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550.34 (547.1)

Temporal variations of t_s/t_p ratios before and after Koyna earthquake of 10 December 1967 and calculation of its magnitude

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ABSTRACT. An analysis of the body wave travel time ratios (t_s/t_p) has been made for four seismographic stations Koyna Nagar, Satara, Mahabaleswar and Pune-from 24 October to 15 December 1967. The arrival times of body waves in different stations have been taken from published reports on Koyna Earthquakes. Origin times of the fore-shocks and aftershocks of the main Koyna earthquake of 10 December 1967 ($M=6.2$) have been claculated from the plots of *S-P* intervals and *P* arrival times at different stations. A plot of t_s/t_p ratios against time shows the anomalous variation of the ratio with a fall of about 10 to 14 % from the mean values for the period under consideration in Koyna Nagar, Satara and Mahabaleswar. No such t_s/t_p variations have been observed in Pune which shows more or less steady values. The time interval, which we call anomalous period, from the date of fall of, t_s/t_p from the mean value upto the time of occurrence of the main shock on 10 December 1967 is 32 days in each station. This anomalous period seems to coincide with the reported sharp and simultaneous changes indicated by some strain gauge placed in Koyna Dam, for about a month prior to the occurrence of the main Koyna earthquake. On using empirical relations based on dilatancy-fluid diffusion model, this amount of anomalous period is equivalent to that of a smaller shock of magnitude between 4 and 5. Consideration of aftershock area coupled with other empirical relations also indicates similar magnitude.

These facts tend to suggest either (1) the empirical relations used here do not hold good for Koyna earthquake or, (2) a smaller shock of magnitude between 4 and 5, occurring just ahead of the main shock, gave rise to t_s/t_p anomalies.

1. Introduction

Recently several workers have reported anomalous temporal variation of t_s/t_p or V_p/V_s ratio before certain classes of earthquakes (Rikitake 1976). But until now, no such variation of the above mentioned ratios have been reported to be associated with the so called reservoir related earthquakes such as Koyna earthquake of 10 December 1967. In this paper we present some evidence of what seems to be a short duration anomalous t_s/t_p variation with time before Koyna earthquake.

2. Data

Koyna earthquake ($M=6{\cdot}2$) is one of the most extensively studied earthquakes. Several seismographic stations were operating before, during and after the main event near about the meizoseismal area. Details of seismological and allied data that have been collected during October 1963 to December 1973, together with their analyses have been published by Guha *et al.* (1974). The present study is based on these data. No correction of any sort has been applied to the published data.

The stations used in this study are Pune (POO), Mahabaleswar (MAH), Satara (STA) and Koyna Nagar (KNI). All the stations except Pune are shown in the in-set of Fig. 4.

3. Analysis of data and presentation

Only those events which were simultaneously recorded by at least three stations were considered here for study. The travel times of compressional (t_p) and transverse waves (t_s) were calculated for each recording station by finding the origin time from a plot of the difference of arrival times of S_g and P_g waves against P_g arrival times for each shock. Shocks for which at least three plotted points did not fall on a straight line were not considered. For each shock t_s/t_p ratio was calculated for each station and plotted against time in Fig. 1. Average of all t_s/t_p values for Mahabaleswar, Satara and Koyna Nagar for a particular date was calculated and plotted against time in Fig. 2. Assuming flat earth for short distances and using the depth and location given by Guha *et al.* (1974), the distance of each recording station from the hypocentre of each event was found out. Using travel time as obtained above, P_g and S_g velocities (V_p and V_s) were calculated. The average of all velocities obtained in this way for a particular date was calculated for the three stations mentioned above and plotted in Fig. 3.

Only those events which occurred between 24 October 1967 and 15 December 1967 were considered here for study. The main shock occurred on 10 December 1967. The main reason, for this restriction was that no event before 24 October 1967 satisfied our criterion for selection of event. The average depths of the foreshocks and aftershocks were 6·2 km and 12·0 km respectively.

4 Discussions

Fig. 1 shows that t_s/t_p values fall by about 14·4, 10 and 11 per cent in Mahabaleswar, Satara and Koyna Nagar respectively, from the average values for the period under consideration. But in Pune the fall is less than 2 per cent. In all the stations the fall starts around 9 November reaching minimum around 10-21 November and finally regaining average value on 1 December, that is, 9 days before the main earthquake. Thereafter the values remain more or less steady with some smaller fluctuations—most of the time the values remaining higher than the average. The duration of the t_s/t_p anomaly, that is, the time interval from the date of fall of t_s/t_p values upto the time of occurrence of the main shock is 32 days in all the cases.

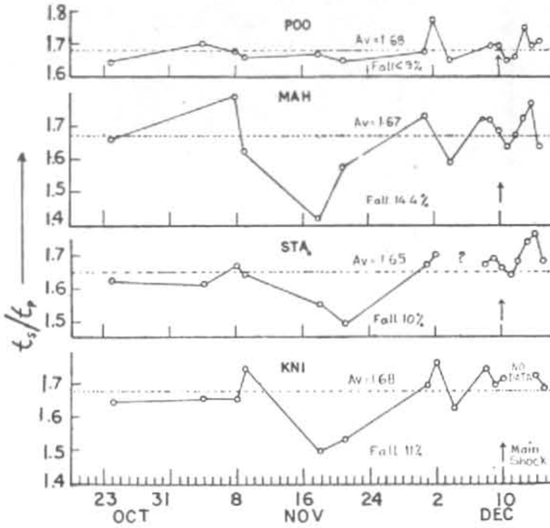

Fig. 1. Variation of t_s/t_p with time during 24 October-15 December 1967 in Pune (POO), Mahabaleswar (MAH), Satara (STA) and Koyna Nagar (KNI). The arrow represent the date of the main shock. The dashed lines represent average values for the period for each station

Fig. 2 (a) shows the composite curve for all the stations except Pune. The Fig. 2 (b) shows the variation of the number of earthquakes per day with time. The relatively quiet periods during the period of t_s/t_p anomaly are 30 October to 8 November, 13 to 20 November and 24 to 30 November. Diminishing trend of seismic activities along with lowering of t_s/t_p ratio until 20 November, but with increasing t_s/t_p ratio from 24 to 30 November is evident here. As is evident in Fig. 3, the compressional and shear wave velocities (V_p, V_s) also show temporal variations similar to that of t_s/t_p, the fall of V_p values being more (30 per cent) than that for V_s (21 per cent), from their average vaules for the period under consideration.

The observations made above are more or less similar to those reported by workers from U.S.S.R., U.S.A. and Japan (Kondratenko and Nersesov 1962. Aggarwal *et al.* 1973, 1975; Whitcomb *et al.* 1973, Ohtake 1973). They found a fall of V_p/V_s or t_s/t_p ratio by about 10 per cent from the average which is very close to what we have observed here. So we can assume a mechanism involving dilatancy hardening and flow of fluid giving rise to sudden drop and slow recovery of t_s/t_p and associated seismicity similar to those observed before the earthquakes in Blue Mountain Lake and San Fernando in the U.S.A., Garm region of U.S.S.R. and Japan (Scholz *et al.* 1973, Nur 1972) to be also present before the main Koyna shock of 10 Dec 1967. Using anomaly time (t) and magnitude (M) relation suggested by Wihtcomb *et al.* (1973).

$$\log t = 0.80M - 1.92$$

we get M=4.3 for an anomaly time of 32 days. On the basis of the same formula the anomaly time or a 6.2 magnitude earthquake will be about 3

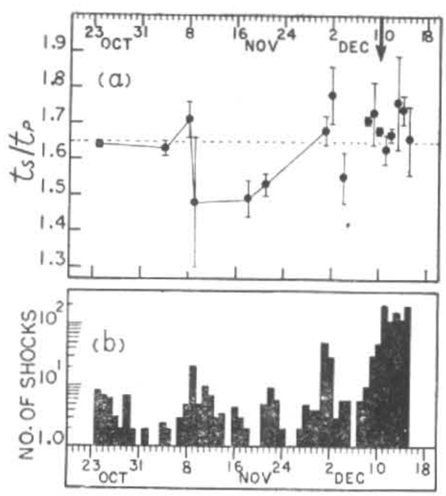

Fig. 2. (*a*) Variation of the average value of t_s/t_p ratio for Mahabaleswar, Satara and Koyna Nagar The vertical bars represent the spread of t_s/t_p values obtained on the particular date from all the stations. The dashed line represents grand average value for the period (1.65)

(b) Variation of the number of earthquakes per day with time before and after the main Koyna earthquake, as recorded by Koyna Nagar seismographic station from 24 Oct to 10 Dec. and 15 Dec. 1967 and by Govalkot-(Gov) station from 10 to 14 Dec 1967

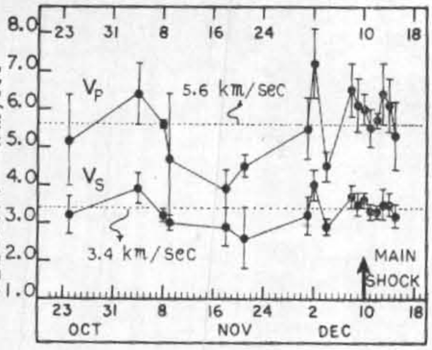

Fig. 3. Variation of V_p and V_s of P_g and S_g waves during 24 Oct., 15 Dec 1967. The arrow represents the date of occurrence of the main shock and the dashed lines represent average V_p, V_s values during the period

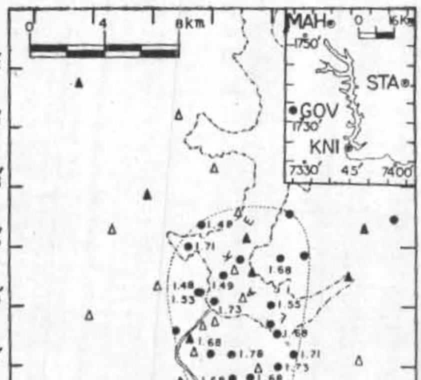

Fig. 4 Map of the portion of Shivaji sagar lake area showing the locations of the fore-shocks and after-shocks during 24 Oct to 15 Dec 1967. The solid circles and triangles represent fore-shock and after-shock respectively. The circle with a numberical value which is the t_s/t_p value on the Particular date of occurrence, and the solid triangles are the shocks used in this study. The egg-shaped areas covered by dotted lines contain about 90% of all the fore shocks (bigger area) that occurred during the period under consideration and about 50% of the after shocks (the smaller area) that occurred during the next two days of the main shock. The cross mark (X) represents the probable location of the shock of magnitude 4·3. The inset shocks the location of Mahabaleswar (MAH), satara (STA), Govalkot (Gok) and Koyna Nagar (KNI) relative to the lake.

years which is much longer than what we found here. But, absence of long period data does not permit us to verify the occurrence of this long duration anomaly. Thus the dilatancy fluid diffusion model of earthquake precursor (Scholz 1973, Nur 1972) requires the presence of a shock of magnitude around 4.3 which occurred almost at the same time as the main shock of the Koyan earthquake.

Locations of the fore-shocks and after-shock that occurred during 24 October to 15 December 1967 are shown in Fig. 4. About 90 per cent of the located fore-shocks lie within an egg-shaped area of about 62 sq km, lying in a North South direction,with the narrow end towards the highest intensity region. After-shocks that occurred during the next five days after the main shock, seem to be scattered all over the area. However, 50 per cent of the located after-shocks, which occurred during the next two days of the main shock, seem to have been clustered in another egg-shaped area of about 18 sq km, oriented in an east-west direction with the narrow and towards highest intensity region. The fore-shock area is about 3.5 times larger than this area. In terms of characteristic linear dimension (L) defined as the square root of area, linear dimension of fore-shock area (about 8 km) is almost double that of egg-shaped aftershock area (4.2 km), bounded by dotted line in the Fig. 4.

Putting L=4.2 km for the egg-shaped after-shock area and using the empirical formula relating focal dimension (L) with precursor time (t) (Whitcomb *et al.* 1973).

$$L \text{ (km)} = 0.58 \, [\, t \text{ (days)} \,]^{\frac{1}{2}}$$

t comes out to be about 50 days. This compares favourably with the t_s/t_p anomaly duration period of 32 days observed here.

Again putting t=32 days in the same formula we get L=3.2 km which compares favourably with the characteristic linear dimension (4.2 km) of the bounded aftershock area. In both the cases, the uncertainties involved in the empirical relations will have to be taken into account.

For a shock of magnitude 6.2, the characteristics linear dimension of the aftershock area on the basis of the formula mentioned above, should be about 35 km. The fore-shock area dimension should be more than this. But here it is much less than these expected values.

It is interesting to note that the maximum intensity region of Koyna earthquake passes through a region where the two egg-shaped areas come closer. The closest point (shown as cross-mark in the figure) lies near the end of an aftershock region which might be very close to the epicentre of the shock giving rise to t_s/t_p anomaly, if we assume here the existence of a main shock-aftershock spatial relationship, similar to those observed by Mogi (1969) and Aggarwal *et al.* (1975).

Another fact that might be directly related to the variation of t_s/t_p ratio is the readings of some strain-gauges located in the foundation level of Koyna dam. These Carlson type strain-gauges recorded sharp and simultaneous strain changes since about a month prior to the occurrence of the main shock of 10 December 1967 (Guha *et al.* 1974). This period of strain varation seems to be simultaneous with the anomalous variation of t_s/t_p.

The facts mentioned above, such as anomaly duration period of 32 days, smaller dimension of foreshock area, strain-gauge readings at Koyna dam etc correspond to an earthquake of magnitude much less than what has been accepted so far (M=6.2), obviously, if it is of magnitude 6.2, and if the anomalies etc, are due to this earthquake, the empirical relations mentioned here will not be applicable in this case. However, we should note that the Koyna earthquake of 10 December 1967 has been regarded as a highly complex type of earthquake (Langston 1976). Several events occurring in the first few seconds of Koyna earthquake have been identified in the accelerograms of 10 December 1967 (Gupta *et al.* 1971). Langston (1976) indicated the possibility of a small precursor event occurring approximately one second before the main shock. These facts suggest the possibility of occurrence of at least one smaller shock before the main Koyna shock, which might vary well be responsible for the anomalous variation of t_s/t_p ratio, smaller foreshock area and sharp and continuous fall of strain gauge readings since about a month prior to the main shock.

The main drawback of this study is the lack of sufficient amount of earthquake data for a longer period before the main shock to study t_s/t_p variation during "quiet" period. Beidses t_s/t_p anomaly hangs critically on a few data points only. The detailed crustal structure of the Koyna region is also not available. Nevertheless, this study probably indicates the necessity of more detailed and thorough analyses of the near station seismic data to understand more about the complex Koyna earthquake.

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DISCUSSION

(Paper presented by S. K. Sarmah)

G S. MURTHI (BARC) : Your extrapolated result for the origin of event can be compared to the exact value observed at Koyna. Is this done? Because the variations you observe may as well be due to extrapolation.

AUTHOR : The locations of the origins of the events used in this study were not necessary. Only origin time of each event was necessary which was found by standard method So the question of comparison with Koyna does not arise.