Paper No. 208, Bull. ISET, Vol. 17 No. 3, September 1980 pp. 1–16

CASE STUDY OF KOYNA DAM*

J. KRISHNA[1]

Introduction

On the morning of December 11, 1967, an earthquake of magnitude 6.7 struck the western hills of India and damaged a 103 meters tall concrete gravity dam, killed more than 200 people, dislocated electric supply and put out of gear industries of the area resulting in loss of millions of dollars to the economy. The earthquake had several firsts to its credit—(i) it recorded the first accelerogram in a dam with the acceleration of 0.63 g, which was the maximum value recorded upto that time, (ii) it caused serious damage to a well built concrete dam, which necessiated emptying the lake, stitching the dam itself through prestressing and strengthening it with additional concrete on the downstream face, and (iii) it created a serious controversy whether or not such big size earthquakes could be traced for their cause to the filling of a lake. Was it of tectonic origin? If so, where does the active fault lie?

It is proposed to describe various aspects of this problem in the following paragraphs.

Particulars of Earthquake

The earthquake occurred within 3 km to the south of Koyna Dam with its depth of focus about 10-20 km (1). Fig. 1 shows the location of Koyna Dam on the Indian map and the enlargement gives its location alongwith the relevant features such as sites of seismological observatories, hot springs, faults as known and suspected, and epicenters of earthquakes of magnitude greater than 4.

The shock was recorded in various parts of the world and was given a Magnitude varying from 6.25 to 7.50 by different stations and an average value of 6.7 was considered appropriate for describing its size. Intensity allotted to the worst affected area was VIII–IX on the Modified Mercalli scale.

This shock was felt extensively in the Indian peninsula upto Surat, Ujjain, Nagpur, Hyderabad and Bangalore, giving a radius of 600 km of "felt area" (Intensity II and higher) and it caused damage to poorly built mud and brick houses as far away as 200 km.

It was somewhat surprising that the earthquake was felt over such a large area, not warranted by its size. The explanations offered were :

(a) There were perhaps two shocks, one with a deep focus, and the other with a shallower one. The former caused the shock to be felt at long distances and the latter explains the large intensity in the epicentral area. The records at various stations did not support this view.

(b) The source of the earthquake extended from the depth of 10-20 km downward to 25-35 km. Seismic waves from the lower part of the source caused the shock to be felt at long distances, while from the upper part the large intensity in the epicentral

---

*Paper presented at U.S.–Yugoslav, Workshop on Earthquake Engineering Research in July 1980 at Skopje.

[1] Professor Emeritus, Department of Earthquake Engineering, University of Roorkee, Roorkee, India

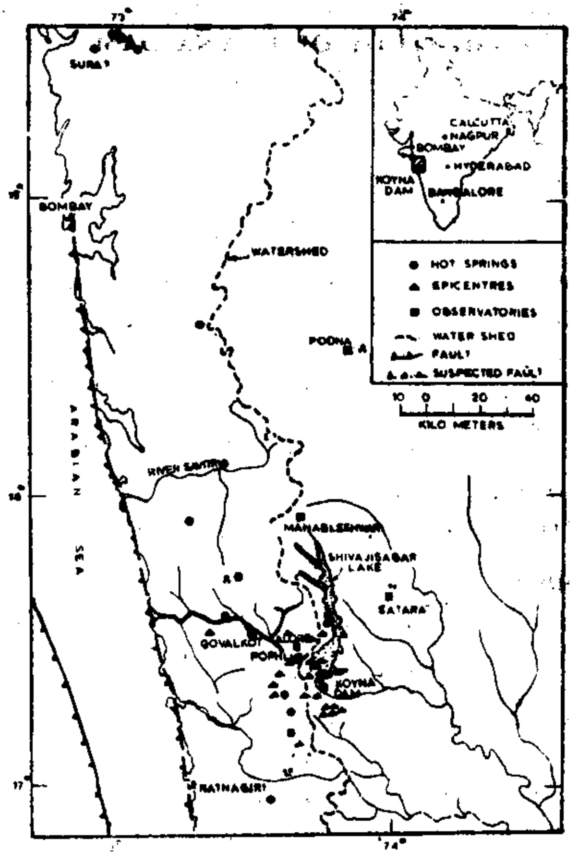

Fig. 1 Koyna dam location and sites of hot springs observatories, epicentres and faults

area. Here also, the depth of 35 km was not large enough for such a large "felt" area.

(c) Most probably, very large area of perceptibility was due to good transmission of energy in the Indian Shield.

The explanation (c) was also illustrated by the extensive study (2) carried out over the area by estimating the forces exerted by the earthquake observed through sliding and overturning of objects. More than 1200 observations yielded isoacceleration curves and its attenuation with distance from epicenter (see Figs. 2 and 3).

The axis of the isoacceleration lines in Fig. 2 follows the same direction as the coastal fault and the line of hot springs. In Fig. 3, a comparison of attenuation of acceleration with distance has been made for the main Koyna shock with that of Parkfield, 1966. It will be seen that energy absorption in Koyna region has been much slower since the energy travelled through very compact and dense basalt trap deposits. Probably this accounted for a very large "felt" area for a comparatively moderate size shock.

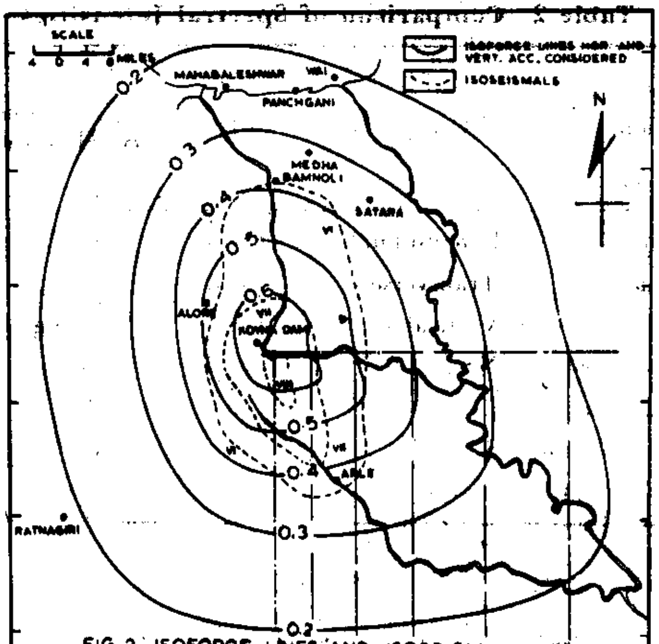

FIG 2. ISOFORCE LINES AND ISOSEISMAL LINES

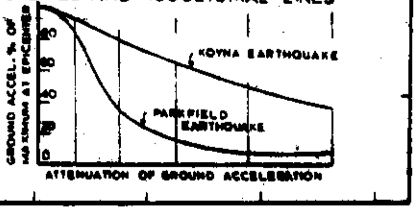

FIG 3. ATTENUATION OF GROUND ACCEL. WITH DISTANCE COMPARED WITH PARKFIELD EARTHQUAKE (1966)

The accelerogram (3) recorded in the dam is shown in Fig. 4, and the response spectra in Figs. 5, 6 and 7 for the three components. For this shock, near its epicentre, spectral intensities indicate that vertical component of ground motion is as intense as the horizontal components. Comparing with other strong motion records, though peak ground acceleration is larger at Koyna, its spectral intensities are smaller. They are shown in Table 1 and a comparison of their values with other shocks in Table 2. It will be seen that inspite of the big peak of acceleration, spectral intensity of Koyna earthquake was much smaller than those of El Centro and Olympia shocks. The accelerogram indicates higher frequency

Table 1 Spectral Intensities for Koyna Earthquake

No.	Location and Component	$SI_{0.00}$	$SI_{0.02}$	$SI_{0.05}$	$SI_{0.10}$	$SI_{0.20}$	Peak Ground Acceleration
1.	Koyna-Longitudinal	134.5	113.3	98.2	83.9	65.6	0.63 g
2.	Koyna-Transverse	91.8	72.1	60.6	51.5	42.6	0.49 g
3.	Koyna-Vertical	111.1	90.1	75.9	64.1	51.6	0.34 g

Table 2 Comparison of Spectral Intensities

No.	Location	Component	$SI_{0.0}$	Peak Ground Acceleration	Approximate Duration of Ground Motion in Second
1.	Koyna, India	Longitudinal	134.5	0.63 g	10.3
2.	Koyna, India	Transverse	91.8	0.49 g	10.3
3.	Koyna, India	Vertical	111.1	0.34 g	10.3
4.	El Centro, California	NS	274.0	0.33 g	30.0
5.	El Centro, California	EW	238.0	0.23 g	30.0
6.	Olympia, Washington	S 80 W	185.0	0.31 g	25.0
7.	Olympia, Washington	S 10 E	171.0	0.18 g	25.0

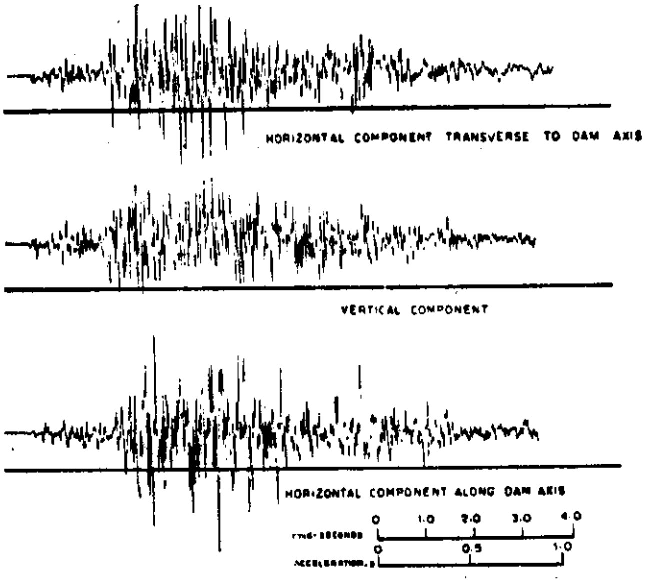

Fig. 4 Accelerogram recorded at block 1-A of Koyna dam on December 11, 1967 at 04-21 I.S.T.

ground motion than has been common for past recorded earthquakes. For example, the peak Koyna acceleration of 0.63 g is associated with an average zero-axis width of 0.05 seconds, to give a pulse area of approximately 15 cm/sec, whereas the El Centro earthquake of May 18, 1940 (N-S) had a peak acceleration of 0.33 g, a zero-axis width of 0.23 seconds, and hence a pulse area of approximately 37 cm/sec. The damage potential of the Koyna shock was, therefore, not great.

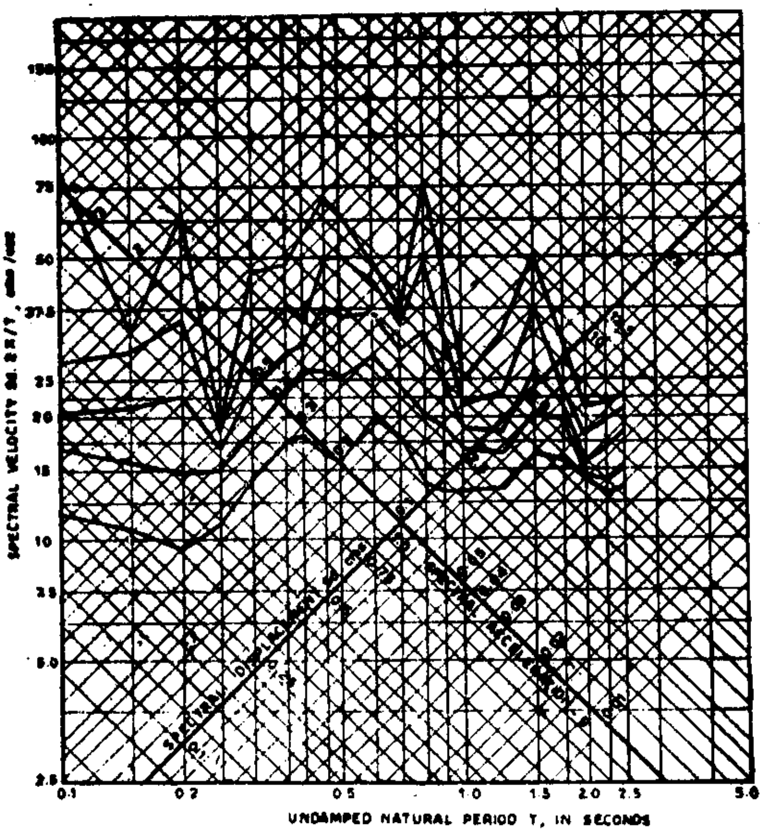

Fig. 5 Response spectra for transverse component, the curves are for 0, 2, 5, 10 and 20 percent damping

The maximum ground velocity of the longitudinal component is 24.19 cm/sec and is nearly equal in value to 25.58 cm/sec of the vertical component. The transverse component has a smaller value of 20.08 cm/sec. The maximum ground displacement is the smallest for the longitudinal component and the maximum for the vertical component. The values of ground displacement are 13.30 cm, 21.64 cm and 28.84 cm corresponding to longitudinal, transverse and vertical components. The peak displacements are obtained in the first waves. That emphasizes the importance of initial peaks of an earthquake wave.

The accelerograph was located in a monolith of the dam, which was very close to the abutment. The gallery housing it was just a little higher than ground motion itself and has not been materially influenced by the characteristics of the dam (4). While analysing the response of the dam, the accelerogram has been taken as the ground motion.

Seismicity of the Region

Since the seismicity in the region has been studied mainly after lake started filling behind the dam, the microtremors occurring between 1963 and 1967 have been attributed to

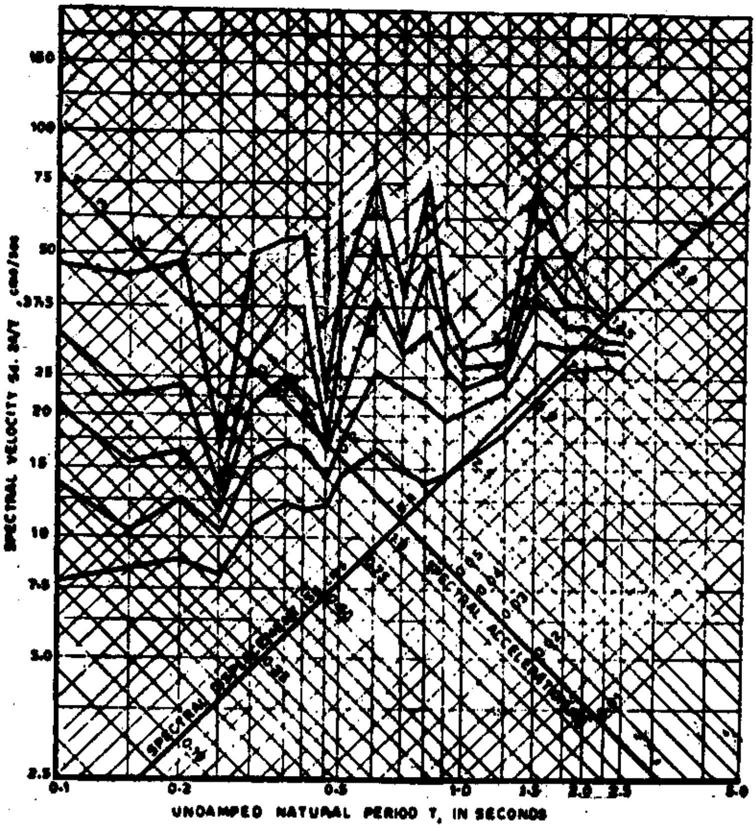

Fig. 6 Response spectra for vertical component, the curves are for 0, 2, 5, 10 and 20 percent damping

the lake filling, but earthquakes of September 13, 1967 (M = 5.5) and December 11, 1967 (M = 6.7) were perhaps too big to be accounted for by "lake load" only. It may, therefore, be appropriate to look into the main Geological features of the region to assess whether these shocks had tectonic features as their cause.

The Koyna Dam lies at an elevation of 580 m above sea level on the Koyna River, just east of the continental divide (see Fig. 1). South of latitude 20°N, the continental divide lies within 100 km of the west coast of India, and the greater part of the peninsula is drained by rivers which flow eastwards. The continental divide forms the top of a great escarpment overlooking the Arabian Sea, with peaks rising as erosional remnants to 1650 m from a general plateau level of 600 m. At the foot of the escarpment on the western side is a narrow zone of ridges and outliers, resting on a step like floor almost at sea level.

Western India is dominated by the Deccan Volcanics. The Volcanic deposits consist mainly of basalts and are spread out over an irregular surface of Archaean, Algonkian and Gondwana Rocks. They are likely to be at least 2000 m thick. Underneath the Deccan Volcanics is the great peninsular shield. The Volcanics rest upon an irregular topography, which was an erosion surface created in late Mesozoic times. It was though possible that the

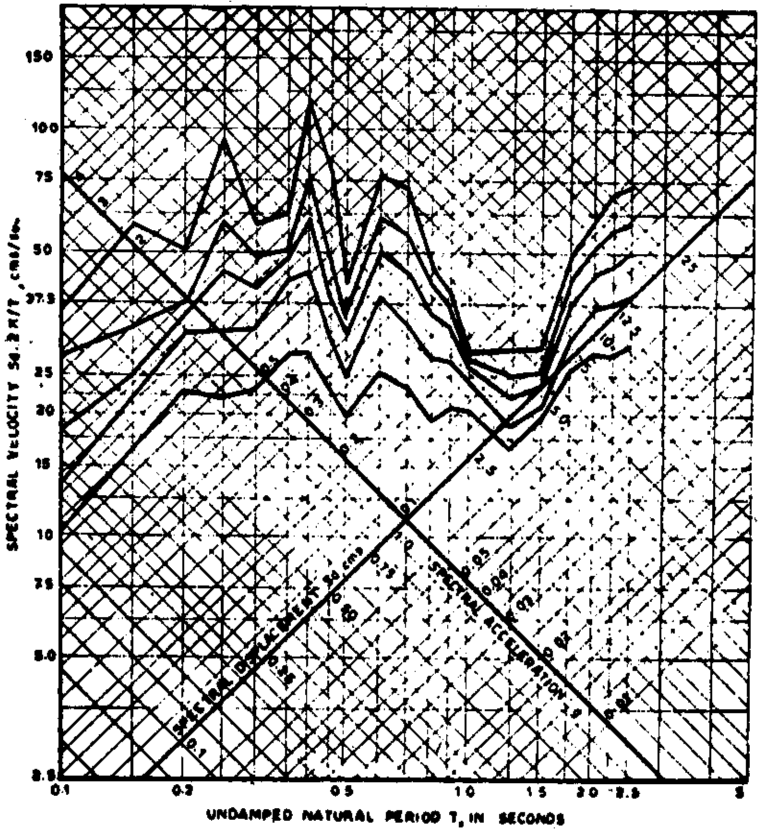

Fig. 7 Response spectra for longitudinal component, the curves are for 0, 2, 5, 10 and 20 percent damping

depression of the contact between volcanics and basement might be due to a fold, but a reconnaissance flight made in January, 1968 showed that the volcanics are horizontal and rest against a sloping and undulating basement surface (1). It is not considered probable that irregularities in the contact between volcanics and basement were responsible for any differential movement between the two formations which might cause seismic tremors.

Cutting the lava-flows are numerous basaltic and doleritic dykes. These are widespread in dispersed form throughout the western plateau and, in the Koyna area, sporadic dykes are found. These dykes indicate a period of tension within the volcanics.

Major faults have only seldom been noticed in the main area of the volcanics. Air survey over the area between Bombay and Ratnagiri did not locate any fault of sufficient importance. It has generally been assumed that a major fault exists off-shore, running approximately parallel to straight edge of the Continental Shelf. There is however, no positive evidence of the fault associated with the west coast of India. On the basis of geomorphological analysis, however, it is very unlikely that such a straight coast, right from Cambay basin to southern tip of India does not have tectonic origin. The general feeling is that the west wast is a faulted coast, though there is no positive evidence either on the land or in the off-shore.

The line of 33 thermal springs is at present the surest indication that a fault may exist concealed below a cover of Deccan volcanics.

Much of the peninsula is affected by a series of fractures along which vertical and lateral displacements are not evident but considerable brecciation and shattering has taken place. These fractures are considered to arise from shearing of the crust.

Fig. 1 shows the epicenters of earthquakes that have occurred in the present century. The records of old earthquakes are very sketchy and are described below (9):

(1) 1594. In the Mahim-Bassien region of North Konkan, earthquakes occurred on the eve of new-moon day at mid-night on Monday and the next day.
(2) 1618, May 26. Earthquakes at Bombay, accompanied by hurricane. 2000 lives and 60 vessels were lost.
(3) 1678. Earthquakes at Bassien and Agashi. The tremors were felt for five days in a row.
(4) 1702. Earthquake in North Konkan area.
(5) 1751, December 9. Earthquake in Bombay, Bassien and Salsette areas.
(6) 1752, February 5. Earthquake in area from Lohagad to Arabian Sea was accompanied by land-slides.
(7) 1757, October 31, Shock was felt.
(8) 1764, August. Earth tremor occurred in a large area.
(9) 1792, May 29. Houses, temples, props were shaken to foundation by earthquake.
(10) 1812, February 23. Shock was felt at Poona.
(11) 1826, March 20. Konkan territory experienced earthquake.
(12) 1828, August 22. Sharp shock was felt all along the Malabar Coast. Tremors lasted quarter of a minute and were accompanied by a loud rumbling noise.
(13) 1832, October 4. The quake occurred, sleeping people were displaced from their cots, rumbling sound was heard from the interior of the earth.
(14) 1951. Two shocks had been felt at Ratnagiri on the western coast of Indian peninsula.
(15) 1962, September. An earthquake of moderate intensity occurred at Ratnagiri.
(16) Five shocks from 1965 upto April 25, 1967 were recorded instrumentally along west coast of India. On June 1965, two tremors were felt at Ratnagiri.
(17) 1967, September 13. Earthquake occurred in the area of lake near the Koyna dam. Intensity 7 in MM scale, magnitude 5-5. 5.

Over a period of about 370 years, upto 1963, when lake started filling, there was some seismic activity and most of the tremors had their epicenters along the coast, which could be attributed to the fault in the Arabian sea or a suspected fault along the coast (see Fig. 1). After 1963, when some tremors were felt around Koyna, some seismological stations were set

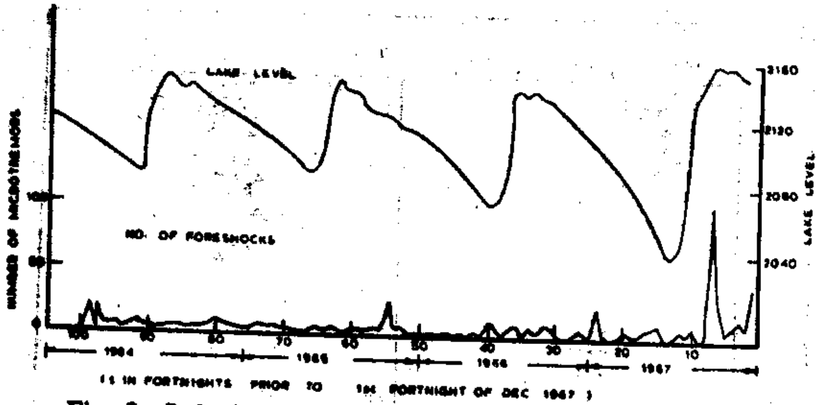

Fig. 8 Lake level and number of foreshocks 1963 - 1967
(After Guha et al.)

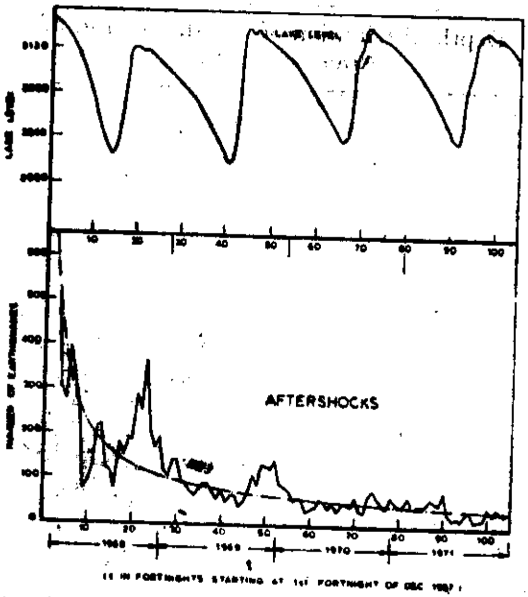

Fig. 9 Lake level and number of aftershocks
(After Guha et al.)

up as shown in Fig. 1, and as the lake filled up, these stations recorded microtremors increasingly (see Fig. 8). Between 1964 and 1966 there was a swarm of microtremors but none exceeded magnitude 3.7 and their focus was estimated at 4 kms. They were probably induced by the lake. The question as to whether the foreshock of September 13, 1967 and the main shock of December 11, 1967 were caused by the same process or they were normal seismic activity of the hidden faults below the trap deposits remains unanswered. Figs. 10 and 11 show the depth distribution and location in plan of microtremors of magnitude greater than 3.

The presence of 33 hot springs (Fig. 1) and the fact that, along the same watershed, earthquakes did occur to the south and north even in the present century, seems to point out that

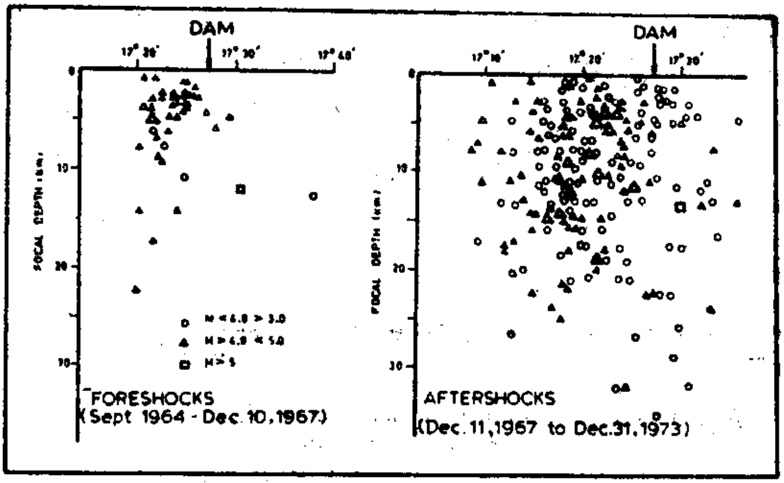

Fig. 10 Depth distribution of foreshocks and aftershocks (After Guha et al.)

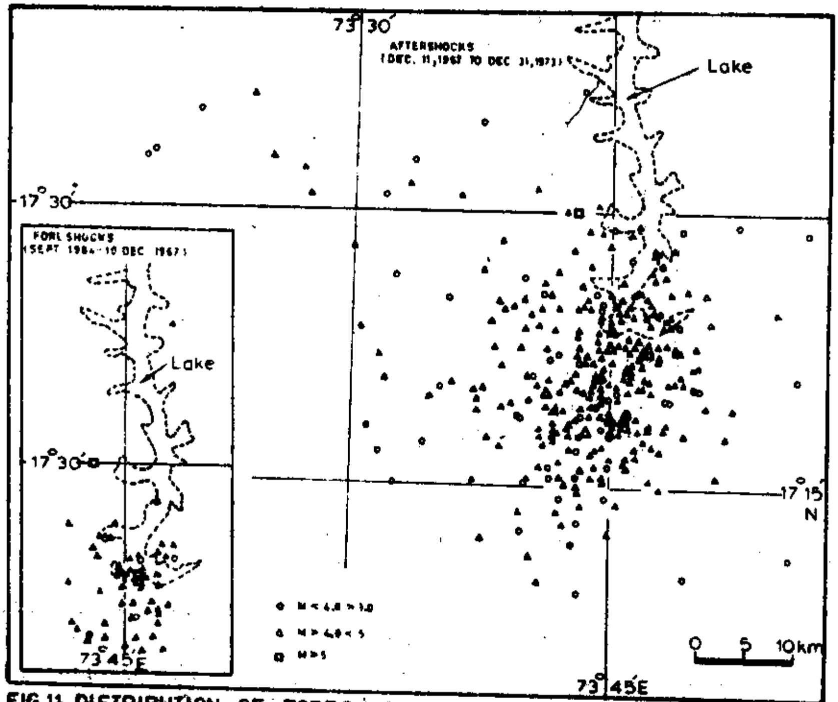

FIG 11. DISTRIBUTION OF FORESHOCKS AND AFTERSHOCKS IN PLAN (After Guha et al.)

it was a coincidence that whenever lake filled to the highest point microtremors occurred at the same time. Perhaps it could be said that the "lake load" may be the last straw on the camel's back or the water percolating down may have lubricated some clayey layers and induced some large scale sliding (as indicated by tests conducted in Denver, Colorado between 1964 & 68 by pushing down waste water). It is quite possible that these shocks were normal seismic activity particularly because lake has filled up again and again afterwards and have not caused any strong tremors although some microtremor activity has been associated with lake filling. Further, there are other lakes in this region, which did not induce any seismicity. Other factors pointing to this conclusion is that the focii of the substantial shocks are located between 10 and 30 kms deep and this finding is confirmed by the large area over which the main shock was felt. The epicenters of the tremors as shown in Fig. 1 indicate that they lie on both sides of the ridge, & a good deal south of the dam. It may thus be appropriate to conclude that the lake filling, was not directly resposible for the main earthquake although minor microtremor activity could be associated with it. The indirect contribution of the lake could be through lubrication of joints and sliding of big masses causing earthquakes. It, however, seems to be quite unlikely.

Damage to Dam

Fig. 12 shows the general elevation of the dam showing its monolith, position of gallery in which the accelerograph was installed. The dam was damaged by the earthquake and developed cracks and consequent leakage of water seen in the gallery and the downstream face. In order to determine the strengthening required, model tests and elastic analysis based on "Beam Method" and "Finite Element Technique" were carried out. The model studies and the analysis forecast the cracking at more or less the same levels as it occurred in practice.

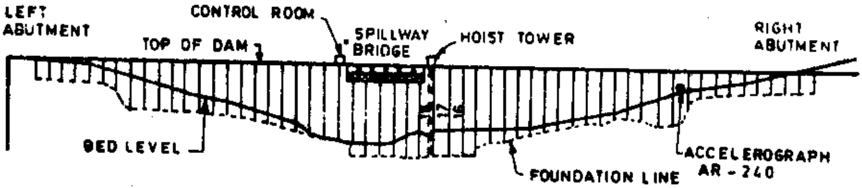

Fig. 12 Valley showing various monoliths of koyna dam

The analysis of the dam was carried out by the beam method and the finite element technique (5). The stresses due to earthquake forces are shown in Figs. 13, 14, 15, 16 and 17. The assumptions made in the analysis were :

Density of concrete	165 lb./cft
Longitudinal Wave Velocity	10000 ft/sec.
Poisson's Ratio	0.2

Water level at 92 meters above base as it was at the time of earthquake

First three modes were considered adequate.

Fundamental period	0.35 sec.

Damping assumed in the analysis was :

Mode	**Percent of the Critical**
I	10
II	15
III	20

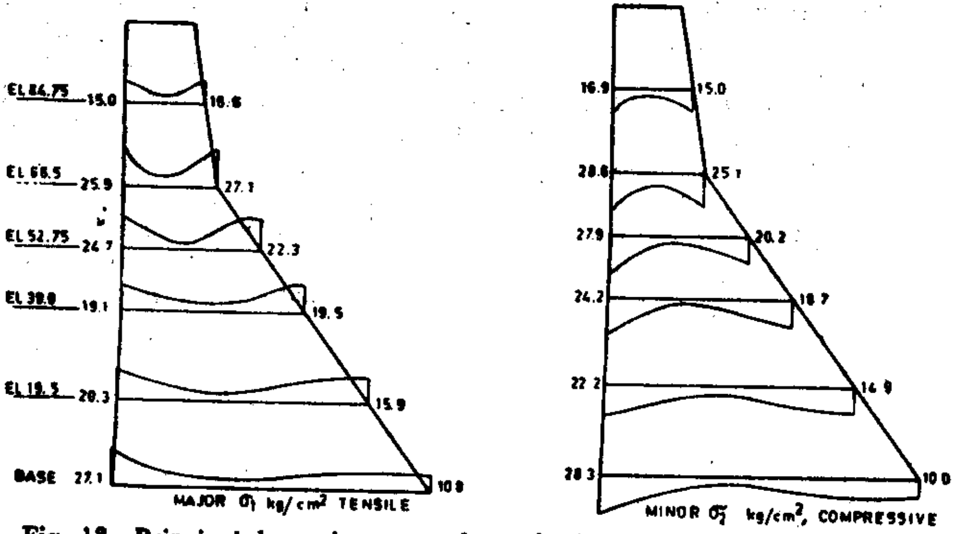

Fig. 13 Principal dynamic stresses due to horizontal ground motion without reservoir water (maximum during earthquake)

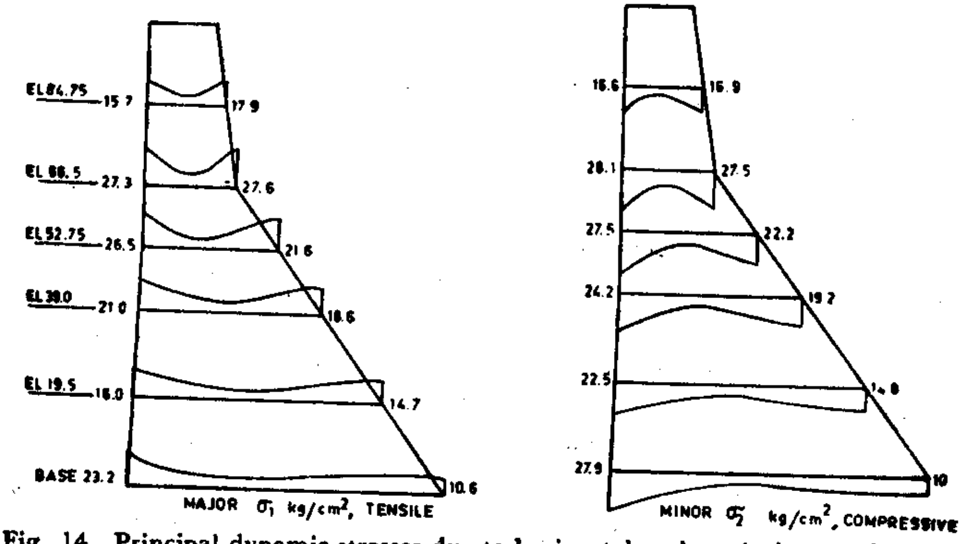

Fig. 14 Principal dynamic stresses due to horizontal and vertical ground motion without reservoir water (maximum during earthquake)

The first mode damping was taken from field tests on the dam (6). Damping in higher modes is higher and was assumed arbitrarily.

Uplift pressure at the U.S. face was taken to be 100% and decreasing linearly to 50% at the gallery and then to zero at the toe.

Figs. 13, 14, 15 and 16 indicate the variation of stresses due to the earthquake. Fig. 17 gives the total stresses static and dynamic due to horizontal ground motion. It will be seen

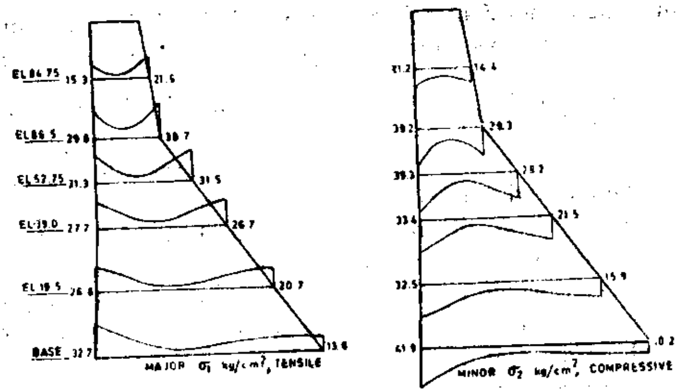

Fig. 15 Principal dynamic stresses due to horizontal ground motion with reservoir water as virtual mass (maximum during earthquake)

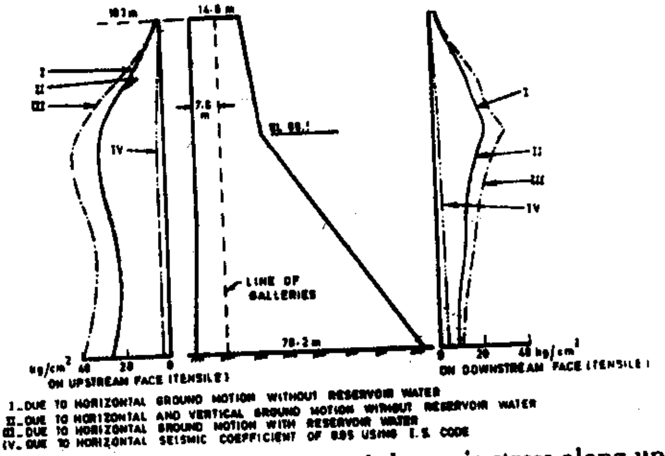

Fig. 16 Variation of vertical normal dynamic stress along upstream and downstream face of dam

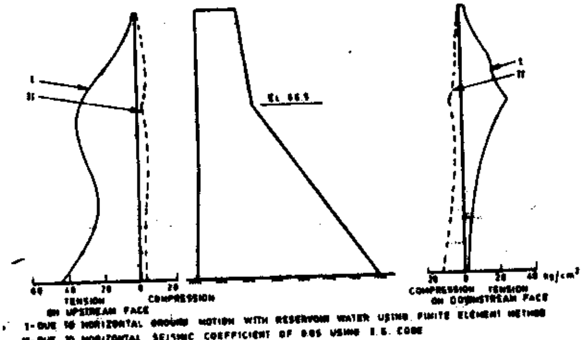

Fig. 17 Variation of vertical normal total stress along upstream and downstream face of dam

that a provision of 5%g as horizontal force as per code is wholly inadequate compared with the type of forces that actually develop in a dam during a strong earthquake.

It would, be interesting to note that a study (7) (described in more detail later) showed that a highly oscillatory motion like that of an earthquake with varying acceleration could not overturn the top profile, which cracked in the total width of the dam, inspite of full upthrust of water on the cracked part even if this motion was repeated again and again. This result in no case obviates the necessity of strengthening the dam. Fig. 18 shows the position of cracks on the upstream and downstream faces of monoliths 16, 17 and 18 of the dam. These are the cracks which were clearly visible but as will be seen from Fig. 17, there was considerable height between the cracks and near the base (embedded in river debris) which had quite high stress and there might be fine cracks elsewhere also. The dam was, therefore, strengthened at the downstream side as shown in Fig. 9.

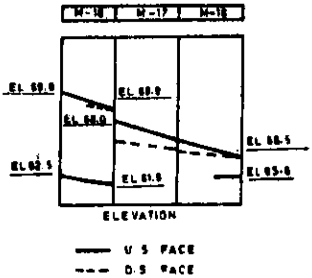

Fig. 18 Cracks on upstream and downstream faces of monolith Nos. 16, 17 and 18

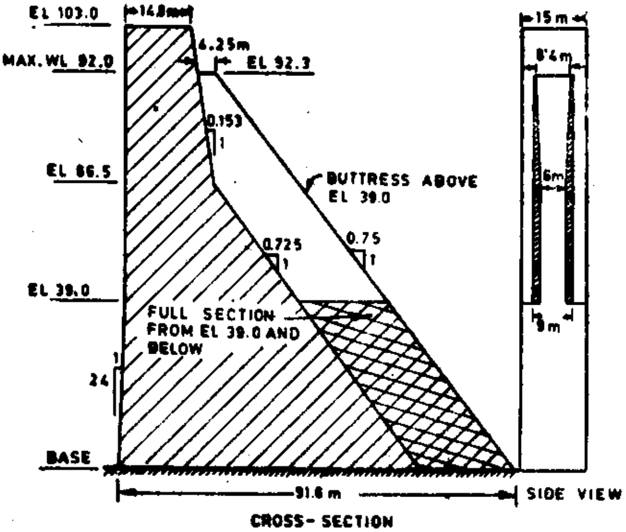

Fig. 19 Section of Koyna dam after strengthening

Repair work consisted of filling epoxy resin in the cracks under pressure till refusal. Tests were carried out on samples cored from the uncracked concrete and from a crack filled by epoxy under tension and the strengths were found to be similar. Certain length of the dam was also stitched through prestressing by making holes in concrete and embedding high tension cables and stretching them at the top. This step was taken to close any cracks that may have developed and may not have been seen on surface. The cables were anchored below the weakest section. This was a sort of temporary safeguard since ensuring adequate anchorage in holes about 130 ft. deep was rather difficult. For permanent strengthening, buttresses were added on the downstream side above elevation 39.0. Below this level upto the base rock, concrete was added throughout the length of the dam. The overflow section was undamaged and the analysis also showed that it should not crack.

The cost of repairs was several times the additional cost in making a stronger dam, which could not be damaged by the earthquake of the same size.

Dynamic Behaviour of Top Profile

With the recording (7) of a peak ground acceleration of 0.63g (largest upto that time) and the cracking of the dam, it was necessary to review the seismic design of the dam. The stability of the cracked portion was considered doubtful during aftershocks and hence emergency as well as permanent strengthening of the dam was considered necessary. Among the emergency measures were :

(a) Depleting the reservoir to a low water level

(b) grouting the cracks with a suitable epoxy mixture

(c) prestressing of the section.

For permanent strengthening of the dam, buttresses have been added on its downstream face as shown in Fig. 17.

The behaviour of the top profile of the dam above the crack has been investigated when subjected to a pseudostatic horizontal force equivalent to 50 percent of its weight, applied at its centre of gravity. The actual dynamic force to which the top profile of the dam would be subjected during the severe ground motion that occurred at the site is much larger. Therefore, one would be led to conclude that overturning of the cracked portion would occur if the site is visited by another severe shock of the intensity that occurred earlier. However, it should be realised that the motion during an earthquake is oscillatory and the duration of peak ground motion was of the order of 0.05 sec. Therefore, though the magnitude of force, to which the top profile of the dam will be subjected to, is higher than the equivalent static force required to cause overturning, the oscillatory nature of the force and the small duration of its application will not cause actual overturning.

Treating the top profile of the dam as a rigid body, its dynamic behaviour has been studied by working out the response of this body, when subjected to the recorded ground motion at the base of the dam. Reservoir water was represented by its equivalent mass for working out its effect on the profile.

The lower part of the monolith below the crack has been analysed considering transverse vibrations assuming the dam material to behave elastically. Since the width of the monlith is also significant in comparison to its height, shear and rotary inertia deformations have been considered in addition to bending deformations.

It is seen that due to the oscillatory nature of the dynamic force, the rotation of the cracked portion of the monolith is quite small and its actual overturning will not occur for any severe earthquake that may occur in future. Thus emergency measures adopted such as depletion of the reservoir and prestressing of the monoliths were not necessary. However, as permanent measures, grouting of cracks to prevent leakage of water and strengthening of the dam by increasing the section are necessary in order to avoid its instability due to crushing of concrete on deterioration and to avoid a repetition of what happened in 1967.

Damage to Power House

The power house did not suffer extensive damage but even the minor one led to stoppage for about two weeks. There was a slight damage to the brushes of the geneator commutator. The deflection of the shaft increased resulting in wobbling. The guide bearings were also damaged and had to be replaced. Bolts fixing the bearings were deformed. In the outdoor switchgear clamps got loosened.

References

1. Report of the committee of Experts-Vol. I-Koyna Earthquake. December 11, 1967 - Published by Goverment of India Press, New Delhi, 1968.
2. Distribution of the maximum intensity of force in the Koyna Earthquake of December 11, 1967 Report of the School of Research and Training in Earthquake Engineering, University of Roorkee, 1969.
3. Krishna. J., Chandrasekaran, A.R., Saini, S.S. - Analysis of Koyna Accelerogram of December 11, 1967, BSSA Vol. 59, No. 4, pp1719-31, Aug, 1969
4. Spectral Analysis of Koyna Earthquake - Report of the School of Research and Training in Earthquake Engineering, University of Roorkee - February, 1968
5. Saini, S.S., Krishna, J., Chandrasekaran, A.R. - Behaviour of Koyna Dam-Decmber 11, 1967 Earthquake - Proceedings of the ASCE - July, 1972
6. Krishna, Nand, et. al - Vibration Studies of Large Hydraulic Structures - Proc. of IV Symposium of Earthquake Engineering, Roorkee, November, 1970
7. Saini, S.S., Krishna, J.-Overturning of Top Profile of Koyna Dam During Severe Ground Motion - International Journal of Earthquake Engineering & Structural Dynamics Vol. 2, No. 3, January-March, 1974
8. Saini, S.S. - Dynamic Behaviour of Gravity Dams - Jai Krishna Volume - Published by Sarita Prakashan, Meerut, India, November 1974
9. Guha, S.K., et. al - Koyna Earthquakes - Published by CWPRS, Poona, India