Mausam (1979), **30**, 2 & 3, 281—288

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Feasibility of earthquake prediction in Koyna region (India)

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ABSTRACT. Seismicity alongwith various parameters, *viz.*, tilt, strain and geomagnetic field intensity has been observed over a long period in the active Koyna region. Geohydrological parameters like ground water levels, hot spring temperatures and discharge rates have also been observed. Study of these parameters alongwith the earthquakes has indicated feasibility of utilizing *b*-values, seismic wave velocity anomalies, ground tilts, *in-situ* rock strains and geomagnetic field measurements for prediction of earthquakes. The anomaly (premonitory) periods observed for these parameters are in good agreement with those reported for other earthquakes. Extensive data over long period confirm the results obtained earlier by the authors regarding application of *b*-values, ground tilt and rock strain measurements for earthquake predictions.

1. Introduction

The Koyna dam and the Shivajisagar lake formed by it are located in the Deccan trap region of the Peninsular India. The Peninsular shield had been considered to be broadly aseismic though very rare occurrences of moderate earthquakes in parts of the shield, *viz.* the Cutch and Cambay region, the Tapi-Narmada-Son zone, the Godavari rift valley and the eastern and western margins, have been recorded in historical documents. This is in agreement with the general observation by Gutenberg and Richter (1949) for shield regions of the world. However, the Koyna earthquake of 10 December 1967 aroused great interest amongst earth scientists and engineers particularly because of its close vicinity to the Koyna dam. After this moderate Koyna earthquake (M:7), the dam has been strengthened subsequently in view of similar earthquake that could occur in future in its close vicinity. The time series analysis shows that the decay rate of Koyna seismicity is quite small. However, resurgence of the activity cannot be positively ruled out. In view of this and the presence, in this region of important structures, like the Koyna dam and the power house, it seems worthwhile to investigate various aspects of the seismicity and associated geological, geodetic and geophysical phenomena observed in this region, to study feasibility of prediction of significant earthquakes.

Attempts to predict earthquakes on precise and scientific basis have been made in recent times in different parts of the world. Determination of return periods of earthquakes, migration of strain foci, etc have been studied for number of regions. This achieves to some extent the goal of earthquake prediction in that seismic zones and their associated seismic risks are fairly well estimated. However, earthquake prediction as defined today, *i.e.*, in terms of accurate estimation of time, location and magnitude, is far from achieved, though a few successful cases have been reported from China, USSR, Japan and USA. Better understanding of earthquake processes, availability of fairly precise measuring devices and accumulation of large amount of earthquake and related data may enable earth scientists to attain this goal.

2. Observations of premonitory parameters in Koyna region

More than a dozen parameters likely to be useful in earthquake prediction have been identified through detailed observations at epicentral tracts of several earthquakes and laboratory experiments on rock samples of greatly varied nature subjected to tensile, compressive, shearing and triaxial stresses. Based on these, various models for earthquake generation have been postulated (*e.g.*, Scholz *et al.* 1973, Brady 1974, Mjachkin *et al*,. 1975, Avchyan *et al.* 1977). These are broadly based on the dilatancy phenomenon.

The premonitory parameters could be broadly grouped in three catagories, *viz.*, seismic, geode tic and geophysical. Seismic observations have been carried out in the Koyna region since 1963. Installation of tiltgraphs, strain and stressmeters, magnetometers, etc, and periodic measurements of related geohydrological parameters, *viz.*, well levels and temperatures and discharge rates of hot springs in close vicinity of the seismically active area have also been undertaken.

Attempts to predict locations of impending earthquakes have been made for some regions on the basis of seismic gaps between migrating active areas. The pattern in Fig.1 exhibits clustering of foci a few kilometres southwest of the Koyna dam between depths 6 and 12 km.

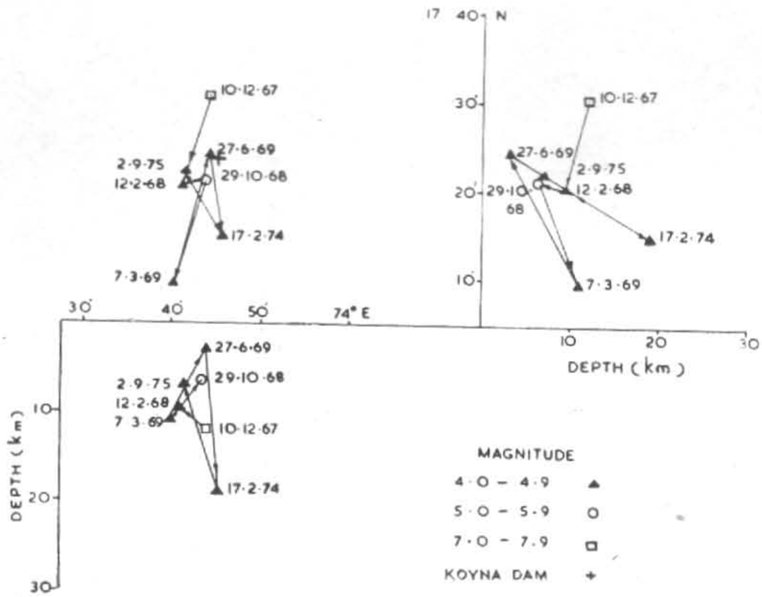

Fig. 1. Migration of foci of significant Koyna earthquakes ($M \geqslant 4 \cdot 5$)

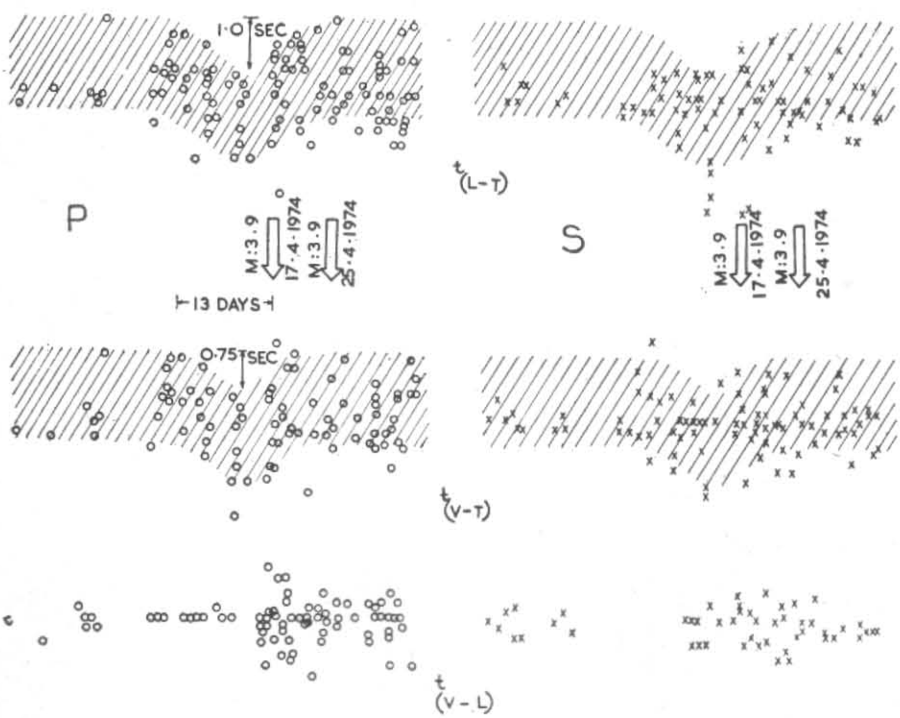

Fig. 2. Differential arrival times of the components L, V and T of direct P and S waves (17 April 1974 earthquake, M : 3·9)

But it does not reveal gaps wherein future significant earthquakes could be anticipated. It is possible that the active Koyna region is comparatively very small for applying this technique usefully.

Similarly, variations in the direct compressional velocity (V_p) and ratio of velocities (V_p/V_s) have been used in a number of cases. The close net of seismograph stations in the Koyna region makes it possible to study the same for Koyna earthquakes. Scrutiny of these extensive data covering a period from early 1967 to 1973 has not revealed any systematic lowering in the (V_p/V_s) ratio that could be associated with Koyna earthquakes. Koyna earthquake sequence is thus one of the many cases for which absence of (V_p/V_s) premonitory change has been noticed. This could partly be due to the limited source region of the earthquakes.

Fig. 2 shows a case in which velocity anisotropy, *i.e.*, splitting of earth waves in two components of slightly different velocities has been exhibited. The three components observed are across the axis of the Koyna dam (T), along the axis (L) and in the vertical direction (V). The observed premonitory period (T_p) of about 2 weeks for an earthquake of magnitude (M) 3·9, *vide* Fig. 2, agrees well with the general relationship:

$$\log_{10} T_p = 0.76M - 1.83 \qquad (1)$$

deduced from observational data by Rikitake (1975). Fig. 2 shows that the changes in differential arrival times of both P and S waves are almost of the same order (1 sec), and this could perhaps be a reason for absence of noticeable V_p/V_s anomaly in Koyna region. Also, the arrival time differences $t_{(V-L)}$ for vertical and longitudinal components are negligible as compared to $t_{(L-T)}$ and $t_{(V-T)}$. This observation suggests that predominant forces related with generation of this earthquake of 17, April 1974 (M : 3.9) are either tensional in vertical (V) and longitudinal (L) directions, or compressional in the transverse (T) direction. Successful application of this technique has been reported by Gupta (1973) for Nevada earthquakes.

The phase of dilatancy hardening in the process of earthquake generation postulated by various models is based on the observation that, prior to a number of earthquakes, foreshock activity has been relatively low. In Koyna region, an earthquake of magnitude 5·8 preceded the main earthquake by a period of about 12 weeks. During this intervening period of 12 weeks, the activity had been much above the background level of seismicity prior to September 1967. This enhancement due to the aftershock activity of 13 Sep. 1967 earthquake does not allow application of dilatancy hardening to prediction of 10 Dec 1967 main earthquake. The same applies to other significant earthquakes ($M > 5.0$) in this area.

From laboratory experiments, Mogi (1962) and Scholz (1968) have established dependence of coefficient b in the Gutenberg-Richter recurrence equation, on the amount of stress applied to rock samples. The accumulation and release of stresses in the source region of earthquakes has been reflected in b-value variations observed for a number of regions (Guha *et al.* 1974, Papazachos 1975, Suyehiro and Sekiya 1972). Periodic b-value estimations on half-yearly and annual bases for Koyna earthquakes reveal some very interesting characteristics (Fig. 3). Prior to the main Koyna earthquake, the annual b-values decreased steadily since 1964, indicating progressive accumulation of crustal stresses. The

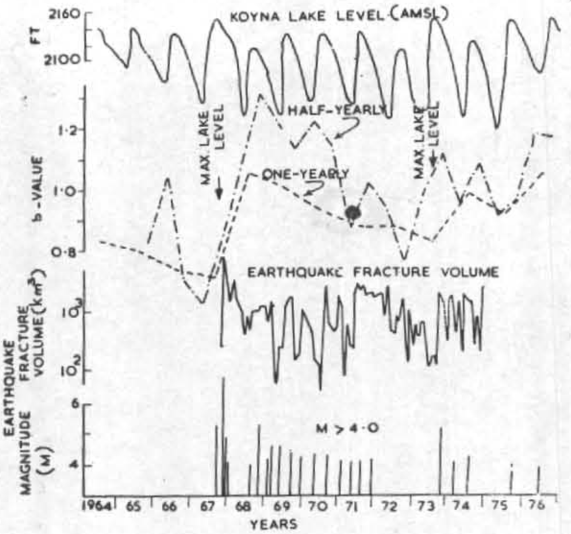

Fig. 3. Significant Koyna earthquakes, associated b-value variations, lake levels and earthquake fracture volumes

rate of lowering of the b-values prior to and after the main earthquake is almost the same suggesting that the tectonic 'loading rate' of the region under consideration has remained unaltered. However, as seen in Fig. 3, the short term fluctuations in half-yearly b-values seem to have some relationship with the loading-unloading cycles of the Konya reservoir and fracture volumes for Koyna earthquakes (Patil *et al.* 1976). The beginning of enhancement in the seismicity of Koyna region was marked by the earthquake sequence of October 1964 (M : 3.5 and 3.3). As the b-values have shown consistent decrease since then till the culmination of the main earthquake, this period of about 3¼ years ($\sim$1200 days) has been considered as premonitory on the basis of b-values. This period agrees with relationship given in Eq. (1) by Rikitake for magnitude dependent premonitory phenomena. Somewhat similar basis has been suggested by Evison (1977) utilizing magnitude and time of occurrence of the preceding significant activity for earthquakes in New Zealand and California. Study of b-value variation with time has also shown consistent lowering of the same prior to micro-earthquake activity (*vide* Fig. 4) observed at Mula dam (19°22'N; 74° 37' E) and also for the earthquake sequences in the Kariba lake region, Zambia (Fig. 5). The estimation of b-value could therefore be considered as a significant and reliable premonitory feature.

Results of tilt measurements with pendulum installed in the body of the Koyna dam had indicated the presence of anelastic creep preceding the main earthquake (Guha *et al.* 1974 b). Tilt measurements in the Koyna dam have also been continually made with sensitive torsion pendulum seismographs since 1966. As experienced by several researchers, the tilt measurements are difficult to interpret because of contribution

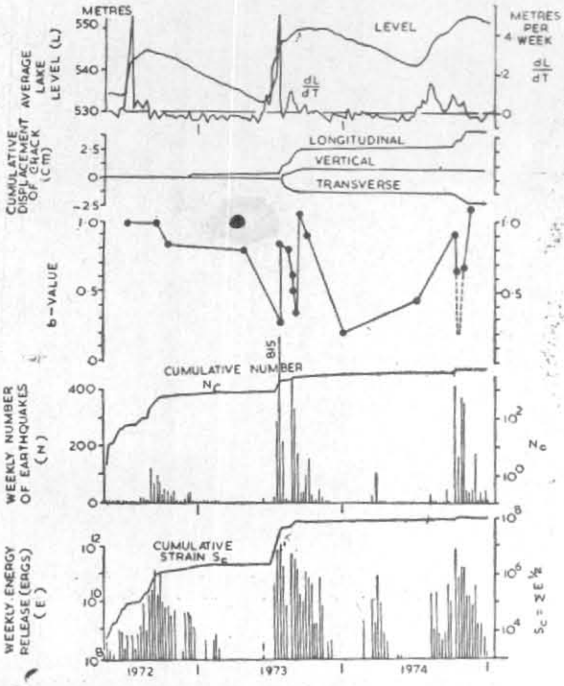

Fig. 4. Showing lake level variations, displacement at the ground crack, *b*-values and micro-earthquake activity at *mula* reservior.

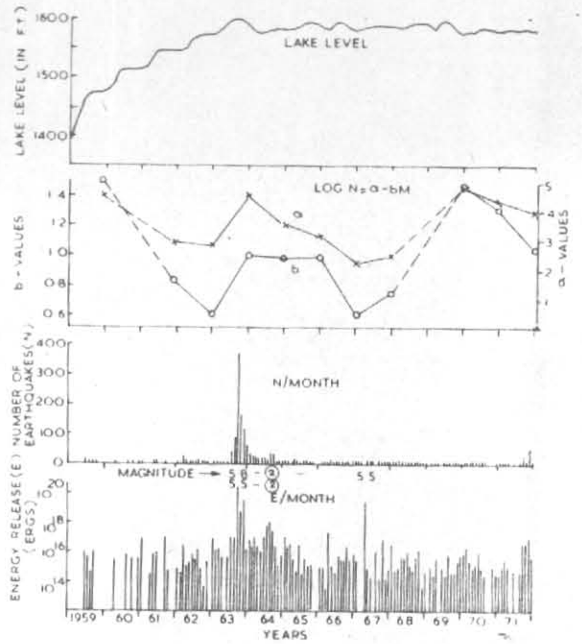

Fig. 5. Showing variation with time of lake levels, *a*-and *b*-values, frequency of occurrence and earthquake energy release (Kariba lake region)

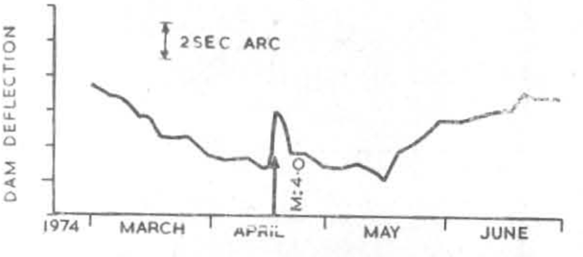

Fig. 7. Coseismic Koyna dam deflection variation accompanying a local earthquake of magnitude (*M*) 4·0 on 17 April, 1974.

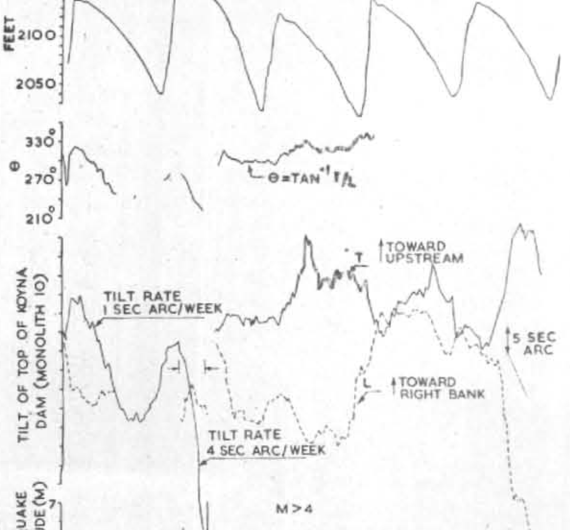

Fig. 6. Tilt of Koyna dam top (Monolith 10) measured with torsion pendulum (T_o : 4·0 sec), earthquakes ($M \geqslant 4$) and lake levels

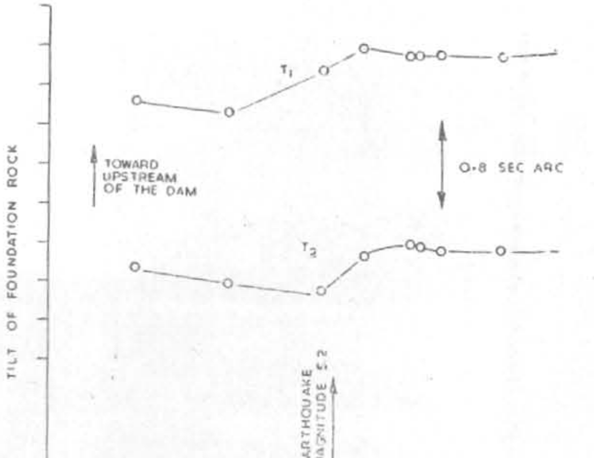

Fig. 8 Coseismic tilt variation in foundation-rock measured with water tube tiltmeters T_1 and T_2.

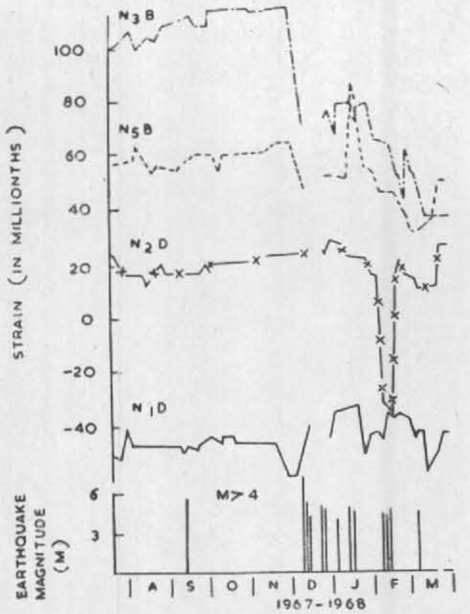

Fig. 9. Variation of strains in Carlson type strain gauges embedded in the foundation level in the Koyna dam.

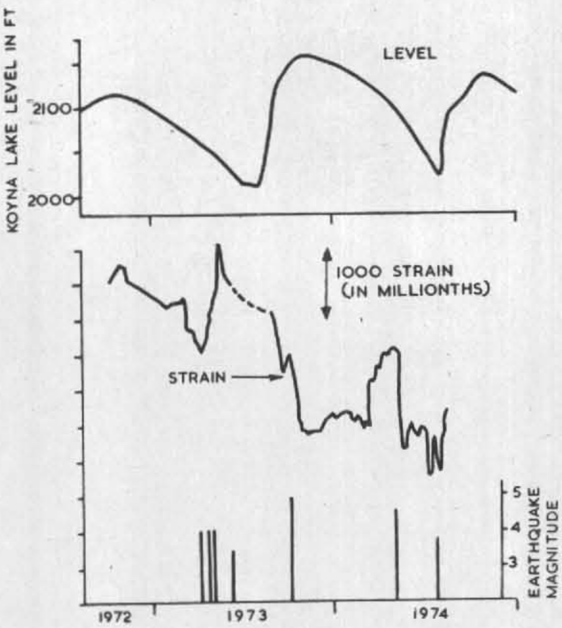

Fig. 10. Variation of strain measured in rock at depths of about 1 km and occurrence of earthquakes in Koyna region

to ground tilt from various meteorological parameters over and above the tectonic movements. Inspite of this, the ground tilt observations in several cases have indicated consistent premonitory variations that could be positively associated with significant earthquakes. It has been postulated from observational data that surficial extent and order of observed tilts could be adequate for the purposes of predicting location and magnitude of impending earthquakes. The accelerated ground tilting due to anelastic creep preceding earthquakes could be used for estimation of time of occurrence of impending events. Tilt measurements therefore form an important part of the Japanese, Chinese and American national programmes. In case of the main Koyna earthquake, it has been observed that the rate of tilting enhanced markedly by about four times from 1 sec arc/week to 4 sec arc/week nearly 14 weeks prior to the main event (Fig. 6). The 13 September 1967 earthquake (M : 5.8) occurred after about 2 weeks from the beginning of this accelerated tilting.

The tiltgraphs have been in operation continually since then. However, due to activities associated with strengthening of the dam, interpretation of these records has been found to be extremely difficult. Coseismic ground tilts have, however, been noticed in case of a few shallow mild earthquakes in close vicinity of the measuring stations (Figs. 7 and 8).

Strain measurements in *in-situ* rocks at depths were made at various locations in the Koyna region. Of these, the strain gauges embedded in the rock under dam foundation have recorded changes, probably coseismic, for the main Koyna earthquake (Fig. 9). However, these have not indicated, for reasons unknown, any long term premonitory variations as has been reported at several regions, *e.g.*, Nevada in U.S.A. (Priestley 1975). Fig. 10 shows variations in strains measured in the underground rock at Alore nearly 15 km west of the Koyna reservoir. These observations for an earthquake of 17 October 1973 (M : 5.2) reveal premonitory changes in rock strains. The period over which this change occurred could not be precisely determined due to paucity of measurements during some period, but could be roughly estimated to be of the order of about 4 to 5 months. Further, the observations also exhibit similar rapid changes in *in-situ* rock strains preceding other earthquakes of lesser magnitudes. The corresponding anomaly

TABLE 1

Premonitory phenomena and periods observed for some Koyna earthquakes

Date	Time (GMT)	Magnitude, (M_L)	Premonitory period, (T_p) (days)	Observed phenomenon
10-12-1967	22:51	7·0	1200	b-value
			~ 100	Tilt (short term)
27-5-1970	12:46	4·4	~ 60	Geomagnetic
19-4-1973	08:45	3·8	28	Strain
17-10-1973	15:24	5·2	4-5 months	Strain
17-4-1974	15:21	3·9	13	Velocity anisotropy
			~ 40	Strain
29-7-1974	23:17	4·3	20	Strain

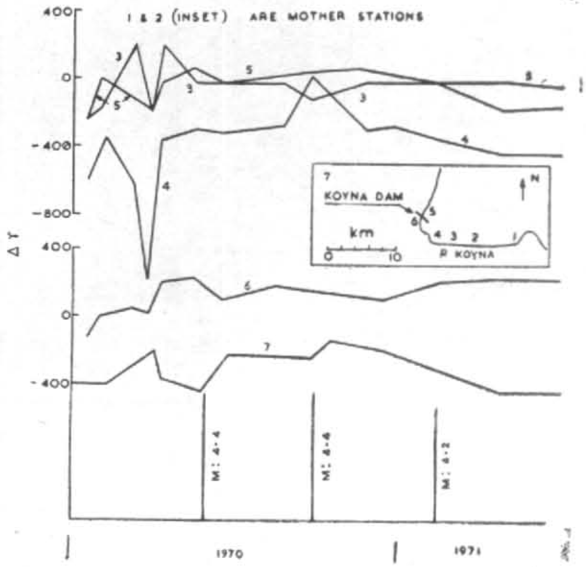

Fig. 11. Geomagnetic field departures ($\Delta\gamma$) and significant earthquakes in Koyna region (inset : locations of magnetic observation stations 1 to 7)

periods are a few weeks. These alongwith other parameter changes have been listed in Table 1, and are in excellent agreement with those observed elsewhere (Rikitake 1975). However, because of the noise present due to other factors, it is felt that application of strain measurements alone may not be sufficient for the purpose of earthquake prediction.

Measurements of total magnetic field intensities at Koyna region had been undertaken during 1970-71. The results obtained from part of these data have been published by Guha *et al.* (1974a) wherein it was concluded that the changes in total field intensities associated with earthquake occurrences were somewhat larger than those observed in other places (Fig. 11), and the same may be attributed to stress field changes in superficial basalt of larger piezomagnetic coefficient. Similar results have been obtained from further measurements (Fig. 12). Whereas the mother stations for the first survey were located just outside the active Koyna region, the same for the second survey has been taken at Alibag, 170 km away from the active source region. Premonitory periods obtained seem to be short term (type A_1 *vide* Rikitake 1975) and of the order of a few days in the second case (Fig. 12). But the premonitory periods for the first case (Fig. 11) are long term, of the order of 2 months ($\sim$60 days), which is in good agreement with that expected on the basis of Eq. 1). The premonitory geomagnetic field variations in case of Koyna region could thus be expected to be short term as also, in few cases, long term and magnitude dependent.

The measurements on plumb line deflections in Koyna region immediately after the main earthquake (Bhattacharji 1970) indicate that the amplitudes of deflections reduced considerably over an extensive region (about 120 km in length) covered by the observation points along the west coast (Fig. 13). These changes are conspicuous in the Koyna region only and hence could be considered as significant, and due to tectonic movements probably associated with uprising of subterranean heavy crustal material. Such changes which have been observed only at few other regions, indicate that measurements in Koyna region at shorter intervals may be at times of great importance in monitoring gravity variations associated with tectonic changes.

Geohydrological parameters, *viz.*, the well levels and temperatures and discharge rates of hot springs have not indicated any significant variations that could be utilized for earthquake prediction.

3. Discussions

Different parameters likely to be associated with changes preceding earthquakes have been identified through numerous experimental and field observations. Detailed monitoring of these parameters have been undertaken in several parts of the world which have been considered to be prone to destructive earthquakes. The San Andreas fault in California, USA, Tashkent and Garm regions of USSR, Tokyo and other areas in Japan, and parts of China are some of the regions where these efforts have been intensified.

Various techniques of predicting earthquakes in respect of time, location and magnitudes have been suggested (Scholz *et al.* 1973, Evison 1977, Brady 1977). Adams (1977) has recently reported on the papers describing techniques employed by the Chinese earth scientists. However, so far it has not been possible to evolve a universal and reliable method, inspite of the fact that a few earthquakes have been successfully predicted during recent years.

It has been reported that, from distinct tilt changes, geomagnetic and seismic velocity variations, possibility of an earthquake of magnitude 5.0 in Central California was foreseen by Healy and his colleagues of U.S. Geological Survey. The Japanese earth scientists seem to favour application of tilt and foreshock patterns, whereas those in USSR seem to rely more on radon emission measurements. As reported for the recent Haicheng earthquake of 4 Feb 1975 (M : 7.3), migration of earthquake foci, levelling variations, enhancements in foreshock activity, well water observations and abnormal animal behaviours had been used for precise prediction of the event (Adams 1977). These reports are very significant and encouraging, though in general, it could be stated that prediction of earthquakes is not as yet a reality but could be at the best a strong possibility.

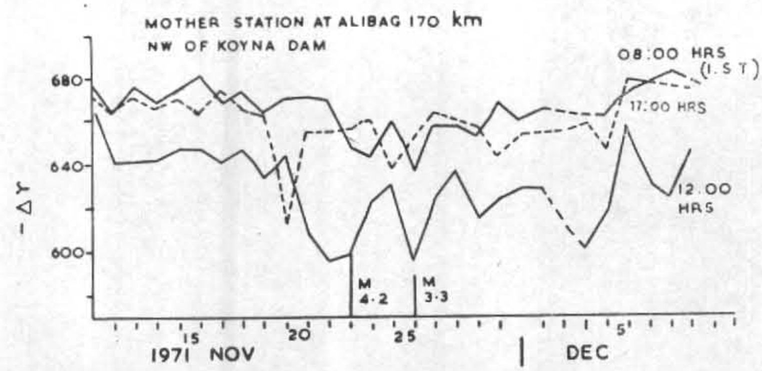

Fig. 12. Geomagnetic field departures ($\triangle\gamma$) and significant Koyna earthquakes

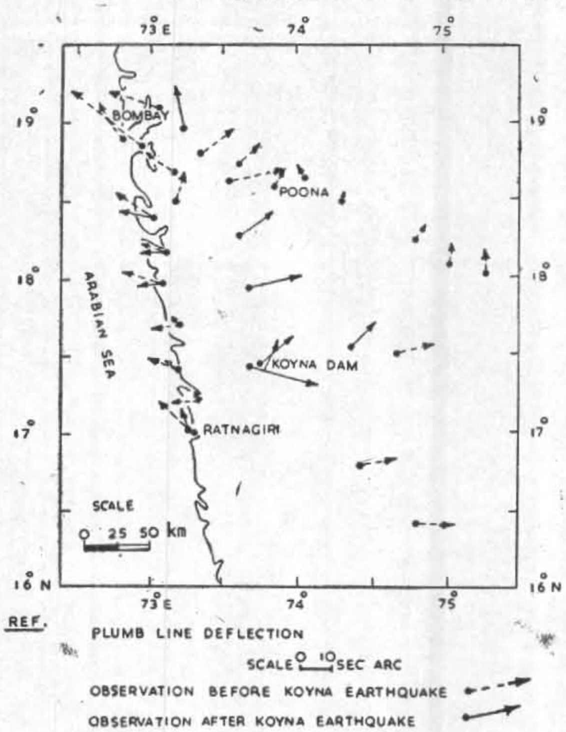

Fig. 13. Plumb line deflections in Koyna region (Bhattacharji 1970)

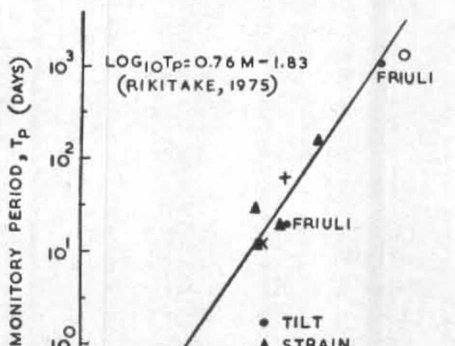

Fig. 14. Premonitory periods in days *Vs* magnitudes of some Koyna (India) and Friuli (Italy) earthquakes

From various such reports on different parameters, attempts have been made by a few researchers to relate anomaly (premonitory) period to earthquake magnitudes (Rikitake 1975, Scholz *et al.* 1973, Whitcomb *et al.* 1973, Tsubokawa 1973). Fig. 14 shows the relationship deduced by Rikitake (1975) alongwith the observations for a few Koyna earthquakes described in this paper. Data on premonitory periods as deduced from tilt observations of Friuli earthquakes, Italy (M : 7.0 and 4.5) reported by Biagi *et al.* (1976) are also plotted in Fig. 14.

For the Koyna region, it has been observed, from the studies discussed here, that variations in *b*-values, ground tilts, seismic wave velocity anisotropy, *in-situ* rock strains and geomagnetic field intensity could be usefully utilized in predicting the local earthquakes. The order of anomalies and the premonitory periods indicated by these parameters agree well with those observed elsewhere. On account of background noises in these parameters due to other factors, it is indicated that only the earthquakes above magnitude 4.5 or so may possibly be predicted in this region.

4. Conclusions

Of the various known geologic, geophysical and seismic parameters, *b*-values, ground tilts, velocity anisotropy, rock strain and geomagnetic field intensity seem to have applicability in prediction of earthquakes. Other parameters like V_p/V_s, resistivity, radioactivity, gravity, etc, may also be helpful in some cases for which more detailed observations are necessary. There are thus significant indications of premonitory changes as discussed here which are in good agreement with the results of earthquake prediction research conducted elsewhere.

Acknowledgement

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References

Adams, R. P., 1977, *Nature*, 269 : 14.

Avchyan, G. M., Belyaevskiy, N. A. and Polshkov M. K., 1977, *Phys. Solid Earth (Izvestiya)*, **12**, 763-768.

Bhattacharji, J. C., 1970, *J. Indian Geeophys. Uui*, **7** 17-27.

Biagi, P. F., Caloi, P., Migani M. and Spadea, M. C., 1976, *Annal. di Geofisi*, **29** : 137-152.

Brady, B. T., 1974, *Pur. appl. Geophys.*, **112** : 701-725.

Brady, B. T., 1977, *Pur. appl. Geophys.* **115** : 357-374.

Evison, F. F., 1977, *N. Z. J. Geol. Geophys.*, 20 : 129-142.

Guha, S. K., Gosavi, P. D., Nand, K., Padale J. G. and Marwadi, S. C. 1974 (a), *Koyna earthquakes* (Oct 1963 to Dec 1973), Central Water and Power Res. Station, Pune-24, India.

Guha, S. K., Gosavi, P. D., Padale J. G. and Marwadi S. C., 1974 (b), Proc., 2nd Internat. Congr. Eng. Geol., Sao Paulo, Brazil, Aug. 74, 1, Theme II-6 i: 1-7.

Gupta, I. N., 1973, *Science*, **182** : 1129-1132.

Gutenberg, B. and Richter, C. F. 1949, *Seismicity of the Earth and associated phenomena*, Princeton Univ. Press, (a) Princeton, N.J., U.S.A.

Mjachkin. V. I., Brace, W. F., Soboled G. A. and Dieterich, J. H., 1975 *Pur, appl. Geophys.* **113**: 169-181.

Mogi, K., 1962, *Bull. Earthq. Res. Inst'.* **40** : 831-854.

Papazachos, B.C., 1975. *Tectonophys*. 28 : 213-226.

Patil S.S., Padale, J.G., Gosavi P.D. and Guha, S.K. 1976 Preprints of the 6th Canadian Cong. App. Mech., CANCAM 77, Vancouver, Canada.

Priestley, K.F., 1975, *Pur. appl. Geophys.* **113**, 251-256.

Rikitake, T., 1975, *Bull. seismol. Soc. Am.*, 65 1133-1162.

Scholz, C.H. 1968, *Bull seismol. Soc. Am.*, **58** : 399-415.

Scholz, C.H., Sykes, L.R. and Aggarwal, Y. P., 1973, *Science*, **181** : 803-810.

Suyehiro, S. and Sekiya, H., 1972, *Tectonophys*, **14** : 219-225.

Tsubokawa, I., 1973, *J. Geol. Soc. Japan.*, **19**, 116-119.

Whitcomb, J.H., Garmany J.D. and Anderson, D.L., 1973, *science*, **180** : 632-635.

DISCUSSION

(Paper presented by J. G. Padale)

G.S. MURTY(BARC) : The observation of *b* values variation is useful only if we can tell how long *b* value decreases. Can we get this result from your observation ?

AUHTOR : Decrease in *b*-value indicates building up of stresses in the source region. These stresses could be released at random in several mild events or few significant ones. The *b*-values for the Koyna and Kariba regions (Figs.3 and 5) indicate the rate of accumulation of tectonic stresses, and as in the case of the Mula reservoir(Fig.4) it also gives some idea regarding regional seismic status. The *b* -value sould therefore be considered as a useful probabilistic parameter in the study of earthquake prediction.

P.N.AGRAWAL(SITEE) : The *b*-value has registered change during 11 December 1967 and the subsequent 5.1 magnitude earthquake. What about the Sep. 1967 earthquake which had 5.7 magnitude ?

2. Rikitake has since used twice the amount of data and revised the equation relating the precursor time to magnitude as follows :

$$\log_{10} T = 0.6M - 1.07$$

Authors may like to refer to this now.

AUTHOR : The half-yearly *b*-values (Fig.3) indicate a gradual decrease prior to 13 September and 10 December 1967 earthquakes. The values also show that partial release of stresses was effected due to the 13 September 1967 earthquake. Till September 1967, the frequency of occurrence of earthquakes had been inadequate for computation of *b*-values for shorter time intervals.

2. The relation (Eq.1 in our paper) deduced by Rikitake (1975) is in good agreement with those computed by other researchers like Scholz *et al.*, and Withcomb *et al.* The premonitory periods observed for Koyna earthquakes as well as Friuli earthquakes show better agreement with Eq. 1 reffered to in the paper rather than the revised one which has not been published as yet.