Reservoir Seismic Effects

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The occurrence of earthquakes in the vicinity of large dams and reservoirs has been studied by many investigators in several regions of the world [*Barnett*, 1968; *Gough and Gough*, 1970*a*, *b*; *Rothé*, 1968, 1969, 1970; *McGinnis*, 1963]. Historically, probably the first reported concern for the effects of reservoir loading on the earth's crust was at Lake Mead [*Mead and Carder*, 1941].

The National Ocean Survey (formerly the U.S. Coast and Geodetic Survey) has been active in monitoring the seismicity around large dams and reservoirs in the United States since establishing a station near Lake Mead in 1938. Many instances have been reported in the literature relating seismic activity to man-made hydrologic structures. Five sites in four states were selected for a detailed study of the seismic characteristics near reservoirs: Glen Canyon, Arizona; Flaming Gorge, Utah; Hoover Dam and Lake Mead, Nevada; San Luis, California; and Cedar Springs, California.

FLAMING GORGE AND GLEN CANYON

These two dams and reservoirs are grouped because the observing area overlaps and both are in the Colorado River storage project. Flaming Gorge Dam, Utah (Green River), is 151 meters high with a reservoir capacity of 4674×10^6 m^3. It was first loaded in November 1962. Seismic measurements started in June 1960.

Glen Canyon Dam, Arizona (Colorado River), is 216 meters high with a reservoir capacity of $33{,}304.2 \times 10^6$ m^3. It was first loaded in May 1963. On-site seismic measurements started in June 1960.

The station locations and the observation area are shown in Figure 1 with the earthquake epicenters for 1968. The major seismic activity is to the west of the two reservoirs along the more prominent tectonic features.

Figure 2 shows the cumulative number of earthquakes per month for Flaming Gorge and Glen Canyon from 1960 through 1968 at different distances from the station. If the reservoir was effecting the local seismicity, it should be apparent in the range of 0–40 km. There was a decrease in seismic activity in this distance zone following reservoir loading. Although Glen Canyon is 65 meters higher and the reservoir is 7 times larger, it has much less seismic activity than Flaming Gorge. The seismicity characteristics for Glen Canyon were affected by the earthquakes series during 1966 in southeast Nevada.

Extreme probability statistics are shown in Figure 3 for Flaming Gorge for 36 months. The equivalent slope is 0.89, very near that for southern California. Although the area is very much less active than southern California, the rate of occurrence of small to large earthquakes is similar.

Figure 4 is a contoured map using the square root of the source seismic energy, which is proportional to strain release. The shaded areas are progressively more seismically active for the period of the present observations. The most active areas correspond to the tectonic zones trending north-northeast with a transverse trend from near Grand Junction, Colorado, to Price, Utah. The areas with the least seismic activity are in the vicinity of Glen Canyon (GCA) and Flaming Gorge (FGU). From September 1960 through December 1968, there were 3182 earthquakes recorded at Flaming Gorge, and there were 1506 recorded at Glen Canyon within the 350-km radius of each station. There were many explosions, rock bursts, and coal bumps recorded at each station, and every effort was made to exclude these data. The data were substantiated by nearby seismograph stations at Logan, Salt Lake

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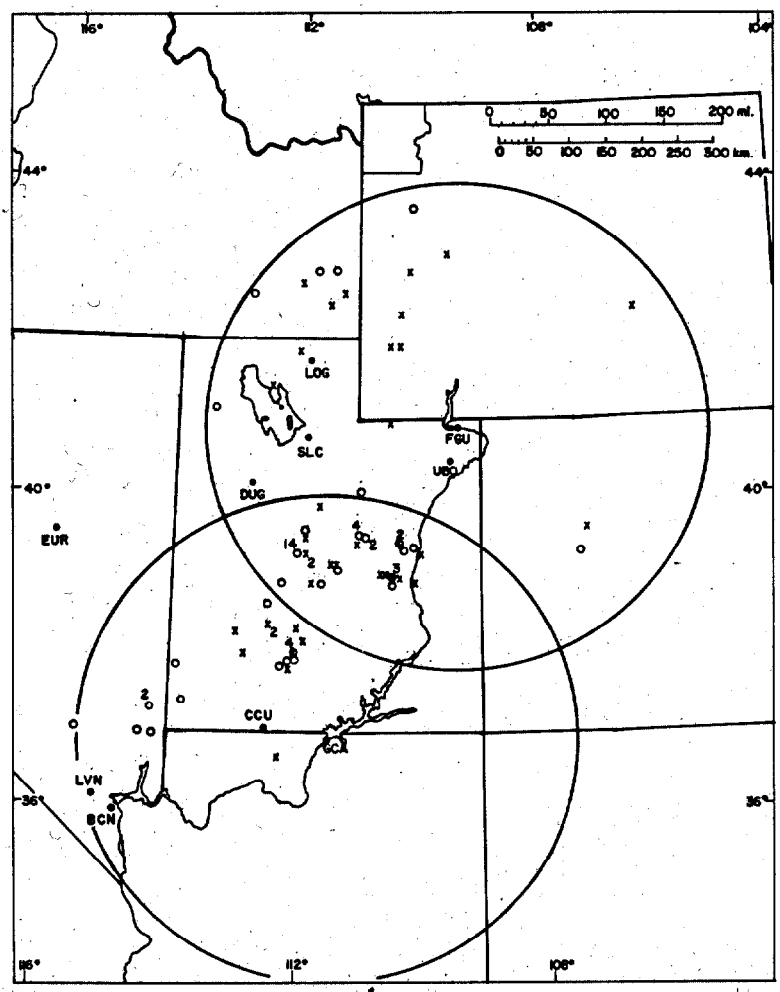

Fig. 1. Seismograph station map showing Flaming Gorge, Utah (FGU), and Glen Canyon, Arizona (GCA), with the area of observations within the 350-km-radius circles. Also shown are stations at Logan (LOG), Salt Lake City (SLC), Dugway (DUG), Cedar City (CCU), and Uinta basin (UBD) in Utah and stations at Eureka (EUR), Las Vegas (LVN), and Boulder City (BCN) in Nevada. Epicenters for 1968 earthquakes within the 350-km radius of Flaming Gorge and Glen Canyon are shown. The open circles indicate the epicenters according to computer solution. The crosses indicate the epicenters according to graphic solution. The closed circles indicate the seismograph stations.

City, Dugway, and Cedar City in Utah and at Eureka, Boulder City, and Las Vegas in Nevada.

SAN LUIS DAM

A histogram of the seismicity within 80 km of San Luis Dam, California, from November 1965 through July 1970 is shown in Figure 5. This dam is 93 meters high and was first filled in June 1965.

The number of earthquakes per month within 80 km of the station varied from 16 to 89, and the average was 52. The size of earthquakes M_L ranged from 0.2 to 5.0. The average monthly minimum-distance earthquake was 7.2 km from the station. During the 57-month monitoring period, there were 2968 earthquakes occurring within 80 km, and 560 of these occurred at distances of ≤ 25 km. The high seismic activity of this area is influenced by a major fault system 22.5 km to the southwest.

Extreme probability techniques were used to compare nearby seismicity to the overall zone of 0–80 km. Figure 6 shows that the rate of oc-

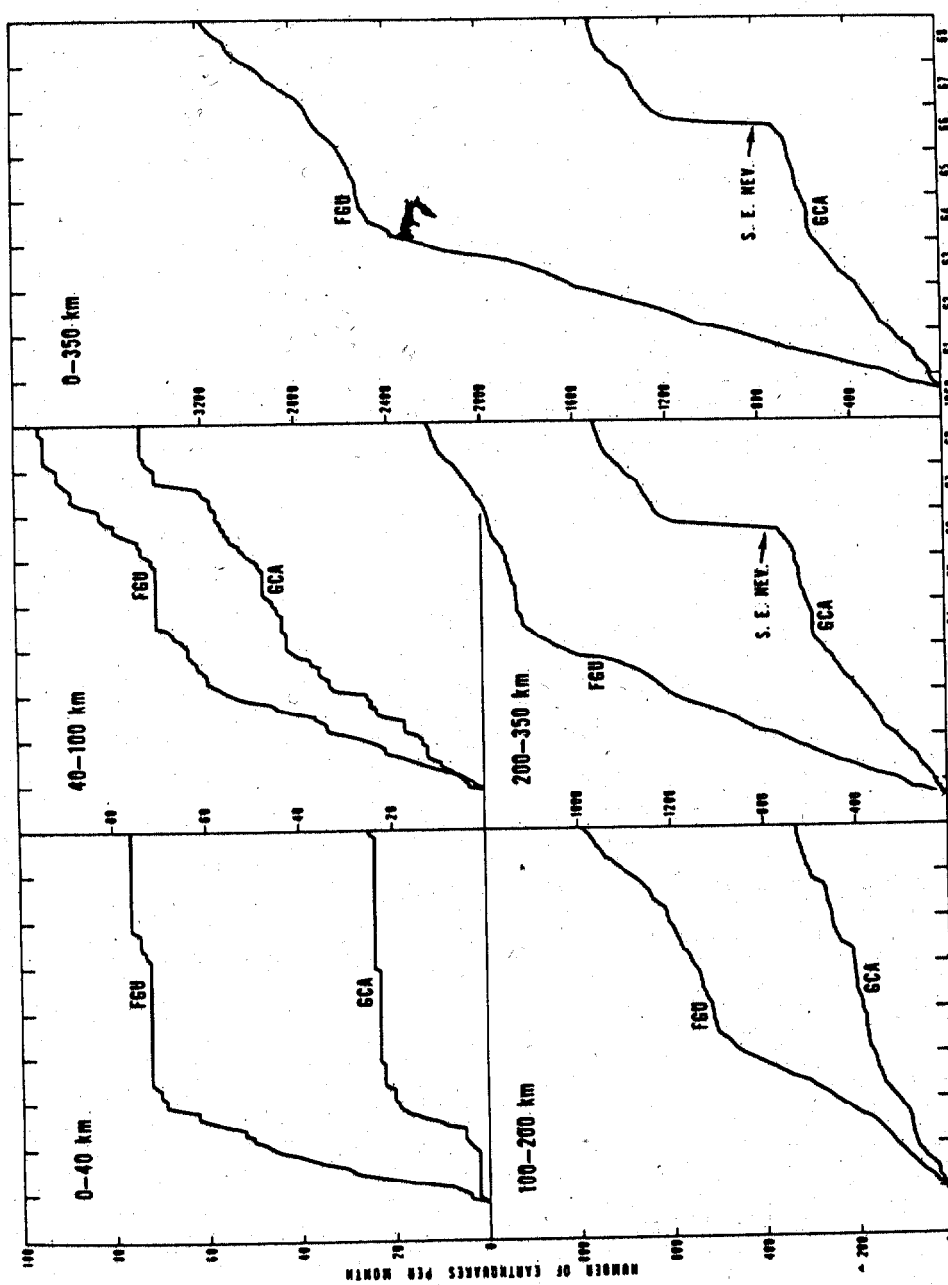

Fig. 2. Cumulative earthquakes per month from 1960 through 1968 at Glen Canyon (GCA) and Flaming Gorge (FGU) at different distance ranges from the station.

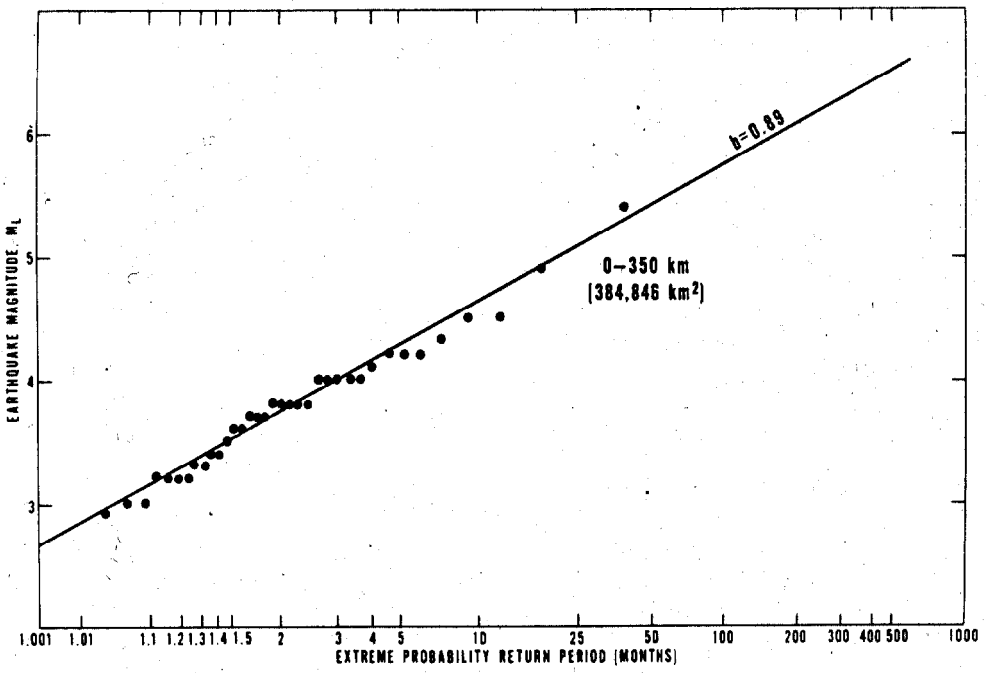

Fig. 3. Extreme probability graph for monthly return period of earthquakes recorded at Flaming Gorge, Utah, for a period of 36 months occurring within 350 km from the station.

currence is similar and that there are identical b values of 0.7. When the observing area was reduced by a factor of 10, the probabilities were also reduced a similar amount.

CEDAR SPRINGS DAMSITE, CALIFORNIA

The Cedar Springs project is about 80 km east of Los Angeles on the north edge of the San Bernardino Mountains. The seismograph station at this site started operations in February 1965. Figure 7 shows the occurrence characteristics of this site. There were 682 earthquakes within a 50-km radius of the site during the 28-month monitoring period ranging in size M_L from <1 to 3.7. This site differs from the others discussed because it shows more seismic activity near the site (radius of 25 km and area of 1964 km²) than in an area 3 times as large (annulus of 25–50 km and area of 5890 km²). The other major difference is that the reservoir has not been built in this area as yet. This site is near an active area of the San Andreas fault.

HOOVER DAM AND LAKE MEAD, NEVADA

Hoover Dam, 40 km southeast of Las Vagas, Nevada, was completed in 1936. Its height is 221 meters and the reservoir capacity is 38,296.2 × 10^6 m³. A seismograph monitoring system of one or more units has been in operation near the dam from 1938 to the present time. There have been several reports written about the seismic characteristics of this area [*Carder and Small,* 1948; *Mead and Carder,* 1941; *Jones,* 1944; *Carder,* 1945; *Carder,* 1968].

Figure 8 shows the seismic activity at Lake Mead from 1939 through 1951. The data were especially prepared to check for periodicity and correlation of seismic activity with reservoir water level. The top curve is the average monthly water level for the period plotted from January through December; the period from January through September is repeated so that more than one cycle is shown. Because of the reservoir recharge characteristics, the water level in Lake Mead is periodic, and the high levels usually occur in July and minimum levels occur in April. The second curve is the number of earthquakes for a 3-month period, plotted at the center month; i.e., the first point is plotted above M for March and is 1242, which is the number of earthquakes that occurred during the period of February, March, and April. The third graph is prepared as the second but represents the

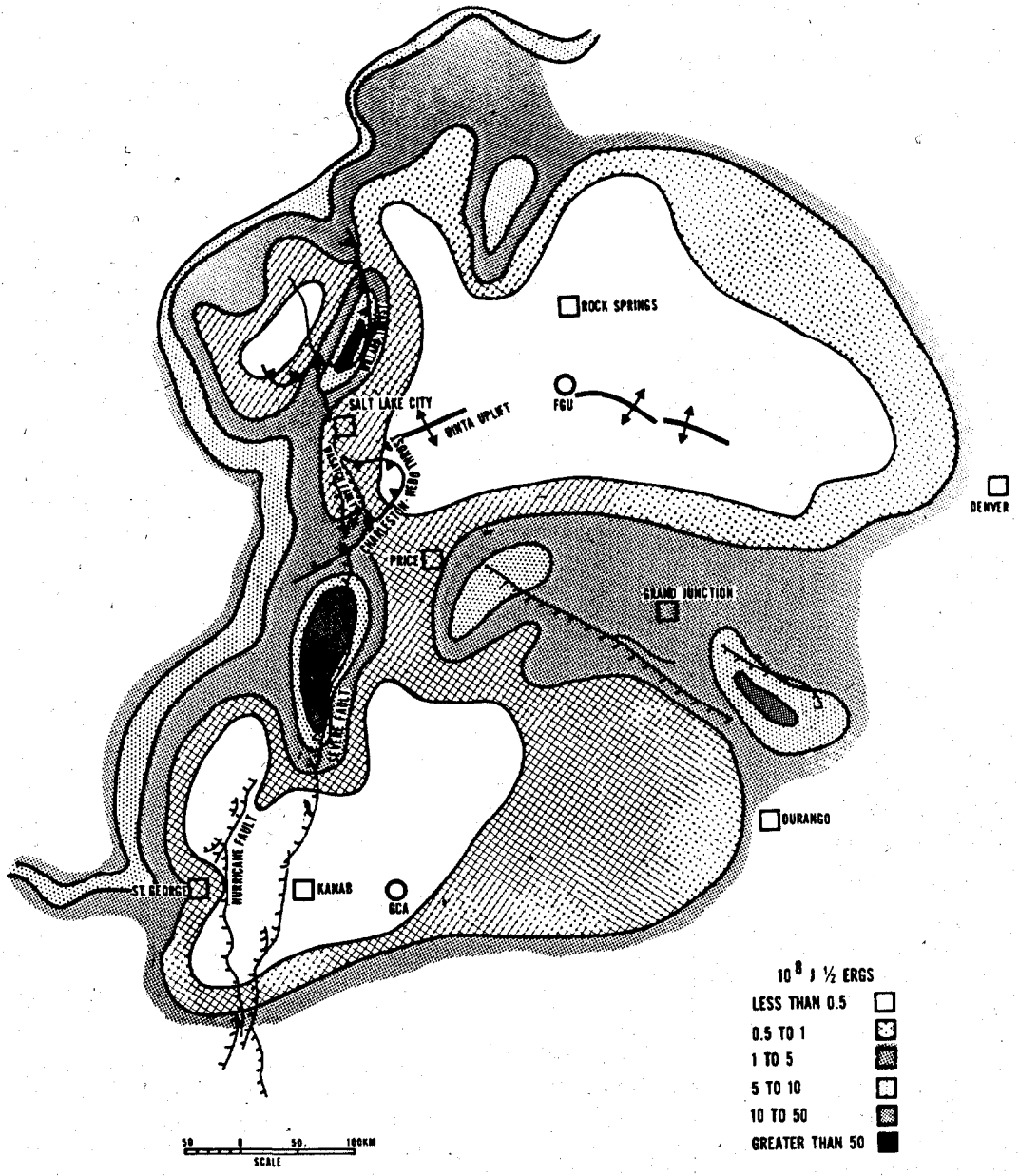

Fig. 4. Contoured map of the square root of seismic source energy, which is proportional to strain release. An increase in density of shading indicates an increase in strain release.

number of earthquakes felt during the period 1939–1951. The correlation is very apparent but has a low level of significance. When other averages, monthly combinations, or chronological earthquake and water level statistics are used, the correlation is much less apparent.

SUMMARY

The number of earthquakes per unit time per unit area is a measure of relative seismicity for the five sites. The ranking in the order of most to least seismically active is as follows: (1) Cedar Springs, California; (2) San Luis, California; (3) Hoover

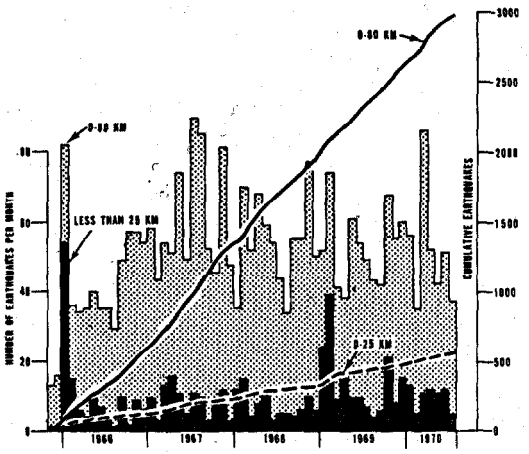

Fig. 5. Number of earthquakes per month at San Luis Dam, California, from November 1965 through July 1970 in two distance ranges.

Dam and Lake Mead, Nevada; (4) Flaming Gorge, Utah; and (5) Glen Canyon, Arizona.

Cedar Springs was the most seismically active, but the dam and reservoir have not been built. The seismic activity near San Luis Dam is along a fault zone that was active historically before the dam was built. Of the five areas considered, the seismicity around Lake Mead seems to be related to the reservoir. *Jones* [1944] reported,

> According to T. C. Mead, of the Bureau of Reclamation, no earthquakes were reported by the few local inhabitants in the fifteen-year period prior to the construction of Boulder Dam.

Since 1936, there have been >10,000 earthquakes recorded, and approximately 10% were felt in the Hoover Dam and Lake Mead area.

RECOMMENDATIONS

Although four of the five examples of reservoir seismicity did not indicate effects of reservoir loading, the scientific literature is replete with references affirming a causal relationship. The best place to build a dam is in a deep narrow gorge with an upstream reservoir of sufficient

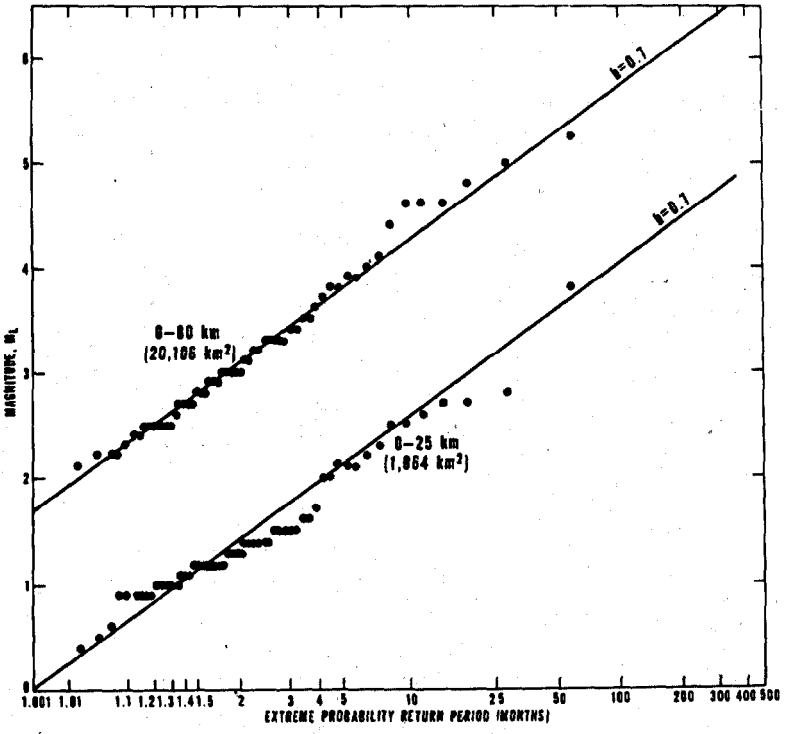

Fig. 6. Extreme probability statistics for the seismicity within 0–80 km and 0–25 km at San Luis Dam from November 1965 through July 1970.

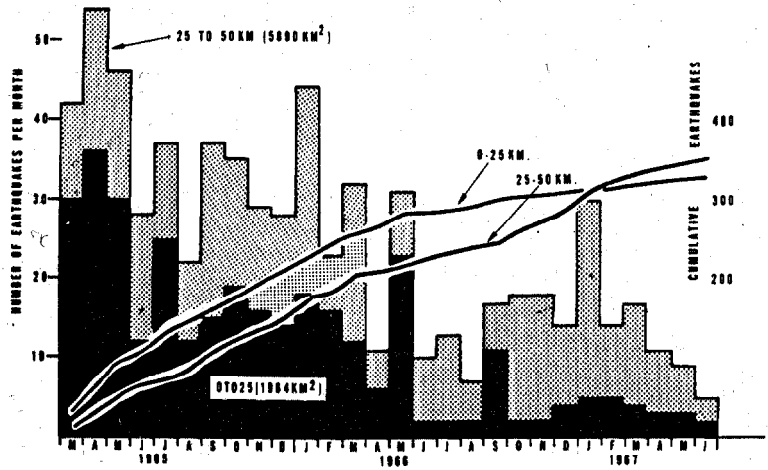

Fig. 7. Earthquake occurrence characteristics in two distance ranges from Cedar Springs, California, and cumulative number of earthquakes from March 1965 through June 1967 (total of 682 earthquakes).

dimensions and inflow potentials to make such a project feasible and economical. These optimum areas are also where past tectonic activity has been present to create the desired deep narrow gorge, which is associated with faulted structures and concomitant earthquakes. Current seismic activity, however small, along the faults within the reservoir indicates a potential for fault movement.

It is recommended that a seismograph station be installed in proposed areas of large man-made lakes, dams, and reservoirs at the time the site is proposed to provide a history of seismicity prior to construction.

If the area is seismically active, additional stations should be deployed to locate the earthquake hypocenters and, if possible, to determine the earthquake mechanisms in addition to frequency of occurrence characteristics and magnitudes. Close coordination should be maintained with the project geologists. If the earthquakes can be considered associated with surface

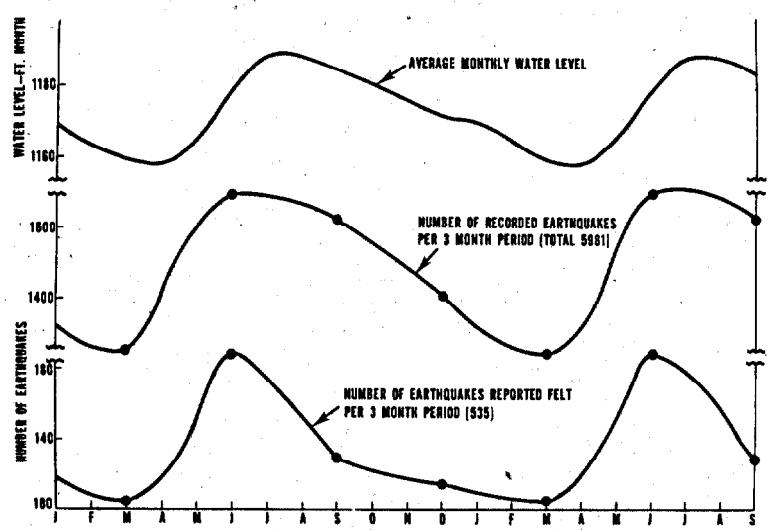

Fig. 8. Periodicity and correlation plots of average monthly water level, number of earthquakes recorded per 3-month period, and number of felt earthquakes per 3-month period for Lake Mead from 1939 through 1951.

faulting, there should be monitoring networks of stations across the fault to determine if there is movement.

The demand for water reservoirs will increase, and the construction rate of man-made lakes will increase. *Mermel* [1970] reported that there are 125 dams a year being built in the United States with heights of >15 meters. Worldwide, >300 dams a year are being constructed.

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