EARTHQUAKES AND LAKE LEVELS

Exhibit: X-9

AT OROVILLE, CALIFORNIA

By

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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 on figure 1. Three other earthquakes of M 5.0 to 5.9 have occurred since 1900 on 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.

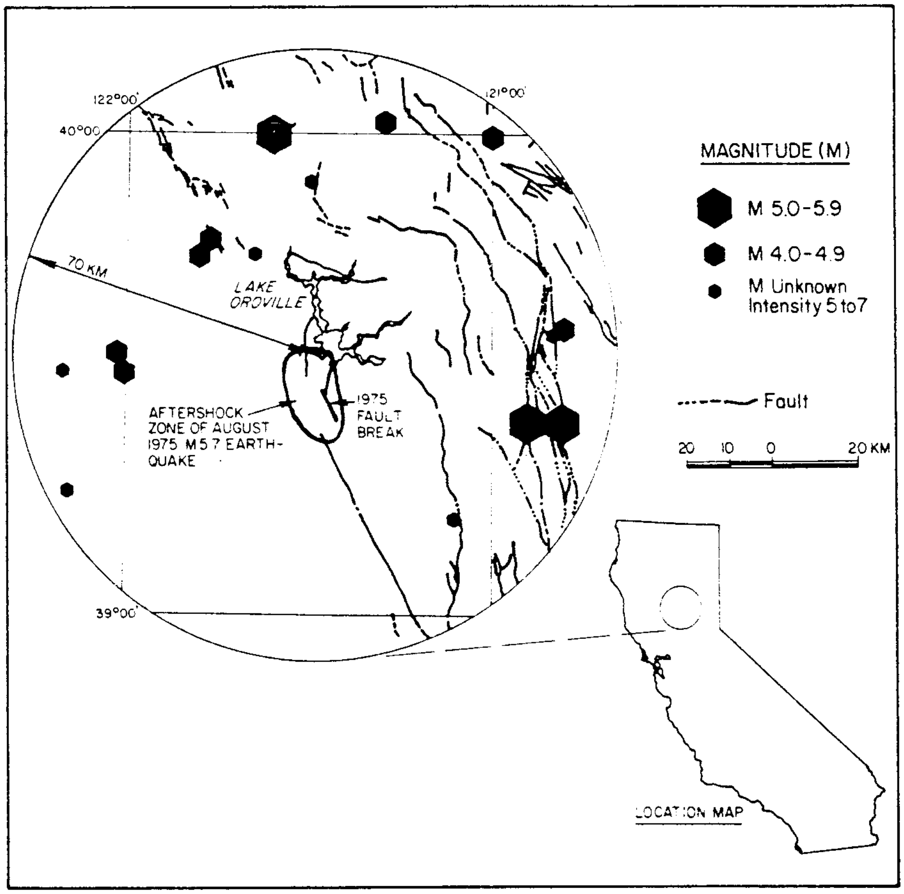

Figure 1. Faults and earthquakes (M ≥ 4.0, intensity ≥ V) within 70 kilometers of Oroville Dam, 1900-1980. The aftershock zone of the M 5.7 earthquake of 1975 is outlined.

Two factors suggest that Lake Oroville (maximum depth 220 m; storage capacity 413 billion m^3) 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.

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 for Koyna reservoir and the month-

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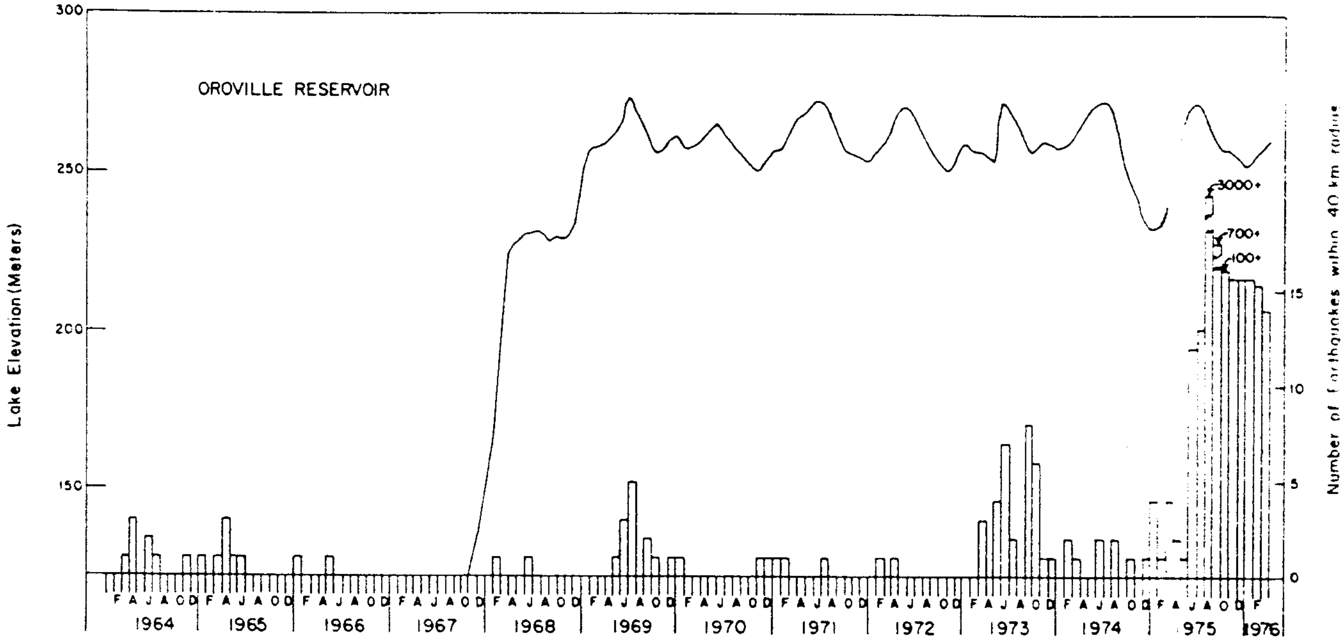
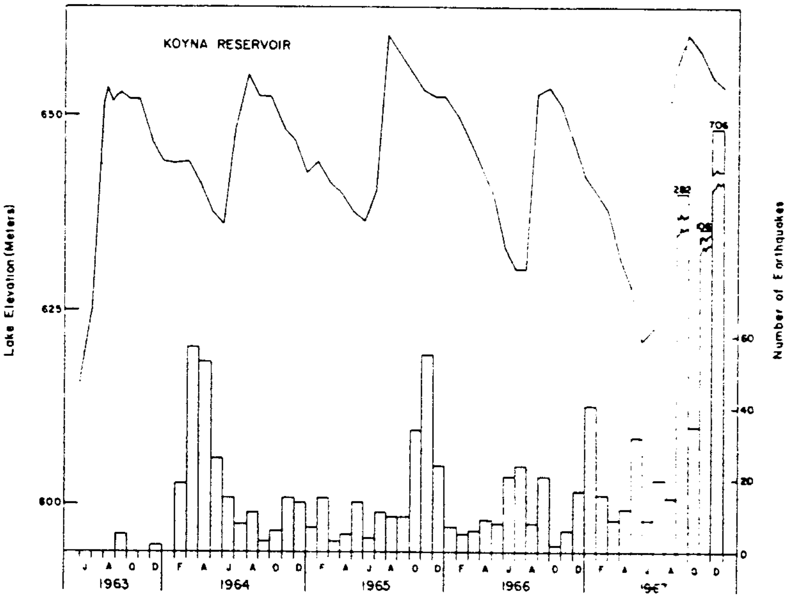


Figure 2. ↑(a) Oroville Lake levels in meters above sea level and number of earthquakes within 40 kilometers, 1964-1976; ↓(b) Koyna Lake levels in meters above sea level and number of nearby earthquakes, 1963-1967.



ly 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.

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 $\geq$ 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 $\geq$ 2.5) stopped abruptly. The remarkable eight-month period of seismic quiescence starting in November 1977

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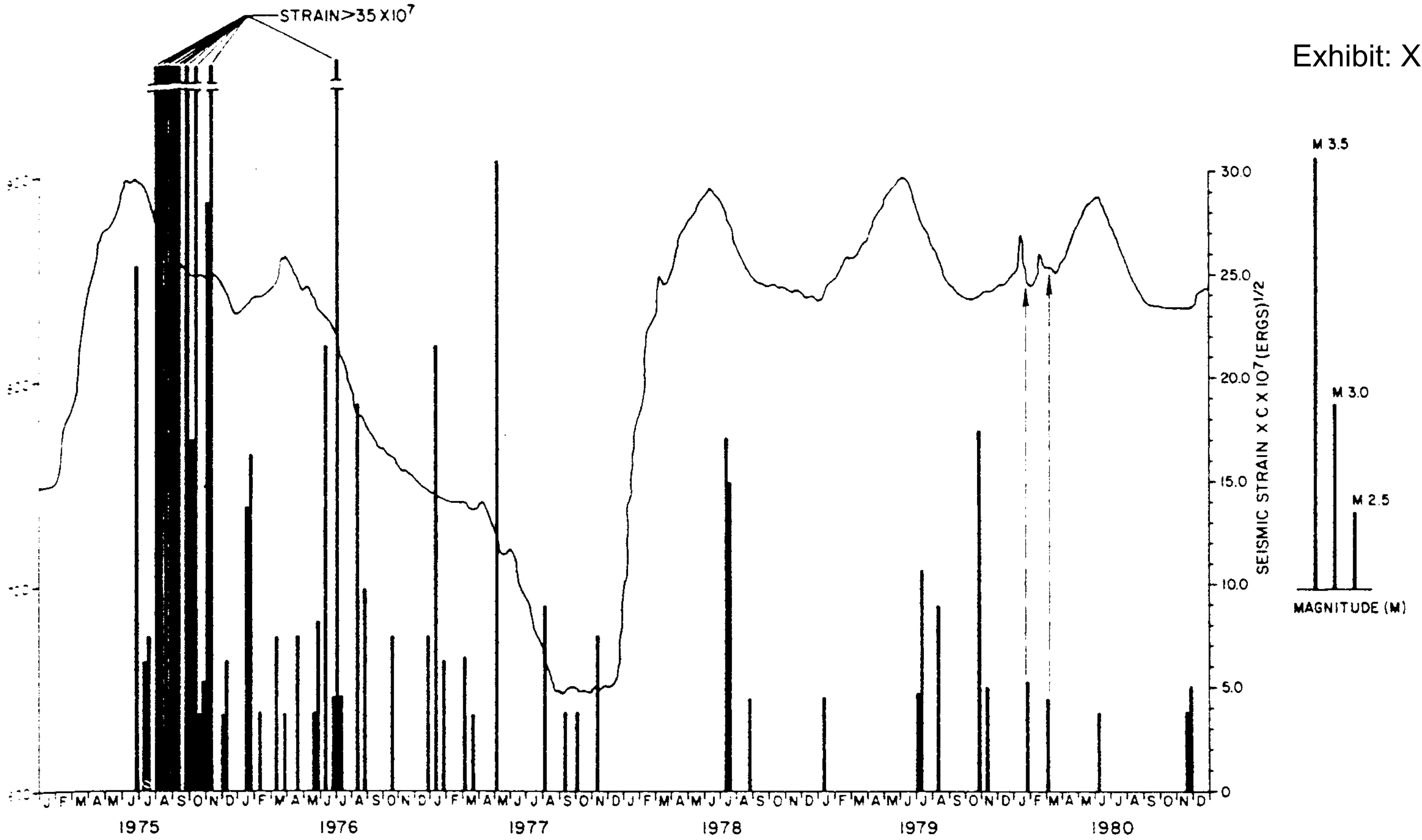

Figure 3. Lake Oroville water levels in meters above sea level for 1975-1980. Vertical bars show the square root of the energy released each week by earthquakes of M $\geq$ 2.5 occurring within 20 kilometers of the dam.

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.

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

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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.

ACKNOWLEDGMENTS

John H. Bennett and Chris H. Cramer reviewed the manuscript and participated in constructive discussions of the observations.

REFERENCES

Akers, R.J. and McQuilkin, M.J., 1975, Geologic investigation of the Oroville earthquake *in* Sherburne, R.W., and Hauge, C.J., editors, Oroville, California, earthquake, 1 August 1975: California Division of Mines and Geology Special Report 124, p. 45-52.

Bolt, B.A. and Miller, R.D., 1975, Catalogue of earthquakes in northern California and adjoining areas, 1 January 1910-31 December 1972, Seismographic Stations: University of California, Berkeley, California, 567 p.

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

Cramer, C.H. and Toppozada, T.R., 1980, A seismological study of the May, 1980, and earlier earthquake activity near Mammoth Lakes, California *in* Sherburne, R.W., editor, Mammoth Lakes, California earthquakes of May 1980: California Division of Mines and Geology Special Report 150, p. 91-130.

Department of Water Resources, 1979, The August 1, 1975 Oroville, California earthquake investigations: Bulletin 20-78, 669 p.

Fletcher, J.B. and Sykes, L.R., 1977, Earthquakes related to hydraulic mining and natural seismic activity in western New York: Journal of Geophysical Research, v. 82, no. 26, p. 3767-3780.

Galanopoulos, A.G., 1966, The influence of the fluctuation of Marathon Lake elevation on local earthquake activity in the Attica Basin: Annals Geologiques des Pays Helleniques, v. 18, p. 281-306.

Gupta, H.K. and Rastogi, B.K., 1976, Dams and earthquakes: Elsevier Scientific Publishing Company, Amsterdam, 229 p.

Hart, E.W. and Rapp, J.S., 1975, Ground rupture along the Cleveland Hill fault *in* Sherburne, R.W., and Hauge, C.J., editors, Oroville, California earthquake, 1 August 1975: California Division of Mines and Geology Special Report 124.

Lahr, K.M., Lahr, J.C., Lindh, A.G., Bufe, C.G., and Lester, F.W., 1976, The August 1975 Oroville earthquakes: Bulletin of the Seismological Society of America, v. 66, no. 4, p. 1085-1100.

Lester, F.W., Bufe, C.G., Lahr, K.M., and Stewart, S.W., 1975, Aftershocks of the Oroville earthquake of 1 August 1975 *in* Sherburne, R.W., and Hauge, C.J., editors, Oroville, California, earthquake, 1 August 1975: California Division of Mines and Geology Special Report 124, p. 131-138.

Morrison, P.W., Jr., Stump, B.W., and Uhrhammer, R., 1976, The Oroville earthquake sequence of August 1975: Bulletin of the Seismological Society of America, v. 66, no. 4, p. 1065-1084.

Perman, R.C., Packer, D.R., Coppersmith, K.J., and Knuepfer, P.L., 1981, Collection of data for data bank on reservoir-induced seismicity: Woodward-Clyde report to U.S. Geological Survey.

Simpson, D.W., 1976, Seismicity changes associated with reservoir loading: Engineering Geology, v. 10, no. 2-4, p. 123-150.

Snow, D.T., 1972, Geodynamics of seismic reservoirs, Proceedings symposium on percolation through fissured rocks, Deutsche Geselleschaft Erd-Grunbau Stuttgart, TS-J, p. 1-19.

Toppozada, T.R., Parke, D.L., and Bates, G.T., 1978, Isoseismal map for the M 5.5 earthquake of 22 June 1909: CALIFORNIA GEOLOGY, v. 31, no. 8, front cover.

Toppozada, T.R., 1979, Seismicity, possibly induced by Lake Crowley, on the eastern front of the Sierra Nevada, California (Abstract): Transactions of the American Geophysical Union, December 1979.

Withers, R.J. and Nyland, E., 1978, Time evolution of stress under an artificial lake and its implication for induced seismicity: Canadian Journal of Earth Science, v. 15, p. 1526-1534.

CDMG PUBLICATION

OFR 81-12 SF

GEOLOGY AND SLOPE STABILITY IN THE WEST SEBASTOPOL STUDY AREA, SONOMA COUNTY, CALIFORNIA (OFR 81-12 SF). By Trinda L. Bedrossian. 1981. 42 pages, two maps (scale 1:24,000).

This report was prepared in cooperation with the Sonoma County Planning Department. Aerial photo interpretation and field investigation were conducted in a 32-square mile area approximately 60 miles north of San Francisco and 15 miles west of Santa Rosa. The area is underlain by Jurassic and Cretaceous rocks of the Franciscan Complex and Great Valley sequence, and Tertiary rocks of the Wilson Grove Formation (formerly Merced Formation).

Results of the study may be used for land use planning and as general background information for the selection of areas most suitable for buildings, roads, and utilities. Specifically, maps identify geologic hazards and potential geologic problems that should be studied in detail prior to development. An interpretation of relative slope stability is presented, and engineering properties of most of the rock units are summarized.

Copies of OFR 81-12 SF may be obtained from the San Francisco District Office, Information Section.

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OROVILLE EARTHQUAKE

This description of sensations felt very near the seismic epicenter during the Oroville earthquake of 1 August 1975 was sent to us by Dan Tidwell, Lowry and Associates, Geotechnical Engineers, of Sacramento. We think it's interesting and informative—particularly the comment on remaining calm. Also interesting is the roar and the observation of up-and-down motion of the ground and the structures....editor

This is a memo to record my personal impressions of the earthquake and related phenomena near Oroville on 1 August 1975.

Friday, 1 August 1975, I was assigned to batch plant observation at Mathews Ready Mix Plant on Highway 70, approximately 5 miles southwest of Oroville. This plant is situated near the Feather River and dispatches both ready-mix concrete and sand and gravel for various construction requirements.

I arrived at the plant at approximately 10:15 A.M. and observed the first load of concrete dispatched to the Butte Community College. During the batching operation, I was standing in the control room and noticed the entire plant seemed to rock slightly with a subtle jar. I assumed this to be typical of the plant itself as there are approximately 100 tons of material in bins directly overhead and the batching operation necessarily requires shifting of material, "banging" of gates, and cycling of water valves which must cause the plant to move somewhat. Apparently this shock was 3.5 ± Richter and I was unaware of the earlier 5.0±. The batchman told me they had felt shocks frequently this morning. We continued to feel small "bumps" and "shakes".

At approximately 1:00 P.M., I observed batching operation on Load No. 10 and moved my pickup into the shade on the west side of the plant. By this time, there had been much discussion among the people around the plant as to what one could do during a severe quake. I had made a mental note that if a severe shock hit, I would run away from the plant in a direction to avoid the numerous high voltage lines in the area.

At approximately 1:20 P.M., I had just sat down in my truck to have lunch. My first indication was a distant "roar", perhaps like the rumble of a train. The shaking started within a few seconds and seemed to increase sharply after a few seconds of relatively minor movement. At this time, I made the decision to move away quickly from the plant. The door of the truck was open so I started running diagonally away from the plant. I ran approximately 50 yards and stopped and looked back at the plant. At this time, the major shaking was still going on and the entire earth and plant and auxiliary buildings appeared to be moving up and down 6"±. The feeling was one of being on a giant rock crusher, very severe and very rapid, perhaps 10 cycles per second. There was a lot of noise, both from the equipment shaking and the surrounding stockpiled materials settling and also a background roar of the quake itself.

I would estimate the major motion lasted less than 30 seconds. In the minutes after the quake, I stayed in one place and could feel the earth "quiver" as if resonating. The after shocks were frequent, every 5 minutes more or less and were, for the most part, gentle bumps; however, at least one was severe enough to cause us to run out of the control room.

Personally, I did not feel sick or dizzy at any time, although some of the drivers did. I think this is just an individual thing—I did not feel any "fear" at anytime; however, I think this is because I did not feel threatened—I was outside and had effectively planned what I was going to do and had a safe, clear area to run to. For someone closed up in a building, the feeling must be oppressive.

They tell you to be calm. For a quake of this magnitude or greater, I don't think it is possible. The noise and movement compel you to want to move quickly—in any direction!

Concerning Emergency Services—I had a radio with me capable of receiving police and fire frequencies. I turned this on within 5 minutes of the event and monitored their response for some time.

I also switched around to the AM stations. The local station was off the air for 10 to 15 minutes; Sacramento and National stations broadcasted very uninformed vague reports of heavy damage, no communication, many casualties, etc. In other words, the radio seemed to sensationalize and overstate the facts.

If the quake had caused major damage, I feel it would have been every man for himself for several hours. My point being, generally people are not prepared for a major disaster that could come at any time. ⚒

NOAA DIVING MANUAL

"NOAA Diving Manual: Diving for Science and Technology", published by the National Oceanic and Atmospheric Administration was prepared primarily for the nearly 300 divers within the Commerce Department agency. However, it contains basic up-to-date information on the diving technology required to carry out scientific investigations and other working diver tasks. It is designed to provide divers with the knowledge needed for safe and efficient diving, and for carrying out useful scientific research.

One section of the manual is devoted to scientific diving procedures, and covers a wide variety of operations ranging from underwater surveying and photogrammetry to biological surveys and sampling, shellfish capture, geology, micro-physical oceanography, and archaeological diving, and capture techniques, including the use of anesthetics in obtaining marine specimens.

Sections of the manual deal with basic diving physics and physiology, diver training, equipment, breathing media, and procedures. Special topics include diving under varied conditions, such as under ice and in rivers and lakes, air diving and saturation diving, and marine animals hazardous to divers.

Prepared by NOAA's Manned Undersea Science and Technology group, the manual was extensively reviewed and includes contributions by 58 experienced scientific and operational divers from universities, Federal and state agencies, and private organizations throughout the United States. Much of the information in the manual has never before been published.

The work is illustrated with diagrams, sketches, and photographs designed to help the user understand the techniques and procedures discussed. Warnings regarding safe diver procedures are highlighted in red throughout the book.

The NOAA Diving Manual is for sale by the Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 20402, at a cost of $8.55. The Stock number is 003-017-00283. ⚒