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WEIGHT-INDUCED STRESSES AND THE RECENT SEISMICITY AT LAKE OROVILLE, CALIFORNIA

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ABSTRACT

Lake Oroville is a large artificial lake created by the construction of a 235-m-high earth dam on the Feather River, California, near the city of Oroville. Its storage capacity is about $4.4 \times 10^9\,m^3$, and its maximum depth is about 200 m. There was no significant increase in seismic activity in the lake region following impoundment of the dam late in 1967 until the occurrence of many small seismic events which began in June 1975. This activity lead to a $M = 5.7$ main shock on August 1, 1975 with an epicenter about 11 km SSW of the Oroville dam. The main shock produced significant damage in the city of Oroville which lies about 7 km NNW of the epicenter. With several cases of reservoir-induced activity already documented, it is natural to inquire whether the Oroville seismicity was due to the presence of the reservoir. As part of such a study, the stresses induced in the neighboring lithosphere by the weight of Lake Oroville are determined. On the basis of present geological data, it is unlikely that these stresses were responsible for the main shock of August 1, 1975. The weight-induced shear stress across the fault plane in the hypocentral region has a component of about 0.04 bar parallel to the reported fault movement but in opposition to this movement. The greatest weight-induced shear stress is about 3.4 bars and this occurs under the deepest portion of the lake. The greatest vertical deflection at the surface due to the weight of Lake Oroville is calculated to be about 5.5 cm.

Introduction

There are now several well-documented cases of a significant increase in seismic activity following the impounding of certain large reservoirs, for example, Rothé (1969), Gupta *et al.* (1972), Shen *et al.* (1973) and Judd (1974). In four of these cases, Lake Kariba (central Africa), Lake Kremasta (Greece), Hsinfengkiang Reservoir (China) and Koyna Reservoir (India), the principal earthquakes had magnitudes of about $M = 6$. Lake Oroville, California (Figure 1) is a deep, relatively large reservoir created by the construction of a 235-m-high earth dam on the Feather River at a site in the foothills of the Sierra Nevada mountain range. When full, the lake holds $4.4 \times 10^9\,m^3$ of water with a surface area of $64\,km^2$. Its maximum depth is about 200 meters. There was no significant increase in local seismicity within a radius of 30 km of the dam following the impounding of the reservoir at the end of 1967 until a sudden increase occurred in June 1975. During the preceding 4 months the water level had risen at its greatest rate and with the greatest increment since impoundment, but it is not clear whether this was a factor behind the increase in seismic activity. The greatest earthquake in this series was a shock of magnitude 5.7 at 1:20 p.m. on August 1, 1975. The epicenter of this shock was about 11 km SSW of the dam. No damage to the dam was reported but there was significant damage in the city of Oroville.

These events close to the lake have given rise to speculation that the seismic activity may be reservoir-induced. As a basis for further discussion, estimates of the incremental stresses induced in the neighboring lithosphere by the weight of Lake Oroville are described in this paper. The vertical surface deflections around Lake Oroville due to the weight of the reservoir are also given.

The greatest weight-induced shear stress is about 3.4 bars and it occurs 1 km beneath the deepest area of the lake. The corresponding additional vertical compressive stress is 8.3 bars, compared with a lithostatic pressure of about 250 bars at the same location. The maximum shear stress induced at the hypocenter is about 0.12 bar while the vertical compressive stress induced there is about 0.08 bar (0.003 per cent of the lithostatic pressure).

It is argued that for reservoir-induced seismicity to occur, nearby faults must be close to a critical stress state; that is, if a reservoir does induce seismicity it must be through some triggering mechanism. Two principal triggering mechanisms have been proposed: the increased stresses arising from the weight of water and the increased fluid pressure (Rothé, 1969). However, in the case of Lake Oroville, it is shown that it is unlikely that the weight-

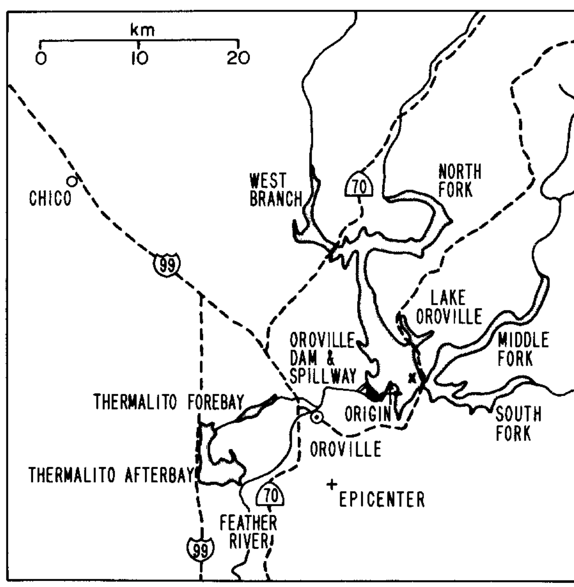

FIG. 1: Map of Lake Oroville region showing the epicenter of the main shock of August 1, 1975 and the origin of the coordinates used in the stress calculations. x denotes the surface coordinates of the point of greatest weight-induced shear stress.

induced stresses directly triggered the main shock since the small incremental shear stress across the fault has no component in the direction of the reported fault movement during the earthquake.

Calculation of Incremental Stress Distribution

The incremental stress distribution due to the weight of the reservoir is calculated by modeling the neighboring lithosphere as an elastic, homogeneous, and isotropic half-space. Of course the total stress distribution cannot be determined since the initial stress is unknown.

The technique used is described in detail by Gough and Gough (1970). One simply approximates the continuous distribution of water load at the surface of the Earth by a number of point loads and then the stress state at any point is given by a superposition of Boussinesq point-load solutions. If only the stress distribution is of interest then only one material parameter is required, Poisson's ratio ν. For the calculations in this paper the value $\nu = 0.25$ has been assumed. The values for the maximum shear stress are insensitive to ν over the range 0.2 to 0.3.

Gough and Gough (1970) have used the above approach also to compute surface deflections near Lake Kariba on the Zambesi River. The calculated deflections were in good agreement with the results of leveling surveys, giving confidence that the model can portray the broad features of the incremental stress-strain distribution in the lithosphere. In making these calculations, Gough and Gough assumed a value of 0.85 megabars for Young's modulus E. This value is also assumed in this paper during the calculation of the surface deflections. Since the vertical deflections are inversely proportional to E, allowance may easily be made for other assumed values.

The details of the discretization of the water-load distribution used by this author differ in certain respects from that of Gough and Gough. The surface of the lake was covered by a nonuniform rectangular grid system so that each grid area in the southern portion of the lake (near the dam) was about 0.25 km square, while to the north and east of this the grid areas were increased with distance from the dam. The linear dimensions of the grid areas were therefore increased to about 0.5 km then 1.0 km, and so on until the distant portions of the lake, such as the West Branch and the narrow portions of the North and Middle Forks, were each represented by a single point load. The rationale behind this was that the main areas of interest were under the central portion of the lake (where the stresses would be greatest), under the dam and under the epicentral region to the south. Thus the grid areas near these regions must be sufficiently small to allow the stresses beneath them to be calculated without the local effects of the individual point loads confusing the results. On the other hand, well away from these regions, larger grid areas could be taken to reduce the amount of work involved. In general, the calculated stress distribution at a point beneath the lake will not give meaningful results if the depth beneath the surface is less than about twice the linear dimensions of the neighboring grid areas.

A total of 115 grid areas was used to cover Lake Oroville. The contributions to the regional stresses due to the Thermalito Forebay and Afterbay were ignored because these reservoirs are small and shallow in comparison with Lake Oroville. To determine the magnitude of the point load assigned to each grid, the lake was imagined to be divided into four horizontal slices by three planes at elevations of 122 m (400 ft), 183 m (600 ft), and 244 m (800 ft) above mean sea level. The water surface was taken at 274.5 m (900 ft), the maximum allowable elevation. The bathymetric information for the lake was obtained from the Oroville Dam quadrangle and the adjacent quadrangles forming part of the map series V895 published by the U.S. Geological Survey in 1970. The area A_{ij} in each grid i ($i = 1, \ldots, 115$) contained within each of the contours $j = 1$ (122 m), $j = 2$ (183 m), $j = 3$ (244 m) and $j = 4$ (274.5 m) was determined by overlaying the maps with a fine, uniform square grid and then counting squares. The process was then checked by computing $A_j = \sum_i A_{ij}$ and comparing it with the known surface area within contour j. The error in each case was less than 1 per cent. The point load f_i associated with grid i was then calculated from

$$f_i = w \sum_{j=1}^{4} \frac{A_{ij}}{A_j} V_j$$

where w is the unit weight of water and V_j is the known volume of water between contours $j-1$ and j. The total load so calculated must equal that given by the total storage of the reservoir since $\sum_i f_i = w \sum_j V_j$.

Each point load was normally placed at the center of its associated grid. However, it was biased slightly toward the deepest portion if the water depth varied markedly over the grid area. Furthermore, all point loads were assumed to be at the same elevation, which was taken to be the surface of the hypothetical half-space used to model the lithosphere. This elevation was arbitrarily taken as 200 m above mean sea level. The surface topography of the region was ignored in the calculations.

Stress Distribution Due to the Full Reservoir

The computer program developed by the author is capable of determining the incremental stress tensor at any point. Naturally for presentation purposes one must be more selective. Of prime importance here is whether the weight-induced stresses could activate local faults, either directly or by the triggering of a fault already in a critical stress state. For this reason, it was considered that contours of maximum shear stress would be most informative. More detailed information is provided for certain points beneath the epicenter, the dam, and the center of the lake. The computer program took 1.5 min for the

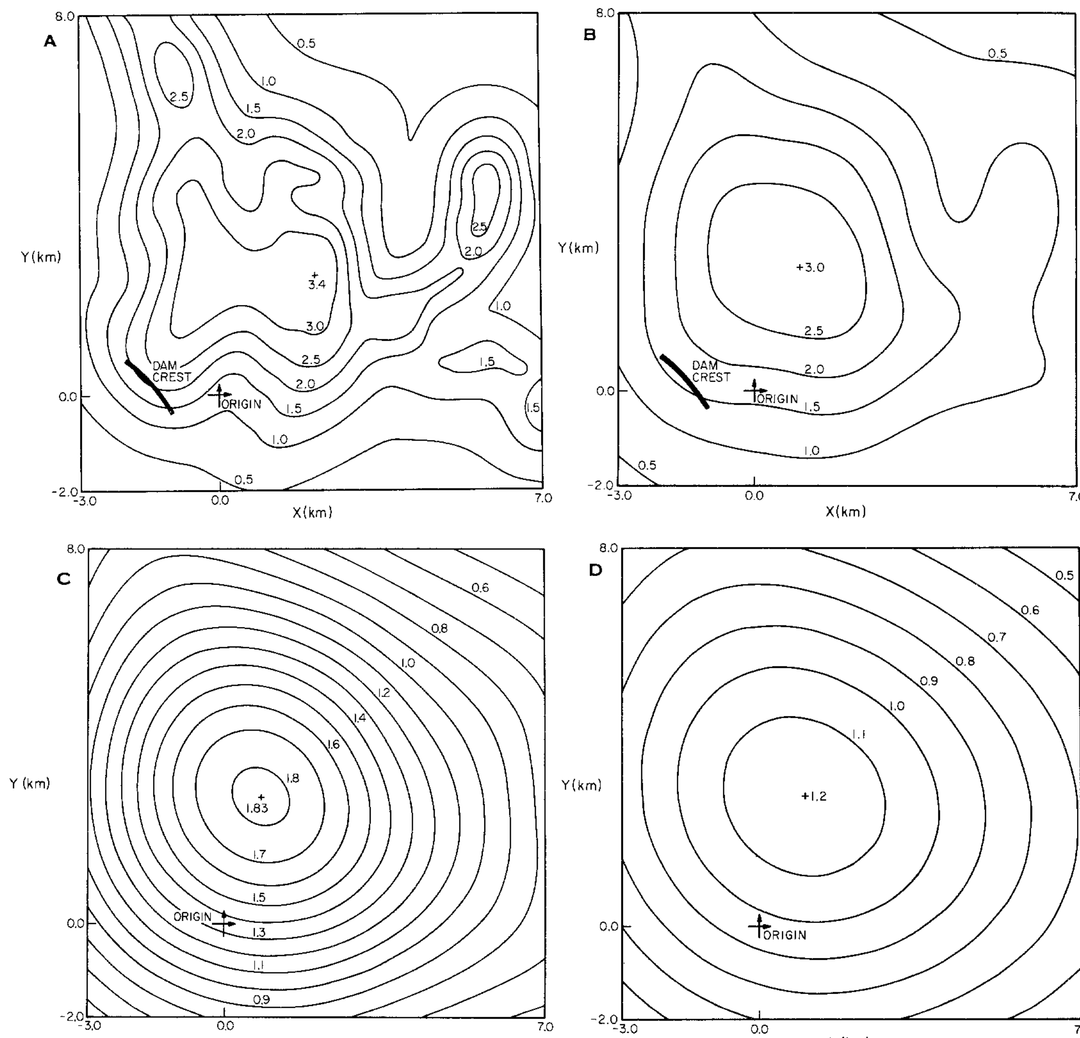

FIG. 2. Weight-induced maximum shear stress (in bars) on a horizontal plane at a depth of (a) 1.0 km, (b) 2.0 km, (c) 4.0 km and (d) 6.0 km, beneath Lake Oroville. The y axis is northward and the x axis eastward.

IBM 370/158 at Caltech to plot contours for a vertical or horizontal plane through the lake region.

Figures 2 and 3 show the contours of maximum shear stress plotted on horizontal planes at different depths beneath the major portion of the lake. The origin of the (x, y, z) coordinates is beneath the Visitor Center on Kelly Ridge, east of the dam, at an elevation of 200 m above mean sea level (Figure 1). The x axis is eastward and the y axis northward. The z axis is vertically downward. It is assumed for all stress and deflection calculations that the water surface of the lake is at 274.5 m (900 ft) above mean sea level. This is the maximum allowable elevation and it is reached, or almost reached, near the beginning of each summer. The stresses at the time of the $M = 5.7$ earthquake would be smaller by about 9 per cent, corresponding to a water surface elevation of 268.1 m (879.5 ft), while the stresses at the time of the 1975 maximum elevation of 273.6 m (897.5 ft) on June 24 would be about 1 per cent smaller.

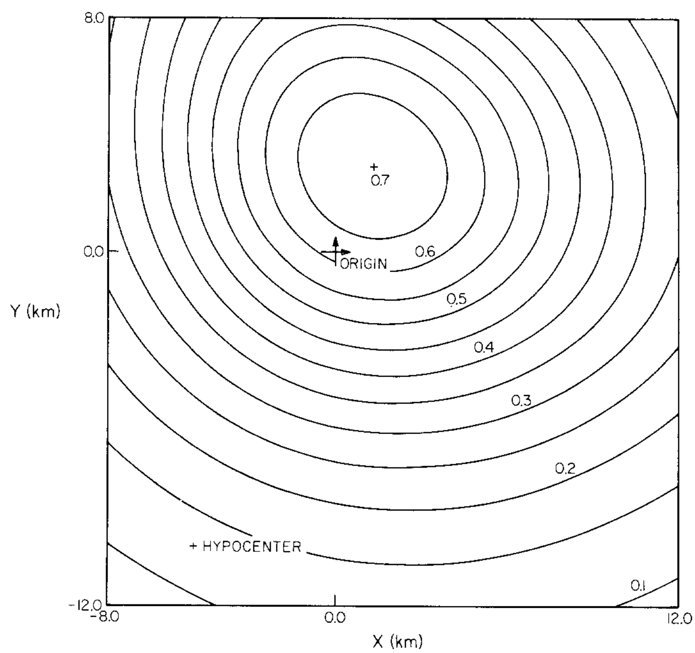

FIG. 3. Weight-induced shear stress (in bars) on a horizontal plane at the hypocentral depth, 9.0 km. The system of axes is the same as in Figure 2 but the scale is different.

The contours of Figure 2A, drawn by the computer, roughly follow the outline of the lake, reflecting the central portion near the dam and part of the three arms corresponding to the North, Middle and South Forks of the old Feather River. The local maxima apparent in Figure 2A beneath the three arms of the lake are almost certainly due to local effects of the point loads since the grid areas there had dimensions of the order of 1 km. An examination of the bathymetric chart for Lake Oroville shows that local maxima in these regions would be unlikely.

Figures 2 and 3 indicate that the maximum shear stress distribution rapidly approaches a form similar to that of a single point load located in the deep, central portion of the lake, except that the contours are slightly elliptical instead of circular. However the magnitude of the equivalent point load depends on the depth of interest since immediately beneath the central portion of the lake the distant portions make a relatively small contribution to the stresses. For example, the magnitude of the equivalent point load for a depth of 8 km is about half of the total weight of the reservoir, whereas for depths greater than 50 km, or for comparable lateral distances from the lake, the equivalent point load is almost equal to the total reservoir weight, as one would expect.

The location of the hypocenter of the main shock at Lake Oroville was in the vicinity of the point $x = -5$ km (121 31.5′W), $y = -10$ km (39 26.5′N), $z = 9$ km (Bolt, personal communication). Figure 3 gives the maximum shear stress contours at the hypocentral

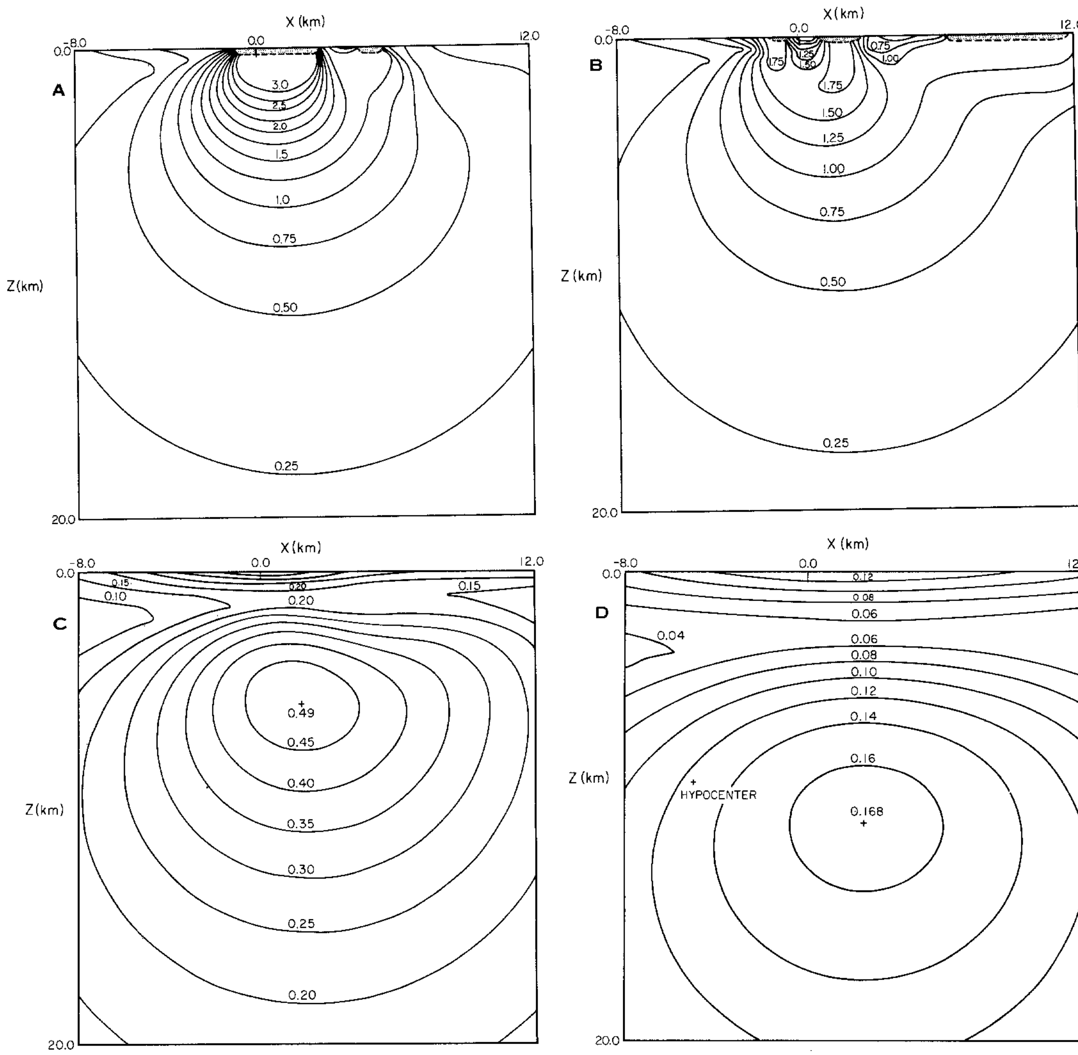

FIG. 4. Weight-induced maximum shear stress (in bars) on a vertical east-west plane located at (a) $y = 2.5$ km (through lake center), (b) $y = 0.0$ km (through Oroville dam), (c) $y = -4.0$ km and (d) $y = -10.0$ km (through hypocenter of main shock). The stippled areas represent the lake in a schematic manner.

depth plotted on a horizontal plane which extends from beneath the epicenter to beneath the lake. The greatest shear stress in the hypocentral region is seen to be about 0.12 bar.

Figure 4, (A) and (B), give the maximum shear stress contours plotted on a vertical, east-west plane through the deepest portion of the lake and through the dam, respectively. The contours have been deleted in the neighborhood of the point loads at the surface. Figure 4, (C) and (D), illustrate the behavior of the maximum shear stress as one moves away from the lake toward the south. It should be observed that although there can be no shear stress on the surface plane, the maximum resolved shear stress at surface points need not vanish, for the maximum shear stress at a point is zero if, and only if, the stress state there is hydrostatic.

From Figures 2 and 4 it may be deduced that the greatest weight-induced shear stress is about 3.4 bars occurring at $x = 2.1$ km, $y = 2.5$ km, and $z = 1.0$ km. This point is beneath the deep portion of the lake lying 1 km west of the North Bidwell Hill (Figure 1). The greatest value for Lake Kariba, central Africa, is smaller, being about 2.1 bars (Gough and Gough, 1970), despite the fact that Lake Kariba has a surface area 100 times that of Lake Oroville and its maximum storage is 35 times as great. The reason for the difference is that the greatest stresses are primarily controlled by the deepest portions of a lake and in this respect Lake Oroville is about twice as deep as Lake Kariba. It should also be observed that the depth, 5.0 km, of the greatest shear stress at Lake Kariba is much greater than that at Lake Oroville.

Lake Kariba and Lake Oroville represent extreme cases of area and depth, respectively, among reservoirs so far associated with an increase in local seismicity. These two cases suggest that the shear stress induced by the weight of any large reservoir is unlikely to exceed 5 bars and that the greatest shear stress will occur at a depth of 1 km or more beneath the deepest portion of the lake. It may therefore be concluded from a simple frictional model of faulting that the weight-induced shear stress could not activate a fault which was not initially under shear, for the shear stresses would be too small compared with the normal stress across a fault which must be of the same order as the lithostatic pressure, that is, of the order of a kilobar or more at a few kilometers depth. It may be possible for a shear stress concentration to occur at a fault if it were a boundary between two types of rock of markedly different elastic properties, but this is unlikely to magnify the weight-induced shear stress by several orders of magnitude (see, for example, the simple model considered by Jaeger and Cook, 1969, 249).

If the reservoir-induced stresses do indeed produce an increase in local seismicity, it follows from the above argument that they must act as a triggering mechanism on a fault which is already close to a critical stress state. However, it is not necessary to assume recent regional tectonic movement in order for a fault to be in a critical stress state. Faults that have not experienced movement for a long time may be close to such a stress state since significant tectonic stress has been found in seismically inactive regions where measurement of stress states at depth have indicated a substantial departure from lithostatic conditions (Jaeger and Cook, 1969, 395). Thus, the argument for a triggering mechanism is not contradicted by the number of occurrences of reservoir-induced seismicity in seismically inactive regions.

Table 1 gives more detailed information about the stress state at three specific points: at the hypocenter, beneath the dam, and at the point of greatest shear stress beneath the deepest portion of the lake. These and other points examined show that the vertical stress, which is always compressive, is of the same order as the maximum shear stress except near the surface away from the lake where it is much smaller. At depths of a few kilometers or more, the induced vertical stress is negligible compared with the lithostatic pressure which is assumed to have a pressure gradient of about 0.27 bar per meter.

Since the approximate orientation of the fault plane for the $M = 5.7$ Oroville earthquake is known, it is possible to calculate the weight-induced shear stress and normal stress across the fault. The strike and dip of the fault have been calculated to be approximately N10°W and 65°, respectively, and the fault motion has been classified as normal dip-slip in which the western portion moved down with respect to the eastern portion (Bolt, 1975). By a standard transformation of the stress tensor at the hypocenter, the weight-induced shear stress across the fault in the hypocentral region was found to have a component of about 0.04 bar parallel to the fault movement, but this shear stress was in the opposite sense to the existing shear stress, the direction of which may be deduced from the reported fault movement. Furthermore, the compressive normal stress across the fault was found to be increased by 0.01 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 are not known precisely so the strike and dip of the fault were also varied about their nominal values from N25°W to N5°E and from 60° to 70°, respectively. This range includes most of the fault-plane solutions that have been published (Bufe, 1975; Hart *et al.*, 1975; Langston and Butler, 1975; Ryall and Van Wormer, 1975; Savage and Tocher, 1975). In addition, the position of the hypocenter was varied about its nominal position by ± 1 km in the direction of each coordinate axis, that is, north, east and vertical. In all the cases examined, the conclusions above remained unchanged; that is, the weight-induced stresses decreased the existing shear stress and increased the normal stress across the fault.

TABLE I

DETAILS OF WEIGHT-INDUCED STRESS STATE AT THREE POINTS NEAR LAKE OROVILLE*

	Hypocenter			Under Dam			Under Deep Portion of Lake		
Coordinates (km)	(−5.0,	−10.0,	9.0)	(−1.5,	0.3,	0.5)	(2.1,	2.5,	1.0)
Cartesian components of stress tensor	0.046	0.047	−0.055	1.640	1.147	−1.529	2.273	−2.052	1.444
	0.047	0.115	−0.108	1.147	1.798	−1.719	−2.052	2.479	2.961
	−0.055	−0.108	0.076	−1.529	−1.719	2.866	1.444	2.961	8.307
Vertical/lithostatic stress		3.1×10^{-5}			0.021			0.031	
Least principal stress		−0.017			−0.005			1.834	
Direction cosines	0.275	0.546	0.791	0.542	0.562	0.625	−0.897	−0.385	0.218
Intermediate principal stress		0.022			1.597			2.580	
Direction cosines	−0.893	0.451	−0.001	0.736	−0.677	−0.030	−0.384	0.922	0.049
Greatest principal stress		0.232			4.712			8.644	
Direction cosines	−0.358	−0.706	0.611	0.406	0.476	−0.780	0.220	0.040	0.975
Maximum shear stress		0.125			2.359			3.405	

* Stresses in bars with compression positive.

This conclusion relating to the shear stress is consistent with the simple argument that for a strike west of north with a large dip, all of the reservoir weight is on the eastern side of the extended fault plane, yet this side moved up with respect to the western side. This same argument suggests that as the strike is rotated east or the dip is reduced, the dip-slip component of the weight-induced shear stress will eventually change sign since then the bulk of the reservoir weight will have moved to the western side of the extended fault plane. Calculations were made which show that the dip-slip shear stress component on the fault plane does indeed behave in this manner. For a given angle of dip, as the fault strike is rotated eastward, there is a critical strike at which the shear stress component changes sign. At the nominal hypocenter, the critical strike corresponding to dip angles of 45°, 50°, 55°, and 60° is about N15°W, N5°W, N3°E and N9°E, respectively. Thus, for a given angle of dip, if the fault strike lies to the west of the critical direction, the weight-induced shear stress on the fault plane would have opposed the relative motion which occurred across the fault during the main shock. Finally, since some authors have reported a shallower focal depth than the 9 km used here, calculations were made with several smaller values of this parameter. These showed that the effect of decreasing the hypocentral depth was to rotate the critical strikes farther to the east.

The arguments above suggest that the main shock at Lake Oroville was not directly triggered by the water load. It is possible that the series of foreshocks redistributed the tectonic stress field in such a way that the main shock was triggered. However, if the foreshocks had similar fault-plane solutions to that of the main shock, as would be expected, similar arguments to those above would again eliminate the water load as a causal mechanism.

Vertical Surface Deflection due to the Full Reservoir

Figure 5 shows the calculated vertical surface deflection over an area of 400 km^2. The contours for deflections greater than 4.5 cm have not been shown because they were

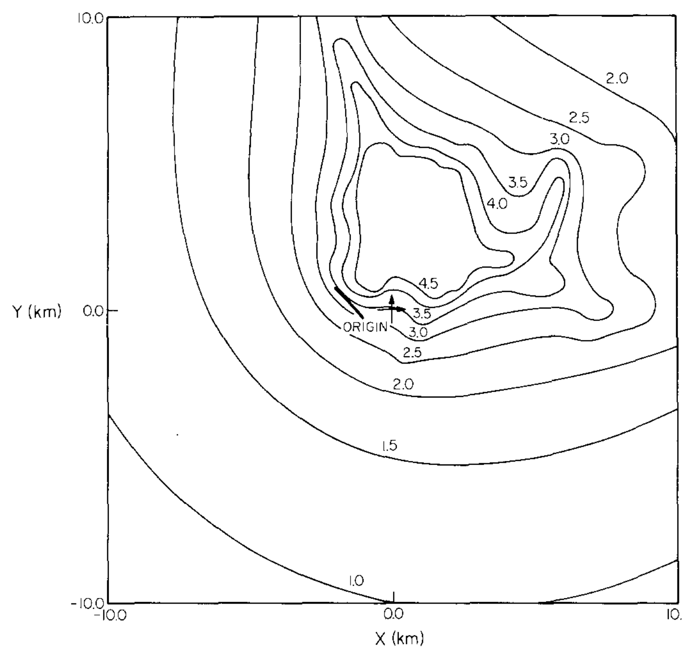

FIG. 5. Vertical surface deflection (in centimeters) in the Lake Oroville region due to the weight of the reservoir. The contours for deflections greater than 4.5 cm have been omitted (see text).

severely distorted by the local effects of the point loads. All the omitted contours lay well within the lake boundaries and they indicated that the maximum surface deflection would be about 5.5 cm. Some of the contours in the lake area in Figure 5 also showed signs of local distortion at a few points, but they were smoothed during the redrawing of Figure 5.

It can be seen that the surface deflection decays rather slowly as one moves away from the lake. The deflection is roughly inversely proportional to the distance from the lake center when this distance is large. The surface deflection is still greater than 1 cm at the city of Oroville.

The magnitude of the calculated deflections may be compared with those measured during a recent leveling survey, using a survey carried out during impoundment in 1967 as a base. Vertical settlements of 2 and 3 cm were measured around the southern portion of the lake (Department of Water Resources, State of California, 1975).

Discussion

Both direct activation and triggering of the fault of the main Oroville shock by the water load have been shown to be unlikely, at least on the basis of present geological data. The remaining principal hypotheses for the origin of the increased seismicity near the reservoir are:

1. The seismicity was triggered by a decrease in shear strength at the fault. This can occur if the fluid pressure at the fault is increased, thereby reducing the normal effective stress across the fault (see, for example, Jaeger and Cook, 1969, 210), and
2. The seismicity was not related to the presence of the reservoir, that is, it was part of the natural seismicity of the region.

If it were found that the surface expression of the fault zone of the main shock extends up to the southern portion of Lake Oroville, this would enhance the credibility of the first hypothesis. The pressure head of 200 m of water (20 bars) at the reservoir together with the possibility of a permeable zone along the fault would indicate that substantial fluid pressure could diffuse out to the hypocentral region. If the surrounding region is saturated down to the hypocentral depth, another source of fluid pressure diffusion could be the consolidation of the medium under the weight of the reservoir (Jaeger and Cook, 1969, 201, and Lane, 1970). The main barriers preventing adequate analysis of these phenomena in actual situations is the lack of knowledge of the large-scale inhomogeneities, joints and faults, of the medium and the large uncertainty surrounding the values of some of the relevant properties of the medium.

The possibility that the Oroville seismicity was completely unrelated to the presence of the reservoir cannot be discounted. Its swarm-like activity, consisting of a long series of earthquakes with a foreshock-peak-aftershock pattern, is characteristic of known cases of reservoir-induced seismicity, but this type of behavior has also been observed in regions well away from reservoirs. Again, if the increase in seismicity beginning in June 1975 was indeed due to the presence of Lake Oroville, it remains to explain the dormant period of about 6 years since the first topping of the reservoir. In most of the previously documented cases of reservoir-induced seismicity, the increase in seismic activity began soon after impoundment of the reservoir, and there are no recorded cases with a delay as long as 6 years.

The fluid-pressure diffusion mechanism allows some time delay. Using a simple dimensional argument it may be shown that if the fluid pressure is to take 6 years to diffuse to the hypocenter of the main Oroville shock, an average diffusivity along its path of the order of 1 m^2/sec would be required. This value may be considered plausible; for example, a diffusivity of 1 m^2/sec could arise from a permeability of 0.1 Darcy and a rock compressibility of 1 per cent per kilobar, suggesting that the apparent delay in the increase in seismic activity could have been due to the time taken for the fluid pressure to diffuse to the hypocentral region. However, at this stage this argument must be considered as no more than speculation.

Conclusions

The incremental stresses produced in the lithosphere by the weight of the water in Lake Oroville have been determined. It is suggested that these stresses are too small to directly activate a fault which is not already severely stressed and that this conclusion is likely to be valid for any large reservoir. Thus, for reservoir-induced seismicity to occur the reservoir must be able to give rise to some mechanism which can trigger an earthquake on a fault which is already close to a critical stress state. It is known that even presently inactive faults may be in such a stress state, and this may explain why reservoir-induced seismicity can occur in seismically inactive regions.

The reservoir-related triggering mechanism could be an increase in shear stress across a fault due to the water load, or a decrease in shear strength at the fault due to fluid pressure, or a combination of these two factors. In the case of the main shock at Lake Oroville, the first mechanism is considered to be unlikely since the incremental shear stress across the fault opposed the known movement of the fault. The fluid pressure hypothesis remains open to examination.

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