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ARTIFICIAL WATER RESERVOIRS AND EARTHQUAKES

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ABSTRACT

The seismicity in late 1930s associated with Lake Mead, formed by the Hoover Dam on the Colorado river in the United States of America is known to be the first example of reservoir induced earthquakes. Over the years, several more reservoir sites are known to have induced earthquakes. At present more than 70 such sites have been identified. In this paper a worldwide distribution of reservoir induced earthquakes is presented. Special emphasis is paid to the induced earthquakes at Koyna in Maharashtra, India where, so far, the largest known induced earthquake occurred on December 10, 1967. Unlike other reservoir sites, the seismic activity at Koyna has continued. In the end, the mechanism of reservoir induced earthquakes is briefly reviewed.

INTRODUCTION

There are more than 70 examples of reservoir sites where earthquakes have been associated with filling up of reservoirs. The first example is that of Lake Mead formed by the Hoover Dam on the Colorado River in the United States of America. Earthquakes began to occur in late 1930s and the largest event was of magnitude 5. During the 1960s damaging earthquakes exceeding magnitude 6 occurred at large reservoirs at Hsinfengkiang in the People's Republic of China, At Kariba in the Zambia-Zimbabwe border, at Kremasta in Greece, and at Koyna in India. The December 10, 1967 Koyna earthquake of magnitude 6.3 is known to be the largest and most damaging reservoir induced earthquake having claimed over 200 human lives and injuring more than 1500, and rendering thousands homeless. Other reservoir induced earthquakes such as at Kariba, Kremasta and in the later years at Oroville in California and Aswan in Egypt caused damage to nearby towns and villages. Papers published by Rothe (1968, 1970) Gupta et al (1969), Archer and Allen (1969) and Gough and Gough (1970a, b) drew attention to the correlation between reservoir loading and enhanced seismicity. The work relating to reservoir induced earthquakes has been comprehensively reviewed by Gupta and Rastogi (1976), Simpson (1976, 1986), Kisslinger (1976), Packer et al (1979), Gupta (1985), Scholz (1990), Hudson (1991) and more recently in a book "Reservoir Induced Earthquakes" by Gupta (1992a). Material in this paper is largely taken from Gupta (1992a).

It has been pointed out that while assessing the seismic risk of induced earthquakes near a reservoir, one has to worry about the acceptable risk in terms of the lifetime of the reservoir and not the annual probability of ground shaking. Another important factor is change in temporal distribution of seismicity (Simpson, 1986). It is found that areas of low natural seismicity are more vulnerable where adequate precautions are usually not taken to build structures to reduce earthquakes. In areas of high seismicity, the reservoirs may have less impact in changing the seismic regime and the civil works are usually designed to withstand natural seismicity of a higher magnitude. A frequently asked question is how to assess the potential of reservoir induced earthquakes at a given reservoir site and what would be the magnitude of the largest induced earthquake. Additionally, the reservoir induced earthquakes provide an excellent opportunity to test various earthquake prediction models and hypothesis as very often reservoir induced earthquakes are confined to a small area and often there is no other seismic activity in the vicinity of reservoir to complicate interpretation. During the past three decades we have gained some knowledge about reservoir induced earthquakes but a lot more needs to be learned.

RESERVOIR INDUCED EARTHQUAKES : WORLDWIDE DISTRIBUTION

Gupta (1992a) has updated the earlier compilations of worldwide distribution of seismicity influenced by filling of reservoirs. It can be categorised as follows:

a) Where induced earthquakes of magnitude 6 or larger have occurred. There are 4 such sites.

b) Reservoirs where induced earthquakes of magnitude 5.0 to 5.9 have occurred. There are 6 such cases.

c) Reservoir induced earthquakes of magnitude 4.0 to 4.9 with 23 examples.

d) Sites where induced earthquakes were of magnitude < 4 occurred. There are 35 such examples.

e) Decrease in micro earthquake activity after impounding a reservoir have been reported at 8 sites.

f) There are 16 suspected cases of reservoir induced seismicity where due to lack of data induced seismicity could not be established.

g) Fluid injection/withdrawal related induced seismicity has been reported at more than a dozen sites. However, we must mention that this list is not complete.

Figure 1 depicts the present status of worldwide distribution of the reservoir-induced changes in seismicity. In this figure all cases of induced earthquakes of magnitude ≥ 4 are included. Reservoir induced seismicity cases of magnitude < 4 are too numerous and hence are not updated in this figure.

For a long time efforts have been made to better understand the correlates of reservoir-induced earthquakes (for example Stuart-Alexander and Mark, 1976; Simpson , 1976; Beecher and Keeney, 1982). The results of these investigations are summarised in figures 2, 3, 4 and 5 which are self explanatory.

The largest reservoir-induced seismicity event at a given site does not seem to depend upon the time interval between the first filling and its occurrence. At most reservoir sites, major events have occurred following rapid changes in water levels. However, the size of event does not seem to

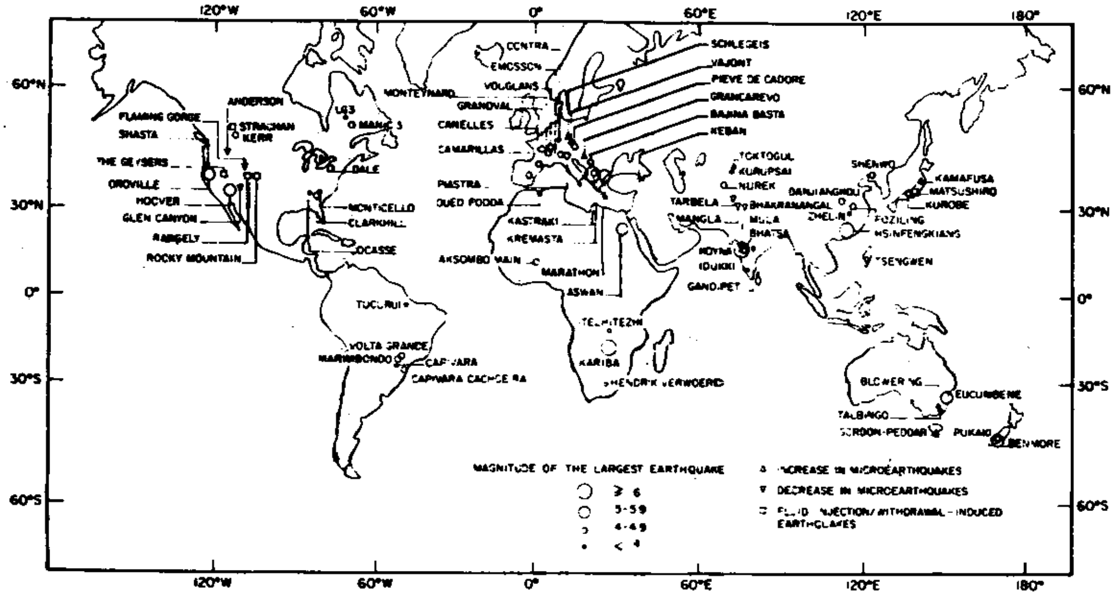

Fig.1. worldwids distribution of the reservoir-induced changes in seismicity consequent on reservoir impoundment. The figure is taken from Gupta 1992a and includes all cases of magnitude ≥ 4.0.

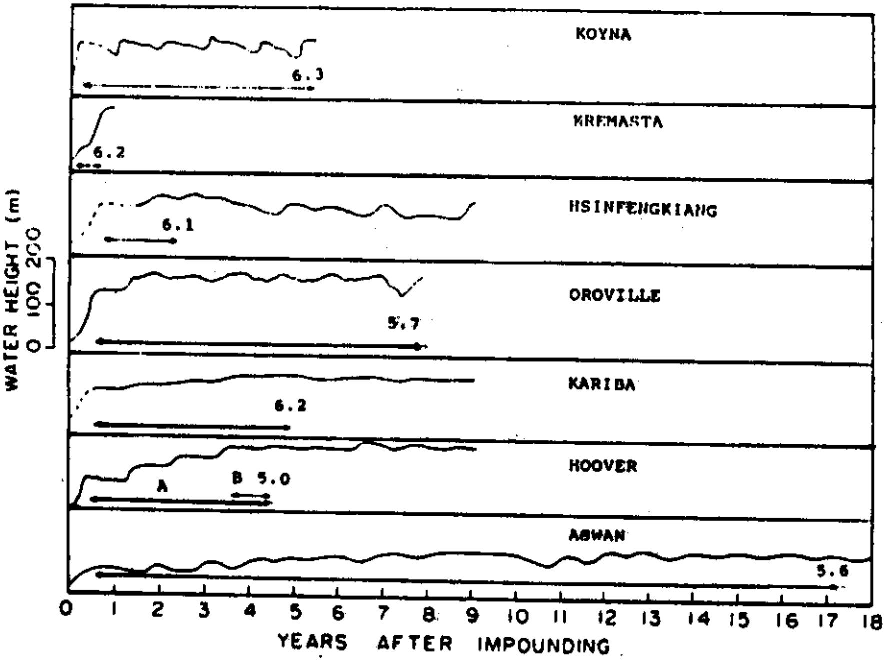

Fig.2. Reservoir levels, largest induced earthquake and the time interval after which these events occurred for seven major sites of reservoir induced seismicity. The arrows indicate the time intervals used in Figure 3. The figure updated from Gupta 1985.

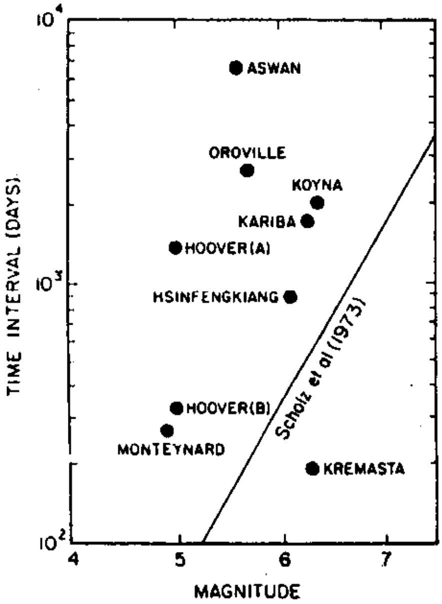

Fig.3. Time interval for the largest RIS events to occur after first filling of the reservoir plotted against its magnitude. Time intervals correspond to the arrows in Figure 2. Two time intervals are used for Hoover, one corresponding to the time interval after the completion of the first stage of filling (A) and the other corresponding to the time interval after first reaching the maximum water level (B). The relation between the earthquake magnitude and duration of premonitory phenomenon by Scholz et al. (1973) is also shown. Figure after Gupta (1985); modified from Simpson (1976) and adopted from Gupta (1992a).

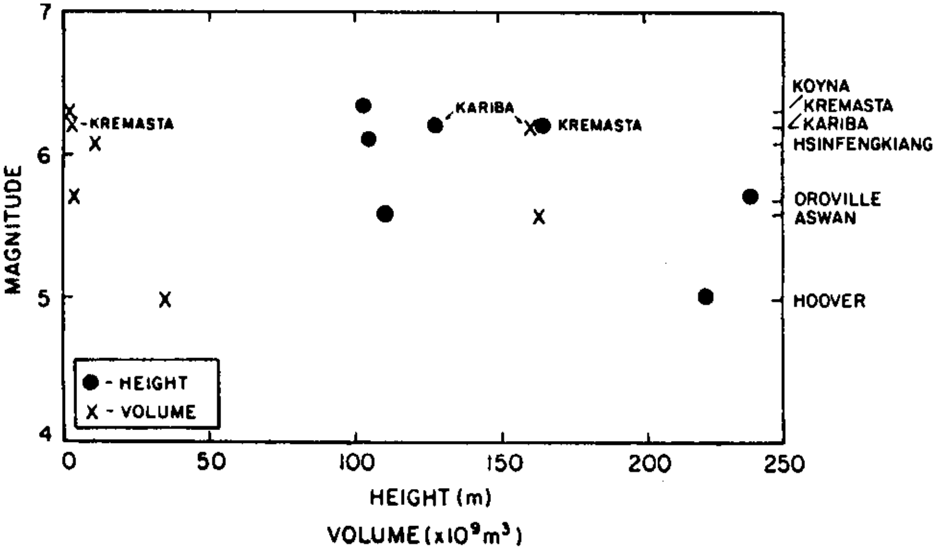

Fig.4. Reservoir volume, magnitude of the largest induced earthquake and the height of the dam for seven major cases of induced seismicity (after Gupta 1992a).

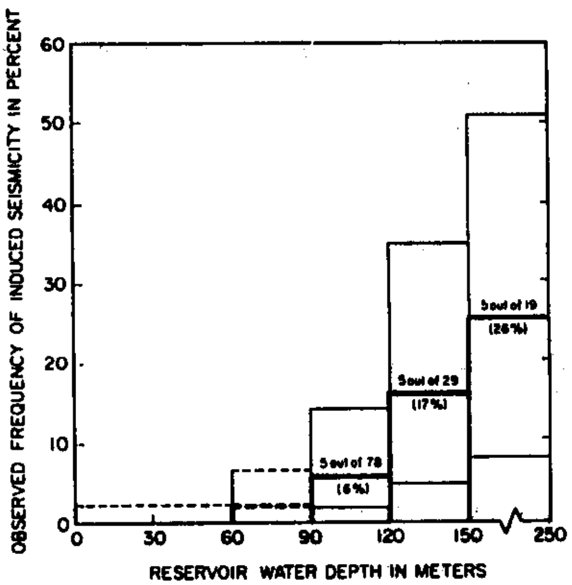

Fig.5. Histogram showing observed frequency percentage (heavy lines) of reservoirs associated with impoundment-induced seismicity (earthquake magnitudes ≥ 3) within certain water-depth intervals, which percentages are taken as the best estimate of mean probability (includes the three equivocal cases). The light lines are 95% confidence limits of the probability estimates assuming a binomial distribution; the lines are dashed where rough estimates were made for the large number of reservoirs in the lower depth classes. The association of seismicity with impoundment is questionable for two reservoirs considered seismic in the 90-120 m depth category (after Stuart-Alexander and Mark, 1976 and modified from Gupta, 1992a)

depend upon the time lapse after filling of the reservoir. Figure 5 shows the histogram between the frequency percentage of reservoir induced seismicity (earthquakes of magnitude ≥ 3) and the depth of the water column. With the increase in water depth the percentage of reservoir induced seismicity cases increase from a meagre 6% for reservoirs with water columns of 60 to 90 m to 26% for reservoirs with water column of 150 to 200 m depth (Stuart-Alexander and Mark, 1976). In an interesting study Beecher and Keeney (1982) statistically examined various correlates for 29 cases of reservoir induced earthquakes and 205 reservoirs where no induced earthquakes had occurred. They found a significant correlation between induced seismicity and the reservoir volume. The correlation of induced seismicity with stress and geology was less significant. In a nutshell it may be mentioned that as of now there are more than 70 sites globally where induced earthquakes have occurred and among all the factors depth of water column in the reservoir appears to be the most important correlate for induced seismicity.

EARTHQUAKES IN KOYNA REGION

As mentioned earlier, the Koyna earthquake of December 10, 1967 with a magnitude of 6.3 is till today the largest known induced earthquake to have occurred anywhere in the world. Over the years, induced seismicity has continued at Koyna region and earthquakes of magnitude ≥ 5 occurred in 1973 and 1980. Gupta and Rastogi (1976) have dealt in detail with various aspects of reservoir induced seismicity in the vicinity of Koyna Dam. We shall not repeat that here.

Relocation of Koyna Earthquakes

Rastogi and Talwani have relocated 39 larger events (M ≥ 4) and about 300 selected smaller events from among 1500 events reported by Guha et al (1974) for a period 1962 through 1973 using a more appropriate velocity model for the region and better location techniques. They discovered three major groups on which the relocated epicentres fall. A majority of epicentres including the December 10, 1967 earthquake, lie on the NNE trend in the vicinity of reservoir.

During the period October 1973 through December 1976, 12 earthquakes of M ≥ 4 occurred in the Koyna region. Gupta et al (1980) investigated these 12 earthquakes, their foreshocks and aftershocks and estimated the focal parameters, source mechanism and energy release. As the time corrections are not regularly marked on Koyna network of seismograms for this period, instead of using P-O time interval they estimated hypocentral parameters using Sg-Pg time intervals for significant events which could reliably be read on atleast 4 stations of the network. They found seismic activity to be much less diffused and identified a N-S trending fault at 73°45'E longitude on which a number of epicentres lie. Figure 7 depicts these epicentres as well as the three groups identified by Rastogi and Talwani (1980a). The epicentral trends located by Gupta et al (1980) and Rastogi and Talwani (1980a) are mutually consistent.

Focal Mechanism

The focal mechanism of the main Koyna earthquake of December 10, 1967 has been investigated by a number of authors using various techniques. These include Tandon and Chaudhury (1968), Lee and Raleigh (1969), Khattri (1970), Sykes (1970), Tsai and Aki (1971), Banghar (1972), Singh et al (1975), Chandra (1976), Langston (1976) and others. The favoured solution is strike of the fault N10°E, dip 78°W, slip 175° and a focal depth of 10 km. The seismic moment is estimated to be 8.2×10^{25} dyne cm. The values of average dislocation, apparent stress, apparent strain and seismic energy are estimated to be 108 cm, 15.4 bars, 5.3×10^{-5} and 2.25×10^{21} ergs respectively. Additionally, composite focal mechanisms for Koyna earthquakes have been reported by Gupta et al (1980) and Rastogi and Talwani (1980a). It has been pointed out that inspite of large errors in focal parameter estimates, the apparent N-S trend of the epicentres along 73°45'E longitude, north of 17°15'N latitude cannot be ruled out (Figure 8). The Koyna river flows in a N-S direction to 17°20' N and then takes a sharp turn to the east. All these observations favour a set of conjugate faults, with a strike slip and normal faulting sense of motion, basically associated with the earthquakes in the vicinity of Shivaji Sagar Lake.

Frequency of Earthquake occurrence and Reservoir level

A close relationship exists between reservoir levels, rate of loading and earthquake frequency at Koyna reservoir Gupta (983). Earthquakes exceeding magnitude 5 occurred in the vicinity of the Koyna Dam in 1967 (two), 1973 (one) and 1980 (three). It may be noted that no earthquake of $M \geq 5$ has since occurred in the Koyna region until December, 1992. It may be concluded that through proper manipulation of reservoir levels earthquakes exceeding magnitude 5 which are locally damaging, could be avoided in the vicinity of Shivaji Sagar Lake. Simpson and Negmatullaev (1978) have reported similar results for Nurek Dam in Kazakistan. Smooth filling/emptying may be a key to reduce the hazard of earthquakes in the vicinity of artificial dams which are known to induce earthquakes.

MECHANISM OF RESERVOIR INDUCED EARTHQUAKES

A global review of reservoir induced earthquakes globally has revealed over 70 sites. We believe that there may be many more cases of induced seismicity, particularly in developing countries, which have not been recognised due to lack of adequate seismic surveillance. For a long time, the part played by the reservoir in inducing earthquakes was not well understood. The fluid injection experiment carried out at the Rocky Mountain Arsenal near Denver Colorado in the early 1960's and application of Hubbert and Rubey's (1959) proposed mechanism of triggering earthquakes by increase of fluid pressure laid the foundation for understanding the phenomenon of induced earthquakes (Evans, 1966). Induced earthquakes in the vicinity of Lake Kariba on the Zambia-Zimbabwe border were explained as due to incremental stresses caused by the load of reservoir by Gough (1969) and Gough & Gough (1970a,b). Gupta et al (1972a) identified the rate of increase of reservoir water level, duration of loading, maximum level reached and duration of retention of high water levels among the important factors affecting the frequency and magnitude of shocks near artificial lakes. Greatly simplified models of reservoirs with finite depth but infinite width were investigated by Snow (1972) to study the influence of pore fluid pressures in inducing earthquakes. More sophisticated models of the effects of reservoir impounding on induced earthquakes, based on Biot's (1941) consolidation theory (Rice and Cleary, 1976), were used by Withers and Nyland (1976) and Bell and Nur (1978). The much needed field verification of theoretical model developed to explain the concepts of induced seismicity was provided through the insitu measurements of physical properties of rocks and examination of physical mechanisms controlling the induced seismicity at the Monticello reservoir in South Carolina (Zoback and Hickman, 1982). The effect of lake level changes and related parameters on induced seismicity for Nurek Dam, USSR was reported by (Simpson and Negmatuliaev, 1981. Similar results were obtained for Koyna Dam in India (Gupta, 1983). The part played by pore pressure diffusion in inducing earthquakes was investigated by Talwani and Acree (1984/1985). In recent years, the fault stability changes induced by cyclic variations in water levels below a reservoir have been reported by Roeloffs (1988). Simpson et al (1988) have identified rapid response and delayed response types of reservoir induced seismicity. At the sametime, Simpson and Narasimhan (1990) have reported the effects of inhomogeneity in rock properties on induced earthquakes.

The above mentioned works can be described as landmarks in improving our understanding of the mechanism of reservoir induced earthquakes. Several investigators including Bell

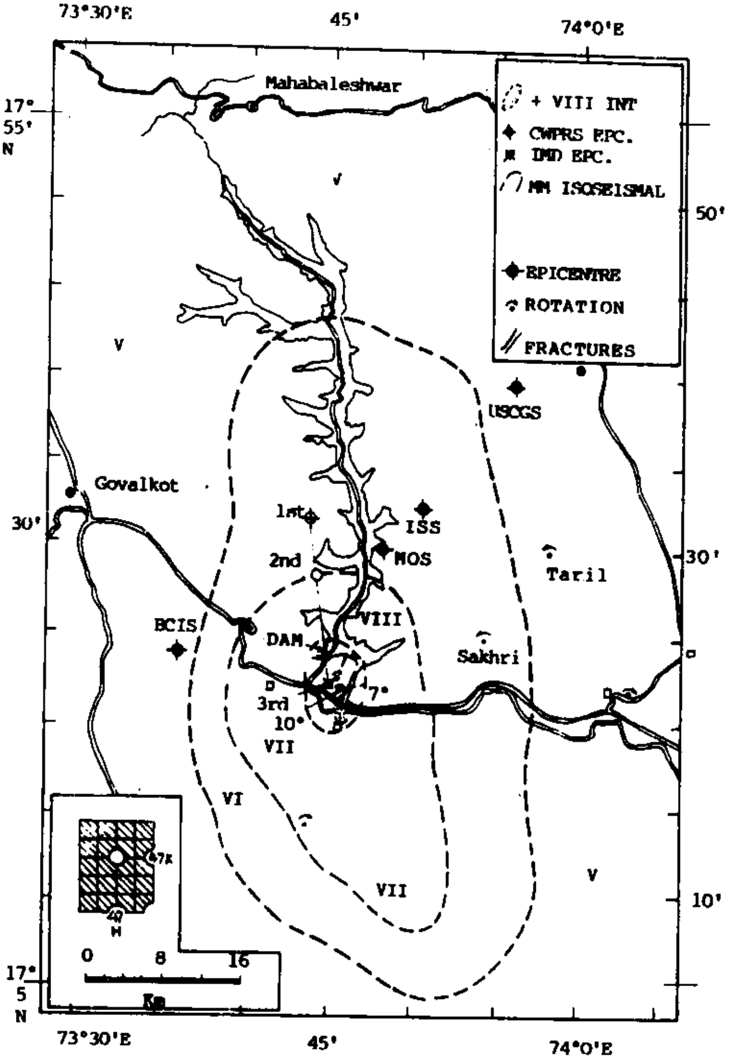

Fig.6. The isoseismals of the December 10, 1967 Koyna earthquake. Figure adopted from Gupta 1992a.

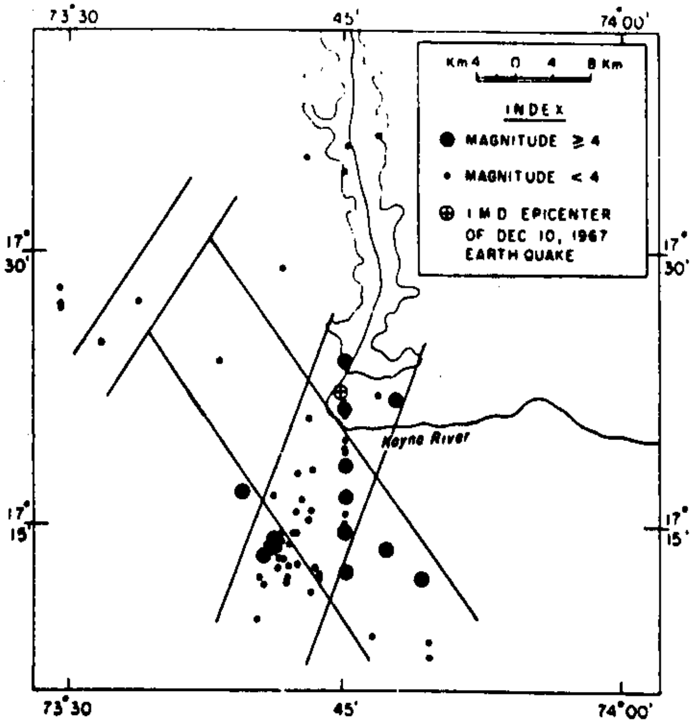

Fig.7. Epicenters for the period 1973 through 1976 for M ≥ 4 earthquakes, their foreshocks and aftershocks located by Gupta et al. (1980). The three trends, from Rastogi and Talwani (1980a), are shown by parallel lines (Diagram taken from Gupta 1992a).

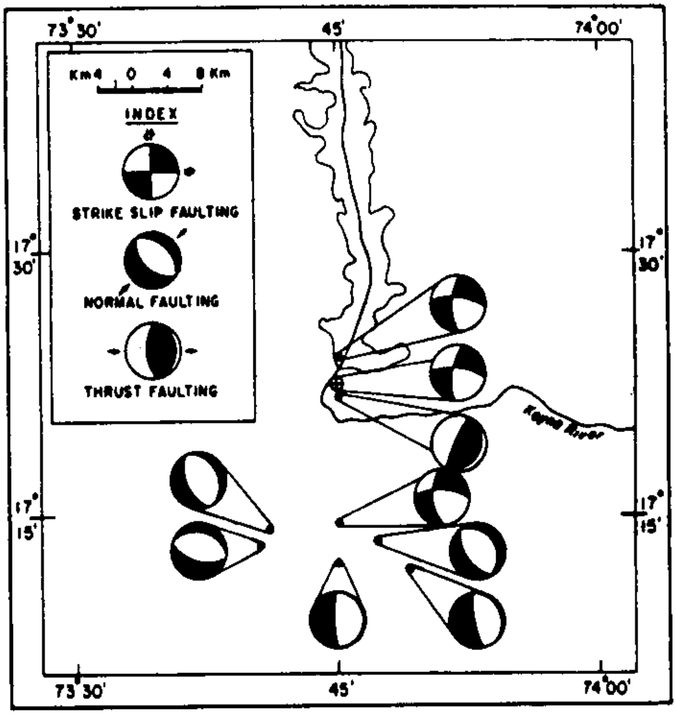

Fig.8. Depicts the composite focal mechanism solution for nine earthquakes of M ≥ 4 in Koyna region. Focal mechanism for the December 10, 1967 earthquake is shown by an open circle with a cross. Earthquakes south of 17°15' latitude have normal fault mechanism.

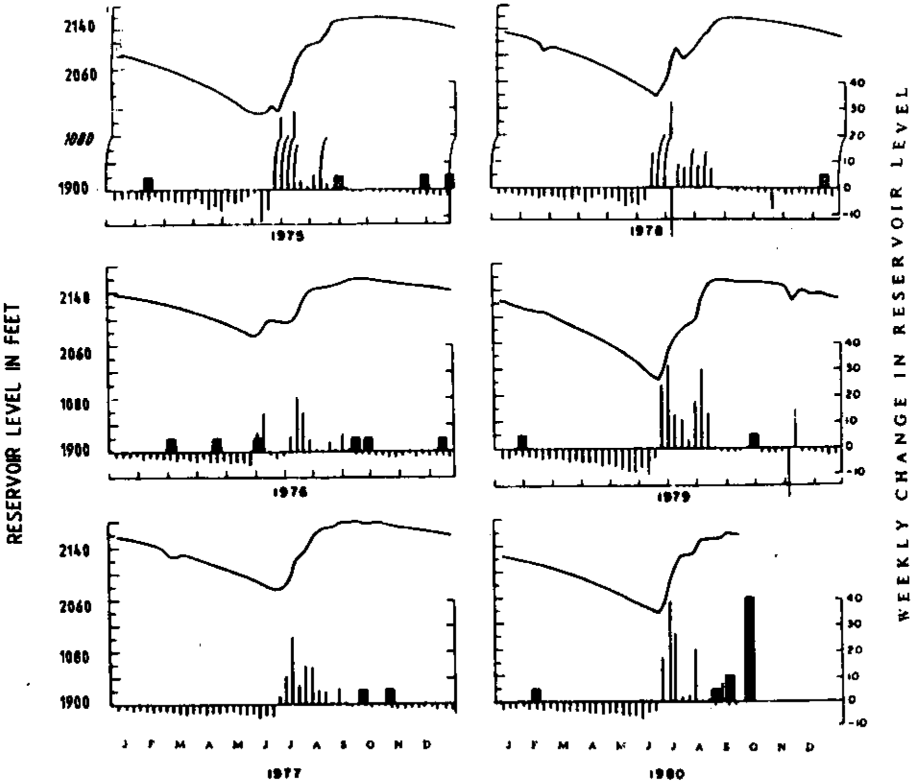

Fig.9. Water levels at the Shivajisagar Lake (curve, scale on the left), weekly change in water levels (vertical bars, scale on the right), earthquakes of magnitude ≳ 4 (hatched column) and magnitude ≥ 5 (filled column). The height of the column is proportional to the number of earthquakes (e.g., one earthquake of magnitude ≳ 4 occurred on February 10, 1975, two earthquakes of magnitude ≳ 5 and six earthquakes of magnitude ≳ 4 occurred on September 20, 1980). Figure adapted from Gupta (1983).

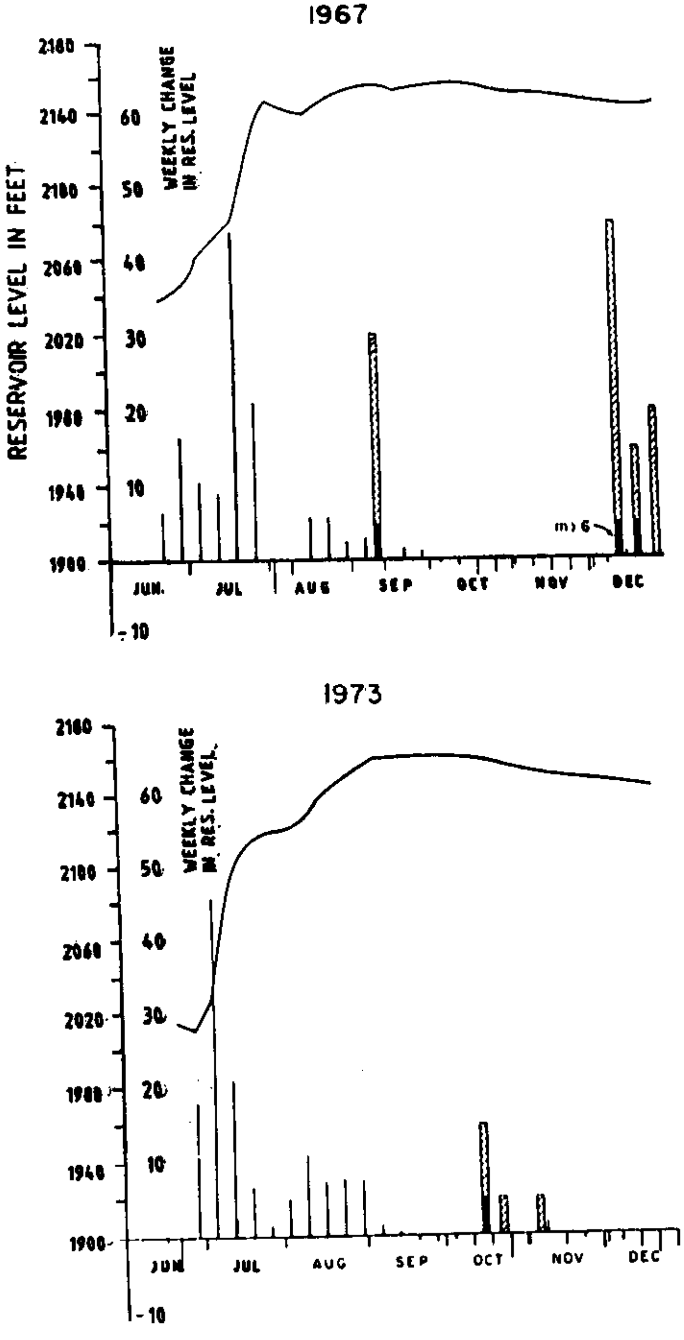

Fig.10. The scheme of the figure is the same as for Figure 9. The December 10, 1967 earthquake had a magnitude 6.3. Figure adapted from Gupta (1983).

and Nur (1978) have pointed out the following three main effects of reservoir loading relevant to induced earthquakes.

(1) The elastic stress increase that follows the filling up of reservoir.

(2) The increase in pore fluid pressure in saturated rocks (due to the decrease in pore volume caused by compaction) in response to the elastic stress increase, and

(3) Pore pressure changes related to fluid migration.

In addition to the above three effects, in a region with low water table prior to impoundment of reservoir, the flow of reservoir water into unsaturated level and thereby raising the ground water table also becomes an important factor. (Snow, 1972, Bell and Nur, 1978 and Simpson et al 1990).

CONCLUSIONS

In the above, a review has been made of global status of reservoir induced earthquakes, earthquakes in the Koyna region and mechanism of induced seismicity. This is a fast developing science and holds promise to solving several physics of earthquake related problems as well as improving our understanding as to how to mitigate the possible hazard of reservoir impoundment.

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