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On two recent earthquakes in the Deccan

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ABSTRACT. A macroseismic study of the calamitous Koyna earthquake of 10 December 1967, 22h 51·3m GMT and the Andhra Pradesh earthquake of 13 April 1969 has been made and the results presented in this paper. These disturbances, particularly the former one, possess many special features warranting study of the various aspects. Further, the microseismic parameters of the Koyna earthquake, such as, the depth of focus, magnitudes etc, as published from different centres are at variance with one another beyond reasonable limits of reconciliation. A fresh examination of the position using different techniques was, therefore, felt necessary.

1. Introduction

The Peninsular shield of India, regarded as the Pre-Cambrian Blocks, is one of the most stable segments of the earth's crust. The area has been free from any folding or compression due to orogenic or tectonic disturbances during long period of geological ages. The Koyna dam (17° 23′ N, 73°45′ E), is situated on the western part of the Peninsular shield on Basalt rock known as the 'Deccan Trap'. This Basalt rock formation over the Granite, was due to successive flows of lava of varying thicknesses. In between two different layers of Basalt are found layers of trap ash or red boles of varying thicknesses which are gradually converted into brecciated rock.

According to geological theory, the straight outline of the Malabar coast, the great Malabar fault, stretching from Kutch to Cape Comorin, was caused by the slipping of a large part of the sub-continent into the Arabian Sea, along this line. This was in recent Pliocene period. Thus the Western Ghats came up as a system of faults. The Malabar fault is accompanied by a system of fractures (faults) and it is possible that some of these faults must be passing by the Koyna dam area.

2. Materials for study

Earthquake reports from some seventy stations could be deciphered for use. These were supplemented by over two dozen reports from the Scientific Report (India met. Dep. 1968). These figures were each increased by one unit which was found to be the mean difference between our assessed values of intensity and those in the Report for some fourteen common stations. Thus modified, the intensity figures picked up from the Scientific Report fitted reasonably well with our system of isoseismals of the Koyna earthquake.

The results of observations by Phadke (1968) on fissures and cracks due to the Koyna earthquake provided materials for delimitation of the mezoseismal zone and assessment of the maximum intensity of the shock.

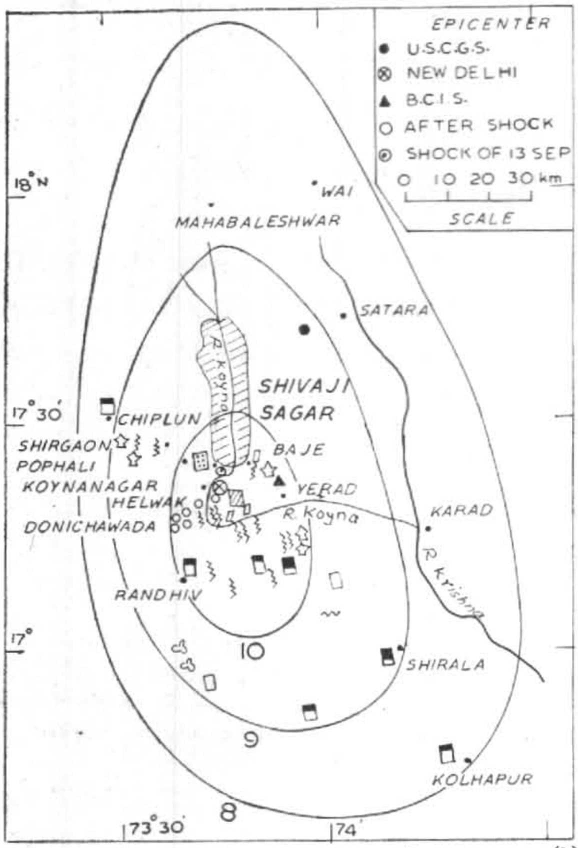
The isoseismals of both the Koyna and Andhra Pradesh earthquakes have been drawn in modified Mercalli scale of 1931 by Wood and Neumann and reproduced in Figs. 2 and 3. Observations of fissures and cracks, landslides, rock-falls etc by Phadke (1968) are summarised for a large majority of the stations and depicted symbolically in Fig. 1. This indicates the nature and extent of the mezoseismal area.

3. Analysis

3.1. *Koyna earthquake*

Radius of perceptibility (r) — The isoseismal lines (Fig. 2) are elongated. The major axes of the inner lines are aligned north-south indicating the direction of the fault. The lines are closer to one another on the west sector and farther apart from one another on the east side and, perhaps, indicate that the fault hades towards this side.

The epicentre as given in the Scientific Report is within a few kilometres from the centre of the innermost isoseismal where the surface effects due to the earthquake, such as, development of fissures, landslides, rock-falls etc were most



FISSURE CRACKS: SINGLE ∿; SOME ⌇; A NUMBER ⌇⌇; LAND SLIDES ▱, ROCKFALLS ☆, MOVEMENT OF ROCK & SOIL ♧ DAMAGE/DESTRUCTION TO HOUSES: NEGLIGIBLE □; SMALL ◫; MODERATE ■; TO OTHER STRUCTURES SEVERE/EXTENSIVE ▨; TO PROPERTY: SEVERE / EXTENSIVE ⊞

Fig. 1

prominent. The U. S. C. G. S. epicentre is some 45 km on the NNW of this area and is definitely out. The B. C. I. S. epicentre is some 15 km to the east.

The outermost isoseismal which stands for the felt-area, encloses an area of 697600 sq. km corresponding to the radius of perceptibility of 470 km.

Maximum intensity of the shock (I_0) — To arrive at a definite conclusion on the maximum intensity, we shall briefly discuss the field observations of Phadke (1968) in the mezoseismal zone.

Two types of fissures and cracks were observed. The first type was on the steep slopes of high hills and were due to slumping of the soil. These were confined to the soil and sub-soil only. The length and breadth of a fissure at Palsi-Panery area for instance, were 15 metres and 3 to 15 centimetres. The depth was 2 metres.

The second type of fissures/cracks were confined to a narrow zone of about 30 km in length along Baje-Nanel-Donicha Wada-Kadoli in a direction N 20° E-S 20° W. The zone extended further south to Rundhiv-Lotiv. The large majorrity of these fissures and cracks were individually aligned N 15° W-S 15° E, in a right handed echelon pattern. These were also confined to soil and sub-soil only having length and breadth not exceedig 100 metres and 20 centimetres respectively. The Karad-Chiplun road was badly cracked. The breadths of the cracks were 15 to 20 cm. A masonry structure having 75 cm height and cross-section 40×40 cm near Baje was detached from the base and rotated by 9° in an anticlockwise direction.

Innumerable instances of rock-falls were observed in the regions of Kumbharlighat hills, Prachitgad, Gunabhatgad hills. Some cases of falls were noticed at Baje and minor ones, at Ambaghat. Numerous instances of movements of rock and soil were observed at Devrukh-Shakharpa road area. Hills from which rocks fell, had columnar joints on the tops. The joints were opened due to the earthquake and masses of rock fell. There were some deaths due to rock-fall.

A number of cases of landslides were observed on the hills north of Donicha Wada, some cases at Prachitgad and a few at Baje. Donicha Wada was the scene of potential landslide. The zone of landslide is also aligned N 20°E-S 20°W, that is, along the zone of second type of fissures and shear cracks.

It has been reported that nearly 85 per cent of the houses were razed to the ground due to the earthquake at Koynanagar. Also 50 per cent of the total deaths took place at this place. The Helwak bridge collapsed and the Chiplun-Karad road was badly cracked. The ravage of death and destruction extended to as many as 991 villages where 47300 houses were rendered unfit for habitation, 177 persons died and 2272 persons injured. According to an authentic report, the number of houses destroyed, damaged and partly damaged in Shirala Tehsil alone was 135, 1,719 and 1,148 respectively. Of the damaged buildings, 487 were public buildings, such as temples, school buildings, Panchayat offices etc.

We reproduce below the relevant tests in grades 9, 10 and 12 of the intensity scale used.

Intensity 9 — Cracked ground conspicuously; damage great in substantial (masonry) buildings.

Intensity 10 — Cracked ground upto widths of several inches; fissures upto a yard in width ran parallel to canals and banks; open cracks and wavy folds in asphalt road surfaces ; landslides considerable from river banks and coasts ; damage severe to bridges, some destroyed ; destroyed most masonry and framed structure.

Intensity 12 — Landslides, falls of rock of significant character, numerous and extensive; wrenched loose, tore off large rock masses; disturbances in the ground numerous and varied and numerous shearing cracks.

It will thus be clear from above that maximum intensity due to Koyna earthquake definitely exceeded the grade 9 and reached the grade 10. The shock may be termed a major one.

It is surprising that many of the tests of grade 12 were noticed in the present instance. Of course these effects—landslides, rock-falls etc occurred extensively in a gigantic and terrific scale in the case of very major shocks, such as, the Assam earthquakes of 1897 and 1950. In the present instance, these were mild and comparatively localised. From the nature and magnitude of the effects observed and other considerations that follow we have concluded that the maximum intensity of the Koyna earthquake cannot be matched with the maximum range of the grade 10 and that it was between 9 and 10. For practical purposes, we have adopted the figure 9·5.

The area over which the above effects were conspicuous was about 3,000 sq. km.

The depth of focus — The depth is calculated as on a previous occasion from the following empirical formulae. The calculated values are as in Table 1.

$$\frac{r}{h} = \sqrt{10^{I_0/3 - 1/2} - 1} \qquad (1)$$

$$\frac{r}{h} = \frac{I_0^3 - 3 \cdot 4}{2H} \qquad (2)$$

$$I_0 - I = s \log \frac{D}{h} \qquad (3)$$

where,

r=Radius of perceptibility in km,

h=Focal depth in km,

I_0=Maximum intensity of the shock (in M. M. scale, 1931)

I=Intensity corresponding to a particular isoseismal (1-2 in the scale used),

H=18±km,

D=Hypocentral distance in km, *i.e.*, $\sqrt{h^2 + \triangle^2}$

$\triangle$=Epicentral distance in km, at the limit of perceptibility and

s=A parameter taken as 6.

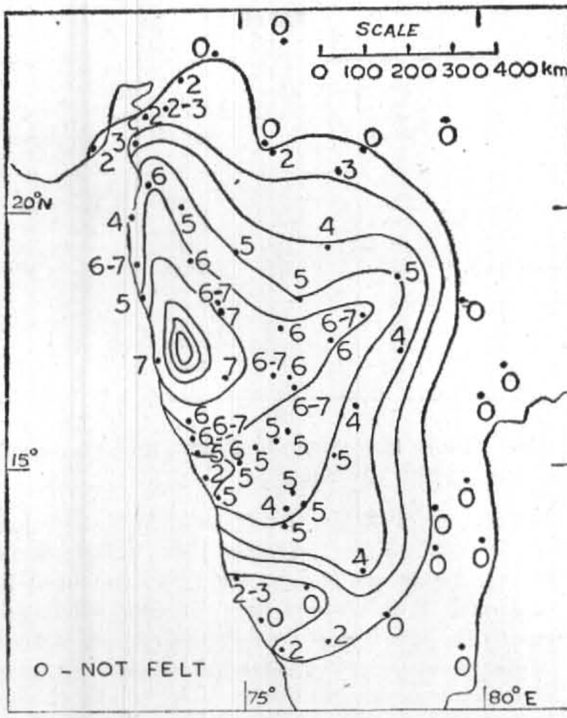


Fig. 2. Isoseismals, Koyna Earthquake, 10 Dec 1967
Modified Mercalli Scale 1931

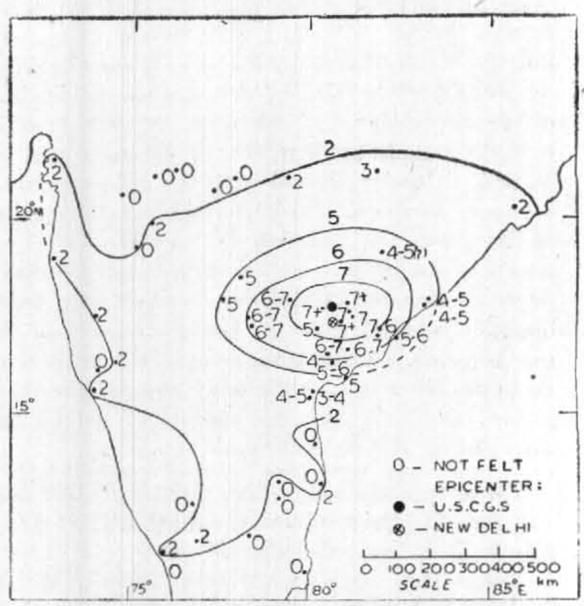


Fig. 3. Isoseismals, A.P. Earthquake, 13 Apr 1969

TABLE 1

r (km)	I_0	h(km) Eq. 3	Eq. 1,2,3 (Av)	Eq. 1,2 (Av)
470	9	19	22·4	22·7
	9·5	14·7	18·1	20·4
	10	12·1	15·2	17·4
Mean		15	19	20

TABLE 2

I_0	h (km)	M Karnik	Shebalin
9·5	15	7·27	7·34
	18	7·35	7·52
	20	7·40	7.64
Mean	—	7·34	7·50
10	15	7·57	7·7
	18	7·65	7·9
	20	7·70	8·0
Mean	—	7·64	7·87

We adopt the value 15-20 km, for the depth of the Koyna earthquake.

The value of the depth as published in the Scientific Report is 8 km and in the U.S.C.G.S. bulletin, 33 km. These are widely divergent and need be explained. It is noticed that the first movement due to the shock was a weak onset in the Indian seismograms and this was missed even by the highly sensitive seismographs at most of the foreign observatories. The origin time ($22^h\ 51^m\ 19{\cdot}0^s$) and the depth 8 km in the Scientific Report refer to the first onset and those published by U.S.C.G.S., that is, $0{=}22^h\ 51^m\ 24{\cdot}3^s$ and 33 km, obviously refer to the second onset. Further, in the Scientific report, it has been remarked that if the origin time of the second onset is taken as $22^h\ 51^m\ 23{\cdot}0^s$ it will give a depth of focus for the second event as 15-20 km, in agreement with the value deduced by us. It, therefore, stands to reason that our value of the depth also refers to the second onset. Evidently it should be so as the surface manifestations of the effects due to the shock on which our deductions are based, must be equated wholly to the second onset. Further from a depth of 8 km assigned to the first onset, only a shock of magnitude 8 or above can shake an area equivalent to the felt area of the Koyna earthquake.

The magnitudes (M) — The magnitude has been calculated by the formulae of Karnik ($M{=}0{\cdot}6\,I_0{+}\log h{+}0{\cdot}4$) and Shebalin ($M{=}0{\cdot}7\,I_0{+}2{\cdot}3\log h-2{\cdot}0$). The values are shown in Table 2. We are inclined to give preference to the deductions from Karnik's formula.

It appears that the best representative value for the magnitude can be taken between 7·3 and 7·4 ($I_0{=}9{\cdot}5$). It is found that the agreement between this value and those registered at four or five Indian stations by the standard Wood-Anderson seismographs situated at different directions and distances from the epicentre is 7·5 and is surprisingly close. The range may therefore be extended and put between 7·2 and 7·5 to represent the true magnitude of the shock.

The magnitude of the shock from body waves has been given as between 6·0 and 6·5 by New Delhi, B.C.I.S. and U.S.C.G.S. It will be interesting to study the difference of the magnitudes from both the surface and body waves of the shock at the different observatories.

Comparison of macroseismic and microseismic depth

(*a*) We next proceeded to find out how the macroseismic depth of an earthquake obtained by the above method, compares with the microseismic depth. For this purpose a few Indian earthquake shocks were collected for which microseismic depths were known from special studies or otherwise and the macroseismic depths of those shocks were calculated, from the known values of I_0 and r. When one set of these values are plotted as obscissae against another as ordinates, a straight line relation emerges.

(*b*) Next we picked up a specific earthquake shock with magnitude near 7·3 and 7·4, whose microseismic depth and felt-area are known from a special study. Such a shock was the Quetta earthquake of 1935 which had a magnitude of 7·5 and felt-area of 259, 200 sq. km. The felt-area of the Koyna earthquake is 697,600 sq. km. The approximate ratio of the two areas is 2·7. From seismological study, the depth of the Quetta earthquake was found to be definitely less than 10 km. By above formulae, we get a value between 7 and 8 km for the depth. The depth of the Koyna shock should, therefore, be ($7{\cdot}5\times 2{\cdot}7$) km or 20 km.

(*c*) A different approach to the problem was to study the variation of r with h in the case of those Indian shocks which had the values of M in the neighbourhood of 7·0 and 7·5. The resulting curve is reproduced in Fig. 4. From this curve which also serves the purpose of a nomogram, we get 20 km as the depth for the Koyna earthquake corresponding to its radius of perceptibility 470 km.

Thus, from different approaches to the problem we get a value very near to 20 km for the depth which gives 7·4 for the magnitude from Karnik's formula. This value of the magnitude (7·3—7·4) is also supported by results of analysis represented in Fig. 4.

Origin of the shock — The zone of fissures and cracks along Baje-Nanel-Donicha Wada etc over a length of some 30-40 km, in the direction N 20° E-S 20°W, has been described as a shear zone being associated with the epicentral tract. From the nature of development and orientation of the individual fissures and absence of surface indication of any vertical movement, a nearly horizontal and south to north movement of the eastern block

TABLE 3

r (km)	I_0	h (km) Eq. (1,2)	Eq. (1,2,3)	Eq. 3	Mean
540	7·5	50	46	39	45
	8·0	41	39	34	38

TABLE 4

I_0	h (km)	M Karnik	Shebalin
7·5	46	6·55	6·93
	39	6·49	6·91
	50	6·60	7·16
Mean		6·55	7·00

relative to the western one along this zone, has been visualised as the origin of the shock by Phadke (1968). From fault plane analysis using seismological data, Tandon and Chaudhury (1968) have reached identical conclusion regarding alignment of the originating fault which trends N 26° E-S 26°W. They found a nearly north to south movement of the western block relative to the eastern one. Such a block movement can also produce the type of shearing cracks/fissures etc observed and at the same time explain the pattern of distribution of the available epicentres of aftershocks, extension of damage and fissures west of Koynanagar along Pophali-Shirgaon-Chiplun and absence of major effect due to the earthquake on the north of the dam etc.

3.2. *Andhra Pradesh Earthquake*

Radius of perceptibility (*r*) — The isoseismals in Fig. 3 are elongated and the major axes of the inner ones are oriented east and west indicating alignment of the originating fault. These lines are close to one another on the west and farther apart on the east. The locations of epicentre of the shock by U.S.C.G.S. and New Delhi are plotted in the curve. They are near one another and not far from the centre of the innermost isoseismal.

The area over which the earthquake was felt is enclosed by the outermost line. This is about 907,000 sq. km having 540 km as the radius of perceptibility.

Maximum intensity — According to reports from a number of stations, this shock was the strongest one in living memory in that area. The generating sets at Kothagudem and Ramagudem were thrown out of commission and power supply to a number of

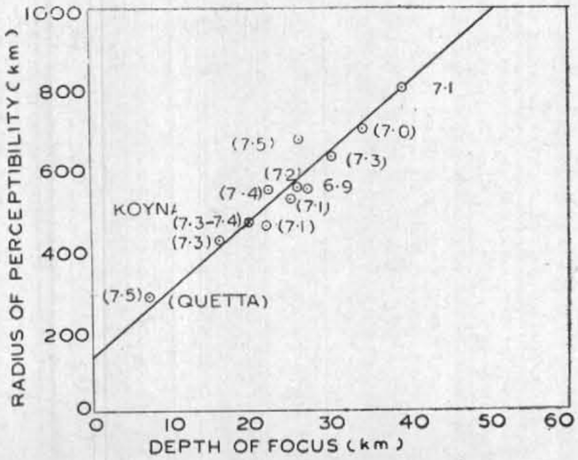


Fig. 4

stations was cut off. The power lines between upper Sileru and Kothagudem was snapped due to the earthquake. Shri Ram temple and some towers at Dharamsala near Bhadrachalam collapsed. Tiles came down from roofs of buildings at Karepalli. A Post Office building at Dummagudem collapsed partially, injuring some people. Even at Hyderabad at a distance of 250 km from the epicentre, a number of windows were broken and an old wall collapsed. At Erraguda two persons were injured due to collapse of a wall. At Kovvur, at a distance of some 160 km from the epicentre cracks appeared in roads here and there due to the earthquake. Cracks also developed in a number of new buildings including colliery buildings, station buildings, State Bank buildings at Bhadrachalam, Singereni collieries, Karepalli, Kothagudem, Dummagudem, Kovvur and other places. Cracks also appeared in walls of buildings at Eluru. The average distances of the places from the U.S.C.G.S. epicentre is 30 to 40 km. No report from places near the epicentre or from north is available. Considering all the aspects, we have adopted 7·5 as the maximum intensity for this shock near the epicentre, also in MM scale of 1931.

Depth of focus — The values of depth of focus calculated by above formulae are set forth in Table 3. We expect 45 km as the depth of the shock. The depth found by New Delhi is 30 km.

Magnitude — The magnitude calculated from the formulae of Karnik and Shebalin are given in Table 4. The most probable value of the magnitude is 6·5 and this agrees with the value found out by New Delhi. This gives a depth of 40 km from Karnik's formula.

We next examined the nature of variation of *r* with *h* for those Indian shocks which had *M* (microseismic) as 6·5 or near about this value. The relation is a straight line one. From this curve we get 38 km for the depth corresponding to the radius of perceptibility 540 km. We finally adopt 40 km for the depth and 6·5 for the magnitude of the Andhra Pradesh earthquake.

We may apply some check on the value of the depth obtained by comparison of this shock with the Satpura earthquake of 1938 which had nearly the same values of the various parameters — the maximum intensity (7·5), the radius of perceptibility (560 km), and consequently the depth of focus (40 km). The microseismic value of the magnitude was 5·5. Assuming somewhat smaller value for the maximum intensity from the available reports of surface effects, we may adopt 6·2-6·5 as the macroseismic magnitude for the magnitude of the Satpura earthquake.

4. Summary

Analysis of the macroseismic data of the two earthquakes has brought out the following parameters —

Parameters	*Koyna earthquake (10 Dec 1967)*	*Andhra Pradesh earthquake (13 Apr 1969)*
Felt area (sq. km)	697,600	907, 000
Radius of perceptibility	470 (km)	540 (km)
Max. intensity	9-10	7-8
Depth of focus	15-20 km, most probably near 20 km	40-45 km, most probably near 40 km
Magnitude	7·2-7·5, most probably near 7·3-7·4	6·5

Above parameters as well as the data used for fault-plane analysis of the Koyna shock are found to be related to the strong and most conspicuously recorded second onset, 4 sec after the first, in the Indian seismograms. The first onset which was weak and not recorded at most of the foreign observatories, had evidently no significant contribution either to the surface manifestations of the effects or seismic sequence that followed the second onset in the seismograms. A fresh examination of the whole question, using the second onset as the beginning of the main shock, is considered desirable.

From the shape of the isoseismals of the Koyna shock the direction of the originating fault is found to be aligned generally in a north and south direction.

Results of field survey of the mezoseismal zone of the Koyna earthquake (Phadke 1968) have revealed the existence of an epicentral tract (shear-zone) aligned NNE-SSW along Baje-Donicha Wada-Kadoli etc over a length of some 40 km as being due to some block movement where the eastern block moved nearly south to north relative to the western block. Among alternative suggestions, movement of the central block relative to the eastern and western blocks to south has also been surmised. Nearly identical conclusions on the orientation of the originating fault has been reached (Tandon and Chaudhury 1968) from faulty plane analysis using seismological data and nearly north to south movement of the western block relative to the eastern one has been visualised. Such a movement will explain the development and orientation of the fissures/cracks etc and also other effects such as the pattern of distribution of the available epicentres of the aftershocks, extension of fissures/cracks etc further west along Popahali-Shirgaon-Chiplun and absence of conspicuous damage and destructions in the area north of the Koyna dam.

The Andhra Pradesh earthquake appears to be almost a prototype of the Satpura earthquake of 1938.

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