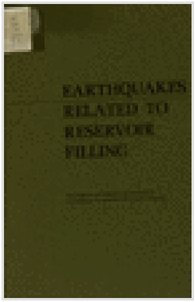

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EARTHQUAKES RELATED TO RESERVOIR FILLING

A REPORT BY
THE JOINT PANEL ON PROBLEMS
CONCERNING SEISMOLOGY AND ROCK MECHANICS
DIVISION OF EARTH SCIENCES

National Academy of Sciences National Academy of Engineering
January 1972

NOTICE: The study reported herein was undertaken under the aegis of the National Research Council with the express approval of the Governing Board of the NRC. Such approval indicated that the Board considered that the problem is of national significance, that the elucidation of the problem required scientific or technical competence, and that the resources of NRC were particularly suitable to the conduct of the project. The institutional responsibilities of the NRC were then discharged in the following manner:

The members of the study committee were selected for their individual scholarly competence and judgement with due consideration for the balance and breadth of disciplines. Responsibility for all aspects of this report rests with the study committee, to whom sincere appreciation is expressed.

Although the reports of study committees are not submitted for approval to the Academy membership or to the Council, each report is reviewed by a second group of scientists according to procedures established and monitored by the Academy's Report Review Committee. Such reviews are intended to determine, *inter alia*, whether the major questions and relevant points of view have been addressed and whether the reported findings, conclusions, and recommendations arose from the available data and information. Distribution of the report is permitted only after satisfactory completion of this review process.

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Preface

The association of earthquakes with the impoundment of water in some large reservoirs in various parts of the world has become a matter of concern as the numbers and sizes of such reservoirs have increased. In the United States, this phenomenon has been given limited attention by various individual investigators and by several governmental agencies (largely the U.S. Coast and Geodetic Survey, recently renamed the National Ocean Survey, the U.S. Geological Survey, and the Department of Water Resources of the State of California). While the problem in the United States does not appear to require an immediate "crash" effort by government agencies, it is of sufficient importance to warrant increased effort on a sustained basis. For this reason, the Joint Panel on Problems Concerning Seismology and Rock Mechanics met on January 28, 1971, to consider the problem of seismicity related to reservoir filling and to make recommendations aimed at reduction of the hazard through a clearer understanding of its causes.

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Introduction

There is evidence that local seismic activity, including earthquakes of moderate magnitude (up to Richter magnitude 6.4), some of them quite destructive, has occurred in association with the impounding of water in large reservoirs in several countries. For many other large reservoirs, there is no evidence of earthquakes related to filling.

As populations have continued to increase and the demand for water has grown correspondingly, this phenomenon has generated a considerable amount of international interest. Though reservoir-related earthquakes have not thus far caused loss of life or notable damage in the United States, in at least three foreign areas such earthquakes have had quite serious, even disastrous, effects–at Koyna Reservoir in India, at Kremasta Lake in Greece, and at lake Kariba in the Zambia–Rhodesia boundary region. In the past, such earthquakes were not given sufficient scientific attention to permit a comprehensive evaluation of the associated hazards. It now seems wise to review all aspects of the problem to determine the types and amounts of additional information needed to evaluate these hazards. Of equal importance, perhaps, to the question of why these earthquakes occurred in these places is the question of why no increase in seismicity has been observed with the filling of other, equally large, reservoirs in other places (for example, the Aswan Dam in Egypt).

This report summarizes the history of recorded correlations between seismic activity and the filling of large reservoirs, discusses scientific considerations, and provides background for the recommendations on the following pages. It is important to consider that for a relatively small increase in the investment of manpower, effort, and equipment called for in the recommended monitoring and study program, very large benefits might be realized in terms of greatly improved understanding of the mechanisms of much larger, potentially catastrophic, natural events and in the prospects for predicting and controlling such events or for modifying their effects.

Recommendations

The Panel offers the following recommendations, whose purpose is to provide an improved understanding of the relationship between earthquakes and the impoundment of large reservoirs*—of whether there is, indeed, a cause-and-effect relationship in some cases; of the triggering mechanism, or mechanisms, if such a relationship is clearly shown; and of what we might do to mitigate or prevent such earthquakes. Ultimately, this knowledge would also provide the basis for consideration of the question of what constitutes "acceptable risk"—a question that will have to be faced increasingly in the future as man's needs, with growing frequency, come into conflict with risks associated with his efforts to satisfy those needs.

GEOLOGIC STUDIES

In addition to the detailed geological maps usually prepared for the area around the foundation of a proposed dam, geologic mapping must be carried out for the entire area of the reservoir. Although great detail may not be required, special attention should be given to patterns of faulting and the competency of the rock in the reser-

*A "large reservoir" is defined empirically, in this study, as one with a volume of one million acre-feet or more, usually impounded behind a dam 300 feet or greater in height. Although earthquakes have also been reported in association with the filling of some smaller reservoirs, the damaging quakes of relatively large magnitudes have occurred near large reservoirs as defined above.

voir area. A clearer understanding of the hydrologic regime, particularly as related to the faulting, is required. If large faults are present, and especially if these show evidence of recent movement, a complete re-evaluation of the chosen site, and of possible alternative sites, should be made before construction is begun. In any case, the orientations and positions at depth of such faults should be determined. Such information would be extremely important in subsequent geological and seismological considerations of the area.

GEODETIC STUDIES

The question of whether earthquakes occurring in the vicinity of large reservoirs might be triggered by increased fluid pressure or by crustal loading, or both, remains to be resolved. Geodetic studies before and after reservoir filling, with special emphasis given to vertical measurements, would help to answer this question. Such studies are being conducted in conjunction with seismic investigations at the Libby Reservoir in Montana and should be included in the planning for all future large reservoirs.

It has been shown at Lake Kariba that the crust behaved in an elastic manner when subjected to reservoir loads and that the elastic-strain energy induced was approximately equivalent to the seismic energy released. The most useful data in this study were from long level-lines run before and after filling. An additional check on the response of the crust to loading could be obtained by trilateration using electro-optical measuring devices.

Crucial information about elastic deformations at dam sites can be obtained from long geodetic level-lines established before construction has begun and repeated after the dam has been completed. An important addition to such geodetic measurements could be made by some form of continuously recording strain meter. Tiltmeters for emplacement in boreholes have been developed recently. These instruments should be installed in at least three widely spaced boreholes prior to filling of a reservoir and recorded on a time base comparable to that of the seismic recording. If the response of the reservoir to loading takes place in discontinuous steps, when earthquakes occur, rather than smoothly as the reservoir is filled, the tiltmeters will be able to resolve these strain steps. However, it should be emphasized that the continuously recording strain-meter-type measurement is not a substitute for the long level-lines.

SEISMIC STUDIES

Comprehensive and continuing seismic studies should be carried out before, during, and after reservoir filling. Five years before filling, a tripartite network of seismographs should be installed. These will serve to give approximate locations of earthquakes that may occur prior to filling and to provide a reasonable record of their frequency of occurrence. If the pattern of seismicity changes as the reservoir is filled, the network should be expanded to the number of stations needed to provide good coverage of the entire reservoir area. Experience has shown that at least 10 high-gain, short-period stations are required for accurate locations of microearthquakes and determination of their focal mechanisms. Strong-motion instruments should also be placed within and near the dam to monitor the larger quakes and the response of the structure to large motions.

The proposed dam site and the surrounding area should be examined critically for geologic faults using microearthquake-detection techniques and other methods. If faults exist, an evaluation should be made of the degree of hazard associated with the planned reservoir and, as recommended above, alternative sites should be considered.

Case Histories

In presenting the following case studies, the authors recognize that some of the increases in seismic activity described, especially near reservoirs in seismically active regions, may be only apparent rather than real. Most reservoirs are in sparsely populated areas and few had been instrumented in advance to detect seismic activity. Seismic events that might have occurred before filling would thus have gone unreported and unrecorded. Moreover, there are notable examples of large reservoirs whose filling has not been accompanied by increased seismic activity. It is clear, therefore, that this question can be resolved only if careful seismic surveillance is maintained for several years both before and after the filling of reservoirs. Unfortunately, no such observations exist for any reservoir areas showing seismicity. In all the examples discussed below, knowledge of seismicity prior to impounding is meagre.

LAKE MEAD

The seismicity associated with Lake Mead has been cited by some workers as a classic example of earthquakes caused by reservoir loading. Filling of the lake began in 1935, and the maximum lake level was reached in 1941. Though seismographic evidence was not available, this region was considered aseismic prior to the construction of the dam (Jones, 1944; Raphael, 1954). The first seismograph was installed near the lake in early 1938 (Ulrich, 1938, 1941; Jones, 1944). Shocks were first felt in 1936 during the annual peak of the lake level, and the main shock (magnitude 5.0) was recorded in 1939 when the reservoir had reached 80% capacity. Significant shocks have been felt occasionally since then (Carder, 1945; Carder and Small, 1948; Carder, 1968). The epicenters of these earthquakes are distributed around Lake Mead (Figure 1).

Extensive geologic study of the Lake Mead area was carried out prior to the construction of the dam (Longwell, 1936), and the entire region was found to be broken up by countless minor faults. None was considered to be active prior to the construction of the dam, however, and the subsequent seismic activity is believed to have been caused by reactivation of some of these pre-existing faults. (Table I lists the important facts concerning Lake Mead and other reservoirs discussed in this paper.)

Figure 2 plots the frequency of earthquakes and the variations of water load at Lake Mead from 1935 to 1949. Carder (1968) deduces from these graphs an implied association between seismic activity and water load.

KARIBA LAKE

A situation similar to that at Lake Mead is found at Kariba Lake, along the Rhodesia–Zambia border. There is no indication that any detailed geologic studies were carried out prior to the filling of the reservoir, except for the publication of a fracture-pattern map in 1958 at a scale of 1:250,000 (Gough and Gough, 1970). This region was regarded as aseismic, and no earthquakes were reported prior to the filling of the lake in 1958 (Rothe, 1968; Gough and Gough, 1970). Three permanent seismological observatories have been in existence since 1959 in Rhodesia, Zambia, and Malawi, and three other seismographs were in operation near Lake Kariba intermittently from 1961 to 1963 (Gough and Gough, 1970). Earthquakes were first recorded near the lake in 1961 (Rothe, 1969). Seismic activity continued to increase, and a strong earthquake sequence began on August 14, 1963, a few days after the lake reached its maximum water load. Nine shocks with magnitudes from 5.1 to 6.1 were felt between August 14 and November 8, 1963. Earthquake activity has continued, but at a reduced rate. Since 1963, only one large shock (magnitude 5.5) has been felt, in April 1967 (Rothe, 1969; Gough and Gough, 1970). All epicenters of the main seismic activity are

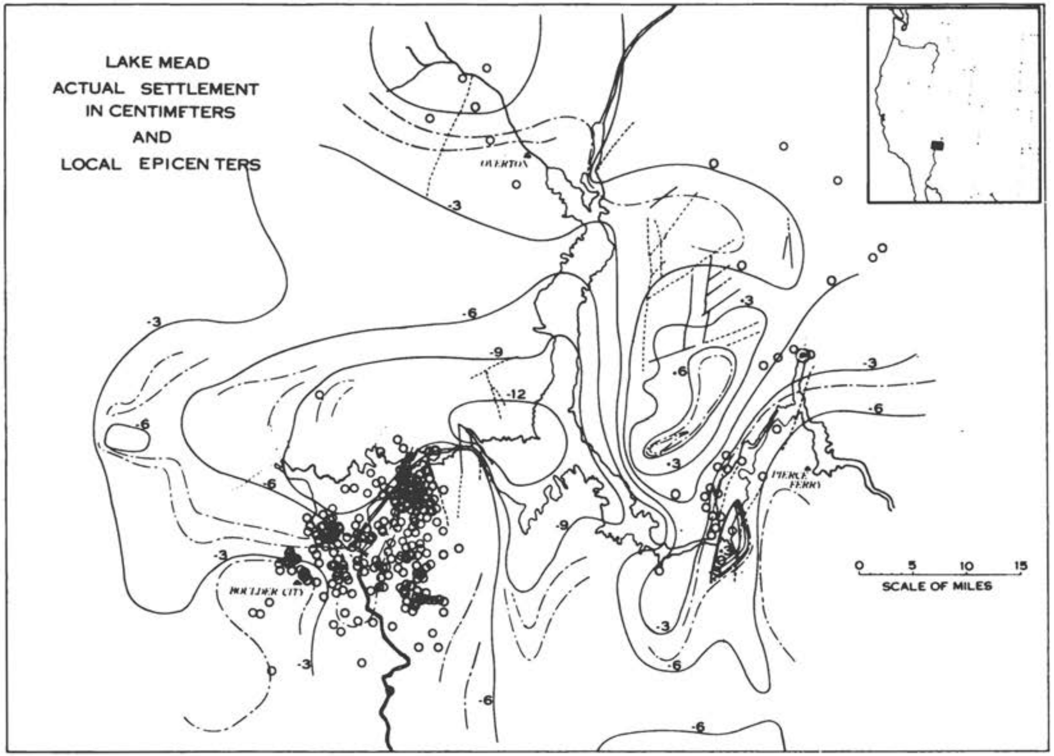

FIGURE 1 Epicenters of earthquakes in the Lake Mead area and settling of the surrounding land surface, 1940–1947 (*Carder and Small, 1948*).

TABLE I Reservoirs Where Earthquakes Occurred during and after Filling

Reservoir	Year Built	First Earth-quake Reported	Emplacement of Seismographs before Construction of Dam	Occurrence of Earthquakes during and after Filling	Prior Geologic Study	Damage
L. Mead	1935	1936	none	yes	yes	None known
L. Kariba	1958	1961	none	yes	not known	None known
Koyna Reservoir	1962	1963	none	yes	yes	177 people killed, 2,300 injured, and extensive damage to houses
L. Kremasta	1965	1965	none nearby	yes	not known	1 death, 60 injuries, landslide, and 1,680 houses damaged
L. Monteynard	1962	1963	?	yes	not known	Light damage, rock fall, chimneys fell
Vogorno	1964	1965	?	yes	not known	Not known—evacuation of village considered
Oued Fodda	1932	1933	?	yes	extensive	Not known
L. Grandval	1959	1961	?	yes	not known	Not known

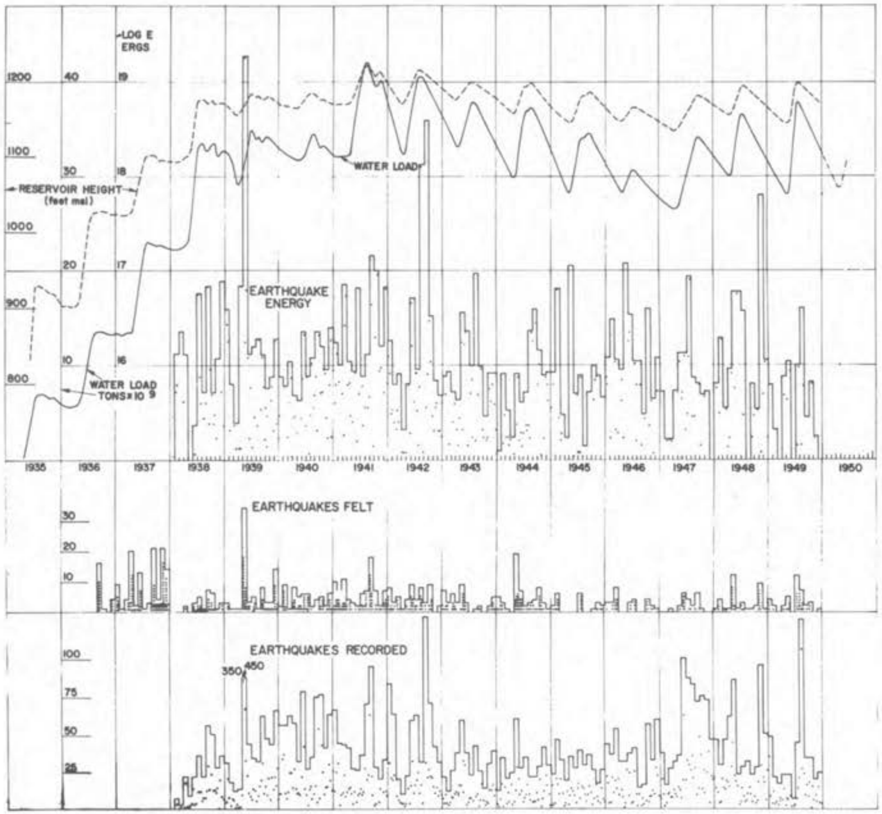

FIGURE 2 Lake Mead earthquake and hydrographic chart, 1935–1949. The dots refer to ten-day periods (*Carder and Small, 1948*).

concentrated in an area approximately 0.4° square, close to the deepest portion of the reservoir (Rothe, 1970).

Gough and Gough (1970) have graphed water level, water volume, frequency of earthquakes, and seismic energy in the Kariba region from 1959 to 1968. The graphs suggest a correlation between water level and frequency of earthquakes for the first few years, during and after filling. Later, both seismicity and the correlation with water level declined. The seismic sequence at Kariba, as at Lake Mead, seems to be in agreement with Rothe's observation (1970) that seismic activity generally increases after the initial filling of a reservoir and, after reaching a maximum, decreases over a period of several years.

KOYNA RESERVOIR

This reservoir, impounded by Koyna Dam, is located on the Indian Precambrian Shield, one of the least seismic areas of the world. Filling of the lake began in 1962, and by the end of that year the lake was partly filled. The first mild tremors were felt a few months later, in 1963 (Rothe, 1968, 1969; Guha *et al.,* 1971), and five seismographs were then installed in and around the lake (Murthi, 1968). In 1970, there were seven seismograph stations and two earth tilt stations recording in the area (Guha *et al.,* 1971). Maximum lake level was reached in 1965. Two severe shocks were felt in September 1967, and the largest shock (magnitude 6.4) occurred on December 10, 1967; three strong shocks were felt (Rothe, 1969, 1970) on December 12, 1967 (magnitude 5.4), December 24, 1967 (magnitude 5.5), and October 29, 1968 (magnitude 5.4). Minor seismicity continued until the spring of 1970 (Ram and Singh, 1971). The December 10, 1967, shock resulted in the deaths of 177 people and injuries to 2,300. Most buildings in the village of Koyna Naga either collapsed or were damaged.

The epicenters of most of these earthquakes are either in the vicinity of the dam or under the reservoir (Rothe, 1970). Similarities between the events at Koyna Reservoir and Lake Mead are many (Rothe, 1968, 1969, 1970). At each, the seismicity started after filling of the reservoir, the epicenters are located in its vicinity, and an apparent correlation exists between water load and seismicity.

The Geological Survey of India is reported to have carried out geologic mapping of the area prior to construction of the dam (Mane, 1968). No faults have been mapped, but most Indian geologists believe that a fault probably exists in this area (Wadia, 1968; Krishnan, 1968). Some Indian investigators see a cause-and-effect relationship between the filling of the Koyna Reservoir and the earthquakes (Narain and Gupta, 1968; Krishnan, 1968). The focal mechanism has been shown to be strike-slip faulting, and Lee and Raleigh (1969) and Housner (1970) have suggested that filling of the reservoir provided the trigger for release of stored tectonic strain. Other investigators consider the earthquakes to be tectonic in origin (Wadia, 1968; also the following, cited in Rothe, 1970: Report of the Committee of Experts, 1968; Petruchevsky *et al.*, 1968; Berg *et al.*, 1969), because the Koyna Reservoir is relatively small and the region is geologically similar to that of Grand Coulee Dam, where no earthquakes have been recorded. Both Grand Coulee and Koyna Dams are located on basalt plateaus. However, the geologic structure below the basalts may not be the same. Moreover, no seismicity has been observed at several other dams built in similar surface geologic settings not too far from Koyna Dam (Murthi, 1968).

KREMASTA AND MARATHON LAKES

Kremasta Lake in Greece started filling in July 1965. Earthquake shocks were first felt (though not recorded instrumentally) in August 1965 (Comninakis *et al.*, 1968). Before these shocks, there were only two seismic stations in Greece, in Athens and Patara, but four additional seismographs were installed soon afterward. The closest one is 115 km from the dam.

The rate of water loading increased rapidly from November 1965 to January 1966 (Figure 3). Seismic activity also increased rapidly during this period, culminating in a strong earthquake in February 1966 (magnitude 6.3), when the lake had almost reached its maximum elevation (Galanopoulos, 1967). This earthquake caused one death, 60 injured, landslides and slumps, and collapse of or damage to 1,680 houses (Rothe, 1969). This large shock was followed by many smaller earthquakes up to November 1966; at least six of these had magnitudes greater than 5.0 (Comninakis *et al.*, 1968; Rothe, 1970). No reports are available for the period after November 1966.

Kremasta Lake is located in the seismically active arc of Greece extending from the Mediterranean Sea north along the Adriatic coast, although the Kremasta region itself had been relatively inactive. It is

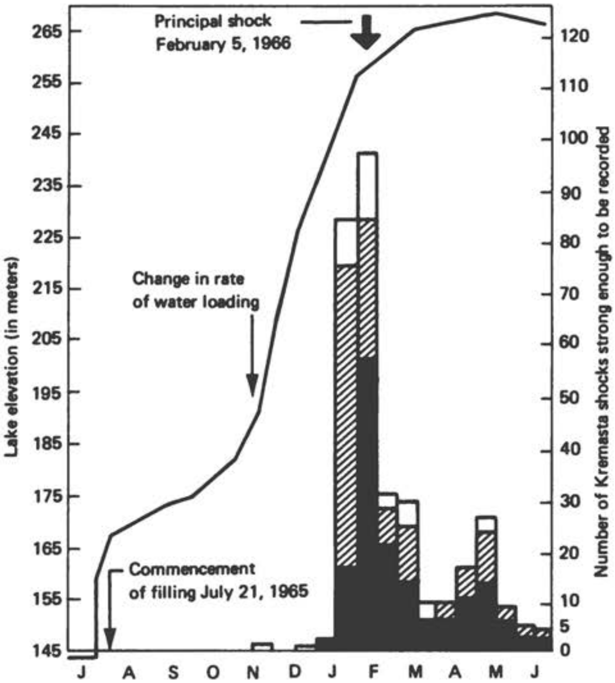

FIGURE 3 Comparison of filling of Kremasta Lake with local earthquake activity (after *Galanopoulos, 1967*).

not known whether any geologic study preceded construction of the dam. However, the epicenters of shocks in this region between 1951 and 1965 were concentrated 40 km below the dam site, while most shocks since the filling of Kremasta Lake have occurred very close to the lake (Rothe, 1969).

Another example of reservoir-related earthquakes in Greece is found in the Attica Basin near Marathon Lake. This is the earliest known correlation between reservoir filling and earthquakes. Filling began in 1929 and earthquakes were first felt in 1931 (Galanopoulos, 1967). Two damaging earthquakes of magnitudes greater than 5 were felt in 1938, and the earthquakes have continued. According to Galanopoulos (1967), all but two of the numerous earthquakes occurred during periods of rapid rise in water level. The epicenters fall within 15 km of Marathon Lake.

MONTEYNARD LAKE

The filling of Monteynard Lake, in France, was begun in 1962, and maximum lake level was reached on April 20, 1963. An earthquake was recorded on April 25, 1963 (magnitude 4.9), and another shock (magnitude 4.4) was recorded on April 27 (Rothe, 1968). Some damage occurred in neighboring villages as a result of the first shock, and rock falls occurred above and below the dam. A new swarm of earthquakes began in 1966, shortly after the lake again reached its maximum level. The largest of these had a magnitude of 4.3. All of the earthquakes occurred near the reservoir (Rothe, 1968, 1969, 1970).

A seismograph was installed at Monteynard in August 1963. Another seismic station, 110 km away, was in operation before construction of the dam (Rothe, 1969).

No detailed geologic studies of this region conducted before filling of the reservoir were found in the literature. It is known, however, that this region is tectonically very complex, containing numerous faults. A severe earthquake occurred here in 1962, just before construction of the dam.

VOGORNO LAKE

The filling of Vogorno Lake, impounded behind Contra Dam in Switzerland, began in August 1964 (Rothe, 1970). Earthquakes began in May 1965, and the most severe shocks were felt in October and November of that year, several weeks after the lake reached its maximum capacity. Though the extent of damage is not known, the shocks were strong enough that evacuation of the village of Berzona was considered. The epicenters were located between the surface traces of two faults near the dam.

The lake was subsequently emptied and refilled, and this resulted in a decrease of seismic activity. Seismicity appears to have ceased in April 1968 (Susstrunk, 1968, cited by Rothe, 1970). Lombardi (1967, cited by Rothe, 1970) believes that a new equilibrium was achieved that was no longer disturbed by successive variations in the water load. No detailed geologic studies conducted prior to construction of the dam have been identified in the literature, although numerous faults are now known to exist in this region.

OUED FODDA RESERVOIR

One of the oldest examples of earthquakes associated with reservoirs is that of Oued Fodda, in Algeria (Rothe, 1970). Filling of the reservoir was begun at the end of 1932, and earthquakes were felt frequently near the dam from January to May 1933. None has been felt since then. It is not known whether any seismic stations were in operation near the dam prior to its construction, but the geology of this area had been studied in great detail. Three sites for the dam had been selected; two of them were rejected for geologic reasons. Seismic risk evaluation of this region had been carried out, and the permeability of the rocks had been studied. The decision to build a gravity dam rather than an arch dam was dictated by the geology (Gourinard, 1952).

The seismicity associated with this reservoir appears quite different from that of all the others discussed here. One of the various explanations offered is that water leaking from the reservoir at the time of filling was absorbed by an anhydrous nucleus under the reservoir, which then became inflated (Gourinard, 1952).

GRANDVAL LAKE

Filling of the Grandval Lake, in France, began in 1959, and maximum lake level was reached in 1960. Minor earthquakes were first noticed in 1961. The reservoir was emptied in 1962 and then refilled. A violent shock, originating beneath the lake, was felt in 1963 when the lake again reached its maximum level. The two strongest shocks, of the many that occurred, came when the lake level was at its highest (Rothe, 1969). No information is available about seismic stations in this region prior to the filling of the lake, and it is not known whether any geologic studies preceded the construction of the dam.

OTHER POSSIBLE CASES

There are other possible cases in which earthquakes are suspected to have been caused by, or in some way related to, reservoir loading. Rothe (1968) mentions a close correlation between the reservoirs north of Lerida, Spain, and the earthquakes in that region. Of particular interest is the earthquake of June 1962, whose epicenter coincided with the Canalles Dam (Rothe, 1970).

Mickey (in press) reports that earthquakes have been attributed to reservoir filling in the states of Washington, Nevada, California, and Montana. Of the five specific sites that Mickey studied, only Lake Mead has reservoir-related earthquakes, while Cedar Springs and San Luis, California, Flaming Gorge, Utah, and Glen Canyon, Arizona, do not.

Bolt and Miller (1971) report that water loading of the Oroville, California, reservoir in 1967–1968 has not been associated with increased seismicity in the area.

According to Shurbet (1969), numerous earthquakes have occurred in the vicinity of Lake Meredith, behind Sanford Dam near Amarillo, Texas. Filling of the reservoir began in 1965 and the lake was half full in 1967. The strongest shock was felt in 1966, and the earthquakes are thought to be related to the filling of the reservoir.

Evans (1967) reports minor seismic activity associated with the filling of the Cabin Creek Reservoirs near Georgetown, Colorado. No investigations have been made to determine whether the earthquakes were related to the reservoirs.

Carder (1968) mentions dam sites in California, Montana, Arizona, and Utah where seismographs were actually installed prior to the filling of reservoirs. No earthquakes have been correlated with reservoir loading in any of these locations.

Roksandíc (1970) reports increased seismic activity upon filling of the Biléca Reservoir in Yugoslavia. The relation between the time of filling of the reservoir and the increase in earthquake activity in the near vicinity is well documented, although accurate hypocentral locations are lacking.

Possible Mechanisms of Reservoir-Related Earthquakes

In at least some of the examples discussed previously, a correlation can be seen between earthquakes and reservoir loading. Several explanations of this relationship have been given. Carder (1945) concluded that the earthquakes near Lake Mead were triggered by the weight of the water, which caused movement along pre-existing faults previously considered inactive. The weight of the water depressed the underlying crustal blocks by several inches and was sufficient to cause earthquakes. Carder (1968) states that the earthquakes near Lake Mead and Lake Kariba could be accounted for by as little as 30% of the energy involved in the depression of the crust. He considers this mechanism inadequate to explain earthquakes in the vicinity of some other reservoirs where water loads are much smaller. According to Carder (1968), the presence of pre-existing faults is a necessary condition for all reservoir-related earthquakes, and their absence explains the lack of seismicity in areas such as that of Grand Coulee Dam, where crustal deformation takes the form of downward flexure caused by the weight of water.

Gough and Gough (1970) have shown theoretically that at Kariba the gravitational energy released by the depression of the crust due to the weight of the water was sufficient to cause the main seismic activity in this region. This explanation does not require the accumulation of natural tectonic strain energy along local faults. Gough and Gough prefer the explanation that pre-existing faults were reactivated by a triggering mechanism caused by the weight of the water.

Evans (1966b) used the hypothesis of increase in pore pressure to explain the Denver earthquakes. According to Hubbert and Rubey (1959), increase in pore pressure results in a decrease in shear strength of the rock, which could in turn release tectonic strain. Some investigators believe this mechanism to be fundamental in earthquake activity associated with reservoir loading.

Recent experience involving earthquakes induced by fluid injection at Rangely, Colorado (Raleigh, Healy, Bredehoeft, and Bohn, 1971), suggests that it may be possible to reduce earthquake activity in selected small regions. If earthquakes associated with reservoir filling are induced by an increase in fluid pressure along faults buried beneath the reservoir area, local reduction of fluid pressure by pumping from that fault zone may be useful. If, on the other hand, the earthquakes are related to crustal loading by the impounded water, their number and intensity might be decreased by lowering the reservoir level.

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The studies of seismicity associated with reservoir loading conducted by Drs. J. P. Rothe and D. S. Carder were important background sources for this report. Dr. Rothe provided us with copies of his publications, and Dr. D. I. Gough provided copies of his papers concerning Lake Kariba.

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