Attachment A

Seismic Hazard Analysis

APPRAISAL-LEVEL PROBABILISTIC GROUND MOTION EVALUATION FOR THE UPPER SAN JOAQUIN RIVER BASIN INVESTIGATION, CENTRAL VALLEY PROJECT, CALIFORNIA

Bureau of Reclamation
Technical Service Center
Seismotectonics and Geophysics Group

Technical Memorandum No. D-8330-2002-10

August, 2002

Prepared by:

Larry W. Anderson
Geologist

Chris Sneddon
Geophysicist

Peer Review:

Jon Ake
Geophysicist

Appraisal-Level Probabilistic Ground Motion Evaluation for the Upper San Joaquin River Basin Investigation, Central Valley Project, California

1.0 Introduction

This memorandum provides preliminary earthquake loading parameters for use in appraisal-level designs for facilities that may be constructed as a result of the Upper San Joaquin River Basin Storage Investigation of California. Sites considered in this study are located throughout the eastern San Joaquin Valley and Sierra Nevada foothills of California (**Figure 1**). The results of this study are based on readily available information and are appropriate for appraisal-level designs only. No detailed, site-specific seismotectonic investigations have been conducted for this preliminary analysis. More detailed, site specific studies will be required for higher-level designs.

2.0 Seismic Sources

Two types of potential earthquake sources are generally considered in this type of analysis: fault sources and areal or background sources. Each will be discussed below. The parameters which need to be defined for fault sources are: probability of activity, geometry (location, length, dip and down-dip extent), expected sense of slip, maximum magnitude (M_{max}), slip-rate, and recurrence model. For areal source zones, the parameters of interest are maximum magnitude, recurrence model and associated rates. Magnitudes used in this study are moment magnitudes (**M**).

2.1 Fault Sources

Twenty-two fault sources have been identified as potential seismic sources for the identified sites (**Figure 2**). The characterization of fault sources listed in **Table 1** was based on readily available data, primarily contained in Jennings (1994) and Petersen and others (1996). These data sources were supplemented by limited data from recent Reclamation studies such as those for B.F. Sisk and O’Neill Forebay Dams (Anderson and Piety, 2001) and for New Melones Dam (Sneddon, 2001). No site specific investigations were conducted, nor have aerial photographs or other remotely-sensed imagery been evaluated for the identification of lineaments or possible active faults. This represents a fundamental limitation to the conclusions regarding seismic hazards and active faulting at or near the sites under investigation.

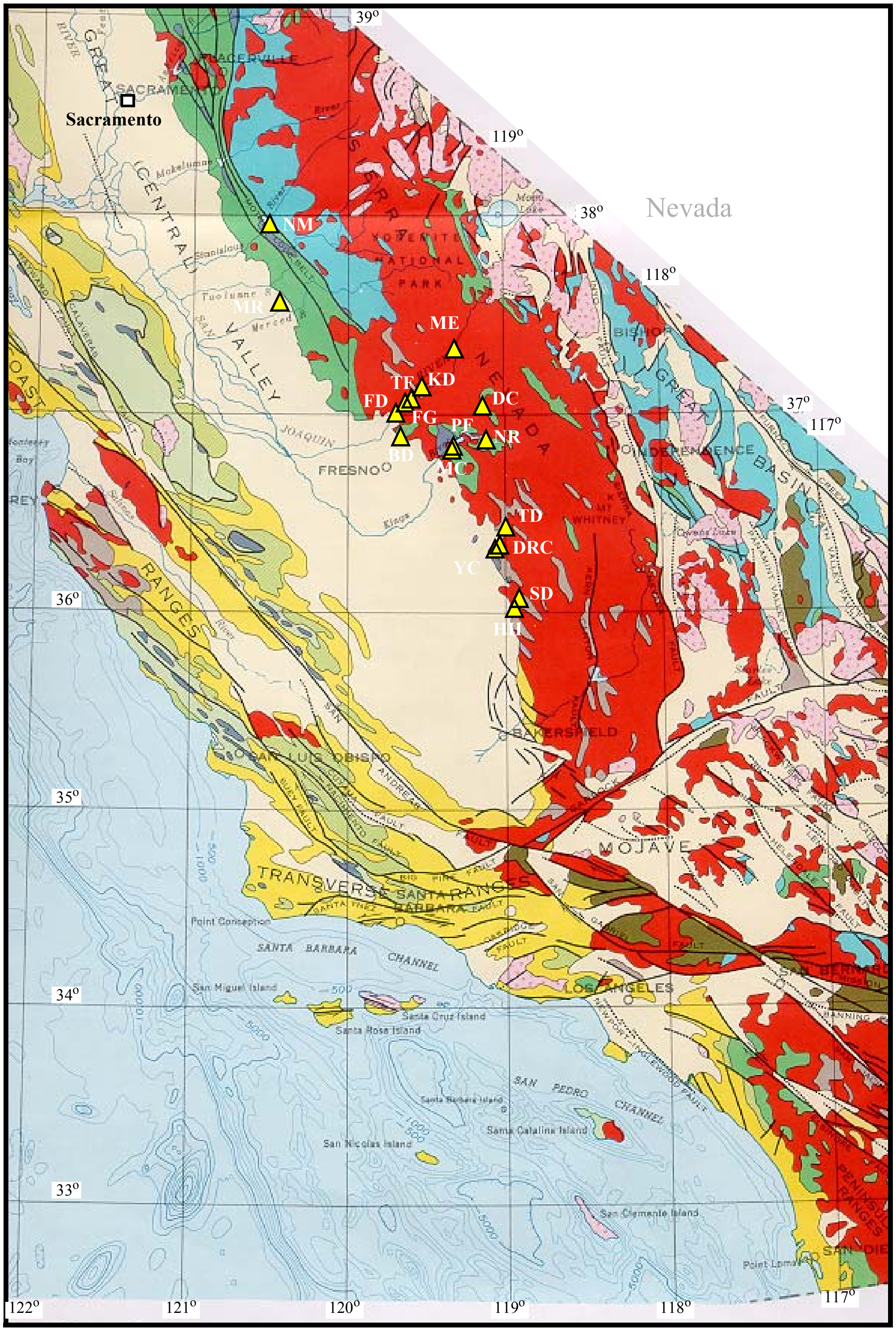

Figure 1. Geologic map of Central California. Approximate location of the subject sites are shown with yellow triangles (base map from CDMG, 1966).Site abbreviations are: NM New Melones; MR Montgomery Reservoir; ME Mammoth Pool Expansion; KD Kerckoff; Fine Gold Creek Dam; TF Temperance Flat Dam; DC Dinkey Creek Dam; FD Friant Dam; BD Big Dry Creek Reservoir; NR New Rogers Crossing; PF Pine Flat Dam; MC Mill Creek; TD Terminus Dam; DRC Dry Creek Dam; YC Yokohl Creek Dam; SD Success Dam; HH Hungry Hollow Reservoir.

Only one of the sites being considered, Montgomery Reservoir, is in the immediate vicinity of a fault or faults considered to be potential seismic sources. This site is near the Foothills fault system, a 300-km-long zone of northwest-striking faults within the western foothills of the Sierra Nevada (**Figures 1** and **2**). The other fifteen sites (essentially between 36° N and 37° N) are all on either the granitic core of the Sierra Nevada, on metasedimentary rocks that predate the emplacement of the batholith, or on late Cenezoic sediments of the San Joaquin Valley or the Sierra Nevada foothills (Jennings, 1977). No major thru-going faults or shear zones have been identified in this area of the Sierra Nevada and historic rates of seismicity are low. For those sites located at the western margin of the Sierra Nevada, the closest potential seismic sources are those associated with the western margin the San Joaquin Valley. These sources consist of the west-dipping thrust faults such as produced the **M** 6.7, Coalinga earthquake of 1983. Although estimated slip rates for these sources are around 1.5 mm/yr, these sources are all at least 70 km from the sites being considered. For several potential sites within the central Sierra Nevada (for example, Mammoth Pool Expansion and Dinkey Creek), the closest potential sources are the range-bounding faults of the eastern Sierra Nevada near Mammoth Lake and the Long Valley caldera. Slip rates on these faults are generally less than 1 mm/yr and these faults are at least 45 km from the closest sites.

One possible earthquake source (or sources) is not included in table or in our analysis. This potential source consists of several suspected Quaternary faults referred to here as the Pond Poso faults (Jennings, 1994). These faults were studied extensively during the 1970's as part of siting studies for proposed nuclear power plants in the southern San Joaquin Valley. Although these faults were not considered capable under Nuclear Regulatory Commission criteria that existed at that time, the faults are shown as Quaternary on the state fault map (Jennings, 1994). Further analysis of these structures may be required if studies continue on possible sites near the southern Sierra Nevada.

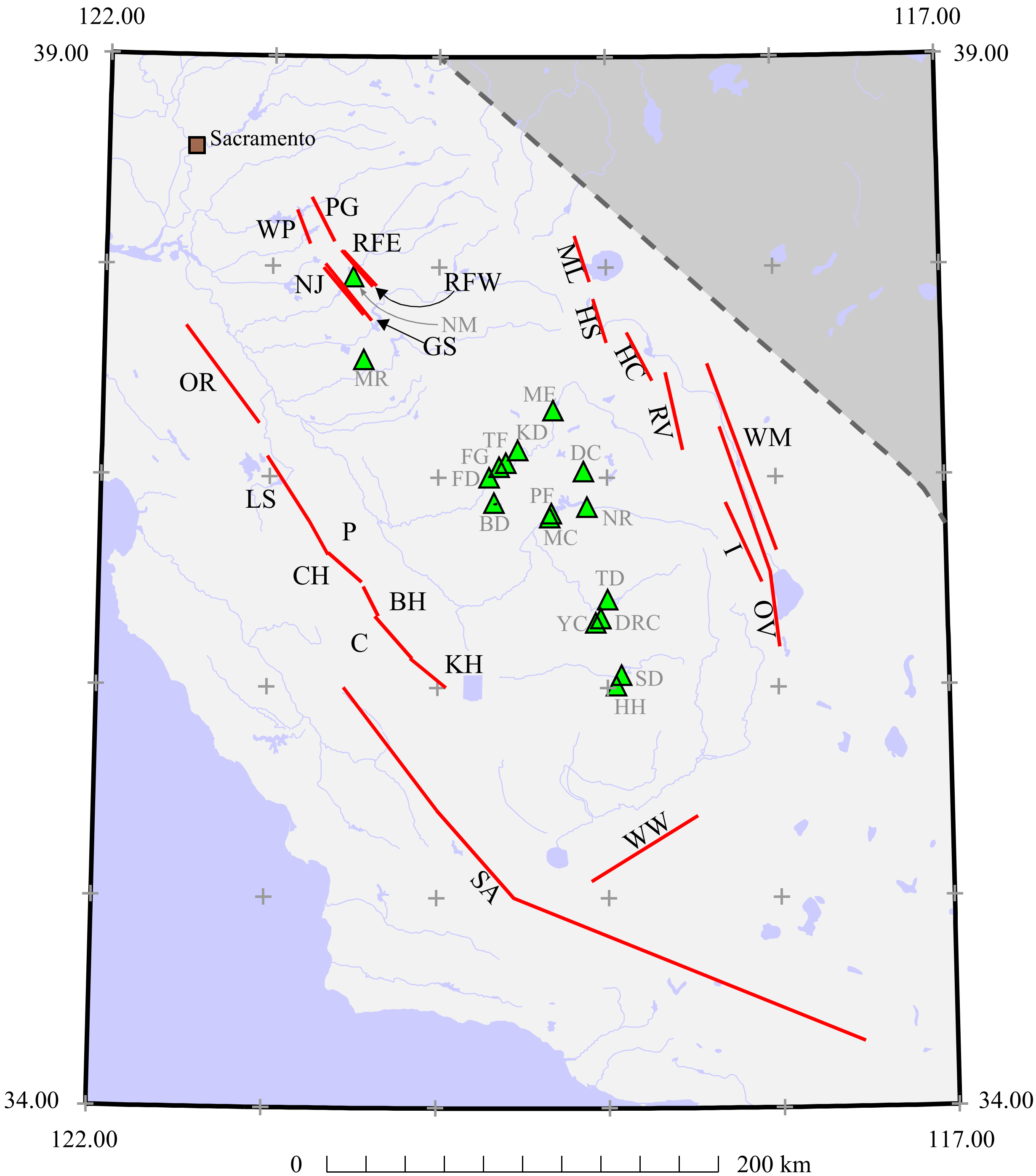

Figure 2: Fault locations used for PSHA analysis. Approximate location of the Sites are shown with green triangles. Site abbreviations are: NM New Melones; MR Montgomery Reservoir; ME Mammoth Pool Expansion; KD Kerckoff; Fine Gold Creek Dam; TF Temperance Flat Dam; DC Dinkey Creek Dam; FD Friant Dam; BD Big Dry Creek Reservoir; NR New Rogers Crossing; PF Pine Flat Dam; MC Mill Creek; TD Terminus Dam; DRC Dry Creek Dam; YC Yokohl Creek Dam; SD Success Dam; HH Hungry Hollow Reservoir. Fault Abbreviations are in Table 1.

Table 1: Fault Parameters for Potential Seismic Sources - Upper San Joaquin River Basin Storage Investigation.

#	Fault	Characteristic Magnitude (M)	Slip Rate (mm/yr)
1	San Andreas - 1857 (SA)	7.8	29 - 39
2	Great Valley #7 Orestimba (OR)	6.7	0.4 - 0.6
3	Great Valley #9 Laguna Seca (LS)	6.6	0.6 - 1.8
4	Great Valley #10 Panoche (P)	6.4	0.5 - 1.5
5	Great Valley #11 Ciervo Hills (CH)	6.4	0.5 - 2.5
6	Great Valley #12 Black Hills (BH)	6.3	0.5 - 2.5
7	Great Valley #13 Coalinga (C)	6.5	0.5 - 2.5
8	Great Valley #14 Kettleman Hills (KH)	6.4	0.5 - 2.5
9	Mono Lake (ML)	6.6	1.25 - 3.75
10	Hartley Springs (HS)	6.6	0.2 - 0.8
11	Hilton Creek (HC)	6.5	1.9 - 3.1
12	Round Valley (RV)	6.8	0.5 - 1.5
13	White Mountains (WM)	7.4	0.5 - 1.5
14	Owens Valley (OV)	7.6	1.5 - 2.5
15	Independence (I)	6.7	0.1 - 0.3
16	White Wolf (WW)	7.0	1.8 - 2.2
	Foothills System		
17	Green Springs (GS)	6.5	0.001 - 0.05
18	Negro Jack (NJ)	6.5	0.001 - 0.05
19	Poorman Gulch (PG)	6.5	0.01 - 0.1
20	Rawhide Flat East (RFE)	6.5	0.001 - 0.05
21	Rawhide Flat West (RFW)	6.5	0.001 - 0.08
22	Waters Peak (WP)	6.5	0.01 - 0.1

2.2 The South Sierran Source Block Source Zones

To estimate hazard from earthquake activity that is not associated with any of the major faults identified in the study area, the Sierran Source Block I areal source zone, defined by LaForge and Ake (1999), was modified and incorporated into PSHA analyses. The area included in the Sierran Source Block I source zone represents a region surrounding the dams with relatively uniform seismotectonic characteristics. For this study, the Sierran Source Block I zone was extended southward from the area used in Laforge and Ake (1999) to include the region around all study sites. This updated source zone, referred to here as the South Sierran Source Block (SSSB), covers approximately 50,945 square kilometers (**Figure 3**). Hazard from 'random' events within this source zone is estimated by first calculating recurrence rates for the source area, then using those rates to calculate hazard at the dam sites.

Recurrence calculations require a declustered catalogue of earthquakes not associated with known faults. This catalogue is separated into magnitude bins, each of which is assigned a completeness period. These bins are compiled into an occurrence table for the source zone. For this study, the occurrence table from Laforge and Ake (1999) was updated to include events occurring after publication of that report, and to include events within the new source zone area. The declustered catalog for the SSSB zone includes 139 events (**Table 2**). Using this table, and truncated exponential form of the Gutenberg-Richter recurrence relationship (Log $\mathbf{N} = a + b\mathbf{M}$), the recurrence parameters and associated rates shown in **Tables 3** and **4**, respectively, were calculated (an $\mathbf{M}_{max}$ of 7.0 was chosen for this model, based on LaForge and Ake, 1999). **Figures 4** and **5** show the incremental and cumulative recurrence curves, respectively, for these calculations.

Table 2: Completeness Periods and Event Counts for the SSSB Source Zone

Magnitude Range	Completeness Period	Number of Earthquakes
3.0 - 4.0	1/1948 - 7/2002	118
4.0 - 5.0	1/1942 - 7/2002	18
5.0 - 6.0	1/1910 - 7/2002	3
6.0 - 7.0	1/1852 - 7/2002	0

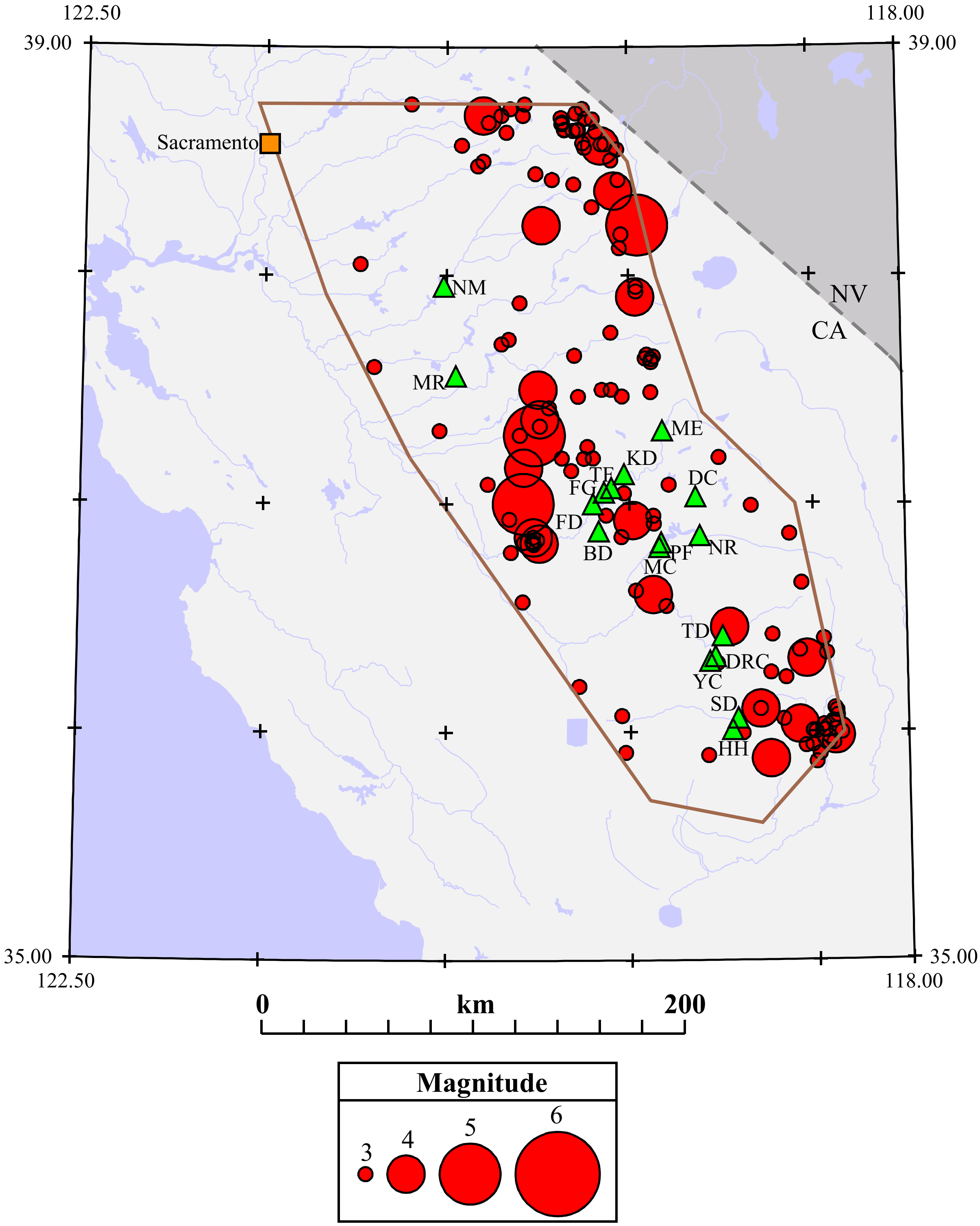

Figure 3: Boundaries of the SSSB source zone and events used in this study, relative to locations of the subject sites (indicated by green triangles). Site abbreviations are: NM New Melones; MR Montgomery Reservoir; ME Mammoth Pool Expansion; KD Kerckoff; Fine Gold Creek Dam; TF Temperance Flat Dam; DC Dinkey Creek Dam; FD Friant Dam; BD Big Dry Creek Reservoir; NR New Rogers Crossing; PF Pine Flat Dam; MC Mill Creek; TD Terminus Dam; DRC Dry Creek Dam; YC Yokohl Creek Dam; SD Success Dam; HH Hungry Hollow Reservoir.

Table 3: Recurrence Parameters for the SSSB Source Zones

Parameter	Incremental	Cumulative
a (σ) [Maximum Magnitude = 7.0]	-1.05 (0.30)	-1.47 (0.24)
b (σ) [Maximum Magnitude = 7.0]	0.95 (0.08)	0.95 (0.07)

Table 4: Earthquake Recurrence Data for the SSSB

Magnitude range (**M**)	Predicted (yrs)	High (yrs)	Low (yrs)	Observed (yrs)
3.0-4.0	0.44	0.53	0.37	0.45
4.0-5.0	3.9	5.5	2.8	3.5
5.0-6.0	34	68	17	34
6.0-7.0	180	450	70	0

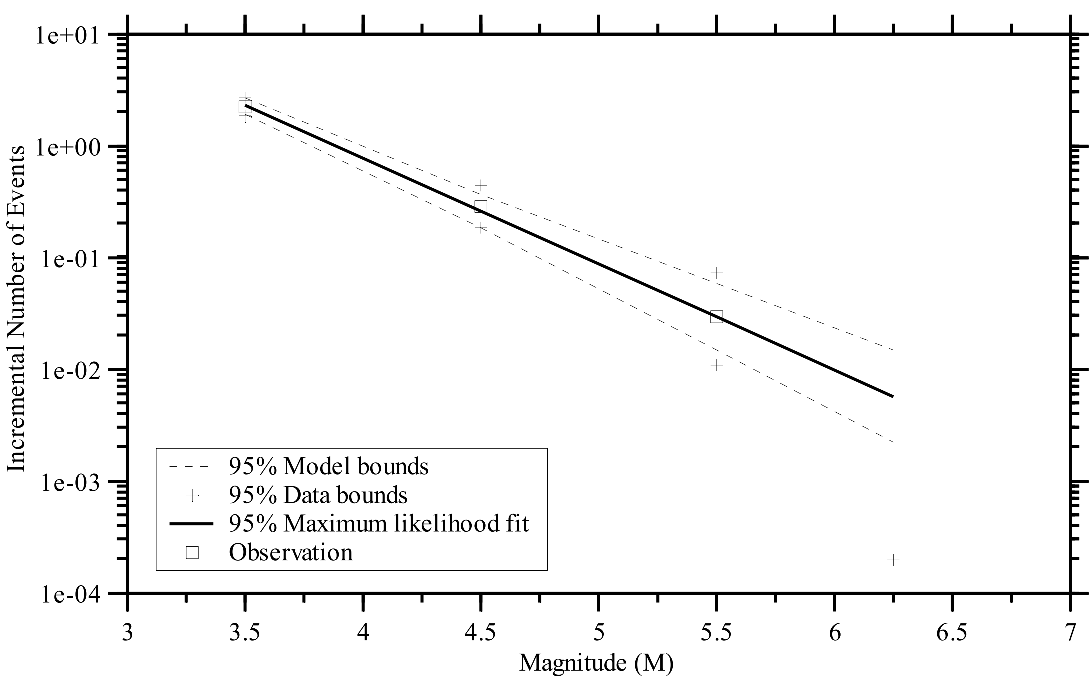

Figure 4: Incremental recurrence curve for the SSSB source zone.

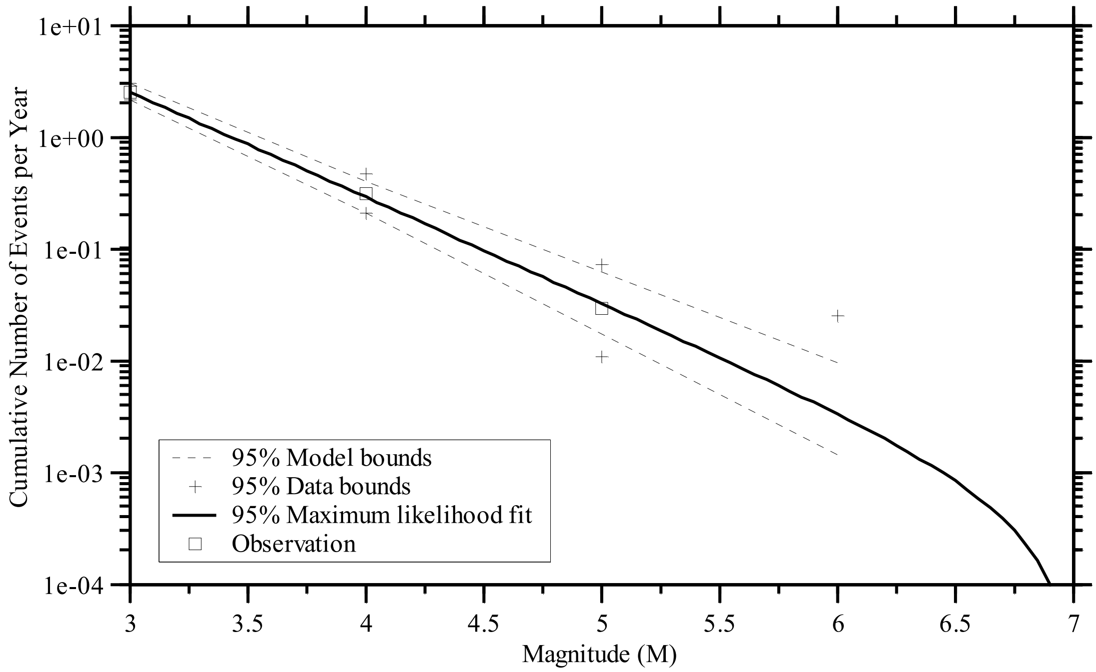

Figure 5: Cumulative recurrence curve for the SSSB source zone.

3.0 Probabilistic Seismic Hazard Assessment

Probabilistic seismic hazard analyses (PSHA) performed for the subject sites follow the basic concepts outlined in Cornell (1968) and McGuire (1974, 1978). Formal error distributions in the random seismicity rates were directly incorporated by complete enumeration. Earthquake foci are distributed over the depth range 2-20 km with a peak at 10 km. The upper bound is estimated as the midpoint of a circular 60-degree-dipping rupture with a 100-bar stress drop that just intersects the surface (described in LaForge and Ake, 1999).

For this appraisal-level evaluation only a single attenuation function was used for the hazard calculations. The attenuation relationship of Sadigh and others (1997) was chosen to estimate ground motion values. Previous studies (e.g. LaForge and Ake, 1999) found this relationship to lie near the median when several attenuation functions were used. It should be noted however, that use of a single attenuation function reduces total variance in hazard calculations. Ground motion computations were carried out assuming rock site conditions. Uncertainties in ground motion attenuation were directly incorporated by complete enumeration.

4.0 PSHA Results

Results of the PSHA in terms of mean peak horizontal acceleration (PHA) and uncertainties are summarized in **Figures 6-22**. **Table 5** lists figure numbers for each site. **Table 6** summarizes PHA results for the subject dams for selected annual frequencies of exceedance (AFE's).

Table 5: List of PSHA summary figures

Figure #	**Site** (from N to S)
6	New Melones (NM)
7	Montgomery Reservoir (MR)
8	Mammoth Pool Expansion (ME)
9	Kerckhoff (KD)
10	Fine Gold Creek Dam (KD)
11	Temperance Flat Dam (TF)
12	Dinkey Creek Dam (DC)
13	Friant Dam (FD)
14	Big Dry Creek Reservoir (BD)
15	New Rogers Crossing (NR)
16	Pine Flat Dam (PF)
17	Mill Creek (MC)
18	Terminus Dam (TD)
19	Dry Creek Dam (DRC)
20	Yokohl Creek Dam (YC)
21	Success Dam (SD)
22	Hungry Hollow Reservoir (HH)

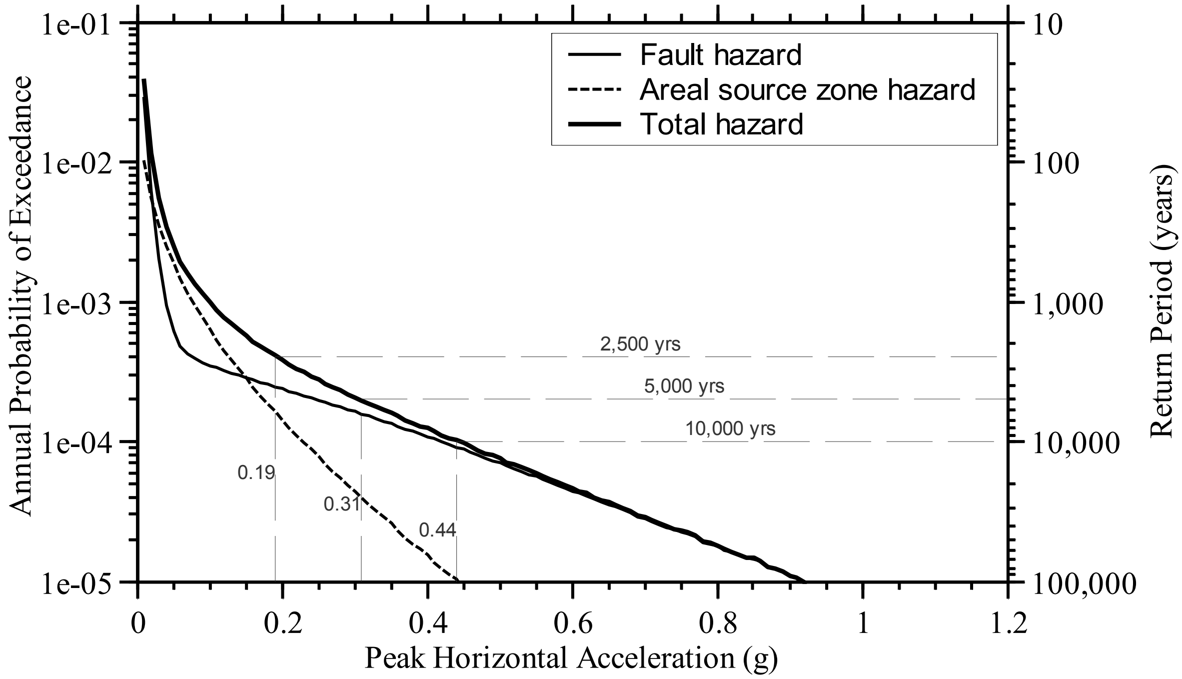

Figure 6: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for New Melones Dam.

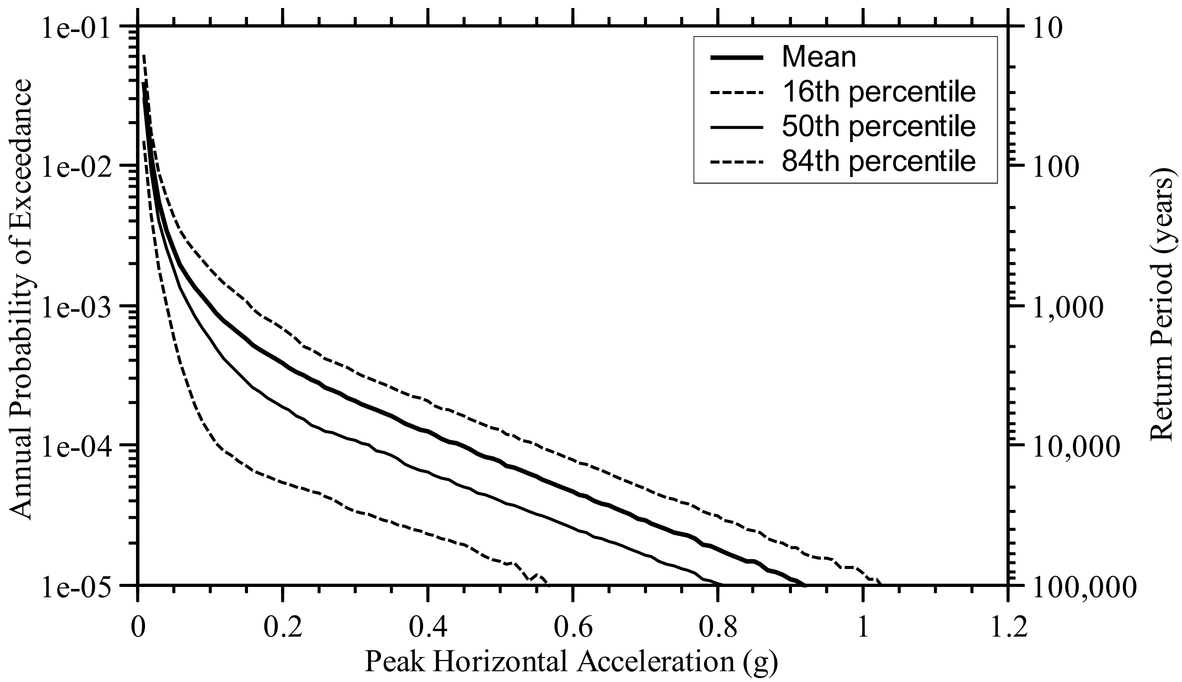

Figure 7: PHA hazard curves for New Melones Dam. Mean, median, 16th- and 84th-percentile values indicated.

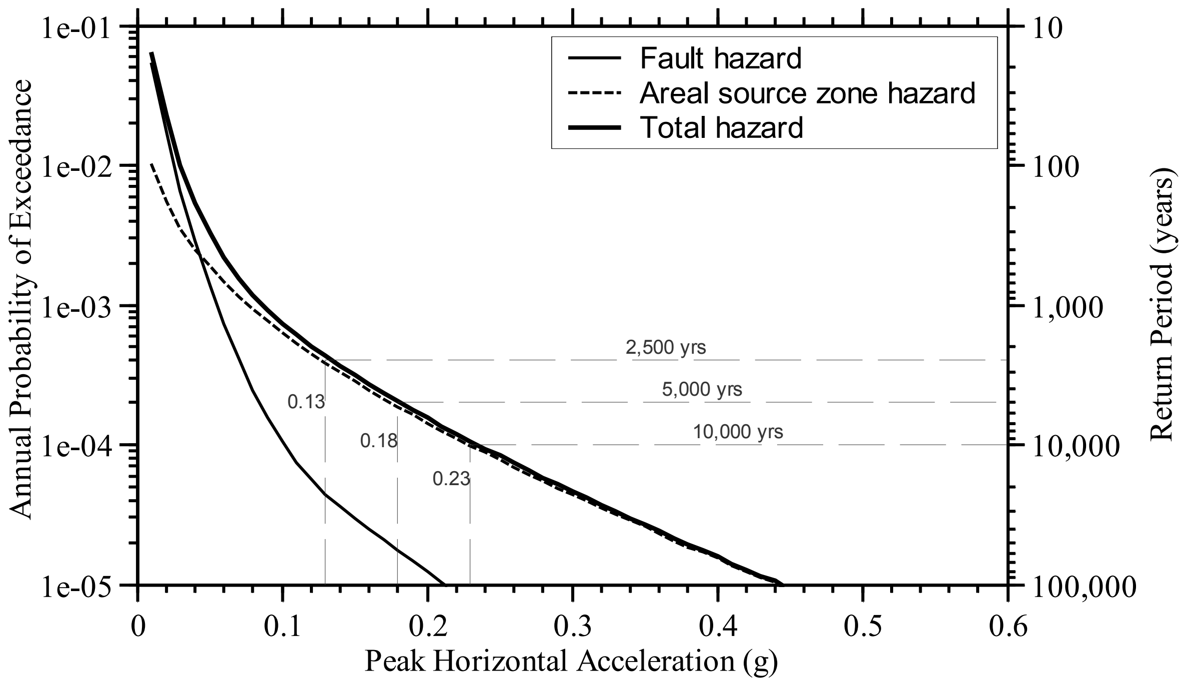

Figure 8: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Montgomery Reservoir Dam.

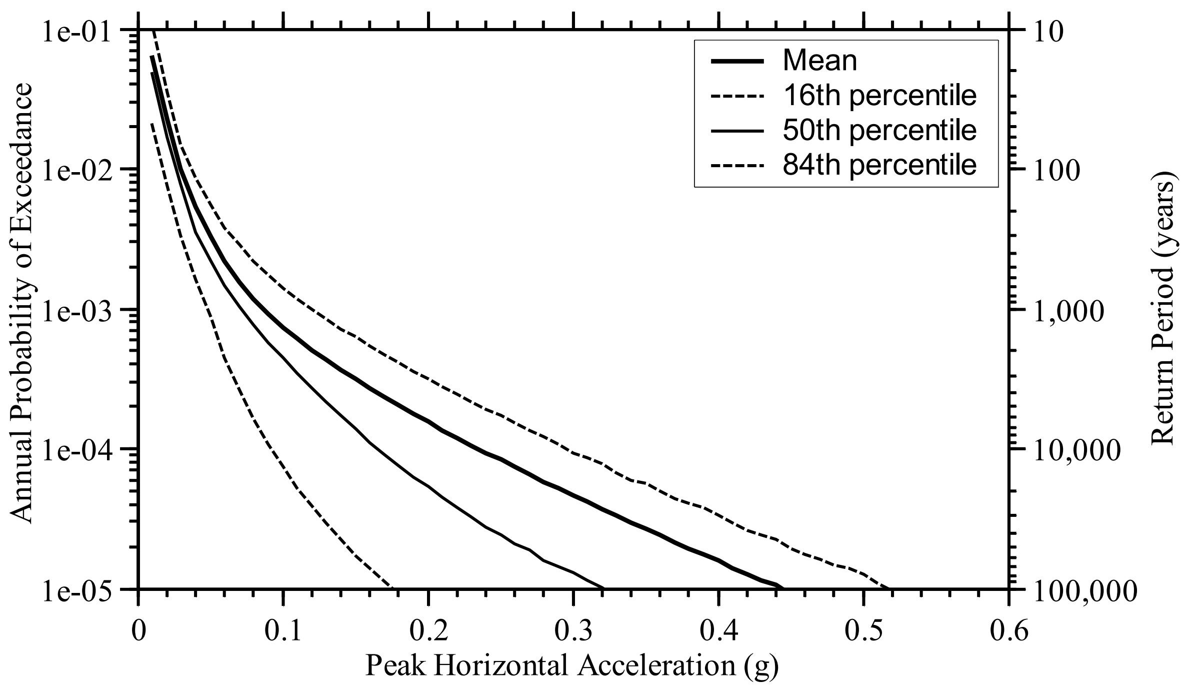

Figure 9: PHA hazard curves for Montgomery Reservoir Dam. Mean, median, 16th- and 84th-percentile values indicated.

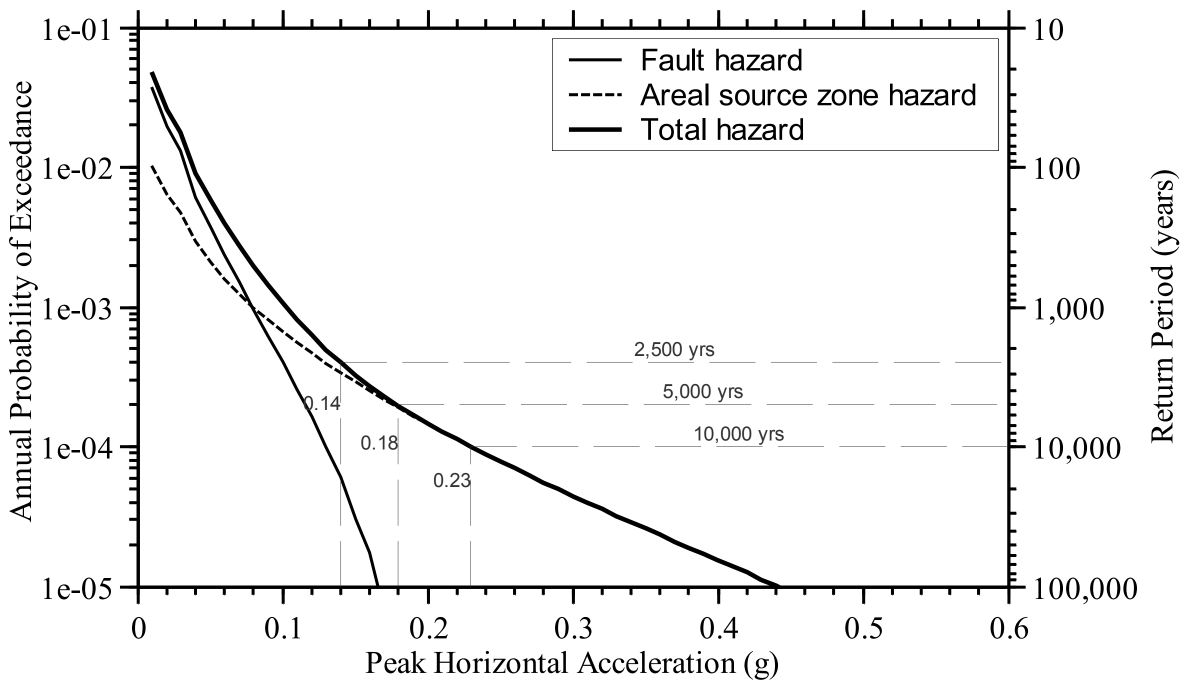

Figure 10: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Mammoth Pool Expansion.

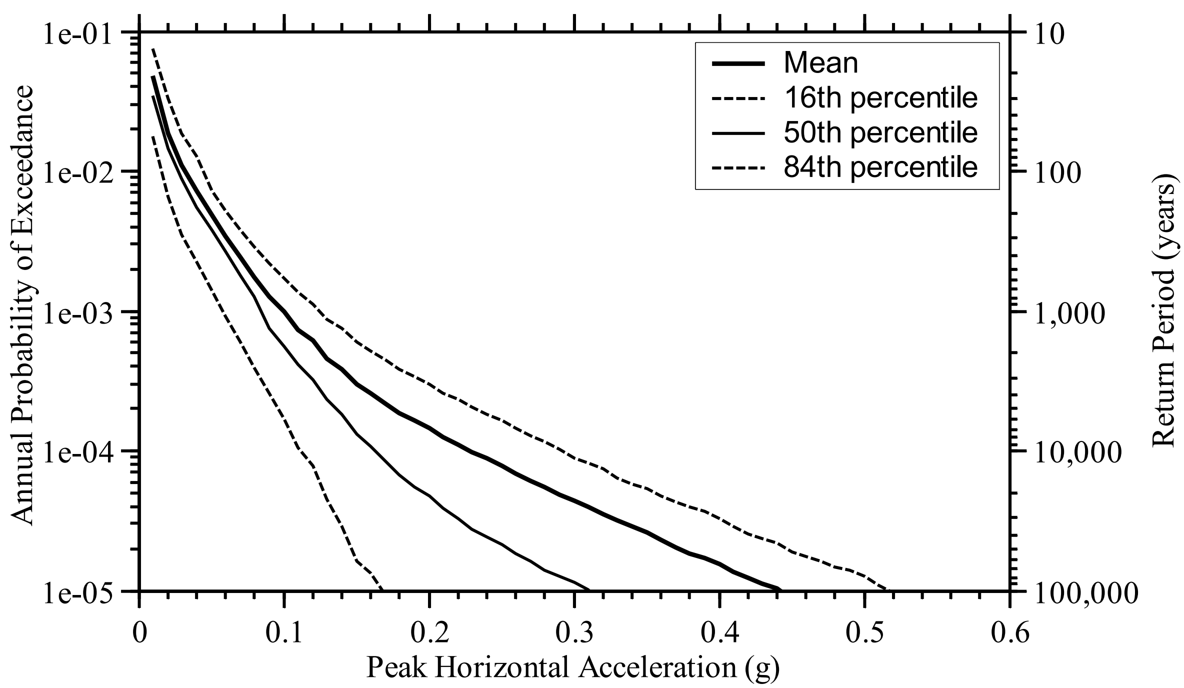

Figure 11: PHA hazard curves for Mammoth Pool Expansion. Mean, median, 16th- and 84th-percentile values indicated.

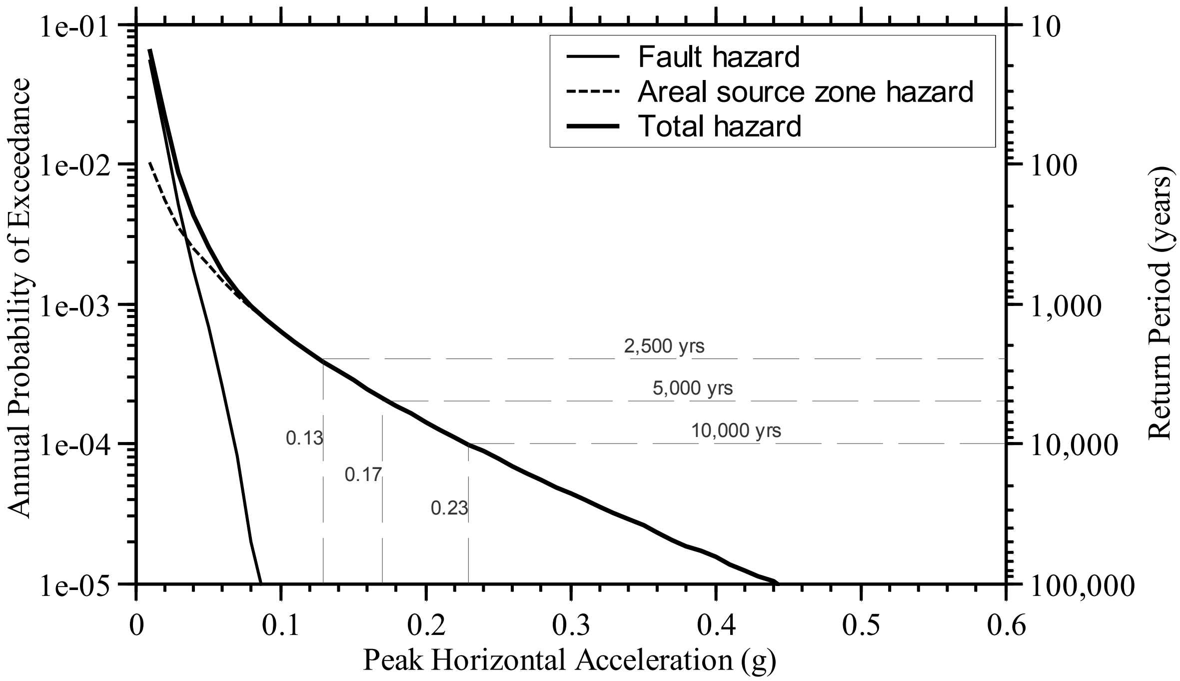

Figure 12: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Kerckhoff Dam.

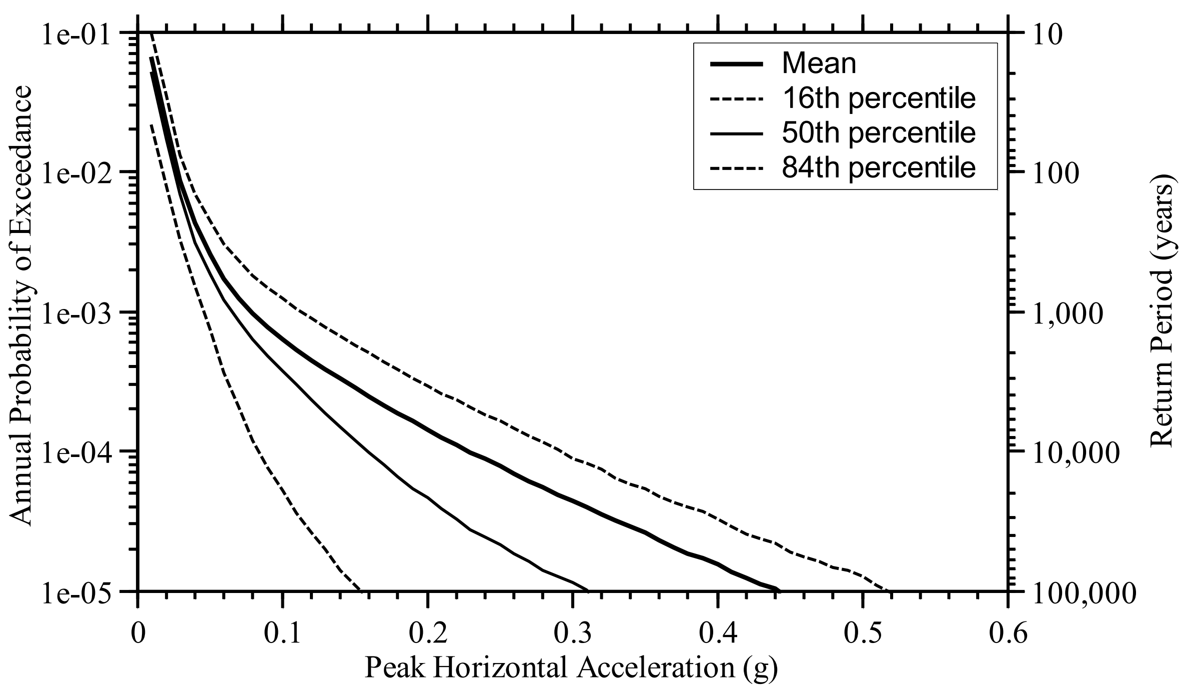

Figure 13: PHA hazard curves for Kerckhoff Dam. Mean, median, 16th- and 84th-percentile values indicated.

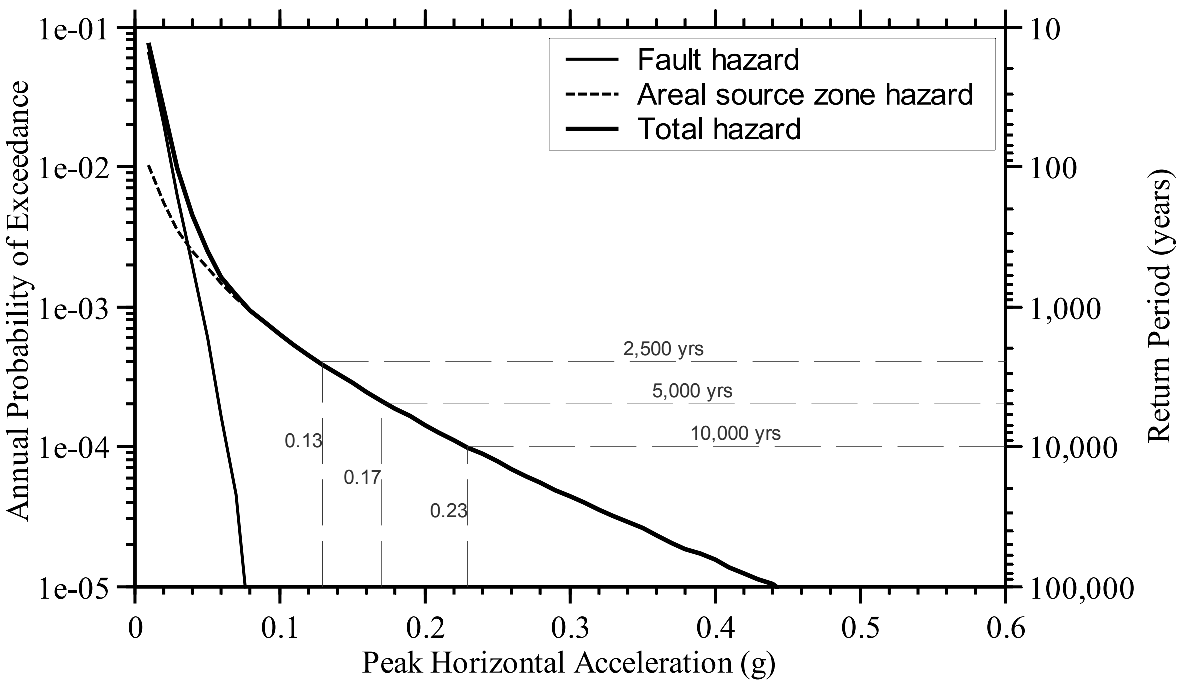

Figure 14: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Fine Gold Creek Dam.

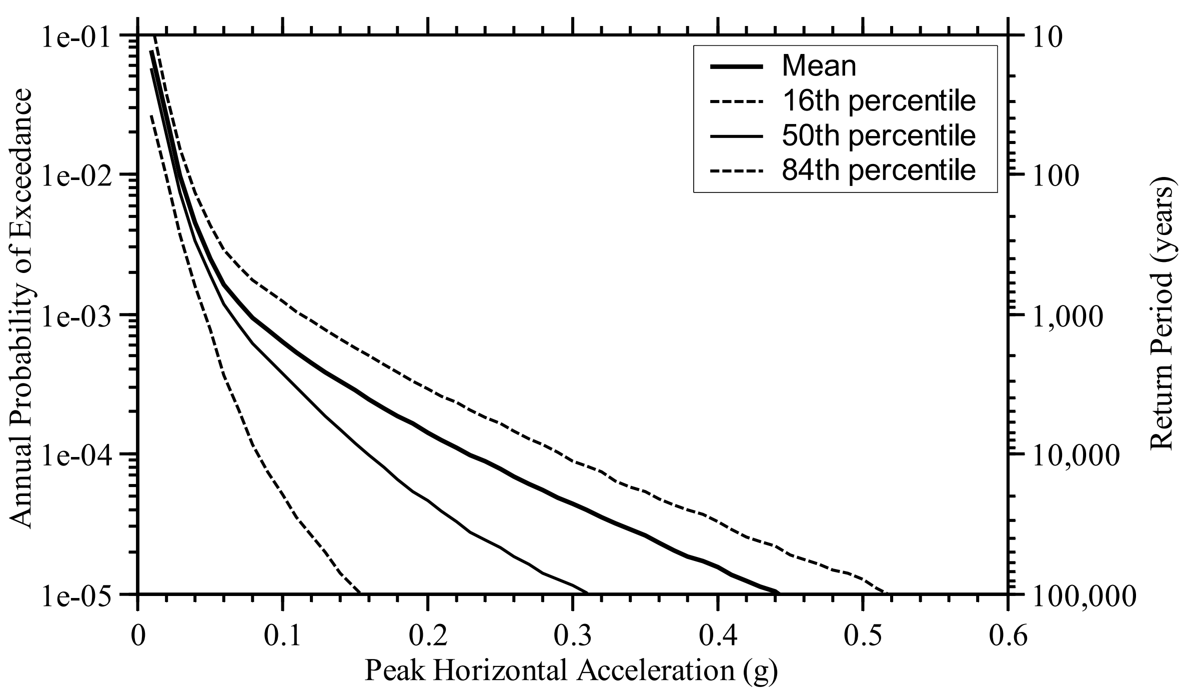

Figure 15: PHA hazard curves for Fine Gold Creek Dam. Mean, median, 16th- and 84th-percentile values indicated.

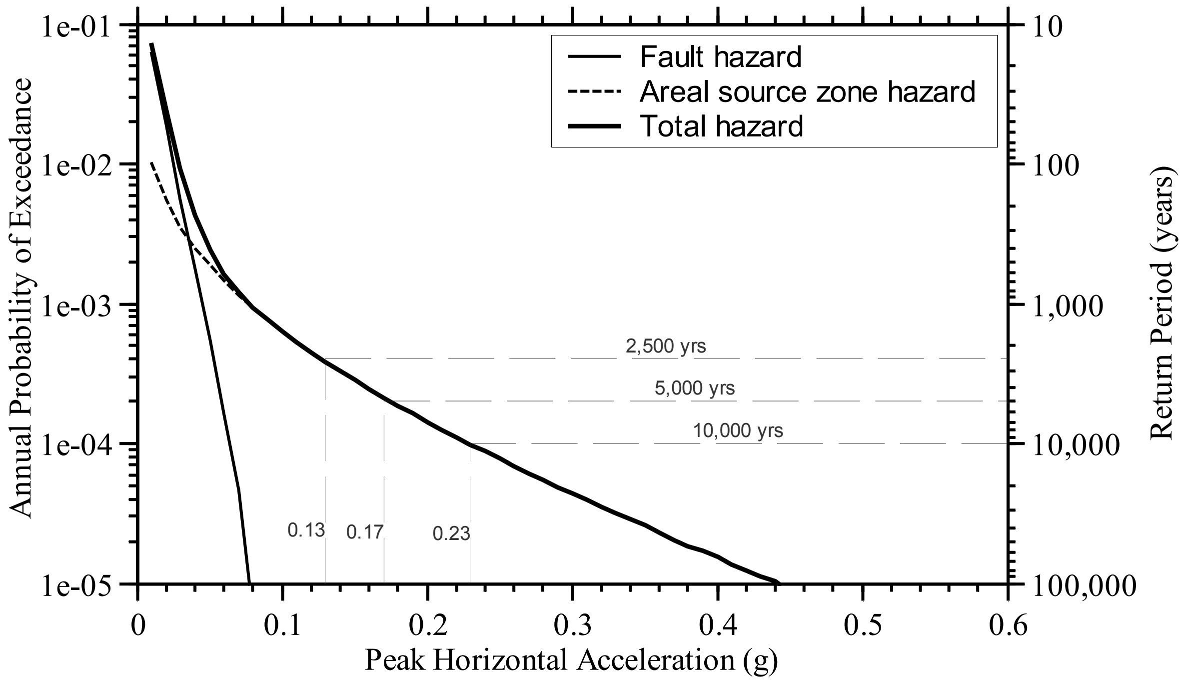

Figure 16: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Temperance Flat Dam.

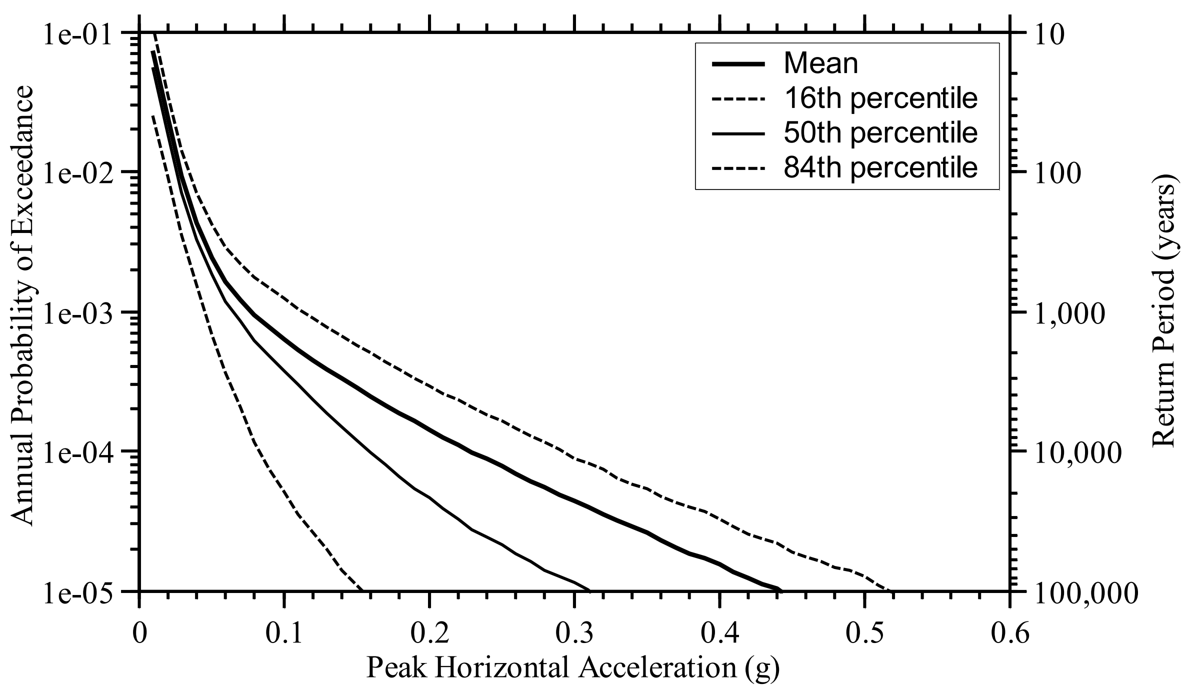

Figure 17: PHA hazard curves for Temperance Flat Dam. Mean, median, 16th- and 84th-percentile values indicated.

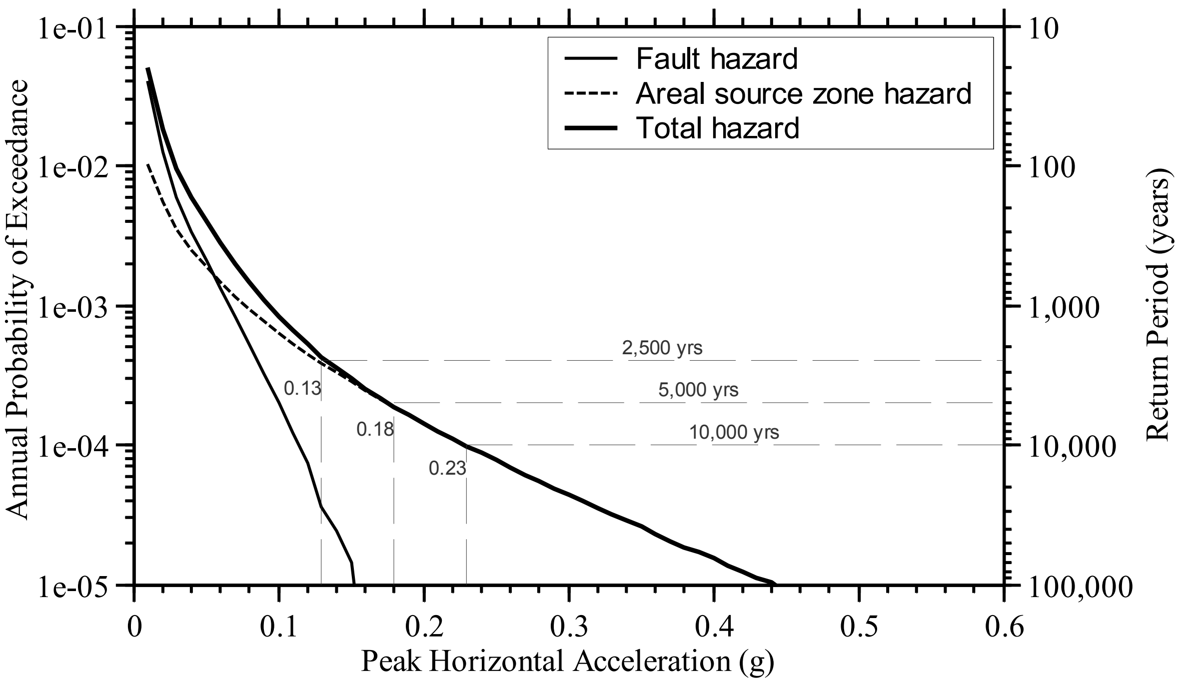

Figure 18: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Dinkey Creek Dam.

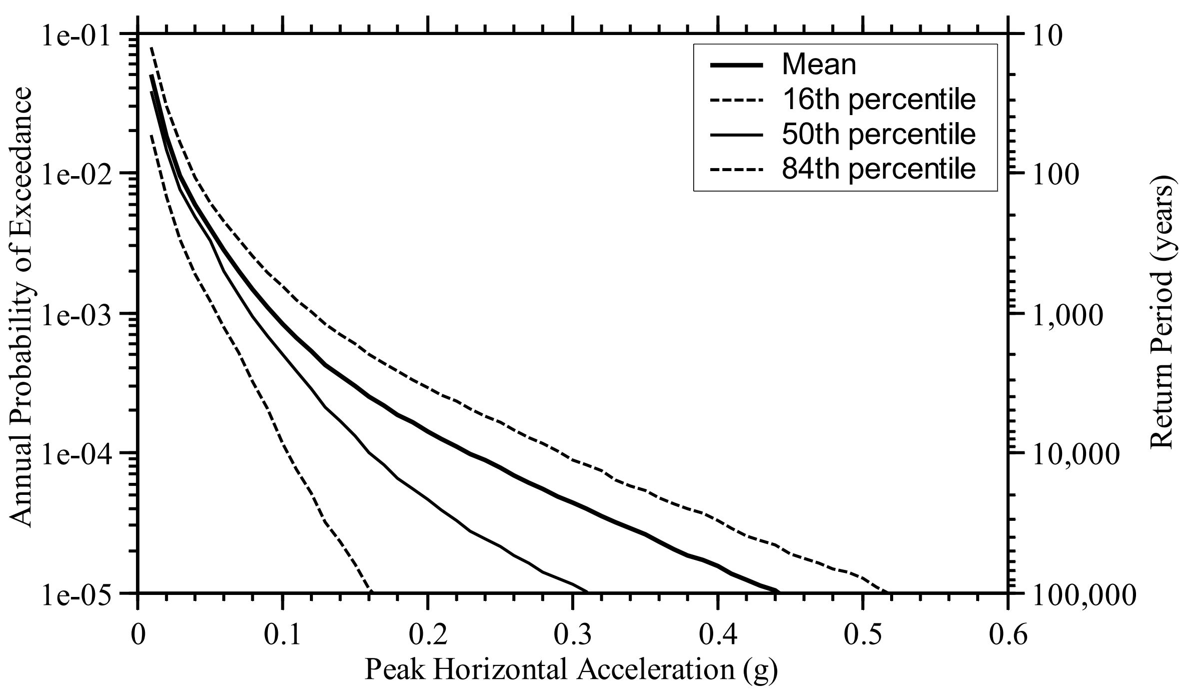

Figure 19: PHA hazard curves for Dinkey Creek Dam. Mean, median, 16th- and 84th-percentile values indicated.

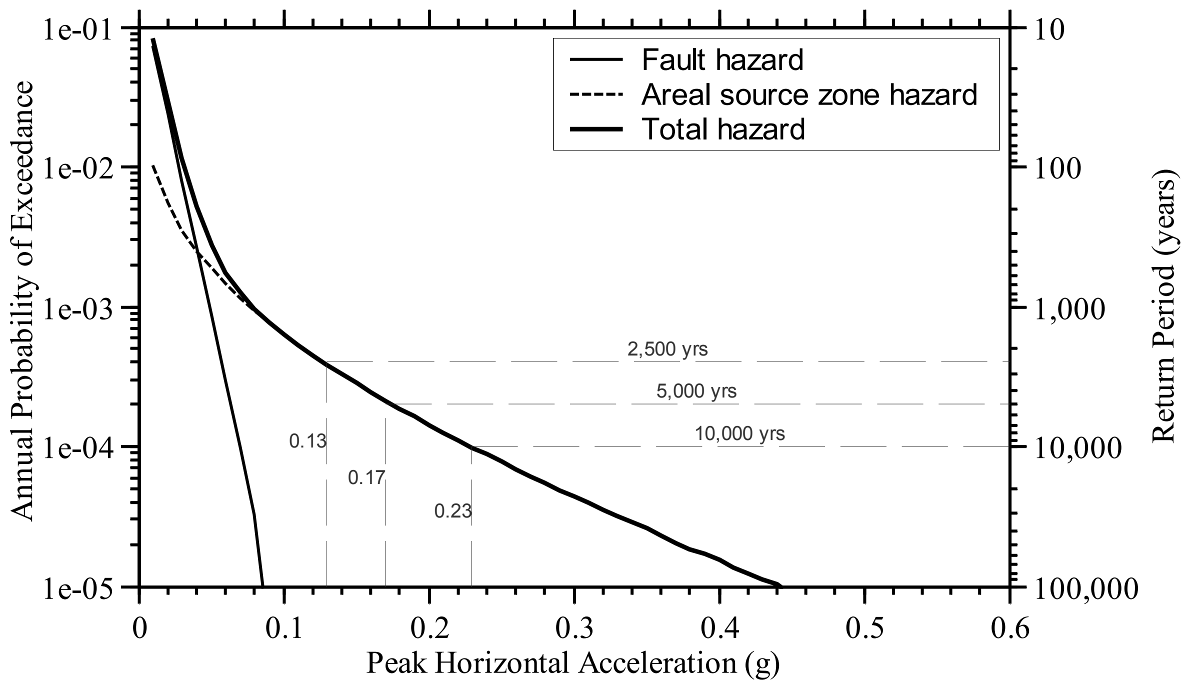

Figure 20: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Friant Dam.

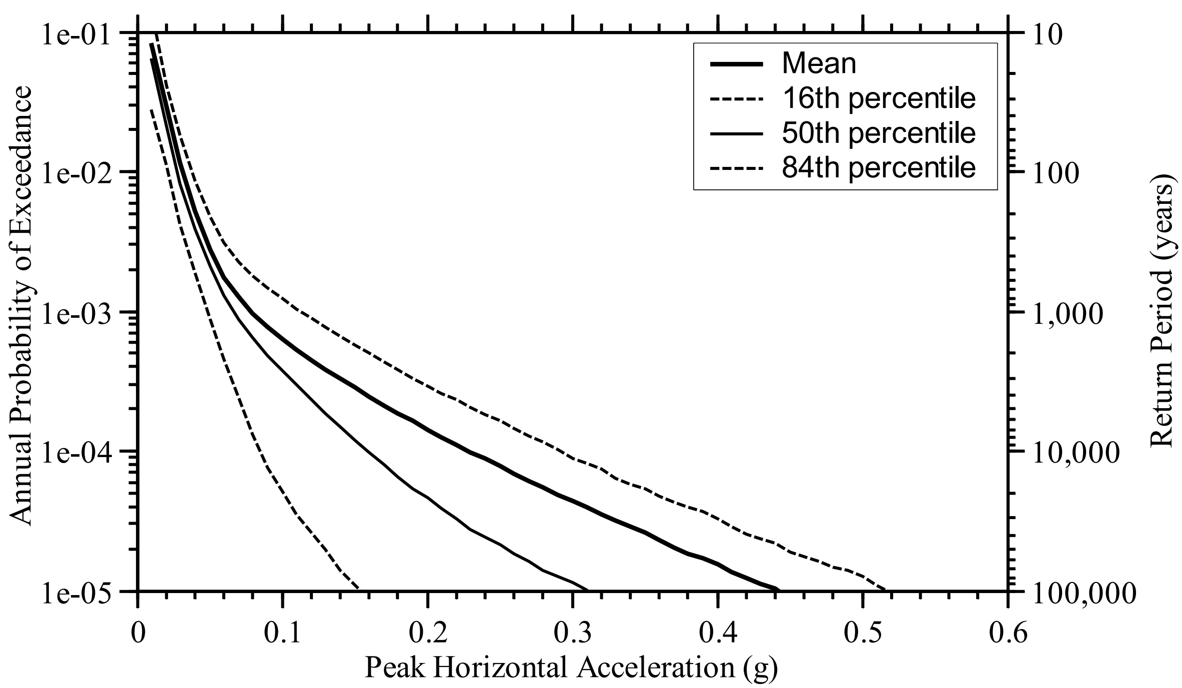

Figure 21: PHA hazard curves for Friant Dam. Mean, median, 16th- and 84th-percentile values indicated.

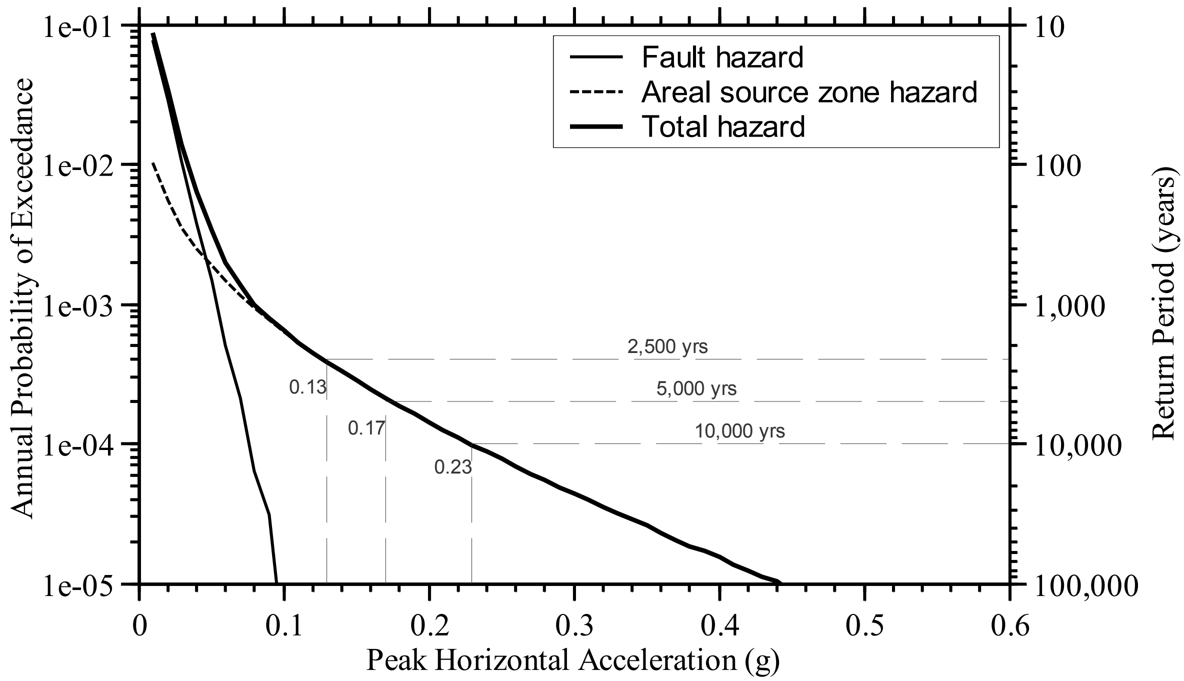

Figure 22: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Big Dry Creek Dam.

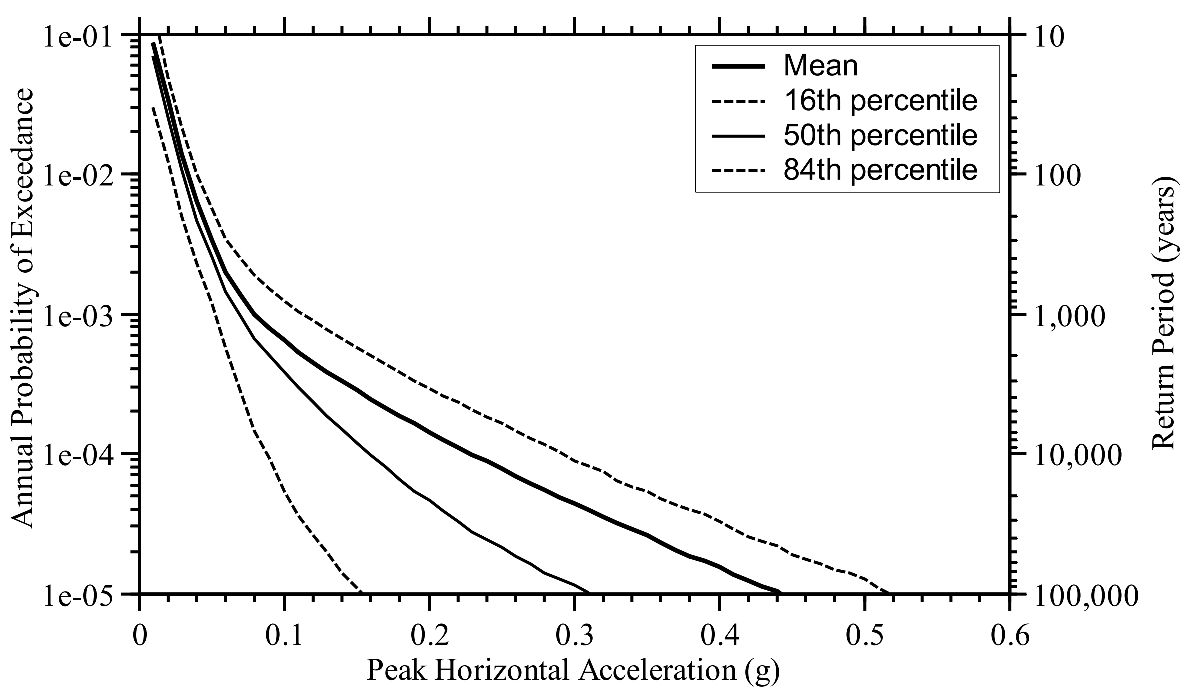

Figure 23: PHA hazard curves for Big Dry Creek Dam. Mean, median, 16th- and 84th-percentile values indicated.

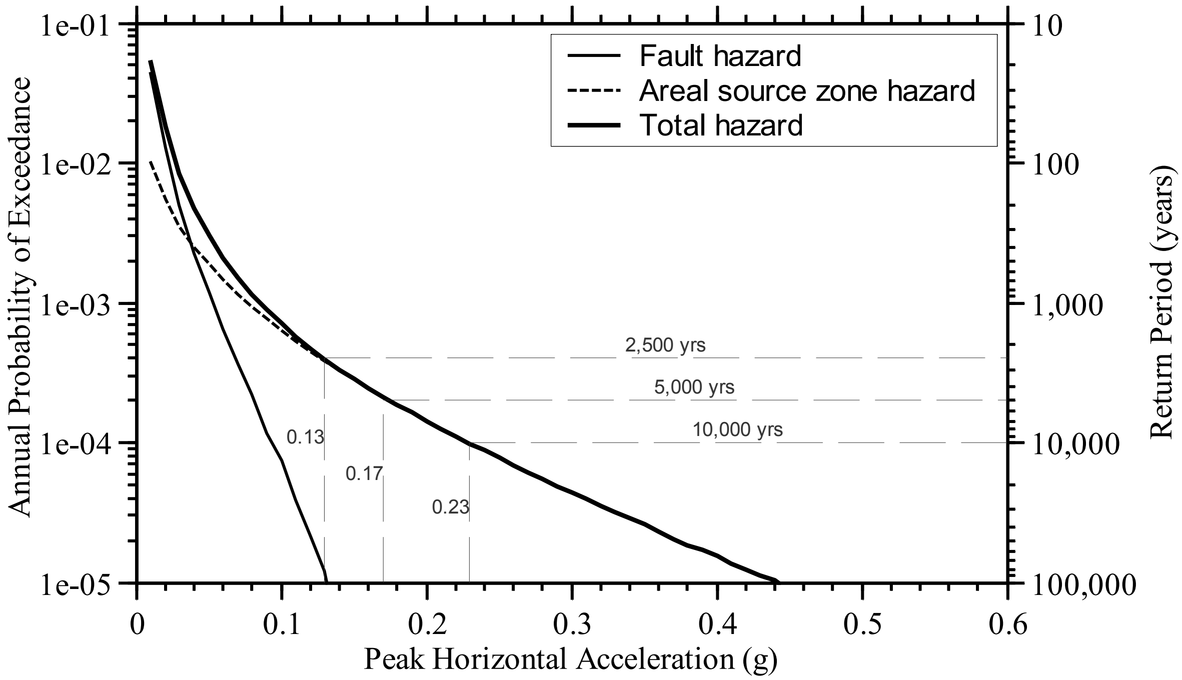

Figure 24: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for New Rogers Crossing.

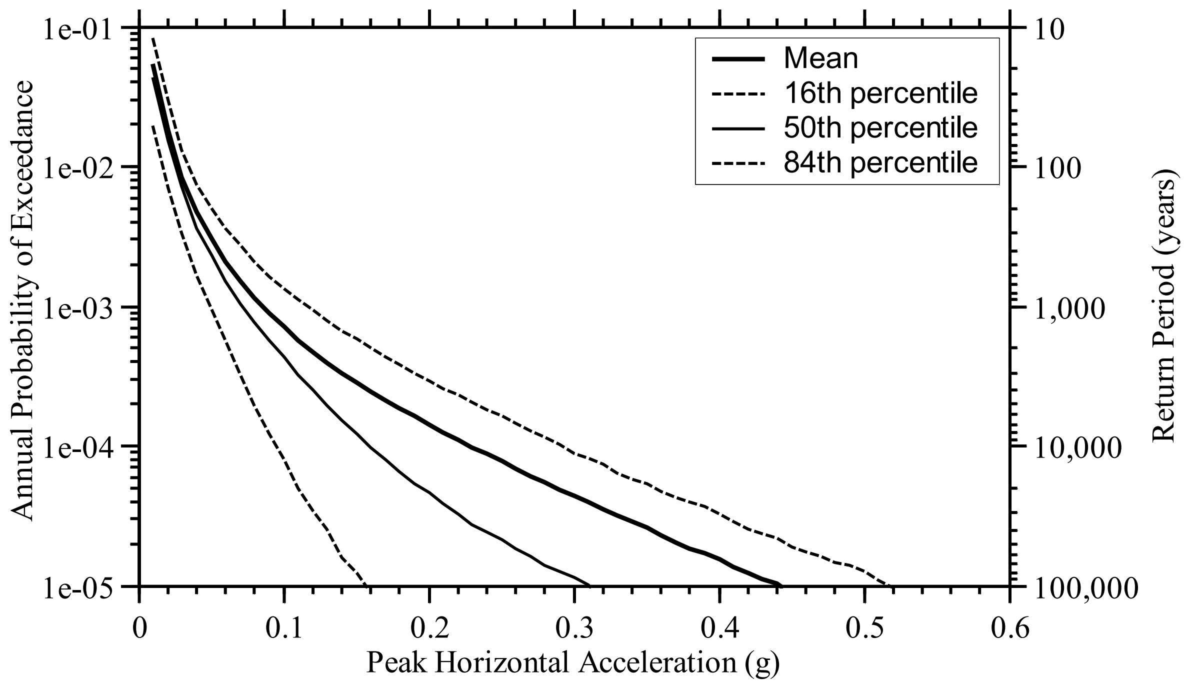

Figure 25: PHA hazard curves for New Rogers Crossing. Mean, median, 16th- and 84th-percentile values indicated.

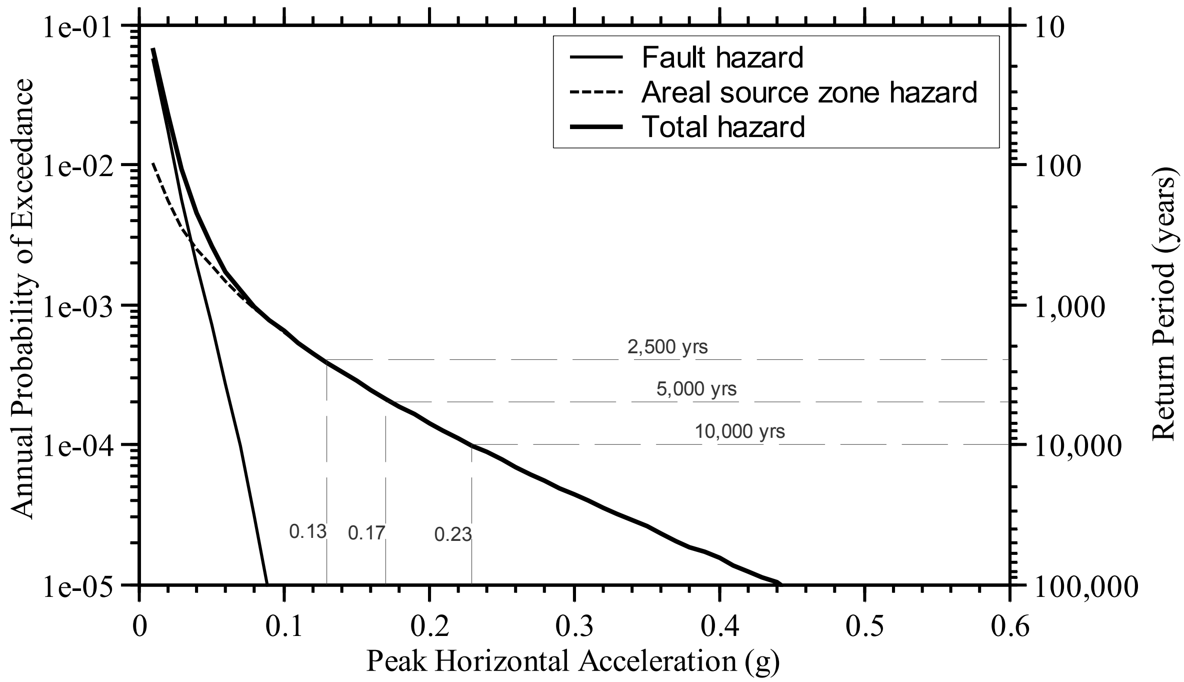

Figure 26: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Pine Flat Dam.

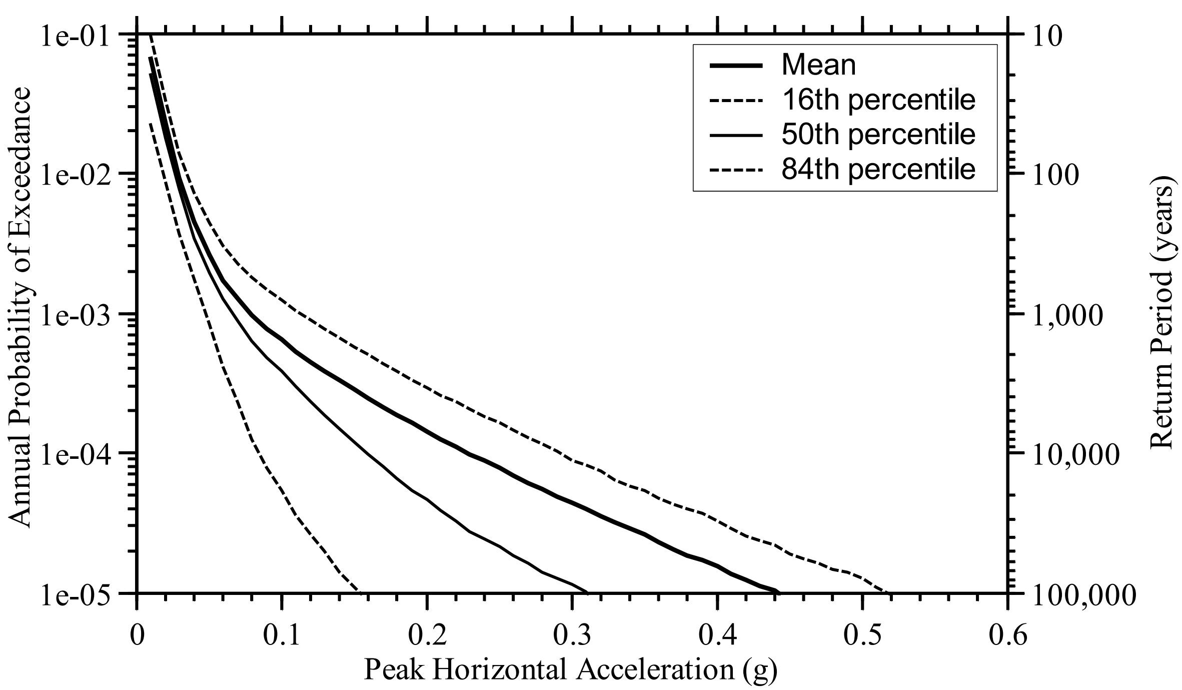

Figure 27: PHA hazard curves for Pine Flat Dam. Mean, median, 16th- and 84th-percentile values indicated.

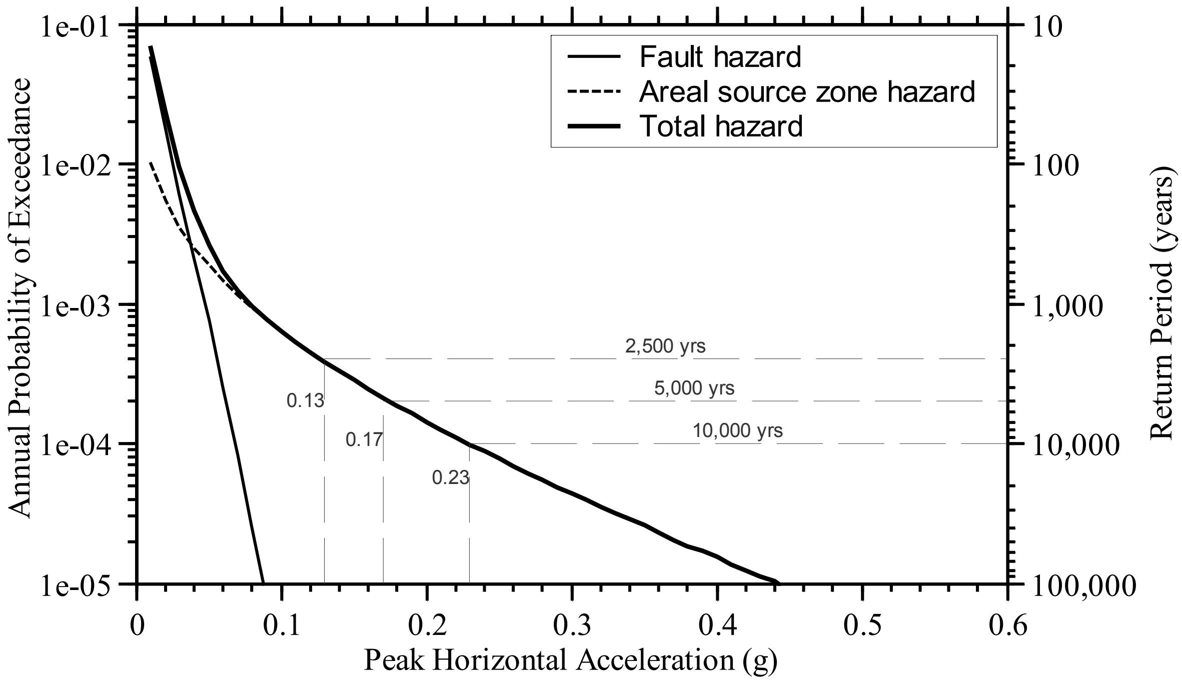

Figure 28: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Mill Creek.

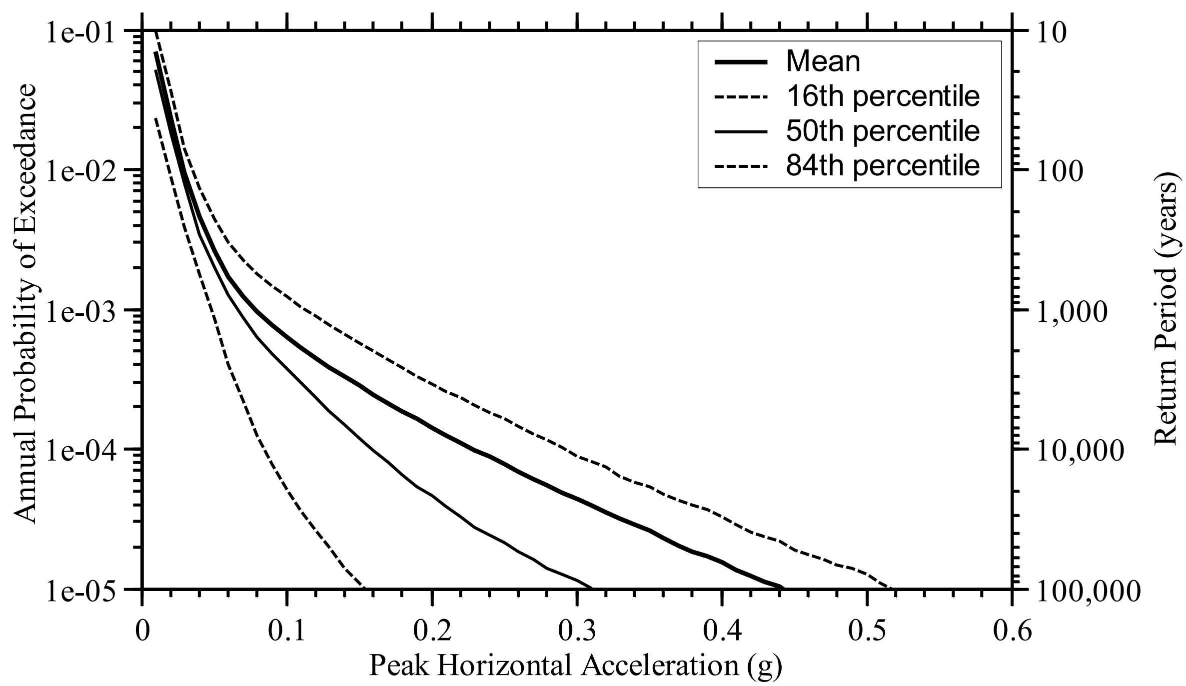

Figure 29: PHA hazard curves for Mill Creek. Mean, median, 16th- and 84th-percentile values indicated.

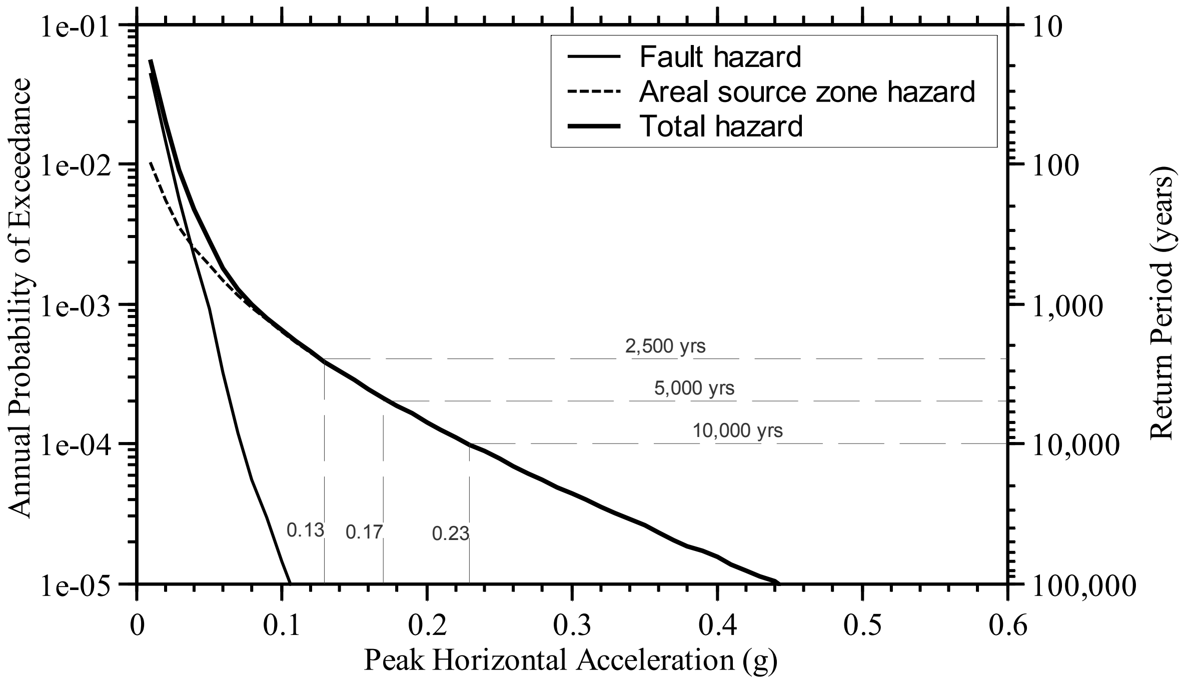

Figure 30: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Terminus Dam.

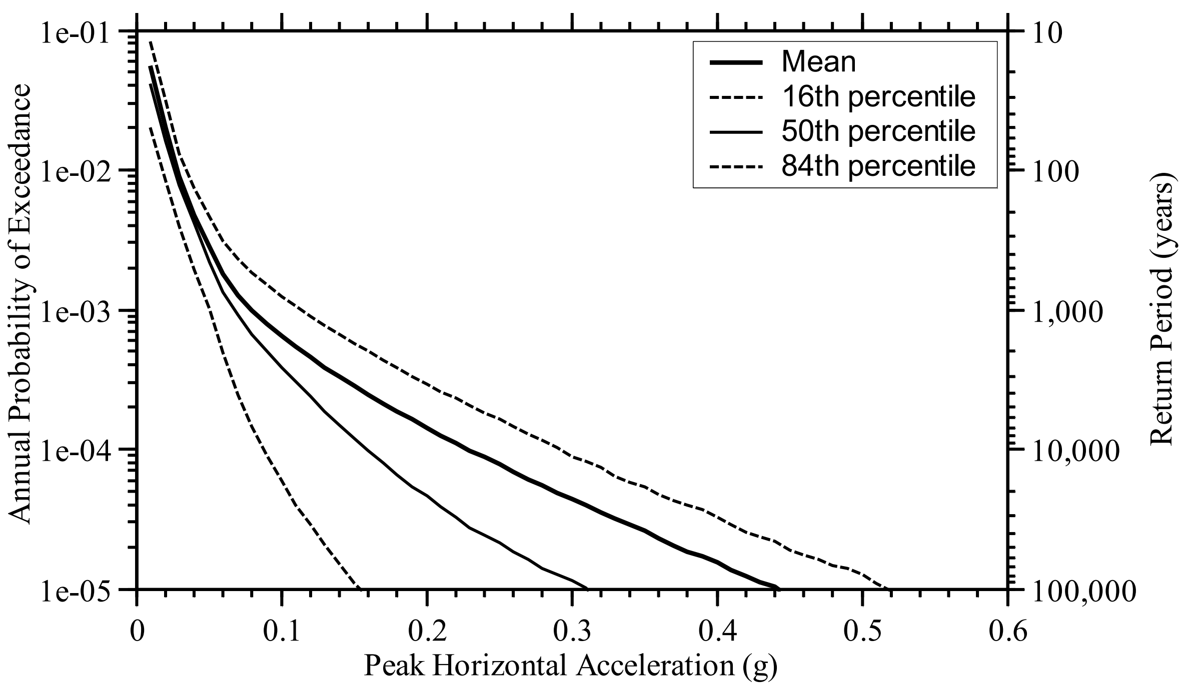

Figure 31: PHA hazard curves for Terminus Dam. Mean, median, 16th- and 84th-percentile values indicated.

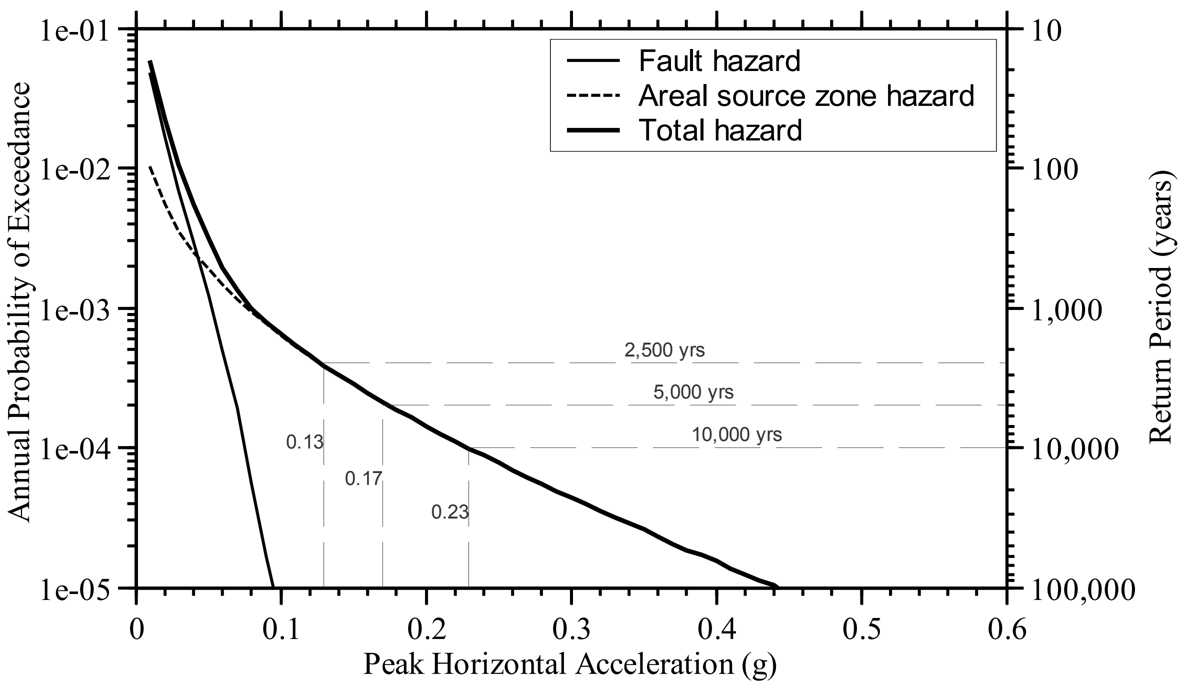

Figure 32: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Dry Creek Dam.

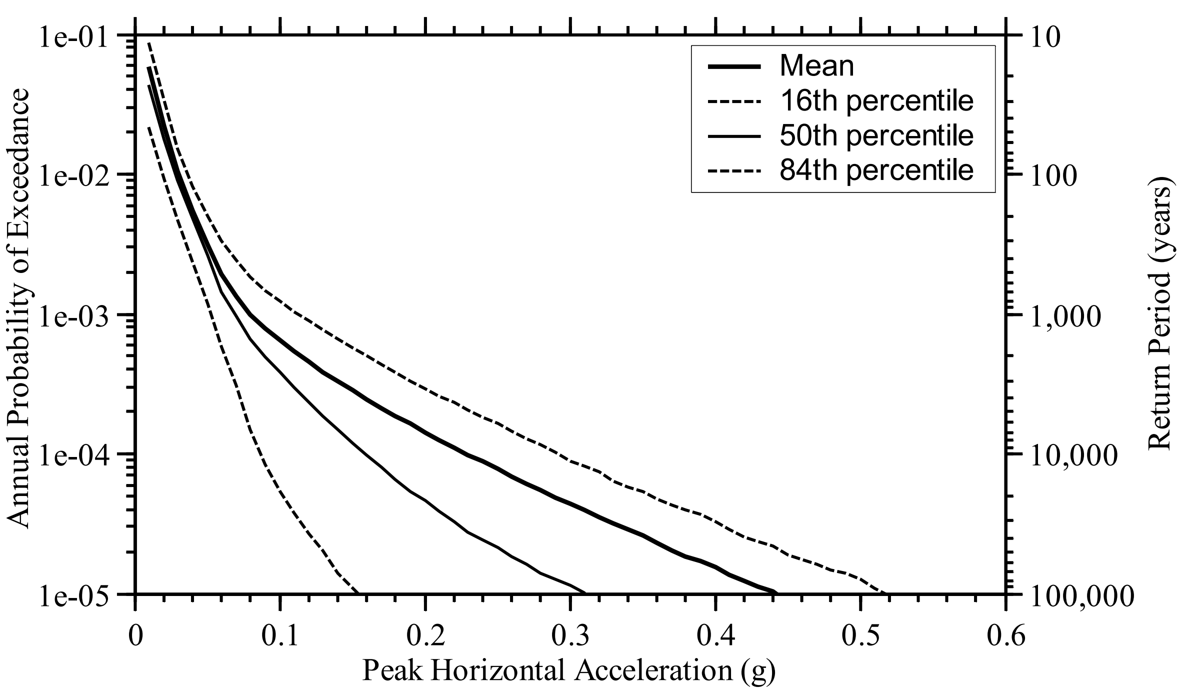

Figure 33: PHA hazard curves for Dry Creek Dam. Mean, median, 16th- and 84th-percentile values indicated.

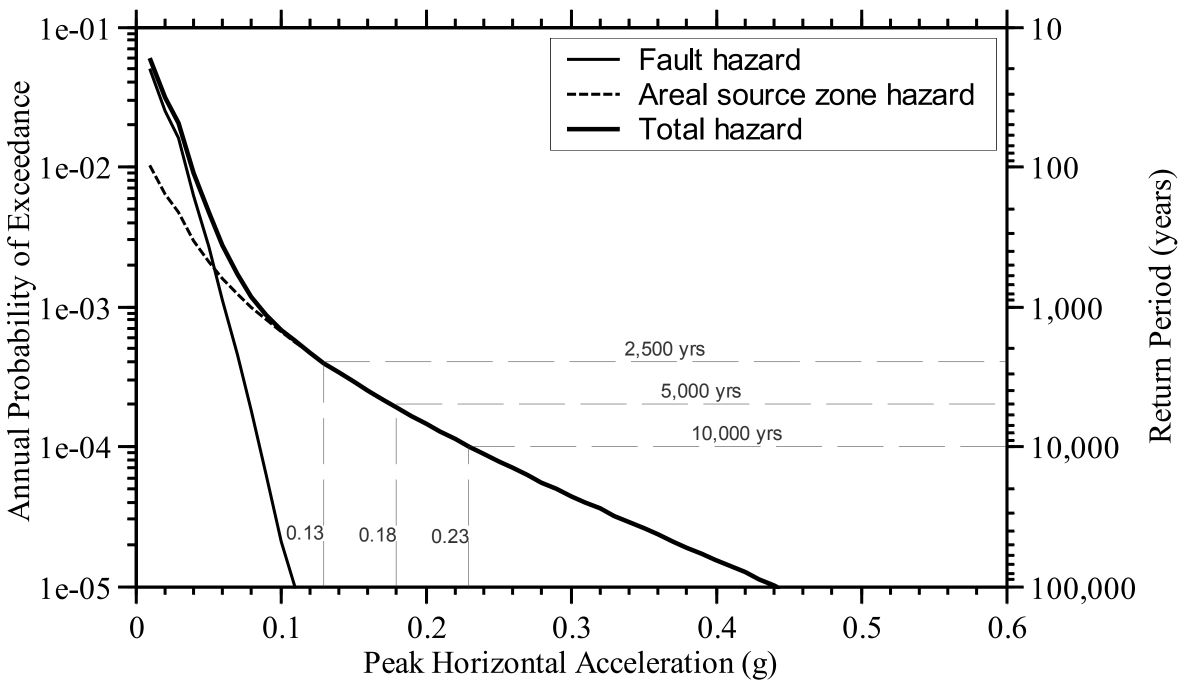

Figure 34: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Yokohl Creek Dam.

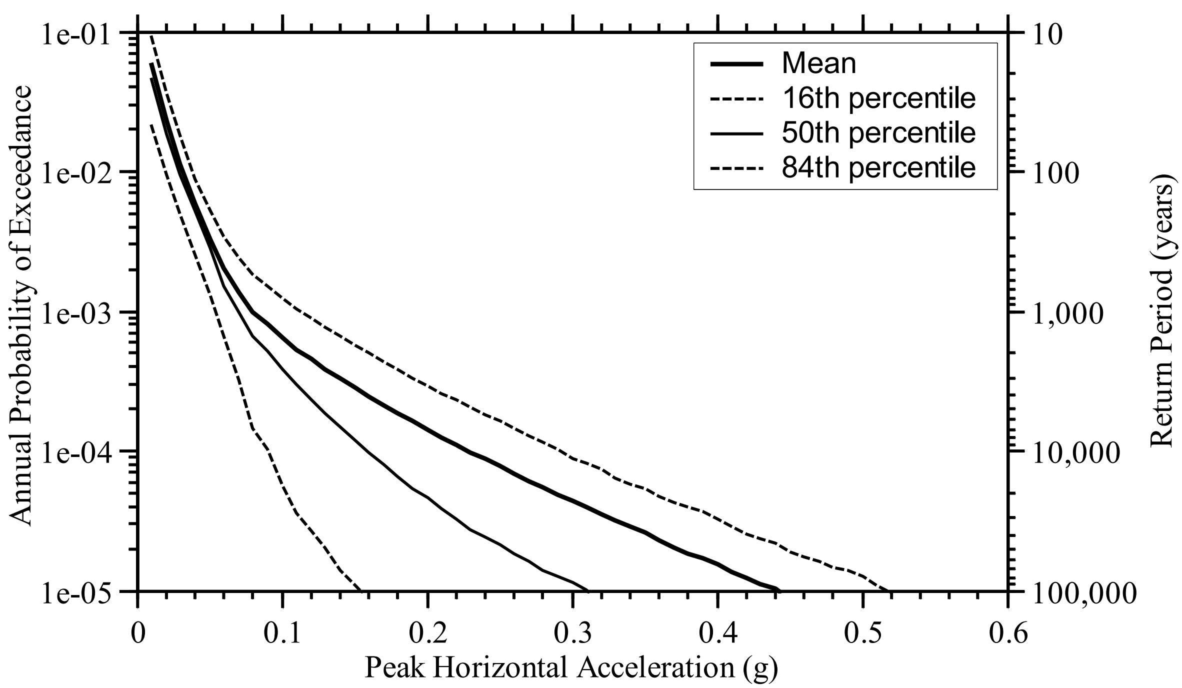

Figure 35: PHA hazard curves for Yokohl Creek Dam. Mean, median, 16th- and 84th-percentile values indicated.

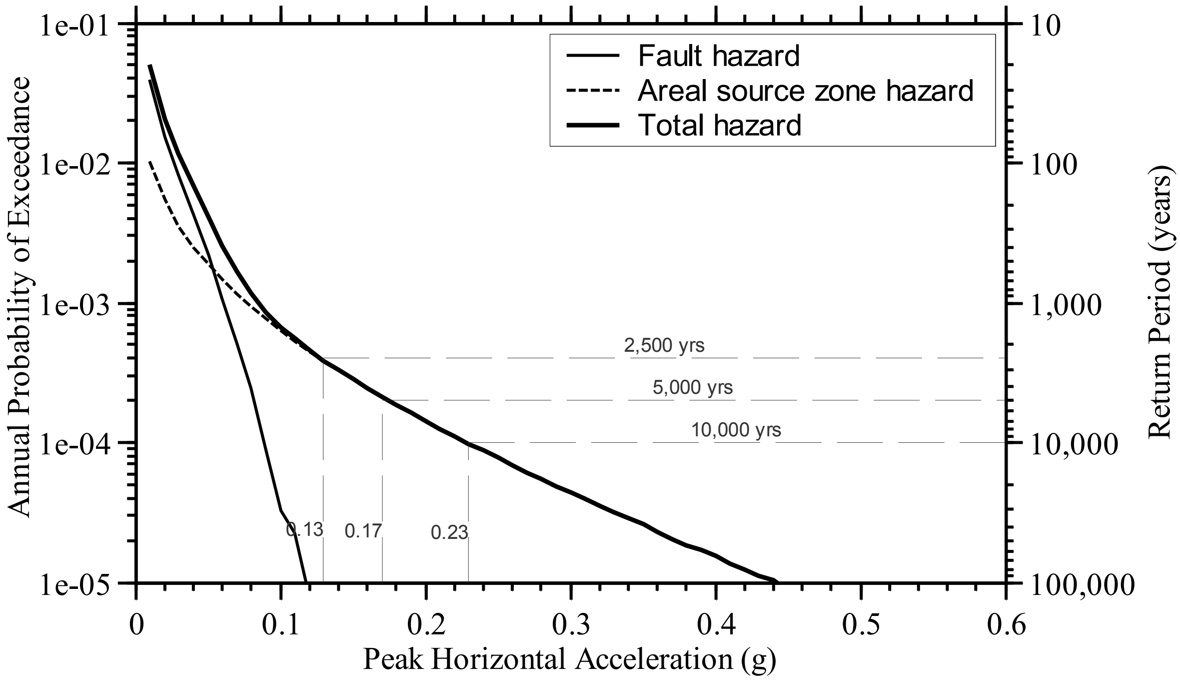

Figure 36: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Success Dam.

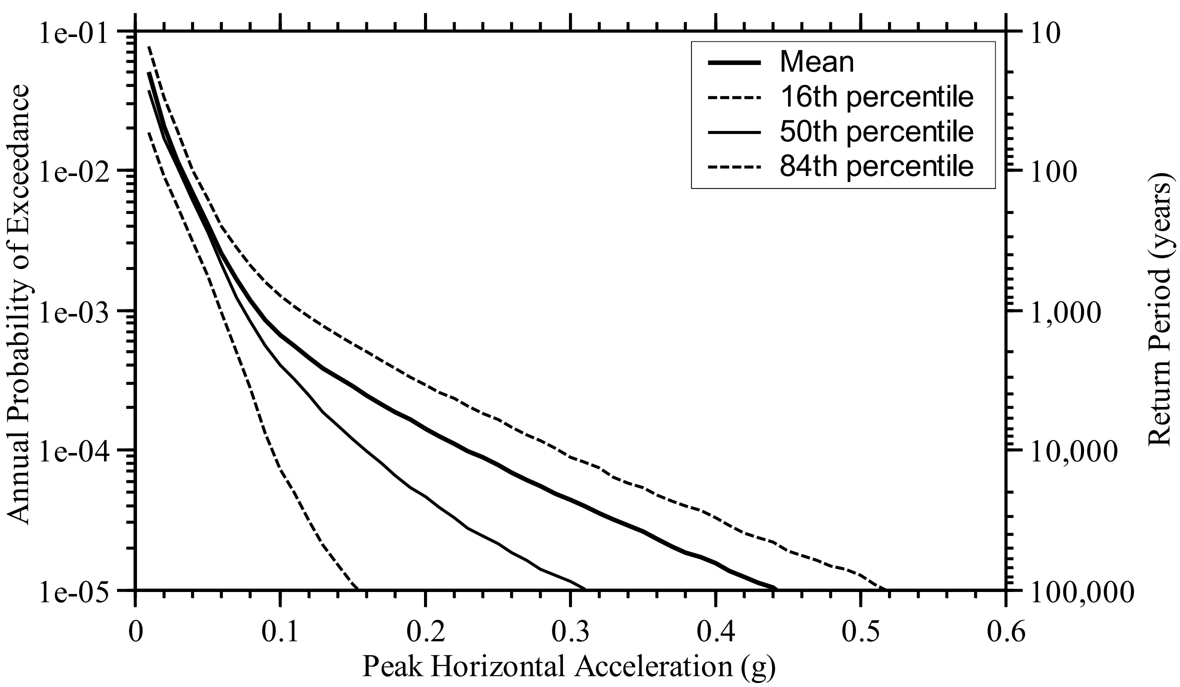

Figure 37: PHA hazard curves for Success Dam. Mean, median, 16th- and 84th-percentile values indicated.

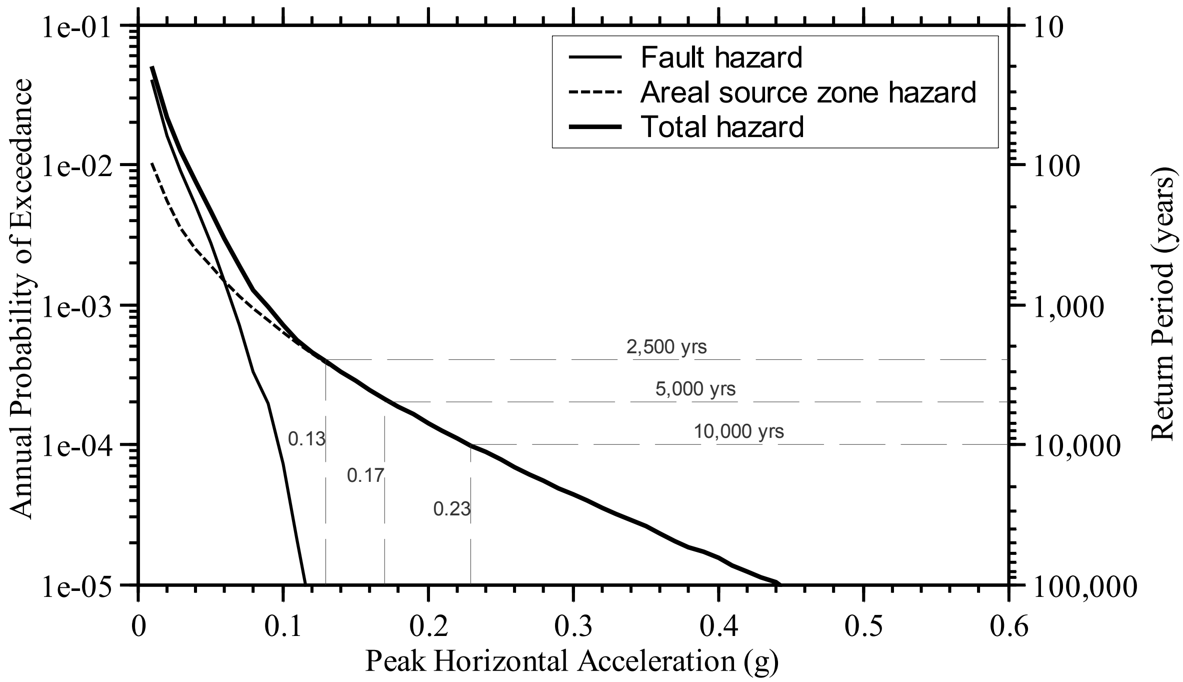

Figure 38: Mean PHA hazard curves from fault sources, areal source zone seismicity and total mean hazard for Hungry Hollow Reservoir.

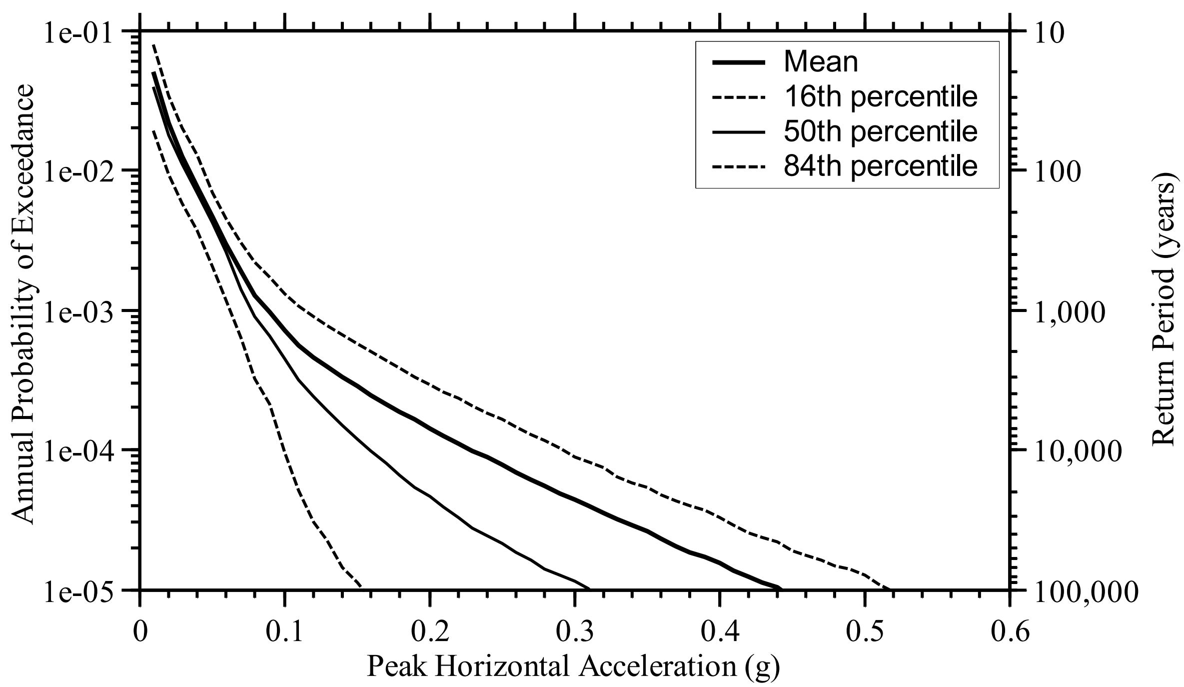

Figure 39: PHA hazard curves for Hungry Hollow Reservoir. Mean, median, 16th- and 84th-percentile values indicated.

Table 6: PHA Accelerations at the subject sites for selected AFEs/return periods

Site	4E-4 2,500 yrs	2E-4 5,000 yrs	1E-5 10,000 yrs
New Melones (NM)	0.19	0.31	0.44
Montgomery Reservoir (MR)	0.13	0.18	0.23
Mammoth Pool Expansion (ME)	0.14	0.18	0.23
Kerckhoff (KD)	0.13	0.17	0.23
Fine Gold Creek Dam (KD)	0.13	0.17	0.23
Temperance Flat Dam (TF)	0.13	0.17	0.23
Dinkey Creek Dam (DC)	0.13	0.18	0.23
Friant Dam (FD)	0.13	0.17	0.23
Big Dry Creek Reservoir (BD)	0.13	0.17	0.23
New Rogers Crossing (NR)	0.13	0.17	0.23
Pine Flat Dam (PF)	0.13	0.17	0.23
Mill Creek (MC)	0.13	0.17	0.23
Terminus Dam (TD)	0.13	0.17	0.23
Dry Creek Dam (DRC)	0.13	0.17	0.23
Yokohl Creek Dam (YC)	0.13	0.18	0.23
Success Dam (SD)	0.13	0.17	0.23
Hungry Hollow Reservoir (HH)	0.13	0.17	0.23

5.0 References

Anderson, L.W. and Piety, L.A., 2001. Geologic seismic source characterization of the San Luis-O'Neill area, eastern Diable Range, California for B.F. Sisk and O'Neill Forebay dams, San Luis Unit, Central Valley Project, California: Report 2001-2, U. S. Bureau of Reclamation, Denver, CO, 12 pp. 76.

CDMG, 1966. Geologic map of California (1:2,500,000 scale).

Cornell, C.A., 1968. Engineering seismic risk analysis: *Bulletin of the Seismological Society of America*, **58**, p. 1583-1606.

DePolo, C. M., 1994. The maximum background earthquake for the Basin and Range Province, western North America: *Bulletin of the Seismological Society of America*, **84**, p. 466-472.

Jennings, C. W., 1977. Geologic Map of California, 1:750,000: California Division of Mines and Geology, Geologic Data Map No.2.

Jennings, C.W., 1994. Fault activity map of California and adjacent areas, with location and ages of recent volcanic eruptions: California Department of Conservation, Division of Mines and Geology, Geologic Data Map No. 6, scale 1:750,000.

McGuire, R. K., 1974. Seismic structural response risk analysis incorporating peak response regressions on earthquake magnitude and distance: Massachusetts Institute of Technology, Department of Civil Engineering, Research Report No. R74-51.

McGuire, R.K., 1978. FRISK: Computer program for seismic analysis using faults as earthquake sources, U.S. Geological Survey Open File Report No. 78-1007, 62 pp.

Peterson, M. D., W. A. Bryant, C. H. Cramer, T. Cao, M. S. Reichle, A. D. Frankel, J. J. Lienkamper, P. A. McCrory, and D. P. Schwartz, 1996. Probabilistic seismic hazard assessment for the State of California, California Division of Mines and Geology, Open-File Report 96-08; (issued jointly as: U. S. Geological Survey, Open-File Report 96-706), Sacramento, California, 33 pp.

Sadigh, K., C. Y. Chang, J. A. Egan, F. Makdisi, and R. R. Youngs, 1997. Attenuation relationships for shallow crustal earthquakes based on California strong motion data: *Seismological Research Letters*, **68**, p. 180-189.

Sneddon, 2001. Screening-Level Seismotectonic and Ground Motion Evaluation for New Melones Dam, Central Valley Project, California: Technical Memorandum No. D8330-2001-11, U. S. Bureau of Reclamation, Denver, CO, 12 pp.