COMPREHENSIVE STUDY OF SEISMICITY AND ASSOCIATED PHENOMENA IN THE KOYNA REGION (INDIA)

by

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SUMMARY

The detailed studies on seismicity at Koyna region have been useful in understanding and identifying characteristics of reservoir induced seismicity, associated parameters and relative efficacies of precursors. Possible earthquake control through reservoir loading/unloading is indicated similar to fluid injection at Denver well and Rangeley oil fields, U.S.A.. Observations on ground motion characteristics, viz. displacement, period of earth waves, etc. have helped in formulating relationships useful for earthquake resistant design of structures.

SEISMOGENIC SET UP AND SEISMICITY OF KOYNA REGION

Occurrence of moderate seismicity in close vicinity of vital engineering structures at Koyna has been instrumental in generating concern over the phenomenon of reservoir induced seismicity (RIS). Though only over sixty such cases have been reported todate, the serious hazard due to large impounded water mass is now well recognized and seismic monitoring of new reservoir sites is widely undertaken. Understanding of this phenomenon is essential (i) to minimize risk to life and property due to seismic failure of dams; and (ii) for earthquake control through release of stresses in smaller seismic events. The Koyna dam is situated in the Deccan Trap region of the Peninsular Shield of India. Fig.1 shows the geological and geophysical features and earthquake epicentres in western India. Based on the seismicity and geotectonic, geophysical features and stress pattern indicated by geodynamic movement of the Indian plate, four prominent seismogenic zones are identified in the Peninsular India, viz. the Cambay graben and the Cutch region, the Tapi-Narmada-Son zone, the East and West coast strips. The maximum earthquake magnitude expected to occur over the West Coast is 7.0 with probable recurrence period of about 300 years. The concentration of fractures, dykes and hot springs along this narrow coastal zone suggests presence of deeper crustal discontinuities probably associated with the paleovolcanic activity resulting in trap formations. Thickness of basalt blanket over the shield is estimated to be generally 1.2-1.5 km, though at Koyna, a thickness of about 3 km is indicated from the computed earthquake wave velocity data (Fig.2). The phenomenon (RIS) has been attributed mainly to the presence of inhomogeneities in the upper crust and location of the reservoir site in marginal area marked

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by low ambient tectonic stresses(30 to 40 bars). Review of seismic data on over 250 deep/very large reservoirs, and reported RIS cases, shows dependence of the phenomenon on geology, tectonic stress, reservoirs depth ($\geq$100 m), impounded water mass, rate and number of cycles of loading/unloading (Packer et al, 1979). RIS is thus a complex phenomenon and needs more data and careful analyses of all the parameters involved in order to predict seismogenic probability of the site.

The seismological network around the reservoir and at dam site was intensified as the seismicity increased. Observations on seismicity were further supplemented by those on ground tilt, electrical resistivity, magnetic field intensity, strain and well levels. For engineering studies, strong motion accelerographs (AR 240 and RFT 250 models) were installed. The earthquake foci delineate a 20 km wide fault zone extending over 50 km in NE-SW direction, corroborating the fault plane solution deduced from first ground motions during the main earthquake of Dec.10, 1967 (M:7.0) which occurred about 4 years after the initial impounding. The earthquakes generally originate at depths between 3 and 10 km i.e. within basaltic-granitic layer (Fig.2). Earthquake foci also delineate weakness extending NW-SE towards Chiplun lying to the west of the Koyna region. This comparatively less active feature has been the seat of periodic microearthquake swarms. Composite fault plane solutions suggest that the predominant tectonic forces have been adequately dissipated resulting in low seismic activity. This is also indicated by the rise in b-values. Coefficient 'b' in the Gutenberg-Richter recurrence relationship, $\log N = a-bM$, has been found to be a very useful parameter in assessing seismic status of reservoir sites. Consistent b-value decrease prior to significant earthquakes is noticeable in Fig.3, and has also been observed in induced seismicity sequences at Kariba(Zambia) and Idukki and Mula in India(Guha et al, 1979). The premonitory period observed for this parameter is in good agreement with that given by Rikitake, viz. $\log T = 0.76M-1.83$, which also holds for geomagnetic field intensity, seismic wave velocities and strain observed in Koyna region(Padale et al, 1979). Ground tilt measurements (Fig.3) revealed accelerated tilting four weeks prior to the main Koyna earthquake —very useful as a short term precursor. Similar results have been obtained at Idukki dam(India). Fig.3 also shows that significant earthquakes($M > 5$) in Koyna region occurred following rise of reservoir level to maximum. The corresponding rise in b-values suggests substantial release of tectonic stresses through these events. These observations are suggestive of earthquake control by means of reservoir level changes similar to controlled studies at Denver well and Rangeley oil fields in U.S.A..

EARTHQUAKE GROUND MOTION AND STRUCTURAL RESPONSE

The strong motion accelerographs are installed in the body of the dam at different elevations, on ground surface(rock) at Koyna and at Alore 20 km NW of Koyna dam, and on surface and in underground power house at Pophali about 6 km west of the Koyna reservoir. The accelerograms recorded in magnitude range 3.1 to 7.0 enabled formulation of magnitude-dependent relationships useful for design purposes and in seismic risk estimation :

$$\begin{array}{ll} \log A_o = -6.5 + 1.3\ M\ (\mathrm{cm}) & \log V_o = -6.9 + 1.3\ M\ (\mathrm{cm/sec}) \\ \log a_o = -1.2 + 0.6\ M\ (\mathrm{cm/sec^2}) & \log T_o = -1.4 + 0.1\ M\ (\mathrm{sec}) \\ \log t_o = -0.9 + 0.3\ M\ (\mathrm{sec}) & \log T = -2.1 + 0.2\ M\ (\mathrm{sec}), \end{array}$$

where A_o is maximum ground displacement(peak to peak);V_o,maximum ground velocity(peak to peak);a_o,maximum ground acceleration;T_o,period of earthwaves;t_o,duration of earth movement recorded on accelerograms, and T, period of structure at which maximum acceleration response spectra are highest. The earthquake intensity is seen to decrease inversely with the square of the epicentral distance, whereas with depth the recorded acceleration reduced to nearly one-third of the ground acceleration recorded on surface(140 cm/sec^2 at Koyna as against 50 cm/sec^2 at underground power house at Pophali about 300 m below ground surface). The velocity response spectra at various levels in the Koyna dam(Fig.4) are useful in assessing dynamic characteristics of the structure at different elevations, as also the average acceleration spectra for geological conditions similar to Koyna region.

Since reservoir impounding is generally found to activate faults already present in the vicinity, it seems merely to accelerate the occurrence of normal shallow tectonic earthquake activity mainly through the pore pressure effect. On the basis of the Koyna earthquakes and seismicity of the West Coast, the methodology for estimating, M_d, the design earthquake magnitude especially for regions of low seismicity, could consist of finding regional characteristic maximum earthquake magnitude (M_{max}) occurring within 100 km radius or so, for use as M_d. Due to higher probability of occurrence of RIS,this is more applicable to reservoirs of over 100m depth located near recent faults.

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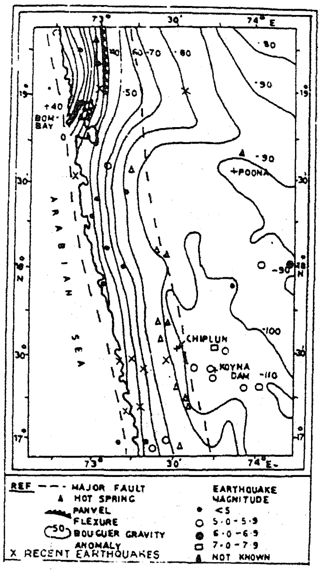

FIG. I GEOLOGICAL, GEOPHYSICAL FEATURES AND SEISMICITY OF WESTERN INDIA

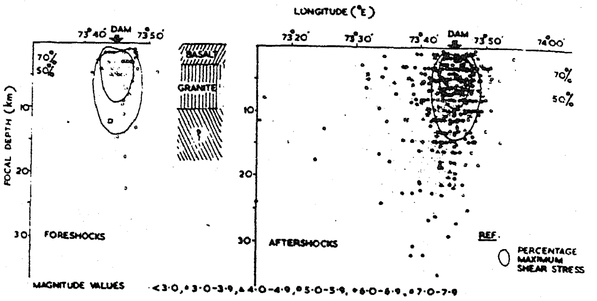

FIG. 2 LONGITUDE-DEPTH DISTRIBUTION OF EARTHQUAKE FOCI AND UPPER CRUSTAL STRUCTURE (KOYNA REGION) AS DEDUCED FROM SEISMIC WAVE VELOCITIES

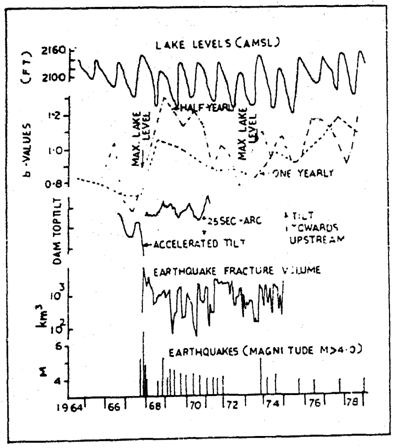

FIG. 3 SIGNIFICANT KOYNA EARTHQUAKES, ASSOCIATED b-VALUE VARIATIONS, GROUND TILT, EARTHQUAKE FRACTURE VOLUMES AND LAKE LEVELS

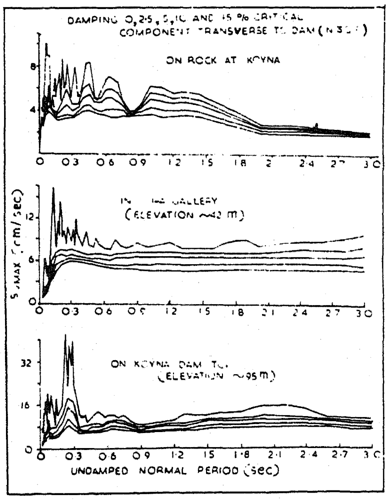

FIG. 4 MAXIMUM VELOCITY RESPONSE SPECTRA UNDER VARIOUS CONDITIONS FOR KOYNA EARTHQUAKE OF OCT. 17, 1973 (M: 5·2; 5 km SW OF DAM, FOCAL DEPTH: 5 km)