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Thickness of the Earth's crust between Delhi and Shillong from surface wave dispersion

A. N. TANDON and H. M. CHAUDHURY

Meteorological Office, New Delhi

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ABSTRACT. The paper presents the results of a study of the surface waves recorded by Long-Period (30-100) seismographs at Delhi and Shillong from an earthquake in the Atlantic Ocean. The crustal Rayleigh and Love wave dispersions for the composite continental path Epicentre—Delhi-Shillong as well as for the path Delhi—Shillong have been studied. The results indicate an average crustal thickness of 37 km for the former and between 40 and 45 km for the latter.

Mantle Rayleigh waves R_2, R_3 and R_4 were also well recorded. Results of the study of their dispersion show close agreement with those of Ewing and Press.

1. Introduction

During the months of March and April 1963, standard sets of seismographs were installed at Delhi and Shillong through the co-operation of the United States Coast and Geodetic Survey. Except for peak magnification, the other instrumental operating characteristics at the two places were the same.

On 3 August 1963, an earthquake of magnitude 6·1 and a depth of focus of 35 km occurred with its epicentre at Latitude 7·7°N and Longitude 35·8°W—origin time $10^h\ 21^m\ 36{\cdot}6^s$. The above data have been obtained from the epicentre cards issued by the United States Coast and Geodetic Survey. The position of the epicentre was about 21° west of the Atlantic Coast of North Africa and lay close to the great circle passing through Delhi and Shillong. The distance of the epicentre from Delhi was 106·1° and from Shillong 119·4°, whereas the shortest distance between Delhi and Shillong is 13·4°. At both Delhi and Shillong the long period seismographs recorded surface waves very prominently. The short period Benioff instruments also recorded prominently surface waves of periods around 20 seconds at both these places. This provided us with an opportunity of studying the dispersion of surface waves between the epicentre and the two observing stations and also the nature of the surface wave dispersion curves between Delhi and Shillong.

2. Observations

Dispersion curves of Rayleigh waves have been obtained by using only the records obtained by the vertical components. The records of the horizontal components were also compared with those of the verticals at both these places to see if the particle motion conformed to that of Rayleigh waves. This was found to be the case for both the places. In the Delhi records, Rayleigh waves which had travelled from the epicentre to Delhi by the longer path (the R_2 waves) were very clearly recorded and the nature of their dispersion has also been studied. R_3 and R_4 waves were also recorded at Delhi, although with much less amplitudes. These waves showed very clear inverse dispersion and provided us with dispersion data of Rayleigh waves upto periods of about 220 seconds. The record obtained by the vertical component—L. P. seismograph at Delhi is reproduced in Fig. 1.

The azimuth of the epicentre of the earthquake both at Delhi and at Shillong was not far from west. Consequently the N-S component L. P. seismographs at the two stations gave good records of Love waves. Calculations showed that the records

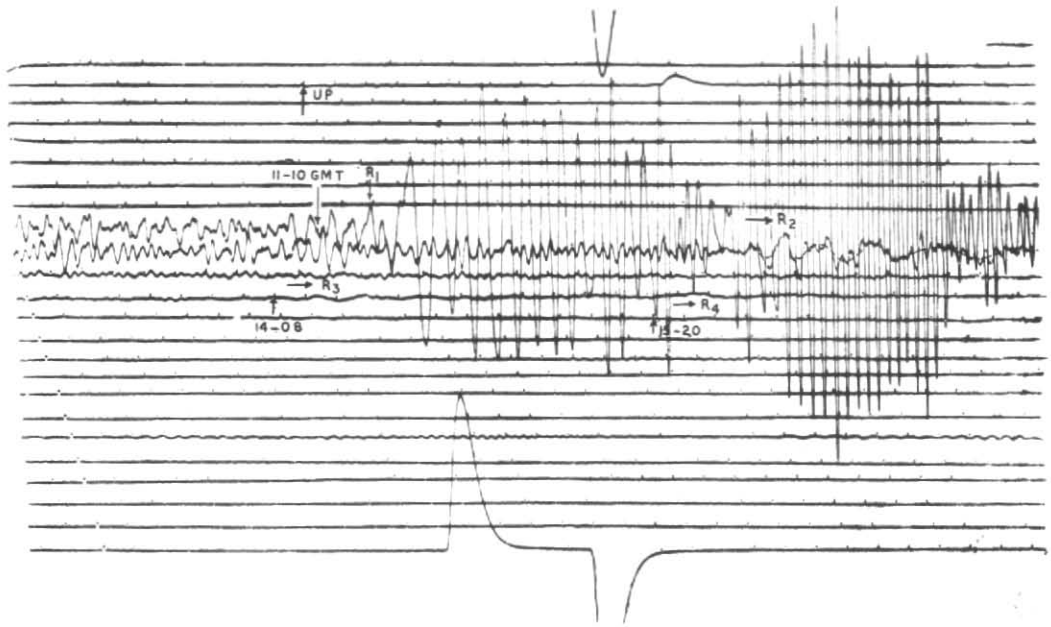

Fig. 1

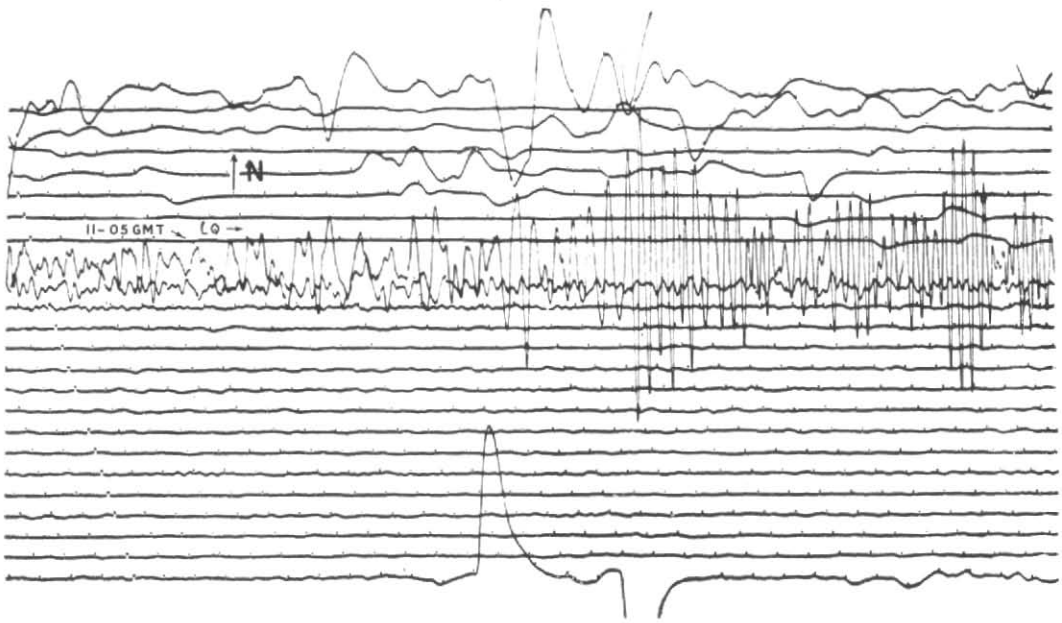

Fig. 2

of Love waves in the N-S component seismographs were mixed with a small fraction of Rayleigh waves—about 20 per cent of the total horizontal. The presence of the Rayleigh wave energy, however, did not create much difficulty and the Love waves could be studied from the N-S components. The N-S component L.P. seismogram of Delhi is reproduced in Fig. 2.

In studying the dispersion of Rayleigh waves, we have employed the method outlined by Ewing and Press (1952). The arrival times of every crest and trough were plotted against crest and trough numbers and smooth curves were drawn through them. No phase corrections to travel times were applied as the operating characteristics of the instruments both at Delhi and Shillong were similar. From these curves, periods corresponding to different arrival times were obtained by finding the slopes of the curves at the appropriate arrival times. It was thus possible to construct arrival time *versus* period curves both for Shillong and Delhi. These curves are given in Fig. 3. Knowing the arrival times at different periods and the origin time of the earthquake as well as the distance of the observing station, it is easy to calculate the group velocity for different periods and then plot the usual group velocity *versus* period curve. In this particular case, the path from the epicentre to the observing stations consisted of nearly 80 per cent of continental path, and only about 20 per cent of oceanic path. In order to derive the dispersion curve for the continental portion of the path only, corrections had to be applied to the travel times, to take into account a length of 21° of oceanic path. The results obtained for the paths, epicentre to Delhi and epicentre to Shillong, for group velocities at different periods after corrections are given in Table 1. In applying the corrections for oceanic paths, results obtained by Oliver, Press and Ewing (1953) for dispersion of Rayleigh waves through the Atlantic Ocean were used.

With the help of the arrival time *versus* period curves of Delhi and Shillong, it has also been possible to study the dispersion of Rayleigh waves between Delhi and Shillong only, by using the method adopted by Brilliant and Ewing (1954). The results obtained are given in Table 2.

TABLE 1

Group velocity (km/sec) of Rayleigh waves (R_1)

Period (sec)	Epicentre–Delhi (continental path)	Epicentre–Shillong (continental path)
16	2·82	2·95
18	2·80	2·84
20	2·85	2·87
22	2·92	2·95
24	3·00	3·00
26	3·07	3·06
28	3·14	3·12
30	3·22	3·20
32	3·30	3·27
34	3·36	3·32
36	3·46	3·42
40	3·55	3·50
45	3·60	3·61
50	3·66	3·67
55	3·71	3·73
60	3·77	3·76
65	3·78	3·78
70	3·80	3·80

In Table 3, the dispersion data obtained from the record of R_2, R_3 and R_4 Mantle Rayleigh waves at Delhi are given. These waves could not be read clearly in the record of Shillong, due partly to the larger drum speed at that place and partly due to superimposition of successive traces. In Fig. 4, a composite dispersion curve for surface waves for the continental path between the epicentre and Shillong through Delhi is plotted, between the period range 20 to 220 sec. The observed points for Mantle Rayleigh waves are in close agreement with those obtained by Ewing and Press (1954).

The dispersion of Love waves was also studied in the same manner as the Rayleigh waves. From the arrival time *vs* crest trough number curves, periods were measured and the period *vs* arrival time curves for Love waves were drawn for Delhi and

TABLE 2

Group velocity of Rayleigh waves (Delhi—Shillong)

Period (sec)	16	18	20	22	24	26	28	30	32	34
Group velocity (km/sec)	3·14	2·97	2·90	2·90	2·90	2·95	3·02	3·10	3·16	3·22
Period (sec)	36	38	40	45	50	55	60	65	70	
Group velocity (km/sec)	3·30	3·35	3·47	3·64	3·73	3·73	3·73	3·79	3·82	

TABLE 3

Group velocity of Mantle Rayleigh waves

R_2	Period (sec)	63	80	90	104	110	117	120	126	132	132	141	150	156	165	182
	Group velocity (km/sec)	3·81	3·79	3·78	3·76	3·75	3·74	3·72	3·70	3·69	3·68	3·66	3·65	3·63	3·62	3·61
R_3	Period (sec)	90	105	108	120	132	138	150	162	174	198					
	Group velocity (km/sec)	3·80	3·78	3·76	3·75	3·73	3·71	3·70	3·68	3·67	3·59					
R_4	Period (sec)	114	120	126	132	138	147	156	164	177	186	198	220			
	Group velocity (km/sec)	3·74	3·72	3·71	3·70	3·69	3·68	3·67	3·65	3·64	3·63	3·62	3·56			

TABLE 4

Group velocity (km/sec) of Love waves

Period (sec)	Epi.–Delhi (continental)	Epi.–Shillong (continental)	Delhi–Shillong	Period (sec)	Epi.–Delhi (continental)	Epi.-Shillong (continental)	Delhi–Shillong
20	3·15	3·17	3·36	45	3·75	3·73	3·64
22	3·20	3·22	3·39	50	3·87	3·82	3·75
24	3·25	3·27	3·42	55	3·94	3·90	3·85
26	3·30	3·32	3·43	60	3·98	3·97	3·94
28	3·35	3·37	3·44	65	4·04	4·04	4·01
30	3·41	3·43	3·48	70	4·10	4·09	4·03
32	3·47	3·46	3·49	75	4·16	4·15	4·09
34	3·50	3·51	3·52	80	4·21	4·20	4·14
36	3·55	3·56	3·56	85	4·26	4·25	4·18
38	3·61	3·61	3·58	90	4·30	4·29	4·28
40	3·65	3·63	3·60	95	4·34	4·33	4·29
				100	4·36	4·36	4·36

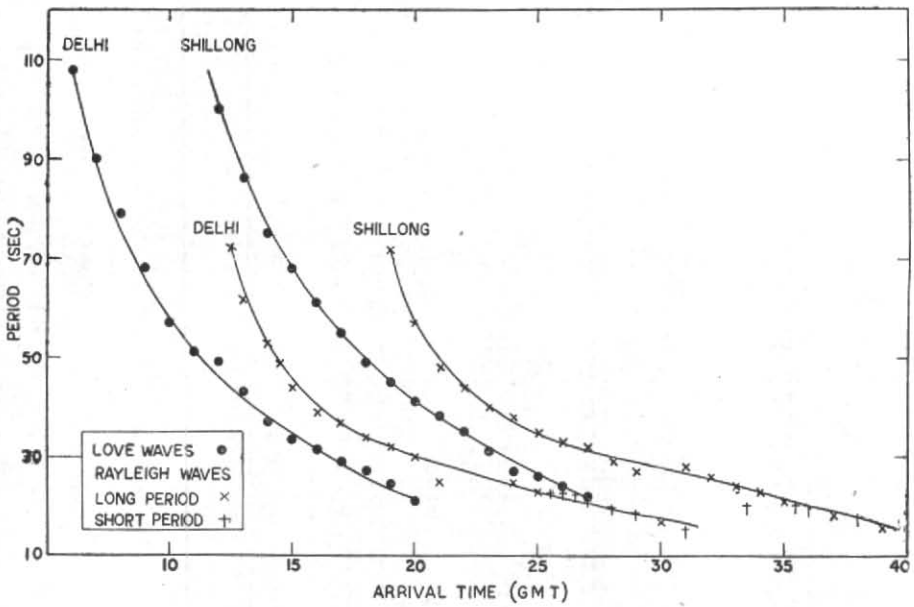

Fig. 3. Earthquake of 30 August 1963

Epicentre 7·7°N, 35·8°W; Origin time—10 : 21 : 36·6 GMT; h=33 km; M=6·1±0·4

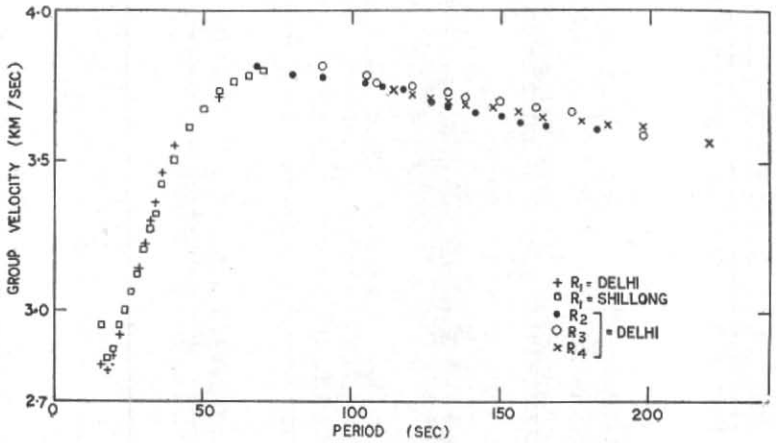

Fig. 4

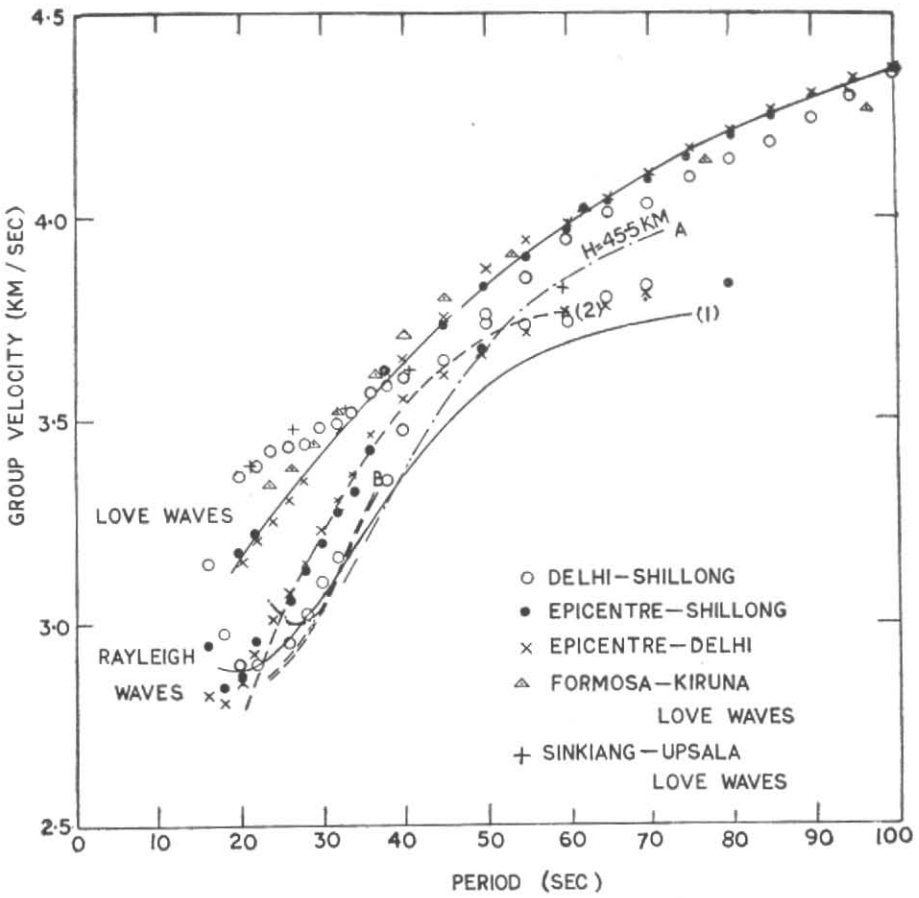

Fig. 5. Surface wave dispersion

A—Dorman case 8007 ($H = 45 \cdot 5$ km) Rayleigh waves

B—Dorman case 8043 336/03800 Rayleigh waves

(1)—Novaya Zemlya–Delhi observed Rayleigh waves

(2)—Aleutian–Lwiro observed Rayleigh waves

Shillong. These are shown in Fig. 3 along with those for Rayleigh waves. Correction for the portion of oceanic path was also applied, as for Rayleigh waves and the group velocities only for the continental part of the path were calculated, for periods from 20 to 100 sec. The results are given in Table 4, both for Delhi and Shillong. The group velocities of Love waves between Delhi and Shillong were also calculated and are given in Table 4.

3. Discussion

Dispersion curves for the path epicentre–Delhi–Shillong and for the path Delhi–Shillong are shown in Fig. 5, along with the dispersion curves for Rayleigh and Love waves obtained by other workers for different paths. In the case of Rayleigh waves it will be seen that in the period range 20-35 sec, the dispersion curve between Delhi and Shillong is in close agreement with the theoretical model 'B' given by Dorman, which corresponds to a total thickness of the crust of about 45 km including about 2·73 km of sediments. The observed group velocities between the periods 35 and 45 sec are nearly 0·1 km/sec higher than those given by the theoretical model 'A' of Dorman for a crustal thickness of 45·5 km. The observed velocities are also slightly higher than those obtained by the authors (1963) for the path Navaya Zemlya to Delhi. For periods over 50 sec, the observed group velocities become progressively lower than the theoretical model 'A' of Dorman, the maximum difference being about 0·2 km/sec. This difference is usually attributed to the increase of shear velocity with depth in the mantle. These observations, therefore, suggest a crustal thickness between 40 and 45 km for the path Delhi–Shillong. This value seems to be quite possible in view of the fact that the path passes through the foot-hills of the great Himalayan mountain chain. It may be mentioned here that the thickness of the earth's crust in Assam through a study of near earthquakes was found to be about 46 km by Tandon (1954).

The dispersion curve for the path epicentre–Delhi–Shillong shows group velocities higher by about 0·1 km/sec than those obtained for the path Delhi–Shillong. The group velocity minimum also occurs at a lower period of about 18 sec and at lower velocity than that obtained for the path Delhi–Shillong. This suggests that the crustal thickness of the continental path epicentre–Delhi–Shillong is lower than that of Delhi–Shillong. This curve agrees very closely with the curve obtained by Kovach (1959) for the path Aleutian Is–Lwiro, and by Porkka (1960) for the paths Kamchatka and Japan to Finland, suggesting an average crustal thickness of nearly 37 km for this path.

The dispersion curves of Love waves for the paths epicentre–Delhi and epicentre–Shillong as well as for Delhi–Shillong are also shown in Fig. 5. The data obtained by Bath (1959) for the group velocities of Love waves for the path Formosa to Kiruna and Sinkiang to Uppsala are also shown in the figure for comparison. It is seen that the group velocities for the continental paths epicentre–Delhi and epicentre–Shillong are in close agreement with the observations of Bath and lend support to the conclusion, obtained above from Rayleigh wave studies, that the average thickness of the crust is near to 37 km.

The group velocities at Delhi and Shillong are also close to each other, with the difference between their values lying within experimental errors. In the period range 40-65 sec, there is a consistent tendency for the group velocities at Shillong to be lower than those at Delhi, this difference being maximum at a period of 50 sec. Even though the difference is small, it seems to indicate the effect of a slightly thicker crust between Delhi and Shillong than that between the epicentre–Delhi. The dispersion curve computed for the path Delhi–Shillong also reflects the same. These observations lend support to the conclusion drawn from Rayleigh waves that the thickness of the crust between Delhi and Shillong is between 40 and 45 km.

4. Conclusion

Summing up, the results of the computations suggest the following—

(*i*) The average crustal thickness along the continental part of the path from the epicentre (7·7°N, 35·8°W), through Delhi to Shillong lies close to 37 km.

(*ii*) The thickness of the earth's crust along the path Delhi–Shillong is estimated to be between 40 and 45 km.

(*iii*) Observations from this earthquake of Mantle Rayleigh waves R_2, R_3 and R_4 are in close agreement with those of Ewing and Press (1954).

In presenting the above results, it is realised that they have been arrived at from the records of only one earthquake. There was, however, no choice. These observations would be supplemented as more data for the path discussed become available. There may be slight deviation of the wave path from the great circle due to refraction at the African West Coast and this has not been taken into account. Finally the distance between Delhi and Shillong is rather short to give results of high accuracy in the dispersion data for this portion of the path. Inspite of these limitations, it is rather encouraging that the results obtained are quite consistent and prove the adequacy of the methods employed.

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