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Seismic surface waves dispersion and crust-mantle structure of Indian peninsula

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ABSTRACT. The variations of group velocities with period of the fundamental Rayleigh and Love waves along two profiles Kodaikanal (KOD)-New Delhi (NDI) and Kodaikanal (KOD)-Poona (POO) as well as along paths from few epicentres in the neighbourhood of New Delhi to KOD have been used to investigate the average crust-mantle structure of Indian Peninsula. The periods range from 6 to 80 sec for Rayleigh waves and from 11 to 95 sec for Love waves. Theoretical dispersion curves for suitable models have been obtained to fit the observed data by using the group velocity perturbations for the variations of crust-mantle structural parameters. The structural models obtained show that the total crustal thickness is 41 km in the central part of the Peninsula and rises to 50 km in the Western Ghats region. The thickness of the granitic layer in these models is about 12 km. It has been observed that assumption of a simple isotropic mantle does not give a satisfactory fit to both Rayleigh and Love waves data at higher periods. A satisfactory fit has been obtained by considering the mantle to be anisotropic between the depths 50 and 140 km, where *SH* velocity is higher than *SV* velocity.

1. Introduction

The Indian Peninsula, or the Deccan shield, which occupies nearly two third of the area of Indian subcontinent, is one of the oldest blocks of the earth's crust and has maintained its continental character since Precambrian times. Very few studies have been made to investigate the structure of the crust and upper mantle of this important geological block. In the present paper the average crust-mantle structure of this area has been obtained from a study of dispersion of fundamental Rayleigh and Love waves.

2. Data and method

The long period seismograms of Kodaikanal (KOD), Poona (POO), New Delhi (NDI) belonging to USCGS world wide seismological stations network have been used in this study. The locations of the stations are KOD (10° 14′ N, 77° 28′ E), POO (18° 32′ N, 73° 51′E) and NDI (28° 41′ N, 77° 13′E) and shown in Fig. 1. In this paper the group velocities of fundamental mode surface waves along KOD-NDI and KOD-POO profiles as well as along paths from a few epicentres around New Delhi to KOD have been considered. The positions of the stations are well suited to study the average crust-mantle structure of the Indian Peninsula. The KOD-NDI profile crosses the central part of the Peninsula, KOD being at the southern side and NDI being at the northern tip of the peninsula. On the other hand, KOD-POO profile runs along a little to the east of Western Ghats, the most important hill range of the Peninsula.

All earthquakes during the period 1964 to 1968 giving clear records of surface waves and lying approximately on the great circles through KOD-NDI and KOD-POO have been used. The parameters of these earthquakes have been taken from USCGS source (for earthquakes upto 1966, the monthly seismological bulletin and 1967 onward, preliminary epicentral cards have been used) and are given in Tables 1 and 2. The azimuths (measured eastward from north) of the wave paths at the epicentres as well as the differences of epicentral distances from the stations have also been given in these tables. The calculated distance between KOD and NDI is 2040 km and that between KOD and POO is 996 km. For Rayleigh waves, in both the profiles it has been possible to obtain data in direct as well as reverse profiles. The periods range between 18 sec to 80 sec in the case of KOD-NDI profile and 18 to 66 sec in the case of KOD-POO profile. For waves which are coming from a northern direction and having long continental paths, lower periods (less than 30 sec) could not be used. And for waves reaching the station from southern direction higher periods (greater than 42 sec) were absent due to their long oceanic paths. Love waves coming from north have been used along the KOD-NDI profile in the period range between 28 to 97 sec. Some of the typical seismograms are shown in Figs. 2, 3 and 4. The method to obtain group velocities at different periods between two stations from earthquakes lying on the great circle through them is same as described by Brilliant and Ewing (1954), Tandon and Chaudhury (1964). The periods have been obtained,

TABLE 1

List of earthquakes used KOD-NDI profile

No.	Date	Time			Epicentre		Magnitude	Depth (km)	Azimuth (deg.) at epicentre		Difference of epicentral distance from KOD and NDI (km)
		h	m	s	Lat. (°N)	Long. (°E)			KOD	NDI	
					Rayleigh waves						
1	23 May 1966	11	51	26·6	21·3	−108·7	5·4	37	−11·5	−6·8	2011
2	13 Jul 1966	11	35	39·6	−41·6	80·1	5·1	33	−3·3	−2·7	2039
3	08 Aug 1966	08	02	45·8	19·3	−108·2	5·2	33	−11·3	−6·4	2013
4	12 Feb 1967	11	50	49·5	−42·6	83·9	5·4	—	−7·9	−6·2	2032
5	13 Feb 1968	18	48	06·1	−37·3	78·0	5·4	33	−0·7	−0·8	2039
6	14 Feb 1968	03	43	49·9	−37·2	77·8	—	33	−0·4	−0·6	2039
7	14 Feb 1968	11	32	03·1	−37·2	78·0	5·4	33	−0·7	−0·8	2040
					Love waves						
8	06 Dec 1965	11	34	51·9	19·0	−107·1	5·9	20	−9·2	−5·1	2021
9	06 Dec 1965	18	42	32·9	18·7	−107·0	5·3	40	−9·1	−5·0	2022

TABLE 2

List of earthquakes used in KOD-POO profile

No.	Date	Time			Epicentre		Magnitude	Depth (km)	Azimuth (deg.) at epicentre		Difference of epicentral distance from KOD and POO (km)
		h	m	s	Lat. (°N)	Long. (°E)			KOD	POO	
10	01 Mar 1965	21	32	13·3	15·4	−92·7	5·9	117	21·5	21·9	996
11	03 Dec 1965	15	21	24	−47·4	99·9	—	33	−25·5	−26·3	992
12	16 Dec 1965	10	09	24·2	−47·5	100·0	5·5	33	−25·6	−26·5	992
13	06 Apr 1966	02	59	02·4	−45·8	−96·2	5·7	33	−21·8	−23·0	989
14	18 Aug 1966	10	33	17·7	14·6	−91·7	5·6	85	24·1	23·8	996
15	07 Jan 1967	00	27	25·2	−48·8	112·7	5·8	33	−38·3	−37·9	995
16	27 Jun 1967	21	37	48·1	−46·4	96·0	5·4	33	−21·5	−22·8	988
17	25 Sep 1968	10	38	38·4	15·6	−92·6	5·7	138	21·6	22·0	995

TABLE 3

List of near earthquakes considered

No.	Date	Time			Epicentre		Magnitude	Epicentral distance from KOD (km)
		h	m	s	Lat. (°N)	Long. (°E)		
18	05 Nov 1966	18	53	07	28·6	83·9	—	2138
19	20 Feb 1967	15	18	40	33·6	75·2	5·5	2595
20	21 Feb 1967	12	37	44	33·5	75·4	5·0	2582
21	27 May 1967	19	05	46	35·8	77·6	5·5	2828
22	27 May 1968	18	36	00	30·1	80·5	—	2218

as usual, by plotting arrival times of peak and/or trough against their numbers and by measuring the slopes of the resulting curve. Since both the profiles are nearly in the NS direction, for Rayleigh waves the vertical as well as the NS (whenever possible) components have been used. For Love waves the EW component has been used. The particle motions of Love waves were noted to confirm their identity. The seismographs at all these stations have the same operational characteristics and thus no phase correction has been applied. The observed surface wave dispersion data of KOD-NDI profile and KOD-POO profile have been plotted in Figs. 5 and 8 respectively. The dispersion data obtained by this method is independent of error due to normal inaccuracies in epicentre and origin time data; however, the method neglects the refraction effect which the waves may suffer during their travel, especially at the continental margins. But such an effect decreases with the increase of period.

Short period Rayleigh waves have often been clearly recorded at KOD from earthquakes lying in and around the northern side of India. Love waves have also been recorded in some cases. A few of these earthquakes with epicentres close to NDI, have been used to determine the group velocities of Rayleigh and Love waves from the epicentres to KOD. The parameters of these earthquakes have been taken from Seismological Bulletin of the Institute of Physics of the Earth, Moscow and are given in Table 3. Moscow epicentral data have been preferred in view of the proximity of the Russian seismological network to these epicentres. The wave paths from epicentres to KOD are shown in Fig. 1. The periods of the waves greater than or equal to 13 sec were measured in the usual way, but periods less than 13 sec have been obtained by direct measurement of peak to peak or trough to trough The periods of Rayleigh waves for the earthquake of 27 May 1967 lie between 8 and 26 sec and for other four earthquakes the same lie between 6 and 12 sec. The periods of Love waves lie between 11 and 38 sec. The group velocity data have been obtained after applying the group velocity correction of the instrument. These data have been plotted in Fig. 10. Short period Rayleigh waves recorded at KOD are shown in Fig. 9.

3. Interpretation of data

Utilising world-wide group velocity data of Rayleigh waves of period range 20 to 45 sec, Santo (1965) divided the earth's surface into a few regions each having a standard dispersion curve. The group velocity data of Rayleigh waves obtained in KOD-NDI profile lie between the standard curves denoted as 6 and 7, which correspond to stable masses in a land area (Santo and Sato 1966).

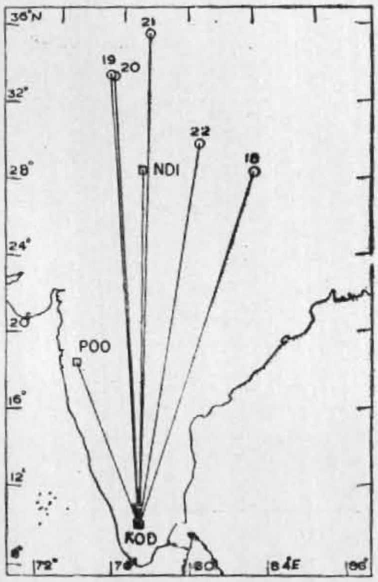

Fig. 1. Locations of the stations (squares) and of the near earthquakes (circles) given in Table 3. The thin lines show the paths for which group velocities have been considered

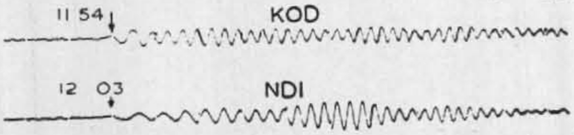

Fig. 2. Vertical component record of Rayleigh waves at KOD and NDI from earthquake No 7 (Table 1) of 14 Feb 1968

On the other hand those in KOD-POO profile are not parallel to the standard curves but lie close to a special dispersion curve denoted as *g*. Such a special type of dispersion was found along a path through rift valley in the eastern part of Africa (Santo 1965).

The group velocities of Love waves obtained in the KOD-NDI profile are quite high and agree with the values observed in a shield area (Brune. *et al.* 1963). The corresponding data of Rayleigh waves are, however, not relatively so high at higher periods. Fig. 5 shows the dispersion data in KOD-NDI profile and the theoretical dispersion curves for the models CANSD (Brune *et al.* 1963, Takeuchi *et al.* 1964) and 6 EG (Kovach 1965). The former model being used in the Canadian shield and the latter for the African region. Fig. 5 also shows that the theoretical curves for CANSD model more or less fit to the Love wave data but not the Rayleigh wave data; whereas the theoretical curves for model 6 EG fit to the Rayleigh wave data but not the Love wave data. Rayleigh waves dispersion data in NDI-Lahore profile have been used earlier by Gabriel and Kuo (1966) to investigate the crust-mantle structure in that

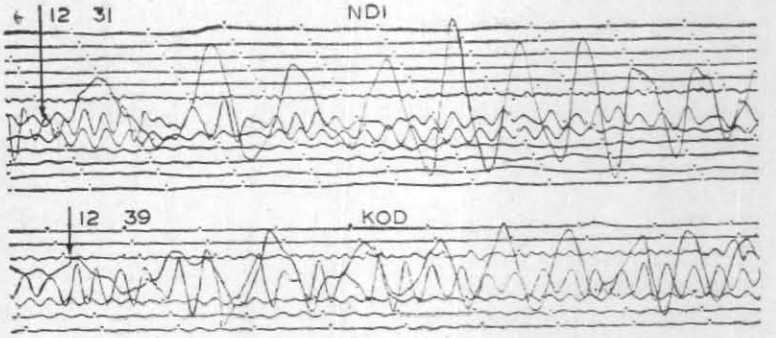

Fig. 3. East-west component record of Love waves at New Delhi and Kodaikanal from earthquake No.8 (Table 1) of 6 Dec 1965

TABLE 4

Earlier geophysical studies of Indian peninsula

Author	Region		Layer parameter	Sedimentary	Granitic	Basaltic	Subcrust
Tandon and Chaudhury (1968)	Deccan shield		V_p	—	5·67	6·44	8·24
			V_s	—			4·73
			T	—	22·5	18·5	
Qureshy *et al.* (1968)	Cuddapah Basin	I	ρ	—	2·7	2·81	—
			T	1	20	10	
Do	Do	II	ρ	—	2·7	3·01	3·27
			T	1	20	16·5	

NOTE: $Vp = P$-wave velocity (km/sec), $V_s = S$-wave velocity (km/sec), T=Thickness (km), ρ=Density (gm/cm^3)

profile. This profile lies to the north of the Peninsula. They used INDSD model in their study. This model is somewhat similar to CANSD and its theoretical curve (for Rayleigh waves) does not agree with the present observational data.

Our next task is the inverse problem to find out suitable crust-mantle structures, such that the corresponding dispersion curves satisfy the observed group velocity data. It has been seen that several theoretical models of the crust-mantle structure may sometimes be able to explain fairly well the observed dispersion data. In order to obtain a unique solution of this inverse problem it is therefore necessary to restrict a few parametes of the assumed crust-mantle structure which have been obtained by some other geophysical methods. A study of the earth's crust in this region was made by Tandon and Chaudhury (1968) using body waves from the main Koyna Earthquake of 10 December 1967. They obtained the thickness of the granitic and basaltic layers in the region as also the wave velocities. By using gravity data Qureshy *et al.* (1968) also estimated the structure of the crust in the Cuddapah Basin. All these results are given in Table 4. By keeping a few parameters same as obtained in these studies we shall now determine theoretical dispersion curves for suitable crust-mantle models satisfying the observed dispersion data. The theoretical curves have been obtained from Savarensky *et al.* (1965, 1967) and Bloch *et al.* (1969) using group velocity perturbations for the variations of structural parameters.

The crustal and subcrustal structure (model IP-1) adopted for Indian Peninsula along KOD-NDI profile and the corresponding theoretical curves obtained from Savarensky *et al.* (1965, 1967) are shown in Fig. 6 along with the observed data. It may be seen that the theoretical curves fit fairly well to the observed **data** except for Rayleigh waves at higher periods, where the theoretical curve lies above the observed values. The theoretical curves at higher periods could be lowered to fit the observed values of Rayleigh waves if lesser shear wave velocity (less than 4·73 km/sec) in the subcrustal half space had been assumed. This step would have however upset the fit to the Love wave data. In view of this and also the fact that this velocity has been observed for the subcrustal region by Tandon and Chaudhury (1968) a lesser velocity has not been assumed for interpretation.

The periods observed in the case of KOD-NDI profile range upto 80 sec for Rayleigh waves and 95 sec for Love waves and provide an opportunity

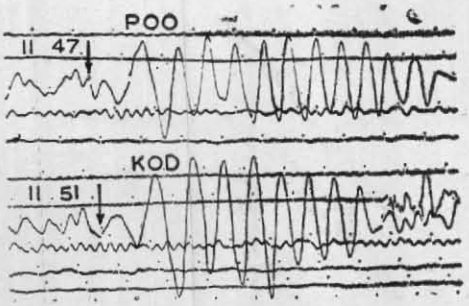

Fig. 4. Vertical component record of Rayleigh waves at Poona and Kodaikanal from earthquake No. 17 (Table 2) of 25 Sep 1968

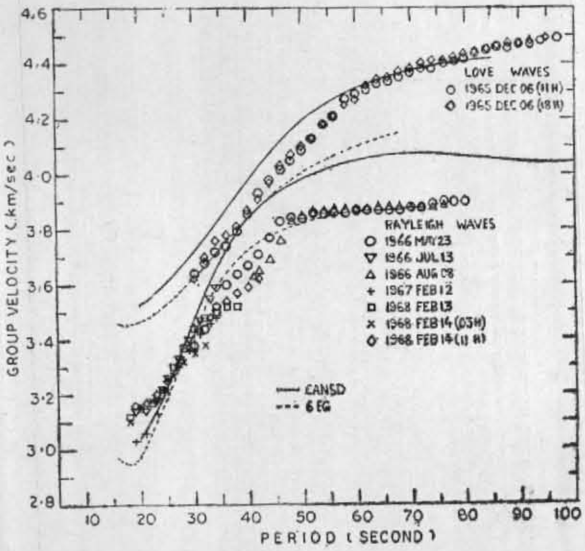

Fig. 5. Rayleigh and Love wave dispersion data of KOD-ND profile compared with CANSD and 6 EG models

to study the structure of the upper mantle in detail. In order to get the upper mantle structure the group velocities and group velocity perturbations as given by Bloch *et al.* (1969) for a shield model have been used. The perturbations have been given only for the variations of shear wave velocity, which affects more prominently the dispersion curve than the density or *P*-wave velocity. But no reasonable isotropic mantle structure could be determined so as to fit both Love and Rayleigh waves data. It may be noted that the discrepancy between the theoretical curve and the observations lies in the period range 55 to 95 sec, which is mostly affected by the structure between the depths 50 km and 140 km. Such a discrepancy was also observed earlier by McEvilly (1964) in central United States and Kaminura (1966) in Japan for phase velocities of Love and Rayleigh waves. McEvilly found that satisfactory fit to the observed data of both Rayleigh and Love waves in central U.S. required the assumption of anisotropy in the upper mantle. He found that *SV* velocity was 8 per cent less than *SH* velocity. Nuttle and Whitmore (1962) found that in case earthquakes having their foci at depths of 105, 120 and 125 km the *SH* component preceded the *SV* component by 1-2 sec, a possible indicator of anisotropy in those regions. Christensen and Crosson (1968) suggested transverse isotropy for the upper mantle from both laboratory studies of elasticity and petrofabric studies. The phase velocity discrepancy between Love and Rayleigh waves has recently been attributed by Thatcher and Brune (1969) as due to contamination by higher modes. This happens due to the fact that in some frequency range the fundamental and the first higher mode group velocity curves are very close or actually overlap. But Boore (1969 has shown that such a contamination would make the phase velocity both higher and lower and when a large amount of data is taken they will scatter around the mean curve. However, such a contamination will, in any case, not explain the present discrepancy of group velocities of Rayleigh and Love waves. The explanation which has been given to the present data is the anisotropy of the upper mantle between the depths 50 and 140 km; the structural parameters thus obtained (model IP-1M) and the corresponding dispersion curves are shown in Fig. 7. The shear wave velocity distribution in the crust of the model IP-1M is same as in the model IP-1. Anderson (1967) demonstrated the difference between the upper mantle structures in a shield area and a tectonic area; the mantle structure of the model IP-1M in its upper part shows that *SV* velocities correspond to those obtained in a tectonic structure and *SH* velocities to those in a shield structure. The Rayleigh waves theoretical curve in Fig. 7 at lower periods 20 to 40 sec could still be lowered by taking the proper *P*-wave velocities in the crust as in the model IP-1.

The crustal and subcrustal structure (model IP-2) adopted for KOD-POO profile and the corresponding theoretical curve obtained from Savarensky *et al.* (1965, 1967) are shown in Fig. 8 along with the observed data. The theoretical curve agrees well with the observed data except only for lower periods, where the effect of shallow structures is predominent. It may be noted that the shallow structure in this profile is complex and consists of Deccan trap in the northern part and precambrian gnesses and schists in the southern part. It seems

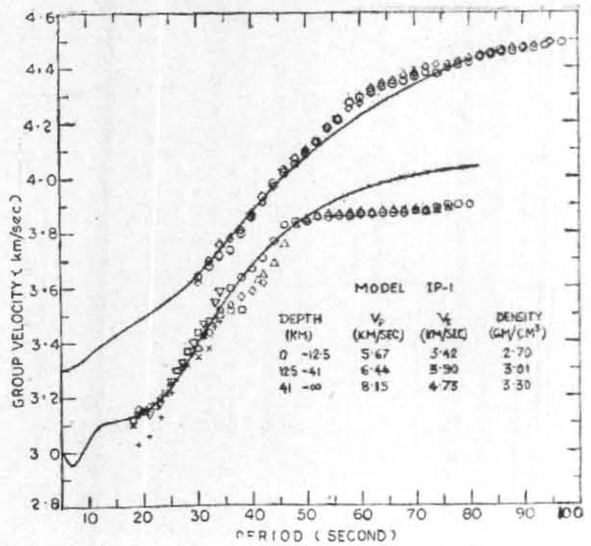

Fig. 6. Rayleigh and Love waves dispersion data and adopted crustal and sub-crustal structure (model II-1) along KOD-NDI profile

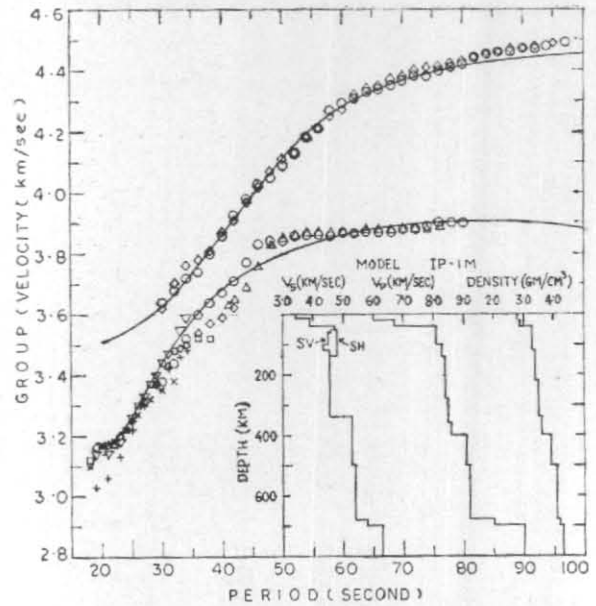

Fig. 7. Rayleigh and Love waves dispersion data in KOD-NDI profile. The theoretical dispersion curves have been drawn for the model IP-1M (inset)

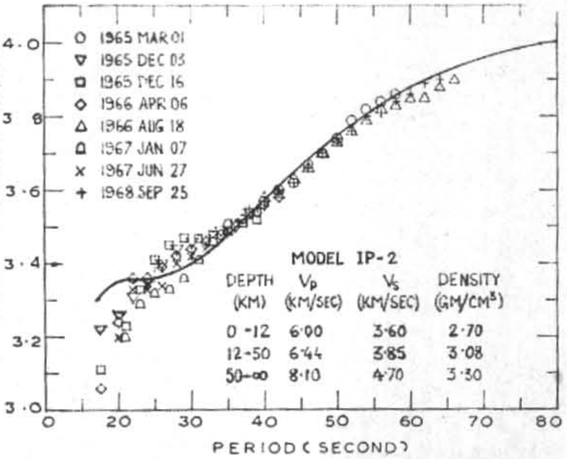

Fig. 8. Rayleigh waves dispersion data and the adopted crustal and sub-crustal structure (Model IP-2) along KOD-POO profile

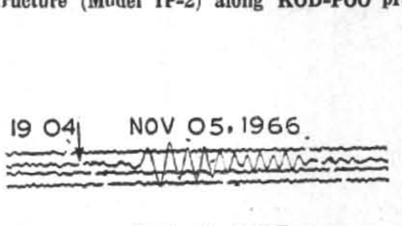

Fig.9. Vertical component record of short period Rayleigh waves at KOD from the earthquakes Nos. 18 and 20 (Table 4)

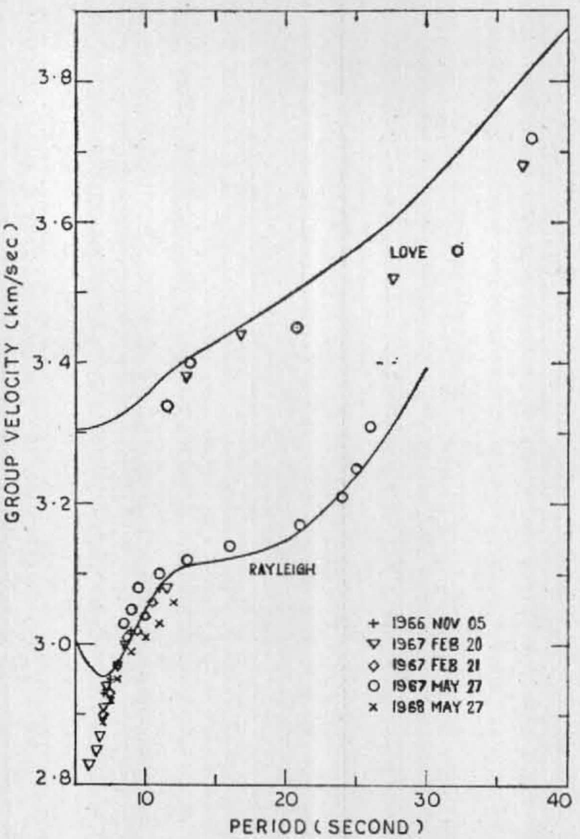

Fig. 10. Rayleigh and Love waves dispersion data from near earthquakes. The theoretical dispersion curves have been drawn from the model IP-1 (Fig. 6)

that a thin low velocity layer at the top of the crust may modify the theoretical curve to give a better agreement to the observational data.

Let us now consider the group velocity data of Rayleigh and Love waves from earthquakes originating near New Delhi and recorded at KOD. The observed data have been plotted in Fig. 10. The wave paths as may be seen from Fig. 1, are close to the KOD-NDI profile. In Fig. 10 the theoretical curves for the model IP-1 have also been drawn and show a close fit to the observed Rayleigh wave data. Love wave data remains a little below the theoretical curve for IP-1. This is probably due to the difference of crustal structure in the northern side of Delhi, which these wave paths have crossed.

4. Discussions and conclusions

The crustal and subcrustal structure of central part of Indian Peninsula and that of the Western Ghats region are given by models IP-1 and IP-2 respectively. In both these cases the granitic layer is quite thin compared to the basaltic layer, as generally observed in ancient platforms (Beloussov 1962, p. 71). As we go from central part of the Peninsula to the western side, the Conrad discontinuity remains approximately horizontal whereas, the Mohorovicic discontinuity deepens showing a thicker crust in Western Ghats region. The thickness of the granitic layer is much smaller than obtained by Tandon and Chaudhury (1968) for this region by body waves studies. The assumption of thin granitic layer for this region, where sedimentary layer is negligible, is esssential for the propagation of short period Rayleigh waves, which have often been recorded at KOD from the earthquakes in and around the northern part of India. The dispersion curves (Fig. 6) for the structure of this region (IP-1) do not have a minimum at a shorter period for Love waves as obtained in the case of Rayleigh waves; and due to this reason periods shorter than 11 sec could not be observed for Love waves although they travelled the same paths as the corresponding Rayleigh waves.

The mantle structure obtained (model IP-1M) for the Indian Peninsula shows an anisotropic structure between the depths 50 km and 140 km, where *SH* velocity is higher than *SV* velocity. This conclusion can be confirmed by using observations of higher modes of surface waves for this reason. The *SV* velocity profile determined here gives a shallow depth of the low velocity layer and this profile is similar to a shear wave velocity profile of mantle in a tectonic region (Anderson 1967). The *SH* velocity profile shows a deeper depth for the low velocity layer and is similar to a shear wave velocity profile of mantle in a shield region.

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