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CONTROL OF RESERVOIR INDUCED SEISMICITY BY MANAGEMENT OF WATER LEVELS AT BHATSA AND SRISAILAM RESERVOIRS

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ABSTRACT

It is generally believed that the rapid filling of dams may trigger strong earthquakes in areas prone to Reservoir Induced Seismicity. This effect implies a transient response to loading having a decay time of pore pressure to be short compared to loading rate. Solutions of the diffusion equation on this phenomenon are described here in terms of hydraulic properties of the media. Based on empirical observations, the recommendations made to control the water levels at Bhatsa and Srisailam reservoirs, during the initial years of filling might have helped in controlling the seismicity near these reservoirs. These recommendations are described.

INTRODUCTION

Reservoir Induced Seismicity (RIS) is related to the rate of impounding of the dam reservoirs. In some cases the critical rates of loading were estimated. The obvious inference from these observations was that the level of seismicity can be contained by manipulation of reservoir water levels and the same was actually tried for some of the reservoirs. The attempts at Nurek, Idukki, and Koyna are described here. A similar attempt made by us at Bhatsa and Srisailam is reported here.

PARTICULARS OF THE DAMS

The particulars of the dams discussed here are given below :

		Height m	Capacity cub.km	Year of impounding	M
1.	Nurek.	315	10.40	1978	4.5
2.	Idukki	169	2.00	1981	3.0
3.	Srisailam	144	8.72	1984	3.2
4.	Nagarajuna-sagar	125	11.56	1974	3.6
5.	Koyna	103	2.78	1967	6.3
6.	Bhatsa	89	0.957	u/c	4.9

MATHEMATICAL PREDICTION OF RIS

In numerous cases of dam reservoirs, seismicity is correlated with the changes in water level (Gupta et.al., 1972, Gupta and Rastogi, 1976). In some cases seismicity follows immediately after filling and in others after delay of a few years.

Seismicity seems to be related to certain characteristics of the filling history which are : (i) rate of loading, (ii) highest level achieved, and (iii) duration for which the high levels are maintained.

Extending Snow's (1972) analysis, Sengupta and Saxena (1986) have given mathematical relations which explain the above empirical observations and predict RIS under some types of filling histories, ambient stress and hydrological as well as mechanical properties of the surrounding rocks.

In the model, fractured rock is simulated by a fluid-filled elastic material subject to Mohr-Coulomb failure criterion. According to this criterion, materials fail when shear stress on the failure plane reaches some unique function of the normal stress on that plane. The unique function is known as failure envelope.

In the areas of induced seismicity the existing stress state is near critical when the Mohr circle would be almost tangent to the failure envelope. RIS will occur if the changes brought about in the effective stresses by the creation of a reservoir would drive the Mohr circle towards the failure envelope. The failure occurs if, the ratio R, of the effective principal stresses σ_x and σ_z should satisfy the following condition

$$R = \frac{\sigma_x}{\sigma_z} > \frac{1 - \mathrm{Sin}\,\phi}{1 + \mathrm{Sin}\,\phi} \tag{1}$$

where, ϕ is the slope of the envelope.

The effective stresses are a function of initial stresses and the pore pressure. The initial stresses have to be known and can be determined by hydrofracturing. The pore pressure, u, is related to the total pressure, P, by the relation

$$P = \gamma z + u \tag{2}$$

To evaluate pore pressures or total pressures, the seepage into rock must be determined. The water mass balance is expressed as

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial P}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial P}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial P}{\partial z}\right) - 2\,\beta\,\gamma\,k_z \frac{\partial P}{\partial z}$$

$$= \gamma\; S^* \frac{\partial P}{\partial t} - \gamma\,\alpha \frac{\partial\, \Delta\sigma_z}{\partial t} \qquad ....(3)$$

A numerical integration approach was attempted to solve equation 3. In case of infinitely large reservoir area and a homogeneous-isotropic rock, the flow equation reduces into an integrable form :

$$\frac{\partial^2 P}{\partial z^2} - 2\gamma\beta \frac{\partial p}{\partial z} = \frac{\gamma S^*}{k_z}\left(\frac{\partial P}{\partial t} - \frac{\gamma\alpha}{S^*}\frac{\partial H}{\partial t}\right) \tag{4}$$

For this equation a solution of the following form exists :

$$P = \gamma z + \gamma H(t) \qquad \text{When} \qquad z < \frac{A}{B} t$$

$$P = \gamma z + \gamma \left(1 - \frac{\alpha}{S^*}\right) \frac{2}{\sqrt{\pi}} \int_{\eta}^{\infty} H\left[t - \frac{\left(Z - \frac{At}{B}\right)^2}{4 \xi^2 / B}\right] e^{\xi^2} d\xi + \frac{\gamma\alpha}{S^*} H(t)$$

when $Z > \frac{A}{B} t$ ....(5)

Where,

$A = 2 \beta\gamma$
$B = \gamma S^*/k_z$
$\eta = (Z - At/B) / 2(t/B)^{0.5}$
$H(t)$ - Water level in the reservoir
α = Global compressibility of the fractured rock
S^* = Storativity coefficient for fractured rock
ξ = Integral variable
β = Compressibility of water
k_z = Permeability in vertical direction

From the total pressure P we can calculate the effective principal stresses, the ratio of which is used to assess the likelihood of triggering of RIS. Sengupta and Saxena (1988) have calculated number of triggerings with time under different conditions. The salient results of their study are described in the following paragraphs.

Majority of RIS activities occur during the rising phase of a filling history. However, a number of triggerings take place long after variations in reservoir level and/or during a recession period. This is expected as the triggerings depend on both filling history and the initial state of stress.

The dependence on the initial state of stress is modelled for the factor Ko i.e. coefficient of lateral pressure. For Ko of 0.2 and 0.3, failure takes place during the first year. For Ko of 0.4 triggering will be activated within the 13th month during which water level is descreasing. For Ko of 0.5 activation of triggering is further delayed to take place during the 31st month, the second recession phase. For Ko of 0.6, triggering will not be activated at all.

Regarding the dependence of number of RIS activities on the filling history, the model predicts a large number of triggerings during the first year of filling when rate of rise of reservoir level is 200 m/yr. If the reservoir is depleted for some time or filling rate is 100 m/yr triggerings are delayed to 3rd or 4th year. The total number of triggerings at the end of 60 months observation period are more for the deepest reservoir level of 250 m. Following the stabilisation of water level, there are no triggerings after 60 months according to the model. However, triggerings have occurred for more than 20 years in some cases.

A permeability around 10 m/s appears to be a threshold and for any permeability above or below, the cumulative number of RIS will be less. If the permeability is large, the high seepage velocity will cause less pressure build-up. Conversely, if the permeability is less, the seepage velocity will be smaller causing longer time lag and triggering at distant points.

RECOMMENDED FILLING HISTORY

Figure 1 illustrates the central ideas of water level management for controlling RIS.

For the initial filling as well as a few years of exploitation the following factors should be considered :

i) the rate of filling should be less

ii) the water level should not be kept high for a long duration.

iii) the rise and fall of water level should be gradual and not sudden so that the peaks are rounded off.

iv) the level should not be much depleted which results in higher rate of filling in the following year

These factors need to be observed only for a few years after impounding. If stronger earthquakes are noticed, the period of safety measures has to be extended.

CONTROL OF SEISMICITY AT KOYNA

At Koyna large earthquakes of magnitude 5 or more occurred in 1967, 1973 and 1980 when rate of loading exceeded 12 m (40 feet)/week (Gupta, 1983). Hence, it was suggested to keep the rate of filling within 12 m/week.

For the impounding period it was observed by Gupta et al. (1969) that whether the water level has crossed 652 m (2140 ft) mark, more and stronger earthquakes were triggered (in 1965 and 1967). It was suggested to keep the maximum level less than 652 m (2140 ft). As this suggestions was implemented, seismicity was low from 1969 to 1972. It again increased in 1973 when the level crossed the 652 m mark (Gupta and Combs, 1976). Though from 1975 onwards, the water level has crossed 652 m mark every year, strong seismicity has not occurred except in 1980. This is perhaps due to the reason that the threshold level has increased in the area.

CONTROL OF SEISMICITY AT IDUKKI

After the Koyna experience, Idukki reservoir (1600 km smooth of Koyna near West Coast) was decided to be filled in a controlled manner. The rate of imponding has been kept 8 to 11 m/month all through except in 1985 when it was 14 m/month or 4 m/week. Seismicity, though increased after the start of filling, has been of low magnitude (Rastogi et al., 1989).

CONTROL OF SEISMICITY AT NUREK

Nurek Dam in Soviet Central Asia, completed in 1978 is tallest in the world being 315 m high. There was an order of increase in number of near earthquakes since the water level first exceeded 60 m in 1971. The strongest sequence with two tremors of magnitude 4.5 occurred in November 1972 just after the first stage of filling to 125 m. As Nurek is in a thrust fault environment, abrupt decrease (eg. in March 1975 when the water level was dropped by more than 3 m/day) in water level has been followed by pronounced increase in seismicity as the stabilizing load is removed and the high pore pressure remains.

When the water level is decreased less rapidly (eg., two downdraws in 1974 when the rate did not exceed 2 m/d), the pore pressure appears to have time to dissipate with the load and no increase in seismicity is observed. Based on these observations. Simpson and Negmatullaev (1978) recommended that the second stage of filling in late 1976 be carried out as smoothly as possible without any rapid fluctuations in either the water level or rate of filling. As the water level smoothly peaked at 215 m at the end of 1976, there were no large earthquakes such as those at the end of the first filling of 1972. This way, a large earthquake has been probably avoided.

Combining the observations of the above three cases we see that at Koyna a weekly rate of filling less than 12 m is safe. Similarly at Nurek a drawdown less than 12 m/week is safe. The hypocentral distances are mostly within about 10 km at Koyna and Nurek. At Idukki a weekly rate of 4 m has been safe. Here, the hypocentral distance could be about 2 km. From these observations the following linear relationship is obtained between the safe rate of filling F (in meters), reservoir depth, h (in meters) and hypocentral distance D (in km)

$$F = \frac{100\,D}{h} + 2$$

For reservoirs of depth about 100 m or more h is taken as 100. For the shallower reservoirs the threshold rates become higher in inverse proportion to depth. For example at Bhatsa the threshold has been 12 m/week for hypocentral distance of about 5 km when the reservoir depth has been about 50 m. Based on these observations it is deduced that the safe rate of loading/unloading would depend, besides hydrogeological factors, on the following :

(i) Distances to fault zone
(ii) Depth of reservoir

CONTROL OF SEISMICITY AT SRISAILAM

The Srisailam Dam, of height 144 m and capacity 8.72 cub.km., started filling in 1975. It was filled to capacity in 1984 (Fig. 2). Seismic monitoring around Srisailam reservoir started in 1981. There is no firm evidence (to date) of RIS near Srisailam reservoir, though shocks have occurred near it. There were 9 shocks of magnitude about 1 to 3.2 at distance of 10 to 40 km from the reservoir boundary during 1981-89. Seven of these occurred in 1986 and one each in 1983 and 1989. Largest shock near Srisailam of magnitude 3.2 on 31.3.1986 was located about 40 km SE of Srisailam Dam (Fig. 3). It was felt in an area of 20 km radius.

Additionally there were a few hundred events of magnitude less than 1 occurring within 5 km from Srisailam during 1981-85. The events are most probably the quarry blasts but in 1984 for some period, the project authorities mentioned that there was no blastings done but the events were recorded and for other period the times of known blasts did not match with the times of the events. Hence, there came a doubt that some of these events could be microtremors. This necessitated safety measures to control the seismicity. One of the safety measures suggested was to keep the rate of filling within 6 m/week for a few years after impounding and to keep loading as smooth as possible. This was observed for 1985 and 1986. Microevents from close distance were not recorded any more. In 1987 again the maximum weekly rate of filling was 19 m or monthly rate of 39 m and in 1988 weekly maximum was 27.6 and monthly 36 m. These high rates in 1987 and 1988 did not trigger any seismicity. There were no close microevents and there was only one shock within 10-40 km from the reservoir boundary during 1987-89. Though it can not be said with certaintly that earthquakes were inhibited due to control of water level of Srisailam Reservoir, it is a fact that RIS has not occurred in this area which is prone for it due to existence of several faults/fractures, weak shale rocks and moderate seismicity in the area.

Epicenters of shocks of magnitude 1.5 to 3.6 occurring within 50 km of Nagarjunasagar and Srisailam reservoirs during 1981 to 1987 are plotted in Fig. 3. Epicenter of the damaging shock of magnitude 3.6 shown 10 km NE of Nagarjunasagar occurred on October 10, 1979. It was felt with a thundering sound and caused cracks to some buildings in the nearby villages. For the first time shocks very close to Nagarjunasagar Dam have occurred in 1989-90. One shock on 11.8.89 was of magnitude 1.9. The shock of magnitude 2.3 on 11.1.90 was felt in an area of about 8 km radius most strongly on the dam and nearby localities. It was followedby two after shocks within half-an-hour. A total of 29 shocks are known to have occurred near Nagarjunasagar during 1968-89 and a total of 9 shocks near Srisailam during 1981-89. Out of these 6 could be located near Naragjunasagar and 5 near Srisailam. These epicenters are shown in Fig. 3. These located as well as non located, events are definitely earthquakes as recognised from signal character. The closeby occurring micro events are different in character than these.

At Nagarjunsagar five shocks had occured during 1968-69 after the reservoir was initially filled to 100 m. The damaging shock of magnitude 3.6 in 1979 occurred five years after full impounding in 1974 (Rastogi, 1989) and shocks during 1989-90 occurred 15 years after impounding.

CONTROL OF SEISMICITY AT BHATSA

Construction of Bhatsa Dam started in 1976 about 200 km north of Koyna near the west coats. In 1983, when the dam was half built to a height of 50 m, the seismicity started (Rastogi, et al., 1986). Impounding was rapid during this year at a rate of 18 m/month. There was a damaging earthquake of magnitude 4.9 and a sequence of more than 13,000 shocks in a period of about two years during 1983-85. Subsequently, the seismicity was at very low level. But in June 1990 there was a burst of 426 shocks largest of which was of magnitude 4 on June 2.

The Koyna dam has been built rapidly. In about 5 years or so a height of about 100 m was reached. Bhatsa dam has been built relatively more slowly. In eight years it was built to a height of 50 m. The filling has been done in stages (Fig. 4). The rate of raising was about 5 m/y. The maximum rate of filling has been less than that at Koyna i.e. less than 12 m/week.

After the earthquakes started in the Bhatsa area, we advised to defer raising of the dam for a few years. If at all the dam is to be raised, the rate of raising should be less than 5 m as in the previous years. During 1983 to 1987, the maximum rate of filling has been about 12 m/week or 26 m/month as in the previous years. It needs to be pointed out that the maximum monthly rate is not four times the maximum weekly rate as the filling is not uniform.

The dam was raised for about 5 m during 1984. The increased level of seismicity continued until 1985 beginning. In 1985 and 1986, construction of the dam was stopped and seismicity has almost ceased since then. No earthquake of magnitude 5 or greater has occurred in the area where a Koyna type earthquake of magnitude 6 or greater was expected. Although we can not conclusively prove, we feel a large earthquake has probably been avoided by controlled filling of Bhatsa reservoir.

Figure5 shows the epicenters of more than 400 shocks located around the Bhatsa reservoir during 1983-85. Faults, fractures and dykes which may be the weak zones for the occurrence of earthquakes are also shown. The earthquakes are confined in an area of 7 km x 5 km extending in NW-SE direction along the faults. Focal depths are less than 6 km. The space-time pattern of these shocks indicated that the seismicity started near the reservoir and has spread outwardly for about a year. The extent of the epicentral area has grown at about 1 km/month.

DISCUSSIONS

As the level of triggered seismicity is found to depend upon the rate of impounding in case of several cases of reservoirs, a natural inference is that the level of seismicity can be controlled by manipulation of water levels. Hence, the same has been recommended for several reservoirs. The recommendations have been to raise the dam in stages during preimpoundment period. The rate of raising per year should be less and if the seismicity is noticed, the raising of the dam should be stopped for a couple of years. During the initial few years of exploitation after impounding, the filling and emptying should be as smooth as possible. The reservoir should not be emptied much which results in high rate of impounding in the succeeding year. The threshold rate of loading/unloading, to avoid occurrence of strong earthquakes, would vary from one site to another.

Even if these measures could be successful, it is difficult to prove their effectiveness. The seismicity depends on geological conditions besides the rate of loading/unloading. Hence, it is difficult to say whether the seismicity has stopped due to water level manipulation or naturally.

Induced seismicity is a transient phenomenon. In several cases, the greatest seismicity has occurred soon after impounding and has then gradually waned out. After few years (may be tens of years) a new equilibrium is reached and the reservoir has no more effect on the seismicity than would a natural lake.

Our results from Bhatsa and Srisailam suggest that by careful control of reservoir filling, it is possible to reach the new equilibrium in a safe manner. This way the rate of stress buildup and the pore pressure can be controlled so that the seismic energy is released as small earthquakes, and the large, destructive ones can be avoided.

CONCLUSIONS

For dams of height 60 m or more, the impounding must be done in a controlled manner to avoid larger triggered earthquakes.

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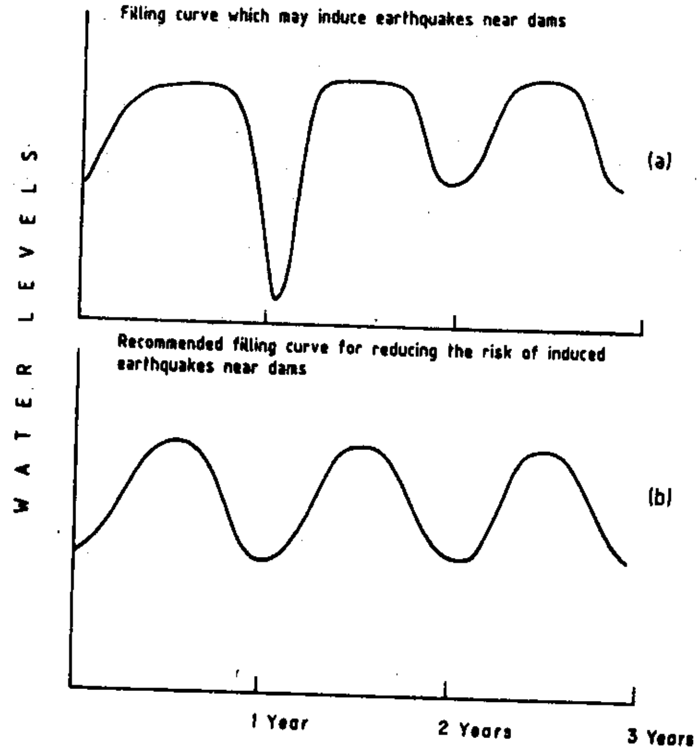

Fig. 1 : Filling curve in the first few years of full impounding of the large dams. The base line represents the river bed level in this as well as other figures.

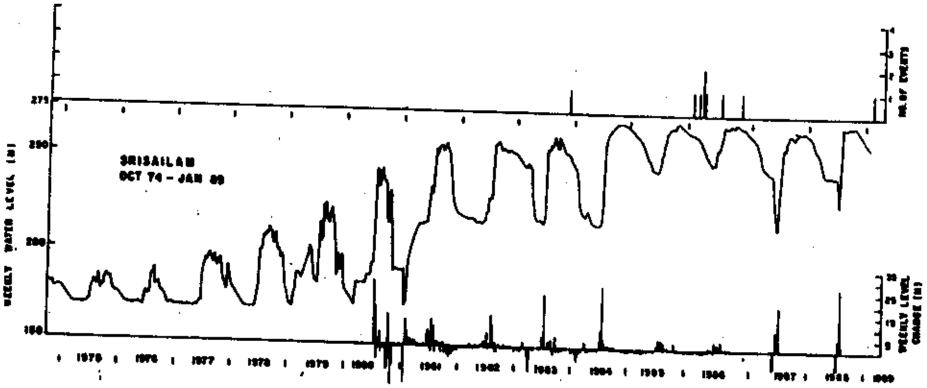

Fig. 2 : Weekly Srisailam reservoir water level, rate of impounding and no. of events occuring within 50 km from the reservoir boundary.

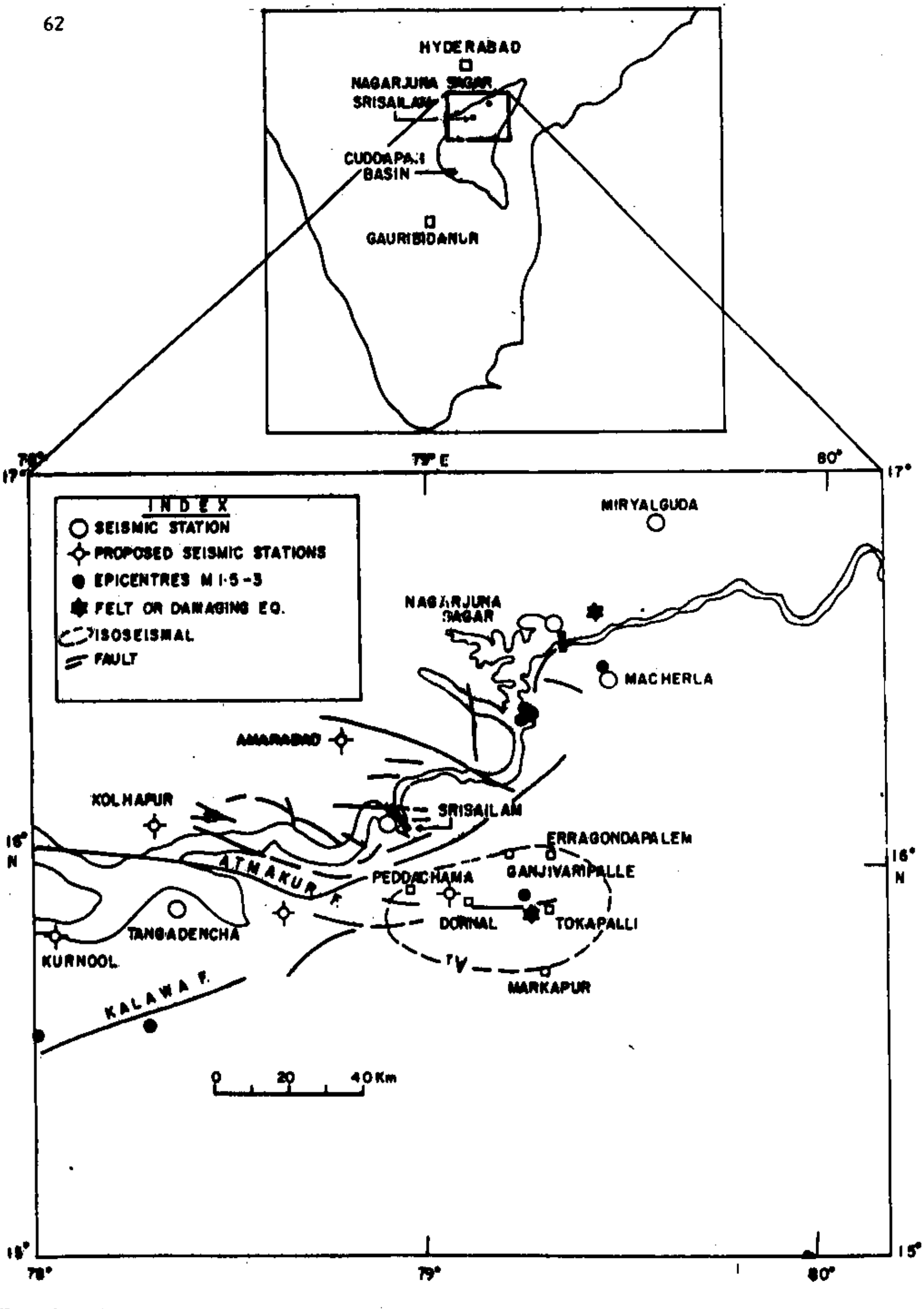

Fig. 3 : Faults around Srisailam and Nagarjunsagar reservoirs taken from the maps prepared by Geological Survey of India. The epicenters of shocks from 1981 to 1987 and seismic stations around the two reseavoirs are also shown. The seismic stations at Macherla and Miryalaguda have been discontinued from April 1987 and the seismic stations at Amarabad, Kollapur, Kurnool and Dornal have been installed subsequently.

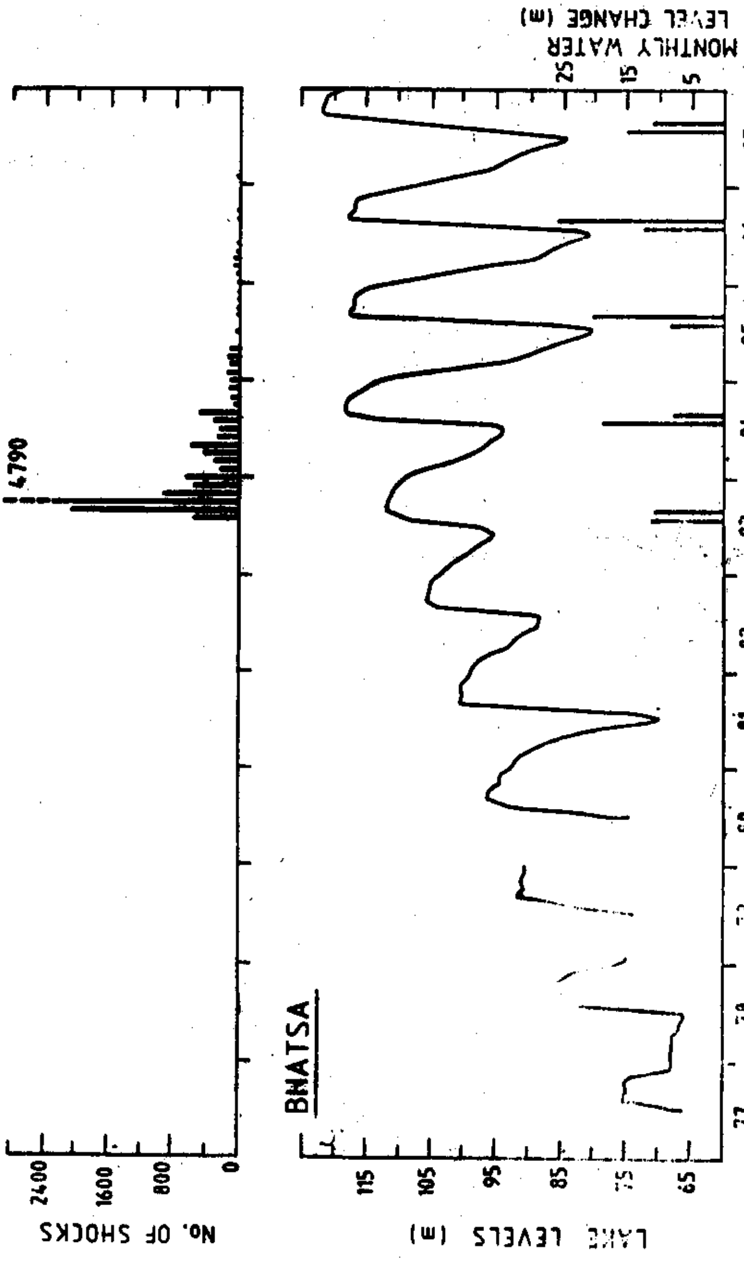

Fig. 4 : Monthly Bhatsa Reservoir levels, rate of impounding and number of shocks (data provided by MERI, Nasik)

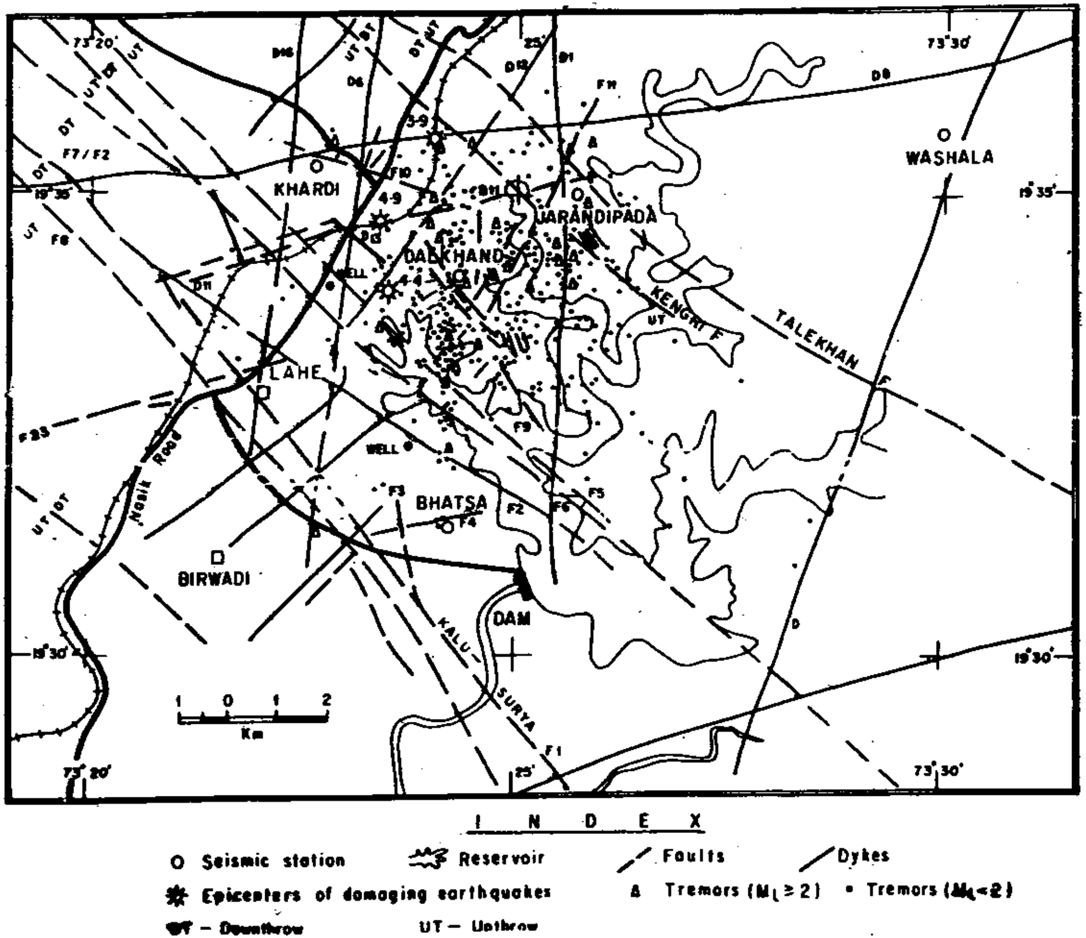

Fig. 5 : Epicenters of shocks around Bhatsa reservoir, Maharashtra from October, 1983 to April, 1985. The faults, fractures and dykes shown in the map are taken from GSI and Poona University reports. The two wells whose positions are marked have been found to yield copious water in the area where wells are usually dry in summer.