THE KOYNA, INDIA, EARTHQUAKES

by

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Synopsis

On December 11, 1967, a destructive earthquake occurred near the Koyna hydroelectric project in peninsular India. It was preceded by a smaller earthquake three months earlier.

The Indian peninsula is generally considered to be nearly non-seismic. Tremor occurrences after the reservoir at Koyna was impounded led to the installation of seismographs near the project. The 1967 earthquakes were recorded by strong-motion accelerographs in Koyna Dam.

This paper discusses the geology and seismicity of the Koyna region, the characteristics of the 1967 earthquakes, and the effects of the earthquakes on Koyna Dam and other structures in the epicentral region.

Topography, Geology, and the Koyna Project

Koyna is located at $17^{o}23'N$; $73^{o}45'E$, about forty miles inland from the Arabian Sea in the peninsula of India. Figure 1 shows its location. The Koyna River flows southward from its source 35 miles above Koyna through a canyon roughly parallel to the continental divide. Three miles below Koyna it turns abruptly eastward, ultimately draining into the Bay of Bengal 480 miles to the east.

About 200 inches of rain falls in the 345 square mile watershed above Koyna during the four months of the monsoon, from mid-June to mid-October, and almost no rain falls during the rest of the year. From the continental divide just a few miles west of Koyna the western ghats drop steeply some 2,000 feet, providing a natural fall for power generation. Koyna Dam impounds a peak storage of 99×10^9 cubic feet of water in a long narrow lake with a surface elevation of 2,158.5 feet. Part of the inflow is diverted westward through a tunnel under the continental divide, and then is dropped through pressure shafts to hydraulic turbines nearly 1,700 feet below lake level. The rest of the inflow is released in controlled discharge to the Koyna River below the dam (1,2,3,4).

Koyna Dam and its reservoir, Shivajisagar Lake, are situated in Deccan Trap terrain. The Deccan Traps are the result of extensive lava flows in the Cretaceous-Eocene period and occupy an area of about 200,000 square miles in the western and central parts of peninsular India. The traps are

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mainly basaltic in composition, and the terrain is characterized by flat-topped hills with step-like terraces. The individual flows vary from a few feet to 120 feet in thickness and are separated by thin intertrappean sedimentary formations. The vesicles in the top layers of the basalt are filled with secondary minerals. The total thickness of the flows is a maximum of about 7,000 feet near Bombay, diminishing to the east. At Koyna the traps have a total thickness well over 3,000 feet (5) and the thickness of the individual flows ranges from 40 to 120 feet. A shear zone 6 to 15 feet wide with disturbed rock extending down to elevation 1,870 feet was found crossing the axis of Koyna Dam on the right bank (4).

The Deccan Traps lie on an uneven basement topography (6). The basement rocks are mostly Dharwarian metamorphites (preCambrian) with granites and gneisses, and a few patches of preCambrian and Gondwana sedimentary formations. The Dharwars are intensely folded with a general NW-SE trend of fold axes.

There is evidence of tectonic movements and crustal adjustments in the Deccan Traps. Although the general dip of the traps is toward the east at very slight angles, the dip near Bombay is 10° toward the west. This is due to a long monoclinal N-S flexure, the Panvel flexure, passing through Panvel and believed to extend down to Mahabaleswar with its trend parallel to the west coast, as shown in Figure 2. The west coast of India is of tectonic origin. The land mass formerly to the west of the present coast line has been faulted down and covered by the Arabian Sea. This Miocene fault, the Malabar fault, trends almost N-S and is a part of a major structural feature (7). Faults parallel to the coast are indicated by several warm springs ranging in temperature from 40°C to 69°C which lie on a line near and parallel to the west coast extending from Ratnagiri 350 miles northward to Cambay (2). This system of N-S faults in the Deccan Trap region resulted from tectonic activity that occurred during the formation of the west coast. In fact, the N-S trend of the Koyna River above Koyna is believed by many geologists to be the consequence of a fault.

Gravity anomalies reflect a general gravity low in the Deccan Trap area, with a gravity high on the western part in the immediate vicinity of the coast (9). In the eastern part the gravity anomaly, wholly negative, diminishes away from the west coast. The northern part of the region, with its gradually decreasing negative anomaly, has been delineated as a regional downwarp in a recent tectonic map published by the Geological Survey of India in 1963. Also, there is a marginal deep along the west coast with an upwarp to its immediate west. The marginal depression in the western part of peninsular India is correlated tectonically with the Himalayan foredeep. Thus it is evident that the western part of the Deccan Trap region has suffered tectonic movements and crustal disturbances in the geological past.

Seismic History

Peninsular India has long been considered nearly non-seismic (10), and this is reflected in the seismic zone map of India shown in Figure 1. Historically the only earth tremors in the Koyna region prior to the construction of Koyna Dam occurred rarely and were of low magnitude (11). After the reservoir was impounded in 1962 there were frequent reports of earth tremors, especially near the dam site. This led to the installation of seismographs in the area, including two strong-motion accelerographs in the galleries of the dam. Tremors occurred more frequently after mid-1963, and an attempt was made to relate their occurrence to the inflow or to the lake level, but no significant correlation was found except a weak indication of an increase in the rate of energy release following the monsoon with a time lag. None of the tremors in the Koyna region prior to September 1967 exceeded Magnitude 3.5 (11,12).

On September 13, 1967, a shock occurred at Koyna that was felt for a radius of 120 kilometers. Plaster was cracked in a few buildings in Koynanagar, the project town just downstream from the dam, and a few poorly constructed houses of rubble masonry were damaged to the extent of partial wall failure. The maximum intensity was VII (MM). On the basis of macroseismic data, seismologists of the Central Water and Power Research Station at Poona (CWPRS) estimated that the shock had Magnitude 5.7 and a depth of focus of 6 to 10 kilometers (12). The event does not appear in the Seismological Notes of the Bulletin of the Seismological Society of America, and an inquiry to the U. S. Coast and Geodetic Survey revealed no information. Within two or three weeks after the September 13 event, tremor occurrences dropped to the normal level of activity of the past few years and remained there until early December (12).

On December 11, 1967, an earthquake occurred at Koyna that was among the greatest earthquakes of historical time in the Indian peninsula. It was felt for a radius of 700 kilometers and had an intensity of VIII (MM) at Koynanagar. CWPRS reported its Magnitude as 7.0, whereas other reports vary from 5.9 (Athens) to 6.5 (Pasadena) with an average of 6.2 (13). CWPRS computed the epicenter to be two kilometers west and 13 kilometers north of Koyna Dam, and the depth of focus to be 12 kilometers (12). After the December event seismic disturbances tapered off, and by February, 1968, tremor occurrences had again dropped to the normal level of activity of recent years.

Possible Causes of the Earthquakes

There has been speculation that the earthquakes at Koyna may have been caused by or triggered by the water load in the reservoir, and the increase in seismic activity after the reservoir was impounded has been cited as evidence to support this hypothesis. While there can be little doubt that the reservoir load is related to the increase in tremor activity, the relation between the water load and the September and December earthquakes is not clear. The potential energy of the impounded water, using stream bed at the dam as a datum, is about 10^{15} foot pounds, which is about 30 times the amount of energy released in a Magnitude 6.2 earthquake. But while the energy of the impounded water seems adequate to have caused the events, no plausible mechanism is apparent for converting it to earthquake motion. The proximate cause of the earthquakes must have been fault breakage or fault slippage, which must have been associated with strains in the rock formations. The maximum water pressure at the bottom of the reservoir is about 100 p.s.i., so the increased stress in the rock would be a maximum of 100 p.s.i. and would decrease rapidly with depth as the water load distributed itself over a greater effective area. The hypothesis that the added stresses in deep rock formations might be those corresponding to a head of water extending from the deep formations to the lake surface must be rejected because the ground water level is never very deep--indeed, during the monsoon it is almost at the surface (14). Hence the greatest added stress in the rock would be that due to the additional head of stored water, or about 100 p.s.i. While such a stress difference seems too small to be the cause of an earthquake, it could conceivably trigger an earthquake or alter the time of its occurrence if the internal stresses in the rock formations had already built up due to tectonic movements.

Spectral Analyses

Both the September 13 and December 11 earthquakes were recorded by instruments located in Koyna Dam. There were two United Electrodynamics AR-240 strong-motion accelerographs in the dam, located as shown in Figure 3. The instrument in monolith 13 functioned at the time of the September earthquake, and the one in monolith 1A recorded the December event. Three components of accereration were recorded for each of the earthquakes, but only the analyses of the horizontal components transverse to the axis of the dam are considered here. Re-tracings of the accelerograms for these components are shown in Figure 4.

Because of the greatly different dimensions of the monoliths in which the two instruments were housed, the two records are not strictly comparable. Moreover, the instrument in monolith 1A was located in a gallery at about mid-height of the monolith, and therefore it must have been influenced by the dynamic characteristics of the monolith. It is not feasible to adjust the record to correct for this. For the analyses reported here, both records were treated as records of true ground accelerations.

The December accelerogram was faint, and it was not possible to reproduce the original record photographically. A tracing was made by CWPRS seismologists, and the present analyses were made from a print of that tracing. Because additional inaccuracies may have crept into the record in the tracing process, these analyses are subject to a greater than normal degree of uncertainty.

The two transverse components were digitized and their base lines were adjusted parabolically to minimize the mean square ground velocity (15). The first four seconds of the September record was used, and the first 20 seconds of the December record. Spectral analyses were made by digital computer. Velocity spectra for the two records are shown in Figures 5 and 6.

The undamped spectrum for the September record shows a sharp peak at 0.1 second period, and the spectral values for periods shorter than 0.6 seconds are substantially greater than those for longer periods. The December spectrum, on the other hand, does not favor short periods. Its peak is at 0.6 seconds, but this is nearly equalled at periods substantially shorter and substantially longer. This is evidently not a result of the properties of the monolith, for the block in which the December record was written has a fundamental period shorter than 0.1 second.

Some of the significant properties of the two earthquakes are tabulated below:

		September 13	December 11
	Vertical	.08 g	.36 g
Peak acceleration	Longitudinal	.11 g	.45 g
	Transverse	.11 g	.39 g
Undamped response	Peak velocity	.26 ft/sec	2.5 ft/sec
(transverse)	at period	.1 sec	.6 sec
Undamped spectral intensity		.23 ft	4.0 ft

Spectral intensity is defined as the area under the undamped velocity spectrum curve between 0.1 and 2.5 seconds period (16). It provides an objective measure of the destructiveness of the earthquake at the recording station. For comparison, the spectral intensity of the S69E component of the Taft, California, earthquake of July 21, 1952, was 4.8 feet, and the N-S component of the El Centro, California, earthquake of May 18, 1940, had a spectral intensity of 8.9 feet (16).

The peak accelerations of all components of the December event were greater than the .33g peak acceleration of the notorious El Centro 1940 earthquake, but they are somewhat smaller than the .50g acceleration recorded in the Magnitude 5.5 earthquake at Parkfield, California, in 1966.

Earthquake Effects in Koynanagar

Koynanagar, located on the right bank of the river a mile or so below the dam, was the town built to house the personnel of the Koyna project. Most of the project-owned buildings had cement-asbestos roofs with interior walls and partitions of brick and exterior walls of random rubble masonry.

The September earthquake caused plaster cracking in a few of the buildings in Koynanagar and caused partial failure of a few rubble masonry walls

The December earthquake demolished much of Koynanagar. Many houses collapsed, and most of the buildings with masonry walls suffered at least partial collapse of some of the walls. Only the corrugated metal shops and warehouses were spared. Figure 7 shows the damage to a school building. The roof was supported by wood purlins on wood trusses which bore on the side walls. Bond beams were not used. In this building, as in most of the buildings of Koynanagar, the extent of the destruction appears to have been largely due to the type of construction. Random rubble masonry is perhaps as susceptible to earthquake damage as any type of construction that can be imagined, and the lack of bond beams increases its vulnerability. There were several buildings in which brick walls remained standing while the rubble walls collapsed.

The pattern of damage in the surrounding area suggests that the worst shaking occurred a few miles southeast of Koynanagar. This does not coincide with the computed location of the epicenter.

Earthquake Effects on the Koyna Project

The structures of the Koyna project were not damaged by the September earthquake.

The effects of the December earthquake on the intake structure and the power plant were of no consequence. These works are located about 3 miles NW and 5 miles WNW of the dam. The intake tower is a reinforced concrete framed structure rising 214 feet from headrace tunnel invert to approach bridge level. It was designed for dead, wind, and live loads and temperature effects, but apparently not for seismic forces (17). An 11-span approach bridge connects the intake tower to the shore. There were a few cracks at the juncture of the tower and the approach bridge, but no damage of any significance to either. The power plant is underground, with several hundred feet of Deccan Trap rock above it. A few fine cracks were found in the walls of the generator room, and the turbines and generators were shaken badly enough to require adjustment of their alignment, but there was no damage.

Koyna Dam is a straight gravity dam 2,600 feet long and 340 feet high above its deepest foundations. It is built of rubble concrete with a 6-foot thickness of conventional concrete on the upstream face. Figure 3 shows the upstream elevation and the overflow and tallest non-overflow sections (4). The unusual choice of cross-section came about because design changes were made while construction was in progress. Originally the intent was to build the dam in two stages, first to impound water to a level lower than final design level, and later to thicken the dam to permit raising the lake level. However, after construction was started there were indications that the additional storage would be needed earlier than had been originally anticipated. It was found that by increasing the height of the dam about 10 feet above the height originally planned for maximum storage and making the top portion thicker, a modified section could be achieved that would incorporate without alteration the base section then already built, enable construction to be completed in a single stage to accommodate planned maximum water storage, and still be as safe as the standard section (4).

Mane and Gupte (4) report the earthquake design provisions thus: "Though the area is not specially subject to any earthquake disturbance, some provision has been made for earthquake, viz. 0.05 g. and this coincides with the maximum water level in the lake. In such a situation, a small tension of about 5 p.s.i. is permitted in some of the non-overflow deepest sections of the dam."

The dam suffered structural damage in the December earthquake, both in the body of the dam and in the auxiliary structures at roadway level. The most spectacular damage was found in the tower over the elevator shaft in block 18, just west of the overflow portion. Block 18 is the tallest monolith in the dam. The tower, extending 50 feet above roadway level, was a concrete framed structure with solid concrete block exterior walls. Some of the block walls were dislodged, as seen in Figure 8, the reinforced concrete stairs were cracked and spalled at the landings, and cracks were found in a reinforced concrete shearwall running transverse to the axis of the dam. The gate control house at the other end of the overflow section, seen at the left of Figure 8, was also severely damaged. Its concrete walls were cracked at a horizontal construction joint at mid-height, short reinforced concrete columns between the observation windows on the downstream side were fractured, and diagonal cracks formed in the interior reinforced concrete shearwall parallel to the axis of the dam.

The roadway bridge over the overflow section is supported on two lines of reinforced concrete girders spanning between piers located centrally on each monolith. The girders are seated on fixed bearings at the end piers and at alternate interior piers, i.e., on the even-numbered monoliths, and on sliding bearings at the piers on the odd-numbered monoliths. Evidently there was considerable relative movement between adjacent monoliths, which showed up as displacement or damage at the girder seats. The fixed bearing consists of a steel plate anchored to the top of the pier, a matching plate anchored to the bottom of the girder, and a bearing pad between, all connected so as to prevent relative displacement. Movement of the girder relative to the pier caused spalling of the concrete in both the pier and the girder at these bearings, as shown in Figure 9. At a sliding bearing the girder has a plate anchored to it similar to that for a fixed bearing. The plate on top of the pier was evidently not anchored to the pier. Two bearing pads were used, with two thin slip sheets between them to permit the girder to slide relative to the pier. During the earthquake such movement evidently occurred, but without significant damage. At some piers there was the curious result that although there was no residual longitudinal displacement of the girders relative to the pier, the bottom bearing plates slid longitudinally away from the center of the pier. This can be seen in Figure 10. The top bearing plate, i.e., the plate anchored to the girder, is still aligned with the edge of the pier, but the bottom plate has been dislodged and overhangs the edge of the pier by about an inch and a half, and there is a void at the inner edge of the plate.

The dam showed evidence of relative movement of the adjacent monoliths. This should be expected, for the monoliths are of different heights and thus would tend to oscillate at different periods. The dam was built to tolerate the relative movements that would occur due to water pressure and temperature changes. The maximum residual displacement between blocks was of the order of half an inch.

The most important structural damage to the dam was a horizontal crack that appeared in the upstream face of some of the taller monoliths near elevation 2060 feet, at which elevation a break in slope of the downstream face occurs, as shown in Figure 3. Block 18 was the worst affected. Several factors may have contributed to the vulnerability of this particular block. It is the tallest monolith and it is unsymmetrical, the east half of it being overflow section and the west half non-overflow. The west half contains the elevator and stair shaft to the operating galleries, a vertical shaft 14'-6" x 16'-8", which reduced the cross-sectional area at elevation 2060 about 7%. Also, the elevator tower extends 50 feet above the roadway, giving rise to additional bending moment due to the inertia forces in the tower.

The crack was first noticed inside the shaft, where water seeped in around all four sides near elevation 2060, 83 feet below the surface of the lake. Dye released at the upstream face at that elevation took from five to 45 minutes to reach the shaft, depending on where it was released. Faint traces of seepage could also be observed on the downstream face just before sunrise, when the rate of evaporation from the face was slowest. Inspection of the upstream face by means of an underwater television camera revealed that cracks had occurred in other monoliths as well, and it was decided that the lake should be lowered to permit repairs to be made.

Repairs to the Dam

The major cracks were repaired by injecting epoxy resin. Holes were drilled into the upstream face at 45° from the vertical to intersect the horizontal crack at distances of two to five feet back from the face. To verify that the drill holes had intersected the crack, compressed air was blown into the holes and its escape was traced at the face of the dam. Epoxy grout was then injected into the drill holes at high pressure, starting with the holes that intersected the crack farthest from the face, and working toward the face. Finally, the surface concrete was loosened in the vicinity of the crack, wire mesh was placed over the face, and the area was patched with gunite. Fine tension cracks also appeared at the upstream face of the taller monoliths above elevation 2060. Polyester repairs are to be made but have not yet been accomplished (June, 1968).

Some of the monoliths are being prestressed. Holes 150 mm. in diameter are drilled from the roadway down through the blocks a distance of 160 feet, i.e., down to elevation 2020, which is 40 feet below the principal cracks. In each 50-foot monolith five holes are drilled near the upstream face and five near the downstream face, all drilled parallel to the face. Cables of 64 parallel wires 8 mm. in diameter are fabricated, bulbs are formed at 3-foot intervals over the bottom 30 feet by inserting spacers between the wires, the cables are placed in the holes, anchored by grouting the bottom 30 feet, and then tensioned to 270 tons, anchored at the top, and grouted for the full length. The blocks being prestressed are the tallest non-overflow blocks, Nos. 15 to 18 and 24 to 26. Blocks in the overflow section are not being prestressed.

Consideration is being given to strengthening the entire dam, possibly by adding concrete to the downstream face to thicken the dam, or by buttressing the downstream face. The decision is not known at this writing.

Computed Stresses in the Dam

The monoliths of a concrete gravity dam are of different heights and interact with each other, with the foundation, and with the water in a manner that is not amenable to precise analysis. To simplify the problem we use the following approximations:

1. Only the transverse horizontal component of ground motion, transverse horizontal motion of the dam, and transverse plane motion of the water are considered.

2. Each monolith acts as a vertical cantilever beam, independent of the other monoliths. Shear deformation is taken into account, but rotatory inertia is neglected.

3. The hydrodynamic effect of the water is equivalent to an added mass moving with the dam, a concept due to Westergaard (18).

With these approximations one can compute the response by standard normal modes techniques. Figure 11 shows the properties of the first mode of the tallest non-overflow monolith with water to elevation 2143, its elevation on December 11. The response of this mode to the December earthquake, with damping taken to be .05, gives the maximum stresses shown in Figure 11. These are the normal stresses in the vertical direction at the upstream face, including the effect of gravity on the dam and reservoir, but excluding the effect of vertical earthquake acceleration. For comparison, the figure also shows the stresses computed from the design procedures specified by the Indian Standard (19), using a design acceleration of .05g both horizontally and vertically. The seismic provisions of the Indian Standard for the design of dams are the same as those used by the U. S. Bureau of Reclamation (20). The modal response indicates an extreme tension of 253 p.s.i. at elevation 2060, while the design procedures for .05g acceleration show a compressive stress.

Summary and Conclusions

The Koyna earthquakes of September 13 and December 11, 1967, occurred in a region known for its seismic stability. Prior earthquakes in the region in historical time have been small and infrequent, although large tectonic movements and crustal disturbances have occurred in geologic time. The causes of the earthquakes are believed to have been tectonic. Although the water load in the reservoir may have affected the time of occurrence, it does not appear to have been the cause of the events.

In terms of maximum acceleration the December earthquake at Koyna surpassed the El Centro earthquake of 1940. Its Magnitude of 6.2 places it among moderate earthquakes, and its spectral intensity of 4.0 feet is about half that of the El Centro 1940 earthquake.

The town of Koynanagar suffered vast destruction in the December earthquake, largely because of the type of construction.

Koyna Dam had been designed for an acceleration of .05g according to the Indian Standard. We believe that most engineers would have agreed prior to the earthquakes that the design precautions were adequate, considering the seismic history of the region. Earthquake damage to the dam included a horizontal crack through some of the tallest monoliths about 83 feet below water level, but the damage did not interfere with the operation of the dam and the dam was not in danger of failure. The computed first mode response of the dam to the recorded motion indicates that the tensile strength of the concrete at the upstream face should have been exceeded.

The occurrence of these earthquakes puts engineers on warning that seismic forces must be taken into account, even in seismically inactive regions, wherever structural failure could lead to a major disaster.

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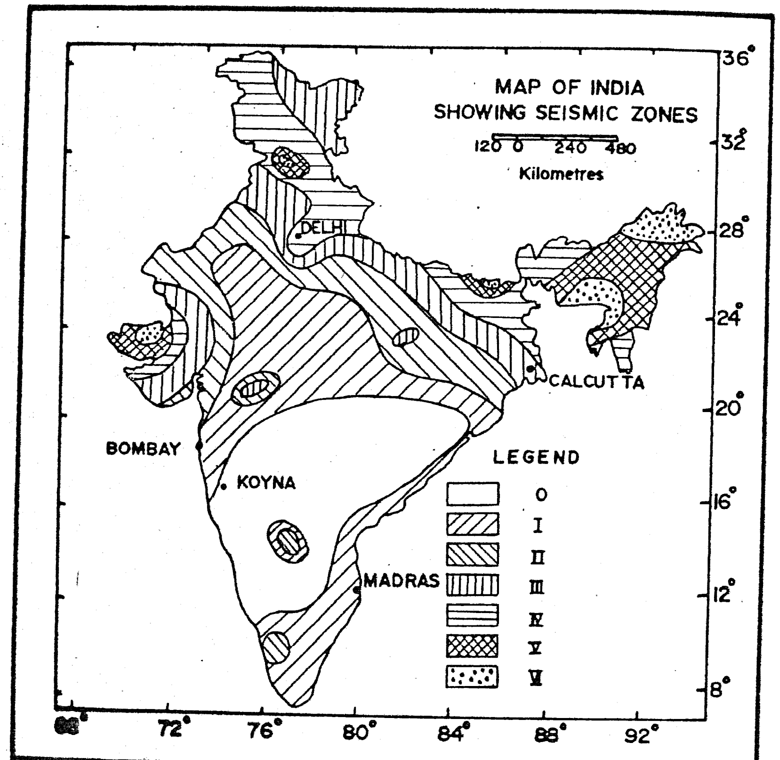

FIG. 1. SEISMIC ZONES OF INDIA
(From Reference 19)

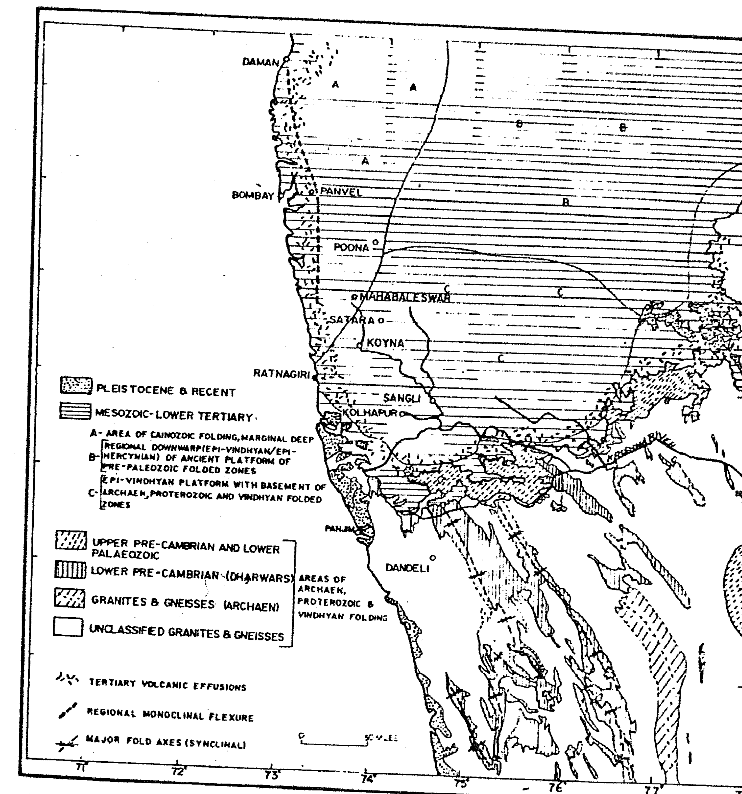

FIG. 2. GEOLOGY OF WESTERN PENINSULAR REGION
(From Geological Survey of India)

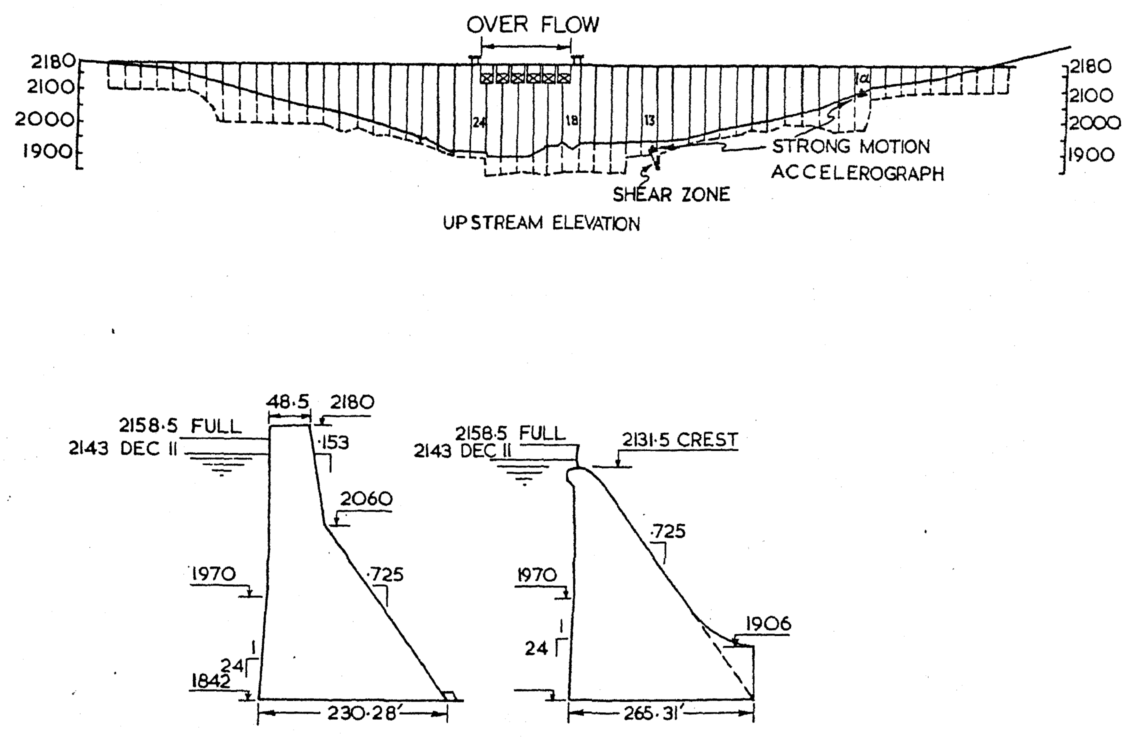

FIG. 3. ELEVATION AND SECTIONS OF DAM
(From Reference 4)

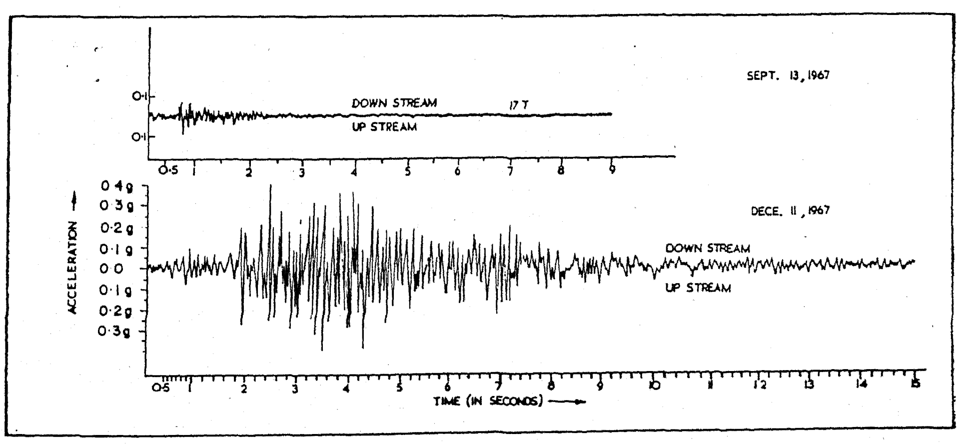

FIG. 4. ACCELEROGRAMS
(From Reference 12)

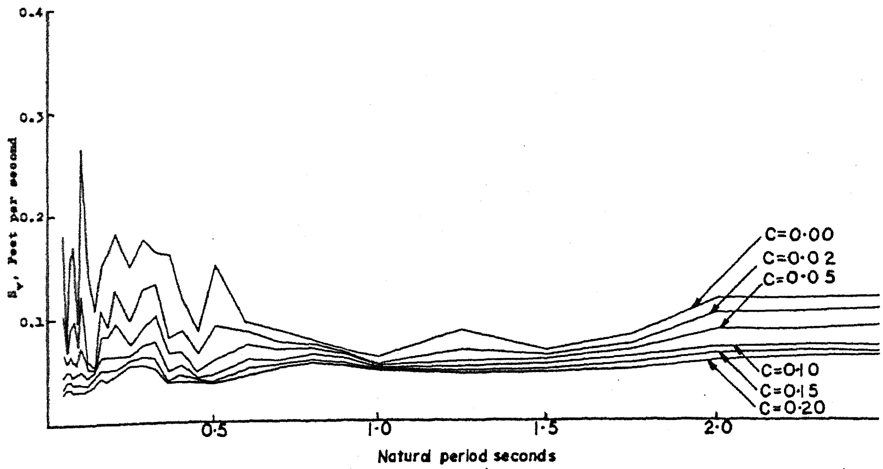

FIG. 5. VELOCITY SPECTRUM, SEPTEMBER 13 EARTHQUAKE

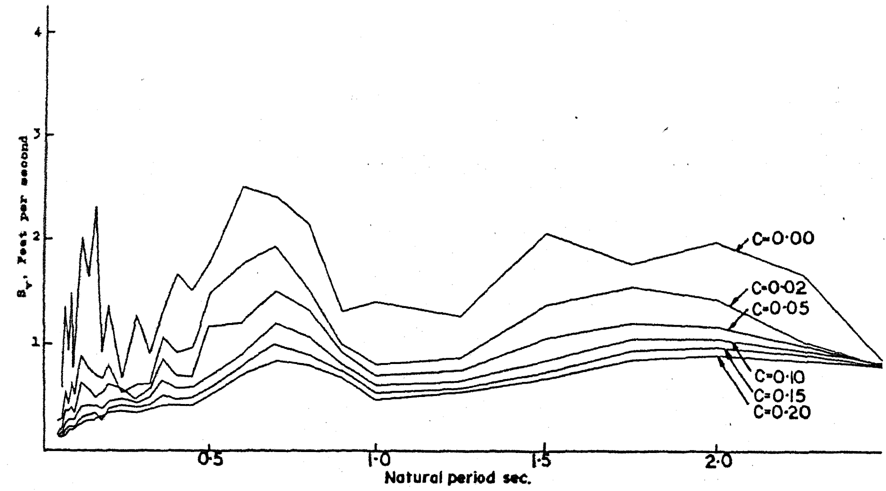

FIG. 6. VELOCITY SPECTRUM, DECEMBER 11 EARTHQUAKE

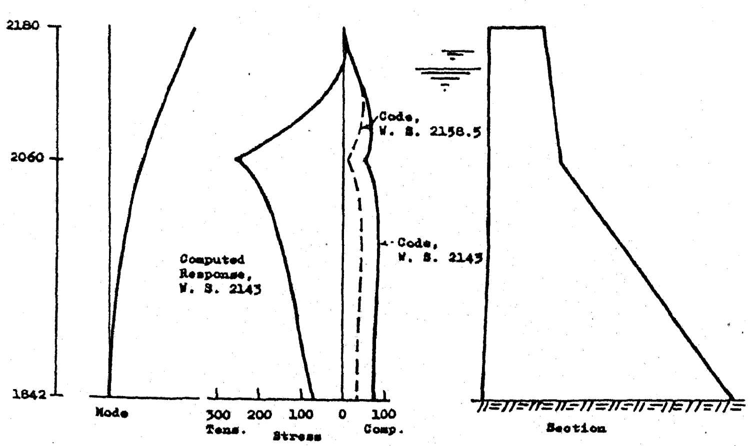

FIG. 11. EXTREME STRESSES AT UPSTREAM FACE

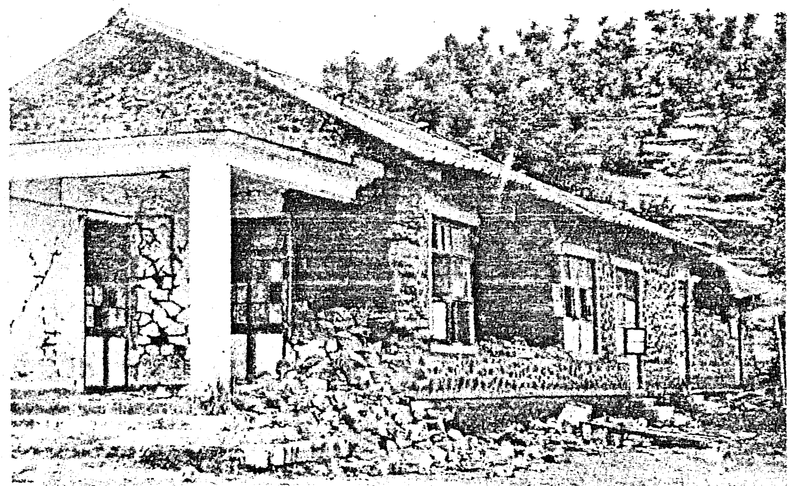

FIG. 7. KOYNANAGAR SCHOOL

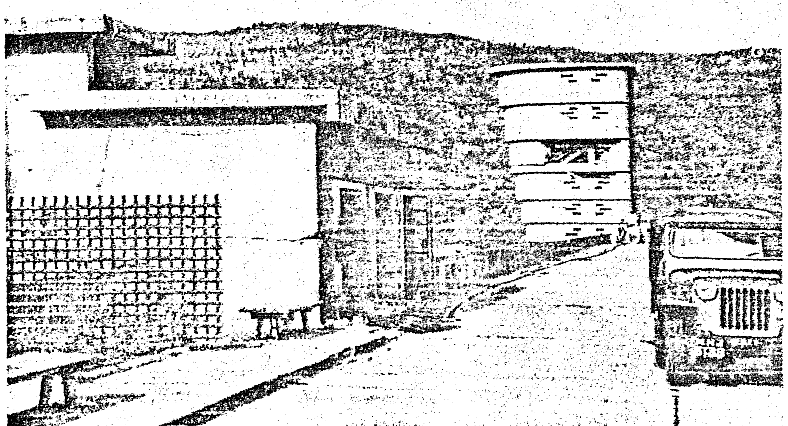

FIG. 8. STRUCTURES AT ROADWAY LEVEL

FIG. 9. FIXED GIRDER SEAT.

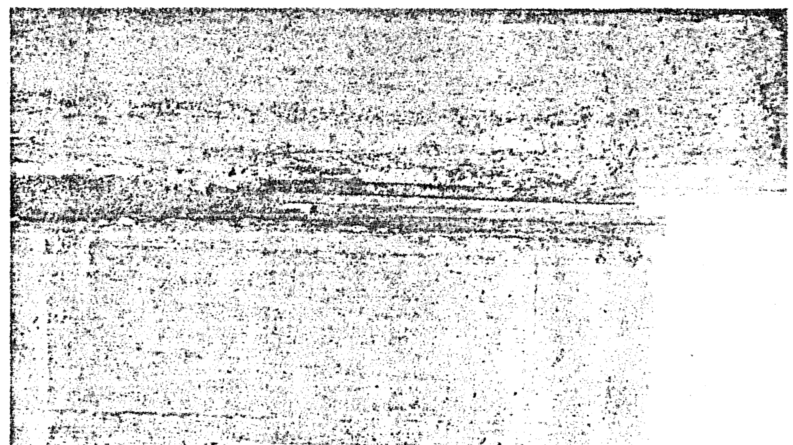

FIG. 10. SLIDING GIRDER SEAT