TECHNICAL SERVICE CENTER
Geotechnical Services
Geophysics, Paleohydrology, and Seismotectonics Group
Denver, Colorado

Technical Memorandum No. D8330-2000-006

Probabilistic Ground Motion Evaluation For Horsetooth,
Spring Canyon, Soldier Canyon, and Dixon Dams,
Colorado-Big Thompson Project,
North-Central Colorado

Prepared by
Jon P. Ake
Ute Vetter

U.S. Department of the Interior
Bureau of Reclamation

February 2000
RECLAMATION'S MISSION

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

DEPARTMENT OF THE INTERIOR'S MISSION

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. Administration.
Probabilistic Ground Motion Evaluation for Horsetooth, Soldier Canyon, Dixon, and Spring Canyon Dams, Colorado-Big Thompson Project, north-central Colorado

Prepared By

Jon Ake
Seismologist

Ute Vetter
Geophysicist

Peer Review

Roland LaForge
Geophysicist

Fred Hawkins
Geologist
Probabilistic Ground Motion Evaluation for Horsetooth, Soldier Canyon, Dixon, and Spring Canyon Dams, Colorado-Big Thompson Project, north-central Colorado

1.0 Introduction and Scope

This memorandum presents earthquake loading parameters for Horsetooth, Soldier Canyon, Dixon and Spring Canyon Dams, north-central Colorado. The results of this study are based on all presently available information and are appropriate for use in all levels of dam safety evaluations. The results of this investigation supersede all previous studies.

Horsetooth, Soldier Canyon, Spring Canyon, and Dixon Dams are located in Larimer County, north-central Colorado (Figure 1). The subject dams impound Horsetooth Reservoir and are located on the western margin of the city of Fort Collins.

A probabilistic seismic hazard assessment including all relevant seismic sources was used to determine the seismic hazard at these dams. Previous investigations have concluded no faults in the area are considered to be potentially significant sources of strong ground shaking or capable of producing surface faulting in the immediate vicinity of the dams (Unruh et al., 1996). Consequently, this study has focused on the hazard posed to the dams by strong ground shaking from areal earthquake source zones. The results of this study are presented as hazard curves of peak horizontal acceleration (PHA), 5%-damped uniform hazard response spectra (UHS) for selected annual frequencies of exceedence (AFE), and acceleration time histories consistent with the UHS.

2.0 Seismic Sources

2.1 Tectonic Setting
The subject dams lie along the boundary between the Southern Rocky Mountains and the Great Plains physiographic provinces (Figure 1). The Southern Rocky Mountains province extends from south-central Wyoming southward into northern New Mexico, is bounded on the west by the Colorado Plateau, and its eastern boundary defines the eastern margin of the North American Cordillera. The Great Plains slope gently eastward in this area away from the mountain front towards the mid-continent.

The present physiography of the region appears to have developed since the late Miocene (Unruh et al. 1996; Tweto, 1979; Eaton, 1986). Late Cenozoic crustal extension and normal faulting have been superimposed on preexisting structures associated with Laramide crustal shortening. A number of late Cenozoic or suspected Quaternary faults in Colorado lie along the traces of Laramide-age thrust or reverse faults (Kirkham and Rogers, 1981). Zoback and Zoback (1989) include the Southern Rocky Mountain region in their larger Rocky Mountain/Intermontane tectonic province. This province is characterized by generally east-west tensile crustal stresses, high topography, high heat flow, normal faulting, and low to moderate levels of seismicity. This portion of the Great Plains province is included by Zoback and Zoback (1989) within their Mid-Plate stress province.
Southern Rocky Mountains

Horsetooth Reservoir
Soldier Canyon
Oxen Canyon
Spring Canyon

Carter Lake Reservoir

FORT COLLINS

Great Plains

BOULDER

Figure 1. Location of subject dams and major tectonic elements
This region is characterized by very low rates of seismicity and deformation and low heat flow. The boundary between the Cordilleran and Mid-Plate stress provinces is not well defined, as very little stress data are available for the central Great Plains. What little data exists for the province (borehole breakout data from the Great Plains of Oklahoma and Texas and a single focal mechanism from Kansas) suggests east-west oriented maximum principal stress (Unruh et al., 1996). This is in marked contrast to the east-northeast--west-southwest oriented minimum principal stress inferred for the Cordilleran within Colorado (Wong, 1991; Goter et al., 1986; Ake et al., 1994; Ake et al., 1997).

LaForge (1996) provides a good summary/discussion of seismicity within stable continental interiors and the central United States (CUS) in particular. The primary source of earthquake-inducing stresses in the mid-continent is clearly related to large-scale tectonic processes; however, the exact mechanisms are not well understood at this time. Some possible mechanisms that have been suggested include: isostatic adjustment due to glacial rebound (Richardson et al., 1979), movements in the ductile lower crust resulting in high stresses in the rigid upper crust (Zoback, 1987), and hydrologic and/or thermal transients near the base of the crust resulting in stress perturbations in the upper crust (Long, 1988).

2.2 Fault Sources
A comprehensive, deterministic seismotectonic evaluation was conducted for Rattlesnake and Flatiron Dams by Unruh et al. (1996) (Figure 1). The region evaluated in detail in that study included the area around Horsetooth Reservoir. As part of their investigations, Unruh et al. conducted a thorough review of available geologic and tectonic data (Kirkham and Rogers, 1981, 1985; Colman, 1985), contacted additional researchers working in the area, performed photogeologic interpretation, and conducted aerial reconnaissance as well as field reconnaissance and mapping. The present study relies entirely on the results of Unruh et al. (1996) for fault characterization, and much of this section is abstracted from that report.

Within a distance of approximately 100 km of Rattlesnake and Flatiron dams, Unruh et al. (1996) evaluated 20 potential seismic sources (Table 3-1 of Unruh et al., 1996). Many of these potential sources were located quite some distance from the subject dams. Eighteen of these structures were located within the Southern Rocky Mountains province and two (the Valmont fault and the Rocky Mountain Arsenal "fault") were within the Great Plains province. Unruh et al. concluded none of the surface faults were active and capable of producing significant earthquakes. Only the zone of persistent microseismicity near the Rocky Mountain Arsenal (RMA) was designated as potentially active. For the present study we have chosen to include seismicity associated with the RMA as part of one of the areal (background) source zones. Areal source zone characterization is discussed in more detail in Section 2.3.

Of particular, potential importance to the seismic hazard at the dams impounding Horsetooth Reservoir are the east segment of the Buckhorn Creek, Bellvue, and Rist Canyon faults. All of these faults are in the immediate vicinity of Horsetooth Reservoir and will be discussed separately below (Figure 2).

Bellvue Fault
The interpretation of this structure by Unruh et al. (1996) is based on evaluation of existing litera-
Figure 2. Faults in the vicinity of Horsetooth Reservoir. Figure from Unruh et al. (1996). Scale 1:62,500.
ture as well as aerial and field reconnaissance. The Bellvue fault strikes north-south and passes several hundred meters to the east of Horsetooth and Soldier Canyon dams. The fault locally juxtaposes Jurassic Morrison Formation over Cretaceous Lytle Formation and Dakota Group. Total reverse displacement appears to be approximately 100 m (Braddock et al., 1989). The fault has a length of at least 3 km. Unruh et al. (1996) reported an absence of scarps, lineaments or other anomalous features during their aerial survey. To the north of the reservoir, the fault is mapped beneath Holocene floodplain and terrace deposits of the Cache La Poudre River. The fault is not expressed as scarps or lineaments in the late Quaternary surface adjacent to the river (Braddock et al., 1989; Unruh et al., 1996). Braddock et al. (1989) interpret this fault to have developed as a minor accommodation structure during development of Laramide-age folds in this area. Unruh et al. (1996) concurred with this interpretation and concluded this fault was not an active seismogenic source.

Rist Canyon Fault
The Rist Canyon fault strikes north-northwest and extends westward from Horsetooth Reservoir into the Front Range. The east-dipping fault has a length of approximately 9 km and less than 100 m of reverse dip-slip separation in the vicinity of the reservoir. To the north of the reservoir the fault is mapped as juxtaposing Precambrian basement rocks against Paleozoic-age Fountain Formation sedimentary rocks (Braddock et al., 1989). Braddock et al. (1989) show the southeastern end of the fault (which passes near Horsetooth Dam) to be a bedding-parallel feature located within the Paleozoic sedimentary rocks, indicating fault displacement dies out to the southeast (Unruh et al., 1996). Unruh et al. (1996) observed no scarps, lineaments, or other anomalous geomorphic features along the fault trace during aerial reconnaissance. The fault trace is mapped beneath Quaternary sediments in Empire Gulch, north of Horsetooth Dam. Unruh et al. (1996) reported no scarps or lineaments in the Holocene floodplain or low terrace surfaces in the Empire Gulch locality. They concluded the Rist Canyon fault was not an active seismogenic structure.

Buckhorn Creek Fault
The Buckhorn Creek fault as described by Braddock et al. (1989) is a west-northwest-striking fault that extends westward from Horsetooth Reservoir into the Front Range. In the vicinity of Horsetooth Reservoir (the southeastern end of the fault) Precambrian crystalline rocks are juxtaposed against Paleozoic sedimentary rocks. Outcrop patterns and regional structural relationships suggest a moderate to steep dip to the north for this fault (Unruh et al., 1996). Total length of the fault may be as much as 47 km (Unruh et al., 1996). Unruh et al. (1996) observed no scarps, lineaments or other anomalous geomorphic features during aerial reconnaissance of the eastern portion of the Buckhorn Creek fault. The trace of the fault is crossed by several streams draining into Inlet Bay at the southeastern end of Horsetooth Reservoir. Several unfaulted, late Pleistocene to Holocene-age, fluvial terraces are present adjacent to the streams. The nearby Redstone Creek drainage also contained unfaulted late Quaternary surfaces and deposits. Based on these observations, Unruh et al. (1996) concluded the Buckhorn Creek fault was not an active seismogenic structure.

Based upon the lack of existing evidence for late Quaternary displacement on faults close enough to the subject dams to produce ground motions of engineering interest, no fault sources have been included in the present assessment.
Figure 3. Location of Horsetooth Reservoir (shaded triangle) relative to areal source zones used in hazard assessment. Southern Rocky Mountains source zone is modified from Hawkins and Vetter (1998) and Ake et al. (1999). Seismicity of magnitude 1 and above also plotted.

2.3 Areal Source Zones
To account for the hazard from earthquakes not associated with previously identified fault sources, regional (areal) source zones were incorporated into the analysis. The four subject dams lie near the tectonic/physiographic boundary between the Southern Rocky Mountains and the Great Plains (Figure 1). Based on tectonic characteristics (discussed in Section 2.1), these two regions were treated as discrete source zones (shown on Figure 3). The parameters which need to be defined for each areal source zone are maximum magnitude, recurrence model, and associated seismicity rates.
Most of the original data sources used in this study report earthquake size in terms of Richter magnitudes ($M_L$). When other magnitude scales were cited in addition to or in lieu of $M_L$, e.g. $m_b$ or $M_D$ (the coda duration-based magnitude for recent, smaller events), the largest of the cited magnitudes for each event was used. Magnitudes of earthquakes prior to widespread instrumental recording were transformed from the maximum felt intensities (Modified Mercalli Intensity (MMI) or $I_{max}$), using a formula originally developed by Gutenberg and Richter (1956) for southern California earthquakes, as adjusted to Colorado attenuation conditions by McGuire (1993) ($M_f = 2/3 \text{MMI} + 0.63$). The relationship relates maximum felt intensity to an equivalent Richter magnitude. Uncertainties in magnitudes based only on felt reports are estimated to be at least 0.5 to 1.0 magnitude unit. $M_L$, $M_D$, and $M_f$ are assumed to be equivalent. All estimated magnitudes given henceforth in this report are moment magnitudes ($M_W$), which are assumed to be equivalent to $M_L$ within the magnitude range of interest.

Data sources used in the compilation of historical seismicity were: the Decade of North American Geology (DNAG) catalog (Engdahl and Rinehart, 1991) covering the time period through 1985; the National Earthquake Information Center Preliminary Determination of Epicenters (NEIC/PDE) listings from 1985 to 1999; National Oceanic and Atmospheric Administration (NOAA) data files; the earthquake compilation of Kirkham and Rogers (1985), covering Colorado earthquakes from 1867 to 1985; the Earthquake History of the United States, compiled by Coffman and others (1982); and revised by Stover and Coffinan (1993). Additional recent data came from the local networks operated by Reclamation in the Paradox Valley and Ridgway Dam areas and by MicroGeophysics Corporation in the Colorado Front Range (under contract to the Denver Water Department).

2.3.1 Southern Rocky Mountains Source Zone

The Southern Rocky Mountains occupy most of western Colorado and include portions of northern New Mexico and southern Wyoming. The area is bounded to the east by the Great Plains and to the west by the Colorado Plateau. The Rio Grande Rift, a portion of the Basin and Range Province, protrudes into the Southern Rocky Mountains from the south (Figure 4). As discussed in Section 2.1, this province is characterized by generally east-west tensile crustal stresses, high topography, high heat flow, normal faulting, and low to moderate levels of seismicity. Recurrence statistics for a portion of this region were previously developed by Hawkins and Vetter (1998) and updated by Ake et al. (1999). They designated this areal zone as the Southern Rocky Mountains source zone. For the present study, in order to better represent the tectonic setting of the subject dams, the Southern Rocky Mountains zone used by Ake et al. (1999) was revised slightly (Figure 4). Portions of the source zone of Ake et al. (1999) in southern-most Colorado and northern New Mexico were deleted and the region was extended northward to include northern Colorado and the Laramie Mountains in southern Wyoming. The area of the zone is approximately 99,000 km$^2$. The recurrence parameters determined by Ake et al. (1999) were $a = -2.68$ and $b = 0.707$, where $a$ is normalized to annual number of events per km$^2$. The largest event in the data set for the present study area is the November 8, 1882 $M_f$ 6.2 earthquake that occurred somewhere in north-central Colorado (Kirkham and Rogers, 1985).

2.3.2 Central Great Plains Source Zone

A region encompassing the eastern third of Colorado was selected to develop recurrence statistics for the central Great Plains source zone (Figures 3 and 4). The tectonics of eastern Colorado have
Figure 4. Comparison of tectonic features and areal source zones used in hazard assessment. Tectonic elements indicated in blue. Southern Rocky Mountains source zone from Hawkins and Vetter (1998) and Ake et al. (1999) shown in red, Southern Rocky Mountains zone of present study shown in black. Colorado-Great Plains source zone of present study also shown in black. Location of Horsetooth Reservoir indicated by shaded red triangle.
not been studied in detail. However, based on the limited information available, this region appears to have generally consistent tectonic characteristics. The Great Plains of Colorado are characterized by a relatively low level of seismicity and are inferred to have generally east-north-east directed compressional stresses. The region may not be totally devoid of seismic hazard; Crone et al. (1997) have recently reported late Quaternary/Holocene activity on the Cheraw fault in southeastern Colorado (Widmann et al., 1998).

A more extensive area of the northern Great Plains, covering portions of northeastern Wyoming, eastern Montana, northern Nebraska and North and South Dakota, was used by LaForge (1996) for a seismic hazard assessment for a number of dams located in the northern Great Plains. LaForge (1996) developed recurrence relationships for two sub-regions within his larger study area. He computed a normalized $a$-value of -3.208 and a $b$-value of 0.843 for the northern portion of his study area, and for southern South Dakota he determined $a = -2.737$ and $b = 0.829$ (although these values were developed using $m_b$ as the magnitude scale). A smaller region, covering only the southern part of the Colorado Great Plains, was studied by Unruh and others (1994) from which they determined recurrence parameters of $a = -2.36$ and $b = 1.0$. The largest event in the data set for the present analysis is the 1966 $m_b$ 5.3 earthquake that occurred north of Denver in the Derby area.

2.3.2.1 The Rocky Mountain Arsenal Earthquakes
The most remarkable earthquakes that have occurred in this area were connected with fluid injection into the Rocky Mountain Arsenal well northeast of Denver. A significant episode of seismic activity began after fluid injection at the Rocky Mountain Arsenal (RMA) northeast of Denver started in 1962 and continued after the end of fluid injection in 1966. Many of these earthquakes were felt over the years in the Denver area and some caused damage, which ultimately led to the termination of the fluid injection experiment in 1966. Events of MMI (felt intensity) VI occurred in 1962, 1965, 1966, 1967 and 1981; in 1967 the strongest event reached MMI VII (magnitude 5.3).

The 3.67 km deep well was drilled through the sedimentary rocks of the Denver Basin into fractured Precambrian basement rocks (which was the target injection horizon). The earthquakes occurred within a broad zone, centered on the Rocky Mountain Arsenal well (Healy et al., 1968). A temporary seismic network was operated in the area during 1966. This allowed Healy et al. (1968) to locate a number of events. These events defined a 10-km-long, 3-km-wide zone with depths between 4.5 and 5.5 km. Healy et al. (1968) reported focal mechanisms based on P-wave first motions consistent with right-lateral strike slip on a vertical fault striking northwest (parallel to the epicentral trend). This solution is consistent with northeast directed minimum principal stress.

An especially interesting (and as yet unexplained) observation is that small earthquakes in the area sporadically continued to occur (but with a decreasing frequency) for at least as long as monitoring was available (through 1993), more than 25 years after the termination of deep-well fluid injection. Bollinger et al. (1983) monitored and relocated a number of events using a temporary seismograph array in the early 1980s. These earthquakes were located within the same zone as the 1966-67 events, approximately 5-10 km northwest of the RMA well. A well constrained composite focal mechanism for these events indicated oblique-reverse faulting on a northeast or east-
southeast trending focal plane. The change in focal mechanism may be due to the presence of multiple fracture systems within the source zone, or could represent the return to ambient (i.e. pre-injection) stress conditions (Bollinger et al., 1983).

The evidence that the RMA earthquakes were associated with the high-pressure injection appears inescapable (Hsieh and Bredehoeft, 1981). However, due to the duration of enhanced seismicity and distance from the well, it also appears that pre-existing tectonic stresses played a significant role in the observed seismicity. The presence of high fluid pressures acts to reduce the normal stress across existing fault planes thus allowing slip to take place at lower applied shear stresses than otherwise would occur. However, if the existing deviatoric stresses are not sufficiently high, merely reducing the normal stress by a moderate amount will not be capable of producing seismic slip.

Unruh et al. (1996) chose to treat the RMA seismicity separately by defining a “fault” in the vicinity of the zone described originally by Healy et al. (1968). Due to the distance from the subject dams and the modest $M_{\text{max}}$ assigned ($M_W 6.0$), the resulting contribution to the hazard for the Horsetooth area would be negligible. Based upon the inference that fluid injection has merely accelerated the occurrence of earthquakes in this area, we have chosen to include some of the RMA events in the earthquake catalog and not treat the area around the RMA as a separate zone but include it within the broader Great Plains zone. As discussed above, the sequence in the RMA area persisted for much longer than would be expected for a typical mainshock-aftershock sequence. Hence application of a typical declustering algorithm would fail to link these events as part of a swarm or sequence. We included the first significant event of the RMA sequence (12/05/1962, $M_L 3.8$), the largest event observed in the area (08/09/1967, $m_b 5.3$), and the largest of the events in the 1980's (04/02/1981, $M_L 3.8$). The selection of which events to include was arbitrary, but was influenced by a desire to reflect the persistent nature of seismicity in the area (hence the choice of first and last significant events) and the potential size of events in the area (hence the largest event in the sequence).

2.3.3 Determination of recurrence parameters
A truncated exponential form of the Gutenberg-Richter recurrence relationship ($\log N = a - bM$), was assumed for both source zones. A curve having the form,

\[ N(M) = 10^a \cdot (10^{-b \cdot M_o} - 10^{-b \cdot M_{\text{max}}}) \]

where $N(M)$ is the number of events per year of magnitude $M$ or larger, $a$ and $b$ are constants from the Gutenberg-Richter relationship, $M_o$ is the minimum magnitude in the data set, and $M_{\text{max}}$ is the maximum magnitude, was fit to the earthquake data for each zone. The maximum magnitude of non-surface rupturing earthquakes in the western U. S. has been estimated to be $M_W 6.5$ (DePolo, 1994). Repeated ruptures on a fault of earthquakes larger than this are assumed to produce identifiable features on the earth’s surface. An $M_{\text{max}}$ value of 6.5 was assumed for the southern Rocky Mountains source zone. Determination of $M_{\text{max}}$ for the eastern Great Plains of Colorado was more problematic. As described briefly above and in more detail in LaForge (1996), the process of earthquake generation is poorly understood in the low seismicity regions of the central U.S. This makes estimation of the maximum earthquake size especially difficult. LaForge (1996) assumed a maximum magnitude of ~6.0 for the southern South Dakota por-
tion of the northern Great Plains. We have assumed a value of $M_W 6.5$ for the Great Plains of Colorado. Based on crustal thickness, lower heat flow, and the potential for relatively higher stress drops in the eastern and central United States, we find it difficult to argue for a smaller $M_{\text{max}}$ than we assume for the Southern Rocky Mountains zone.

In order to model earthquake occurrence as a random process, the catalog must approximate random space-time characteristics. It is therefore necessary to identify and delete dependent events of foreshock-mainshock-aftershock sequences and swarms. A declustering algorithm based on Reasenberg (1985) was used as described in more detail in LaForge and Ake (1999). Earthquake recurrence statistics for both source zones were computed from the declustered catalogs using unequal observation periods for different magnitude ranges and the maximum likelihood method (Weichert, 1980). Data variances were computed as suggested in Weichert (1980). Activity rate uncertainty bounds were calculated using the method of Bollinger and others (1989).

The completeness periods for the Southern Rocky Mountains source zone were modified from those used by Hawkins and Vetter (1998) and were based on plots of earthquakes in discrete magnitude bins as a function of time. The resulting completeness estimates were similar to those suggested by Engdahl and Rinehart (1991). The completeness periods assumed for the Great Plains source zone were similar to those used by LaForge (1996) which were modified slightly from Engdahl and Rinehart (1991) and EPRI (1986).

Tables 1 and 2 show the completeness periods and event counts in each magnitude bin for the revised recurrence calculations. Figures 5 through 8 show the incremental and cumulative recurrence curves, respectively. The resulting recurrence parameters are listed in Table 3 and the return periods in Tables 4 and 5. Comparison of Tables 4 and 5 shows the earthquake activity rate is somewhat lower in the Colorado Great Plains zone than in the Southern Rocky Mountains. The revised recurrence values summarized in Tables 3 and 4 for the Southern Rocky Mountain source zone differ little from those computed by Ake et al. (1999) for the source zone shown in Figure 4. The values estimated for the Great Plains of Colorado (Tables 3 and 5) are only slightly different than those determined previously by LaForge (1996) for the southern South Dakota region of the northern Great Plains.
Table 1: Completeness Periods and Event Counts Used in Recurrence Calculation for Southern Rocky Mountains Source Zone

<table>
<thead>
<tr>
<th>Magnitude Range</th>
<th>Completeness Period</th>
<th>Number of Earthquakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 - 3.5</td>
<td>3/1983 - 12/1999</td>
<td>18</td>
</tr>
<tr>
<td>3.5 - 4.0</td>
<td>1/1962 - 12/1999</td>
<td>6</td>
</tr>
<tr>
<td>4.0 - 4.5</td>
<td>1/1950 - 12/1999</td>
<td>9</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>1/1950 - 12/1999</td>
<td>3</td>
</tr>
<tr>
<td>5.0 - 5.5</td>
<td>1/1925 - 12/1999</td>
<td>1</td>
</tr>
<tr>
<td>5.5 - 6.0</td>
<td>1/1900 - 12/1999</td>
<td>2</td>
</tr>
<tr>
<td>6.0 - 6.5</td>
<td>1/1870 - 12/1999</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2: Completeness Periods and Event Counts Used in Recurrence Calculations for the Great Plains of Colorado

<table>
<thead>
<tr>
<th>Magnitude Range</th>
<th>Completeness Period</th>
<th>Number of Earthquakes</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 - 3.5</td>
<td>1/1983 - 12/1999</td>
<td>6</td>
</tr>
<tr>
<td>3.5 - 4.0</td>
<td>1/1975 - 12/1999</td>
<td>4</td>
</tr>
<tr>
<td>4.0 - 4.5</td>
<td>1/1962 - 12/1999</td>
<td>2</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>1/1962 - 12/1999</td>
<td>1</td>
</tr>
<tr>
<td>5.0 - 5.5</td>
<td>1/1925 - 12/1999</td>
<td>1</td>
</tr>
<tr>
<td>5.5 - 6.0</td>
<td>1/1900 - 12/1999</td>
<td>0</td>
</tr>
<tr>
<td>6.0 - 6.5</td>
<td>1/1870 - 12/1999</td>
<td>0</td>
</tr>
</tbody>
</table>
Table 3: Recurrence Parameters for Southern Rocky Mountains and Great Plains of Colorado Seismic Source Zones

<table>
<thead>
<tr>
<th>Source</th>
<th>Parameter</th>
<th>Incremental</th>
<th>Cumulative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern Rocky Mountains</td>
<td>a (σ)</td>
<td>-2.675 (.390)</td>
<td>-2.622 (.174)</td>
</tr>
<tr>
<td>Southern Rocky Mountains</td>
<td>b (σ)</td>
<td>.745 (.098)</td>
<td>.745 (.047)</td>
</tr>
<tr>
<td>Great Plains of Colorado</td>
<td>a (σ)</td>
<td>-2.757 (.659)</td>
<td>-2.759 (.281)</td>
</tr>
<tr>
<td>Great Plains of Colorado</td>
<td>b (σ)</td>
<td>.839 (.171)</td>
<td>.839 (.078)</td>
</tr>
</tbody>
</table>

Table 4: Earthquake Recurrence Data for Southern Rocky Mountains Source Zone, with 95% Confidence Bounds

<table>
<thead>
<tr>
<th>Magnitude range (M_w)</th>
<th>Predicted Return Period (years)</th>
<th>Upper Bound</th>
<th>Lower Bound</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 - 3.5</td>
<td>1.3</td>
<td>1.9</td>
<td>0.8</td>
<td>0.9</td>
</tr>
<tr>
<td>3.5 - 4.0</td>
<td>3.0</td>
<td>4.1</td>
<td>2.2</td>
<td>6.3</td>
</tr>
<tr>
<td>4.0 - 4.5</td>
<td>7.0</td>
<td>10.0</td>
<td>5.0</td>
<td>5.6</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>16.5</td>
<td>26.7</td>
<td>10.2</td>
<td>16.7</td>
</tr>
<tr>
<td>5.0 - 5.5</td>
<td>38.9</td>
<td>75.8</td>
<td>19.9</td>
<td>75.0</td>
</tr>
<tr>
<td>5.5 - 6.0</td>
<td>92</td>
<td>219</td>
<td>38</td>
<td>50</td>
</tr>
<tr>
<td>6.0 - 6.5</td>
<td>216</td>
<td>636</td>
<td>73</td>
<td>130</td>
</tr>
</tbody>
</table>
Figure 5. Incremental recurrence curve for Southern Rocky Mountains areal source zone.

Figure 6. Cumulative recurrence curve for Southern Rocky Mountains areal source zone.
Figure 7. Incremental recurrence curve for Colorado Great Plains areal source zone.

Figure 8. Cumulative recurrence curve for Colorado Great Plains areal source zone.
Table 5: Earthquake Recurrence Data for the Colorado Great Plains Source Zone, with 95% Confidence Bounds

<table>
<thead>
<tr>
<th>Magnitude range (M_w)</th>
<th>Predicted Return Period (years)</th>
<th>Upper Bound</th>
<th>Lower Bound</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0 - 3.5</td>
<td>2.6</td>
<td>5.1</td>
<td>1.4</td>
<td>2.8</td>
</tr>
<tr>
<td>3.5 - 4.0</td>
<td>6.9</td>
<td>11.7</td>
<td>4.1</td>
<td>6.3</td>
</tr>
<tr>
<td>4.0 - 4.5</td>
<td>18.2</td>
<td>34.3</td>
<td>9.6</td>
<td>19.0</td>
</tr>
<tr>
<td>4.5 - 5.0</td>
<td>47.7</td>
<td>118.7</td>
<td>19.2</td>
<td>38.0</td>
</tr>
<tr>
<td>5.0 - 5.5</td>
<td>125</td>
<td>436</td>
<td>36</td>
<td>75</td>
</tr>
<tr>
<td>5.5 - 6.0</td>
<td>329</td>
<td>1642</td>
<td>66</td>
<td>none observed</td>
</tr>
<tr>
<td>6.0 - 6.5</td>
<td>864</td>
<td>6238</td>
<td>120</td>
<td>none observed</td>
</tr>
</tbody>
</table>

3.0 Probabilistic Seismic Hazard Assessment

The probabilistic seismic hazard analysis (PSHA) performed for Spring Canyon, Soldier Canyon, Dixon, and Horsetooth Dams follows the basic concepts outlined in Cornell (1968) and McGuire (1974, 1978). Formal error distributions in the random seismicity rates and ground motion attenuation functions were directly incorporated by complete enumeration.

3.1 Ground Motion Attenuation

The boundary between the Cordillera and Great Plains not only defines a significant physiographic and tectonic boundary but is also inferred to be an important boundary in crustal wave propagation (i.e. attenuation) properties. For this level of evaluation, two attenuation functions were used for the hazard calculations in each zone. The ground motion computations for the Southern Rocky Mountain zone were carried out assuming rock site conditions, the eastern U.S. relationships used do not differentiate between site types.

The attenuation relationships of Sadigh et al. (1997) and Spudich et al. (1999) were chosen to estimate ground motion values in the Southern Rocky Mountains zone. Both of these rely heavily on data obtained in the western United States. The relationship of Spudich et al. (1999) was developed exclusively for extensional tectonic regimes. Because we infer the regional stress pattern in the Southern Rocky Mountains to be one of northeast-directed extension (Section 2.1), we favor the extensional relationship of Spudich et al. (1999). We assign subjective probabilities of 0.6 to Spudich et al. (1999) and 0.4 to Sadigh et al. (1997). The distance measure used in the Sadigh et al. (1997) relationship is based on closest distance to the rupture surface. To estimate distances for
This relationship, earthquake foci are assumed to be 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 (Kanamori and Anderson, 1975), described in detail in LaForge and Ake (1999). The relationship of Spudich et al. (1999) uses the closest distance from the site to the surface projection of the fault as distance measure (the so-called “Joyner-Boore” distance), therefore no assumptions regarding focal depth need to be made.

Estimation of ground motion attenuation within the central and eastern U. S. has proven to be a difficult problem. The paucity of strong motion recordings from the stable continental interior has made estimation of crustal attenuation characteristics problematic. All of the relationships published to date for the central and eastern U. S. rely at least in part on theoretical modeling to supplement the meager data base. For this assessment we have used the eastern U. S. relationships of Atkinson and Boore (1995) and EPRI (1993) with equal weights assigned to each. The same relationships were used by LaForge (1996) and additional details on the functions are contained in that document. In the Atkinson and Boore (1995) relationship the depth was fixed at 10 km. In the EPRI (1993) formula, a focal depth distribution for non-margin regions within the eastern U. S. was developed (5-30 km). Depth is treated as a random quantity with weights assigned based on the derived focal depth distribution for these areas.

4.0 Results

Because no fault sources are included in this analysis and the relative distance from all four of the subject dams to the areal source zone boundaries is essentially identical, results are presented only for Horsetooth Dam. The results for the other dams that impound Horsetooth Reservoir (Soldier Canyon, Spring Canyon and Dixon) can be assumed to be identical.

The contribution to PHA hazard for the magnitude range 5.0-6.5 by source zone is plotted in Figure 9. The hazard from the Southern Rocky Mountains source zone is greater than that from the Great Plains zone. Since the dams are located near the boundary between the two source zones, the contribution from each would be expected to be equal if the activity rates were similar, however, as discussed in Section 2.3, the activity rate in the Southern Rocky Mountain zone is greater than that in the Great Plains zone. This effect is somewhat offset however, by the larger ground motions predicted by the central-eastern U.S. attenuation functions for a given magnitude and distance. The result is only a slightly larger contribution from the Southern Rocky Mountains zone. The uncertainty in PHA hazard at the Horsetooth site is shown in Figure 10. Figures 9 and 10 show that the hazard at this site is low relative to many other sites in the western United States.

To properly evaluate the likelihood of liquefaction and select representative time histories, it is necessary to understand the contribution to the total hazard by magnitude. Figures 11-14 are analogous to Figures 9 and 10 but with the hazard broken out into two magnitude intervals, 5.0-6.0 and 6.0-6.5. Comparison of Figures 11 and 13 shows the hazard is dominated by the smaller magnitude earthquakes (due to the more frequent occurrence of these events). The Southern Rocky Mountains zone dominates the hazard for both magnitude ranges. Table 6 summarizes PHA results for all three magnitude ranges for selected annual frequencies of exceedence (AFE).

To facilitate evaluation of liquefaction hazard at the Horsetooth site, we have computed the annual
frequency of occurrence for four selected PHA intervals for each of the two magnitude ranges described above (M 5.0-6.0 and M 6.0-6.5). The results are summarized in Table 7.

Uniform hazard acceleration response spectra (UHS) were developed for two representative annual frequencies of exceedance: $1 \times 10^{-4}$ and $2 \times 10^{-5}$. These correspond to return intervals of 10,000 and 50,000 years, respectively. The contribution by source zone for an AFE of $2 \times 10^{-5}$ is shown in Figure 15. The different character of ground motions produced by the western U. S. (Sadigh et al. (1997) and Spudich et al. (1999)) and eastern U. S. (Atkinson and Boore (1995) and EPRI (1993)) attenuation relationships is evident from the figure. The mean UHS for each of the desired AFE are shown in Figure 16.

Table 6: Summary of PHA Values for Selected Annual Frequencies of Exceedence

<table>
<thead>
<tr>
<th>Annual Frequency of Exceedence (Return Period, yrs)</th>
<th>Mean Peak Horizontal Acceleration (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_W$ 5.0-6.5</td>
</tr>
<tr>
<td>$4 \times 10^{-4}$ (2500)</td>
<td>0.10</td>
</tr>
<tr>
<td>$1 \times 10^{-4}$ (10,000)</td>
<td>0.17</td>
</tr>
<tr>
<td>$2 \times 10^{-5}$ (50,000)</td>
<td>0.30</td>
</tr>
</tbody>
</table>
Figure 9. Mean PHA hazard curves for Horsetooth Dam, contribution by individual source zones, magnitude range 5.0-6.5.

Figure 10. Uncertainty in total PHA hazard for Horsetooth Dam, magnitude range 5.0-6.5.
Figure 11. Contribution to mean PHA hazard by individual source zones at Horsetooth Dam for the magnitude range: 5.0-6.0.

Figure 12. Uncertainty in PHA hazard for Horsetooth Dam, magnitude range: 5.0-6.0.
Figure 13. Contribution to mean PHA hazard by individual source zones at Horsetooth Dam for the magnitude range: 6.0-6.5.

Figure 14. Uncertainty in PHA hazard for Horsetooth Dam, magnitude range: 6.0-6.5.
Figure 15. Mean UHS for AFE of $2 \times 10^{-5}$ (return period of 50,000 yr) for Horsetooth Dam, magnitude range: 5.0-6.5. Contribution by source indicated.

Figure 16. Mean UHS for AFE of $2 \times 10^{-5}$ and $1 \times 10^{-4}$ for Horsetooth Dam, magnitude range: 5.0-6.5.
Table 7: Summary of Annual Frequency of Occurrence for PHA Range by Magnitude Interval

<table>
<thead>
<tr>
<th>Acceleration Interval (g)</th>
<th>Annual Frequency of Occurrence</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$M_w$ 5.0-6.0</td>
</tr>
<tr>
<td></td>
<td>$M_w$ 6.0-6.5</td>
</tr>
<tr>
<td>0.01-0.1</td>
<td>16%: $3.90 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>50%: $8.76 \times 10^{-3}$</td>
</tr>
<tr>
<td></td>
<td>Mean: $1.25 \times 10^{-2}$</td>
</tr>
<tr>
<td></td>
<td>84%: $1.41 \times 10^{-2}$</td>
</tr>
<tr>
<td>0.1-0.2</td>
<td>16%: $1.74 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>50%: $1.40 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>Mean: $3.25 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>84%: $4.72 \times 10^{-4}$</td>
</tr>
<tr>
<td>0.2-0.4</td>
<td>16%: $1.99 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>50%: $1.70 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>Mean: $6.65 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>84%: $8.96 \times 10^{-5}$</td>
</tr>
<tr>
<td>&gt; 0.4</td>
<td>16%: $2.40 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>50%: $1.35 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>Mean: $6.65 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>84%: $7.43 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

5.0 Suggested Accelerograms

The dynamic response of many structures depends not only on spectral amplitude, but on the phase content of the waveforms as well (Abrahamson and Bolt, 1985). To ensure sufficient variability in phase content for dynamic analyses, two appropriate, existing three-component strong motion recordings have been selected. In selecting acceleration time histories, consideration was given to providing a good spectral match near the natural period of the dam-foundation system, which is estimated to lie between 0.5 and 1.0 second for Horsetooth Dam. In order to better fit the target UHS with empirical accelerograms, a measure of acceleration response spectrum intensity similar to the acceleration spectrum intensity (ASI) of Von Thun et al. (1988) was defined between the period range of 0.5 and 1.0 sec. (denoted as ASI*). For the 10,000 yr ($1 \times 10^{-4}$ AFE) UHS, the target ASI* value is 88.2 cm/sec; the $2 \times 10^{-5}$ AFE (50,000 yr) value is 155.7 cm/sec. The mean UHS shown on Figure 16 were used as the target spectrum for selecting appropriate acceleration time histories.
The Del Valle Dam (toe) recordings of the 24 January 1980 Livermore, California, earthquake were selected for use as the 1x10^-4 AFE loadings at the Horsetooth site. The recordings have been scaled slightly (by a factor of 0.90) so that the average ASI* of the two horizontal components is equal to the target ASI*. The Del Valle site is listed as a thin (< 20 ft) soil site with a source-site distance of ~13 km in the data base of Silva (pers. comm., 1999). The M\(_w\) 5.8 Livermore earthquake was a strike-slip event. The scaled horizontal components of the Del Valle recordings of the Livermore event are compared to the target UHS in Figure 17; the three-component time history is shown on Figure 18.

The Palmer Avenue station recordings of the M\(_w\) 5.8, 22 July 1983 aftershock of the Coalinga earthquake were selected for use as the 2x10^-5 AFE (50,000 yr) loadings for the Horsetooth site. These recordings were obtained at a shallow (< 20 ft) soil site (Silva, 1998, pers. comm.). The 7/22/83 Coalinga event had an oblique/thrust mechanism. The source-site distance for this event was ~12 km. A scaling factor of 0.95 was applied to the horizontal components of this recording to achieve a match with the target ASI* value. The scaled, horizontal 5%-damped acceleration response spectra are compared to the target UHS in Figure 19; the acceleration time histories are shown on Figure 20.

The selection of suggested acceleration time histories has been motivated by the following factors: fit to the target UHS within the desired bandwidth with a minimum of scaling, rock or thin soil site conditions, magnitude of M\(_w\) 5.5-6.0, and source-site distance < 15 km. Both of the sets of recordings suggested meet these criteria. Characteristics of the target UHS and suggested time histories are compared in Table 8.

### Table 8: Comparison of Uniform Hazard Spectra and Spectra of Suggested Acceleration Time Histories (Horizontal Components)

<table>
<thead>
<tr>
<th></th>
<th>PHA (cm/sec²)</th>
<th>ASI* (0.5-1.0 sec) (cm/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHS, AFE 1x10^-4 (10,000 yr)</td>
<td>173.4</td>
<td>88.2</td>
</tr>
<tr>
<td>Empirical Records: Del Valle Dam-toe station, 1/24/80 Livermore, CA earthquake</td>
<td>156.4</td>
<td>88.8</td>
</tr>
<tr>
<td>UHS, AFE 2x10^-5 (50,000 yr)</td>
<td>286.1</td>
<td>155.7</td>
</tr>
<tr>
<td>Empirical Records: Palmer Ave. station, 7/22/83 aftershock of Coalinga, CA earthquake</td>
<td>262.0</td>
<td>154.4</td>
</tr>
</tbody>
</table>
Figure 17. Target, mean UHS for AFE of $1 \times 10^{-4}$ for Horsetooth site, magnitude range: 5.0-6.5 (shown in black). Horizontal components of Del Valle Dam recordings of 1980 Livermore, CA earthquake shown in red (dashed). Scaled average of two components shown in solid red. Expected response band of dam/foundation shown by dashed black lines.

Figure 19. Target, mean UHS for AFE of $2 \times 10^{-5}$ for Horsetooth site, magnitude range: 5.0-6.5 (shown in black). Horizontal components of Palmer Avenue recordings of 7/23/1983 aftershock of Coalinga, CA earthquake shown in blue (dashed). Scaled average of two components shown in solid blue. Expected response band of dam/foundation shown by dashed black lines.
Figure 18. Acceleration time histories from Del Valle Dam (toe) of 24 January 1980, $M_W$ 5.8 Livermore, CA, earthquake. Horizontal records scaled (factor=0.90), vertical unscaled. Selected to be consistent with mean UHS for AFE of $1\times10^{-4}$ for Horsetooth site.
Figure 20. Acceleration time histories from Palmer Avenue station of 23 July 1983, $M_W$ 5.8 aftershock of Coalinga, CA, earthquake. Horizontal records scaled (factor=0.95), vertical unscaled. Selected to be consistent with mean UHS for AFE of $2 \times 10^{-5}$ for Horsetooth site.
6.0 References


