, fault displacement, and seiche waves, also need to be considered. The designer needs to demonstrate that damage will not occur to the dam (or will be minor) from moderate earthquakes, whereas in extreme earthquakes, the designer needs to demonstrate that the dam will not fail catastrophically. Again, modern dams are designed and built to perform satisfactorily during earthquakes.

Determination of the seismic hazard is a practice that is becoming more consistently practiced around the world, particularly in high seismic countries and those countries participating in the Global Earthquake Model program (www.globalquakemodel.org). However, some countries rely on outdated seismic hazard assessment practice, or they have insufficient data. Seismic hazard assessment practice and earthquake engineering capacity tend to be more closely aligned with countries in high seismic zones.

This Technical Note contains the minimum level of technical detail for seismic design of new structures and seismic assessment of existing structures, so that non-specialists can use it. The key objective is to provide guidance for addressing seismic aspects of dam projects early on in project preparation. The Note is intended to raise awareness and inform specific studies and investigations, as appropriate, during project preparation. The material presented should be used to assess the required level of seismic hazard assessment, review the adequacy of the dam's seismic design and resilience measures, and recommend required expertise for quality assurance of projects involving dams in seismic areas.

Dams in Zones of High Seismicity

High seismic areas[2] are typically located near tectonic plate boundaries that contain active faults capable of generating significant ground shaking and co-seismic displacements. Historical records are usually a good indicator of seismic activity. Typically, there would be a history of M5 and greater earthquakes in the region, although there may be periods of seismic quiescence in the record.

1 The Richter Scale or magnitude is what most people have heard about, but in practice it is not commonly used anymore, except for small earthquakes recorded locally. As more seismograph stations were installed around the world, it became apparent that the method developed by Richter was strictly valid only for certain frequency and distance ranges. In order to take advantage of the growing number of globally distributed seismograph stations, a more uniformly applicable extension of the magnitude scale was developed as moment magnitude (M or Mw) as above noted. (Sources: adapted from the US Geological Survey website)

2 Annex A to the Environmental and Social Standard 4 indicates that a dam "located in a zone of high seismicity" should be subject to dam safety requirements in the same manner as a large dam regardless of its size.

Paleoseismic investigations, where geological formation can be dated, would provide an indication of repeated seismic events over thousands of years. Dams located within high seismic areas need to consider earthquake loading as part of their design, based on their risk classification or potential consequences of failure.

The seismic environment away from these tectonic boundary regions tends to have considerably fewer active faults and correspondingly lower seismic activity. Intraplate areas are still subject to significant earthquakes, but these are more likely a result of the release of strain built up in the earth's crust and can be more random and not always appear on known faults.

The level of seismic defense should be commensurate to the dam risk classification considering the likelihood of failure event, seismic zones, and consequence in case of failure regardless of dam size, as noted in the Good Practice Note (GPN) on Dam Safety. The required level of seismic hazard assessment and the dam's stability checking should be proportionate to the potential risk of the dams and can be performed in phases beginning with simplified methods and, if the result is uncertain, moving up to using more-detailed methods.

Seismic Hazard Assessment

A seismic hazard assessment is required to estimate the seismic parameters for the dam's seismic design and performance assessment, including (a) identification of potential sources of earthquakes; (b) evaluation of the characteristics of each potential earthquake source such as tectonic, geological conditions, magnitudes, and rates of activities; and (c) empirical attenuation equations to complete ground motion amplitudes or intensities (ICOLD 2010). Appendix 1 of ICOLD (2010) includes a useful list of primary factors to consider in seismic hazard assessment. The Bulletin further recommends that the assessment should provide a set of seismic evaluation parameters—such as anticipated magnitude of maximum earthquakes, peak ground acceleration, duration, and so on—using a deterministic seismic hazard assessment (DSHA) or probabilistic seismic hazard assessment (PSHA) (see the Earthquake Intensity Levels for Dam Design section).

Many countries have produced a national map showing three to four seismic zones with indicative seismic intensity (peak ground acceleration, seismic coefficient, return periods, and so on). This will not be a substitute for the site-specific seismic hazard assessment pertaining to a dam, but it can provide inputs for the initial level of seismic safety checking.

It is important to ensure that the feasibility study and design of dams in seismic areas would collect required information in coordination with the national seismological and geological institutes and undertake sufficient seismic hazard assessment considering potential risk of dams.

Earthquake Intensity Levels for Dam Design

The Operating Basis Earthquake (OBE) is the level of earthquake at which little or no damage occurs, and therefore dam operation should continue without interruption. Any damage will be minor and easily repaired. The OBE is typically represented by ground motions with average return period (ARP) of 145 years (that is, a 50 percent probability of not being exceeded in 100 years). If the risks associated with loss of reservoir operation are considered too great at this relatively low return period, stronger ground motions at the 500-year return period may be used as the OBE.

The Safety Evaluation Earthquake (SEE)[3] is the earthquake that produces the maximum level of ground motion for which a structure is to be designed or evaluated. Factors to consider in establishing the size of SEE are the risk or potential hazard classification of the dam (see Chapter 7.2 of the GPN), criticality of the project function (water supply, recreation, flood control, and so on), and the turnaround time to restore the facility to operation.

The associated structural performance requirement for the SEE is that the dam does not suffer catastrophic failure or uncontrolled release of water from its reservoir that presents a life safety risk downstream. Significant damage to the dam or economic loss may be tolerated, provided these criteria are met (ICOLD 2016). If the dam's functions include critical water supply, hydropower generation or other services, the expected damage should be limited to allow the dam to be restored to operation in an acceptable time frame.

The SEE may be determined based on the Maximum Credible Earthquake (MCE) which is the largest conceivable earthquake that could occur along recognized faults or tectonic plate boundaries if earthquakes have more frequently occurred or anticipated to occur along such well-identified sources.

Aftershock loading should be considered for dams following the SEE. A strong aftershock may lead to cracking, increased seepage, and reduced strength, on top of the damage caused by the main shock. The most common estimation of aftershock for design purposes is at one magnitude less than the SEE, occurring near the structure within one day of (or sometime after) the SEE. So, if, for example, the SEE is a M7.0 earthquake, the aftershock to be considered would be M6.0. For design and dam safety assessments, the time-related development of post-earthquake conditions (for example, increased uplift pressure caused by earthquake shaking on rock foundations or seepage along cracks caused by the earthquake) should be incorporated when applying the aftershock load. The dam structure must meet the performance requirement of the SEE with the consideration of aftershock loading.

If reservoir-triggered seismicity (RTS) is considered possible (see Methods for Identifying and Characterizing Faults Affecting Dam Sites), the OBE ground motion parameters should cover those from the RTS scenarios. Because the magnitude of RTS is much smaller than that of SEE, the seismic design of the main dams should not be affected by RTS, but RTS loading may be relevant for appurtenant structures, non-dam structures, and infrastructure in the dam area as per lower design standards.

3 Sometimes the Maximum Design Earthquake (MDE) is used for seismic design of new dams, as in the first edition of ICOLD (1989), but this Technical Note follows the terminology of its 2010 revision, replacing the MDE with SEE.

Seismic parameters used for dam design include the peak ground acceleration (PGA), acceleration response spectra (with damping)[4], and time histories of acceleration[5] during the earthquake. Seismic parameters can also show spatial variation of ground motion for special (long) structures. PGA and response spectra are sufficient for simplified structural evaluations. Response spectra or acceleration time histories are needed for dynamic finite element response analyses. Where nonlinear behavior is expected, time histories will be required, using both horizontal and vertical components for concrete dams and for embankment dams with very steep slopes. Vertical component time histories may not be essential for finite element analyses of most other embankments (with flatter slopes). In addition, amplification of the ground motions because of topographic effects or as a result of the dynamic response of the structure may need to be considered for structures in prominent positions.

If not provided by hazard assessments, the peak vertical accelerations can generally be taken equal to two-thirds of the peak horizontal accelerations, unless the seismic source is within 10 kilometers of the dam. At sites close to the assumed epicenter, account should be taken of the type of fault movement anticipated (that is, normal, reverse, or strike-slip), and the peak vertical acceleration may be equal to, or possibly even greater than, the peak horizontal acceleration.

Probabilistic and Deterministic Seismic Hazard Analyses

The level of ground motion at a dam site due to an earthquake depends on the geological and tectonic conditions of the region including the dam site as well as the earthquake source, magnitude, and distance to the dam site. PSHA and DSHA are thus performed to develop the design ground motions for evaluating the performance of a dam (ICOLD 2016). The SEE can be selected from either the probabilistic or deterministic values, depending on the results and uncertainties in seismic hazard assessment and dam failure consequences, but the deterministic approach may be more appropriate in locations with frequent earthquakes that occur along well-identified earthquake sources. The analysis should also consider near-field or -fault effects.

Probabilistic Seismic Hazard Analysis

The PSHA numerically quantifies the contributions to seismic motion, at the dam site, of all sources and magnitudes larger than a designated minimum (typically M 4 or 5) up to and including the MCE on each source. The probabilistic approach provides a uniform basis for evaluating the hazard and is more likely to give consistent results in low to moderate seismic zones and where faults are not well characterized. Delivery of the PSHA is the expertise of seismologists.

4 Response spectra represent the maximum response in terms of acceleration, velocity, or displacement of a single degree of freedom elastic oscillators to a time-dependent excitation for a given damping as a function of frequency. Thus, a response spectrum analysis provides an estimate of the maximum absolute response of a structure to an earthquake. The structure is assumed to vibrate in several of its natural modes, and the maximum dynamic response resulting from each mode is calculated (ICOLD 1989, 2010).

5 A time history represents the continuous free-field response of the ground to a specific earthquake. Several acceleration time histories for horizontal and vertical motion may be prepared, possibly using real accelerograms like the site condition for undertaking nonlinear analysis of high-risk dams in seismic areas.

The SEE, if determined using PSHA method, is typically represented by ground motions at a 10,000-year return period for high-risk or high-hazard/consequence -category dams. The SEE is typically represented by ground motion at the 2,500- to 3,000-year return period for moderate-risk or moderate-consequence dams and at the 500- to 1,000-year return period for low-risk or low-consequence dams.

Appurtenant structures with a dam safety function, such as spillway facilities for flood discharge and outlet works for reservoir drawdown, should be designed for the same SEE as the dam. Other structures that do not have a critical dam safety function (for example, penstocks and power stations) can be designed with a lower standard represented by ground motions in the order of 500-year return period.

Many countries produce seismic hazard maps for their building design codes. PSHA methods should be used to create the map. Some countries used earlier, less accurate methods to develop their maps. Note that most national seismic hazard maps are produced for residential and urban buildings. The loads concerned are at the OBE level. Hence, they are usually not appropriate to use to select design loads for a high-risk or high-hazard/consequence dam.

The OBE is typically probabilistically derived to provide ground motions with a 145-year return period. If the risks associated with loss of reservoir function are considered too great at this relatively low return period, stronger ground motions at the 500-year return period may be used mainly from economic/financial consideration.

Deterministic Seismic Hazard Analysis

Deterministic ground motions are based on earthquake behavior on known faults within a reasonable distance of the dam site. The DSHA method may be more appropriate in locations with relatively frequent earthquakes that occur on well-identified faults. The capability of active faults must be ascertained through use of established earthquake geology methods (for example, a rupture length-magnitude relationship or a fault movement and magnitude relationship). The distances of fault rupture to the site needs to be determined to estimate attenuation of ground shaking and other parameters. Many attenuation formulae have been developed to provide an estimate of valuables, such as PGA, but the most appropriate ones should be used considering specific tectonic setting and their weighted average of calculated values. The investigation for the DSHA is the expertise of seismologists.

A DSHA is generally performed to estimate the ground motions at a dam site under the MCE. The MCE is regarded as the largest hypothetical earthquake that may be reasonably expected to occur along a given fault or other seismic source. The maximum earthquake for each identified fault is determined to identify the maximum ground shaking and define the seismic design parameters under the MCE.

The SEE, if determined using a DSHA method, is represented by ground motions at the 84th percentile of the MCE for high-risk or high-hazard/consequence dams. The SEE is typically represented by ground motions between the 50th and 84th percentile of the MCE for moderate-risk or moderate-hazard/consequence dams and at the 50th percentile of the MCE for low-risk or low-hazard/consequence dams.

The return period associated with the MCE earthquake scenario may be defined if controlled by a single earthquake scenario on a well-characterized fault. It is however usually not possible to define the return period if the MCE scenario is associated with the rupture of multiple fault segments (co-seismic) unless there is a comprehensive seismic source model.

Table 1 shows that existing dams need to meet the same standard for seismic safety as new dams. It may be difficult and time-consuming for dam owners to raise the safety standard of existing dams to the more rigorous modern one. In such cases, a risk management approach can assist to assess the required seismic safety level and to improve seismic safety standards in a phased manner with due consideration to the potential risk of existing dams.

Seismic Design Method

The general approach for the seismic design of embankment and concrete dams is to start with simplified methods and use more-rigorous methods until an acceptable and justifiable result is obtained. The level of analysis required for acceptance of a design or remedial design depends on the dam consequence, severity of the potential loading, and characteristics of the dam and foundation. Simplified seismic design will normally be sufficient for low-risk or low-consequence dams, whereas more-detailed analyses will be required for higher-risk or higher-consequence dams. Validation of the results of seismic analyses is an important quality-assurance practice to ensure that results are as realistic as possible. Progressing analysis from simplified methods to more-rigorous methods allows the earlier analyses to be used when validating the more rigorous ones.

Embankment Dams

Seismic design methods of embankments need to consider the effects of seismic-induced deformations in the dam or foundation that may result in settlement and slope instability, cracking, and loss of freeboard for initiation of internal erosion or damage to appurtenant structures.

TABLE 1. Summary of Earthquake Return Periods

Earthquake level being considered	New or existing	Performance requirement	Risk or hazard/ consequence category	Typical return period of design earthquake (years)
Safety Evaluation Earthquake (SEE)	New and existing dams and their appurtenant dam safety critical structures	The dam must not suffer catastrophic failure or uncontrolled release of its reservoir that presents a life safety risk downstream.	High	10,000
			Medium or significant	2,500–3,000
		Significant damage to the dam or economic loss may be tolerated.	Low	500–1,000
Operating Basis Earthquake (OBE)	New and existing dams	Little or no damage occurs. Dam operation should continue without interruption.	High or medium	150–500
			Low	150

Source: Original figure for this publication.

The progression for estimating seismic-induced deformations includes the following steps:

1. Screening based on case histories of dams subjected to earthquake loading and empirical methods to estimate damage or crest settlement

2. Limit equilibrium methods (LEMs) with deformations estimated using Newmark-type sliding block methods; earthquake loads are applied using pseudostatic methods to determine the yield acceleration of the critical failure surface

3. Post-earthquake LEM analysis used for the preliminary evaluation of deformation including the effects of liquefaction

4. Linear finite element method (FEM) or finite difference method (FDM) analysis with sliding block analysis to find the acceleration time history of the sliding mass and use this to estimate permanent deformations as a function of time

5. Nonlinear FEM or FDM analysis of dynamic deformations

Empirical methods, such as Newmark and Makdisi/Seed, are appropriate for estimating deformation when there is no potential for liquefaction, such as an embankment dam which is well compacted with the upstream and downstream slopes gradient of 2.5 (horizontal) to 1 (vertical), and is subject to moderate earthquake shaking (PGA ≤ 0.35 g [6]; the embankment static stability with steady state seepage condition has a factor of safety (FOS) greater than 1.5, and no appurtenant features are susceptible to being harmed.

Simplified LEM methods are used to determine the FOS and yield acceleration. Under the OBE, a FOS above 1.3 would indicate that minor deformations under the earthquake load won't occur, if no component is sensitive to small displacements. Under the SEE, if peak horizontal acceleration within the embankment is only slightly smaller than the yield acceleration, deformations can still occur but will likely to be minor. When considering post-earthquake static stability, if the FOS is in the range of 1.25 to 1.5 using strengths expected after the earthquake, experience from past earthquakes suggests that deformations will be small and the dam will meet performance criteria.

Simplified LEM methods are not appropriate to assess potential deformation resulting from an earthquake with unusually long duration (for example, those occurring on a subduction zone) and Newmark-type sliding block methods are not appropriate to estimate deformations if embankment or foundations materials may liquefy.

A higher level of analysis may be needed if simplified analysis indicates that the impacts of deformations are large and threaten embankment freeboard. Results of a higher-level analysis should verify or refine findings of the simplified analysis.

6 The unit of "g" is referred to as the acceleration of gravity. Its value is 9.8 m/s^2 on Earth.

Equivalent linear analysis is advantageous in simplicity and input to provide a rational estimate of the dynamic response of the structure. It does not directly consider such effects as pore pressure generation, plastic yielding, or pore water flow.

A site-specific Newmark deformation analysis with dynamic response determined by FEM or FDM analysis is likely necessary for cases where the embankment is on thick alluvial foundations.

Advanced methods of nonlinear FEM or FDM analyses are used to model permanent deformations including the effects of generation of excess pore water in saturated soils. However, results of nonlinear FEM or FDM analysis should not be considered definitive predictions of deformation. Still, they can be useful for showing general trends in deformation behavior, for insight into potential locations for tensile or shear strains to cause cracking, and for evaluating sensitivity to variation in input assumptions.

When undertaking nonlinear FEM or FDM, three to seven sets of time history earthquake records (that are spectrally matched to the site target spectrum) should be used. Where three records are used, the performance should be based on the maximum response, and where seven records are used, the performance can be based on the average response.

Concrete Dams

Dynamic analysis of concrete dams is evaluated in terms of sliding stability, position of force resultant, and maximum stresses. The various levels of dynamic analyses are applied in the order of complexity and include:

1. Screening based on case histories of dams subjected to earthquake loading
2. Global stability analyses using pseudostatic techniques
3. Linear-elastic response spectrum and elastic time-history analyses
4. Nonlinear time-history FEM methods

Potential failure modes (PFMs) relating to seismic risk for concrete dams involve sliding or overturning along defects in the dam body, the contact surface between dam and foundation, or geological defects in the foundation. High-tensile stress concentrations may induce cracking with unfavorable consequences (sliding or introduction of high uplift pressures).

Global stability is normally expressed in terms of FOS; however, this approach is likely to be violated when calculating stability during a strong earthquake. Hence, the design process for concrete dams involves determining whether permanent deformations occur during the earthquake and calculating post-earthquake static stability after deformations have occurred, uplift conditions have stabilized, and damaged material properties are applied. There are several technical guidelines outlining the process (for example, Chapter 3 of FERC [2018a] for gravity dams and Chapter 11 of FERC [2018b] for arch dams).

For a concrete gravity dam on a rock foundation, the stability during earthquake loading of PGA ≤ 0.2 g should be satisfactory if it is constructed with high-quality concrete and good attention to lift joints, the force resultant location is within the middle one-third of the base of the gravity dam under static conditions, and the FOS against sliding is acceptable for static conditions (FEMA 2005).

Although pseudostatic methods are likely to be sufficient for small dams (less than 15 meters high), the methods should be used only for screening sliding and overturning (global) stability at large dams. Structures that are indicated to fail using this screening method should be subjected to in-depth study.

If the structural performance is entirely within the linear elastic range, the response spectrum analysis will suffice. However, in the case of earthquakes for which the calculated stresses for mass concrete structure may approach or exceed the tensile strength of the concrete, a time-history linear dynamic analysis provides valuable information for approximating the potential damage or the expected inelastic response behavior.

Evaluation of dynamic time-history analyses results will determine whether there is a risk of stability failure. Linear and nonlinear analyses should be completed using several time histories to effectively analyze the dam performance.

A nonlinear analysis should be performed if the response of the dam would be significantly influenced by nonlinearity from material behavior or changes in geometry. A complete and reliable nonlinear dynamic analysis includes tensile cracking of concrete, yielding of reinforcement, opening of joints, and foundation/abutment displacements.

Validation of analysis results is essential to demonstrate that modeling results are reasonable estimates of dam behavior in earthquakes. The validation process involves comparison of the latest analysis alongside the results of alternative analyses including those for pseudostatic and linear elastic analyses and the sensitivity of the results to variations in the assumed model parameters.

Sound engineering judgment is required to evaluate the effects of stresses that exceed the tensile strength and should be based on the expected effects of nonlinear behavior and past performance of the dam under similar earthquake loading.

A post-earthquake sliding stability analysis using conservative assumptions is recommended to demonstrate continued stability. If the sliding assessment indicates displacement, then the amount of displacement that has occurred and location of the sliding surface need to be considered. Aftershocks should be applied to the post-main shock dam condition.

Co-seismic Deformations

While it is strongly recommended to avoid active faults in the dam foundation or crossing the reservoir, it could be extremely difficult to avoid such a site, or such a fault may be discovered at an existing dam.

Mitigation measures should be provided to minimize possible damage from displacements associated with an active fault located beneath a dam. Damage might be in the form of cracking, offsets, or development of potential seepage pathways. Fault displacement in the reservoir can result in the massive landslide and the generation of seiche waves in the reservoir, resulting in overtopping failure/ incidents.

There are limited references but, in the unlikely situation of an active fault presence, NZSOLD (2015) (based on Mejia et al. [2001]) provides design recommendations for fault displacements relating to dams.

Paleoseismic investigations in which seismologists examine the evidence of movement of any identified faults in the geological formation of dam sites by trenching and so on are likely to be necessary to establish whether a fault is active. Geological definitions for classifying when a fault is active vary, but ICOLD (2010) recommends identifying critical active faults that show evidence of movements in Holocene time (in the past 11,000 years), large faults that show evidence of movements in latest Pleistocene time (between 11,000 and 35,000 years ago), or major faults that show evidence of repeated movements in Quaternary time (1.8 million years ago).

The selection of dam type should consider the orientation, direction, and quantum of expected movement on any active faults. Embankment dams can be designed with mitigating features (for example, incorporating wide filters) to make the structure resilient to fault displacement. This approach would require a dam designer who is experienced in designing mitigating measures for deformation by fault movement, such as ample freeboard height and filter width. Concrete gravity dams are extremely difficult to align with the fault to accommodate movement, and it is recommended that concrete gravity and arch dams should be avoided.

Methods for Identifying and Characterizing Faults Affecting Dam Sites

For low- and moderate- risk or hazard /consequence- dams, the locations of active faults can be obtained from geological databases by the national seismologic/geologic institutes if available. The design consultancy should assess the currency and accuracy of the information being utilized for design.

For high-risk or high-hazard/consequence dams, the characterization of fault displacement should be based on knowledge of the regional and site-specific geology and a careful study of any foundation faults. Site-specific studies should be undertaken to determine the potential for active faulting and to quantify fault hazards (that is, direction, magnitude, and recurrence of future faulting). Expert seismologists should conduct these studies. Aerial photos have traditionally been used to identify potential faults for ground investigation, but in recent years satellite remote sensing and the use of light detection and ranging (LiDAR)-based topographic profiles have provided significant advancements for characterizing ground deformation and estimating co-seismic and creep fault displacements for use in design.

Soil Liquefaction Risk

Liquefaction of the dam and foundation soils can lead to slope failure, overtopping, and internal erosion. Loose saturated sands, silty sands, and gravelly sands with poor drainage in a dam's foundation or inadequately compacted materials in embankment dams are susceptible to softening and the reduction of shear strength when subjected to cyclic loading, which may lead to large cyclic shear deformations or development of instability in large soil masses. The shear strength reduction is caused by a rapid increase in pore water pressure and reduction of effective stress from contractive response when subjected to shear deformations.

When such soils are present in dam foundation or proposed to be used for dam construction, their susceptibility to liquefaction should be assessed under the design earthquake loading (USBR 2015). The loss of strength may be exhibited as liquefaction of sands and gravels (cohesionless materials) or cyclic softening of clays (cohesive materials).

The initial screening procedure determines the liquefaction susceptibility of the soil based on the following criteria (MBIE and NZGS 2016):

- *Geological criteria*. Young Holocene (less than 10,000 years old) sediments are particularly susceptible to liquefaction or the embankment includes poorly compacted/constructed fill sections.

- *Compositional criteria*. Sands, non-plastic silts and gravels, and their mixtures are susceptible to liquefaction.

For fine-grained soils, the criteria by Bray and Sancio (2006) are used to evaluate liquefaction susceptibility. The criteria consider plasticity index (PI) and the ratio of water content to liquid limit. However, satisfying the criteria as not susceptible to liquefaction does not rule out severe strength loss from cyclic loading or large permanent shear strains (yielding) that may occur in sensitive soils.

Clayey soils generally require higher strains to reach a state of strength loss ("cyclic softening"). When they do, the strength loss is more likely to be in the form of cyclic mobility with limited displacements (strains) rather than continued deformations associated with flow liquefaction. Cyclic softening empirical correlations are used in this case for clay soils.

If material is determined to be susceptible to liquefaction, then to rule out the potential of liquefaction triggering requires proof that the soil is unsaturated or sufficiently dense that it will not lose strength under earthquake loading.

Liquefaction Analysis and Mitigation Measures

To determine whether the material has sufficient strength (dense consistency) relative to applied earthquake loading, simplified procedures are used to determine liquefaction triggering. These measures include comparing the soil's liquefaction resistance, commonly referred to as the cyclic resistance ratio (CRR), to the applied earthquake loading, referred to as the cyclic stress ratio (CSR).

Procedures for determining the resistance to liquefaction are widely described in several publications by Seed and Idriss (1982). The liquefaction resistance of soils can be determined by means of cyclic shear laboratory tests, but in general should be reserved for high-risk projects considering the difficulties in acquiring undisturbed samples, costs of testing, and so on. Also, as the state of the art is evolving, designers should check the currency of the methods to be applied for projects.

Post-earthquake static stability of the embankment must be analyzed assuming reduced (residual) strengths for liquefied or sensitive materials. Sensitive clays with reduced shear resistance will likely lead to post-earthquake instability similar to liquefied cohesionless soils.

To address the liquefaction risk during or after earthquakes, it is recommended to improve the foundation condition by removing loose foundation materials and replacing them with highly compacted materials or densify the loose materials by vibro-flotation or other suitable techniques. It is also recommended to decrease shear stresses by reducing the slope gradient of structures, adding berms at the toe and so on and to increase the undrained shear strength of the soil by adding drainage reinforcements such as piles, slurry walls, and so on.

Considering Seismic Upgrades on Existing Dams

After reassessment of the seismic hazard, existing dams may be found to be vulnerable to earthquake damage. Remediation of an existing dam is often significantly more difficult than installing appropriate defensive design in the first place. Investigation of the existing dam is usually required to understand its vulnerabilities. The analysis of PFMs is useful in understanding what needs to be addressed. Existing dams should include measures to reduce the risk of credible PFMs developing.

Because the hazard of the stored water body to downstream communities is the same whether it is a new or existing dam, the objective is to bring the existing dam as close to the safety of a new dam as is realistically and economically practicable. After remediation, it may not be possible to achieve entirely the same low level of risk, so management of the residual risk is even more important through non-structural measures (such as emergency preparedness planning and reservoir level management).

Investigation and design of remedial works may take a few years. Managing dam safety risk from the time a deficiency is identified until remediation is complete is essential. During this time, the risk of dam failure must be kept as low as possible. A risk assessment will be necessary to determine whether the reservoir can remain fully operational or managed to reduce risk. This is a function of how vulnerable the dam is to failure from an earthquake and the hazard category of the dam. A low-risk or low-hazard/consequence dam may be allowed to operate unchanged until upgrades are installed. An earthquake with a return period of 150 to 500 years that would cause a high consequence in case of dam failure would be considered an unacceptable risk, and action should be taken immediately to draw down the reservoir or even evacuate communities at risk.

Remedial options may be more limited than for a new dam. However, innovative techniques have been employed on several dams to address deficiencies. Some measures are placed on the external face of the dam (for example, filter or stability buttresses); others are more invasive, such as foundation remediation. Several options are those that a new dam design would incorporate and are listed in the next section. Experts experienced in seismic upgrades of dams should be involved throughout the project, particularly when remedial concepts are being developed and continue involvement during implementation.

Any interference with the existing dam while the reservoir remains requires careful risk management. The reservoir may have to be temporarily drawn down. If the reservoir remains present, intense dam safety monitoring and surveillance will likely be essential, along with elaborate emergency preparedness planning. Experts experienced in dam upgrades while the dam is in operation should also be involved throughout the project.

Defensive Design

New dams need to incorporate defensive design measures and redundancy to ensure adequate seismic performance (USBR 2011), whereas existing dams should include measures to reduce the risk of credible PFMs developing. Also, non-structural alternatives should be employed to maintain dam and public safety in the post-seismic dam condition.

The following are examples of seismic mitigation options (ICOLD 2001 per USBR 2015).

Defensive measures for embankment dams

Foundation treatment:

- Removal or treatment of loose or weak foundations soils.
- Shaping of embankment foundation to remove sharp changes in grade that would otherwise be an obvious location for differential settlement and corresponding threat of inducing potential transverse cracking through the dam.
- Upstream blanketing (with filter) over faults crossing the dam site with impervious material to lengthen seepage path.
- Although the recommendation is to avoid active faults, if inevitable or encountered, then the fault or co-seismic shear zone under embankment dams can be treated with upstream blanket and downstream filter with sufficient dimensions to remain functioning after potential fault displacement.

Filters and drainage:

- Controlled processing and careful selection of filter and drainage materials.
- Sand and gravel upstream crack stopper zones near the dam crest to provide additional staunching capability and to reduce risk from seismic-induced cracking.
- Filters should have less than 5 percent fines when in place.

- Wide filter and high-capacity drain zones must be used to accommodate dam deformation and remain functional. About 50 percent of the fine sand filter should still be available after faulting and earthquake-induced slip movement of slopes to ensure functionality.
- The upstream and downstream transition zones should be self-healing and of such gradation as to also heal cracking within the core.

Embankment geometry and construction:

- Thick core made of ductile material with a high failure strain to minimize the propagation of a crack and prevent internal erosion if the core is cracked.
- Wide crest to produce longer seepage paths through any transverse cracks that may develop during earthquakes.
- Static slope stability with FOS of at least 1.5 under high-level steady state seepage.
- Sufficient freeboard should be provided to cover the settlement likely to occur during the earthquake and possible water waves in the reservoir resulting from mass movements. Freeboard at least 5 to 10 percent of the embankment height and never less than 0.9 meters should be provided. Special risk assessment could be needed covering other mitigation measures beyond freeboard.

Downstream filter buttress or drainage ("Swedish") rockfill berm should be used for protection against slope instability of the downstream face or to prevent seepage unravelling the downstream face. This approach may be necessary if the downstream shoulder material is not well drained and able to transport considerable leakage without transporting the dam fill particles. If the embankment becomes saturated, the stability of the downstream face will be significantly reduced; hence, the consideration of buttressing.

Embedded structures should be designed to withstand earthquake loading without excessive deflection and with engineered filters and drains around them in case cracking does occur.

Treatment of potentially unstable slopes around the reservoir rim should be used as outlined in the Technical Note on Geotechnical Risk.

Defensive measures for concrete dams

- Treat foundation defects, such as considering use of shear keys, to improve foundation sliding resistance.
- Avoid the site if the concrete dam would be sited on an active fault.
- Consider geometry of the dam to minimize tendency for sliding behavior.

- Provide sufficient drainage facilities for the control of uplift pressures post-earthquake. The dimensions of drainage features, location, and orientation should consider foundation displacement during the SEE. At least 50 percent of the drainage feature should remain open post-earthquake.
- Provide sufficient freeboard for seiche or landslide wave in reservoir caused by earthquakes in combination with other remedial options.
- Avoid prominent crest features, particularly if required for dam safety systems such as spillway gates. Elevated equipment can be subject to greatly amplified loads during an earthquake.
- Provide shear transfer between dam blocks.
- Design the upstream face to reduce the likelihood of tensile cracking and seepage.
- Avoid sharp changes of profile and dam alignment if possible.
- Apply careful treatments to joint details including horizontal lift joints and construction, contraction, expansion, and isolation joints.
- Design spillway surfaces for high-velocity flow.
- Design concrete mix with due consideration to the required compressive strength, tensile strength, and modulus of elasticity.

Appurtenant structures essential for seismic safety

- Adopt low- or intermediate-level dewatering discharge facilities to enable prompt reduction of the reservoir level post-earthquake.
- Locate discharge equipment and emergency power supply facilities where they are not vulnerable to rockfall.
- Consider whether amplified ground motions will affect the design of appurtenant structures located in prominent locations. Gantry structures located on dam decks or abutments for lifting gates are especially vulnerable to amplified ground motions.
- Assess the reliability of discharge equipment post-earthquake.
- Install robust power and communications equipment, including independent backup systems (for example, diesel generator) because the power supply could be lost post-earthquake.
- Frequently test discharge equipment, backup power supply, and control systems to provide assurance that they will work when needed.
- Consider free overflow discharge if the reliability of gate or valve discharge equipment cannot be ensured.

Other improvements for safety enhancement

- Remediate unstable slopes that could block road access to the dam.
- Protect equipment and power stations from falling rocks.
- Apply multiple power sources and communications to the dam.
- Ensure multiple access routes to the dam.

Nonstructural mitigating actions

- Apply temporary or permanent reservoir restrictions.
- Install enhanced seismic and other dam safety monitoring system.
- Establish an early warning system.
- Strengthen the emergency action plan.
- Relocate people at risk.

Reservoir-Triggered Seismicity

RTS is not common, but the risk should be assessed for construction of new dams, particularly those higher than 100 meters and with a reservoir capacity greater than 500 million cubic meters. Points to note about RTS are:

- The main mechanism for RTS is the release of tectonic stresses from changes in stress and strength properties in fault planes caused by the reservoir loading. This mechanism requires that the fault that can produce an earthquake is already near failure so that the added weight or pore pressure built up from reservoir impounding can trigger a seismic event. Triggering resulting from impounding would not change the underlying tectonic processes and the seismic hazard at a dam site. The added weight of water cannot substantially increase the seismic energy release because the increase of energy potential from impounding is practically insignificant in view of the size of the actual seismic energy release (ICOLD 2011). RTS is typically a result of relatively shallow earthquakes and linked with normal and strike slip faults. Seismic events can also be triggered by the collapse of underground cavities in mining areas, liquid injection or extraction, geothermal energy, or hydraulic fracturing.

- The relationship between reservoirs and seismicity continues to be studied in the scientific community, but there are fewer RTS cases compared with the total number of large dams in the world (more than 58,000). Thirty-nine cases of RTS are presented in ICOLD 2009, of which there were four major RTS events with a magnitude more than 6.0. The highest observed earthquake magnitude was 6.3.[7]

---

7 The highest observed earthquake magnitude was at the Koyna Dam in India, 1967, with 103 meters in height and 2.8 million cubic meters in reservoir capacity.

- The height of dams and size, shape, depth, and volume of reservoirs may contribute to the possibility of RTS. All four RTS cases with a magnitude greater than 6.0 were associated with reservoirs with water depths and capacity exceeding 100 meters and 500 million cubic meters, respectively. ICOLD (2016) recommends that RTS should be considered for large dams, especially those exceeding these thresholds. ICOLD (2011) presents the state of knowledge on reservoirs and seismicity.
- According to ICOLD recommendations, high-risk (or high-hazard) dams are to be designed to safely withstand ground motions caused by the SEE or MCE. Therefore, RTS seismicity should not be a direct safety problem for a well-designed dam because the maximum reservoir-triggered earthquake cannot be stronger than the SEE or MCE. However, RTS may still be a problem for other structures, buildings, and appurtenant works near the dams because they may have a much lower earthquake resistance than the dam. Also, access roads and non-dam structures in the vicinity will be affected. If RTS is a concern, the OBE ground motion parameters may be increased to cover RTS events.
- Adequate monitoring of RTS before, during, and after impoundment of a reservoir provides the most conclusive evidence as to whether water impoundment causes triggered earthquakes. To help distinguish between background seismicity and RTS, monitoring should start well in advance (for example, two years) of impounding of the reservoir to understand the site's natural background seismicity.

Seismic Instrumentation and Monitoring

A seismic monitoring network for detecting and notifying the location and strength of earthquakes enhances emergency response, contributes to post-earthquake safety assessments, and provides valuable data for advances in earthquake engineering.

In moderate to high seismic areas where there is sufficient coverage of strong motions seismic sensors near the dam, automated information may be available via an agency's intranet or from public agencies. More than 70 countries have seismic monitoring networks, and most of these share their monitoring information in real time with international agencies such as the European-Mediterranean Seismological Centre (EMSC).

Installation of strong motion seismic sensors at the dam site may be needed where network coverage does not adequately cover the dam site and where measurement of ground motions at the dam site is required. The number of sensors and their installation locations should reflect the site conditions and needs for subsequent use. Preferred locations in order of usefulness are:

1. The base of the dam to record the peak ground acceleration
2. The abutment(s) to record topographic amplifications of the peak ground acceleration
3. The dam crest, midspan, to record the amplification of the peak ground acceleration within the embankment/structure

4. Other locations including intermediate elevations along the structure and nearby the dam site to record free-field motions

Basic requirements for strong ground motion accelerometers include reliability and sensitivity to measure the three components of ground motion.

Monitoring reservoir-triggered seismicity

An array of seismic stations is needed to record and locate relatively small shocks in the dam site area. These stations would include micro-seismic recorders and strong motion recorders. In general, a minimum of five seismic stations is recommended to determine the epicenter and hypocenter depths. Monitoring should start at least a couple of years before impounding of the reservoir to characterize the nature of background seismicity.

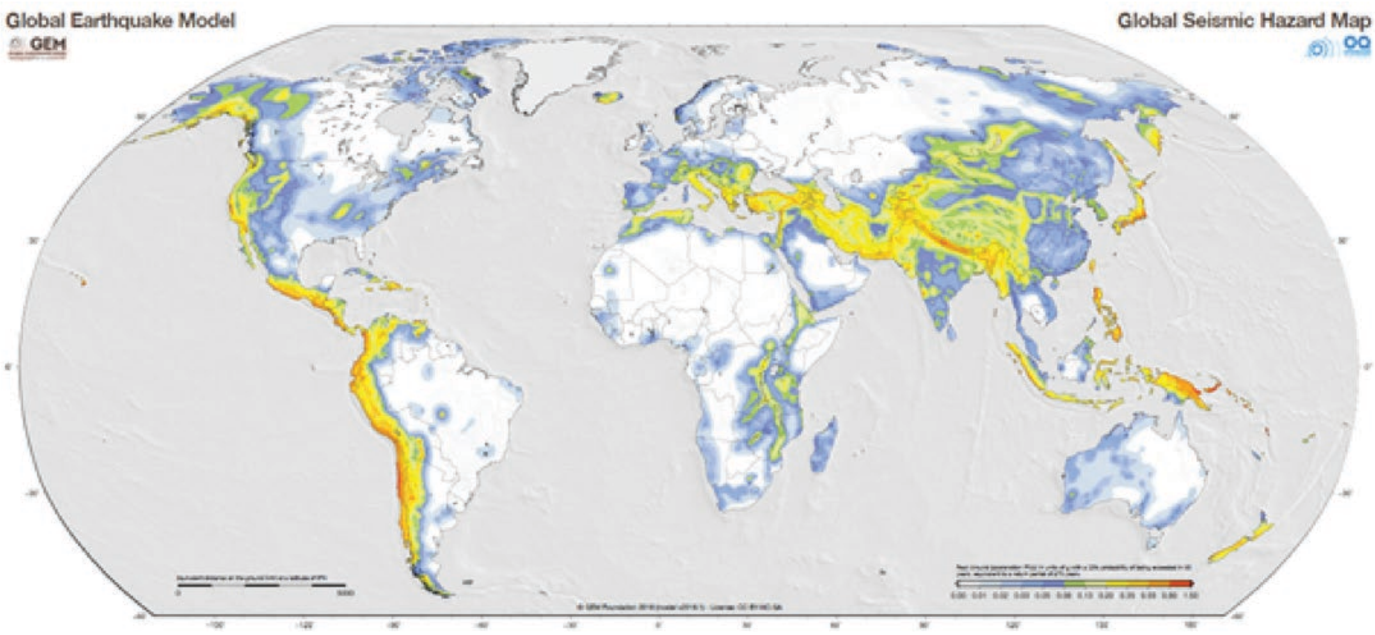
Special monitoring provision

The following are special monitoring provisions for seismic hazards:

- Video cameras for real-time visual observations
- Temperature (high-resolution) water sensing systems within the foundation and embankment to detect any changes in seepage conditions indicative of foundation leakage and possibly piping that may not occur following an earthquake
- Extensometers and inclinometers to identify ground deformation, particularly relating to faults and shears
- Simple joint offset marks or instruments across monoliths of concrete dams, on the crest or within galleries

Annex A: Global Seismic Hazard Map

FIGURE A.1. Global Seismic Hazard Map (by Global Earthquake Model)



Source: https://www.globalquakemodel.org/gem

References

Bray, J. D., and R. B. Sancio. 2006. "Assessment of the Liquefaction Susceptibility of Fine-Grained Soils," *Journal of Geotechnical and Geoenvironmental Engineering* 132(9): 1165–77.

Fell, R., P. MacGregor, D. Stapledon, G. Bell. 2005. *Geotechnical Engineering of Dams*. London: CRC Press

FEMA (U.S. Federal Emergency Management Agency). 1998: "Hazard Potential Class System for Dams," *FEMA* 333 (October).

——. 2005. "Federal Guidelines for Dam Safety: Earthquake Analyses and Design of Dams," *FEMA* 65 (May).

FERC (U.S. Federal Energy Regulatory Commission). 2018a. "Engineering Guidelines for the Evaluation of Hydropower Projects, Revised Chapter 3: Gravity Dams," *FERC* (May).

——. 2018b. "Engineering Guidelines for the Evaluation of Hydropower Projects, Revised Chapter 11: Arch Dams," *FERC* (March).

Global Earthquake Model Foundation website. https://www.globalquakemodel.org/. Pavia, Italy: GEM Foundation

ICOLD (International Commission on Large Dams). 1989. *Bulletin 72: Selecting Seismic Parameters for Large Dams*. Paris: ICOLD.

——. 2001. *Bulletin 120: Design Features of Dams to Resist Seismic Ground Motion—Guidelines and Case Studies*. Paris: ICOLD.

——. 2010. *Bulletin 72: Selecting Seismic Parameters for Large Dams, Revised Edition*. Paris: ICOLD.

——. 2011. *Bulletin 137: Reservoirs and Seismicity—State of Knowledge*. Paris: ICOLD.

——. 2016. *Bulletin 148: Selecting Seismic Parameters for Large Dams—Guidelines (Revision of Bulletin 72)*. Paris: ICOLD.

MBIE (Ministry of Business, Innovation and Employment New Zealand) and NZGS (New Zealand Geotechnical Society Inc.). 2016. *Earthquake Geotechnical Engineering Practice, Module 3: Identification, Assessment and Mitigation of Liquefaction Hazards*. Wellington: MBIE and NZGS, Rev 0 (May).

Mejia, L., M. Gillon, J. Walker, and T. Newson. 2001. "Criteria for Developing Seismic Loads for the Safety Evaluation of Dams of New Zealand Owners," : The Australian National Committee on Large Dams 2001 Conference on Dams, Hobart, Australia.

New Zealand Society on Large Dams (NZSOLD) and IPENZ-Engineers New Zealand. 2015: *New Zealand Dam Safety Guidelines.* Wellington.: NZSOLD/IPENZ.

Seed, H. B., and I. M. Idriss. 1982. *Ground Motions and Soil Liquefaction During Earthquakes.* Berkeley, CA: Earthquake Engineering Research Institute (134).

USBR (U.S. Department of the Interior, Bureau of Reclamation). 2011. *Design Standards No. 13: Embankment Dams*. Washington, DC: USBR (November).

——. 2015. *Design Standards No. 13 Embankment Dams Chapter 13: Seismic Analysis and Design Phase 4: Final*. Washington, DC: USBR (May).

United States Geological Survey (USGS) website. https://www.usgs.gov/science-explorer-results?es=earthquakes. Reston, Virginia: USGS

World Bank. 2020. *Good Practice Note on Dam Safety*. Washington, DC: World Bank.World Bank. 2020. *Technical Note on Geotechnical Risk*. Washington, DC: World Bank.

GWSP
GLOBAL WATER
SECURITY & SANITATION
PARTNERSHIP

THE WORLD BANK
IBRD • IDA | WORLD BANK GROUP

SKU W20083