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Review of seismic-hazard issues associated with the Auburn Dam project, Sierra Nevada foothills, California

By USGS Auburn Project Review Team [1]

U.S. Geological Survey Open File Report 96-0011

SUMMARY

The U.S. Geological Survey was requested by the U.S. Department of the Interior to review the design values and the issue of reservoir-induced seismicity for a concrete gravity dam near the site of the previously-proposed Auburn Dam in the western foothills of the Sierra Nevada, central California. The dam is being planned as a flood-control-only dam with the possibility of conversion to a permanent water-storage facility. As a basis for planning studies the U.S. Army Corps of Engineers is using the same design values approved by the Secretary of the Interior in 1979 for the original Auburn Dam. These values were a maximum displacement of 9 inches on a fault intersecting the dam foundation, a maximum earthquake at the site of magnitude 6.5, a peak horizontal acceleration of 0.64 g, and a peak vertical acceleration of 0.39 g. In light of geological and seismological investigations conducted in the western Sierran foothills since 1979 and advances in the understanding of how earthquakes are caused and how faults behave, we have developed the following conclusions and recommendations:

1. Maximum Displacement. Neither the pre-1979 nor the recent observations of faults in the Sierran foothills precisely define the maximum displacement per event on a fault intersecting the dam foundation. Available field data and our current understanding of surface faulting indicate a range of values for the maximum displacement. This may require the consideration of a design value larger than 9 inches. We recommend reevaluation of the design displacement using current seismic hazard methods that incorporate uncertainty into the estimate of this design value.

2. Maximum Earthquake Magnitude. There are no data to indicate that a significant change is necessary in the use of an M 6.5 maximum earthquake to estimate design ground motions at the dam site. However, there is a basis for estimating a range of maximum magnitudes using recent field information and new statistical fault relations. We recommend reevaluating the maximum earthquake magnitude using current seismic hazard methodology.

3. Design Ground Motions. A large number of strong-motion records have been acquired and significant advances in understanding of ground motion have been achieved since the original evaluations. The design value for peak horizontal acceleration (0.64 g) is larger than the median of one recent study and smaller than the median value of another. The value for peak vertical acceleration (0.39 g) is somewhat smaller than median values of two recent studies. We recommend a reevaluation of the design ground motions that takes into account new ground motion data with particular attention to rock sites at small source distances.

4. Reservoir-Induced Seismicity. The potential for reservoir-induced seismicity must be considered for the Auburn Dam project. A reservoir-induced earthquake is not expected to be larger than the maximum naturally occurring earthquake. However, the probability of an earthquake may be enhanced by reservoir impoundment. A flood-control-only project may involve a lower probability of significant induced seismicity than a multipurpose water-storage dam. There is a need to better understand and quantify the likelihood of this hazard. A methodology should be developed to quantify the potential for reservoir induced seismicity using seismicity data from the Sierran foothills, new worldwide observations of induced and triggered seismicity, and current understanding of the earthquake process.

5. Reevaluation of Design Parameters. The reevaluation of the maximum displacement, maximum magnitude earthquake, and design ground motions can be made using available field observations from the Sierran foothills, updated statistical relations for faulting and ground motions, and current computational seismic hazard methodologies that incorporate uncertainty into the analysis. The reevaluation does not require significant new geological field studies.

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[1]**D.P. Schwartz, W.B. Joyner, R.S. Stein, R.D. Brown, A.F. McGarr, S.H. Hickman, and W.H. Bakun, all at 345 Middlefield Road, Menlo Park, CA 94025**

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Contact: *webmaster@maildcascr.wr.usgs.gov*

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INTRODUCTION

In 1975 the U.S. Bureau of Reclamation (USBR) had already begun construction of a dam on the upper American River near Auburn, Calif., when the magnitude 5.7 Oroville earthquake occurred. Historically, this area has been one of relatively low earthquake activity compared to other parts of California. The Oroville earthquake, located 50 miles north of Auburn in the same tectonic setting of the Foothills Fault System of the western Sierra Nevada (Figure 1), raised concerns about the seismic safety of the Auburn Dam, which was then planned as a double-curvature, thin-arch concrete dam. The geotechnical consulting firm Woodward-Clyde Consultants (WCC) was retained to do a seismic hazard study of the Auburn project, and the U.S. Geological Survey (USGS) was asked to review the WCC report. Both the WCC (1977) and the USGS (1978) reports pointed to significant seismic safety issues. In 1979 the California Division of Mines and Geology (CDMG) conducted a review and made recommendations to the Secretary of the Interior concerning seismic design values (CDMG, 1979), and later in 1979 Secretary Cecil Andrus approved a set of design values consistent with the CDMG recommendations. The design of the dam was later changed to a concrete gravity dam, and still later the decision was made not to proceed with construction.

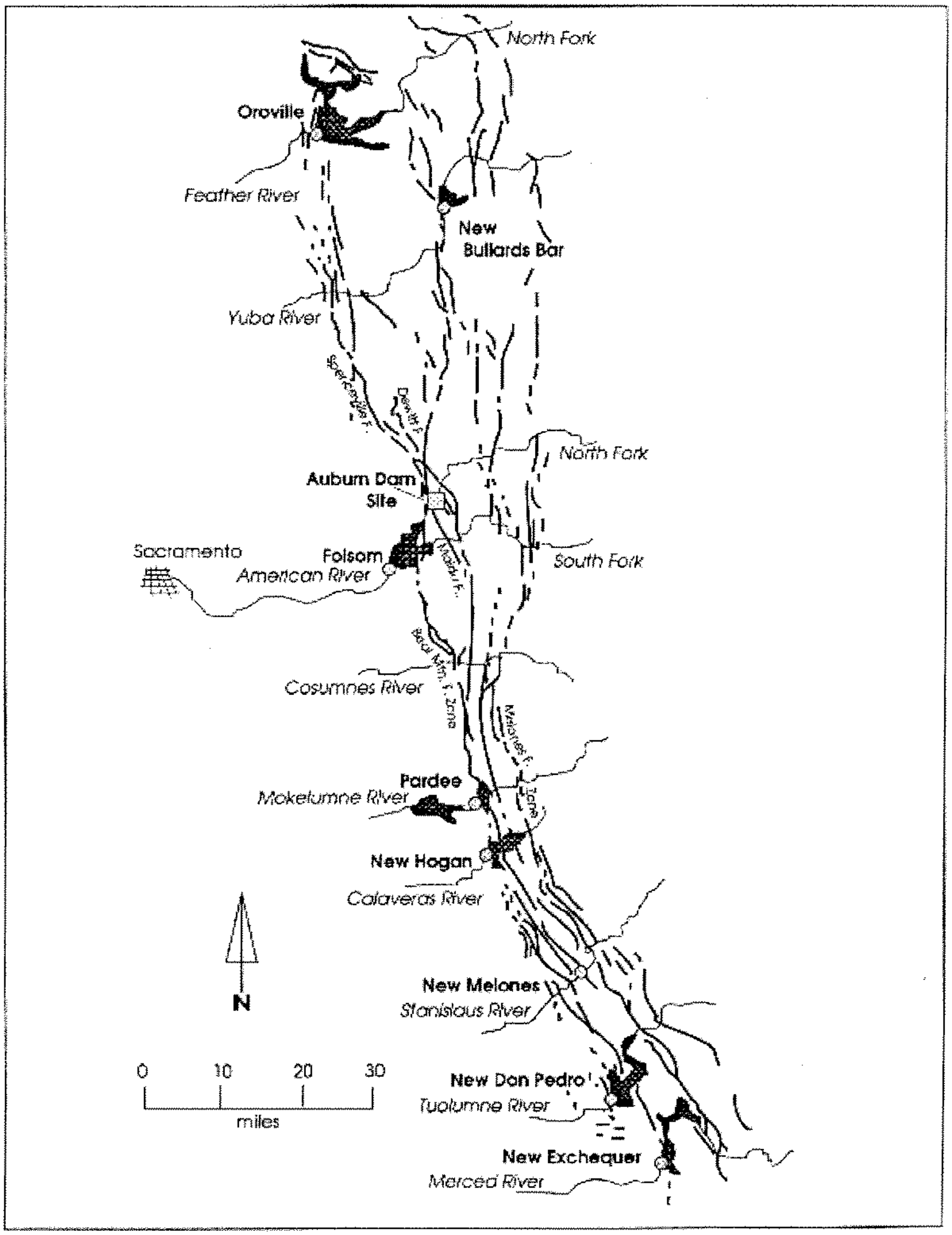

Figure 1. Map showing Auburn Dam site, traces of Foothills fault system (Jennings, 1994), and locations of other western Sierra dams (circles).

In 1991 the U.S. Army Corps of Engineers (the Corps), under instructions from Congress to study alternative means of flood control on the American River, issued a report (U.S. Army Corps of Engineers, 1991) recommending construction of a concrete gravity flood-control dam near the site of the previously proposed Auburn Dam. In 1995 the Corps issued a Supplemental Information Report (U.S. Army Corps of Engineers, 1995) giving additional information on the project. For these planning studies the Corps used the design values approved by the Secretary of the Interior in 1979. These were a maximum displacement of 9 inches on a fault intersecting the dam foundation, a maximum earthquake at the site of magnitude 6.5, a peak horizontal acceleration of 0.64 g, and a peak vertical acceleration of 0.39 g.

The USGS was requested by the U.S. Department of the Interior to review the Corps 1991 and 1995 reports with the goal of evaluating the seismic design values and the issue of reservoir induced seismicity in light of a) geological and seismological investigations conducted in the western Sierran foothills since 1979 and b) present understanding of how faults behave and earthquakes occur. The USGS assembled a team of geologists and geophysicists with a broad range of knowledge of the scientific issues associated with the project. The team reviewed the 1991 and 1995 Corps reports for the newly proposed Auburn Dam as well as those for the previous Auburn Dam project. On November 1, 1995, the team received an overview from William D. Page and Marcia McLaren of the Pacific Gas and Electric Company (PG&E) on recent geologic investigations of potentially active structures and seismicity studies in the western Sierran foothills. The team visited the proposed Auburn Dam site to see those geological structures and faults that traverse the existing foundation excavation and the footprint for the new dam. It also met with Corps and USBR staff involved in the project.

This review focuses on the review focuses on the assessment of seismic hazard associated with the Auburn Dam project. In this report we a) review and evaluate the bases for the original seismic design values for fault displacement, maximum earthquake magnitude, and ground motions; b) discuss the issue of reservoir-induced seismicity; and c) present conclusions and recommendations. We appreciate the thoughtful comments of R. A. Page (USGS, Menlo Park, Calif.), E. A. Roeloffs (USGS, Vancouver, Wash.), M. V. Shulters (USGS, Sacramento, Calif.) and D. Howell (USGS, Menlo Park, Calif.).

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REVIEW OF SEISMIC DESIGN VALUES

Maximum Displacement on a Foundation Fault

In 1979 a value of 9 inches was selected as the maximum displacement that could occur during an earthquake on a single fault, or that could be distributed across a series of faults, that passed through the foundation excavation of the proposed Auburn Dam. Controversy and uncertainty surrounded the assessment of the activity of these faults, which were called F-zones and T-zones, but they were ultimately classified as "indeterminate active" by the USBR and this required that they be considered in the design of the dam. Specific estimates of the maximum displacement per event made by the USBR, its consultants, and reviewers ranged from 1 inch to 3 feet (USBR 1990, Table VI). The 9-inch value reflected a consensus of the various geological teams working on the project.

At the Auburn Dam site geologic deposits that could be used to constrain the amount of displacement per event on faults that passed directly beneath the dam foundation were absent. Therefore, the 9-inch design displacement was developed principally from observations made in paleoseismic trenches excavated across many faults in the western Sierran foothills as part of geologic studies for projects such as the New Melones Dam and the proposed Stanislaus nuclear power plant, as well as for the Auburn Dam. In these trench exposures the maximum observed vertical displacement of a regionally developed soil horizon (termed the "paleo B" and assumed to be approximately 100,000 years old) was 2 feet, and the net displacement across this soil was estimated to be 2.4 feet when an oblique component of slip was added (WCC, 1977). Structural and stratigraphic relations in several of the exploration trenches suggested that the net displacement on the paleo B soil was incremental and resulted from repeated earthquakes. However, there were no consistent measurements of the actual amount of displacement during individual earthquakes. WCC (1977) concluded that the 2.4 feet of offset resulted from at least three earthquakes. This interpretation, plus a number of assumptions, yielded a value of 0.8 feet (9.6 inches) as the maximum net displacement per event that could occur on a fault in the western Sierran foothills, including the faults in the dam foundation. In 1979 the State of California proposed essentially the same value, 9 inches, which became the design basis displacement.

How reasonable is the 9-inch value in light of geological work conducted in the Sierran foothills since 1979 and our present understanding of surface faulting? Recent studies of potentially active faults have been completed by PG&E (1994) for the Rock Creek Dam just north of Auburn and by the Corps (1995) for the New Hogan reservoir on the Calaveras River (Figure 1). Trenching of the Dewitt fault, Deadman fault, and Highway 49 fault near Auburn and the Waters Peak fault and Ione fault near the New Hogan reservoir shows that each of these faults displays evidence of movement characterized by relatively small (less than 2.5 feet) long- term displacements of the paleo B soil and other geologic deposits in the past 100,000 years. These new studies still do not clearly quantify the amount of displacement during individual surface faulting earthquakes, although trenches across the Dewitt fault (Figure 1) at a site six miles northwest of the Auburn Dam site exposed stratigraphic separation of a colluvium younger than the paleo B soil that can be interpreted, at this one location, as a single-event displacement of up to 40 cm (15 inches) (PG&E, 1994).

Detailed mapping of surface faulting earthquakes worldwide since 1979 (for example 1980 El Asnam, Algeria; 1983 Borah Peak, Idaho; 1992 Landers, Calif.) as well as extensive trenching of active faults in the United States and other countries reinforce the observations that (a) surface displacement varies along the length of a rupture and (b) a large percentage of the surface rupture length expresses the average rather than the maximum displacement (Wells and Coppersmith, 1994). Therefore trench observations of surface fault displacement in the western Sierran foothills, which have been made at widely spaced trench locations, are more likely to reflect average rather than maximum values.

Since 1979 there has also been significant growth in the dataset used to derive statistical relations between earthquake magnitude and fault displacement, fault length, and fault area (Wells and Coppersmith, 1994). These relations are most commonly used to estimate earthquake magnitude from field fault parameters (see discussion below). However, they can also be used to estimate fault parameter values for a specific magnitude earthquake. If, for example, it is assumed that the hypocenter for the proposed maximum earthquake for ground motion (presently M6.5) occurs on a fault passing through the dam foundation, the statistical relations yield: a) a mean value for average displacement of 48 cm (19 inches) with a range of 39 cm to 60 cm (15 inches to 24 inches) and b) a mean value for maximum displacement of 74 cm (29 inches) with a range of 60 cm to 92 cm (24 inches to 36 inches). It should be noted that the magnitude versus displacement relation has a larger standard deviation and smaller correlation coefficient than relations between magnitude and length or area (Wells and Coppersmith, 1994). We emphasize that these values are not necessarily those that should be required for design. They simply show that displacements exceeding 9 inches can be calculated using other approaches.

In summary, recent investigations of faults in the Foothills fault system show that cumulative late Quaternary displacements of 2 to 3 feet observed in soils and other geologic deposits are consistent with previous observations. These new field data continue to suggest that during the past 100,000 years displacement rates are low and displacements of a few tens of centimeters per event are reasonable estimates for many of the faults in the western Sierran foothills. However, neither the pre- nor post-1979 field data precisely define the maximum displacement per event. In 1979 a single value was selected for the maximum displacement. In present seismic hazard practice a strong effort is made to identify and incorporate uncertainty into design values. Therefore, alternative interpretations of field observations and alternative tectonic and fault behavior models can be considered, weighted, and combined to derive a design value and the uncertainty associated with it. There is a basis for estimating a range of potential maximum displacements at the Auburn Dam site, and a design value larger than 9 inches may need to be considered. We recommend that the design displacement be reevaluated.

Maximum Earthquake Magnitude

The Corps has used a magnitude of 6.5 for estimates of the design ground motion at the proposed dam site. This was the recommended value in 1979. At the time of the original study, maximum magnitude estimates by the USBR, its consultants, and reviewing organizations ranged from 5.7 to 7.0 (USBR, 1990 Table VI). The 6.5 magnitude was a consensus value.

In 1979 the size of the maximum earthquake was based primarily on a) the statistical relations that had been established at that time between surface wave magnitude (Ms) and fault displacement and length

(Slemmons, 1977) and b) a comparison between estimates of fault length and displacement per event on faults in the Sierran foothills and Auburn area with parameters of historical Sierran events such as the 1975 Oroville earthquake. For ground motion analysis, this maximum earthquake was assumed to occur on a fault traversing the dam foundation. Using the maximum displacement of 0.8 feet (24 cm), a length of 10 miles (16 km) as a typical rupture length for a western Sierran foothills fault, and observations from the Oroville earthquake, WCC (1977) estimated that the maximum earthquake on a fault in the western Sierran foothills was 6-6 1/2. The use of "6 1/2" rather than "6.5" was an expression of the uncertainty in the precision of the upper end of the estimate. The USGS (1978) noted that because of scatter in the dataset for the statistical relations these fault parameters gave "expected" rather than "maximum" magnitudes and showed that higher magnitudes could be calculated using the observed fault parameters.

Wells and Coppersmith (1994) have developed new and more robust statistical relations between earthquake magnitude and fault displacement, fault rupture length, and fault area, and they have quantified the inherent variability in the statistical regressions. These relations use moment magnitude (M) in place of surface wave magnitude (Ms), but in the magnitude range of interest for design ground motions at the Auburn Dam site M and Ms are essentially equivalent. Calculating the "maximum" magnitude that a fault can produce involves geologically and seismologically estimating the best maximum value for a fault rupture parameter such as length, displacement per event, and area. The use of a maximum fault parameter value in the statistical relations gives a mean value or "expected" maximum earthquake. Because there is variability or scatter associated with the statistical relations, both higher and lower magnitude estimates are possible for the same rupture parameter. This variability is +0.2 to +0.4 magnitude units depending on which statistical regression is used (Wells and Coppersmith, 1994). Within the earthquake hazard community there is also ongoing discussion of the definition and use of terms such as "maximum" earthquake, "expected" earthquake, and "characteristic" earthquake and these are often used interchangeably.

Estimates of fault parameter values from field observations also contribute to uncertainties in calculating maximum magnitudes. The most commonly used parameter is rupture length, which is now generally derived from fault segmentation modeling. Since 1979 fault segmentation has emerged as a field of earthquake research with important applications for evaluating seismic hazard (Schwartz and Coppersmith, 1986; Schwartz, 1988; Working Group, 1990; Working Group, 1995)), particularly the identification of individual rupture segments of future earthquakes. In the western Sierran foothills fault segmentation modeling is complicated by the absence of widespread youthful geologic deposits that are helpful in defining the lateral continuity of the most recently active fault traces. However, a variety of geomorphic, stratigraphic, and structural evidence in the foothills appears to be useful in delineating segments of late Cenozic faults which, because of repeated long-term movements, have a better chance of being preserved in this geologic environment (Savage and others, 1991). PG&E (1994) suggests that mapped lengths of late Cenozoic faults in the western foothills closely approximate the lengths of seismogenic faulting. They also suggest that long multiple-segment ruptures are not to be expected because long rupture lengths appear to scale with large displacements (Scholz, 1990), and the observed displacements are generally small. These interpretations are reasonable, although recent earthquakes such as the 1992 Landers event show that segmentation can be complex and that surface ruptures during a single earthquake can involve several geometric fault segments.

In seismic hazard investigations for the Rock Creek Dam PG&E (1994) estimated maximum earthquakes for faults in the Auburn area just north of the proposed Auburn Dam site. Using new field observations and estimates of displacement and fault length, and the updated statistical relations, they conclude that the maximum earthquake on the Spenceville fault (located eight miles northwest of Auburn, Figure 1) is 6.4 and the maximum earthquake on the Dewitt fault (located two miles northwest of Auburn at its closest approach, Figure 1) is 6.1 -6.3. For comparison we have used the Wells and

Coppersmith (1994) relations and the 1979 Auburn Dam maximum displacement (9 inches) and fault length (10 miles) values to calculate M 6.2 and M 6.5, respectively.

In summary, the maximum earthquake magnitude for ground motions at the dam site in 1979 was a single value of M 6.5. We have noted that there is variability in the statistical relations that are now used to calculate maximum magnitude. This statistical uncertainty is better understood and quantified than in 1979. There are also uncertainties in the field interpretations of fault rupture parameters, particularly fault length, that can be reexamined in light of present concepts of fault segmentation. There are no data to indicate a significant change is necessary in the use of M 6.5 to estimate design ground motions at the dam site. However, there is a basis or estimating a range of potential maximum magnitudes, both higher and lower, using recent field information and the updated statistical fault relations. As discussed, present day seismic hazard analysis can take into account and make use of alternative models, observations, and interpretations. We recommend reevaluating the maximum earthquake magnitude using updated seismic hazard methodology.

Design Ground Motions for the Auburn Dam

The peak ground accelerations specified for the design earthquake of magnitude 6.5 can be compared with estimates given by equations for predicting ground motion in terms of magnitude, distance, and site conditions derived by analysis of the data from strong-motion recordings in western North America. Many more data are now available than was the case in 1978, but there are still few data for rock sites at short distance, and equations by different authors give somewhat different estimates. There are few data for extensional tectonic regimes such as the Sierran foothills. In 1978 there was some controversy over the design motions at 1 sec period, but that is not an issue now that the thin-arch design has been replaced by a gravity dam, whose fundamental natural period the Corps has informed us will be about 0.5 sec.

We choose two sets of equations to compare with the design value for peak horizontal acceleration. The design value (0.64 g) is larger than the median value (0.56 g) given by the equations of Campbell and Bozorgnia (1994) for a magnitude 6.5 earthquake at zero horizontal distance at a hard-rock site but smaller than the median value (0.73 g) given by the equations of Abrahamson and Silva (written communication, 1995) for a magnitude 6.5 earthquake at zero distance at a rock site.

There are fewer sets of equations available to compare with the design value for peak vertical acceleration, but again we choose two. The design value (0.39 g) is somewhat smaller than the median value (0.45 g) given by the equations of Abrahamson and Litehiser (1989) for a magnitude 6.5 earthquake at zero distance and smaller than the median value (0.57 g) given by the more recent equations of Abrahamson and Silva (written communication, 1995) for a magnitude 6.5 earthquake at zero distance at a rock site.

In summary, the design value for peak horizontal acceleration is larger than the median value from one of the chosen studies and smaller than the other. The design value for vertical acceleration is somewhat smaller than the median of both the chosen studies. The ground-motion design values for the Auburn Dam should be reevaluated in the light of the large number of strong-motion records acquired since the original evaluations nearly twenty years ago and the significant advances in understanding of ground motion that have been achieved in this time. The reevaluation should take account of recent studies (e.g. Bozorgnia and others, 1995) of the characteristics of short-period vertical ground motions at small source distances. It should also take account of recent studies of ground motion from earthquakes in extensional tectonic regimes (Westaway and Smith, 1989; Spudich and others, 1996). Although we consider it important that the reevaluation be done, we have no reason to believe that any resulting changes in design values will pose serious problems for the design of the dam.

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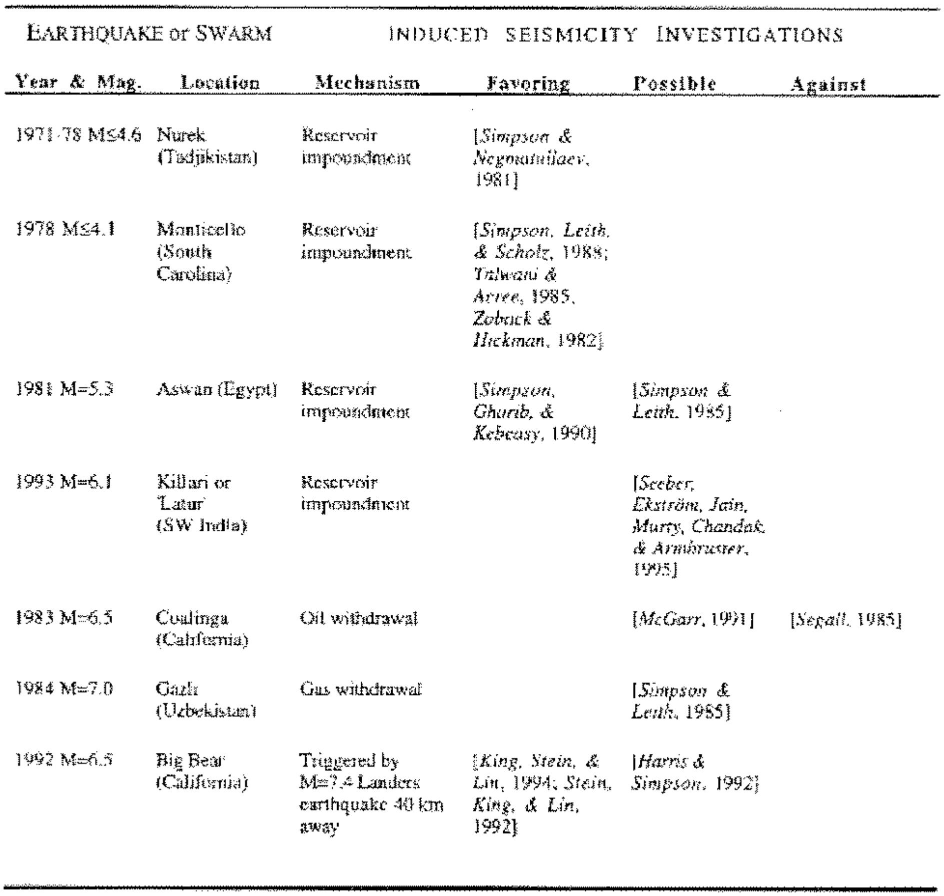
RESERVOIR-INDUCED SEISMICITY

The potential for reservoir-induced seismicity, which is the triggering of earthquakes by the physical processes that accompany the impoundment of large reservoirs, was recognized during the seismic hazard studies for the original Auburn Dam. It remains an important issue for the present project because of the potential to increase the probability of earthquakes near the dam. The reservoir created by the flood-control-only dam is proposed to have a maximum water depth of 508 feet (155 m) (U.S. Army Corps of Engineers, 1991); the permanent-water storage dam would create a reservoir with a maximum water depth of 656 feet (200 m). These water depths place the proposed reservoir (s), as did the 665 foot (203 m) maximum water depth of the original dam, in a worldwide class of reservoirs that are deep (80 m, 263 feet) to very deep (deeper than 150 m, 492 feet). Deep and very deep reservoirs account for the majority of reported examples of reservoir-induced seismicity.

Based on analysis of 55 reported cases of reservoir-induced seismicity worldwide and geologic and seismologic data for 16 selected dams and reservoirs in the Sierran foothills, WCC (1977) reached two sets of conclusions about reservoir-induced seismicity associated with Auburn Dam as proposed at that time. First, if the 1975 Oroville earthquake is assumed not to be reservoir induced, then the likelihood of an induced earthquake of the magnitude of the Oroville event (5.7) or larger is 2% to 5 % during the life of the dam. Second, if the Oroville earthquake is assumed to be reservoir induced, then the likelihood of an induced earthquake of the magnitude of the Oroville earthquake is 30 % during the lifetime of the dam. We have not been able to reconstruct the basis for these probabilities and do not endorse them. The specific probabilities of an induced earthquake of M 5.7 or larger associated with an Auburn reservoir are open for revaluation.

Table 1. M≥4 Earthquakes since 1975 That May Have Been Induced or Triggered



EARTHQUAKE or SWARM			INDUCED SEISMICITY INVESTIGATIONS		
Year & Mag.	**Location**	**Mechanism**	**Favoring**	**Possible**	**Against**
1971-78 M≤4.6	Nurek (Tadjikistan)	Reservoir impoundment	[*Simpson & Negmatullaev*, 1981]		
1978 M≤4.1	Monticello (South Carolina)	Reservoir impoundment	[*Simpson, Leith, & Scholz*, 1988; *Talwani & Acree*, 1985, *Zoback & Hickman*, 1982]		
1981 M=5.3	Aswan (Egypt)	Reservoir impoundment	[*Simpson, Gharib, & Kebeasy*, 1990]	[*Simpson & Leith*, 1985]	
1993 M=6.1	Killari or 'Latur' (SW India)	Reservoir impoundment		[*Seeber, Ekström, Jain, Murty, Chandak & Armbruster*, 1995]	
1983 M=6.5	Coalinga (California)	Oil withdrawal		[*McGarr*, 1991]	[*Segall*, 1985]
1984 M=7.0	Gazli (Uzbekistan)	Gas withdrawal		[*Simpson & Leith*, 1985]	
1992 M=6.5	Big Bear (California)	Triggered by M=7.4 Landers earthquake 40 km away	[*King, Stein, & Lin*, 1994; *Stein, King, & Lin*, 1992]	[*Harris & Simpson*, 1992]	

Since 1979 the body of data on reservoir induced seismicity has grown. Table 1 lists four additional case histories of proposed reservoir-induced seismicity as well as those for other types of induced earthquakes. A better understanding of reservoir-induced seismicity has come from theoretical analyses and from studies of earthquakes induced by other means such as fluid injection, gas and oil production, and stress changes associated with other earthquakes. Recent studies have suggested why some reservoirs produce earthquakes immediately upon filling (due to elastic stress changes), some after a delay (a result of pore fluid diffusion), and some after several years but only when the water level is changed (fluid diffusion accompanied by the elastic stress changes) (Roeloffs, 1988; Segall, 1992; Simpson and others, 1988). As currently understood, the essential features of reservoir-induced seismicity, and in some cases other types of induced earthquakes, are:

1. Observable characteristics (stress drop, ground motions, source parameters) of earthquakes induced by reservoir impoundment, fluid injection, or gas and oil production are indistinguishable from those of naturally occurring tectonic events.

2. The magnitude of the maximum induced earthquake is geologically controlled and is independent of reservoir impoundment.

3. Most examples of induced seismicity occur in regions of low tectonic loading rates dominated by normal faulting as is the case in the Sierran foothills, or strike-slip faulting (Scholz, 1990).

4. The probability of the occurrence of earthquakes at and in the region around a reservoir may be increased by impoundment. In a few of the best controlled studies where a reliable record of seismicity before and after reservoir impoundment exists (Segall, Grasso, and Mossop, 1994; Simpson and Negmatullaev, 1981), an increased rate of activity is seen within 10-15 km of impounded reservoirs and gas fields (Figure 2 and Figure 3/).

5. Observations point to a higher rate of earthquakes after reservoir impoundment, especially during the first decade (Anderson and O'Connell, 1993; Scholz, 1990; Simpson, 1986), although the relationship between impoundment time history and reservoir-induced seismicity is not consistent or well understood. In some cases reservoir induced seismicity has been observed shortly after the initiation of filling (Figure 3). For example, a magnitude 6.3 earthquake was induced by the Kremasta reservoir in Greece less than seven months after the initiation of filling in 1966 (Cominakis et al 1968). Alternatively, the Oroville earthquake, if reservoir induced, occurred ten years after reservoir impoundment.

6. Induced earthquakes, reservoir induced or otherwise, appear to be triggered by very small stress changes, sometimes only a small fraction of one bar. For examples of induced earthquakes listed in Table 1, the calculated stress changes in the seismogenic zone are remarkably small, typically a few percent of the stress drop of the induced earthquake. During the past five years, new evidence has emerged that earthquakes can also be induced by the stress transferred from other earthquakes. Earthquake-induced stress changes of 1-3 bars (about the same as the pressure in a car tire) appear to be able to trigger large earthquakes, such as the M 6.5 Big Bear earthquake, which occurred three hours after and 30 km away from the M 7.4 Landers event (Harris and Simpson, 1992; King, Stein, and Lin, 1994), and stress changes of 20.25 bar can trigger abundant smaller earthquakes (Harris and Simpson, 1992; Harris and Simpson, 1995; Harris, Simpson, and Reasenberg, 1995; Stein, King, and Lin, 1994).

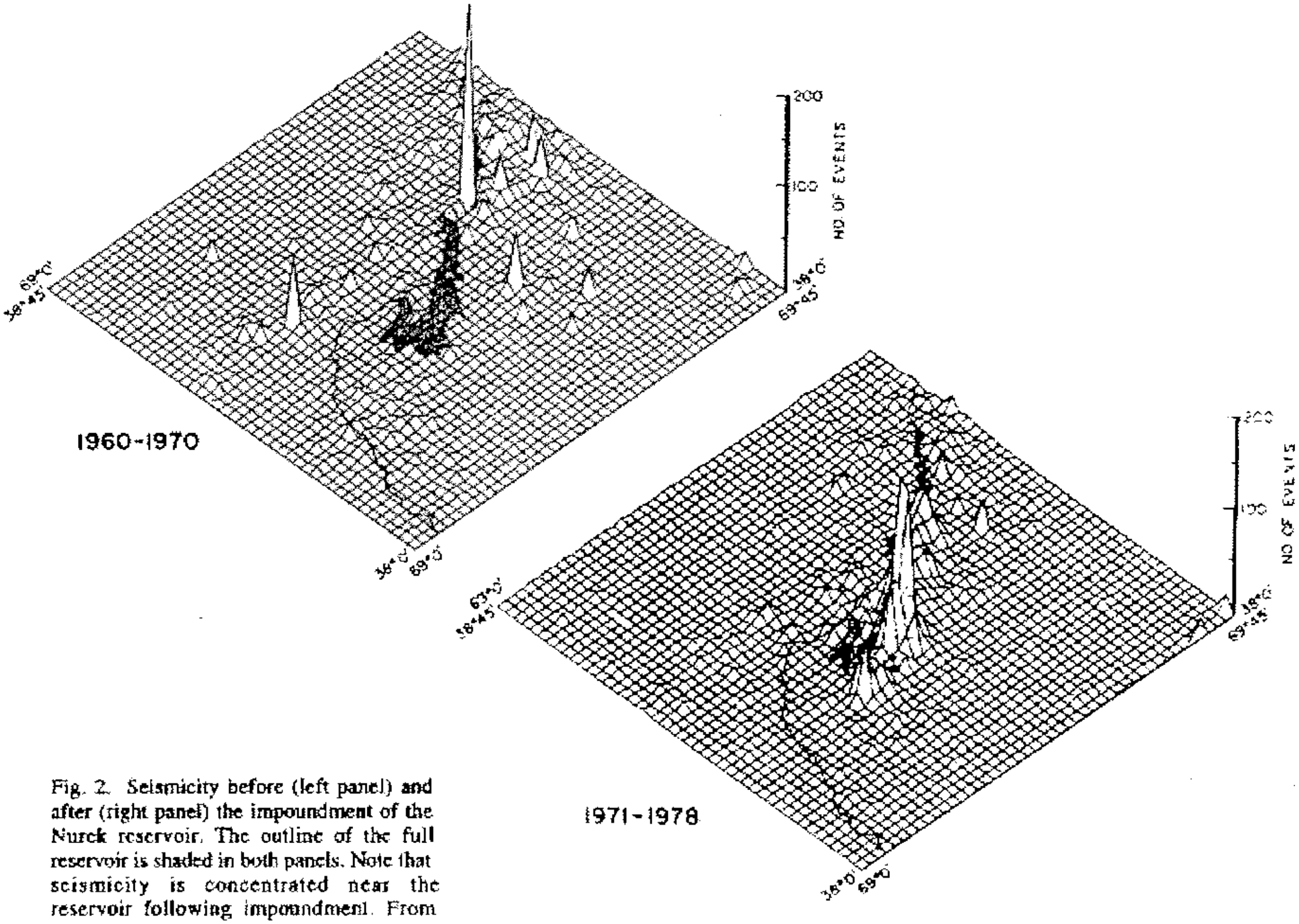


Fig. 2. Seismicity before (left panel) and after (right panel) the impoundment of the Nurek reservoir. The outline of the full reservoir is shaded in both panels. Note that seismicity is concentrated near the reservoir following impoundment. From *Simpson and Negmatullaev* [1981].

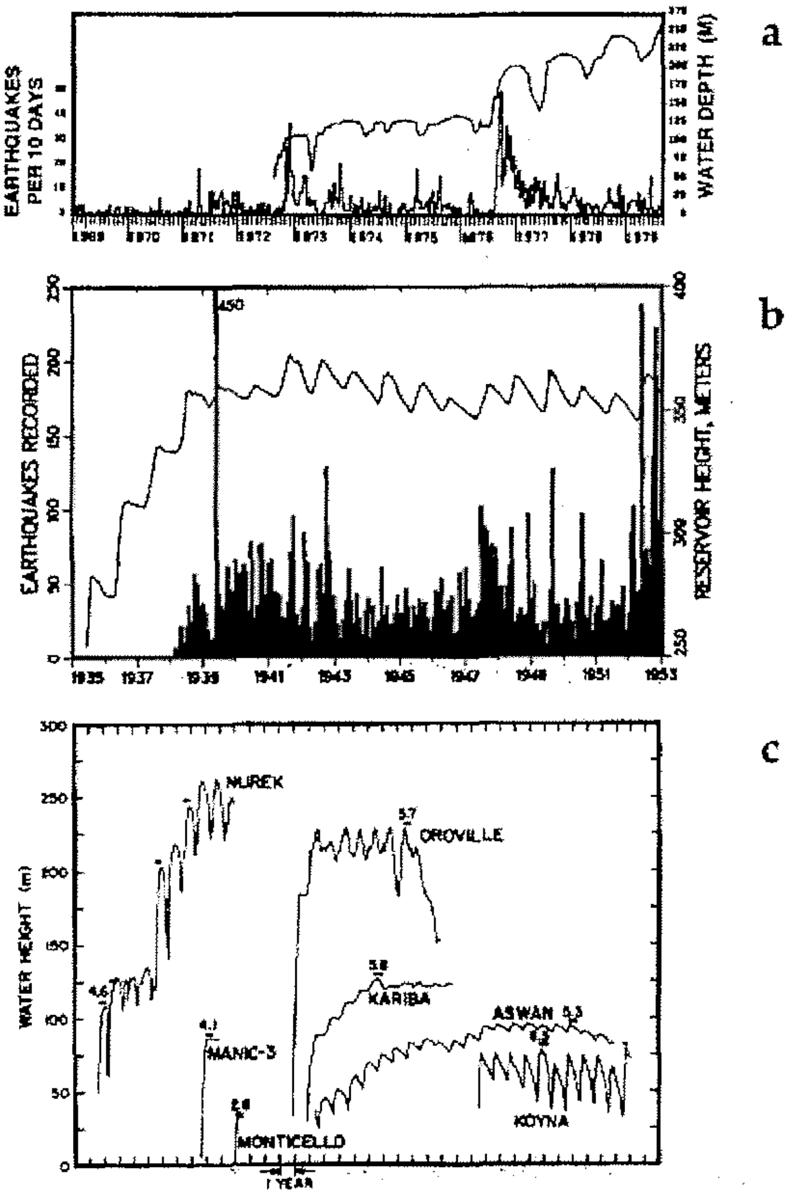


Fig. 3. Water level and seismicity rates at (a) the Nurek reservoir from *Simpson and Negmatullaev* [1981], and (b) Lake Mead, from *Roeloffs* [1988]. M≥1.5 earthquakes within 10 km of the reservoir are plotted for Nurek. The rate of earthquakes climbs in both cases during impoundment. (c) The association between reservoir impoundment and subsequent earthquakes for seven reservoirs, from *Simpson* [1986]. The vertical scale is water depth at the dam. Numbers above the water level curves give the magnitude of the largest recorded earthquake. Bars indicate times of seismicity bursts at each site.

We suggest that the proposed Auburn project entails some likelihood of reservoir-induced seismicity. The probability of a resewoir-induced event could vary significantly depending on whether the dam is a flood-control-only detention dam or is used for permanent water storage. The worldwide correlations among reservoir depth, resewoir volume, and seismicity suggest a greater likelihood of reservoir induced-seismicity for the permanent water storage version of the Auburn project because of the longer period of time the region is exposed to the load and pore pressure changes. The flood-control-only version may involve a lower probability of significant reservoir induced-seismicity than the permanent water storage reservoir. However, in view of the observation that earthquakes can be induced during rapid changes in reservoir level and after impoundment of only a few months, the possibility of reservoir induced-seismicity associated with a flood-control-only dam, for which impoundment would be rapid but only during flood conditions, should not be dismissed.

We recognize there are questions and uncertainties in quantifying this hazard. Aside from Oroville, which may have had reservoir-induced seismicity, there are six existing large dams in the Sierran foothills that have the height and reservoir volume necessary to place them in the worldwide classification of dams that have the potential to produce reservoir induced seismicity. These dams and their construction dates are Folsom (1956), Pardee (1929), New Bullards Bar (1970), New Don Pedro (1970), New Exchequer (1966), and New Melones (1978) (Figure 1). Since the late 1970s these dams have experienced several major episodes of drawdown and filling associated with drought and flood cycles. Between 1978 and 1994 the seismic network operating in the Sierran foothills has not recorded the occurrence of any earthquakes of M24 in this region (M. McLaren, PO&E, written communication) and there is no obvious association between recorded seismicity and these large dams.

In summary, we conclude that reservoir-induced seismicity is an issue that will require additional analysis if the Auburn Dam project continues. There is a need to pursue development of approaches to calculate how reservoir impoundment may affect earthquake probabilities at the Auburn site and its environs. If the Auburn Dam Project is authorized, a dense seismic network should be installed around the Auburn Dam site as soon as possible to determine a baseline level of seismicity before impoundment. A downhole, three-component, wide-dynamic-range seismometer array could be very useful for this purpose. Additionally, borehole measurements of permeability, hydraulic head, and stress should be made in the vicinity before, during, and after impoundment.

Next-Conclusions and Recommendations

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[1]D.P. Schwartz, W.B. Joyner, R.S. Stein, R.D. Brown, A.F. McGarr, S.H. Hickman, and W.H. Bakun, all at 345 Middlefield Road, Menlo Park, CA 94025

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Review of seismic-hazard issues associated with the Auburn Dam project, Sierra Nevada foothills, California

By USGS Auburn Project Review Team [1]

U.S. Geological Survey Open File Report 96-0011

CONCLUSIONS AND RECOMMENDATIONS

Seventeen years have passed since the approval of the design values for the original Auburn Dam. These were based on the field data, the understanding of the earthquake process, and the seismic hazard methodology available at that time. In the interim, new information has been obtained on the behavior of faults in the western Sierran foothills, important advances have been made in understanding the causes of earthquakes and how faults work in time and space, and new methods to quantify seismic hazards and incorporate uncertainties into these analyses have been developed. We have reviewed and evaluated the 1979 seismic design values in light of these considerations and reach the following conclusions and recommendations:

1. Neither the pre- nor post-1979 data precisely define the maximum displacement per event on a fault intersecting the dam foundation. In 1979 a single value was selected for the maximum displacement. In present seismic hazard practice a strong effort is made to identify sources of uncertainty and incorporate these into design values. Alternative interpretations of field observations and alternative tectonic and fault behavior models can be considered, weighted, and combined to derive a design value and the uncertainty associated with it. There is a basis for estimating a range of potential maximum displacements at the Auburn Dam site using available field data and our current understanding of surface faulting. This may require the consideration of a design value larger than 9 inches. We recommend that the design displacement be reevaluated.

2. The maximum earthquake magnitude for ground motions at the dam site in 1979 was a single value of M 6.5. There are no data to indicate a significant change should be made in using M 6.5 to estimate design ground motions. However, the updated statistical relations available to calculate maximum magnitude are more robust, and their associated uncertainties are better quantified, than those used in 1979. Also, there are uncertainties in fault rupture parameters used for magnitude calculations, particularly fault length, that should be reexamined in light of present concepts of fault segmentation. There is a basis for estimating a range of potential maximum magnitudes, both higher and lower, using the recent field information and the new statistical fault relations. We recommend reevaluating the maximum earthquake magnitude using updated seismic hazard methodology.

3. A large number of strong-motion records have been acquired and significant advances in understanding of ground motion have been achieved since the original evaluations. The design value for peak horizontal acceleration (0.64 g) is larger than the median of one recent study and smaller than the median value of another. The value for peak vertical acceleration (0.39 g) is somewhat smaller than median values of two recent studies. We recommend a reevaluation of the

design ground motions that takes into account new ground motion data with particular attention to rock sites at small source distances.

4. The potential for reservoir-induced seismicity must be considered for the Auburn Dam project. A reservoir-induced earthquake is not expected to be larger than the maximum naturally occurring earthquake. However, the probability of the occurrence of earthquakes up to the maximum magnitude event may be increased by reservoir impoundment. Both the flood-control-only dam and a permanent-water-storage dam entail some likelihood of reservoir-induced seismicity, although the flood-control-only version may involve a lower probability of significant induced seismicity than the multipurpose project. There is a clear need to improve our understanding of the probability of this hazard, and this issue will require additional analysis if the project continues. Methods should be developed to quantify the potential for reservoir-induced seismicity using seismicity data from the Sierran foothills, new worldwide observations of induced and triggered seismicity, and current understanding of the earthquake process.

5. The reevaluation of the maximum displacement, maximum magnitude earthquake, and design ground motions can be made using available field observations from the Sierran foothills, updated worldwide statistical relations for faulting and ground motions, and current computational seismic hazard methods that incorporate uncertainty into the analysis. This does not require significant new geological field studies. If the Auburn Dam Project is authorized, a dense local seismic network should be installed around the Auburn Dam site to determine a baseline level of seismicity before impoundment.

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[1]**D.P. Schwartz, W.B. Joyner, R.S. Stein, R.D. Brown, A.F. McGarr, S.H. Hickman, and W.H. Bakun, all at 345 Middlefield Road, Menlo Park, CA 94025**

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Contact: webmaster@maildcascr.wr.usgs.gov

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REFERENCES

Abrahamson, N.A. and Litehiser, J.J., 1989, Attenuation of vertical peak acceleration: Seismological Society of America Bulletin, v. 79, p. 549-580

Anderson, L.W., and O'Connell, D.R., 1993, Seismotectonic study of the northern portion of the lower Colorado River, Arizona, California, and Nevada (Seismotectonic Rep. No. 93-4): U.S. Bureau of Reclamation, Denver.

Bozorgnia, Y., Niazi, M., and Campbell, K. W., 1995, Characteristics of free-field vertical ground motion during the Northridge earthquake: Earthquake Spectra, v. 11, p. 515-525.

Cominakis, P., J. Drakopoulos, G. Moumoulidis, and B. Papazachos, 1968, Foreshock and aftershock sequences of the Cremasta earthquake and their relation to the waterloading of the Cremasta artificial lake, Annali di Geofisica, v. 21, p. 39-71.

California Division of Mines and Geology, 1979, Technical review of the seismic safety of the Auburn dam site: Special Publication 54, 17 pp.

Harris, R.A., and Simpson, R.W. 1992, Changes in static stress on southern California faults after the 1992 Landers earthquake: Nature, v. 360, p. 251-254.

Harris, R.A., and Simpson, R.W., 1996, In the shadow of 1857-the effect of the great Ft. Tejon earthquake on subsequent earthquakes in southern California: Geophysical Research Letters, v. 23, p. 229-232.

Harris, R.A., Simpson, R.W., and Reasenberg, P.A., 1995, Influence of static stress changes on earthquake locations in southern California: Nature, v. 375, p. 221-224.

Hill, D.P., Reasenberg, P. A., Michael. A., Arabasz, W.J., Beroza, G., Brumbaugh, D., Brune, J.N., Castro, R., Davis, S., dePolo, D., Ellsworth, W. L., Gomberg, J., Harmsen, S., House, L., Jackson, S. M., Johnston, J. S., Jones, L., Keller, R., Malone, S., Munguia, L., Nava, S., Pechmann, J. C., Sanford, A., Simpson, R. W., 1993, Seismicity remotely triggered by the Magnitude 7.3 Landers, California, Earthquake: Science, v. 260, p. 1617-1623.

Jennings, C.W., 1994, Fault activity map of California and adjacent areas: California Division of Mines and Geology, map no. 6.

King, G.C.P., Stein, R.S., and Lin, J., 1994, Static stress changes and the triggering of earthquakes: Seismological Society of America Bulletin, v. 84, p. 935-953.

McGarr, A., 1991, On a possible connection between three major earthquakes in California and oil production: Seismological Society of America Bulletin, v. 81, p. 948-970.

Pacific Gas and Electric Company, 1994, Characterization of potential earthquake sources for Rock Creek (Drum) Dam, report for FERC 2310, Drum Spaulding Project State Dam No. 97-43, 89 p. + plates & figures.

Ragosti, B.K., 1994: Latur earthquake: Not triggered, in H.K. Gupta, ea., Latur Earthquake, p. 131-138, Memoir 35, Geological Society of India.

Roeloffs, E.A., 1988, Fault stability changes induced beneath a reservoir with cyclic variations in water level: Journal of Geophysical Research, v. 93, p. 2107-2124.

Savage, W.U., Page, W.D., McLaren, M.K., and Edwards, W.D., 1991, Approach to seismic hazard analysis for dam safety in the Sierra Nevada and Modoc plateau of California: Proceedings of Canadian Dam Safety Conference, September 1991,Canadian Dam Safety Association,p.203-219, BiTech Publishers, Ltd., Vancouver, 404 p.

Scholz, C.H., 1990, The Mechanics of Earthquakes and Faulting: Cambridge University Press, 439 p.

Schwartz, D.P., 1988, Geologic characterization of seismic sources: moving into the 1990's: in von Thun, L., ea., Earthquake engineering and soil dynamics II--Recent advances in ground motion evaluation, American Society of Civil Engineers, Geotechnical Special Publication 20, p. 1-42.

Schwartz, D.P., and Coppersmith, K.J., 1986, Seismic hazards: new trends in analysis using geologic data: in Active Tectonics, National Academy Press, p. 215-230.

Seeber, L., Ekstrom, G., Jain, S.K., Murty, C.V.R., Chandak, N., and Armbruster, J.G., 1995, The 1993 Killari earthquake in central India: A new fault in Mesozoic basalt flows? Journal of Geophysical Research, p. 100, in press.

Segall, P., 1985, Stress and subsidence resulting from subsurface fluid withdrawal in the epicenter region of the 1983 Coalinga earthquake: Journal of Geophysical Research, v. 90, p. 6801-6816.

Segall, P., 1992, Induced stresses due to fluid extraction from axisymmetric reservoirs, PAGEOPH, v. 139, p. 535-560.

Segall, P., Grasso, J.R., and Mossop, A., 1994, Poroelastic stressing and induced seismicity near the Lacq gas field, southwestern France, Journal of Geophysical Research v. 99, p. 15,423-15,438.

Simpson, D.W. and Leith, W., 1985, The 1976 and 1984 Gazli, USSR, earthquakes-were they induced?: Seismological Society of America Bulletin, v. 75, p. 1465-1468.

Simpson, D.W. and Negmatullaev, S.K., 1981, Induced seismicity at Nurek Reservoir, Tadjikistan, USSR, Seismological Society of America Bulletin, v. 71, p. 1561-1586.

Simpson, D.W., 1986, Triggered earthquakes, Annual Rev. Earth and Planetary Science, v. 14, p. 21-42.

Simpson, D.W., Gharib, A.A., and Kebeasy, R.M., 1990, Induced seismicity and changes in water level at Aswan Reservoir, Egypt: Gerlans Beitr. Geophysik Leipzig, v. 99, p. 191-204.

Simpson, D.W., Leith, W.S. and Scholz, C.H., 1988, Two types of reservoir-induced seismicity: Seismological Society of America Bulletin, v. 75, p. 2025-2040.

Slemmons, D.B., 1977, Faults and earthquake magnitude, U.S. Army Corps of Engineers, Waterways Experimental Station, Miscellaneous Papers S-73-1, Report 6, p. 1-129.

Spudich, P. Hellweg, M., Fletcher, J.B., Hanks, T.C., McGarr, A., Joyner, W.B., Baker, L.M., Sullivan, C., Boore, D.M., and Boatwright, J., 1996, Earthquake ground motions in extensional tectonic regimes: Report to Yucca Mountain Project Branch, U.S. Geological Survey, in review.

Stein, R.S., King, G.C.P. and Lin, J., 1992, Change in failure stress on the southern San Andreas fault system caused by the 1992 Magnitude=7.4 Landers earthquake: Science, v. 258, p. 1328-1332.

Talwani, P. and Acree, S., 1985, Pore-pressure diffusion and the mechanism of reservoir induced seismicity, PAGEOPH, v. 122, p. 947-965.

U.S. Army Corps of Engineers, 1991, Feasibility report, American River Watershed Investigation, California, Dec. 1991: Report accompanied by 8 vol. of Appendices.

U. S. Army Corps of Engineers, 1995, Draft Supplemental Information Report, American River Watershed Project, California, Aug. 1995: Report accompanied by 5 vol. of Appendices.

U.S. Bureau of Reclamation, 1990, Auburn Dam interim construction geology report, 249 pp. + plates.

U.S. Geological Survey, 1978, Technical Review of Earthquake Evaluation Studies of the Auburn Dam area (Woodward-Clyde Consultants, 1977): Report to the U.S. Bureau of Reclamation, July, 1978, 143 p.

Wells, D.L. and Coppersmith, K.J., 1994, New empirical relationships among magnitude, rupture length, rupture width, rupture area, and surface displacement: Seismological Society of America Bulletin, v. 84, p. 974-1002.

Westaway, R., and Smith, R. B., 1989, Strong ground motion in normal-faulting earthquakes: Geophysical Journal, v. 96, p. 529-559.

Woodward-Clyde Consultants, 1977, Earthquake evaluation studies of the Auburn Dam area, Report to the U.S. Bureau of Reclamation, Contract No. 6/07/DS/72090, Auburn- Folsom South Unit, Central Valley Project, California, 8 vol.

Working Group on California Earthquake Probabilities, 1990, Probabilities of large earthquakes in the San Francisco Bay region, California. U.S. Geological Survey Circular 1053, 51p.

Working Group on California Earthquake Probabilities, 1995, Seismic hazards in California: probable earthquakes, 1994-2024, Seismological Society of America Bulletin, v. 85, p. 379-439.

Zoback, M.D. and Hickman, S., 1982, In situ study of the physical mechanisms controlling induced seismicity at Monticello Reservoir, South Carolina: Journal of Geophysical Research, v. 87, p. 6959-6974.

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Contact: webmaster@maildcascr.wr.usgs.gov