SELECTING SEISMIC PARAMETERS FOR LARGE DAMS Guidelines

CIGB
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(2010)

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FOREWORD TO FIRST EDITION OF 1989

The influence of seismicity on dams has been of constant interest to ICOLD throughout most of its activity. An ICOLD Committee was set up in 1969 to deal with the related problems and two Bulletins were released as a result:

- A Review of Earthquake Resistant Design of Dams in 1975 (Bulletin no. 27, Committee chaired by M. Nose), and
- Seismicity and Dam Design in 1983 (Bulletin no. 46, Committee chaired by R.G.T. Lane).

The assessment of seismicity at a dam site was the topic in the first chapter of Bulletin no. 46 which summarily treated the problem of seismic input for dam analyses.

As a result of the importance and significance that ICOLD assigns to the selection of seismic parameters for large dams, its Committee on Seismic Aspects of Dam Design has been charged to treat this subject. The objective is to reflect the state of the art in this field and to prepare Guidelines which should help the designers to orient themselves in the matter of selecting the seismic input parameters concerning large dams.

A Sub-Committee was organized to initiate the discussions and the Guidelines for Selecting Seismic Parameters for Dam Projects (published in October *1985)* prepared by the United States Committee on Large Dams (USCOLD) served as basis for discussion at annual meetings of the Committee in 1986 and 1987. Comments and proposed amendments were contributed by several countries (Argentina, France, India, Japan, Norway, Pakistan and Yugoslavia).

The final draft was then edited by the Chairman of the Committee (taking into consideration the mentioned contributions) and then discussed during the Committee's annual meeting in 1988 and approved by the 56th Executive Meeting.

Thanks are extended to all National Committees and Members of the Committee on Seismic Aspects of Dam Design which contributed to the preparation of the Guidelines being now published as an ICOLD Bulletin.

A. Bozovic
Chairman,
Committee on Seismic
Aspects of Dam Design

FOREWORD TO SECOND EDITION OF 2010

Since the publication of the First Edition of Bulletin 72 in 1989 there have been significant improvements in the techniques available for the seismic analysis, design of new dams and the earthquake assessment of existing dams. For this reason it has been felt appropriate to produce an updated version of the Bulletin to reflect recent improvements in methodology.

Bulletin 72 has had a great impact on the earthquake analysis and design of dams as two levels of earthquakes have been specified, i.e. the operating basis earthquake (OBE) and the safety evaluation earthquake (SEE). The term SEE has been introduced in the second editon and replaces the term maximum design earthquake (MDE) used in the first editon.

Dams and safety-critical elements such as bottom outlets, spillway gates and related control units must be able to withstand the ground shaking of the SEE. Structural damage and deformations are accepted as long as the dam is able to store the water in the reservoir safely after the SEE and the water level in the reservoir can be controlled. This means that the performance criteria for bottom outlets and spillways are at least as stringent as for the dam body as they must be operable after the SEE.

The OBE can be considered as an economical criterion and is negotiable, whereas the SEE is a non-negotiable safety criterion for the dam.

By following this concept, dams can be designed to be safe under very strong earthquake action. It is important to note that the earthquake hazard is a multiple hazard, which does not only include ground shaking but also other important site-specific features such as fault movements, rockfall hazard, liquefaction etc. All these hazards must be considered.

Reservoir-triggered seismicity (RTS) is a phenomenon which must be addressed in the selection of the SEE. Therefore the SEE effects are more severe than those caused by RTS.

A Sub-Committee to revise the Bulletin was set up at the 2004 Annual Meeting in Seoul with representatives from the United Kingdom, China, Japan, France and Canada. Valuable assistance was also given from Pakistan and from the USA. Discussions were conducted by e-mail with further meetings in Tehran, Barcelona, St.Petersburg, Sofia and Brasilia.

The final draft was approved at the 78th Executive Meeting in Hanoi, Vietnam, in May 2010.

I hope that this revised version of the Bulletin will contribute to the design of dams that can safely withstand the effects of strong earthquakes.

M. Wieland
Chairman
Committee on Seismic
Aspects of Dam Design

1. INTRODUCTION

1.1 PURPOSE

The preparation of the first draft for these Guidelines was originally undertaken by the Committee on Earthquakes of the United States Committee on Large Dams (USCOLD) and then transacted through the Committee on Seismic Aspects of Dam Design (ICOLD). This led to the publication of the first Edition of the Bulletin in 1989. Since then there have been significant advances in the seismic design of dams and a revised Bulletin is considered necessary which takes into account current practice in a number of countries with the following ends in view:

(1) to provide a guide for the selection of parameters to be used in the seismic design, analysis and safety evaluation of new or existing dams and their appurtenant structures.

(2) to promote consistency in handling the earthquake aspects of dam performance evaluation among owners, designers and various organizations involved in the planning, design, construction, operation, maintenance and regulation of dams.

The use of meaningful seismic parameters is necessary to perform a satisfactory evaluation of the earthquake safety of dams. These Guidelines are intended to help the Engineer and Project Manager to select seismic evaluation parameters for dam projects, based on requirements mandated by the project location and its associated seismic hazard, the design selected, and the risk posed by the completed structure. Appropriate seismic evaluation is not a substitute for, but will complement the use of sound design, high quality materials, effective construction control procedures, and continuous surveillance and monitoring of the performance of the completed structure.

It should be emphasized that, regardless of the seismic parameters and methods of analysis selected, the final evaluation of the seismic safety of the dam usually depends to some degree on engineering judgement and previous experience with similar structures. Newly developed research methods and newly obtained research results should be evaluated and taken into consideration, keeping in mind that each completed structure and its immediate environment form a unique system that is not duplicated elsewhere.

Whilst it is not the purpose of these guidelines to examine mechanisms of failure it must, nevertheless, be pointed out that where failure has occurred to embankment dams in the past it has often been because of liquefaction of the dam foundations or of the dam itself. Users of the guideline are encouraged to bear this in mind when considering the safety of their structure which may be seriously compromised if the dam is constructed on, or comprises, loosely compacted sands or other cohesionless soils.

The present revision to the Bulletin comes after several years of work by the Committee on Seismic Aspects of Dam Design and has, in particular, addressed the following aspects:

(a) A new section on Seismic Input parameters (Section 3.4).

(b) Reference to liquefaction (see above).

(c) Introduction of Safety Evaluation Earthquake (SEE).

(d) Improved references to problems posed when constructing dams across active faults.

(e) Improved references to Reservoir-Triggered Earthquakes (RTE).

(f) Additional material on Peak Vertical Accelerations and Earthquake Durations (Section 3.4).

(g) Updated references to attenuation formulae (Appendix 2).

(h) Updated list of references.

1.2 BACKGROUND

Damage to dams and their appurtenant facilities may result from direct fault movement across the dam foundation or, more likely, from ground motion induced at the dam site by an earthquake located at some distance from the dam. These Guidelines are mainly concerned with the ground motion aspects of dam design although it is noted that a number of dams have been built across known active faults. As shown by the severe damage caused in September 1999 to the Shih-Kang weir in Taiwan, the siting of dams on active or seismogenic faults carries significant risks.

During the May 12, 2008 Richter magnitude 8 Wenchuan earthquake in China, 1803 dams and reservoirs and 403 hydropower plants with a total installed capacity of 3.3 GW suffered damages. Most of the damaged dams were small earth dams; however, four dams with a height exceeding 100 m were also damaged by ground shaking. In addition, numerous rockfalls and landslides in this mountainous region caused substantial damage to hydropower projects and blocked river channels. Although no dam failed, the Wenchuan earthquake has clearly shown that dams must be designed to withstand strong earthquakes and that earthquakes can present multiple hazards.

Ground motion is produced by the passage of a crustal disturbance such as a wave emanating from a region of the earth's crust where fault movement has occurred. The estimation of potential future ground motion requires consideration of a rapidly expanding body of information and the interaction of several disciplines, such as geology, geophysics, seismology, geotechnical and structural engineering. Although knowledge is progressing at a fast pace, numerous uncertainties still exist. Presently, the complex nature of ground motion can only be approximated through relatively simple processes that separate generally recognized, but often insufficiently understood effects, such as the propagation of seismic energy away from the earthquake source, the nonlinear behaviour of rock units and soil deposits and the interaction between the dam, foundation and reservoir. Spatial variations of the ground motion along the base of the dam have generally been ignored, primarily because of the lack of appropriate data.

Historical occurrences of earthquake damage to dams have ranged from minor cracks or crest settlements to total failure and loss of the reservoir retention capacity, although, with the exception of the Shih-Kang weir, no concrete dam has experienced catastrophic failure as the result of an earthquake. In several instances, the affected dams were located at large distances from the source of energy release or the reservoir was at a low level at the time of the earthquake. Hence, the need for either implementing earthquake-resistant design, or fully documenting that a project site is aseismic, cannot be overemphasized.

Design based on earthquake-resistant principles is standard practice for most new dams, but was not considered for many older dams. Investigations of regional earthquake sources and foundation conditions were often less extensive in the past than those required by modern dam engineering practice, and the use of construction procedures now obsolete often makes the seismic performance of older dams poorer and also potentially more difficult to assess. New dams should be shown to be safe before being placed in service, while existing dams shown to be unsafe should be upgraded or taken out of service.There should be no intrinsic difference in the methodology necessary to select earthquake parameters for the design of new structures or for the safety evaluation of older dams. Generally, consistent and sufficiently conservative guidelines, as proposed in the following pages, should be followed to compensate for the uncertainties and the lack of accuracy associated with estimating potential future earthquake ground motions. Furthermore, geologic and engineering experience and judgement have been, and will continue to be essential factors, in determining seismic evaluation parameters that are both conservative and realistic.

Attention is drawn to the particular case of cascades of dams where the failure of an upper dam could put ones lower down the cascade at risk. It is also possible that the same earthquake could damage or cause the independent failure of multiple dams.

Dams, in particular concrete dams, are vulnerable to movements along faults and discontinuities in the foundation. Such movements can be caused by seismogenic (active) faults in the dam foundation but also close to major faults large earthquakes can cause sympathetic movements along discontinuities. In this case, according to ICOLD Bulletin 112 on Neotectonics and Dams, a conservatively designed embankment dam would have to be selected. The dam should be checked for movements that could be caused by the upper bound magnitude earthquake estimated for that fault. However, the best approach is to avoid constructing new dams across potentially active faults.

1.3 SCOPE

This publication contains general guidelines for selecting seismic evaluation parameters to review the safety of existing large dams and provide an earthquake resistant design for any new structure. Such guidelines (which are only intended to apply to large dams according to the ICOLD definition - see below) cover the following subjects:

(1) Primary factors to consider in seismic design.

(2) Selection of design earthquakes for analysis.

(3) Selection of seismic evaluation parameters.

(4) Factors influencing the selection of seismic evaluation parameters.

Note: A large dam according to the ICOLD definition is one more than 15 m high or one between 10 and 15 m high satisfying one of the following criteria:

(a) more than 500 m long;

(b) reservoir capacity exceeding 1 Mm^3 (1×10^6 m^3); or

(c) spillway capacity exceeding 2,000 m^3/s.

This publication is mainly concerned with the earthquake action affecting the dam body and safety-critical elements such as the bottom outlet, spillway gates, control units and power supply. However, it has to be kept in mind that an earthquake will affect all elements of a dam including appurtenant structures, underground structures, equipment, temporary structures like cofferdams etc. Therefore, all these elements have to be able to withstand earthquakes as well. For these elements, lower levels of design earthquake motions may be used than for the dam body and the safety-critical elements. Also, in the case of equipment, the motion of the equipment's support must be used as input. For elements located on the dam crest significant amplification of the support motion has to be expected, especially in the case of concrete (arch) dams.

2. PRIMARY FACTORS TO CONSIDER IN SEISMIC HAZARD ASSESSMENT

A seismic hazard assessment is typically required to develop the seismic parameters that will be required for seismic design or performance assessment of dams. A seismic hazard assessment requires the following:

- Identification of potential sources of earthquakes.
- Evaluation of the characteristics of each potential earthquake source such as geological conditions, magnitudes and rates of activity.
- Empirical equations to compute ground motion amplitudes or intensities (i.e. attenuation equations).

The seismic hazard assessment approach adopted for dam projects should consider the amount of information that is available about seismotectonic conditions in the vicinity of the dam site, and the degree of uncertainty of that information. The primary factors to be considered in the identification of potential sources of earthquakes and evaluation of their characteristics are the tectonic, geologic and seismic activity conditions at, and in the vicinity of, the dam site. The following discussion of such primary factors is intended to be relatively complete, but the order, format and detail in which they should be addressed should remain flexible and tailored to the local conditions, the size of the dam, the intended functions of the structure and the consequences of damage or total failure. Essentially, the selection of seismic parameters for the evaluation of the safety of a new or existing dam is a step-by-step process that should include, as a minimum, the requirements described in the following paragraphs. For reference and a quick overview of the problem, a list of primary factors to consider in seismic hazard assessment is given in Appendix 1.

2.1 REGIONAL TECTONIC AND GEOLOGIC SETTING

Typical tectonic, geologic and seismicity studies consider the regional aspects, and then focus on the local site conditions. Such an approach is necessary to understand the overall geologic setting and seismic history of a particular site. Some sites require consideration of a large regional study area, in order to encompass all geologic features of significance and to account for specific conditions, such as attenuation of earthquake ground motion as a function of distance from the zone of energy release.

The regional geologic study area should cover, as a minimum, a 100 km radius around the site, but should in many cases be extended to as much as 300 km to include any major fault, or area-specific attenuation characteristics. The geological data reviewed should include:

(1) Identification of the physiographic and tectonic province where the project is located.

(2) Geologic history of the project area.

(3) Description of geologic formations, rock types and soil deposits.

(4) Location of major regional geological structural features including folds, and fracture or joint patterns. Imbrication of the major regional geological structures should also be considered as part of studying main features.

(5) Interpretation of the regional tectonic mechanism(s) and associated type(s) of faulting.

(6) Location and description of faults and shear zones and assessment of the capability of faults to generate earthquakes, or to be displaced by earthquakes. This should include documentation on the existence of or the lack of historical or pre-historical activity (paleoseismicity) for each fault.

(7) Estimation of the fault activity for each of the faults of concern to the study area (e.g. average slip rate, slip per event, time interval between large earthquakes, etc.).

Depending on the geological setting, study of the following specific features might also be of value in identifying and characterizing potential earthquake sources:

(8) Study of movement of magma, lava and eruption activity.

(9) Radioactivity and convection current studies.

(10) Changes in gravitational field and Bouguer gravity anomaly surveys.

(11) Aeromagnetic surveys.

(12) Geothermal studies.

(13) Topographic surveys – laser profiling.

(14) Remote sensing surveys (synthetic aperture radar, LIDAR, airphotos, etc.).

(15) Global positioning surveys (GPS).

(16) In-situ stress measurements obtained in engineering investigations or from oil/gas wells.

2.2 SEISMIC HISTORY

Compilation of historical earthquake data helps to identify the seismicity patterns of an area and, in regions where numerous earthquakes have occurred, provides a basis for estimating the probability of future earthquake motion at the site considered. This is based on the assumption that events similar to those which have occurred in the past could reoccur at or near the same location. The lack of historical earthquakes, however, does not necessarily imply that the area considered is aseismic.

When available, emphasis should be given to recorded earthquake data. Comprehensive earthquake catalogues, maintained in different countries by a number of corresponding agencies, provide information on earthquake magnitudes, locations and details on other parameters, such as focal depth and fault mechanism. The listings in such catalogues should be carefully examined for accuracy, completeness and consistency of the data provided. On a world-wide basis sources of earthquake data also include international agencies.

To obtain data that have not been instrumentally recorded it is sometimes necessary to perform a thorough search of the technical literature, newspapers and journals, public and private sources of earthquake information and to catalogue such historical events within the fault study area that may have had an effect on the dam site. The search for seismic history data should, as a minimum, cover a 100 km radius area centred at the dam site, but in most cases it should cover the tectonic province in which the dam is situated as well as including the area of all significant faults, which may extend well beyond the 100 km radius.

When available, the following data should be presented for each event considered:

- epicentre coordinates;
- magnitude (or epicentral intensity)
- date and time of occurrence;
- focal depth;
- focal mechanism;
- felt area;
- accompanying surface effects:
- intensity of ground motion induced at the dam site (known, or estimated);
- reliability;
- source of data.

For significant historical earthquakes that were not well recorded by seismic instruments, intensity maps with isoseismal contours that link points of equal damage or felt earthquake effects remain one of the best ways to derive intensity attenuation functions in the absence of other data, despite the fact that the determination of isoseismals is highly subjective.

Seismic history and geologic considerations may be used to quantify the rate of seismic activity (number of events per year) for the study area and, if possible, for each recognized active fault or tectonic province within this area. Preferably, seismic history data should be statistically processed to develop regional and, if possible, fault-specific magnitude-frequency relationships, for example by plotting on the logarithmic scale the number of events per unit area per year equal to or larger than a specific magnitude against that magnitude value. A plot of earthquake epicentre locations in relation to the dam site is recommended to assess visually the locations of significant historical seismicity. Fault plane solutions from recorded earthquakes may indicate orientations of regional stress conditions and active faults and patterns of microseismic activity may indicate locations of active faults.

2.3 LOCAL GEOLOGIC SETTING

Site-specific geologic information is necessary to ascertain some of the characteristics of the ground motion expected at the dam site and to evaluate the potential for primary or sympathetic fault movement through the dam foundation. Any geologic condition at or near the site that might indicate recent fault movement or seismic activity should be thoroughly documented. Local geologic data are obtained through the review of literature, engineering reports applicable to nearby projects, site inspections, field exploration and material sampling and testing. They should include:

(I) Definition of type, extent, thickness, mode of deposition/formation, and stability characteristics of rock units and soil deposits.

(2) Location and chronology of local faulting, including amount and type of displacements estimated from stratigraphic data, time of last rupture, rates of activity, strain rates, slip rates, etc., using appropriate measurement methods. In some cases the use of special paleoseismic investigative techniques, such as trenching or carbon dating, may be indicated.

(3) Interpretation of the structural geology including orientation and spacing of joint systems, bedding planes, dip and strike of geologic units, folds and intrusive or extrusive bodies.

(4) Determination of hydrogeological conditions, including location of water table, underground water pressure and flow conditions, and permeability characteristics of the formations encountered.

(5) Evaluation of potential for seiches and reservoir slope failures.

(6) Determination of foundation and abutment conditions and their physical properties.

(7) Inventory of strong-motion records from historical earthquakes that occurred near the site or in areas with similar geologic or tectonic setting.

3. SELECTION OF EARTHQUAKES FOR ANALYSIS

3.1 GENERAL APPROACH

Earthquakes must be defined for analytical purposes so that appropriate seismic evaluation parameters (e.g., magnitude, acceleration, spectral ordinates, duration, etc.) can be selected.

The process can be accomplished by using either a deterministic procedure, or a probabilistic seismic hazard evaluation.

In a deterministic procedure for choosing seismic evaluation parameters, magnitude and distance should be ascertained by identifying the critical active faults which show evidence of movements in Holocene time (i.e. in the last 11,000 years), large faults which show evidence of movements in Latest Pleistocene time (i.e. between 11,000 and 35,000 years ago) or major faults which show evidence of repeated movements in Quaternary time (1.8 million years). The capability of these faults must be ascertained through appropriate established methods such as a rupture length-magnitude relationship or a fault movement and magnitude relationship. The distances of these critical faults from the site should be determined to evaluate the other parameters. The appropriate parameters are then obtained by following the methodology summarized in Appendix 2.

A probabilistic seismic hazard evaluation quantifies numerically the contributions to seismic motion, at the dam site, of all sources and magnitudes larger than a designated minimum (typically Richter magnitude 4 or 5*)* up to and including the maximum credible earthquake (MCE) on each source. The possible occurrence of each magnitude earthquake at any part of a source (including the closest location to the dam site) is directly incorporated in a probabilistic seismic hazard evaluation. Section *5* of Appendix 2 provides a summary of such an evaluation procedure.

3.2 TERMINOLOGY

Terminology varies between countries which have produced guidelines for the seismic design and assessment of dams**.**

The level of ground motion experienced at a dam site due to an earthquake depends on the geological and tectonic conditions in the region including the dam site and the earthquake source and consequently on released energy, source mechanism, length of transmission path (and related attenuation) and surface geology of the dam site.

In this Bulletin the Safety Evaluation Earthquake (SEE) is that level of shaking for which damage can be accepted but for which there should be no uncontrolled release of water from the reservoir. The SEE replaces the terms Maximum Design Earthquake (MDE) used in the first edition of this bulletin and Design Basis Earthquake (DBE) used in ICOLD Bulletin 46 (Seismicity and Dam Design). In this Bulletin,the Operating Basis Earthquake (OBE) is that level of shaking for which there should be no or insignificant damage to the dam and appurtenant structures.

- **Maximum Credible Earthquake**

A Maximum Credible Earthquake (MCE) is the largest reasonably conceivable earthquake magnitude that is considered possible along a recognized fault or within a geographically defined tectonic province, under the presently known or presumed tectonic framework. The most severe ground motion affecting a dam site due to an MCE scenario is referred to as the MCE ground motion.

Evaluation of the MCE ground motion is generally done using a deterministic approach, in which the MCE scenarios for each identified fault and tectonic province are taken into account.

The return period of the MCE ground motion generally cannot be determined.

If no obvious earthquake scenarios exist (e.g. no active faults are identified), the ground motions at a dam site are generally estimated using a probabilistic approach, and the ground motions are typically linked to a long return period, for example 10,000 years. Such ground motions estimated using a probabilistic approach may be either lower or stronger than MCE ground motions evaluated using a deterministic approach, depending on factors such as the types of uncertainties incorporated in each approach.

With the foregoing background, the earthquake levels for which the dam should be designed and analysed should be as follows:

- **Safety Evaluation Earthquake**

The Safety Evaluation Earthquake (SEE) is the maximum level of ground motion for which the dam should be designed or analyzed. For dams whose failure would present a great social hazard the SEE will normally be characterized by a level of motion equal to that expected at the dam site from the occurrence of a deterministically-evaluated maximum credible earthquake or of the probabilistically-evaluated earthquake ground motion with a very long return period, for example 10,000 years. Deterministically-evaluated earthquakes may be more appropriate in locations with relatively frequent earthquakes that occur on well-identified sources, for example near plate boundaries.

It will be required at least that there is no uncontrolled release of water when the dam is subjected to the seismic load imposed by the SEE. Depending on the circumstances (e.g. the importance of the dam, the consequences of a dam failure) it is recommended to design safety-critical elements such as the bottom outlet and/or spillway gates for the SEE.

Where there is not a great risk to human life the SEE may be chosen to have a lower return period depending on the consequences of dam failure.

The above return periods are broadly in line with those being used for spillway design.

- **Operating Basis Earthquake**

The Operating Basis Earthquake (OBE) represents the level of ground motion at the dam site for which only minor damage is acceptable. The dam, appurtenant structures and equipment should remain functional and damage should be easily repairable, from the occurrence of earthquake shaking not exceeding the OBE.

In theory the OBE can be determined from an economic risk analysis but this is not always practical or feasible. In many cases, it will be appropriate to choose a minimum return period of 145 years (i.e. a 50 % probability of not being exceeded in 100 years). Since the consequences of exceeding the OBE are normally economic, it may be justified to use a more severe or less severe event for the OBE (i.e. longer or shorter recurrence period).

- **Reservoir-Triggered Earthquake**

The Reservoir-Triggered Earthquake (RTE) represents the maximum level of ground motion capable of being triggered at the dam site by the filling, drawdown, or the presence of the reservoir. There are a limited number of documented cases of reservoir triggered earthquakesand detailed study of such cases is recommended.General environmental features leading to RTE are detailed in the succeeding paragraphs. The reader is also referred to the ICOLD Bulletin 137 on Reservoirs and Seismicity, which provides the state-of-knowledge on reservoir-triggered seismicity.

The consideration of the RTE has been reported as generally linked to dams higher than about 100 m or to large reservoirs (capacity greater than about 500 Mm^3) and to new dams of smaller size located in tectonically sensitive areas. While there exist differences of technical opinion regarding the conditions which cause reservoir-triggered seismicity, it should be considered as a credible event if the proposed reservoir contains active faults within its hydraulic regime and if the regional and local geology and seismic record within that area are judged to indicate potential for reservoir-triggered seismicity. Even if all the faults within a reservoir are considered tectonically inactive, the possibility of reservoir-triggered seismicity should not be totally ruled out, if the local and regional geology and seismicity suggest that the area could be subject to reservoir-triggered seismicity.

Depending on the dam location and prevailing seismotectonic conditions, the RTE may represent ground motion less than, equal to, or greater than the OBE ground motion. RTE ground motion should in no case be greater than the Safety Evaluation Earthquake ground motion and the faults considered capable of triggering seismicity should be taken into consideration during the seismic hazard evaluation. Still the result might be the premature triggering of seismic events due to the the impounding of the reservoir that would have occurred naturally at some longer time in the future. It is therefore justified in case of larger dams and storages located in seismically active regions and regions with high tectonic stresses to install a microseismic network and to monitor the seismicity prior to, during and after impounding.

It is worth noting that there are so far only six generally accepted cases of reservoir triggered seismicity where the magnitude of the event exceeded 5.7. The largest recorded magnitude event that is believed to be due to a reservoir-triggered event is 6.3.

- **Construction Earthquake**

For critical construction phases and temporary structures such as cofferdams, retaining structures etc. it is also necessary to check the earthquake safety. The return period of such earthquakes depends on the type of structure, the duration of its use or the duration and seismic vulnerability of the structure during critical construction stages and the consequences of its failure.

- **Design Earthquake for Appurtenant Structures**

As a minimum, appurtenant structures (penstocks, powerhouses, intake structures, rock caverns etc.) should be designed in accordance with the applicable seismic code for buildings or other structures. Consequently, the site-specific design earthquake ground motion should have a return period equal to that specified in the seismic building codes, which is typically 475 years. For structures which are critical for dam safety, such as bottom outlet, spillway gates, control units and power supply, the design must be based on the safety evaluation earthquake (SEE).

3.3 SEISMIC EVALUATION REQUIREMENTS

The basic seismic loads for the design of new dams or for the safety evaluation of existing structures are derived from the SEE and OBE. Depending on the applicable conditions, a dam may be evaluated for one or both of these basic seismic loads.

The primary requirement for the earthquake-resistant design of dams is to protect public safety, life and property. Hence, large dams must be capable of resisting severe earthquake motion or fault movement at the dam site without uncontrolled release of the water impounded in the reservoir. It is also important that the spillway and bottom outlet should be operational after the earthquake. In the case of the SEE, damage to the dam, even extensive, may be acceptable as long as no catastrophic flooding occurs.

In addition to the foregoing primary requirement, several factors govern the level of effort required for a seismic safety evaluation:

(1) the seismic hazard of the dam site;

(2) the type of dam;

(3) the functional requirements;

(4) the consequence rating of the completed dam and reservoir (see Section 5.2);

(5) the consequences of underestimating or overestimating the risk.

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The decision of analyzing the dam for SEE and OBE conditions should be jointly made by the dam owner, its consultants and involved regulatory or review agencies

3.4 SEISMIC INPUT PARAMETERS FOR ANALYSIS

The typical seismic input parameters for analysis of dams include acceleration time histories, spectral accelerations, or peak ground acceleration developed by either a deterministic or a probabilistic approach, as follows:

(a) For extreme or high consequence dams the SEE ground motion parameters should be estimated at the 84th percentile level if developed by a deterministic approach, and need not have a mean annual exceedance probability (AEP) smaller than 1/10,000 if developed by a probabilistic approach.

(b) For moderate consequence dams the SEE ground motion parameters should be estimated at the 50th to 84th percentile level if developed by a deterministic approach, and need not have a mean AEP smaller than 1/3,000 if developed by a probabilistic approach.

(c) For low consequence dams the SEE ground motion parameters should be estimated at the 50th percentile level if developed by a deterministic approach andneed not have a mean AEP smaller than 1/1,000 if developed by a probabilistic approach.

(d) The ground motions for the OBE will usually have a mean AEP of about 1/145.

The duration of strong shaking is linked to the magnitude of the event and is of considerable importance in assessing the behaviour of dams. This is particularly the case for embankment dams although the duration of shaking can also be a significant factor for concrete dams subject to nonlinear behaviour. Empirical relationships between magnitude and duration of earthquakes can be used to estimate the duration characteristic of the design earthquake.

This bulletin also recommends that peak vertical accelerations be generally assumed equal to 2/3 of the peak horizontal accelerations but that, in estimating peak vertical accelerations at sites close to the assumed epicenter, account be taken of the type of fault movement anticipated (i.e. normal, reverse or strike-slip). Some modern attenuation relationships provide direct estimates of both horizontal and vertical ground motions.

4. SELECTION OF SEISMIC EVALUATION PARAMETERS

The seismic parameters used for dam performance evaluation represent one or several ground motion-related characteristics, such as acceleration, velocity, or displacement values, response spectra, or acceleration time histories that will characterize the SEE and OBE. They may be developed deterministically, or based on a probabilistic seismic hazard evaluation. Various combinations of these parameters are often used. For example, several acceleration time histories may be slected to represent the SEE (as there is no unique way of specifying a given level of earthquake motion).

The seismic evaluation parameters representing the SEE and the OBE often serve as input data for the numerical analyses of a dam. The results of such numerical analyses are used to evaluate the dam performance and safety, given the postulated level of motion.

Many of the factors that affect ground motion and the seismic evaluation parameters are not yet fully understood. Ground motion at any given site is influenced by source, transmission path and local conditions.

‘Source’ effects include fault type, rupture dimensions, mechanism and direction, focal depth, stress drop and amount of energy released.

‘Transmission path’ effects relate to the geometric spreading and absorption of earthquake energy as the seismic waves travel away from the source. They include phenomena such as those due to rock type, regional geological structures including faults and folding, crustal inhomogeneities, deep alluvium, and directivity effects (direction of wave travel vs. direction of fault rupture propagation).

“Local” effects result from the topographic and geologic conditions present at the site and from the possible interaction between structures and the surrounding media. It can also be influenced by whether the site is situated in an inter-plate or intra-plate region.

The factors generally considered the most significant to the specification of seismic evaluation parameters are:

- site classification (alluvium or rock);
- physical properties and thickness of foundation materials;
- closeness to the causative fault (near-field effects);
- distance from the zone of energy release;
- magnitude of the design event.
- type of faulting (normal, reverse or strike-slip).

Other factors, such as direction of fault rupture propagation (directivity effects) and topography, are often significant and are being included in the seismic studies of dams in areas where many earthquakes have been recorded and analysed.

Preferably, the seismic evaluation parameters should be based on site-dependent considerations, making use of existing knowledge and actual observations that pertain to earthquake records obtained on sites with similar characteristics.

However, when applicable site data are too scarce to be meaningful, a site-independent characterization of ground motion must be used.

Ideally, all factors affecting ground motions should be considered, but generally it is not practical to directly include all of them in the estimation of seismic parameters. For example, ground motion attenuation relations typically consider only one or two source factors –(e.g. magnitude and fault type), and a single transmission path parameter (distance). “Local” effects are often disregarded or limited to the simple distinction between rock and alluvial sites and the possible consideration of near-field effects. Other effects are not specifically included but are accounted for in the uncertainty terms defined for these attenuation relations.

The formats used to characterize the seismic evaluation parameters are described in Appendix 2.

5. FACTORS INFLUENCING THE SELECTION OF SEISMIC EVALUATION PARAMETERS

5.1 GENERAL

The design objectives and the possible modes of failure of a dam control its analysis requirements to a large extent and, therefore, the way in which seismic evaluation parameters are selected and specified. Various methods of analysis call for different ways of specifying a given level of earthquake motion. It is, therefore, essential that effective communications be established at an early stage of the work between the geologists, geophysicists and engineers responsible for specifying the earthquake loads and those who will analyze the dam. Factors that affect the specification of seismic parameters are the following

(1) the consequence rating of the completed structure; and

(2) the type of dam and its possible mode(s) of failure.

Judgment and professional experience are required to determine the most appropriate methodology for evaluation of the dam and for specifying the seismic parameters, based on the above factors.

It is not the purpose of these Guidelines to discuss the methodologies of analysis which are available and/or how they should be implemented. The following sections, however, briefly describe how the above factors affect the selection of appropriate seismic evaluation parameters, based on the applied methodology.

5.2 INFLUENCE OF POTENTIAL CONSEQUENCES

The potential consequences of failure, associated with dams, consist of structural components and socio-economic components. The consequences of a dam failure depend on the one hand on storage capacity and on the height of the dam and on the other hand on the population, infrastructure and properties in the downstream inundation area.

Socio-economic consequences can be expressed by the number of persons who would need to be evacuated in case of danger and by potential downstream damage.

It is possible to rate the potential consequences by weighting the mentioned components, associating a larger weighting factor to dams with larger storages, posing larger evacuation requirements and entailing larger potential downstream damage. In this way a consequence rating can be formulated and subdivided into different classes, ranging from low to extreme.

The above mentioned weighting of consequence components, and especially the socio-economic consequence components, are assessments based on judgement and reflect the impact of the socio-economic environment. Different countries will therefore find it necessary to adapt the socio-economic consequence contribution to suit the prevailing circumstances. The foregoing considerations can be used as general guidance in this respect.

It should be noted that, in the case of existing dams, any new or planned downstream development, may affect the consequences associated with a particular structure.

The consequence classification of the dam is needed to further guide the selection of seismic evaluation parameters, as dams with extreme or high consequence ratings will normally require a sophisticated level of evaluation.

Typically, dams with extreme or high consequence ratings will require a detailed method of analysis and the use of acceleration time histories, especially if such dams are also associated with a high site hazard rating. Simpler methods of evaluation, using response spectra or peak ground motion parameters, may be acceptable for dams with low consequence ratings.

It should be understood that the approach discussed in this section (classifying dams according to site hazards, dam size and global downstream consequences) is a possible but not exhaustive treatment of the consequence problem, which should be used with engineering judgement.

5.3 INFLUENCE OF TYPE OF DAM

The type of dam and the possible mode(s) of failure must be considered along with the site hazard and the structure consequence rating to finalize the selection of seismic evaluation parameters. Professional judgement is required to determine how these factors should respectively affect the specification of seismic evaluation parameters.

It is not the purpose of the Guidelines to discuss the most appropriate methods of analyzing a dam, the combination of earthquake with other loads or the applicable performance evaluation criteria.

However, the influence of the type of analysis contemplated, the dam type and possible failure mode(s) upon the selection of seismic evaluation parameters are briefly reviewed below, as they strongly influence the way in which such parameters should be defined.

The most complete way to specify earthquake loading is by using three, mutually perpendicular components of ground motion i.e. two horizontal and one vertical. Depending on the analysis required, the use of all three components may not always be necessary.

5.3.1 Concrete Dams

Safety concerns for concrete dams subjected to earthquakes involve evaluation of the overall stability of the structure, such as verifying its ability to resist induced lateral forces and moments and preventing excessive cracking (overstressing) of the concrete. Various types of analyses can be performed, ranging from a simplified analysis in the case of some gravity dams to more elaborate procedures, such as analysis by the finite element method, which can be applied to any type of concrete dam.

Peak ground motion parameters and response spectra will be sufficient to define the seismic evaluation parameters, if simplified evaluation procedures are contemplated.

Dynamic finite element response analyses may be performed using either response spectra or acceleration time histories, and will normally be required for most dams in extreme or high consequence or hazard classes. Since the induced stresses are a primary factor in assessing the performance of the dam, and since linear elastic behavior is normally assumed, appropriate response spectra or acceleration time histories can be used to specify the Design Earthquakes for peak stress evaluation purposes. However, if nonlinear analysis is contemplated, or if the number of concrete stress cycles or the extent of significant stressing is important to the evaluation of the dam performance, acceleration time histories should be used exclusively. Because concrete dams generally respond at relatively high frequencies, it is important that the acceleration time histories be digitized at a sufficiently short time-step, typically ranging from 0.005 to 0.02 second. The proper selection of the digitization time-step should be verified before an analysis is undertaken.

For straight concrete gravity dams, two components of motion, one horizontal and one vertical, and two-dimensional analysis are generally sufficient. However, concrete gravity dams in relatively narrow canyons should be analyzed three-dimensionally using two components of horizontal motion and a vertical component, if detailed analyses are warranted. For concrete arch dams, and most curved concrete gravity dams, two stochastically independent horizontal and one vertical component of motion must be provided in order to perform a three-dimensional analysis.

Special care is needed in the analysis of particularly long dams where, for example, buttresses can vibrate out of phase.

In the case of concrete dams it will usually be necessary to consider vertical accelerations, amplification effects and also the effects of dam-reservoir interaction which can have a significant effect on the seismically induced stresses in the structure. Damping for concrete dams is usually in the range of 3 to 10 % and is often taken as 5 %.

5.3.2 Embankment Dams

Safety concerns for embankment dams subjected to earthquakes involve either the loss of stability due to a loss of strength of the embankment or foundation materials (e.g., liquefaction due to pore pressure build-up), or excessive permanent deformations (slumping, settlement, cracking of the embankment, and planar or rotational slope failures). Analyses can be performed using the Newmark method or detailed linear or nonlinear dynamic finite element and finite difference procedures. It should be noted that the Newmark method and most numerical analyses only consider shear deformations and do not account for deformations and crest settlements caused by volume changes during earthquake shaking (e.g. compaction of sand, gravel and rockfill). Simplified procedures should always be attempted before using more detailed and complex methods to obtain early information on the effects of the seismic parameters chosen although it should be noted that pseudostatic analyses cannot be relied upon to give a realistic evaluation. Nevertheless, if the embankment materials are not susceptible to loss of stiffness and strength and the hazard and consequence ratings are low, simplified procedures and the derivation of seismic load factors from specified peak ground motion parameters may give a useful first indication of stability.

For estimating the performance of embankment dams in extreme or high hazard or consequence classes, detailed procedures (such as finite element or finite difference analyses) are often performed, and acceleration time histories are required as seismic evaluation parameters. Embankment dams have fundamental periods of vibration that typically range between 0.5 and 1.5 s and, for use in finite element analyses, a digitization interval longer than that recommended for concrete dams may be sufficient; time-steps up to 0.05 s have been shown to be quite acceptable in some cases. However, if an explicit formulation of the equations of motion is used, such as for nonlinear finite difference analyses, an extremely short digitization time-step is required (typically 0.001 s, or less).

If the foundation and embankment materials are not susceptible to loss of stiffness and strength, or if the embankment is not saturated, the dynamic analysis of the dam will serve as a basis to estimate permanent earthquake-induced displacements using the methods of Newmark or others. If the foundation or embankment materials can lose stiffness and strength, a dynamic analysis of the dam should be used for estimating the number and amplitude of induced stress cycles to determine whether the earthquake-induced stresses are sufficient to trigger a loss of strength. Emphasis will be given to the stress response of the dam. For the detailed analysis of an embankment dam, the seismic evaluation parameters cannot be directly specified as a response spectrum, as the development of either increased pore pressures or excessive deformations is largely controlled by the duration of shaking. A specified spectral shape, however, can be used as a guide for evaluating the appropriateness of the selected acceleration time histories.

It is usually considered that the dynamic response of embankment dams does not require consideration of the vertical component of ground motion or of the hydrodynamic effects of the reservoir water. However these factors may need to be considered for embankment dams with particularly steep slopes, such as rockfill dams.

Damping for embankment dams is usually in the range of 5 to 20 %. For strong shaking it is likely to exceed 15%.

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7. GLOSSARY

The following definitions are given to help achieving a uniform understanding of the terms used in these guidelines. For those words or phrases appearing in the ICOLD Glossary (Bulletin 32a) and marked by (*), the definitions are those given in this Glossary.

Active fault: A fault, reasonably identified and located, known to have produced historical earthquakes or showing evidence of movements in Holocene time (i.e. in the last 11,000 years), large faults which have moved in Latest Pleistocene time (i.e. between 11,000 and 35,000 years ago) and major faults which have moved repeatedly in Quaternary time (1.8 million years).

Attenuation: Decrease in amplitude and change in frequency content of the seismic waves with distance because of geometric spreading, energy absorption and scattering.

Bedrock: Any sedimentary, igneous, or metamorphic material represented as a unit in geology; being a sound and solid mass, layer, or ledge of mineral matter; and with shear wave threshold velocities greater than 750 m/s. Bedrock can be exposed at the ground surface or underlie soil layers.

Consequence Rating or Class: In this bulletin consequence rating is a measure of the consequences i.e. the anticipated impact downstream of a failure of a dam and would range from Low to Extreme.

Critical damping: The least amount of damping which will prevent free oscillatory vibration, in a one degree-of-freedom system.

Damping: Resistance which reduces or opposes vibrations by energy absorption. There are different types of damping, such as material (viscous, Coulomb), and geometric (radiation) damping.

Damping ratio: The ratio of the actual damping to the critical damping.

DBE: Design Basis Earthquake

Epicentre (*): The point on the earth's surface directly above the focus (hypocentre) of an earthquake.

Fault: A fracture or fracture zone in the earth's crust along which there has been displacement of the two sides relative to one another, parallel to the fracture.

Focal depth: The vertical distance between the epicentre and the hypocentre.

Focus: See hypocentre.

Free-field: The regions of the ground surface which are not influenced by man-made structures. Also designates a medium which contains no structure (free-field profile), or a region where boundary effects do not influence the behavior of the medium significantly.

Frequency: Number of Hertz of harmonic oscillation

Hazard Class: In this bulletin Hazard Class denotes the likelihood and severity of experiencing an earthquake at the site of the dam**.**

Hypocentre (or Focus) (*): The point within the Earth which is the centre of an earthquake and the origin of its elastic waves.

Intensity: A numerical index describing the effects of an earthquake on man-made structures, or other features of the earth's surface. The assignment of intensity values is subjective and is influenced by the quality of construction, the ground surface condition and the individual perception of the observer. Different intensity scales are used in various countries, such as for instance the Modified Mercalli Intensity scale which is the most widely used in the United States.

Magnitude (*): A rating of a given earthquake independant of the place of observation. It is calculated from measurements on seismographs and it is properly expressed in ordinary numbers and decimals based on a logarithmic scale.

MCE: Maximum Credible Earthquake.

Near-field motion: Ground motion recorded in the vicinity of a fault. For instance, in the United States west of the Rocky Mountains, near-field may be defined based on the following Table

Richter Magnitude M	Modified Mercalli Maximum Intensity I,	Radius of Near-Field (km)
5.0	VI	5
5.5	VII	15
6.0	VIII	25
6.5	IX	35
7.0	X	40
7.5	XI	45

These limits of near-field motions are measured from the epicentre location in the absence of visible fault rupture, or perpendicularly to the trace of the causative fault. In some regions there are no established limits of near-field motions as for example in the Eastern United States. The limits may need to be adjusted in the case of thrust and reverse faults.

OBE: Operating Basis Earthquake.

PGA: Peak Ground Acceleration.

Phase: The angle of lag or lead of a sine wave with respect to a reference. The phase response is the graph of phase shift versus frequency.

Response spectrum: A plot of the maximum values of absolute acceleration, relative velocity, and/or relative displacement response of an infinite series of single-degree-of-freedom systems subject to a time dependent dynamic excitation, such as but not limited to ground motion. The maximum response values are expressed as a function of undamped natural period for a given damping ratio.

RTE: Reservoir-Triggered Earthquake.

Safety-critical elements: Elements associated with a dam that if damaged could have a significant impact on the ability of the dam to be able to lower or control the reservoir imponded by the dam. Examples would include; bottom outlets, spillway gates and support piers, power supply, control panels for gate operation etc.

SEE: Safety Evaluation Earthquake

Stress drop: Initial shear stress acting along a fault plane minus the residual shear stress along the same fault plane after occurrence of slippage.

Strike-slip fault: A fault in which movement is principally horizontal.

Strong motion: Ground motion of sufficient amplitude to be of engineering significance in the evaluation of damage due to earthquakes.

Tectonic province: A geologic area characterized by similarity of geologic structure and earthquake characteristics.

APPENDIX I

LIST OF PRIMARY FACTORS TO CONSIDER IN SEISMIC HAZARD ASSESSMENT

1. REGIONAL FACTORS

1.1. Regional geologic setting

- geologic history of the project area;
- identification of the regional physiographic features;
- description of geological formations (rock types...);
- location of major regional geological structural features (folds, fractures, faults...);
- estimation of the relative degrees of fault activity (rate of displacement...) and deformation activity (rate of subsidence...) of the study area.

1.2. Seismic history

- catalogues:
- epicentre coordinates;
- epicentral intensity;
- surface effects, e.g. isoseismal contours (map);
- focal depth;
- felt area;
- intensity induced at the dam site (known or estimated);
- quantification of the rate of seismic activity (if possible or obvious).

1.3. Seismology

- microseismic activity;
- focal depths;
- focal mechanisms;
- strong motion records (if available).

1.4. Seismotectonic interpretation

- estimation of the regional stresses at different geological periods (from stylolites etc.);

- in situ stress measurements within the region of the site (if available)
- interpretation of the regional tectonic mechanisms and associated types of faulting;
- location and description of faults (and shear zones) able to generate earthquakes (or to be displaced by earthquakes);
- definition of seismotectonic provinces, seismotectonic map.

2. LOCAL FACTORS

2.1. Local geology

- stratigraphy and petrography of the bedrock;
- local tectonics and microtectonics (faults, joints...);
- superficial deposits (alluvium, river terraces, moraines, soils...);
- hypsometric map of superficial deposits (to be used for site effects);
- bedrock contour map.

2.2. Hydrogeology

Periodic changes in static water level, permeability studies, chemical composition of water.

2.3. Geophysical studies

Radon gas monitoring studies, convection currents, geothermal studies and gravity measurements.

2.4. Geotechnical data

- bedrock;
- superficial deposits.

2.5. Exploitation of natural resources in the vicinity of the project area

- ground water;
- oil and gas;
- mineral deposits.

APPENDIX 2

DETERMINATION OF SEISMIC EVALUATION PARAMETERS

1. PEAK GROUND MOTION PARAMETERS

Ground motion can be characterized by peak or effective values of expected acceleration, velocity, and/or displacement. Empirical relationships derived from available earthquake data, termed attenuation equations, relate peak ground motion parameters to distance from the source of energy release and to magnitude. Such equations are, however, very sensitive to the estimates of distance and magnitude, especially in the near-field. The scatter between observed and predicted values is usually fairly significant, as many factors, including but not limited to local site characteristics and the conditions of placement of the recording instruments, affect actual strong motion measurements.

The concept of Effective Peak Acceleration (EPA) is discussed by Chen (Ref. 19). However the simpler concept of Peak Ground Acceleration (PGA), despite recognized shortcomings, such as its lack of predictability in the near-field, or its common occurrence at high frequencies of little engineering significance, remains the most used element to characterize seismic evaluation parameters for dam analysis. Many attenuation equations have been developed in recent years to provide estimates of this variable. These formulae have generally been developed for specific regions and, within those regions, the most reliable available relationships should be used. Formulae should only be used that are appropriate for the particular setting e.g. intra-plate or inter-plate region. Such reliable relationships are not always available and, in such cases, consideration should be given to using a weighted average of values provided by several of the most accepted and reliable equations for this variable. Today, the following references are often used:

- Abrahamson, N. A., and Silva, W. J. (2008). Summary of the Abrahamson & Silva NGA groundmotion relations, Earthquake Spectra 24, 67–97.
- Ambraseys N.N., Douglas J., Sarma S.K., Smit P.M. (2004/2005). "Equations for the Estimation of Strong Ground Motions from Shallow Crustal Earthquakes Using Data from Europe and the Middle East: Horizontal Peak Ground Acceleration and Spectral Acceleration", Bulletin of Earthquake Engineering 3:1–53.
- Boore, D. M., and Atkinson, G. M. (2008). Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s, Earthquake Spectra 24, 99–138.
- Campbell, K. W., and Bozorgnia, Y. (2008). NGA ground motion model for the geometric mean horizontal component of PGA, PGV, PGD and 5% damped linear elastic response spectra for periods ranging from 0.01 to 10 s, Earthquake Spectra 24, 139–171.
- Chiou, B. S. J., and Youngs, R. R. (2008). Chiou-Youngs NGA ground motion relations for the geometric mean horizontal component of peak and spectral ground motion parameters, Earthquake Spectra 24, 173–215.

- Idriss, I. M. (2008). An NGA empirical model for estimating the horizontal spectral values generated by shallow crustal earthquakes, Earthquake Spectra 24, 217–242.
- Stafford, P. J., Strasser, F. O., and Bommer, J. J. (2008). An evaluation of the applicability of the NGA models to ground-motion prediction in the Euro-Mediterranean region, Bulletin of Earthquake Engineering 6, 144–177.

It is generally desirable first to define the PGA as that occurring on “outcropping” bedrock (as all of the foregoing references provide attenuation equations applicable to bedrock, or firm soil sites). The value is then adjusted, as required, to account for specific site conditions, such as topography, or “deep alluvium”, where free-field accelerations generally contain more energy in the long period range than those on a rock site. Soft sediments amplify the low frequency seismic waves of large earthquakes, but will reduce the ground motion of smaller local events by the absorption of high frequency seismic waves. If surface sediments are located at a dam site, the spectra given should be multiplied by a frequency-dependent transfer function fitting to the sediment depth. Chiou and Youngs [21] ground motion model considers the shear wave velocity to a depth of 30 metres and is applicable for velocities ranging from 150 m/s to 1,500 m/s and greater.

The error term associated with attenuation equations, and the statistical significance of the predicted values (absolute maximum, effective, mean, median, or mean plus one standard deviation) should be carefully reviewed and understood prior to using such values for analytical purposes.

So far, few attenuation relationships have been developed for peak velocity, which actually may be a better indicator of ground shaking intensity than the PGA especially in the near-field, for peak displacement, or for the vertical component of ground motion. Vertical motion can be quite significant in the near-field and detailed evaluation of such motion is recommended for all near-field sites. For locations outside the near-field, this Bulletin recommends that the vertical PGA may be generally assumed equal to two-thirds of the horizontal PGA.

2. DURATION

The duration of shaking is one of the most important seismic evaluation parameters for dams, as it has been shown to be directly related to damage, especially in the case of embankments.

The durations of earthquakes can be estimated in different ways. Of significance to engineers are the bracketed duration, measured between the first and the last occurrence of acceleration pulses greater than 0.05 g, at frequencies above 2 Hz [11]. Chang and Krinitzsky [18] reviewed several empirical relationships between magnitude and duration and developed curves, relating bracketed duration, magnitude, and epicentral distance, that differentiate between soil and rock conditions. Local conditions may also affect the expected duration of earthquake shaking and should be considered on a case by case basis.

3. RESPONSE SPECTRA

Response spectra represent the maximum response (in acceleration, velocity, or displacement) as a function of frequency, for a given damping ratio, of a single-degree-of-freedom system subjected to a time-dependent excitation. Response spectra characterizing the SEE and OBE may be determined from peak ground acceleration, velocity and displacement consideration [44], or by using site-dependent or site-independent generalized spectral shapes.

Spectral shapes are generally provided in normalized format (i.e., scaled to 1 g). In order to define earthquake motion they are scaled uniformly and, in most cases, independently from the period considered, to a specified value of peak ground acceleration, peak ground velocity, or another applicable earthquake parameter (e.g., spectral intensity).

If shallow earthquakes are expected, the spectra should be shifted towards higher frequencies.

An alternative to spectral shapes is to directly develop response spectra using appropriate ground motion attenuation relations. Most modern attenuation relations, such as those listed above, include formulae to predict peak spectral accelerations over a range of frequencies.

The level of damping and the number of damping values for which response spectra should be specified to represent the SEE and OBE should encompass *a* range of values applicable to the type of dam and level of ground motion considered. For example, damping values for the analysis of concrete dams typically range from 3 to 10 percent, depending on whether the response is assumed to be predominantly elastic or whether nonlinearities, such as cracking of the concrete, are indirectly included in the analysis by assuming a higher level of damping. The damping values for large arch dams are generally smaller than those of the more massive gravity dams due to radiation damping effects. Damping values for the analysis of embankment dams range from 5 to 20 percent but for strong shaking are in a range higher than 1*5* percent.

For the purposes of characterizing ground motion and comparing various earthquakes, *5* percent damping is the most commonly used value, principally because generalized spectral shapes for that damping value are the most available.

4. ACCELERATION TIME HISTORIES

The definition of seismic parameters by peak values and spectral characteristics is sufficient for many dam applications. For the evaluation of major dams and dams in areas of high seismicity nonlinear analysis techniques are required. For this purpose acceleration time history records are needed. It is recommended that several acceleration time histories be used to represent the SEE or the OBE as certain time histories have a lower energy content at some frequencies and their use may result in an unconservative analysis. Acceleration time histories may be specified for horizontal and/or vertical motion and should preferably be represented by real accelerograms obtained for site conditions similar to those present at the dam site under consideration [14].

Since the strong ground motion data currently available do not cover the whole range of possible conditions, such records must often be supplemented by synthetic motions representing any earthquake size and seismotectonic environment. There exist several techniques for the generation of synthetic accelerograms.

But it should be emphasized that collecting actual earthquake records and establishing observation systems for recording strong ground motions and accumulating these records is the surest way of obtaining basic data for clarification of the properties of earthquake motions acting on dams.

5. PROBABILISTIC SEISMIC HAZARD EVALUATION

A probabilistic seismic hazard evaluation involves obtaining, through mathematical and statistical processes, the relationship between a ground motion parameter and its probability of exceedance at the dam site during a specified interval of time (such as the operating life of the reservoir). The value of the ground motion parameter to be used for the seismic safety evaluation of the dam is then selected after defining an acceptable level of probability for the structure and site considered. Recognized active, or potentially active, faults and seismic provinces are referred to as seismic sources. A seismic province is considered to be an area where the location of active faults is not well known, but where the seismic activity may be reasonably assumed to be randomly distributed. The spatial relationship between the dam site and the seismic source(s) of concern to the site, and the rates of activity assigned to each seismic source, form the basic elements of the seismic hazard model of the site considered. Such model should be consistent with the geologic and tectonic setting of the area under investigation and with the historical and geologic rates of seismic activity that have been established for the faults included.

The evaluation of the seismic hazard at a site due to a single source involves the following probability functions:

(1) The probability that an earthquake of a particular magnitude will occur on this source during a specified time interval.

(2) The probability that the rupture associated with this source and a certain magnitude event occurs at a specified distance from the site.

(3) The probability that the ground motions from an earthquake of a certain magnitude occurring at a certain distance will exceed a specified level at the site.

By combining the three probability functions for each source and adding up the contributions of all sources, the probability of exceeding a specified level of ground motion at the site is computed for the specified time interval.

The advantages of using a probabilistic seismic hazard evaluation, over a deterministic approach, include the following:

(a) contributions from earthquakes ranging in magnitude from the smallest magnitude of concern up to and including the maximum magnitude on each source are included;

(b) contributions from all sources and all distances are included; and

(c) the results provide the means to select design parameters that can produce comparable degrees of risk at two or more sites. For dam sites, the probability of occurrence of SEE should be determined upon a comprehensive examination not only of data concerning seismicity of the dam site, the type and purpose of the dam and the planned service life, but also the consequence rating of the structure (see Section *5.2).*

It should be noted that, in a typical probabilistic seismic hazard evaluation, all magnitudes are assigned equal weight. For most dams, and embankment dams in particular, the level of shaking caused by a large magnitude earthquake is far more serious than the same level of shaking caused by a much smaller magnitude earthquake because of the duration effects.

That aspect of the problem can be addressed by defining earthquake scenarios based on deaggregation plots obtained from the probabilistic seismic hazard analysis.