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EXPLORATION OF FINE STRUCTURE OF THE UPPER CRUST IN THE KOYNA EARTHQUAKE REGION

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Introduction

The Peninsular Shield of India had been regarded broadly aseismic till the occurrence of the Koyna earthquakes. The causative factors of these earthquakes which have been frequently occurring since 1967 have been a matter of wide speculation. A number of geological, geophysical and geodetic investigations has been carried out recently to identify the factors associated with this continuing seismicity, in addition to the detailed seismological studies initiated as early as in 1963.

The Koyna dam (17° 23'. 85 N; 73° 45' E) and the Shivajisagar lake formed by it are situated in Western Marharashtra. This region of the Peninsular India is characterised by the Deccan trap formed by lava flows. Thickness of lava flows separated by short quieter periods between eruptions varies from a meter to 40 meters. Although, these lavas are believed to have erupted through a system of North-South trending fissures rather than cones, no clear cut evidence of their existence and locations has been found as yet. The Deccan trap thus masks the pre-existing geological features which, along with the thickness of Deccan trap in this region form an interesting and significant study while attempting to understand the causes of earthquakes occurring in this region, otherwise dormant.

Attempts to determine the structure of the upper crust in the Koyna region have been made by a number of researchers using seismic reflection and regraction, Deep Electrical Sounding, gravity and surface wave dispersion methods. The structures deduced from these studies are given in the Table. The thickness of the superficial basalt arrived at ranges from 1.0 to 1.5 km, the velocities for basalt obtained being between 4.5 to 5.2 km/sec which are rather low as compared to the velocities of 6.5-7.0 km/sec reported from laboratory measurements for basalts elsewhere. Tandon (1973) from studies of dispersion of surface waves also deduced the trap thickness of 1.25 km, assuming the trappean P-velocity of 4.6 km/sec. However, each of the methods used has its own limitations. An attempt to evolve deeper crustal structure using direct seismic waves from earthquake foci has been made here.

Data and Method

The closely spaced observatories of the Koyna Seismological net (Fig. 1) equipped with highly sensitive instruments have enabled accurate locations of a large number of earthquake foci. Data from five or more observatories was used to solve the equation

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = V_p^2 (t_i - t)^2 \qquad (1)$$

for evaluating x, y, z, the coordinates of the earthquake focus, V_p, the velocity of direct compressional wave P_g and t, the origin time, x_i, y_i, z_i being the coordinates of i^{th} recording

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Table Showing Velocities and Thickness Obtained from Various Studies for the Deccan Traps in Koyna Region

Sr. No.	Velocity of compressional waves V_p in superficial basalt layer (km/sec)	Deccan Trap thickness (km)	Velocity of compressional waves V_p in basement rocks (km/sec)	
1.	4.7 — 5.0	0.5 near Karad	5.85 — 6.5	Kailasam et al (1969) Mem. Geological Survey of India, 100, pp. 125-128; by seismic refraction survey
2.	—	1.2 at Koyna	—	Kailasam et al (1976) Curr. Sc., Vol. 45, p. 13, by D E S
3.	4.6	1.25 (average between Koyna and Bombay)	6.1	Tandon (1973), Pure and Applied Geophys., Vol. 109, pp. 1693-1700; from dispersion studies of Koyna earthquakes recorded at Bombay
4.	—	1.25 at Koyna	—	Athavale and Mohan (1976), Technical Report, National Geophysical Research Institute and Centre of Exploration Geopyhsics, Hyderabad; from D E S
5.	2.3 — 4.9	1.5 at Patan	6.0	—do— ; by seismic reflection survey
6.	—	1.2 at Koyna	—	Guha et al (1974), Report, CWPRS, Khadakwasla, Poona; from study of gravity data
7.	6.3	3 at Koyna	5.6	Present studies; from direct P_g and and S_g seismic velocities of Koyna earthquakes

station and t_i the arrival time of P_g at i^{th} station. For simplification, the origin of the Cartesian coordinate system has been placed at the Koyna Seismological Station (i = 1) of the net. Solution of Eq. 1 then yields

$$x^2 + y^2 + z^2 = V_p^2 t^2, \text{ for } i = 1 \quad (2)$$

and

$$2xx_i + 2yy_i + 2zz_i - 2 V_p^2 tt_i = r_i^2 - V_p^2 t_i^2, \text{ for } i = 2 \text{ to } 5 \quad (3)$$

where, $r_i^2 = x_i^2 + y_i^2 + z_i^2$

Treating the four equations, as per (3), in x, y, z and t, making use of the method of determinants, the values of x, y, z and t thus obtained will be in terms of V_p^2, and when substituted in Eq. 2, these yield a cubic equation in V_p^2 which can be solved to finally evaluate the unknown x, y, z, t and V_p. Similar solutions could also be obtained for the

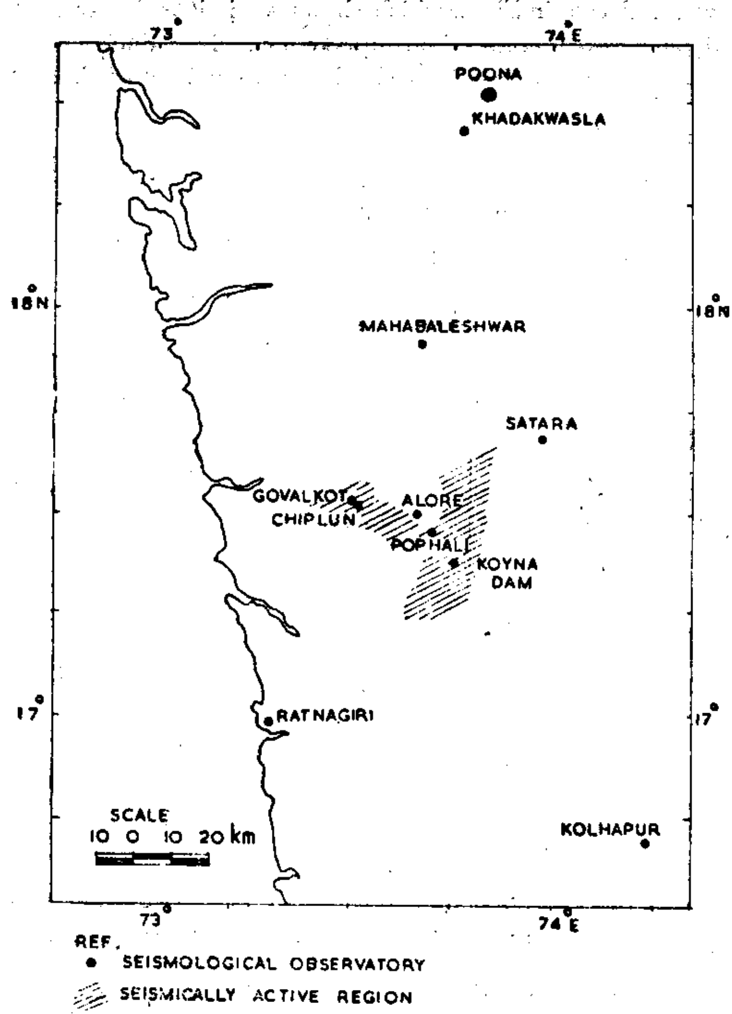

Fig. 1 Observatories of the Koyna seismological net and seismically active region

arrival times of the shear wave (S_g), which will yield the shear wave velocity V_s. The velocities V_p and V_s thus computed will be the average velocities for the crustal layer between the earthquake focus and the ground surface level at Koyna. The detailed computer programme developed for this purpose has been described by Guha et al (1970). Various methods for locating earthquake foci have been developed of which 'HYPOLAYR' (Eaton, 1969) is one of the most commonly used. In all these methods, a suitable crustal structure and the corresponding layer velocities are first evolved. Layer velocities are assumed to increase with depth. However, presence of high-velocity layer overlying a low-velocity one encountered in the Koyna region makes the use, for the purpose of locating foci, of such crustal model difficult. In this respect, the velocities deduced from the solution of equations (2) and (3) are found to be independent of any prior assumptions and hence the same could be used for evolving crustal structure of the region. The utility of the velocities thus obtained for Koyna region is well reflected in Fig. 2 which shows variations in average velocities of P_g and S_g waves with increasing depths of earthquake foci. In deducing crustal structure of the region containing the earthquake foci the following methodology has been used :

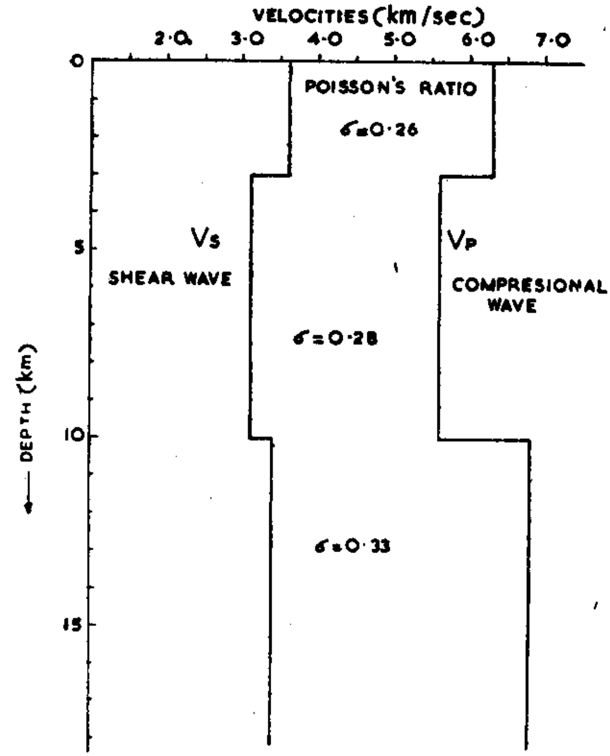

Fig. 2 Variation of average velocities V_p and V_s of direct compressional and shear waves with depth of earthquake foci in Koyna region

Let the average velocities as obtained from above method for earthquake foci located at depths z_1 and z_2 km be V_1 and V_2 km/sec respectively. The travel times of the vertical waves to reach the surface would thus be z_1/V_1 and z_2/V_2 respectively. Velocity V_{1-2} of the crustal layer between foci 1 and 2 can therefore be computed from

$$V_{1-2} = \frac{z_2 - z_1}{z_2/V_2 - z_1/V_1} \text{ km/sec} \tag{4}$$

Thus, velocities of both compressional and shear waves for different layers of the crust can be determined by selecting suitable foci and corresponding average velocities could be obtained from Eqs. (2) and (3). Using earthquake foci within a 15 km × 15 km area around the Koyna dam, an attempt is made to determine crustal structure for this region.

Discussion

The structure as evolved in Fig. 3 results from analyses of more than 1,500 local earthquakes. The depths mentioned are measured with respect to the Koyna dam, i.e. 644 m above mean sea level. Since the epicentres are located well within the closely spaced stations of the Koyna net, the order of error in locating earthquake foci is expected to be very small. The focal depth estimations are controlled by the stations of the net closest to the Koyna dam i.e. the Koyna and the Alore seismograph stations which are only a few kilometers distance away. The correction necessary on account of possible refraction of seismic waves will thus be very small and has not been applied to the results computed here. The distribution of the earthquake foci within the zone under study is fairly uniform upto the depth of 18 km. Below 18 km depth, this distribution is not uniform enough for estimation of velocity structure.

As seen from Fig. 3, the compressional wave velocity of 6.3 km/sec remains constant within the superficial layer thickness of 3 km. The corresponding shear wave velocity is

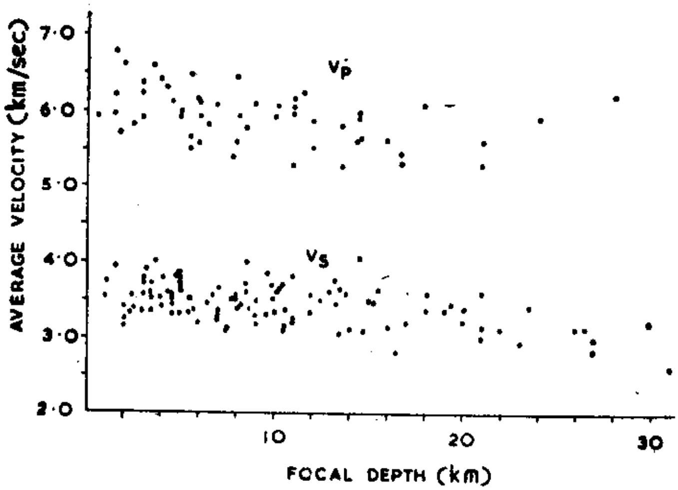

Fig. 3 Crustal structure at Koyna deduced from velocities of direct reaching seismic waves

3.6 km/sec. The velocities obtained by various researchers from seismic refraction and reflection studies (vide Table) for computed depths of 0.5 – 1.5 km are also in the range of 5.85 – 6.5 km/sec. The agreement, in this respect, of these results with those obtained from the present study is quite significant. It is also in good agreement with the velocities determined for basalt in laboratory studies.

For depths between 3 km and 10 km, the velocity of direct compressional waves obtained is 5.6 km/sec, which is significantly lower than that for the overlying layer. This low velocity could possibly be attributed to granitic formations underlying the superficial 3 km thick basalt. The shear wave velocity corresponding to this crustal layer is 3.1 km/sec. However, with the method used, it has not been possible to determine whether the transitions of these velocity structures are gradual or sharp. The velocities for P_g and S_g phases for direct compressional and shear waves for the sub-granitic layer are 6.8 km/sec and 3.4 km/sec respectively. The maximum crustal thickness upto which the present method could be applied is 18 km. This high velocity material is likely to be of tachylitic-basaltic transitional phase properties as indicated by Glennie (1932) from regional gravity interpretations, and may be of low-density but high seismic wave velocity, thus resulting in regional gravity deficiency.

The above structure at Koyna seems to be of localized nature as similar studies for the region about 10 km south-southwest of Koyna dam suggest that the top of the subgranitic layer lies at depth of over 20 km. However, the data available for this latter region is not adequate enough to be conclusive. From the regional gravity interpretation, Glennie (1932) had evolved a structure similar to that obtained at Koyna for a Northeast-Southwest profile through Bombay, which indicated maximum thickness of 3 km of Deccan traps caused by uprising lavas (density 2.83 gm/cc) near the West Coast overlying a layer of probable granitic composition (density 2.6 gm/cc), of average thickness of about 3 km followed by deeper tachylitic layer of density 2.85 gm/cc. Such a structure thus points to possible existence of molten or partially solidified subterranean lava pockets. The presence of such lava pockets has been inferred for Mt. Katmai region, Alaska from seismic wave studies by Matumoto (1971). For this purpose, the characteristics of seismic waves used were disappearance of S_g (shear wave) phase and high absorption of very low period seismic waves during transmission through the molten material. The same techniques have also been applied to Koyna earthquakes. However, so far, no such evidence indicating presence of very shallow lava pockets has been obtained for Koyna region.

The character of basement rocks underlying the top basalt layer in the Deccan trap region could only be surmised from the exposed formations on the fringes. Even this, however, points to a variety of rock types viz. Precambrian Dharwars, granites, gneisses, Kaladgis, Bhimas or Gondawana system of sedimentary formations. The Deep Electrical Soundings by Kailasam et al (1976) and Athavale et al (1976) indicate that the basement may be formed of electrically highly resistive crystalline rocks. The velocities obtained in the present studies indicate to the possible presence of granitic or Kaladgi formations. This is also to some extent supported by the structure obtained from interpretation of gravity data by Guha et al (1974) assuming a density contrast of -0.4 for top basalt and the basement rock.

The use of direct seismic waves from earthquakes and their velocity distribution with depth as employed in the present method has thus provided a simple and direct means to assess though very broadly the fine structure and nature of the upper crust upto approximately the average 'Conrad discontinuity' in the region around the Koyna dam.

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