Earthquake and Lake Levels at Oroville, California

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INTRODUCTION

On 1 August 1975, an earthquake of magnitude (M) 5.7 occurred 12 km south of Lake Oroville (Figure 1). The earthquake was accompanied by surface faulting which extended for several kilometers (Akers and McQuilkin, 1975). The earthquake sequence (M > 3) consisted of five foreshocks, a main shock, and numerous aftershocks. The sequence included seven earthquakes of magnitude greater than 4.6 (Morrison and others, 1976). Faulting occurred on a northwest trending zone of the Foothills fault system (Hart and Rapp, 1975). The aftershocks defined a zone extending 16 km south from the dam and dipping 60 degrees west (Lester and others, 1975). Focal mechanisms indicated normal faulting with the Great Valley side down relative to the Sierra Nevada; leveling surveys confirmed this sense of motion.

SEISMICITY OF THE AREA

The location of Lake Oroville and the areal distribution of historical earthquakes and known faults are shown an figure 1. Three other earthquakes of M 5.0 to 5.9 have occurred since 1900 an or near the Foothills fault system within 60 km of Oroville. The first two occurred in 1909, 60 km east of Oroville (Toppozada and others, 1978) and the third in 1940, 60 km north of Oroville (Bolt and Miller, 1975). Thus, the occurrence of the 1975 M 5.7 earthquake within 70 km of Oroville was not without precedent.

Two factors suggest that Lake Oroville (maximum depth 220 m; storage capacity 413 billion m3) contributed to both the location and timing of the 1975 earthquake. The first factor is the proximity of the earthquake to the lake, and the extension of the causative fault to the lake as indicated by geologic, seismologic, and geodetic data (Department of Water Resources, 1979). This provides a possible avenue for water under pressure as high as 20 bars, resulting from a water depth of more than 200 meters into the fault zone (Lahr and others, 1976). The second factor is the occurrence of the earthquake following an unprecedented seasonal fluctuation in lake levels. This factor is illustrated in figure 2a, which shows lake levels (in meters above sea level) and number of earthquakes per month within 40 km of Oroville from 1964 to 1976. During the winter of 1974-1975, the lake was drawn down to its lowest level since filling to repair the intakes to the power plant. This unprecedented drawdown and subsequent refilling was followed by the earthquake sequence of 1975.

FIGURE 1

Figure 1. Faults and earthquakes (M > 4.0, intensity > V) within 70 kilometers of Oroville Dam, 1900-1980. The aftershock zone of the M 5.7 earthquake of 1975 is outlined.

The earthquake occurrence at Oroville, following the largest seasonal fluctuation in lake level, is very similar to the M 6.5 earthquake occurrence at Koyna, India, which also followed the largest seasonal fluctuation of that lake in 1967. The lake levels far Koyna reservoir and the monthly number of nearby earthquakes are shown on figure 2b. At both Oroville and Koyna the major burst of seismicity did not occur upon initial filling, but occurred several years later following an unprecedented seasonal refilling in each case (Figures 2a and 2b). The occurrence of the strongest earthquakes following the largest seasonal refilling, rather than upon initial filling, has been observed at other reservoirs, such as at Lake Marathon (Galanopoulos, 1966; Gupta and Rastogi, 1976) and at Lake Mendocino (Toppozada and Cramer, 1978). At Lake Crowley, California, upon initial filling in 1941, a swarm of M 5.0 to M 6.0 earthquakes occurred. When the largest refilling occurred in 1978, it also led to a M 5.8 earthquake which was the largest event since 1941 (Toppozada, 1979; Cramer and Toppozada, 1980). Each of these cases is accepted as being induced in the most recent classification of induced seismicity (Perman and others, 1981). The occurrence of earthquakes following record seasonal refilling is consistent with the model of Withers and Nyland (1978), wherein partial emptying and refilling of a reservoir sometime after initial filling can cause anomalously large stresses.

FIGURE 2a

Figure 2a. Oroville Lake levels in meters above sea level and number of earthquakes within 40 kilometers, 1964-1976.

FIGURE 2b

Figure 2b. Koyna Lake levels in meters above sea level and number of nearby earthquakes, 1963-1967.

SEASONAL VARIATIONS SINCE 1975

Detailed seismographic monitoring since 1975 has revealed a relation of earthquake occurrences within 20 km of Lake Oroville to the seasonal variations in lake levels. Seismicity decreases during filling of the lake and increases during drawdown.

A weekly plot of the lake levels and the seismic strain released within the 1975 rupture zone by the earthquakes of M> 2.5 is shown on figure 3. In 1975, the M 5.7 earthquake occurred in August during the summer drawdown following the large volume refilling that culminated in June. In 1976, the strongest earthquake (M 4.1) occurred in July during rapid summer drawdown, following the spring peak of seasonal filling. In 1977 there was no seasonal refilling because of drought, and earthquakes continued to occur during the unusual drawdown. During the drought, the strongest earthquakes occurred during the periods of most rapid drawdown, as in June and July 1976, and May 1977. Conversely, the periods when the lake level either increased, as in February through April 1976, or was stable, as in February through April 1977, no strong (M > 3) earthquakes occurred. After the drought the reservoir filled rapidly in January 1978, and the seismicity (M > 2.5) stopped abruptly. The remarkable eight-month period of seismic quiescence starting in November 1977 ended with a M 3.3 earthquake in July 1978, two weeks after the beginning of summer drawdown. Earthquakes occurred into January 1979, but ceased during the refilling from February through May 1979. Seismicity again increased in July 1979 within a month after the beginning of summer drawdown.

FIGURE 3

Figure 3. Lake Oroville water levels in meters above sea level for 1975-1980. Vertical bars show the square root of the energy released each week by earthquakes of $M > 2.5$ occurring within 20 kilometers of the dam.

Heavy storms in January and February 1980 resulted in two sharp peaks in the lake levels representing rapid filling and rapid drawdown which are unprecedented since 1975 (figure 3). An earthquake of M 2.7 occurred two weeks after the January peak, and an earthquake of M 2.6 occurred two weeks after the February peak. This coincidence is consistent with the seasonal relation of seismicity to the variations in lake level, in that both earthquakes followed filling peaks of the reservoir. Earthquakes occurred in June and November 1980, following the spring filling. The only earthquake of $M > 2.5$ in 1981 occurred in June, again following the spring filling.

The amount of seismic strain released during the successive seasonal drawdowns has generally decreased since 1975 (Figure 3). This indicates that most of the seismic strain stored in the rupture zone of the 1975 earthquake is being gradually released during the seasonal drawdowns in reservoir levels.

DISCUSSION OF OBSERVATIONS

The record indicates that periods of reservoir filling are accompanied by a decrease in seismicity (figure 3). This stability during loading is consistent with the analysis of the effects of loading and pore pressure changes (Snow, 1972). After filling, water diffuses into subsurface voids producing a gradual rise in pore pressure and a corresponding reduction of the effective stress, which results in decreased stability.

Effective stress on a plane is defined as the normal stress minus the pore pressure. Thus, increased pore pressure acts to counter the load effect, and to decrease the strength. During the rapid summer drawdown there is a sudden drop in the surface load and in the stabilizing normal stress. Earthquake failure occurs during this rapid drawdown before the reduction
in pore pressure, resulting from the decreased reservoir depth, can be transmitted to hypocentral distances (1-20 km). Failure occurs because the rapid drawdown immediately reduces the normal stress, whereas the reduction in pore pressure diffuses more slowly in the underlying rocks. The result is excess pore pressure in the underlying rocks which diminishes the effective stress or strength. This is borne out in figure 3 which shows that seismicity is greatly diminished during episodes of reservoir filling, and that the largest earthquakes are associated with the most rapid drawdowns in lake levels.

Thus, not only does the filling of the lake and the resulting increase in subsurface pore pressure influence seismicity, but also the reservoir drawdown promotes failure by reducing the effective stress. In this regard, Simpson (1976, p. 146) noted the paradox "that if there is an indication of an impending increase in the level of seismicity, one of the obvious ways of decreasing danger downstream from the dam---the rapid emptying of the reservoir---may in fact increase the danger by triggering a further increase in the level of activity." This scenario is reflected in figure 3, which shows that the most rapid drawdowns in lake levels are accompanied by the greatest seismic activity.

The occurrence of the two M > 2.5 earthquakes in 1980 following the two peaks of rapid filling and rapid drawdown resulting from severe storms suggests an extreme sensitivity of the fault zone to sharp fluctuations in lake level.

SUMMARY AND CONCLUSIONS

1. The 1975 Oroville earthquake of M 5.7 occurred almost eight years after the creation of Lake Oroville. This earthquake immediately followed the largest seasonal fluctuation in the lake level to that date.
2. The largest known reservoir-induced earthquake (M 6.5) at Koyna, India, did not occur when the reservoir was first filled, but occurred five and one half years later. That earthquake also immediately followed the largest seasonal fluctuation in lake levels to that date. Similar behavior has been observed in other cases of reservoir-induced seismicity.
3. Seismic monitoring at Oroville since 1975 shows that the local seismicity decreases as the lake fills during winter and spring, and that the strongest earthquakes occur as the lake empties during summer and fall. This pattern has been remarkably consistent during the past seven years, and indicates that the seasonal fluctuations in water depth at Lake Oroville control the earthquake occurrences.
4. The magnitude of the earthquakes triggered by Lake Oroville during each seasonal drawdown has generally become smaller since 1975, suggesting that the 1975 rupture zone is being progressively relieved of stress. However, stress has not necessarily been relieved outside the 1975 rupture zone.

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