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## B-2 SEISMIC HAZARD ANALYSIS

### B-2.1 Key Concepts

A critical component of risk analyses is the degree of hazard imposed upon the system of interest, which in this case includes dam and levee facilities that comprise an infrastructure portfolio. Hazard is distinct from the response of system components (which are affected by hazard) and from the consequences (which result from distress or failure of system components); risk is a measure of how hazard affects system response and possible resultant consequences. For risk assessments of dam and levee systems, hazard is generally treated in the form of three types of loading (static, hydrologic, and seismic loading).

This chapter summarizes the Best Practices for characterizing seismic hazard for dam and levee safety evaluations. *Seismic hazard* is often defined as a natural phenomenon (such as ground shaking, fault rupture, or soil liquefaction) that is generated by an earthquake, although there are examples of these phenomena also being produced by human activities. These effects may be severe and damaging, or they may simply be a nuisance, depending on the magnitude of the earthquake, the distance a site is from the earthquake, local site conditions, and the response of the system of interest (e.g., dams, levees, buildings, lifelines, power plants). Also, the term “seismic hazard” in engineering practice can refer specifically to strong ground motions produced by earthquakes that could affect engineered structures, such that *seismic hazard analysis* often refers to the estimation of earthquake-induced ground motions having specific probabilities over a given time period. In this section, seismic source characterization, ground shaking, and the development of ground motions for engineering analyses are summarized. In addition, where the potential for surface fault displacement through a dam site is a concern, seismic hazard analysis should include characterization of the location, amount, style, and recurrence of *permanent ground deformation* (PGD). While characterizing surface rupture hazard differs substantially from assessing strong ground motion hazard, the analytical approaches used to evaluate these two seismic hazards have some similarities.

Overall, seismic hazard analyses can be grouped into three general levels depending on the type of study, the risk analysis being performed, and the intended use of the study. Table B-2-1 provides an outline of the scope and staffing guidelines for three levels of seismic hazard analysis. Unless a detailed and up-to-date seismic hazard analysis has been completed for the site(s) of interest, a first step in developing defensible seismic loading parameters is to conduct an initial, semi-quantitative screening analysis. For seismic loading, a valid initial screening effort can use available online tools developed by the United States Geological Survey (USGS), accessed at <http://geohazards.usgs.gov/hazardtool/application.php>.

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**Table B-2-1.—General Levels, Intended Use, Staffing, and Scope for Seismic Hazard Analyses**

Analysis Level	General Staffing Requirements and Cost Categories	General Scope
Screening or scoping level (periodic assessment, semi-quantitative risk assessment)	1 month \$	<p>Compile and review existing files and recent literature</p> <p>Interview local experts and regional or national subject matter experts</p> <p>Use existing analyses if judged applicable</p> <p>Develop hazard curves based on existing, readily available seismic source models and existing accepted Ground Motion Prediction Equations (GMPE)</p>
Intermediate level (Issue evaluation study) feasibility design	1 month to 1 year \$\$	<p>Limited field reconnaissance</p> <p>Update seismic source model</p> <p>Produce hazard curves based on updated seismic source models and accepted GMPE</p> <p>Develop Uniform Hazard Response Spectra (UHRS) and time histories to assess system response or to inform design parameters.</p>
Detailed characterization level (dam safety modification study, engineering design) appraisal or conceptual design; corrective action; final design	>1 year \$\$\$	<p>Detailed fault-specific seismic source characterization</p> <p>Develop hazard curves, UHRS, Conditional Mean Spectra (CMS), and time histories to inform design parameters; Consider possible seismic monitoring.</p>

Note that the USGS website tool is not intended to provide ground motions for use in evaluating critical structures such as dams, nuclear power plants, or other high-risk facilities. The USGS Web site can be used as a screening tool for prioritizing facilities on a regional basis, if the user understands and acknowledges that the tool has limitations related to its regional, non-site-specific methodology. It must be recognized that using ground motions derived from the USGS website tool is not recommended for critical decisions involving engineering design of modifications to a dam structure.

## Chapter B-2 Seismic Hazard Analysis

Various screening protocols can be developed based on screening criteria that are customized to a specific region or location, utilizing information readily available from the USGS website noted above in conjunction with other regional geologic and geotechnical information. Initial seismic hazard screening may include an initial estimate of the geotechnical seismic site-response conditions estimated based on site-specific information (preferred, if available), by review of available site geologic maps and aerial photography.

One key parameter in estimating the site response is the average shear wave velocity in the upper 30 m (100 ft), or  $V_s^{30}$  (table B-2-2). This parameter which can be estimated using the regional estimated  $V_s^{30}$  mapping tool developed by the USGS: <http://earthquake.usgs.gov/hazards/apps/vs30/>.

**Table B-2-2.—Site Class Definitions**

Site Class	Generalized Description	$V_s^{100}$ (ft/s)	$V_s^{30}$ (m/s)
A	Hard rock	>5,000 ft/s	>1,520 m/s
B	Rock	2,500 to 5,000 ft/s	760 to 1520 m/s
C	Very dense soil/soft rock	1,200 to 2,500 ft/s	360 to 760 m/s
D	Stiff soil	600 to 1,200 ft/s	180 to 360 m/s
E	Soft clay soil	<600 ft/s	<180 m/s
F	Requires site response analysis		

Using the estimated site class, the USGS online ground-motion hazard tool can be used to obtain an estimated peak ground acceleration (PGA) with a mean annual frequency of 1/2,475 (2 percent (%) probability of exceedance in 50 years). Using pre-selected criteria to screen facilities in various site classes and PGA values, a decision can be made to proceed with additional seismic hazard analyses, such as utilizing existing recent seismic hazard analyses from nearby sites or completing a site-specific seismic hazard analysis. Using the USGS tools, ground motions can be estimated for sites across the nation assuming a site class B/C boundary ( $V_s^{30} = 760$  m/s); the USGS website allows estimation of shaking levels for other site classes at locations where appropriate ground motions prediction equations are available. Also, the values at the B/C boundary can be estimated for other site classes using the correction procedures outlined in ASCE 7.

The following sections provide an overview of the probabilistic and deterministic seismic hazard analyses, followed by summaries of analytical outputs and parameters needed for evaluating seismic loading. As noted above, seismic hazards also include surface fault rupture; if applicable to the subject site, a

*Probabilistic Fault Displacement Hazard Analysis* (PFDHA) may also be necessary. Latter sections of this chapter summarize the basic elements of a PFDHA.

### B-2.2 Basics of Probabilistic Seismic Hazard Analysis

A *Probabilistic Seismic Hazard Analysis* (PSHA) collectively considers the contributions from all known potential sources of earthquake shaking. Most importantly, a PSHA considers the likelihood of various earthquakes from multiple potential seismic sources, each having a range of uncertainty in source characteristics (e.g., rupture length, distance, fault dip, maximum magnitude, slip rate). Uncertainty is treated explicitly, and the annual probability of exceeding specified ground motions (commonly expressed as spectral acceleration at periods of interest) are computed. A PSHA thus provides seismic loading parameters over the full range of potential loading time intervals, and provides a complete consideration of site seismic hazard from multiple sources and for appropriate recurrence intervals.

Prior to the acceptance and incorporation of PSHA into standard hazard assessment methodologies, most seismic hazard assessments were completed using scenario-based, “*deterministic*” analyses. A *Deterministic Seismic Hazard Analysis* (DSHA) typically assigns a maximum earthquake magnitude for a particular seismic source, often referred to as the *Maximum Credible Earthquake* (MCE). Based on the minimum distance from the site to the fault source, the level of ground shaking at the site is estimated. Outdated DSHA methodologies typically involved a simple judgment by experts as to the largest earthquake that a significant source could produce. The earthquake identified as the MCE for a given source was acknowledged as being a judgment based on the level of information available to the hazard assessment team; the MCE sometimes is simply (and incorrectly) chosen as the largest magnitude on the nearest major fault.

In current practice, the MCE magnitude for a given seismic source is still a judgment, but the ground motion estimation is informed by empirical relationships between magnitude and distance based on local or worldwide historical earthquakes, which allows a better assessment of uncertainty in the ground motion values. Also, multiple seismogenic sources near and far from the site can be considered. Nearby faults may be less active and limited to generating lower magnitude events than more distant but larger faults, although the motions from those events may yield higher expected PGA and higher short period/high frequency energy content. Because of the attenuation of energy as waves travel through Earth’s crust, distant faults that can produce larger magnitude earthquakes may result in lower expected PGA values and lower high-frequency

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energy at a given site than nearby fault sources. However, large-magnitude earthquakes on distant faults may still result in substantial damage because of long durations of strong ground shaking and, in some cases, long-period wavelengths. This depends in large degree on the type of structure being analyzed. Very stiff structures such as concrete dams may be controlled by acceleration (high frequency content), while very flexible structures such as buildings (depending on the height and construction) may be controlled by displacement (low frequency content). Intermediate structures will be controlled by intermediate frequency content, or ground velocity. The different ground-motion periods produced by different seismic sources emphasizes the need for the hazard evaluation to include collaboration among geologists, seismologists and structural engineers. In many tectonic settings, several different fault sources will be considered as a source of the MCE ground motions required for analysis, to account for variations in PGA, spectral content and duration effects. For example, areas of plate convergence (such as the Pacific Northwest of North America) may be affected by distant large-magnitude subduction-zone earthquakes, as well as nearby moderate-magnitude earthquakes generated by faults in the shallow part of Earth's crust.

Note that the MCE (as defined above) classically refers to the largest **earthquake magnitude** judged to be possible from a given seismic source, although present-day structural engineering and building codes utilize the term *Maximum Considered Earthquake* (also MCE), which represents a **ground motion acceleration** (not an earthquake magnitude) with a certain probability of exceedance in a given time period (usually 2 percent in 50 years; see Luco et al. 2007). When most seismic engineering applications and building codes refer to the "MCE," they are referring to the maximum considered earthquake ground motion value rather than the earthquake magnitude.

The accepted and now commonly utilized PSHA approach is based on the model developed by Cornell (1968), refined by McGuire (1974, 1978), summarized by the Senior Seismic Hazard Analysis Committee (SSHAC 2007) and the U.S. Nuclear Regulatory Commission (USNRC 2007), and utilized by many subsequent analysts. The objective of a PSHA is to estimate the probability in a given future time period that a specified level of some ground motion parameter will be exceeded at a site of interest (SSHAC 2007). The analysis requires characterization of all known earthquake sources that could affect the site, including faults ("line sources") and areas of seismicity ("areal sources"). The analysis also considers the attenuation of seismic energy as it emanates from the earthquake hypocenter to the site of interest, which is evaluated through the use of empirical *Ground Motion Prediction Equations* (GMPE). Analysis of hazard must also consider the geotechnical response of the site to ground motion input, known as "site response."

Products from a seismic hazard analysis typically consist of four basic components related to strong ground motions and will be discussed below:

## Chapter B-2 Seismic Hazard Analysis

1) seismic source characterization; 2) development of hazard curves (including GMPE and site response); 3) development of uniform hazard spectra; and 4) development of acceleration time-histories. Lastly, this section provides summary comments on structural considerations that may be relevant because of seismic strong ground motions.

### B-2.2.1 Seismic Source Characterization

Seismic source characterization involves the identification and documentation of relevant possible earthquake sources in a region, and forms the knowledge base for a site-specific or regional PSHA. As noted by SSHAC (2007) and the Central and Eastern United States Seismic Source Characterization (CEUS-SSC 2012), a proper and complete seismic source characterization includes an evaluation of the complete set of data, models and methods that are relevant to the hazard analysis, and the integration of the center, body, and range of technically defensible interpretations. At present, the CEUS-SSC (2012) effort provides a comprehensive seismic source characterization of the Central and Eastern United States (CEUS, east of longitude 105W degrees), which was developed for seismic hazard analyses of nuclear facilities. This effort provides a high level of confidence in the data, models and methods of the technical community for CEUS PSHA, and establishes guidance for seismic source characterizations in the Western United States (WUS; west of longitude 105W degrees) and elsewhere throughout the world. Similarly, a recent comprehensive seismic source characterization incorporating a broad range of technical interpretations and uncertainty has been completed for the entire State of California (USGS 2013).

The heart of any seismic source characterization for a PSHA is the description of the future spatial and temporal distribution of earthquakes (CEUS-SSC 2012). The seismic source characterization results in a seismic source model, which is a description of the magnitude, location, and timing of all earthquakes (usually limited to those that pose a significant threat); source models consist of several earthquake scenarios, each with its own magnitude, location, and rate. These scenarios usually represent earthquakes on particular faults or within a region (i.e., volume of earth's crust) that have a distribution of events in time and space. Thus, earthquake source models typically consist of possible earthquakes that can occur on either: 1) particular faults; or 2) areal (i.e., background) seismic source zones. These two types of seismic sources are summarized below.

Fault sources are usually modeled as planar surfaces and are described with a set = of parameters such as activity (expressed by either slip rate or recurrence interval), geometry (location, length, dip, and down-dip extent), amount and sense of coseismic slip, maximum magnitude ( $M_{max}$ ), and recurrence model (characteristic earthquake or maximum magnitude and associated frequencies). These parameters are generally defined on the basis of geologic, geomorphologic, and paleoseismologic information, as summarized on table B-2-3. The level of



## Chapter B-2 Seismic Hazard Analysis

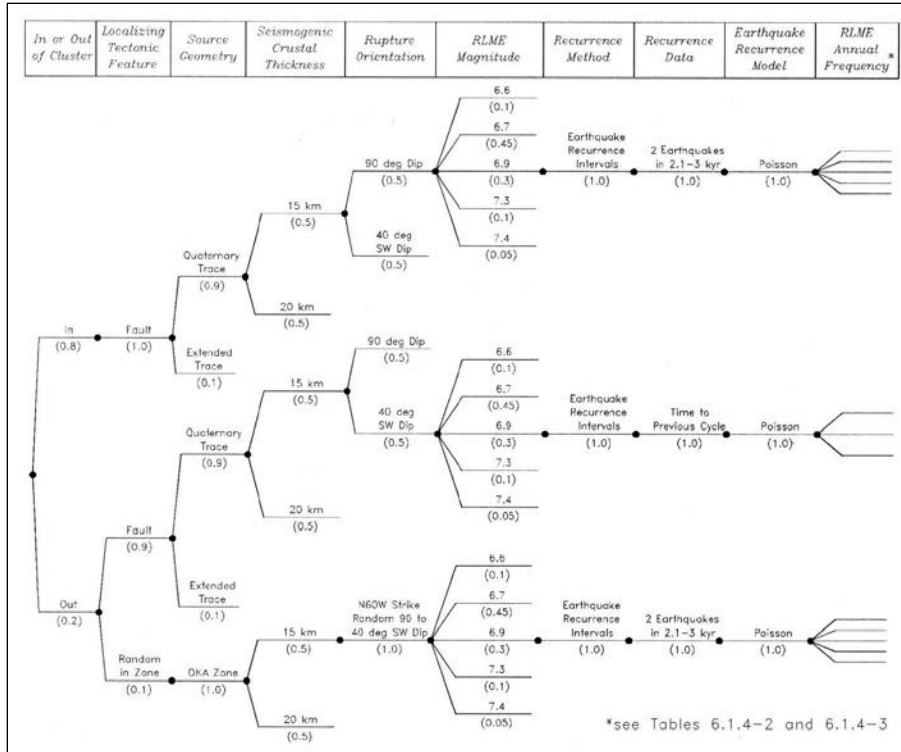
**Table B-2-3.—Table of Types of Geologic, Geophysical, and Seismologic Data that can be Considered for Identifying and Characterizing Seismic Sources (CEUS-SSC 2012)**

Data Type	Seismic Source							
	Individual Faults						Area/Volume Sources	
	Location	Activity	Length <sup>1</sup>	Dip	Depth	Style	Area	Depth
<b>Geological/Remote Sensing</b>								
Detailed mapping	X	X	X	X		X		
Geomorphic data	X	X	X			X	X	
Quaternary surface rupture	X	X	X			X		
Fault trenching data	X	X		X		X		
Paleoliquefaction data	X	X					X	
Borehole data	X	X		X		X		
Aerial photography – Low sun-angle photography	X	X	X					
Satellite imagery	X		X				X	
Regional structure	X			X		X	X	
Balanced cross section	X			X	X		X	
<b>Geophysical/Geodetic</b>								
Regional potential field data	X		X				X	X
Local potential field data	X		X	X	X	X		
High resolution reflection data	X	X		X		X		
Standard reflection data	X			X		X		
Deep crustal reflection data	X			X	X		X	X
Tectonic geodetic/stain data	X	X		X	X	X	X	X
Regional stress data						X	X	
<b>Seismological</b>								
Reflected crustal phase data								X
Pre-instrumental earthquake data	X	X			X	X	X	
Teleseismic earthquake data							X	
Regional network seismicity data	X	X	X	X	X		X	X
Local network seismicity data	X	X	X	X	X			X
Focal mechanism data				X		X		

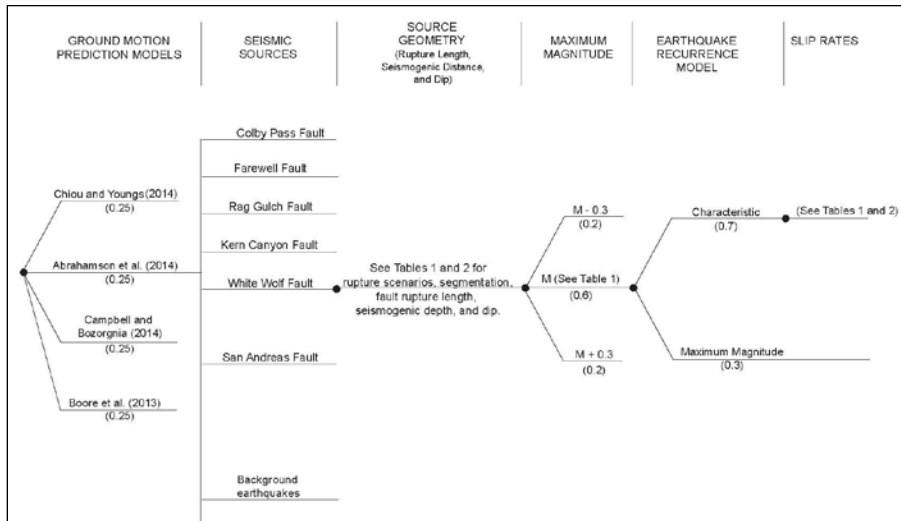
<sup>1</sup> Fault length includes both total fault length and information on segmentation.

information for each fault as a possible seismic source varies according to the degree of past investigation and regional or local field conditions, such that the uncertainties in seismic source parameters needed for a PSHA can vary substantially. To capture and document the range in uncertainties, the data and interpretations of a seismic source model are depicted on a logic tree. Figures B-2-1 and B-2-2 show examples of logic trees for seismic source characterizations from the WUS (for United States Army Corps of Engineers (USACE) Terminus Dam, California) and from the CEUS (Meers fault in south-central Oklahoma). In the more tectonically active WUS, the recognition of

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**Figure B-2-1.—Example fault source logic tree for a single fault, showing fault parameters in boxes above each node, cases considered for each node in the tree, and assigned weights (in parentheses) for each case. Nodes are repeated for entire logic tree, but shown only once on figure (example is Meers fault, Oklahoma [CEUS-SSC 2012]).**



**Figure B-2-2.—Example seismic source characterization logic tree, showing GPME used for each seismic source (listed on chart without a nodal circle), and subsequent fault characterization nodes. The source geometry node consists of several individual nodes similar to logic tree on figure B-2-1.**

## Chapter B-2 Seismic Hazard Analysis

active faults and the collection of detailed paleoseismologic data have allowed inclusion of fault-specific sources and background seismicity sources zones in the seismic source models. In contrast, the relative dearth of identified fault sources in the CEUS has resulted in the use of spatial and temporal patterns of historical small- to moderate-magnitude earthquakes to provide information about the spatial and temporal pattern of future large-magnitude earthquakes.

Many definitions exist for what constitutes an “active” or “potentially active” fault and hence what faults should be considered potential seismic sources. In a PSHA, most faults with evidence of late Quaternary activity (i.e., faults with documented or suspected evidence of displacement during roughly the past 1.6 million years are considered to be active; this criteria has been used in the development of the USGS Quaternary Fault and Fold Database, available here: <http://earthquake.usgs.gov/hazards/qfaults/>.

For most seismic hazard analyses in the WUS, faults within approximately 50 km of the site are characterized, but for some sites that do not have nearby active or potentially active source, the faults as far as 100 km or more are included if they may have a significant impact on the hazard. In the WUS, large earthquakes associated with the Cascadia Subduction zone in the region offshore Washington, Oregon, and northern California will probably produce strong long-period ground motions (and perhaps trigger secondary surface fault rupture) within a large part of the Pacific Northwest. However, local earthquakes generated along faults in the shallow crust above the subduction zone may also generate strong ground motions at sites in the Pacific Northwest, although these ground motions may consist of high-frequency motions and be shorter in overall duration. Similarly, a large magnitude earthquake on the San Andreas fault in California will likely generate strong long-period ground motions in areas more than 50 km from the actual fault trace. In summary, a distant seismic source may be the primary source of long-period spectral accelerations, whereas local fault sources or background seismicity may be primary contributors to short-period ground motions; as a result, both PSHA and DSHA should consider multiple distant sources so that the evaluation includes all possible contributors to hazard.

Developing a complete and defensible seismic source model requires considerable resources and continued efforts to maintain an updated database. During the past decade or so, the USGS has compiled an extensive database of known or suspected Quaternary faults and folds, which can be accessed at <http://earthquake.usgs.gov/hazards/qfaults/>.

This compilation included contributions from USGS scientists, other Government agencies, State geological surveys, academic institutions, and private industry

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experts. Most of the faults and folds in this database are located in the WUS, primarily because of the difficulty in characterizing individual seismic sources in the CEUS.

The USGS quaternary fault and fold database was compiled to help develop the national USGS National Seismic Hazard Map Web site and does not include many faults with low slip rates or those that have been more recently identified or characterized. Also, the quality of data and level of study varies greatly for faults in the database, particularly for faults with low slip rates or outside densely populated areas. This is relevant because seismic hazard for dams and other important facilities may be strongly influenced by nearby faults with fairly low slip rates (~0.01 mm/year). As a result, seismic source characterizations for specific critical facilities should review available geologic information of the site region and strive to develop a complete source model that may include faults presently not in the USGS Quaternary Fault and Fold Database for the United States. Figure B-2-3 is an example map showing a regional earthquake source model, including both fault-specific and areal sources.

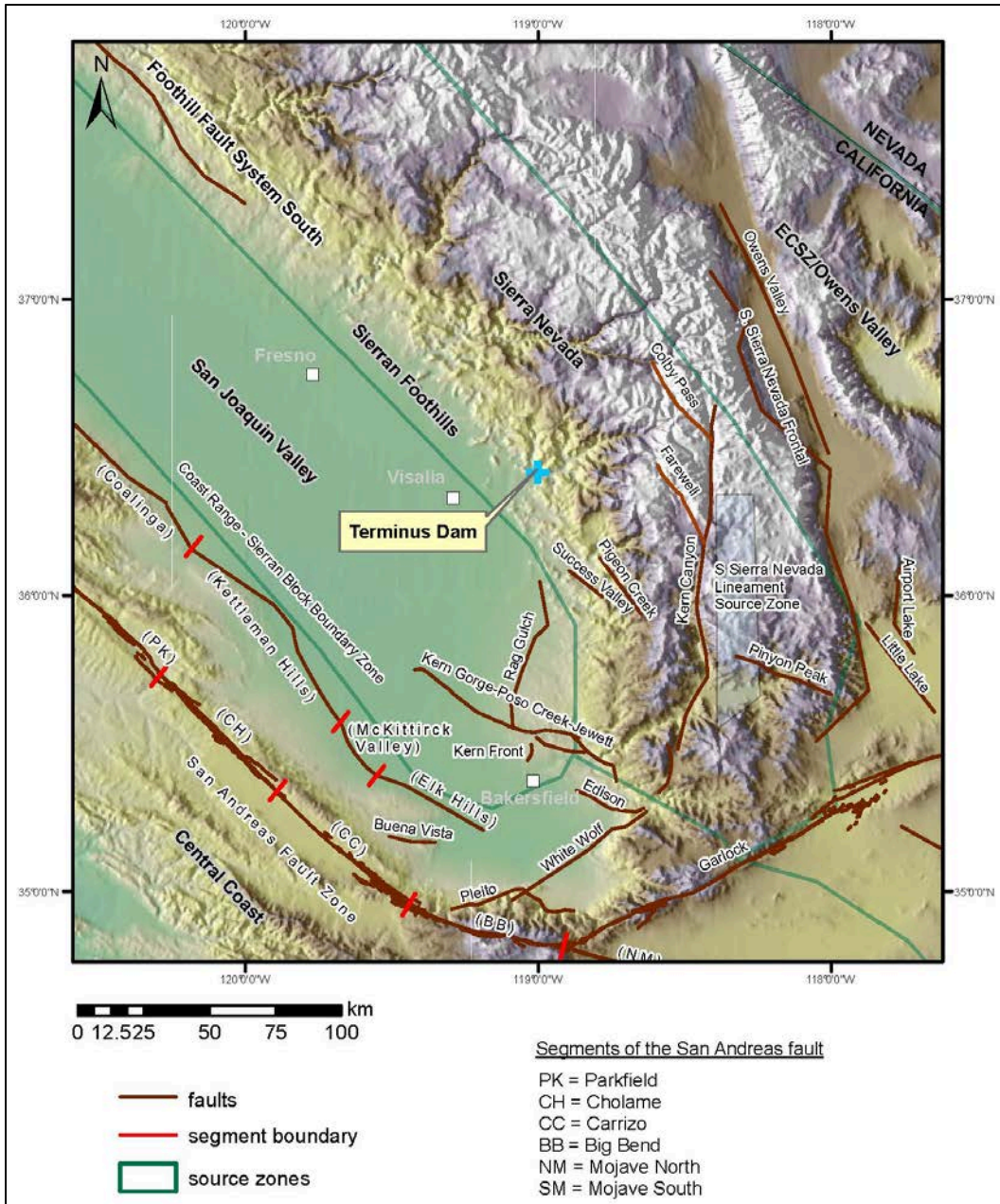
For the State of California, a recent comprehensive compilation of fault sources has been developed specifically for the Unified California Earthquake Rupture Forecast, version 3 (UCERF3 USGS 2013). This effort is summarized in UCERF3: A New Earthquake Forecast for California's Complex Fault System (USGS).

The UCERF3 fault database and supplemental material can be accessed at USGS Quaternary Fault and Fold Database for the United States (USGS).

The UCERF3 effort provides the most comprehensive and up-to-date compilation of fault characteristics and earthquake occurrence models for California, and can be readily incorporated into PSHA and DSHA. A key difference between the UCERF3 approach and previous regional seismic source characterizations is the removal of fault segmentation as a condition on earthquake rupture lengths, which was warranted by an anomalous rate of moderate to large earthquakes predicted by detailed fault segmentation models. The newly minted California source model depicted by UCERF3 will most likely form the basis for future DSHA and PSHA throughout the State, and may help spawn similar data compilation efforts in nearby WUS.

For areas outside of California and west of longitude 105W degrees, the USGS fault and fold database can be utilized as an initial database for fault sources for regional PSHA and DSHA. However, site-specific seismic hazard analyses at this time still require development of seismic source models that are customized to the site of interest and the level of investigation warranted by specific project goals. In this portion of the WUS (including all or part of Washington, Oregon, Idaho, Montana, Wyoming, Nevada, Utah, Colorado, Arizona, and New Mexico), there

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**Figure B-2-3.—Map showing simplified traces (bold red lines) of faults considered potential seismic sources of significance to Terminus Dam, and areal source zones (outlined in green) used in background seismicity analysis (USGS).**

have been many detailed and valuable seismic source characterizations (and PSHA) completed by or for Reclamation, US Department of Energy, Bonneville Power Authority, other Federal agencies, State agencies, and private utilities. Some of these analyses are available publicly and may be valuable resources for completing seismic hazard analyses at a given site. Several private consulting companies also hold proprietary seismic source models compiled through years of experience, and in certain areas these may be the most comprehensive data sets

## Chapter B-2 Seismic Hazard Analysis

available for site-specific analyses. It is prudent that initial phases of a seismic hazard analysis (see table B-2-1) to obtain any potential existing sources of up-to-date seismic source models and seismic hazard analyses.

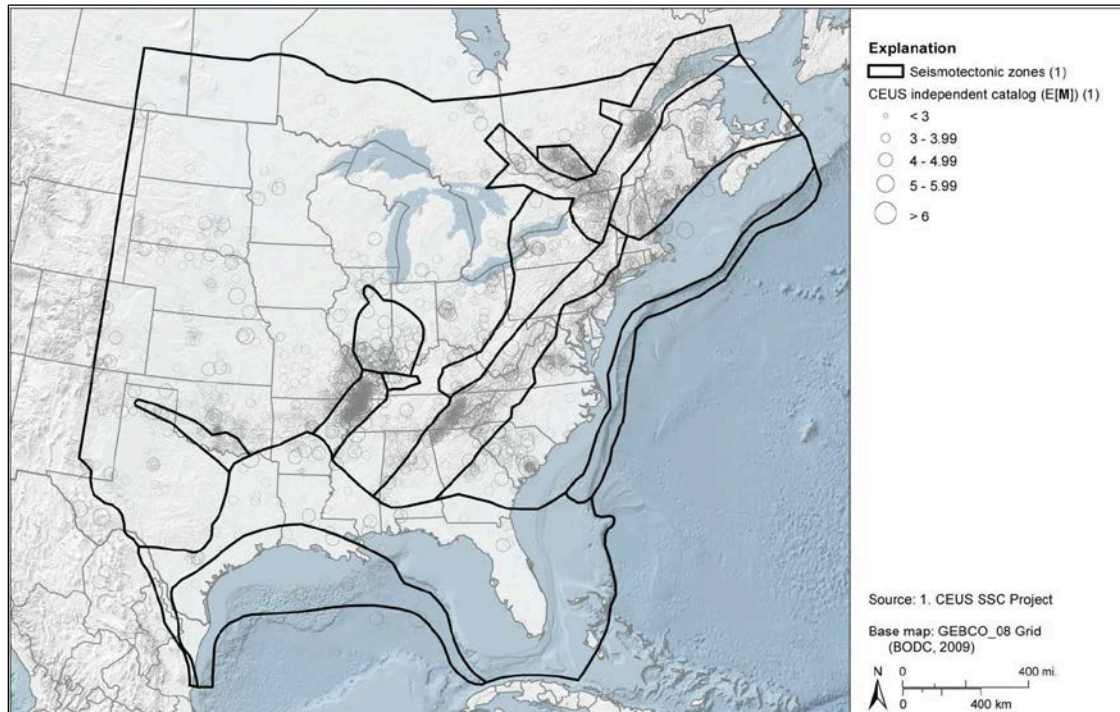
In the CEUS, there are far fewer known or suspected fault-specific source zones than in the WUS, but considerable effort has also recently been completed to develop a defensible database. CEUS-SSC (2012) summarizes the fault-source model for the United States east of longitude 105W degrees.

This database is the most comprehensive and up-to-date compilation of fault characteristics and earthquake occurrence models for the CEUS, and can be readily incorporated into PSHA and DSHA. In addition to fault-specific sources, seismic source characterization for PSHA must include areal seismic sources, or possible seismogenic features for which there is insufficient knowledge to attribute earthquakes to a specific fault source. In regions such as the CEUS where the past occurrence of large earthquakes is not directly attributable to specific causative faults in Earth's crust, the science of seismology has relied heavily on the locations, magnitudes, and rates of historical seismicity to aid seismic hazard assessment. A key criterion is the degree of "uniform" earthquake potential or characteristics, essentially using areas (actually, *volumes*) of Earth's crust that have had consistent rates, locations and sizes of past earthquakes to interpret the characteristics of future earthquakes. BC Hydro (2008), for example, defines a seismic source as "*a volume of the earth's crust that has the same earthquake potential as defined by the size of events that may be generated.*" For the purposes of assessing seismic loading for USACE dams and levees in the WUS, the consideration of areal seismic sources should be consistent with the identification of areal sources by the USGS website (noted above) based on the historical rate and pattern of seismicity and the location of regional seismotectonic zones. In the CEUS, areal source zones can be those identified by the USGS Web site or CEUS-SSC (2012). In this way, the hazard assessment includes possible sources of strong ground motions that are not clearly known to be associated with specific faults or other sources of repeatable large-magnitude earthquakes.

For areal source zones, the parameters of interest are maximum magnitude, associated rate of activity, and recurrence model (typically exponentially truncated Gutenberg-Richter relationship, or just truncated exponential). The areal (or "background seismicity") source zones are characterized using the locations, magnitudes, and rates of historical seismicity in a region. The analysis of background seismicity considers several characteristics of the historical earthquake catalog, and requires processing of the raw historical data on earthquake magnitude, depth, timing, and epicentral locations. A key part of this analysis is the identification of regional or local seismotectonic domains that, based on geologic, geophysical, and geodetic information, may be interpreted to have relatively consistent spatial and temporal variations in historical seismicity.

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Areal source zones are best depicted on a regional seismotectonic map figure; an example map of regional areal source zones in the WUS is given on figure B-2-3. In the WUS, the maximum size of the background earthquake is usually M 6 to 7 because events larger than this usually produce recognizable fault or fold-related features at Earth's surface. The regional seismotectonic domains identified throughout the CEUS are plotted on figure B-2-4, which also demonstrates that the historical seismicity is not uniformly distributed within the seismotectonic zones (CEUS-SSC 2012). The characterization of seismicity patterns and rates in the CEUS is an important component of seismic hazard analysis, primarily because extensive searches have yielded very little definitive evidence of active, causative faults. Even in the WUS where local fault sources may dominate seismic hazard, the contribution of background seismicity to total seismic hazard can be substantial or dominant.



**Figure B-2-4.—Example map of seismotectonic zones in the CEUS (black polygons) and earthquakes in the historical seismicity catalog (grey circles) (CEUS-SSC 2012).**

Key parameters within a historical seismicity catalog that need to be addressed for a PSHA include:

- Catalog temporal and spatial completeness (has varied by region through history)
- Magnitude detection thresholds (have varied by region through history)

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- Location accuracy (both epicentral and hypocentral)
- Consistent magnitude scale (Moment magnitude now preferred)
- Declustering to remove foreshocks and aftershocks
- Removal of non-tectonic events (e.g., human-induced seismicity, explosions)
- Overall rate of seismicity, as defined by the y-intercept of the recurrence line (“a-value”)
- Magnitude-frequency decay, as defined by the slope of the recurrence line (“b-value”)
- Spatial smoothing of b-values within a region

In general, historical seismicity constrains the low-magnitude, high-frequency part of recurrence relationships for given areal source zones. The part of the recurrence relationships derived from historical seismicity are generally viewed as a Gutenberg-Richter process, which is then truncated at higher magnitudes (figure B-2-5); the high-magnitude part of the recurrence relationship is often constrained by paleoseismic information (most often in the WUS) and may take the form of a “characteristic earthquake model” or a “maximum magnitude model” (figure B-2-5). However, in cases where a large earthquake has occurred within an areal source zone during historical time and is not attributed to a specific seismic source, then the historical record provides critical data for the low-frequency recurrence relationships. The best example of this condition is the Charleston, South Carolina, seismic zone, which produced an  $M_L$ 7.3 earthquake in 1886 but has yet to be associated with a causative fault despite decades of geologic and geophysical investigations.

### B-2.2.2 Seismic Hazard Curves

The basic product of a PSHA is a series of seismic hazard curves that show the annual rate or probability at which a specific ground motion level will be exceeded at the site of interest. Hazard curves typically have “annual probability of exceedence” or its reciprocal, “return period”, on the vertical axis on a logarithmic scale, and PGA (usually expressed in terms gravity, or “g”) on the horizontal axis on an arithmetic scale. Hazard curves may also depict another measure of seismic loading, such as the response spectra acceleration at a given period of vibration, on the horizontal axis. The seismic hazard curve is the most important and most commonly used screening tool in analyzing hazard and risk.



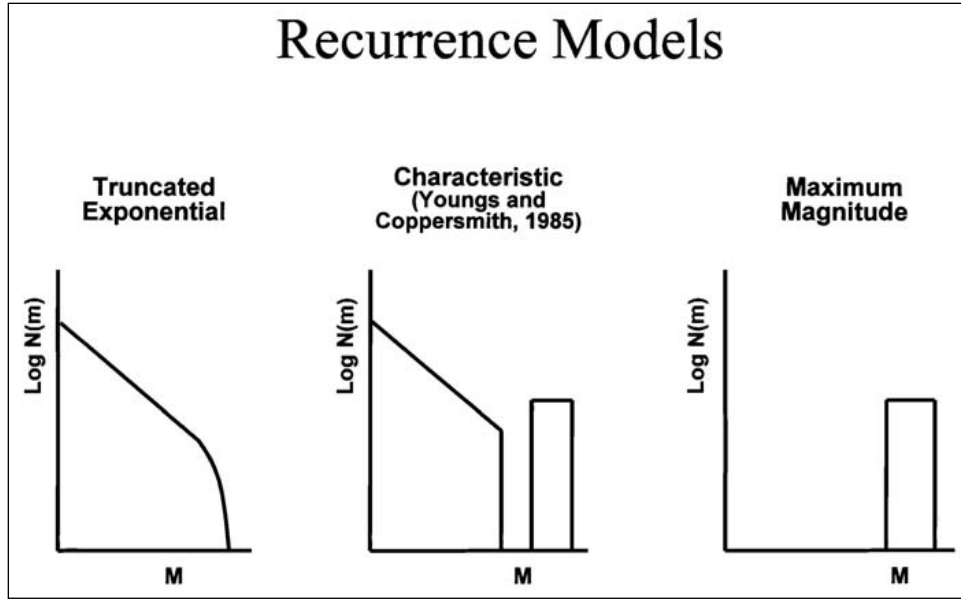


Figure B-2-5.—Three recurrence models typically used in PSHA; M (x-axis) is earthquake magnitude and Log N(m) (y-axis) is number of events per year.

A hazard curve is developed for each seismic source, and these individual curves are added to develop the cumulative hazard curve for the given site. The total rate at which a given ground motion level is exceeded is the sum of the rates for these individual sources. Seismic hazard curves are produced using one of several available computer programs, including the USGS Unified Hazard Tool.

The 2014 version of the USGS hazard application improves upon the previous 2002 and 2008 versions and has been revised to include the new Next Generation Attenuation (NGA) models for the CEUS (NGA-East) and the WUS (NGA-West2). These GMPE were developed as part of the NGA Project sponsored by the Pacific Earthquake Engineering Research (PEER) Center (Lokke 2013).

The seismic hazard curves are calculated using ground motion attenuation relations that relate PGA or spectral acceleration (SA) to the distance between the seismic source and site, and the magnitude of the earthquake associated with the source. Site conditions are very important, and include the footwall versus hanging wall location, rupture direction, and foundation characteristics (*i.e.*, “soil” versus “rock”). Most of the new NGA GMPE incorporate the input parameter  $V_s^{30}$ .

Most dam and levee safety studies include several types of hazard curves, depending on the level of study and the type of dam (embankment versus concrete). Thus, it is important to communicate with the seismic hazard analysis team so that the hazard evaluation includes the parameters most likely to affect

## Chapter B-2 Seismic Hazard Analysis

the dynamic response of the dam. A common curve is one showing mean and percentile values for PGA (or interchangeably, peak horizontal acceleration (PHA), also in  $g$ ), as exemplified by figure B-2-6.

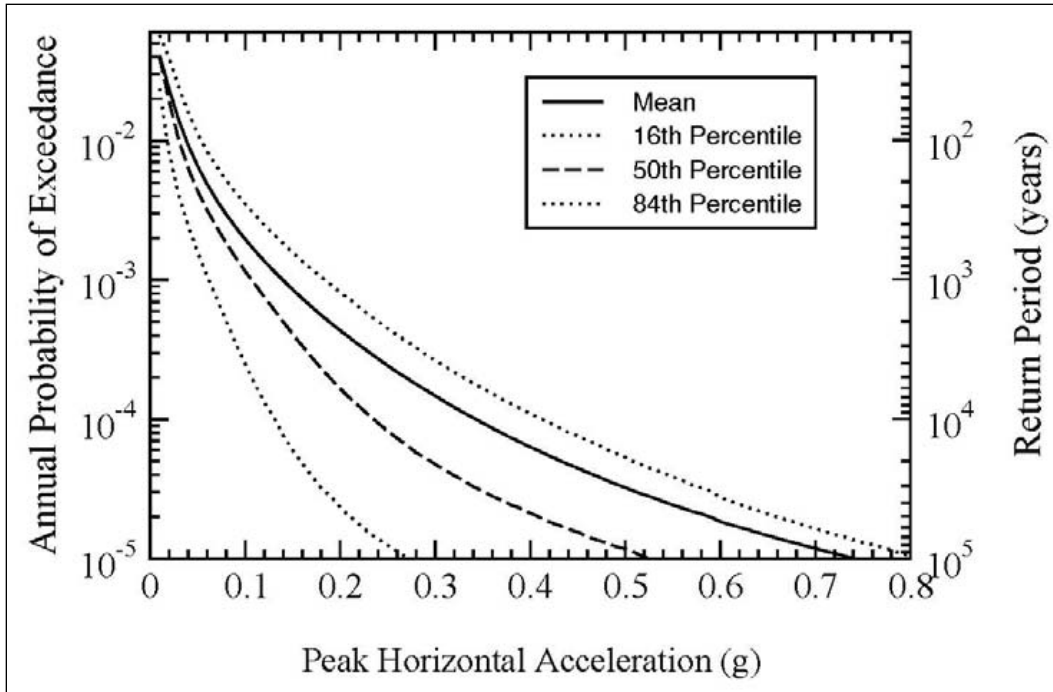
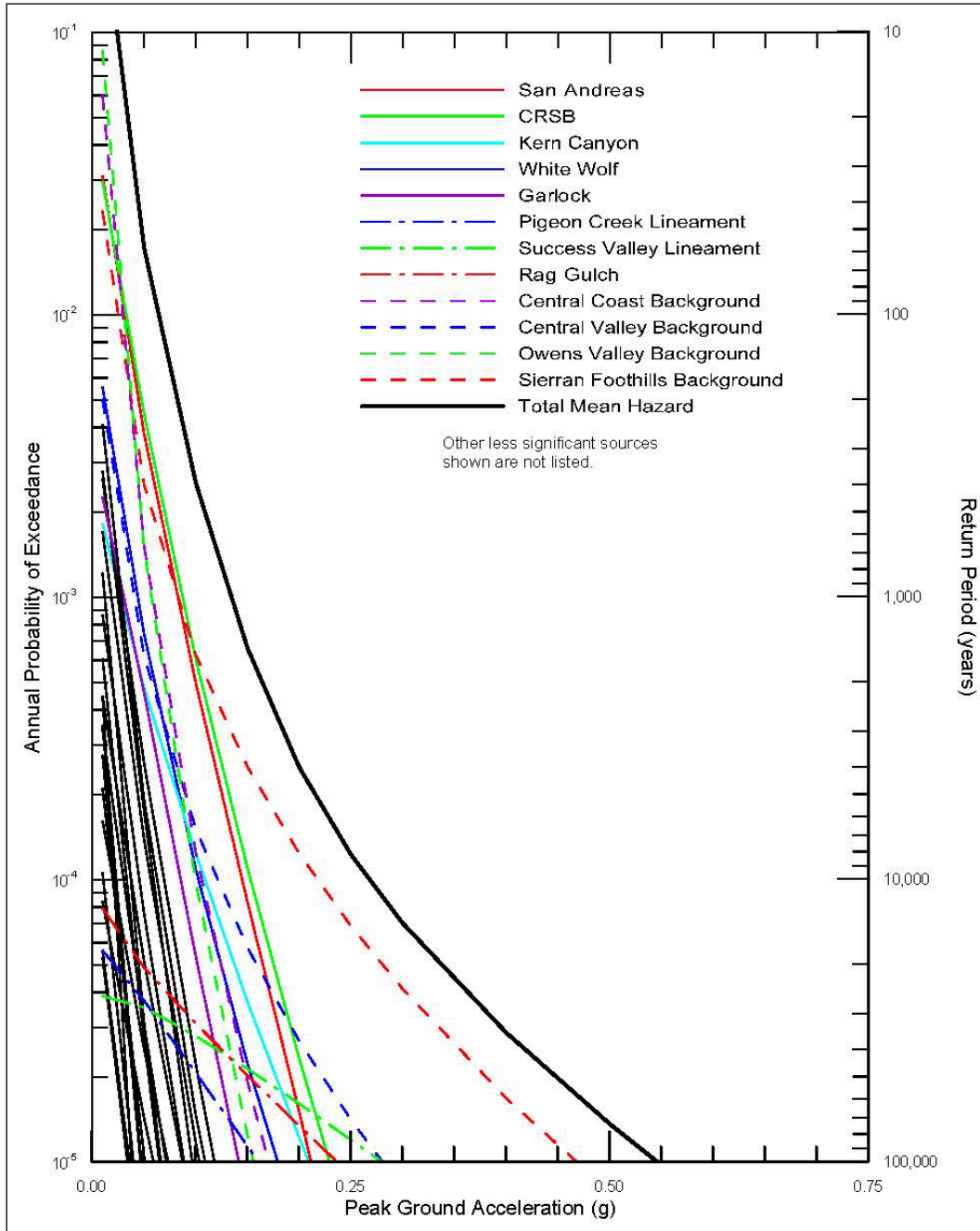


Figure B-2-6.—Example of mean and percentile hazard curves for PHA.

Hazard curves can be developed that show the contribution from various earthquake sources (figures B-2-7 and B-2-8), which help select appropriate time histories for use in the engineering analyses because they help interpret which type of seismic source controls hazard at various spectral accelerations. For example, hazard curves from a nearby moderate magnitude, strike-slip earthquake source will differ from those of a fairly distant, large-magnitude subduction zone earthquake. Also, the identification of the source or sources controlling the hazard is important because this knowledge can focus additional studies on the sources with the most significance to the dam. For example, a nearby fault thought to have a large contribution to hazard (i.e., based on an estimated high slip rate) may be a good target for additional investigation. Subsequent detailed geologic mapping or paleoseismic trenching may demonstrate a lower slip rate and thus indicate that the source contributes less to the total hazard.

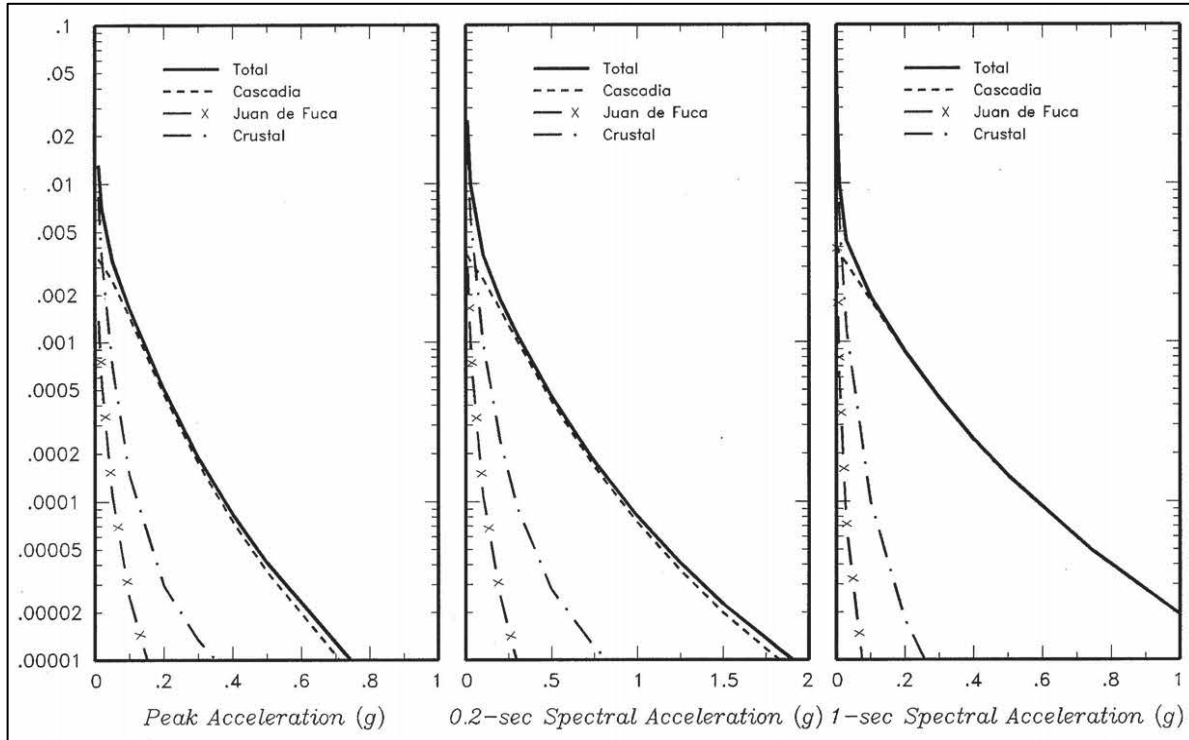
A similar tool for identifying likely major contributors to seismic hazard is a seismic hazard de-aggregation plot, which helps identify the magnitudes and distances of controlling seismic sources. A seismic hazard curve combines all sources (magnitudes and distances) to define the probability of exceeding a given

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**Figure B-2-7.—Seismic hazard curves for Success Dam in south-central California, showing contributions to PGA cumulative hazard from various local and regional fault sources and areal source zone.**

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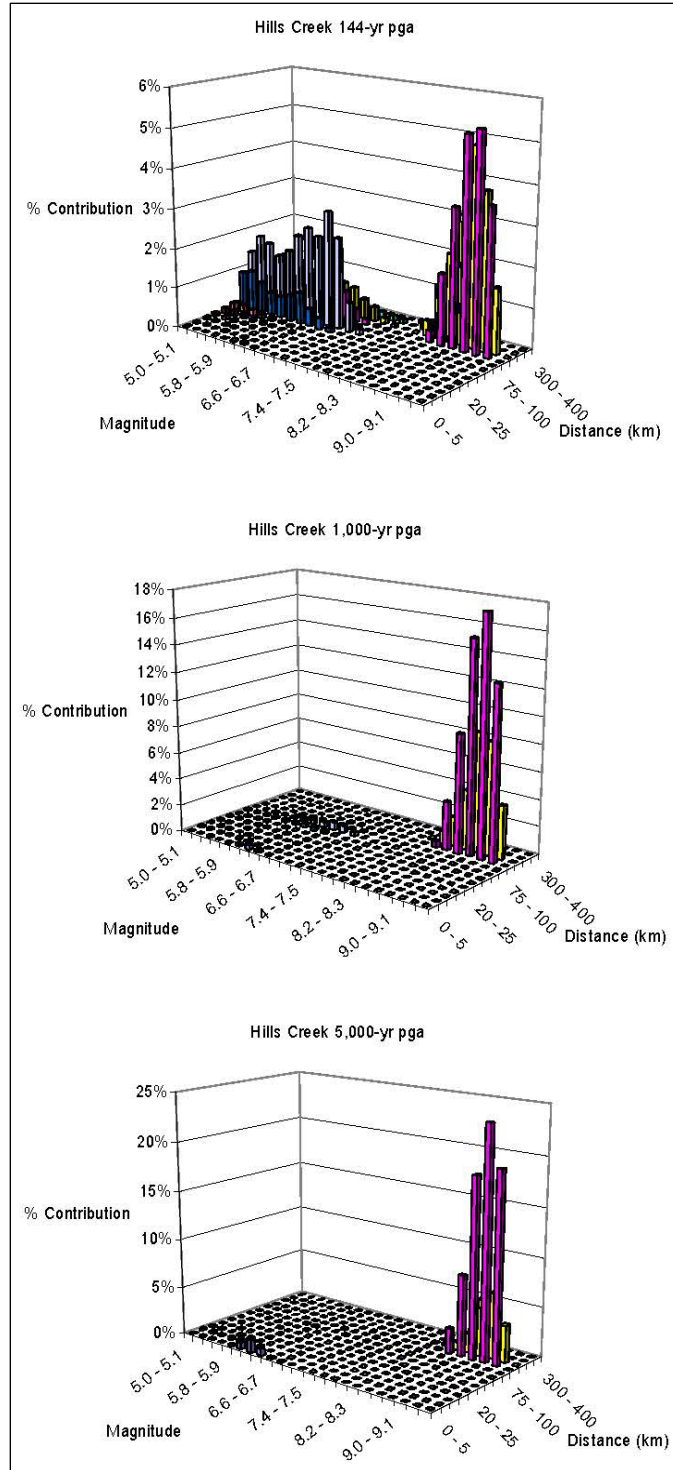


**Figure B-2-8.—Seismic hazard curves for Hills Creek Dam in central Oregon, showing Annual Exceedance Probabilities (AEP) for PGA and two spectral frequencies. The plots show the contributions to various spectral acceleration cumulative hazard from the Cascadia Subduction Zone (CSZ) source, the Juan de Fuca intra-slab source, and shallow crustal fault sources. Note that the CSZ dominates hazard for all three spectral accelerations, but that relative contributions from other sources vary for different spectral accelerations.**

ground motion level. Because all of the sources, magnitudes, and distances are combined, it can be difficult to develop an intuitive understanding about the sources that control the hazard based on just the hazard curve (Hashash et al. 2015). De-aggregation provides the relative contributions to seismic hazard from seismic sources in terms of earthquake magnitude, source-to-site distance, and epsilon ( $\epsilon$ , a measure of ground motion uncertainty) (Bazzurro and Cornell 1999). Figure B-2-9 shows three de-aggregation plots for the same site given different return periods. For this site, the primary contributors to hazard at an Annual Exceedance Probability (AEP) of 1/144 are moderate-magnitude sources less than about 100 km away and a large-magnitude source more than about 100 km away. For AEP of 1/1,000 and 1/5,000, the primary hazard contributor is the large-magnitude source more than about 100 km from the site. These plots suggest that additional information on the local, low slip-rate (but large-magnitude) faults close the site may serve to improve the hazard characterization.

The de-aggregation plots also serve to inform subsequent seismic analyses, in particular the development of deterministic hazard results (i.e., DSHA) and of Conditional Mean Spectra (CMS, addressed in a later section). If deterministic

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**Figure B-2-9.—Seismic hazard de-aggregation plots showing contributions to mean PGA hazard for each magnitude-distance pair for Hills Creek Dam in central Oregon, for return periods of: a) 144 years, b) 1,000 years, and c) 5,000 years.**

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ground-motion parameters are needed for risk-evaluation or design purposes, these can be developed using scenario earthquakes that are shown to be representative based on the modal values of magnitude and distance from de-aggregation results. The modal values of specific scenario earthquakes are generated by the 2008 USGS deaggregation Web site (<https://earthquake.usgs.gov/hazards/interactive/> for certain return periods (including AEP of 1/975 and 1/2,475). For example, Hashash et al. (2015) show that the median deterministic spectrum for the local earthquake scenario is similar to the 2,475-year UHRS at short spectral periods, and the 84th percentile deterministic spectrum for the New Madrid Seismic Zone (NMSZ) earthquake scenario is similar to the 2,475-year UHRS at long spectral periods.

### B-2.2.3 Uniform Hazard Response Spectra

UHRS are developed during the PSHA by developing hazard curves (i.e., spectral acceleration versus exceedance probability) for several vibration periods, to define the response spectra. Then, for a given exceedance probability or return period, the ordinates are taken from the hazard curves for each spectral acceleration, and an “equal hazard” response spectrum is generated for the same return period. The response spectra curves are generated for specified AEP of interest, as chosen by the analyst according to engineering or design needs for the project. The USGS National Seismic Hazard Map website provides UHRS using the regional seismic source model.

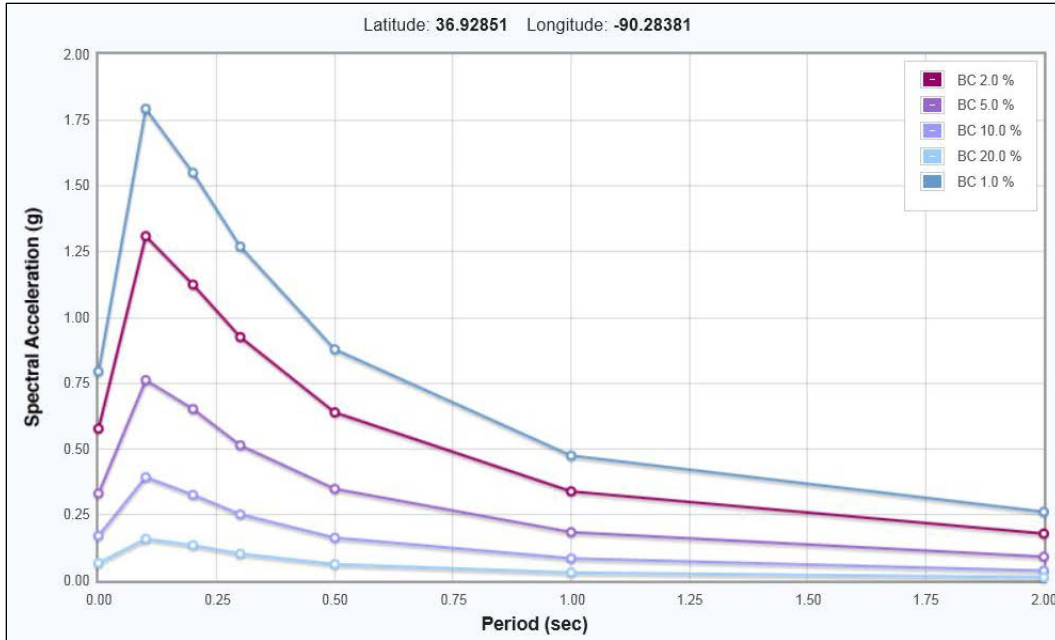
An example of the UHRS generated using this online application is given on figure B-2-10 for Wappapello Dam in eastern Missouri.

### B-2.2.4 Ground Motion Time Histories

Conventional design practice uses the UHRS obtained from PSHA at selected probabilities or return periods. For cases in which time series analysis is needed, ground motion time histories matched to the target UHRS are used. When selecting these motions, it is necessary to associate them with a source and event magnitude to properly represent the duration, amplitude, and frequency content of the anticipated ground motion. In other words, the ground motion time histories most appropriate for analysis of structural response are those that represent the ground motions that are likely to impact the site from primary hazard contributors. If the ground motions (for a selected return period) are dominated from, say, a specific fault source (e.g., the Reelfoot fault in the NMSZ), then the analysis should utilize seed time histories that best represent the hazard-dominant earthquake from that source. The corresponding earthquake magnitude is also required for liquefaction evaluation.

For facilities considered to be exposed to high seismic hazard or likely to impose substantial seismic risk, the analyst may choose to develop acceleration time histories that represent seismic hazards at specific AEP of interest. For some

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**Figure B-2-10.—Mean UHRS from all sources for Wappapello Dam, Missouri, for return periods of 225 years (20% in 50 years), 475 years (10% in 50 years), 975 years (5% in 50 years), 2,475 years (2% in 50 years), and 5,000 years (1% in 50 years) (from USGS Unified Hazard Tool).**

dams where the seismic hazard or probability of failure under certain loading conditions is high, relatively short return periods (e.g., 5,000 or 10,000 years) are considered. Where consequences are high, consideration can be given to longer return periods, and associated higher ground motions that are significant (but less likely on an annualized basis). Expected ground motions at other return periods should be considered when significant changes in failure likelihood are expected. The range in ground motion spectral frequencies at each return period are usually selected to span the likely variability in spectral responses at different periods, and to account for differences in distance, magnitude, and site conditions. The selected ground motions may then be used for dynamic analyses using accepted software tools (e.g., *FLAC*, *SHAKE*, *LS-DYNA*). A wavelet-based method can be used to produce acceleration time-histories through spectral matching to the 5-percent damping mean UHRS at the return period of interest. Because a UHRS calculated from PSHA hazard curves are usually only available for horizontal ground motions, the vertical components of the full response spectra used for spectral matching is developed by scaling the UHRS via a ratio between the vertical and horizontal components observed during historical events (McGuire et al. 2001; Bozorgnia and Campbell 2004; Gülerce and Abrahamson 2011). The vertical/horizontal (V/H) ratios are the regression results of near-field earthquake records. These ratios vary with PGA and frequency, such that higher PGA values typically are associated with larger V/H ratios. At low frequencies, V/H ratios are

## Chapter B-2 Seismic Hazard Analysis

always less than one. Around 14 Hz, V/H ratios are large and sometimes greater than one. The V/H ratio also depends on the distance between the source and the site (figure B-2-11).

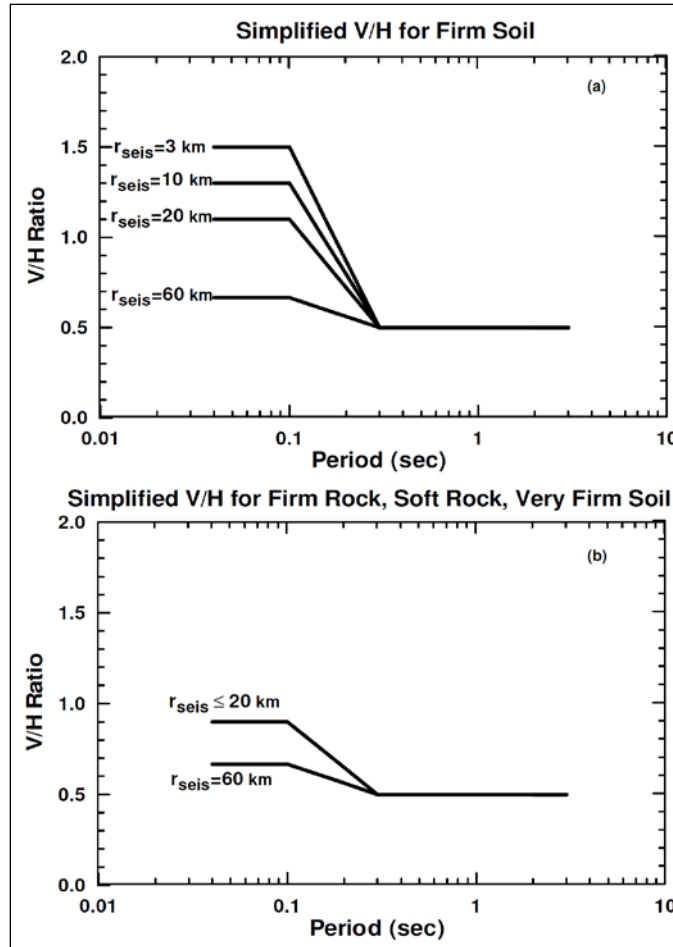


Figure B-2-11.—Plots showing differences in V/H ratios with site class and distance from the seismic source.

Ground motion time histories for use in engineering analyses are developed via several steps:

- From the results of a PSHA, select the magnitude and source locations that contribute the largest to the hazard for the site at the AEP of interest, with consideration to the structure being analyzed. The PSHA de-aggregation plots provide information to interpret the magnitude and distance for sources that contribute significantly to the site hazard, which can be used to guide selection of sources for time history development. The seismic responses of many facilities are sensitive to different frequencies of



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ground motions, and PSHA results can be used to develop facility-specific ground motion characteristics to improve assessment of seismic demand. Some facilities are sensitive to long-period ground motions (i.e., >0.8 sec), while the seismic response of other structures may be controlled by short-period, high-frequency shaking (i.e., <0.4 sec). Different seismic sources (with different earthquake distances, magnitudes, and return periods) may control these different ground-motion parameters for a given site. For example, sites in the Pacific Northwest of North America typically have long-period ground motions controlled by the Cascadia Subduction Zone (CSZ), which can produce potentially very large earthquakes ( $M$  8 to 9) at large distances (more than 100 km). In contrast, short-period ground motions may be contributed by nearby, moderate-magnitude (but less frequent) crustal fault sources. In the CEUS near the NMSZ, short-period (about 0.2 sec) spectral accelerations typically are dominated by the background seismicity from areal sources zones; but for periods of about 1 sec, the NMSZ typically contributes slightly more hazard than the background seismicity for return periods of 975 years (5 percent probability of exceedance in 50 years) to 2,475 years (2 percent in 50 years), but the NMSZ dominates hazard for longer spectral periods ( $\geq 3$  sec) (Hashash et al. 2015). The different hazard contributions from the NMSZ and background seismicity sources are illustrated on figure B-2-12.

- Determine a target spectrum for each source based on the magnitude, distance, and site conditions by using a range of GMPE. Alternatively, the UHRS for the site could be used, which will generally be conservative. The CMS can also be used as a target spectrum (see next section).
- Locate at least one historic earthquake recording for each source, to be used as a “seed time history.” A suitable recording from an historic earthquake is used as the initial time history to provide the required characteristics for spectral matching of ground motion accelerations from the seed time history. Because the amplitude and frequency content will be matched to the site, the most important property of the acceleration recording is the duration. Correlations exist to estimate the target duration given the magnitude and site-to-source distance. There are many websites containing historic earthquake records available for downloading, and the analyst should inquire with local and regional experts for the most appropriate data sources; for example, the following website can be used to search based on site to source distance and magnitude: <http://www.strongmotioncenter.org/>.

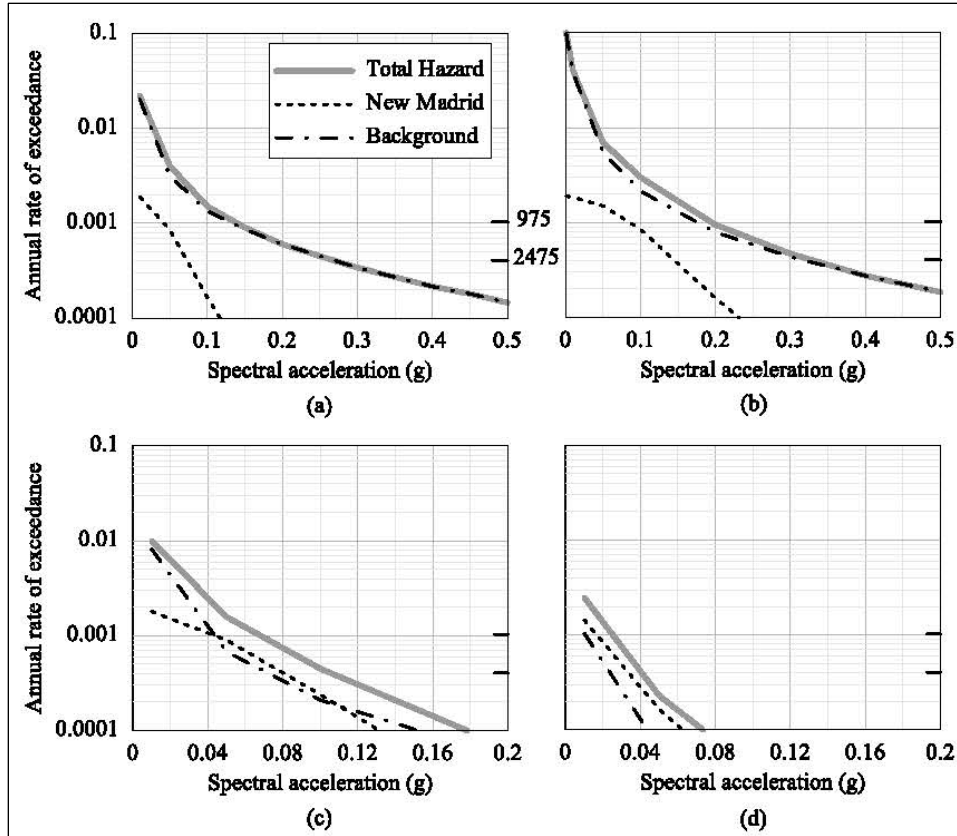


Figure B-2-12.—Mean hazard curves for average horizontal component (a) PGA, (b) spectral acceleration = 0.2 s, (c) spectral acceleration = 1.0 s, and (d) spectral acceleration = 3.0 s; before applying site amplification factors. Two return periods of 975 and 2,475 years are marked on the right y-axis (from Hashash et al. 2015).

- Perform spectral matching of selected time histories to the target spectrum using available software such as RSPMATCH. This can also be done manually by modifying the amplitude spectra of the Fourier transform such that the geometric mean of the two-component ground motion fits the target spectrum. Care should be taken to ensure that the velocity and displacement time series are compatible with the altered time history. Additionally, synthetic time histories can be developed using specialized programs that will generate a random time history that matches the input response spectrum. These can be used directly without acquiring a historic record.
- Develop the vertical target spectrum using V/H ratios based on currently accepted methodology (McGuire et al. 2001, Bozorgnia and Campbell, 2004, Gülerce and Abrahamson 2011). Similarly, match the vertical time history to the vertical spectrum.

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For each AEP of interest (e.g., 1/2,475 versus 1/9,975), accelerations for multiple records can be used to develop the three-component, free-field acceleration time histories. The time history ground motions can be generated synthetically. Time histories reproduce major characteristics of earthquake recordings, such as duration, envelope (defining the build-up of shaking amplitude – duration of strong shaking – and decay of shaking), and change in waveform frequency with time. For some structures where main contributors to hazard are different (Cascadia versus background seismicity), the mean UHRS and acceleration time histories can be developed that correspond to the specific hazard from individual controlling sources. If all source zones are included in the hazard analysis, then each time history is given equal weight. However, if the hazard for the source zones is evaluated separately, then the hazard from each of the sources is additive.

### B-2.2.5 Conditional (Mean) Spectra

As noted above, ground-motion time histories expected at a site, for various return periods, may be needed for seismic analysis of dam structures. These histories are developed to match selected target UHRS. However, in many tectonic settings, critical ground motion parameters differ substantially depending on the controlling seismic source (at different spectral accelerations and earthquake return periods). When developing time histories based on the UHRS, the association of the ground motions with source characteristics can be difficult and may result in ground motions that do not represent the contributing seismic sources. In other words, the UHRS combines the hazard from different sources and does not reflect a realistic spectrum that can be expected to occur during a single earthquake. The UHRS combines large amplitude short- and long-period accelerations generated by two (or more) different sources. Additionally, the response spectra of a given earthquake will tend to have peaks at some periods and valleys at others. Because UHRS are generated by averaging many earthquake recordings, these peaks and valleys are smoothed through the spectrum. This will tend to overestimate the energy through large period ranges of the response spectrum. Also, for less frequent events, the UHRS envelopes many historic response spectra, such that the target spectrum will be equally above average for all periods, which is unrealistic compared to the actual response spectra. Baker and Cornell (2006) propose the use of a CMS for generating ground motion time histories to address this limitation, so that the response spectra are consistent with controlling seismic sources for the site and do not overstate the structural response over the whole spectrum. Developing a CMS should be considered if the site is located in an area of multiple distinct seismic sources (shown by de-aggregation plots) or if it is thought that the UHRS is overly conservative.

As developed by Baker and Cornell (2006), a CMS matches the UHRS level only at the period of interest, which can be the expected fundamental period of the structure. Development of a CMS for specific facilities should follow the

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guidance provided by Baker and Cornell (2006) and subsequent improvements. As shown by example on figure B-2-13, two target periods were selected to represent short and long natural periods of relevance to structural response (Hashash et al. 2015). The plots show that the CMS at 0.2 sec resembles the deterministic spectra from background sources and therefore can be used to estimate seismic demand imposed from the background sources on the structure. In contrast, the CMS at 1.0 sec resembles the deterministic spectra for NMSZ large, distant earthquakes and can be used to estimate seismic demand associated with these events. The high-frequency content of this spectrum is significantly less than that of the UHRS, suggesting that the standard UHRS-based analysis may yield conservatively high seismic demands for structural components affected by high-frequency ground motions. Because seismic hazard is bimodal at many sites across the country, use of the more detailed CMS analysis may better represent the expected ground motions for selected system components and may be worth the additional analytical effort. The 2008 USGS de-aggregation tool allows the calculation of the CMS for the calculated mean and modal site to source distance and magnitude combinations. This may be helpful as a first estimate and to determine if more work should be completed. An example of the USGS calculated CMS is shown on figure B-2-14 for Green Peter Dam located in the Pacific Northwest. On this figure, the M 9.0 event is an interface earthquake on the Cascadia Subduction Zone, while the M 7.15 event corresponds to an intraslab earthquake generated by the subduction zone. As an example, the period used is 0.3 seconds. Using the USGS tool, only a few periods can be selected. The figure shows the mean spectrum; however, the USGS tool allows plotting individual GMPE outputs to determine the range of spectra.

The primary difficulty in using the CMS lies in the fact that it is generated by anchoring the spectrum to the UHRS at the fundamental period of the structure of interest. This means that an estimate of the structural period must be made prior to the detailed analysis of the structure. For concrete gravity dams, the fundamental period is a function of the height of the dam, the ratio of the foundation to structure stiffness, and the reservoir level at the time of the earthquake. Further complicating matters is the fact that the fundamental period will increase during the earthquake if damage to the structure is sustained. Therefore, a reasonable period must be selected that will be representative of a range of possible pools and potential damage to the structure. If a large range is expected, it may be necessary to develop multiple CMS. For concrete gravity dams, an initial estimate of the fundamental period can be made using the methods outlined in Lokke and Chopra (2013) for non-overflow monoliths and Chopra and Tan (1989).

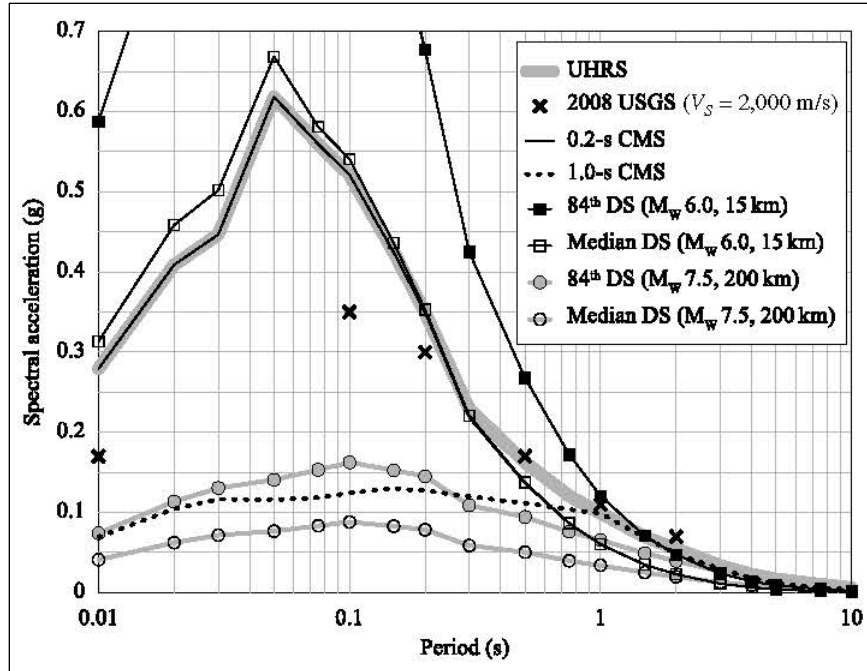


Figure B-2-13.—Horizontal UHRS (with 5% damping) and CMS for  $T = 0.2$  s and  $T = 1.0$  s for a 2,475-year return period, compared with median and 84th percentile for  $M_w 6.0$  and  $M_w 7.5$  deterministic spectra (DS). Also shown is the 2008 USGS-derived UHRS data for a 2,475-year return period and “rock” site conditions ( $V_S = 2,000$  meters per second). Note similarity between the 1.0-sec CMS (dotted line) and the spectra derived from the large ( $M_w 7.5$ ) NMSZ earthquake; and the similarity between the 0.2-sec CMS and the spectra derived from the smaller ( $M_w 6.0$ ) background-source earthquake.

### B-2.2.6 Structural Considerations

It is important for engineers doing fragility evaluations to coordinate with seismic hazard specialists on generating the hazard curves, uniform hazard spectra, and time-history accelerograms. These products should reflect the parameters that control the structural response of the dam and/or appurtenant structures, such that seismic loading of smaller exceedance probabilities produce higher structural response. This is not always peak horizontal ground acceleration, but may instead be spectral acceleration at the predominant period of a structure, or perhaps the area under a response spectrum curve covering more than one structural vibration period if several modes contribute to the structural response. It may be necessary to develop different hazard curves for different structures within the system components at a given site. In some cases, certain combinations of acceleration and velocity may be critical to the structural response, and hazard curves should be developed that relate to simultaneous exceedance of given acceleration and velocity levels.

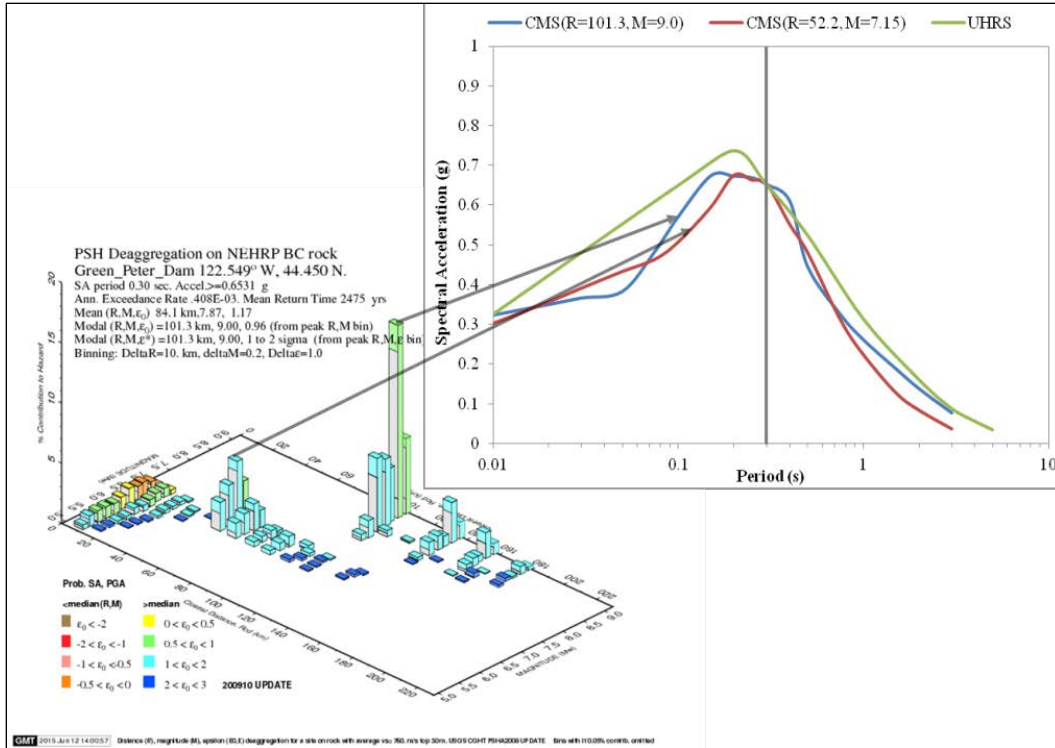


Figure B-2-14.—Example CMS for Green Peter Dam (Oregon) generated using the 2008 USGS de-aggregation tool for probability of exceedance of 2% in 50 yr.

### B-2.3 Surface Fault Displacement/Permanent Ground Deformation

For some dam sites, the potential for surface fault displacement (or the more general case, PGD) through the site or foundation is a major concern (Allen and Cluff, 2000). Basically, two types of surface faulting are generally recognized: principal (or primary) and distributed (or secondary) (Stepp et al. 2001). By definition, principal faulting occurs along the main fault plane (or planes) along which the release of seismic energy occurs. PGD can be generated by moderate to large earthquakes, as exemplified in many recent events (e.g., Kelson et al. 2001, Kelson et al. 2012, Langridge et al. 2018). At the ground surface, displacement may be confined to a single narrow fault or a relatively narrow zone that is a few to several meters wide, or it can occur over a broad zone and on several fault strands. Distributed (or secondary) faulting is displacement that occurs on a fault or fracture away from the primary rupture and can be quite spatially discontinuous. It may occur in response to an earthquake on another nearby fault (possibly due to ground shaking) or it may be due to a structural connection or linkage between the causative fault and the fault upon which the

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secondary displacement occurs. In either case, secondary faulting can occur a few to several kilometers away from the causative fault. Distributed faulting can occur on a fault that is considered capable of principal surface rupture; however, distributed faulting displacement is typically less than that observed by primary faulting. For most dams, primary and secondary fault displacement should be considered, as well as distributed deformation adjacent to an active primary fault if the dam is within a zone of potential distributed deformation.

Although many existing dam sites contain faults, most of these do not contain active faults that could produce surface rupture of the dam foundation and consequent displacement of embankment material. Known examples of active faults beneath dams include Coyote Dam across the active Calaveras fault in Santa Clara County, California (Werner et al. 2017), and Isabella Auxiliary Dam across the active Kern Canyon fault in Kern County, California (Serafini et al. 2015).

In order to assess the possibility of fault rupture in a dam foundation, several steps should be taken in a sequence of progressively more detailed analyses. The results from each phase in the sequence should be used in deciding whether or not additional data are required to confidently evaluate rupture potential and hazard at the site. The steps range from relatively simple collection of existing evidence for or against fault activity, to a complex and comprehensive PFDHA, below.

Any fault or fold that, if active, would pose a surface deformation hazard at the dam site should be evaluated. Faults that have slipped and geologic structures that have deformed during the late Quaternary period should be considered potentially active and evaluated to assess rupture characteristics. Faults and folds of the site region should be evaluated in the context of their structural development with primary attention given to their tertiary-quaternary evolution and relationship to the contemporary tectonic regime. All seismic sources with a potential to cause PGD that may affect performance of dam facilities at a site shall be identified and characterized as described in this section.

A general outline of important phases in assessing surface rupture displacement includes:

- Determine presence/absence of faulting through the dam site, usually based on review of technical literature and geologic maps, and analysis of the current tectonic setting

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- Estimate fault activity or inactivity, typically through basic geologic or geomorphic analyses (e.g., analysis of existing imagery, field reconnaissance; limited age-dating analyses; Angell et al. 1999); if inactivity can be reasonably shown according to applicable criteria, no further action is needed
- If fault activity is demonstrated or indeterminate, the assessment can utilize existing empirical relationships from historical worldwide earthquake ruptures (e.g., Wells and Coppersmi 1994; Wesnousky 2008), or utilize seismologic principles (Hanks and Kanamori 1979), to estimate an expected amount of displacement for specific deterministic scenarios
- If better assessment of uncertainty is needed to constrain the seismic loading, detailed, site-specific geologic or paleoseismic data may be collected (e.g., detailed site geologic mapping, detailed geomorphic analyses, subsurface trenching or drilling, geophysical surveying, age-dating); site-specific data on the location, amount, and timing of ruptures may provide adequate information for the risk assessment
- If loading conditions or design needs warrant, a PFDHA may be required to develop the likelihood and range of rupture beneath the dam foundation, based on site-specific data on the location, amount, and timing of surface rupture

As a general rule, for most dam portfolios, the need to complete a full PFDHA to assess fault rupture characteristics will be limited. However, where potential failure modes related to surface fault rupture are plausible, the information generated by a PFDHA is critical input for assessing the seismic (rupture) loading over time periods of interest in risk assessments. For these cases, the following section provides background and guidance for completing a PFDHA for dam safety purposes.

### **B-2.3.1 Probabilistic Fault Displacement Hazard Analysis**

PFDHA have been done in only a limited number of cases. A recent example includes the analysis conducted for Isabella Auxiliary Dam near Bakersfield, California (Serafini 2015). This analysis basically followed the methodology set forth by Stepp et al. (2001) for the proposed Yucca Mountain, Nevada waste repository.

The hazard calculations done for PFDHA are analogous to the probabilistic ground motion methodology (Cornell 1968; McGuire 1978), and the results are represented by a hazard curve similar to those for PSHA. The curve depicts



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annual occurrence of fault displacement values (i.e., the annual frequency of exceeding a specified amount of displacement). The frequency of displacement  $\nu(d)$  can be computed from the expression:

$$\nu(d) = \lambda_{DE} P(D > d) \quad \text{Equation B-2-1}$$

Where:

$\lambda_{DE}$  = The frequency of displacement events at the point where the fault intersects the dam foundation

$P(D > d)$  = A displacement attenuation function, the conditional probability that displacement,  $D$ , will exceed  $d$ , given the occurrence of an earthquake.

The conditional probability of exceeding a displacement,  $d$ ,  $P(D > d)$ , is based upon empirical data and thus contains event to event variability as well as the variability of displacement along strike of the fault.

Following development of the PFDHA approach noted above, recent efforts have defined the data requirements and refined the analytical approaches, as summarized in American Nuclear Society Standard 2.30 (ANS 2014). Similar to PSHA, a PFDHA consists of calculating the exceedance probabilities of fault-related surface displacements and capturing the range of natural variability and knowledge uncertainty. Youngs et al. (2003) developed two approaches for conducting site-specific PFDHA, an earthquake approach and a displacement approach. The methodology for the earthquake approach is similar to the PSHA methodology, with the ground motion prediction model replaced by a displacement attenuation function. Petersen et al. (2011) extended the Youngs et al. (2003) earthquake approach to include dependence of fault displacement hazard on the accuracy of surface fault mapping and the complexity of the mapped fault trace, and Moss and Ross (2011) also provide clarifications of the PFDHA methodology. In the displacement approach, the characteristics of surface fault displacement (amount of displacement and frequency of occurrence) observed at the site of interest are used to quantify the hazard without invoking a specific mechanism for their cause (i.e., rupture of a fault as for the earthquake approach). The approaches and the basis for selection of the appropriate approach to conduct a PFDHA are described in ANS (2014).

In cases where the potential for surface fault rupture may affect a dam or dam site and additional characterization is needed to address potential failure modes, assessment of surface fault rupture can be completed via site-specific studies or through a PFDHA. An example of a site-specific analysis is summarized by Serafini et al. (2015), in which the expected maximum coseismic slip was evaluated based on (1) site-specific paleoseismic data and worldwide empirical data on event-to-event slip variability, and (2) scenario-based fault displacements

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using empirical relationships between earthquake magnitude and surface displacement. Earthquake rupture scenarios developed from fault-specific paleoseismic and geologic analyses provided a range of expected earthquake magnitudes and associated minimum, mean, and maximum coseismic displacements, with annual exceedance probabilities developed from earthquake magnitude-frequency relations. From these analyses, a design displacement value was chosen for sizing filter and drain zones for the downstream buttress modifications.

Where site-specific data are not available, a PFDHA may be needed to assist PFMA identification and/or mitigation design. For a PFDHA, the geological, seismological, and geotechnical characteristics of a site and its environs should be investigated in sufficient scope and detail necessary to support the evaluation of PGD. Site characterization of PGD should include a review of pertinent literature and field investigations and subject matter experts with experience in PFDHA should help define the program of investigations. Any fault or fold that, if active, would pose a surface deformation hazard at the site should be evaluated. Faults that have slipped and geologic structures that have deformed during the Quaternary period should be considered potentially active and evaluated to assess rupture characteristics. Faults and folds of the site region should be evaluated in the context of their structural development with primary attention given to their geologic development and relationship to the contemporary tectonic setting. All seismic sources with a potential to cause PGD that may affect performance of facilities at a site should be identified and characterized. The characterization of sources of PGD should be evaluated in a probabilistic framework as described in ANS (2014), including fault zone activity, location, width, orientation, sense of movement, and expected amount of coseismic PGD.

### B-2.4 Relevant Case Histories and Examples

Several PSHA have been conducted for the USACE, Reclamation, and Tennessee Valley Authority (TVA) during the past few years.

For recent examples completed by or for Reclamation and TVA, the readers are encouraged to contact respective national technical centers for available up-to-date PSHA examples.

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