EARTHQUAKES AND RESERVOIR LOADINGS

by J.P. Rothé (I)

The paper compares some swarms of earthquakes which occurred near reservoirs in different parts of the World and studies their seismotectonical features : geology, previous seismicity, foreshocks, aftershocks, magnitude, energy release, etc.

The earthquake activity is particularly clear when the reservoir is deeper than 100 meters. The height of the water seems to be more important than the total volume of the reservoir. The action of the interstitial strengths was brought to light. The paper emphasizes the influence of the geological conditions in the underground of the artificial lakes. These conditions should be studied carefully in connection with further designs.

Introduction

In recent years several instances of local earthquakes activity attributed to reservoir loading have been reported. Some shocks thus triggered can be characterized by magnitudes higher than 6 and therefore have caused notable damage. Some examples will be briefly described here in the following paragraphs.

1.- The Monteynard dam

The Monteynard dam is located in a portion of the narrow valley of the River Drac, in the French Alps; it is an arch-dam, 130 m high. The diversion tunnel was closed on April 19, 1962 at the level 397 m, namely 42 m above the river bed; the filling has been continued during the summer and autumn of 1962; the level 480 has been reached in January 1963, the level 490 on April 20, 1963, corresponding to a normal storage of 275 Mm^3.

Some days after, on April 25, two foreshocks were noted and at 14h36mn an important earthquake caused some slight damage in a few places of the area. The isoseist map is presented fig. 1. The pleistoseist zone is closely centered on the lake-reservoir; the macroseismic radius does not exceed 40 km : it means that the focus is at a depth nearly zero. The calculated microseismic epicenter coincides with macroseismic evidence.

It is possible to compare on fig. 2 the curve of the filling and the distribution of the energy which was released in time in the various shocks. The magnitudes have been calculated by E. Peterschmitt (Rapport inédit), either from the seismograms obtained on the seismological station of Roselend (at a distance of 110 km), or from the seismograms of the Monteynard station; this station has operated since August 9, 1963. The energy released was calculated by the formula : $\log E = 2{,}9 + 1{,}9\ M$ (E in joules).

(I) Professeur à l'Université de Strasbourg, Directeur du Bureau Central International de Séismologie.

A new swarm of shocks occurred in 1966; the largest shock (August 24, M = 4,3; log E = 11,0) was felt in the area and was not so strong as in 1963. As before, the main shock and the aftershocks occurred immediately after the maximum lake-elevation was reached again (level 490 m). See fig. 3 and 4.

The examination of the maps and diagrams clearly shows a connection between the seismic activity and the fluctuations of the water level in the reservoir; the two largest shocks in 1963 and 1966 occurred when the level was the highest.

We must point out that the dam is located in a area tectonically perturbed : a net of faults exists, particularly the fault de la Mure, running North-South, and many other faults running East-West; further, fissures and diaclases appear in the substratum, parallel to the course of the river; the real storage is probably greater than the visible basin.

Before the construction of the dam, no earthquake occurred in the area of Monteynard; nevertheless in April 1962, a notable seism shook the Vercors, about 12 km North-West from Monteynard; it was also the first earthquake known in this district.

2.- The Grandval dam

In another part of France, some earthquakes occurred in 1963 and 1964 near the Grandval dam; this dam is located on the River Truyère, in an area of slight seismic activity (an hercynian mountain called Massif Central).

Characteristics of the dam :
Water-height : 78 meters
Maximum elevation level : 742 meters
Normal storage : 292 Mm^3
Beginning of the first filling : September 15, 1959

After a first filling completed at the maximum level in March 1960, some weak earthquakes and many underground noises were observed by the members of the hydroelectric plant, particularly on December 31, 1961 and January 1st, 13 and 14, 1962. The lake was quite completely discharged in March 1962, and filled again. The maximum level (741 meters) was reached in August-September 1963.

However, on August 5, 1963, an earthquake occurred, felt with intensity V by some villages located on the left and the right of the lake. The macroseismic surface was only 650 km^2; the focus was exactly under the lake reservoir. An other stronger shock occurred two months later with the same epicenter. These two shocks have been accurately recorded by eleven French seismographic stations. On February 25, 1964 and September 5, 1964, two other earthquakes have been felt at the Grandval dam and some nearly villages. As in the former Monteynard example, a real connection exists between the shocks and the existence of a reservoir. The two strongest earthquakes occurred just when the water-level reached its maximum.

3.- Dams in Catalogne

In Spain some shocks occurred near lake-reservoirs. The isoseist map of the shock on June 9, 1962, published by Dr. E. Fontséré, is significant : the isoseist curves are centered on the places of the hydroelectric works situated along the Rio Noguera Ribagorzana, in the Spanish Pyrénées (1).

4.- The Hoover Dam and the Lake Mead

This is a classical example; D.S. Carder writes : "A detailed survey of the seismic activity near the Lake Mead was conducted for more than 15 years by the Coast and Geodetic Survey under the sponsorship of the Bureau of Reclamations using for the most part a quadripartite net of seismographs distributed about the lake. From published reports on this activity through 1944, verified by more recent investigations, it is concluded that a definite correlation between local earthquake activity and reservoir loading may exist but that earthquakes may be interpreted as a renewal of Pliocene or post-Pliocene activity brought on by stimulus of the suddenly added load of reservoir. This load merely takes advantage of the mechanism which had been established by earlier orogeny. Earthquakes of magnitude larger than 3,5 probably result from triggering the release of inherent strain" (Abstract N° 140, General Assembly I.U.G.G., Zurich 1967)

The characteristics of the Boulder Dam and the history of the seismic activity (2, 3) are summarized in Tableau I.

5.- The Kariba Lake

The Zambezi valley in which Kariba Lake is situated generally consists of Karoo sediments of the Mesozoic and Palaeozoic ages; the dam site itself is of well banded foliated medium grained biotite gneiss of the Basement Complex (Archean) with the upper portion on the right bank consisting of medium to coarse grained quartzite. A net of faults running SW-NE extends along the Zambezi valley and its sides. The closure of the Zambezi river and the filling of the lake started in December 1958; water reached the nominal lowest operating level of 1560-ft. by March, 1962 and the nominal operating level of 1590-ft. by March 1963. The lowest level of the river bed at the dam is approximately 1200-ft.

The first tremors located near the dam and the lake occurred in the summer 1961 : July 3, September 13 (two shocks); the seismic activity strongly increased on March 3, 1962 with 16 shocks in 24 hours; a total of 155 tremors was recorded in 1962 and 135 tremors, from January 1st to July 31, 1963.

The filling of the Lake was achieved in August 1963; the maximum height ever reached by water so far was 1599-ft.

Some days after, on August 14, the sequence of the strongest earthquakes began; these were recorded by numerous seismological stations.

	h	mn	Coordinates		Magnitude (BCIS)
August 14	00	15	$16^{\circ}7$ S	$28^{\circ}7$ E	5,1
September 23	06	40	$16^{\circ}6$ S	$28^{\circ}6$ E	5,7
September 23	09	01	$16^{\circ}6$ S	$28^{\circ}8$ E	6,1
September 23	15	02	$16^{\circ}7$ S	$28^{\circ}4$ E	5,6
September 23	22	23	$16^{\circ}6$ S	$28^{\circ}7$ E	5,8
September 24	09	13	$16^{\circ}6$ S	$28^{\circ}7$ E	5,5
September 25	07	03	$16^{\circ}7$ S	$28^{\circ}7$ E	6,0
October 5	16	54	$16^{\circ}9$ S	$28^{\circ}6$ E	5,3
November 8	09	59	$16^{\circ}5$ S	$28^{\circ}5$ E	5,8

All the epicenters were located close to the dam in the area where the lake is the deepest.

They are the first examples in the world of triggered shocks of magnitude 6 or more.

750 aftershocks were recorded until September 30, 1963. The seismic activity gradually decreased afterwards but rather numerous tremors were again observed from 1964 to 1967; a shock of magnitude 4,1 occurred on April 5, 1966, another of magnitude 5,5 was recorded on April 20, 1967.

Before the construction of the dam, the area had been known to be without seismic activity; not one epicenter in this country is reported in a recent work devoted to the seismicity of Africa (4).

6.- The Kremasta dam

A strong earthquake of magnitude 6,3 occurred on February 5, 1966 in Eurythania (Greece). "An exceptionally long sequence of small local shocks with an exponently increasing frequency preceded the principal shock. The sequence started after the damming of the Acheloos River and the impounding of the artifical Lake of Kremasta. It was found that the number of the foreshocks could be correlated with the increase of the reservoir loading. There seems, therefore, to be good reasons for believing that the tectonic equilibrium in the area of Kremasta was sufficiently ripe to be disturbed by this comparatively minor additional unilateral load. The weight of the water in the new lake is of the order of $4.7\ 10^9$ Tons. Many earth slides and slump fractures were observed in the mezoseismal area; 480 houses collapsed and about 1200 were seriously damaged; slight damage was incurred in 950 houses; one dead and 60 injured, four of them seriously" (Seismological Bulletin of the National Observatory, Athens, February 1966).

The Eurythania is a seismic area, but during the period 1951-1965 the epicenters were confined in the lower part of the Acheloos Valley, 40 km downstream below the site of the Kremasta dam. The filling of the lake began on July 21, 1965. The first tremors were felt in December 1965 and the main shock occurred on February 5, 1966, just as the water -level reached its maximum height, namely 120 meters. Many aftershocks were recorded and felt; by the station Valsamata 740 foreshocks and about 2580 aftershocks have been recorded (6, 7).

The lake is chiefly located over eocene-oligocene flysch; nevertheless, 11 km upstream of the dam some important faults exist below the lake; it is just the area where the strongest foreshocks and aftershocks occurred.

7.- The Koyna dam

The Koyna dam (17°23'N, 73°45'E) and the Shivajisagar Lake formed by it are situated in the Peninsular Shield of India which is generally regarded as one of the aseismic Precambrian blocks existing on earth today. The frequency of occurrence of the low magnitude earthquakes in the Peninsular Shield is very small excepting in extremely isolated places where swarms of very small earth tremors occur at times. The whole of the Koyna area lies in the region of Basalt rocks, known as "Deccan Trap". The Basalt rock formation is found to be in different successive flows of Lava of varying thickness. The massive basalt layers are underlaid by a thin layer of trap ash or red bole varying in thickness from 10 cm to 150 cms; the bole or trap ash layers gradually change into soft brecciated rock which may be either tuff or flow.

The technical characteristics of the Koyna reservoir are reported in Tableau I.

However, a few months after a partial filling of the reservoir (860 Mm^3) in 1962, earth tremors started and the frequency of the tremors increased considerably from the middle of 1963 onwards. A net of four seismological observatories, including one on the dam was established around the Lake. These have indicated that the tremors are restricted to more or less reservoir area with their epicenters around two regions, one close to the dam-site and the other in the reservoir about 40 kms upstream of the dam. It would be worthwhile mentioning that these tremors are many times accompanied by a sort of hollow muffled sound as if originating from deep waters.

The causes of the tremors near the dam site are attributed to the adjustments due to the water load in the shear zone crossing the dam site and the geotectonic of the tremors occurring about 40 kms upstream has been attributed to a zone of weakness running east-west in this area.

In November 1966 Dr Guha and his collaborators came to these conclusions : "It is thus likely that surimposed water load has triggered these tremors through differential movements along planes of weakness in the underlying strata in the reservoir area ... Amount of release of elastic energy in the form of tremors is perhaps related with the changes of potential energy of the water mass due to the change of lake level ..." (8). In September 1967, P.M. Mane, Chief Engineer at Koyna, wrote : "It is gathered that such tremors gradually decrease over a period of some years and stop completely. It is hoped it will be so here also" (9).

However, on December 10, 1967, a strong earthquake of magnitude 6.4 occurred at Koyna : great damage to buildings have been reported and the number of dead has risen to 200 with many injured. The epicenter, calculated by electronic computing at the Bureau central international de Séismologie, Strasbourg, is close to the dam (17°4 N, 73°9 E). The main shock was followed by many important after-shocks.

The magnitude of the main shock is strictly comparable with the magnitude of the main shock at Kariba and, as at Kariba, the area was aseismic before the construction of the reservoir.

8.- The Vaiont dam

The tremendous accident at the Vaiont dam in Italy, on October 9, 1963, will be briefly recalled. The Vaiont dam is an arch-dam, 261 meters high. The accident has been caused by 350 Mm^3 of rocks suddenly sliding in the lake; this mass of rocks carried out a wave more than 150 meters high, followed by a surge, 15 to 20 meters thick, overpassing the arch. The origin itself of the landslide is not clear. According to some geologists the strata over the "Mont Toc", a hill rising above the lake, were already an unstable equilibrium before the filling of the reservoir; according to other scientists, a double process would have acted : 1°) the filling of the lake would have produced some weak tremors; 2°) the recurrence of these shocks would have broken the uncertain equilibrium of the strata over the Mont Toc and carried the landslide straight away to the lake (10, 11, 12).

Conclusions

In tableau I the seismic activity and the technical characteristics of certain reservoirs are compared. The inspection of this document leads to several remarks.

1°) The earthquake activity is particularly clear when the reservoir is deeper than 100 meters. The height of the water seems to be more important than the total volume of the reservoir.

2°) In many cases, contrary to natural seismicity, the strongest shocks follow after numerous foreshocks, the frequency of the foreshocks increase progressively during a certain period; the more tectonically quiescent the area, the longer this period is.

3°) The seismic activity generally increase at the time of the achievement of the first filling and, after having reached a maximum, gradually disappears in the course of a few years.

4°) The accident at the Malpasset dam, in France, on December 2, 1959, brought to light the risk - underestimated to this time - of a sudden breaking of the rock support of the arch-dam by the action of the interstitial strengths. Consequently it is important to study the water-flowing in the underground and the internal stresses which are created (12).

In this way it is necessary to recall the curious phenomena which occurred in the area of Denver, Colorado, behind the pumping of waste fluids injected into a 3700 meters deep well bottomed in Precambrian gneiss (Rocky Mountain Arsenal Well), north-east of Denver. More than

900 earthquakes have been recorded in the Denver area: a large majority have been microearthquakes and only a few of the larger quakes have approached or exceeded a magnitude of 4.5. The studies confirmed that there is a definitive correlation between the number of earthquakes and the pumping rate into the well : all seismic activity occurred within a 6-to-10 kilometer radius of the well and focal depths of from 4 to 5 kilometers; the epicenters are in a zone which trends approximately N 60° W and fault-plane solutions suggest strike-slip motion parallel to this zone with right-lateral displacement (14).

One remark is important : if the mechanism generating the shocks was triggered by the injection of the water, nevertheless it continued after the closure of the well. The Rocky Mountain Arsenal waste disposal well has not been pumped since February 1966; however "the earthquakes continue, each large one, larger than the one before" (Bull. Seismol. Society of America, vol. 58, 1968, p. 480).

Some recent earthquakes were observed at Denver on April 10, 1967 (m = 4.8), on August 9, 1967 (m = 5.3) and on November 27, 1967 (m = 5.2). This energy release indicates that the action of the internal stresses is still in progress.

5°) Some particular geological conditions are necessary for the release of the shocks (the nature of the strata, faults, diaclases, and so on); of course, in many cases, the filling of reservoirs did not bring any notable seismic activity.

6°) The age of the concerned faults does not seem to be relevant. In the reported examples, there appear strata with an old orogeny and a very low seismicity (African Shield, Deccan), as well as area with a recent orogeny and a notable seismicity (Greece, Alps, Pyrénées, Rocky Mountains). Even if the faults have been quiescent during a long geological time, their activity can be revived under the weight of the water reservoir and the interstitial stresses.

Before the building of a dam, it is therefore necessary to make a meticulous geological study, not only near the projected site of the dam, but also in the whole area which is to be filled by the reservoir.

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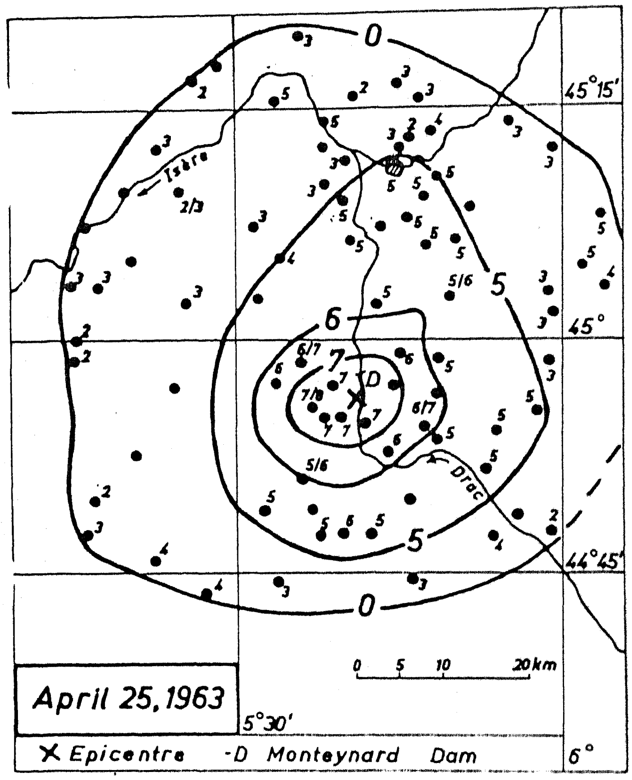

Fig. 1 Monteynard dam; Isoseist map, April 25, 1963

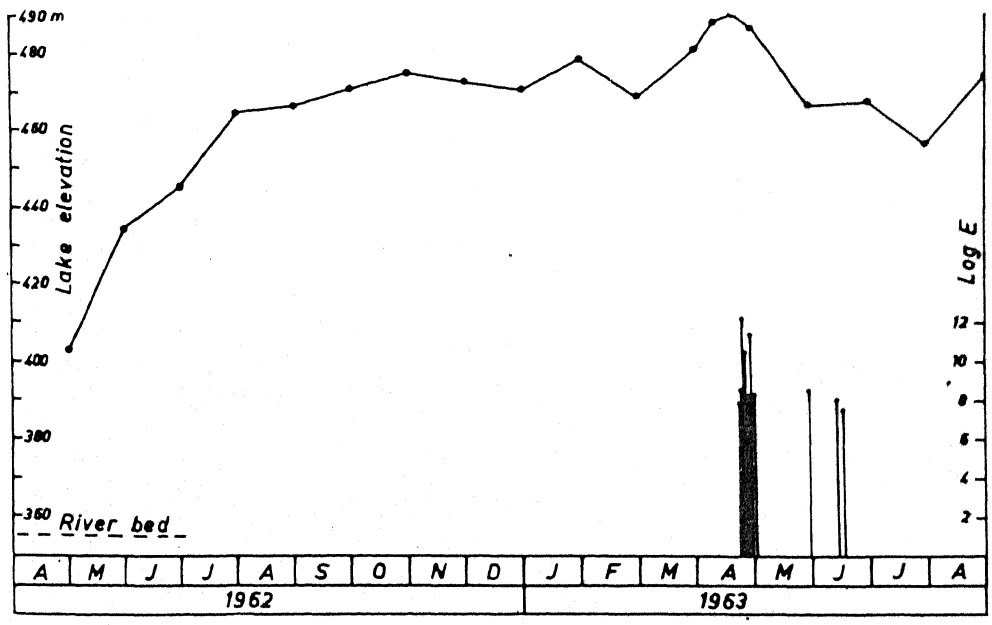

Fig. 2 Monteynard dam; first filling of the reservoir and seismic activity (energy released in joules)

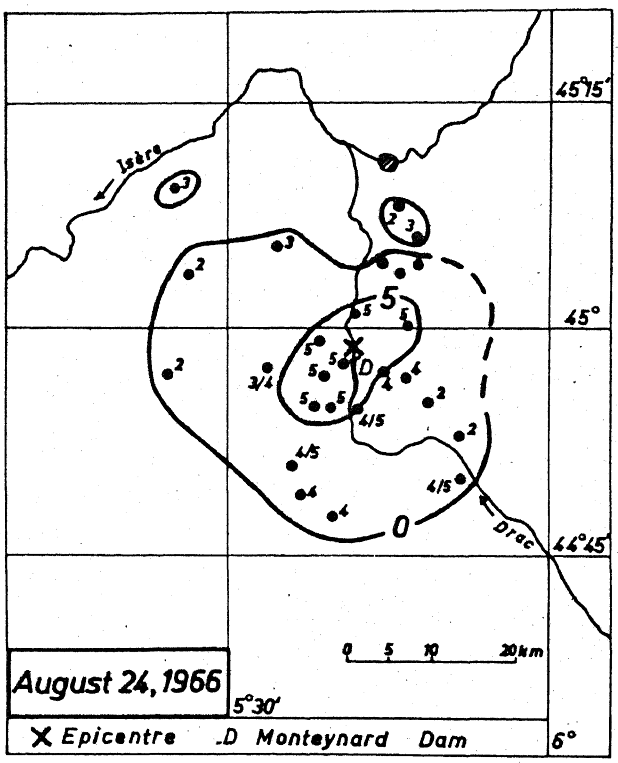

Fig. 3 Monteynard dam; isoseist map, August 24, 1966

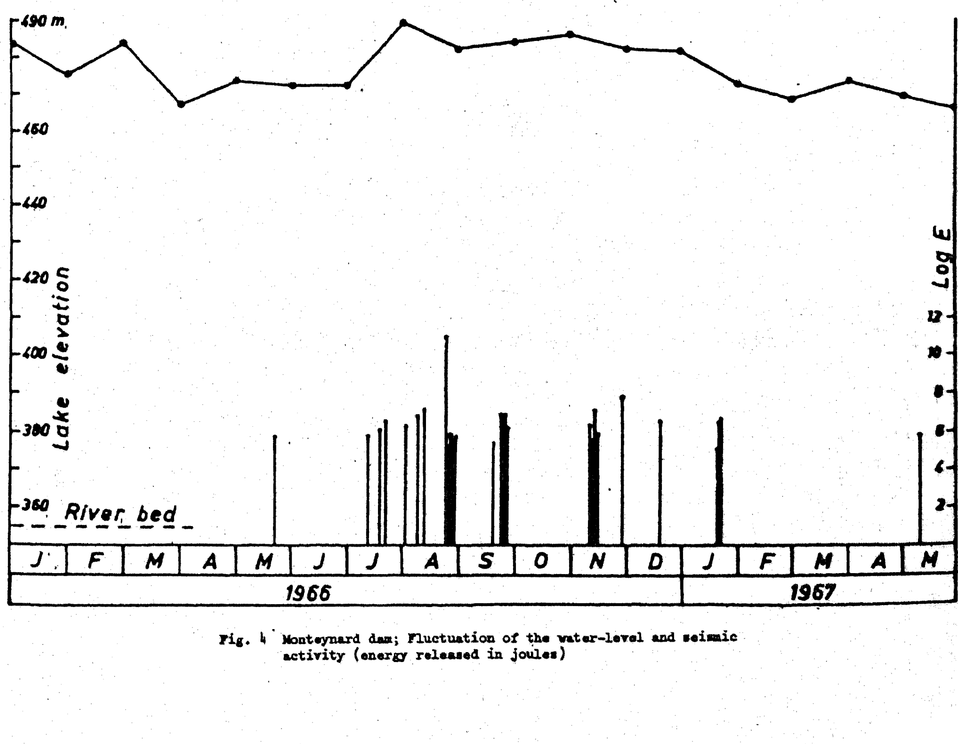

Fig. 4 Monteynard dam; Fluctuation of the water-level and seismic activity (energy released in joules)

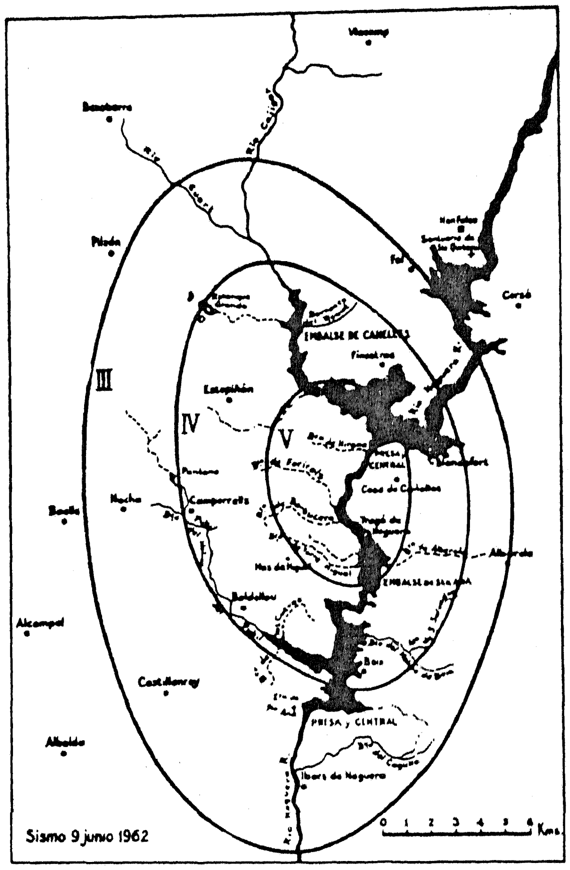

Fig.5 Isoseist map, June 9, 1962 (After E. Fontséré)

TABLEAU I

	Hoover Dam	Monteynard	Kariba	Kremasta	Koyna
Type of the dam	arch	arch	arch	earth	concrete gravity
Height of the dam	142 m	130 m	125 m	147 m	103 m
Maximum capacity Mm^3	35,000	275	175,000	4,750	2,780
Beginning of the filling	1935	April 1962	December 1958	July 21, 1965	1962
Achievement of the first filling	July 1938	April 1963	August 1963	February 1966	1962 * 1964 **
First shocks	September 1936	April 25,1963	July 1961	December 1965	1963
Main shock :	1939	1963	1963	1966	1967
Date	May, 4	April, 25	September, 23	February, 5	December, 10
Magnitude	5.0	4.9	6.1	6.2	6.4
Strong aftershocks:					
Date	August 11, 1942	April 27, 1963	September 25,1963	May 4, 1966	December 12, 1967
Magnitude	4.1	4.5	6.0	5.5	5.4
Date	September 9,1942	August 1966	November 8, 1963	June 11, 1966	December 24, 1967
Magnitude	4.4	4.3	5.5	5.5	5.5
Date	-	-	April 20, 1967	October 29,1966	
Magnitude	-	-	5.5	6.0	-
Geology of the area	Granites and precambrian shales	Liassic limestones	Archean gneiss and Karoo sediments	Flysch	Deccan Trap

* partially filled 860 Mm^3
** 2,000 Mm^3

ADDENDUM

Since this report has been written several works concerning some of the examples mentioned above were published and give interesting details; however, the authors of these papers did not compare the phenomenons which they describe with those produced elsewhere. Therefore their conclusions remain questionable as is given evidence by the following comments.

The Kariba Lake

In regard of the origin of the earthquakes in Kariba region Gough and Gough (15) write : 1) There may be considerable preexisting stresses in the rocks to which the water load is added. 2) There may be significant lubrication effects of the water, i.e. the water may weaken the faults .... The observations leave no doubt that the formation of the lake has caused a very large rise in the rate of release of seismic energy. Whether the mechanism is one of simple loading, of lubrication or of both together is not known ....

The Cremasta dam

P. Comminakis et al (16) made investigations of the time and magnitude distribution of the fore-and aftershocks of the Cremasta lake earthquake. These authors come to the conclusion :"Strong evidence exists that the foreshocks and the main shock have been triggered by the waterloading of the Cremasta artificial lake." However these scientists add :"Nature is responsible for the destruction produced by the main shock. Nature produces the large forces which acting for a long time in the region accumulated energy. It was just a coincidence that the filling of the lake occurred when the stored energy was almost ready to be released. It is even probable that the lake has benefited the inhabitants.... The lake probably operated to some extent as a safety valve."

This opinion which contradicts the thesis of the present report is quoted to show that the problem of the origin of these earthquakes has no simple answer, particularly in areas that show natural seismic activity.

The Koyna dam

The Committee of experts to which the members of the UNESCO mission and some Indian colleagues belong, has briefly compared the reservoirs of Kariba and Koyna and writes in this report : "In Kariba the water load is 160×10^9 m^3; the Koyna reservoir is small with $2{,}7 \times 10^9$ m^3. It was conceivable, however, that such an imposed load may have been responsible for the minor shocks, although it may be pointed out that the much larger Grand Coulee reservoir, also located on basalt, had no such shocks. Since, however, the small shocks were followed by the important shocks of September and December 1967, it would appear more probable that the whole sequence of seismic events is related to a single tectonic cause and that the small shocks were foreshocks to the two main ones, which followed. It is the view of the Committee, therefore, that the reservoir was not responsible for the two major shocks of September and December 1967 (17, 18)."

Such a strong assertion is in complete contradiction with the conclusions I presented in my report.

The Denver earthquakes

A set of seismological, geological and hydrodynamical papers has just been published concerning the earthquakes which accompanied and followed the pumping of waste waters in the Rocky Mountain Arsenal near Denver (19).

"The majority of the investigators believe that the water injected into the well has contributed to the earthquake activity by a mechanism which is as yet unknown; the source of energy is largely of natural crustal origin, therefore, earthquakes might be occurred even if the well had not been drilled ...." However, in conclusion of this paper in the same book, Pickett writes :"Empirical comparison of injection energy with earthquake magnitudes shows that if injection energy is returned as earthquake energy, it is stored for significant lengths of time, before release. If it is assumed that all injection energy has now been returned as earthquake energy, the total energy magnitude is consistent with energy-earthquake magnitude relations proposed by Richter (20).

In addition, D.T. Snow (21) means "that changes of fluid pressures bring about appreciable changes of permeability and of storage; therefore effective stress changes consequent to fluid pressure changes may have significance to the question of the earthquake mechanism, especially if geological evidence, such as faulting, points to a critical state of tectonic stress."

Concerning the part played by the fluid pressures this explanation joins the one I gave above in calling up the accident of Malpasset. Further this explanation is probably available not only for the Denver earthquakes, but even for all those which accompanied the filling of some big reservoirs; the very analogous phenomenons which are produced at Kariba and at Koyna, in two regions of low seismicity show that the part of tectonic stresses is probably overestimated in the interpretation of the shocks and that the action of the fluid by the weight of the water column and by lubrication is most important.

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