Paper No. 100. Bulletin of the Indian Society of Earthquake Technology, Vol. VII, No. 4, pp. 187-195 Dec. 1970

RECENT SEISMIC DISTURBANCES IN WESTERN MAHARASHTRA (1962-69)†

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INTRODUCTION

The Koyna Dam (17° 23. 85′ N: 73° 45′ E) and the Koyna Reservoir formed by it are situated in the Peninsular Shield of India which is generally regarded as one of aseismic Precambrian blocks existing on the earth to-day. Isolated earthquakes of low magnitude (tremors) do at times occur in parts of the Shield such as its southernmost region, Narmada Valley and Eastern and Western Ghats. The frequency of occurrence of the low magnitude earthquakes in the Peninsular Shield is very small excepting in extremely isolated spots where swarms of very small earthquakes do occur at times. Statistics of historical earthquakes in the vicinity of the Koyna Dam and around the epicentre of Dec. 10, 1967 earthquake (lat. 21° 30′ N to lat. 15° N and long 80° E to long 72° E) shows that one earthquake between magnitudes 7 and 7.9, two earthquakes between magnitudes 6 and 6.9 and eleven earthquakes between magnitudes 5 and 5.9 have occurred in the period 1341 to 1968 The historical data are very likely to be incomplete but the area, no doubt, seems to be somewhat active.

After impounding the Koyna Reservoir in 1962 monsoon, reports of experience of tremors specially near the dam began to be prevalent, Frequency of these tremors increased considerably from middle of 1963 onwards. The tremors were invariably accompanied by sound in the vicinity. Intermittently, strongest of these tremors used to rattle windows disturb utensils, etc , and had maximum intensity upto about V (MM Scale) at the epicentre. But these tremors of magnitude (M) 3.7 and below were followed by two moderate earthquakes of magnitude 5.8 and 7.0 on Sept. 13, and Dec. 10, 1967 respectively with epicentres close to the dam. Close instrumental observations have revealed occurrence of large number of aftershocks of smaller magnitudes. Few of the aftershocks were of magnitude 3.0. Preliminary details of these earthquakes upto 1965 have already been reported (5).

SEISMOLOGICAL OBSERVATIONS AND INTERPRETATIONS

A close net of seven seismological observatories (6) including one at the dam was established around the Koyna Reservoir and these are Koyna Dam, Koynanagar, Satara, Mahabaleshwar, Pophali, Alore and Govalkot. The instruments installed in the observatories are Benioff vertical seismographs, Wood-Anderson seismographs ; and only at the Koyna Dam, accelerographs AR-240 and tiltgraphs are installed. Both accelerographs and tiltgraphs are of torsion pendulum type. Figure 1 shows a typical seismogram of large number of aftershocks of Dec. 10, 1967 earthquake. The ground vibrations in the tremors are associated with very high frequency because of high elasticity of the rock formation and because of very small epicentral distance.

The field intensities dueto these tremors are very much localised on account of their low magnitudes and shallow foci. However, in case of the largest of the tremors, the field intensity at the epicentre (I_0) may be about IV–VI in the MM Scale thereby causing very minor damage to weak residential structures. The largest earth tremors are being felt both at Koyna Dam and Pophali over a distance of 10 km. It thus seems from macroseismic data that excepting a few very strong ones, tremors of magnitude 3.7 in which most of the energy has been released at depths of about 3 to 5 km which is roughly of the order of thickness of Deccan

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† Presented at the Fourth Symposium on Earthquake Engineering, Roorkee, November 1970.

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Trap (basalt) at the West Coast (4). Earth tremors observed at Witwatersrand, South Africa (3) and Lake Mead Area, U.S.A. (1) had also shallow focal depths between 2 and 10 km. Jones (7) from analysis of the Lake Mead area tremors suggested a relationship between focal distance R_1 (in km) at limit of perceptibility and magnitude (M) of the tremors as follows :

$$R_1 = 8M - 11 \qquad (1)$$

Macroseismic data for these tremors are not available to utilise equation (1). More detailed and accurate assessment of other earthquake parameters will be given later.

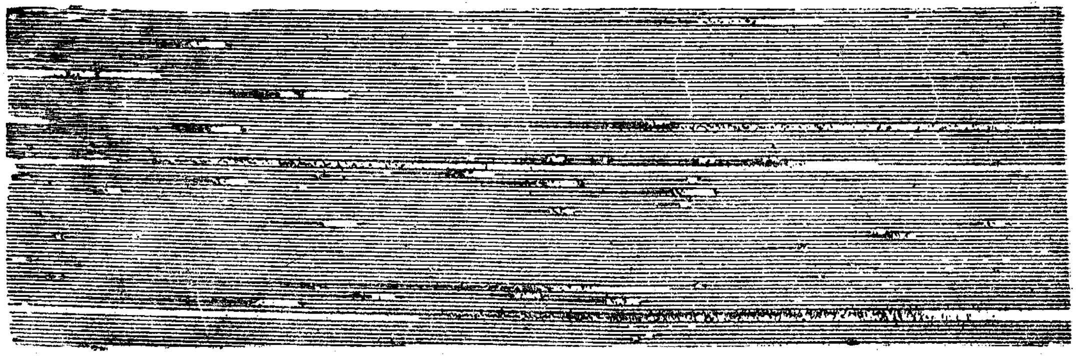

Figure 1. Record Showing large number of aftershocks (12-13 Dec. 67) (Satara seismological observatory; Benioff vertical seismograph; Magnification : 30,000 at 1 cps).

In figure 2, prior to the earthquake of Dec. 10, 1967, frequency of occurrence of the earthquakes does not show any correlation with inflow hydrograph or with reservoir level, but release of elastic energy in the earthquakes does indicate that energy release is enhanced following the floods with a certain time-lag. Similar observations were made in U.S.A. at Lake Mead area of Boulder Dam (1'10). However, when both weekly energy release and frequency of earthquakes are presented according to magnitude groups as in Figure 3. frequency of earthquakes specially of smaller magnitudes (< 3.0) correlate well with lake level. Further, correlation of significant energy with lake level as mentioned above becomes also more evident. The distribution of earthquake epicentres (6) in and around the reservoir area shows that most of the epicentres are clustered near the dam as in the cases of Monteynard and Kariba Dams (2), and Lake Mead area, Boulder Dam. Above analyses show that while the foreshocks of the Dec. 10, 1967 earthquake have epicentres mostly upstream of the dam, a number of aftershocks have epicentres situated downstream in south-westerly direction. The latitudewise distribution (6) of the earthquake foci shows that while the foci of foreshocks of Dec. 10, 1967 earthquake are situated almost within the thin superficial Deccan Trap layer immediately below the reservoir, the foci of the aftershocks are comparatively deep and widespread. This differentiation in the zones of occurrence of the foreshocks and aftershock of Dec. 10, 1967 earthquakes is remarkable and may be an important contributory factor in understanding the origin and cause of this unusual cluster of earthquakes in a very thin section of geological strata.

The depthwise distribution of magnitudes (M) of the earthquakes (6) shows that earthquakes of larger magnitudes have foci at deeper layers. The yearly Gutenberg-Richter relationship for number of earthquakes (N) are very significant in respect of their slopes (b). The yearwise values of the coefficient 'b' in the following equation :

$$\log N = a - bM \qquad (2)$$

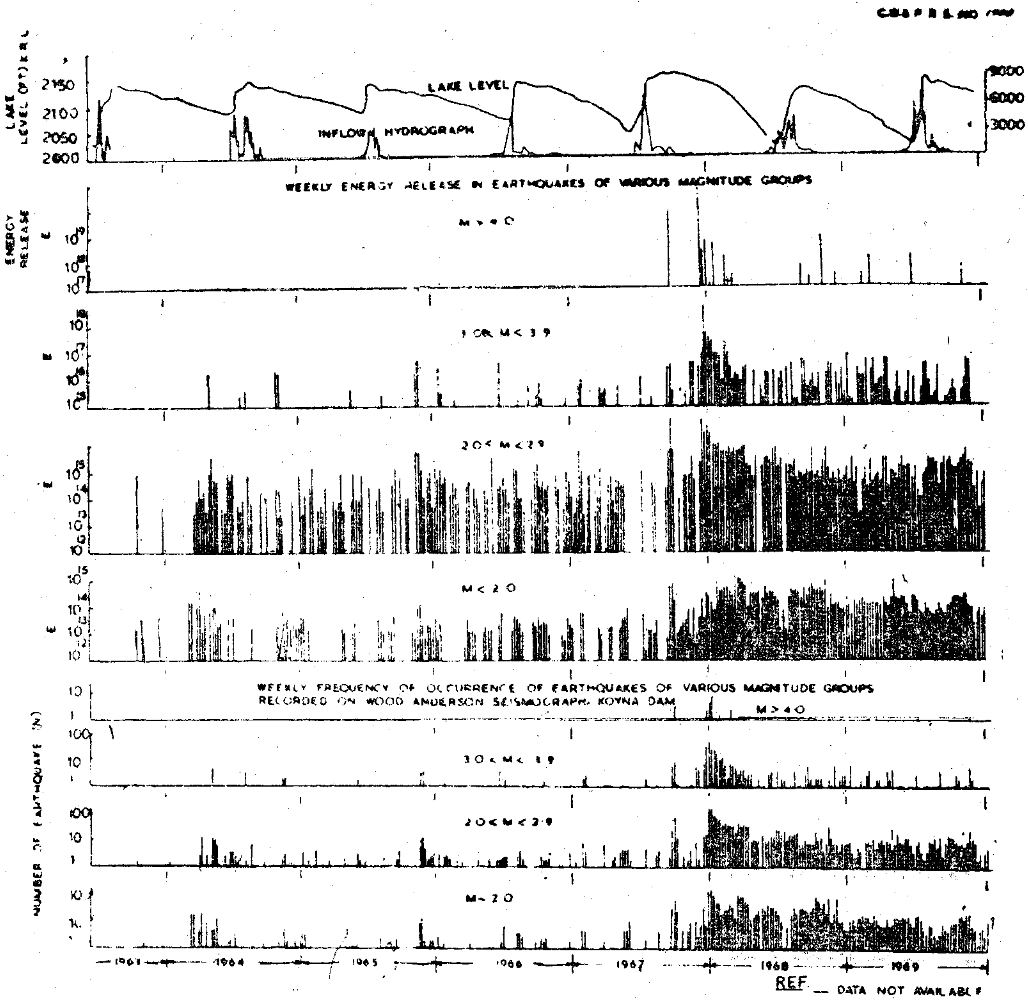

Fig. 2. Frequency of Occurrence of Earthquakes and Associated Energy at Different Observatories Lake. Level Hydrograph and Cumulative Strain Release.

are as follows :

0.79 (1964), 0.45 (1965), 0.51 (1966), 0.49 (1967, upto Dec. 10, 1967), 0.57 (1964–67, upto Dec. 10, 1967), 0.75 (Dec. 11, 1967 – Dec. 31, 1967), 0.94 (1968), 0.90 (Jan. 1, 1969 – June 30, 1969).

The above results show that the values of 'b' have significantly changed immediately after commencement of the tremors in 1964 and again after the earthquake of Dec. 10, 1967. The post-earthquake (Dec. 10, 1967) values of 'b' are more than the pre-earthquake values of the same.

The earthquake parameters like depth of focus (h_1), origin time (T) and compressional wave velocity (V_p) in intervening medium traversed by earthquake waves are obtained from the following equation :

$$(x-x_1)^2 + (y-y_1)^2 + (z-z_1)^2 = V^2_p\,(T_p-T)^2 \tag{3}$$

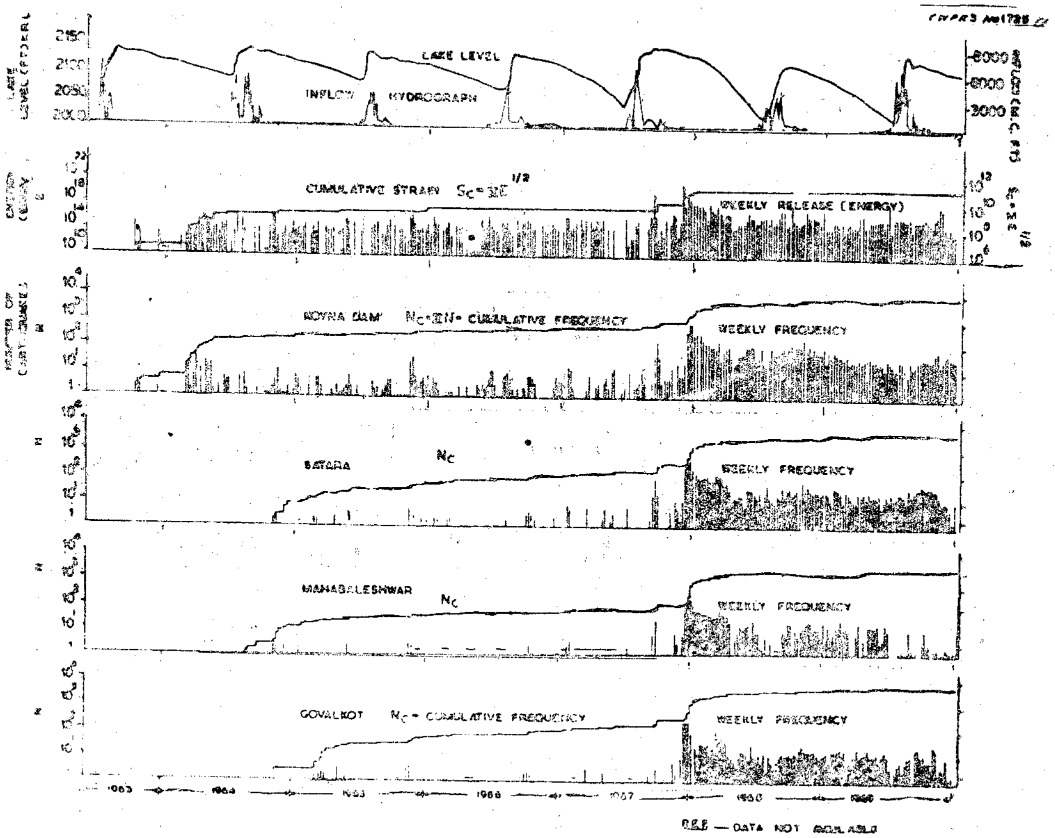

Figure 3. Groupwise Weekly Energy Release, Frequency of Occurrence of Earthquakes. Lake Level and Inflow Hydrograph.

where x_1, y_1, z_1 are cartesian co-ordinates of the observatory ; x, y, z are those of the earthquake focus, and T_p is the arrival time of compressional wave (P_g) at the observatory. Thus, if data from five or more observatories of the net are available, the co-ordinates of the focus (x, y, z), velocity (V_p) and origin time (T) can easily be obtained by solution of equation (3). The results from large number of earthquake studies in the reservoir area suggest that velocity of P_g within the upper crust diminishes with increase in depth of foci of the earthquakes. This possibly explains the existence of fractured zone of granite (perhaps under tension) of lower velocity underneath the superficial basalt layer as anticipated by Glennie (4) from gravity data. This weakness (tension) in the underlying granitic layer may perhaps explain the seat of foci of large number of earthquakes therein.

The foci of major strain release in epicentral map in Figure 4 seem to have oscillated between shallow (granite) and deeper regions (crustal basalt) in the area. This alternating sequence of strained state in the two consecutive layers composing the crust is perhaps determined by magnitude and direction of overall geotectonic force pattern in the area while the crust underneath was in the process of attaining gradual equilibrium following the Dec. 10, 1967 earthquake.

The energy (E) generated in an earthquake can also be expressed by the following conventional equation :

$$E = \tfrac{1}{2} . f . V_e . E_1 . S_1^2 \qquad (4)$$

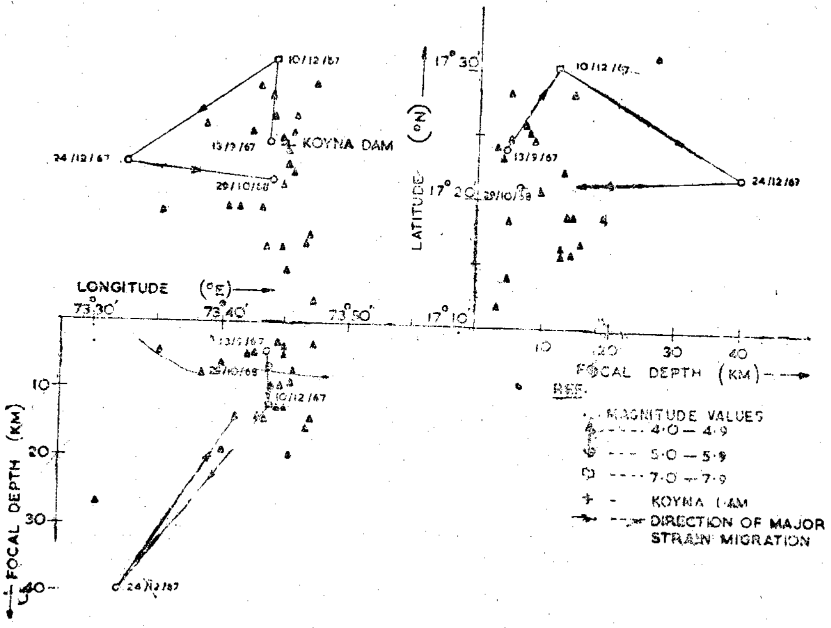

Fig. 4. Projections on Different Planes of Foci of Earthquakes of Magnitude 4.0 and above in the Koyna Project area (Oct. 63–June 69).

where S_1 is the overall strain just prior to rupture and f is the efficiency of the source as a seismic energy generator and is assumed as unity. If stress corresponding to strain S_1 is assumed to be 200 psi, the linear dimension of rock mass (r_1) for generating energy of 10^{16} ergs (M = 3.7) may be of the order of 400 m according to equation (4). The above computation has primarily been done to ascertain only the order of linear dimension (r_1) of the tremor and not for exact quantitative assessment.

Omori's hyperbolic relationship for frequency of occurrence of aftershocks N (t) at any time t, though applicable in general to large number of cases, requires minor modifications in specific cases :

$$N(t) = \frac{K_1}{t + c_1} \tag{5}$$

Utsu (11) modified the above relationship to the following form :

$$N(t) = \frac{K_2}{(t+c_2)^p} \tag{6}$$

and the corresponding equation for E (t), energy in aftershocks at any time t, is

$$E(t) = \frac{K_3}{(t+c_3)^q} \tag{7}$$

where K_1, K_2, K_3, c_1, c_2, c_3, p and q are constants. He had successfully applied equations (6) and (7) to large number of Japanese earthquakes. It is admitted that equations (6) and (7) are very general cases and most of the earthquake (aftershock) data can be suitably fitted to them if data immediately after the main earthquake are available specially at nearby observatory to record very minute aftershocks. The data from the Koyna Seismological net are not available for about half a day following the main Dec. 10, 1967 earthquake, as such all the parameters of equations (6) and (7) cannot be accurately assessed, specially the earthquake constants c_2 and c_3. Further, as the aftershock data had shown large fluctuation at later period, it is found more reasonable to attempt to fit cumulative frequency N_c $[= \Sigma N(t)]$ than simple frequency N (t). Similarly attempts were made to fit cumulative energy E_c $[= \Sigma E(t)]$ and cumulative strain release S_c $[= \Sigma E(t)^{1/2}]$. For Dec. 10, 1967 earthquake, the following types of statistical relationships were obtained for aftershock sequence (vide Fig. 5) :

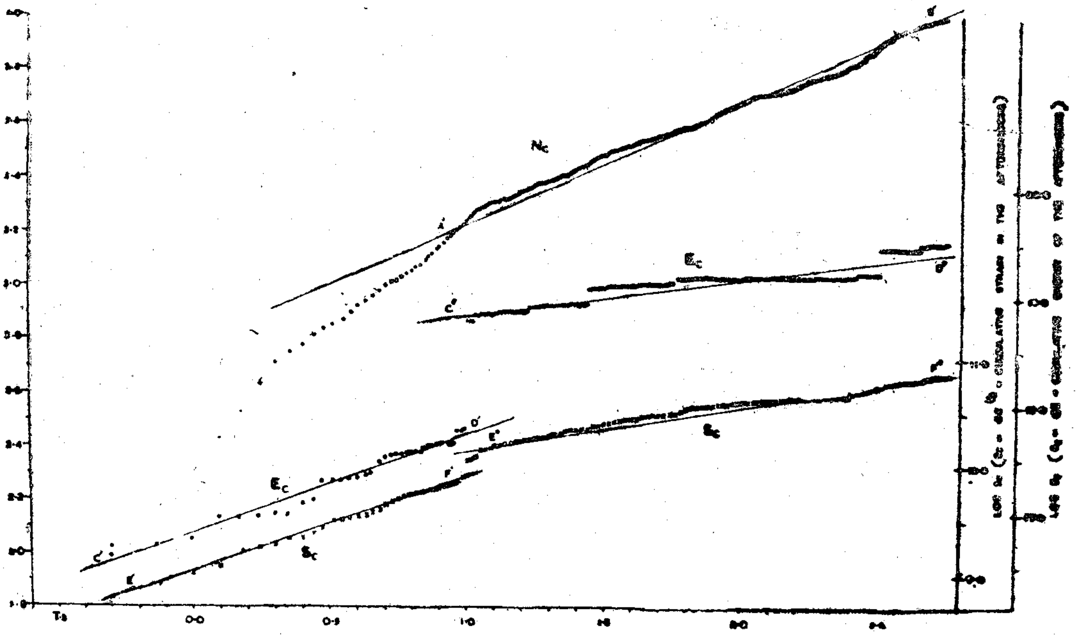

Figure 5. Cumulative frequency, Cumulative Energy and Cumulative Strain Release in Aftershocks of 10 Dec. 1967 Earthquake.

$$\left.\begin{aligned} N_c &= \Sigma N(t) &&= D_1 t^{n_1} \\ E_c &= \Sigma E(t) &&= D_2 t^{n_2} \\ S_c &= \Sigma E(t)^{1/2} &&= D_3 t^{n_3} \end{aligned}\right\} \tag{8}$$

The values of n_1, n_2 and n_3 obtained were 0.435, 0.930 and 0.847 respectively. Similar values of the exponents were obtained by others also specially in recent analyses of Matsushiro earthquake data by Ohtake et al (9).

The difference $(\Delta \bar{M})$ in magnitude of the main earthquake and its largest aftershock is given by Utsu (11) as :

$$\Delta \bar{M} = 4.7 - 0.45\, M \tag{9}$$

Hence for M = 7 of the Dec. 10, 1967 earthquake, $\Delta \bar{M}$ is of the order of 1.5 which reasonably corresponds to the magnitude value of 5.2 of largest aftershock on Oct. 29, 1968.

Further, the value of the linear dimension (D_a) of the aftershock area given by Utsu (11) as :

$$\log Da\ (\mathrm{km}) = 0.5\ M - 1.8 \qquad (10)$$

which yields Da = 50 km, a value only somewhat in excess of the actual linear dimension of the aftershock area of Dec.10, 1967 earthquake (6).

The observed energy per unit volume of aftershocks (E/V_a) of Dec. 10, 1967 earthquake (6) is about 280 ergs/cm^3 a value which is about the same as that obtained from the following equation by Kisslinger (8) :

$$\log \frac{E}{Va} = 2.22 + 0.03\ M \qquad (11)$$

The energy per unit volume (E/Va) according to equation (11) is about 270 ergs/cm^3 and is practically independent of magnitude (M). Thus, the various parameters observed for Dec. 10, 1967 earthquake are found to be in good agreement with similar statistical results obtained for other earthquakes elsewhere.

As mentioned earlier, frequency of the tremors had sharply increased since 1963. One possibility is that these tremors could have been triggered off by the superimposed water load of the reservoir though the exact mechanism may be complex. A comprehensive discussion on similar earthquakes in other parts of the world had already been given earlier (5).

There is a pronounced zone of hot springs parallel to the West Coast (6) indicating major rupture in the upper crustal formations. Temperature, rate of discharge, and chemical and radioactive contents of the spring water were reported in 1948 long before the recent earthquakes as such pre and post-earthquake measurements could not be easily compared. But the comparison of temperature measurements reported in 1948 and immediately after the Dec. 10, 1967 earthquake shows that the temperature had increased, in general, in the hot springs situated in the vicinity of earthquake area. Also, it is important to note that there had been significant changes (rise) in temperature in some of the hot springs before some of the recent aftershocks specially of magnitude 4.5 and above. In the crustal section of the area as obtained from gravity data by Glennie (4), the ultra basic layer (Moho) is very shallow, its depth being roughly of the order of oceanic structures. Extension of occanic rift along the West Coast associated with unusual crustal upwarp characterised by very high gravity anomaly, hot spring zone with minor activity during recent earthquakes and simultaneous occurrence of the large number of tremors in the loaded reservoir area seem to be connected.

The geophysical map (6) and the tectonic map published by the Geological Survey of India do not exhibit any special features in the area which may be attributed to these tremors exeepting that the area is a pronounced gravity low situated quite close to the pronounced gravity high area along the West Coast of India delineating crustal upwarp involving the 'ultrabasic layer' of the upper mantle. Glennie (4) had attributed this upwarp zone to a giant dyke formed of ultrabasic material along a huge tensional crack off the West Coast of India. It cannot be immediately assessed whether such geological juxtaposition could be a favourable situation for triggering off thess tremors in the reservoir area loaded with an average water pressure of about 50 psi or so.

CONCLUSION

The seismological observations made in the Koyna net of observatories before and after the December 10, 1967 earthquake are interpreted in the light of some previous work on similar problems and the limitations are pointed out.

ACKNOWLEDGEMENTS

The authors are grateful to Director, and Joint Director, Central Water and Power Research Station, Poona–34 for encouragement during the preparation of the Paper.

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NOTATIONS

a : constant

b : constant

c_1, c_2, c_3 : constants

D_1, D_2, D_3 : constants

D_a : Linear dimension of aftershock area

E : Energy generated in an earthquake

E_1 : Elastic constant (Young's modulus)

$E_c = \Sigma E(t)$: Cumulative energy release of aftershocks

$E(t)$: energy in aftershocks at any time t

f : efficiency of the source as a seismic energy generator

h_1 : depth of focus

I_0 : Intensity at epicentre (MM Scale)

K_1, K_2, K_3 : constants

M : Magnitude of earthquake (Richter Scale)

$\Delta\overline{M}$: Difference in magnitudes of the main earthquake and its largest aftershock

N : Number of earthquakes

$N_c = \Sigma N (t)$: Cumulative frequency of aftershocks

$N (t)$: Number of aftershocks at any time t

n_1, n_2, n_3 : constants

P_g : Phase corresponding to direct compressional wave travelling through upper crust

p, q : constants

R_1 : Focal distance at limit of perceptibility

r_1 : Linear dimension of strained rock mass

S_r : elastic strain

$S_c = \Sigma E (t)^{1/2}$: Cumulative strain release of aftershocks

T : Origin time of an earthquake

T_p : Arrival time of phase P_g at the recording station

V_a : Volume of aftershock region

V_e : earthquake volume

Vp : compressional wave velocity

x, y, z : Cartesian coordinates of earthquake focus

$x_1, y_1 z_1$: Cartesian coordinates of the observatory,