OROVILLE RESERVOIR, CALIFORNIA AND THE EARTHQUAKES OF AUGUST 1, 1975

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SYNOPSIS

On August 1, 1975, following some foreshock activity beginning June 28, 1975, an earthquake ($M_L = 5.7$) occurred 11 km from a large reservoir near Oroville, California. The effects of this earthquake at Oroville City and at the Oroville Dam, the highest in the U.S.A., are briefly discussed. The possibility that the seismicity may have been reservoir induced is discussed. It is shown that it is unlikely that the water load triggered the main shock but no definite conclusions can be made with respect to triggering by the water pressure.

INTRODUCTION

Lake Oroville, California, a large man-made lake created as part of the California State Water Project, is located on the Feather River in the foothills of the northern Sierra Nevada mountain range (Fig. 1). When full the lake holds $4.4 \times 10^9 m^3$ of water with a surface area of 64 km^2 and a maximum depth of about 200 m. Oroville Dam is a zoned earthfill dam with an outer shell of gravel (Fig. 2). With a height of 235 m, it is the highest dam in the U.S.A.

No significant increase in seismic activity occurred within a radius of 30 km of the dam following impoundment of the reservoir in November 1967 until June 28, 1975. During the preceding 4 months the seasonal increase in the water level had occurred at the greatest rate and with the greatest increment, about 45 m, since impoundment. The 1975 maximum elevation of 273.6 m, which was just below the maximum allowable elevation of 274.5 m, occurred on June 24.

On August 1, 1975 the foreshock activity increased and the main shock of magnitude $M_L = 5.7$ occurred at 1:20 p.m., Pacific Standard Time. This event was followed by a series of aftershocks which included two magnitude $M_L = 5$ events. From the aftershock data, the least squares value for b in the relation $\log N = a - bM_L$ (N = cumulative number of earthquakes of magnitude $\geq M_L$) has been determined to be $b = 0.6$.⁽¹⁾

The epicenter of the main shock was 11 km SSW of the Oroville Dam and 7 km SSE of Oroville City (Fig. 1). The focal mechanism of this event has been analyzed and references to relevant publications may be found in Beck.⁽²⁾ The consensus is that the main shock was caused by normal faulting at a focal depth of about 8 km on a N-S trending fault which had a local dip to the west of about 65°. The fault motion was primarily dip-slip with the western, Great Valley side moving down with respect to the eastern, Sierra Nevada side. Surface rupture occurred over a distance of about 1.7 km, following a NNW trend, on what may be a subsidiary fault that was involved in the Oroville earthquakes.

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ENGINEERING EFFECTS OF OROVILLE EARTHQUAKES

The damage caused by the Oroville earthquakes is discussed in a special report published by the California Division of Mines and Geology.(3) This report, which has contributions by many authors, also discusses the geological and seismological aspects of the Oroville earthquakes.

The Modified Mercalli Intensity assigned to the Palermo-Oroville area was VI to VII. The downtown area of Oroville City (population of metropolitan area 20,000) had slight to moderate structural damage. The downtown buildings are generally 60 to 100 years old and are 1 or 2 story unreinforced masonry structures. About 18 of these buildings were later concondemned. The few modern engineered structures in and around Oroville suffered only architectural and other non-structural damage. The moderate damage may have been partly due to the short duration of strong ground motion during the main shock.

The Oroville dam showed no signs of distress after the earthquakes. The dam was instrumented to record accelerations, pore water pressure and gross deformation (Fig. 2). A report on this data is being prepared by the California Department of Water Resources. The shaking during the main shock was recorded by accelerographs on the crest of the dam and at the Seismograph Station, a bedrock site 2 km NE of the dam. A third accelerograph in the core block of the dam did not operate during the earthquake. Acceleration peaks were 0.13g at the dam crest and 0.12g at the Seismograph Station.

The corrected acceleration, velocity and displacement histories are shown in Fig. 3(a) and (b) for the N37°E component at the Seismograph Station and the transverse (N45°E) component at the crest of the dam. The first few seconds of the crest record were lost owing to a delayed start of the accelerograph light source, The Fourier amplitude spectra corresponding to the accelerograms are shown in Fig. 4 (I). The dominant peak in the dam crest spectrum at 0.85 sec presumably corresponds to the fundamental transverse mode of the dam since there are no peaks at longer periods, despite the fact that the Seismograph Station spectrum shows that the ground excitation had significant amplitude at longer periods. The 0.85 sec component also dominates the dam crest displacement (Fig. 3(b)).

The earthquake design of the dam was originally carried out on the basis of a static analysis using a 0.1g transverse acceleration. Subsequent to the earthquakes, the Department of Water Resources has had a special dynamic analysis of the dam performed for much stronger shaking than the Oroville earthquakes but the results of this analysis have not yet been published.

NATURAL VERSUS RESERVOIR-INDUCED SEISMICITY

There are now several well-documented cases of a significant increase in local seismicity following the impounding of certain large reservoirs.(4, 5, 6, 7) In four of these cases, Lake Kariba (Zambia) Lake Kremasta (Greece), Hsinfengkiang Reservoir (China) and Koyna Reservoir (India), the principal earthquakes had magnitudes greater than $M_L = 6$. It is generally agreed that a reservoir can at most trigger the

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(I) Figures 3 and 4 are from a paper by R. P. Maley, V. Perez and B. J. Morrill in (3).

release of strain energy built up by tectonic processes. The stresses induced by the weight of water in the reservoir are too small to be the sole cause of fault rupture.(2)

The proximity of the Oroville earthquakes to Lake Oroville raises the question of whether they are causally related to the reservoir. Indeed, some Oroville residents have taken preliminary steps to initiate a lawsuit against the California Department of Water Resources under the assumption that the reservoir was responsible for the earthquake damage.

The fundamental question of whether the Oroville earthquakes were part of the natural seismicity or not proves to be very difficult to answer conclusively. One approach is to make use of a phenomenological classification of reservoir-associated earthquakes. Several authors have attempted to find common features of such earthquakes which may be used for characterization. These features include unusually shallow focal depth, a ratio of magnitudes of largest aftershock to main shock of about 0.9 and a well-developed foreshock sequence. The Oroville earthquake sequence exhibits all these features but so have other earthquake sequences in the Western United States well away from any reservoir. A noticeable difference between the Oroville earthquakes and reported cases of reservoir-associated seismicity is their occurrence so long after impounding (7.5 years), or the first topping (6 years), of the Oroville Reservoir.

It has been shown (5) that the b-values in the frequency-magnitude relation for the aftershocks of reservoir-associated earthquakes are generally higher than those of other regional earthquakes, often being greater than 1.0. In contrast, the value for the Oroville aftershocks of $b = 0.6$ is lower than those (0.8 - 0.9) generally found for earthquakes in the Western United States (Ryall and Van Wormer in (3)). Another anomaly was the duration of strong ground shaking during the Oroville main shock which was particularly short (about 3 sec) compared with other California earthquakes of the same magnitude. A similar observation has been made with respect to the earthquakes occurring around the Hsinfengkiang Reservoir in China.(8)

The historic seismic record for the Oroville region prior to the recent earthquakes is one of relatively low seismicity. For example, between 1940 and June 1975, 40 events with $M_L > 3$ occurred within 100 km of Oroville, including an $M_L = 6$ event, but none occurred with 40 km of the recent activity.(3) However, the historic record covers a period of little more than a century and it cannot therefore be used with confidence in a region where return periods may be much longer than this.

It is clear that a phenomenological approach to the origin of the Oroville earthquakes is not persuasive either way. A more basic approach is to examine possible triggering mechanisms directly. However, such an approach is not without difficulties.

Two principal triggering mechanisms have been proposed for reservoir induced earthquakes: a) an increase in shear stress across a fault due to the water load, and b) a decrease in shear strength of a fault, either due to the water pressure decreasing the effective normal stress or due to the physical or chemical alteration by the water of the properties of the material in the fault zone.

The first mechanism a) has been examined by Beck(2). The stresses induced in the neighboring lithosphere by the weight of Lake Oroville when full were determined by discretizing the water load and using a superposition of Boussinesq point load solutions. The greatest weight-induced shear stress was calculated to be about 3.4 bars at a point 1 km below the deepest portion of the lake (Fig. 1). Figures 5(a) and (b), taken from Beck(2), show contours of maximum shear stress for points lying on a horizontal and vertical plane passing through the hypocenter of the main shock. The origin of the (x, y, z) coordinates used in the calculations and plots is shown in Fig. 1. The x-axis is eastward, the y-axis northward and the z-axis points vertically down.

Fault plane solutions that are available for the main shock were used to calculate the weight-induced stresses across the fault at the hypocenter. The weight-induced shear stress was found to have a component of about 0.04 bar parallel to the reported fault movement but directed in opposition to this movement. Furthermore, the compressive normal stress across the fault was found to be increased by 0.0 1 bar by the weight of the reservoir, which, if it had any effect at all, would be expected to produce a small increase in fault strength. The fault parameters (strike and dip) and the position of the hypocenter were varied about their nominal values. In every case the calculations led to the same conclusions, that is, the weight-induced stresses decreased the existing shear stress and increased the normal stress across the fault. On the basis of these calculations it is unlikely that the weight of water in Lake Oroville triggered the Oroville earthquakes.

A theoretical model is available to analyze the water pressure mechanism which is based on the equations for flow through an elastic permeable medium, Terzaghi's effective stress principle and a Mohr-Coulomb criterion for the fault shear strength. However, in applying such an analysis to a particular case, one is faced with the problem of the lack of quantitative data on the local mechanical properties of the medium, the initial tectonic stress field and the shear strength of the fault. It is possible to apply a simple dimensional argument that suggests that it could take several years for significant water pressure to diffuse over the relatively large distance from Lake Oroville to the zone of the recent earthquakes.(2) The triggering mechanisms (b) requiring the presence of water in the fault zone could therefore explain the long time interval of 6 years between the first topping of the reservoir and the increase in seismic activity, if one assumed that there are no faults closer to the reservoir which have been brought to the required critical stress state by tectonic processes. However, there is no direct evidence to show that these latter mechanisms were operative at Oroville.

REFERENCES

1. Morris, P. W., B. W. Stump and R. Urhammer (1976). The Oroville earthquake sequence of August 1975, Bull. Seism. Soc. Amer. 66, August.

2. Beck, J. L. (1976). Weight-induced stresses and the recent seismicity at Lake Oroville, California, Bull. Seism. Soc. Amer. 66, August.

3. Sherburne, R. W. and C. J. Hauge (eds) (1975). Oroville, California, Earthquake 1 August 1975, Special Report 124, California Division of Mines and Geology, Sacramento, California.

4. Rothé, J. P. (1969). Earthquakes and reservoir loadings, Proc. 4th Wld Conf Earthq Engng 1, A-1, 28-38.

5. Gupta, H. K., B. K. Tastogi and H. Narain (1972). Common features of the reservoir-associated seismic activities, Bull. Seism. Soc. Amer. 62. 481-492.
6. Sheng, C-K, H-C Chen, L-S Huang et al (1974). Earthquakes induced by reservoir impounding and their effect on the Hsinfengkiang Dam, Scientia Sinica, No. 2, Peking, China.
7. Judd, W. R. (ed) (1974). Special issue on seismic effects of reservoir impounding, Engng Geol. 8, 1-212.
8. Hsu, T-H, H-H Lo, T-H Ho and C-J Yang (1975). Strong-motion observation of water-induced earthquakes at Hsinfengkiang Reservoir in China, presented at 1st Int. Symp. on Induced Seismicity, Sept. 1975, Banff, Canada.

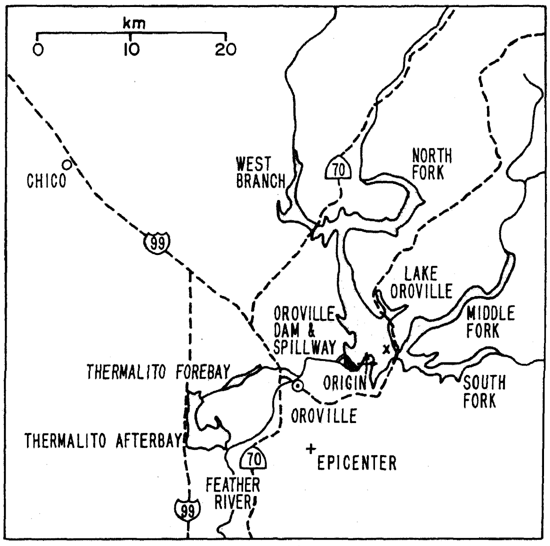

Fig. 1. Map of Oroville region showing epicenter of main shock of August 1, 1975. x denotes surface coordinates of point of greatest weight-induced shear stress.

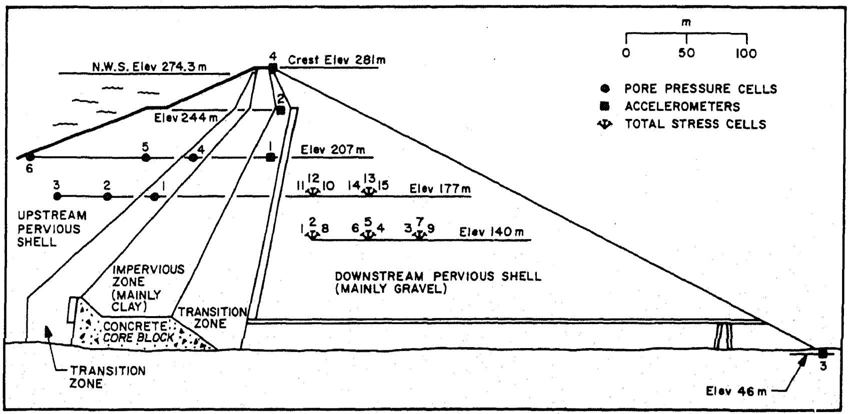

Fig. 2. Cross section of Oroville Dam showing instrumentation.

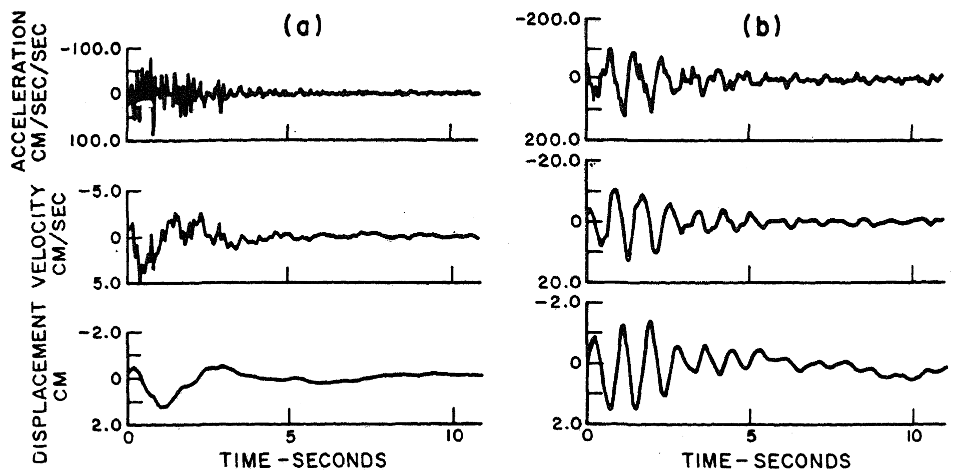

Fig. 3. Time histories from corrected accelerograms. (a) N37°E component at Seismograph Station. (b) Transverse (N45°E) component at crest of Oroville Dam.

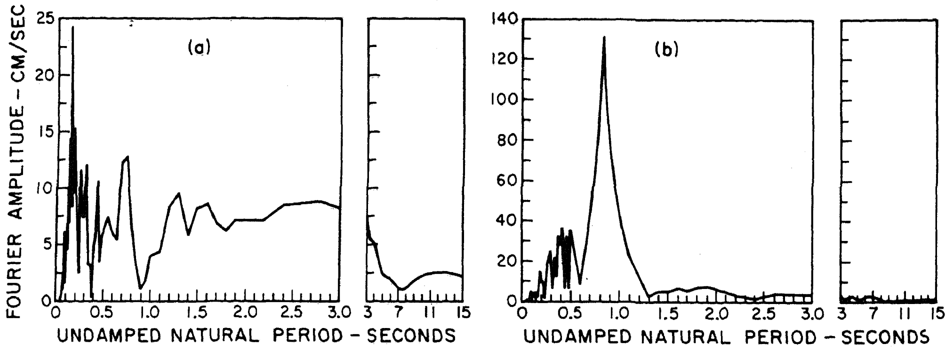

Fig. 4. Fourier amplitude spectra of corrected accelerograms. (a) N37°E component at Seismograph Station. (b) Transverse (N45°E) component at crest of Oroville Dam.

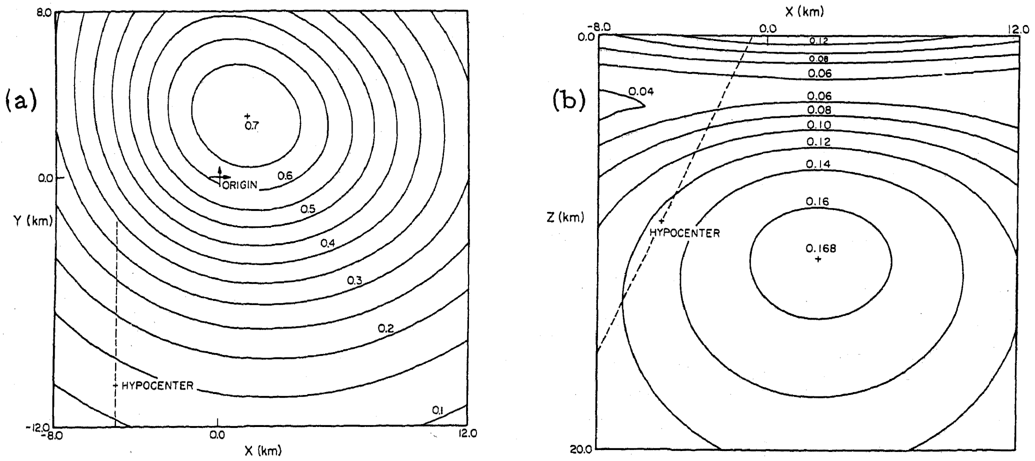

Fig. 5. Weight-induced maximum shear stress (in bars) on a plane through hypocenter of main Oroville shock. (a) Horizontal plane. (b) Vertical E-W plane. The approximate position of the intercept of each plane and the fault is shown by a dashed line.