The Resources Agency
Department of Water Resources
Division of Safety of Dams

Guidelines for Use of the Consequence-Hazard Matrix and Selection of Ground Motion Parameters

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Introduction

Based on information provided by dam owners in their geology and engineering reports and in accordance with Division procedures, the Geology Branch develops ground motion parameters for proposed and existing dams undergoing review. These parameters are those used by the Division as the basis for evaluating the stability of the dam. In the past 20 years there have been many advances in the fields of geology, engineering seismology, and earthquake engineering. For the past several years Geology Branch has closely watched the developments in the field of seismic hazard analysis and recommended that the Division revise their approach to seismic hazard assessment.

Geology Branch staff recommended that a formal consideration of fault slip rate, and ultimately probabilistic seismic hazard analysis be incorporated into the deterministic methods of ground motion parameter selection. Staff also recommended that the attenuation formulas documented in the January 1997 Seismological Research Letters should be used in our practice. These "modern" relationships provide greater utility as well as a perspective gained from an additional 15 years of well-recorded earthquake history.

Preliminary approval to revise the procedures was given after a workshop meeting of the Consulting Board for Earthquake Analysis in May, 2001. The Consulting Board for Earthquake Analysis is a panel of senior experts in the field of Quaternary geology, engineering seismology, and earthquake engineering that advise the Division on issues of technical procedure. The Board agreed with the need for revision and made suggestions to improve the developing draft procedures. Immediately following the May, 2001 meeting, an internal committee, consisting of geologists and engineers, was appointed by Division management to finalize the procedures (referred to as the Guideline Development Committee). After consensus was reached by the Guideline

Development Committee, the procedures were re-presented to the Consulting Board for Earthquake Analysis on May 29 & 30, 2002 and received general endorsement.

This document outlines the new procedures now in use by the Division to develop design ground motion parameters. It is believed that this information will be of interest to dam owners and their engineering representatives. Major differences from past practice include:

- The new procedures involve the use of “modern” attenuation formulas that predict both peak ground acceleration (PGA) and spectral accelerations (SA) as a function of magnitude, distance, fault type and site condition, at both the 50^{th} and 84^{th} percentile statistical level.

- The modern formulas provide a target response spectra for a given scenario expressed as the average of the two horizontal components at 5 percent damping. To account for directivity at near source sites, the new procedures provide a methodology for developing target response spectra for the individual fault-normal and fault-parallel components.

- The new procedures adopt a Consequence-Hazard Matrix (Figure 1) to guide selection of the appropriate statistical level of ground motion based on the consequence of dam failure and slip rate of the causative fault.

- Although the selection of ground motion parameters remains essentially deterministic in practice, the procedures provide for limited use of Probabilistic Seismic Hazard Analysis. The results of the probabilistic analysis are expressed as a hazard curve, which is used to evaluate the conservatism of deterministically-developed parameters. No probabilistically-expressed ground motion standards have been developed.

- The Minimum Earthquake now applies to all new and existing jurisdictional dams undergoing re-evaluation in California. The Minimum Earthquake PGA parameter is within the range of 0.15g to 0.25g. Selection of the appropriate motion level will be based on whether the dam is new or existing, the return period associated with design parameter chosen, and the consequence of failure of the dam.

Deterministic Selection of Target Peak Ground Acceleration and Spectral Accelerations

Geology Branch staff will identify the significant active or conditionally active faults in the vicinity of the site in accordance with the DSOD Fault Activity Guidelines (http://damsafety.water.ca.gov/tech-ref/fault.pdf). Staff also determines the fault’s type, maximum earthquake magnitude, slip rate, closest distance to the dam site in question, as well as the geologic condition of the site. Normally, the 1997 Abrahamson and Silva, the 1997 Boore et. al., and the 1997 Sadigh et. al. relations (referred to herein as AS97, BJF97, and S97) are averaged to develop the acceleration parameters. The maximum earthquake magnitude used in BJF97 equation is limited at M7.5 according to the authors' published limitation. Geology Branch presently does not use special attenuation formulas for normal faults, such as Spudich, 1997 and 1999. Normal faults are treated the same as strike slip faults. For subduction zone events special attenuation formulas are used, such as the 1997 Youngs et. al., relation.

Averaging attenuation formulas addresses the uncertainty associated with the theoretical constraints in each relation. For example, Geology Branch found that averaging the AS97, BJF97, and S97 provides an overall site response model consistent with current views about soil amplification and non-linear response. In special cases, a formula judged inappropriate for a given scenario may be eliminated from the average. An example of a scenario-inappropriate formula is S97, which does not provide for ground motion amplification at hanging wall sites. The 1997 Campbell formula was not used because his preferred formula was under development.

Geology Branch will review new attenuation formulas as they are published and periodically incorporate them as appropriate. Currently, Pacific Engineering Earthquake Research Center is coordinating the development of a set of new attenuation formulas by all major authors. This set of formulas is scheduled to be issued in July, 2004.

PGA and spectral accelerations will be empirically developed for either rock or stiff soil sites, as appropriate. Currently, AS97 and S97 allow specification of rock or stiff soil. For BJF97, Geology Branch assigns shear wave velocities consistent with the Q-T-M classification system developed by Lee et. al. (2000). This system sets the average shear wave velocity parameter for stiff alluvial soil as 332 m/s, soft rock or very dense soil as 406 m/s, and rock as 569 m/s.

For soft soil sites, such as those subject to liquefaction, the ground motion appropriate for the underlying stiff soil or rock conditions is estimated along with a recommendation of the depth at which the ground motion should be applied to a design model. No empirical ground motion estimates are made for soft soil. Design Branch will calculate ground motions for these cases using site response models when necessary.

Procedures to Account for Directivity

Forward rupture directivity is important for dams with periods of interest greater than 0.5 seconds. Although directivity was recognized as early as the 1960's, the increasing number of available strong motion records have significantly better defined the phenomena. Directivity typically results in amplification of long period energy commonly in directions perpendicular to the fault rupture plane. Since empirically predicted target response spectral curves generated by the attenuation formulas represent the average of the two horizontal components, modifications must be made to develop a target for “fault-normal and fault-parallel” horizontal components. The following methods will be used with engineering judgment to modify a target response spectrum to account for directivity:

- The modification is applied to a standard response spectra developed at the appropriate statistical level of design for the project.

- Apply the Somerville et. al. (1997), as modified by Abrahamson (2000), modifications to develop the fault-normal component. Geology Branch uses specific values for assumptions of percent rupture toward the site, namely 40% for strike slip faults and 85% for dip slip faults.

- The standard response spectra at the appropriate level of design is used to represent the fault-parallel component.

For strike slip faults, the direction of the amplified long period motion reasonably associates with the fault-normal direction and this geometry should be preserved in the dam evaluation. For dip slip faults, Geology Branch research has determined that the direction of the amplified long period motion does not reliably correspond with the fault-normal direction. Design analyses should not assume a specific orientation of amplified long period motion. The “fault-normal” component should be applied to the dam with the expectation it could arrive from any direction.

An appropriate time history for analysis should be one which contains directivity and is also a close match in terms of earthquake magnitude, distance, fault type and site condition relative to the project under evaluation. Excessive scaling and spectral matching should be minimized to preserve the natural characteristics of the record. For near source scenarios, the directivity pulse should be early in the record and attain a peak velocity greater than 100 cm/sec.

Development of the Consequence-Hazard Matrix

The Division prefers to continue using deterministically-developed ground motion parameters in evaluating dam safety for reasons rooted in practicality, design philosophy, and compatibility with engineering practices. A representation of a magnitude-distance scenario is often preferred by designers in part because mutually consistent parameters beside acceleration are needed for the various engineering calculations relating to dams. In addition, there has been little serious discussion on what constitutes an appropriate return period for the design of dams in California.

On the other hand, deterministically-developed ground motion parameters, by their very definition, do not incorporate the likelihood of the earthquake event. In practice however, it is common for design engineers to consider earthquake likelihood subjectively. There was misconception that deterministic parameters were inherently more conservative than probabilistic parameters. In reality, probabilistic seismic hazard analysis offers perhaps the most definitive way to measure the actual conservatism of a given parameter, that is in terms of return period of exceeding that parameter.

Seismic hazard assessments in the Division have historically relied on only deterministic methods. The exclusive use of deterministic methods cannot provide the temporal perspective needed to effectively consider earthquake likelihood. The Division sought to find a means by which the strengths of both approaches could be used together to improve our ground motion estimation practice.

The consequence of dam failure has historically been subjectively considered in developing design criteria. It was decided that appropriate seismic design standard should be a function of the consequence of dam failure, as well as the likelihood of the earthquake event. To facilitate this, a 4x4 matrix, providing 16 consequence of failure-earthquake likelihood categories was developed (Figure 1). Fault slip rate of the controlling seismic source is used as proxy for earthquake likelihood. Four slip rate categories were developed to account for the large variation in slip rate exhibited by California faults. Total Class Weight, a damage potential parameter historically used by the Division to evaluate spillway capacity and numbers of annual inspections, is used to represent the range of failure consequences.

The matrix reflects the Divisions existing design policies regarding the appropriate level of design that developed over time within the organization. These so called “philosophical” constraints include:

- Dams with higher consequence of failure should be evaluated with 84^{th} percentile parameters.

- 50^{th} percentile parameters are OK for dams with the lowest consequence of failure.

- 50^{th} percentile parameters are OK for most dams subjected to seismic loading from the Foothill Fault System.

In addition, the matrix represents “probabilistic” constraints, that is, what can be learned about the parameter’s conservatism expressed in terms of return period through probabilistic methods. To provide this insight, Geology Branch performed side by side deterministic and probabilistic analyses for 30 dam sites studied over the course of one year. Probabilistic hazard curves were developed for each site and the return periods that were achieved by both the 50^{th} and 84^{th} percentile deterministically-derived acceleration parameters were noted.

It was found that the conservatism associated with a deterministically-obtained parameter varies significantly. Dam sites near very high and high slip faults associate with return periods of only a few hundred years at the 50^{th} percentile design level. Dam sites in the Sierra Foothills associate with return periods that often exceeded 20,000 years at the 84^{th} percentile design level. At sites near moderate slip rate faults, the choice of the most appropriate deterministic level of design was less clear. Therefore, in some matrix categories "50^{th} to 84^{th}"percentile parameters are indicated as appropriate. In these cases, probabilistic seismic hazard analyses and engineering judgment will be used to select the appropriate level of design.

Use of the Consequence-Hazard Matrix

As described above the selection of the appropriate statisical level of PGA and spectral acceleration parameters will be based on the consequence of failure and the probability of earthquake hazard expressed as the slip rate of the fault. The fault slip rate and Total Class Weight classifications are defined on the Consequence-Hazard Matrix. The fault slip rate that most accurately represents the geologically recent displacement history of the fault is used based on a review of current research. In some cases, owners may wish to obtain slip rate information by field investigation. The Field Engineering Branch will establish the Total Class Weight for the dam based on existing Division procedures.

Geology Branch presently performs probabilistic analyses using the USGS Interactive Deaggregated Website to develop hazard curves. Deaggregation analysis is also performed to understand the contributing sources to the probabilistic hazard.

The Division will continue to rely on deterministically-obtained parameters for its engineering analyses. The Division has not developed probabilistic standards for design. Acceleration values associated with the 50^{th} percentile deterministic levels will be the lowest used. In other words, all dams in California will be designed to at least the expected (50^{th} percentile) level of acceleration associated with a maximum magnitude event on the controlling fault. In recognition that some earthquake events are likely and that some dams have high consequence of failure, many dams will be designed to acceleration values greater than the expected level of acceleration (greater than 50^{th} percentile), consistent with past practice. The 84^{th} percentile level will normally be the highest design value used by the Division.

Minimum Earthquake Parameters

The Minimum Earthquake provides a ground motion that represents an earthquake event on an unrecognized local seismic source. The Minimum Earthquake will likely be invoked in areas such as the western slope of the Sierra Nevada Mountains, the Central Valley, and Southeastern California. The Minimum Earthquake is used whenever the fault-source ground motion estimate is less severe than the ground motion resulting from the Minimum Earthquake. The Minimum Earthquake is used for all new and existing jurisdictional dams being re-evaluated in California.

The Minimum Earthquake PGA parameter will be within the range of 0.15g to 0.25g. The Minimum Earthquake is specified as a peak acceleration value or target response spectral curve associated with an earthquake scenario presumed to be a magnitude 6-1/4 event with duration of 14 seconds. The 0.15g PGA value is the 50th percentile peak ground acceleration for this scenario, and 0.25g PGA value is the 84th percentile value for this scenario.

Selection of the appropriate PGA or target response spectra is based primarily on three criteria: 1) whether the analysis is for an existing dam or new construction/major modification; 2) the consequence of failure associated with the dam under evaluation; and 3) the return periods associated with design parameters chosen. Specific guidance is as follows:

- For existing dams, a PGA of 0.15g is used except where a higher value is indicated by consideration of the return period achieved by 0.15g.

- For new dams/major modifications, 0.20g PGA is used except where a higher value is indicated by consideration of the return period achieved by 0.20g.

- Consistent with general practice, the consequence of failure should also be a consideration. A PGA of 0.25g may be used for higher consequence of failure projects.

The return period, as developed through PSHA analysis, plays a very important role in selecting the appropriate Minimum Earthquake acceleration parameter. Unlike deterministic methods, probabilistic methods can directly account for earthquake activity not associated with known faults. A low return period achieved by accelerations in the range of 0.15g to 0.25g in areas without surface faulting is an indication of an elevated level of background seismicity. An appropriately conservative minimum earthquake needs to directly consider the level of local background seismicity in addition consequence of failure and age of project.

References

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	Very High Slip Rate 9 or greater mm/yr	**High Slip Rate** 8.9 to1.1 mm/yr	**Moderate Slip Rate** 1.0 to 0.1 mm/yr	**Low Slip Rate** less than 0.1 mm/yr
Extreme Consequence Total Class Weight 31-36	84^{th}	84^{th}	84^{th}	50^{th} to 84^{th}
High Consequence Total Class Weight 19-30	84^{th}	84^{th}	50^{th} to 84^{th}	50^{th} to 84th
Moderate Consequence Total Class Weight 7-18	84^{th}	50^{th} to 84^{th}	50^{th} to 84^{th}	50^{th}
Low Consequence Total Class Weight 0-6	50^{th}	50^{th}	50^{th}	50^{th}

DSOD Consequence-Hazard Matrix

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Used to Determine the Appropriate Statistical Level of Acceleration for Deterministic Seismic Hazard Analyses

Figure 1