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Dispersion of short period surface waves and the surficial layer in the region west of Delhi

H. M. CHAUDHURY

Meteorological Office, New Delhi

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ABSTRACT. Short period surface waves with periods between 5 and 20 seconds recorded at Delhi due to earthquakes in West Pakistan have been studied. Dispersion of both Rayleigh and Love waves obtained from the study has been compared with theoretical single layer models and it is inferred that the sediments overlying the granitic basement over the wave paths are about 5-km thick.

1. Introduction

It is well known that the surface wave train in the records of earthquakes comprises of waves of widely different periods. Extensive studies of dispersion of such waves in the period range of 20 to 60 sec have been made in the study of the structure of the earth's crust. Periods longer than 60 sec and extending even upto about ten minutes have also been detected on the records of strong earthquakes. These waves have been found to reveal information concerning the deeper layers of the earth's mantle. On the other hand surface waves of shorter periods, *i.e.*, of periods less than 20 sec depend more on the properties of the surficial layers of the crust. As such, their study has provided a convenient means of getting an overall picture of such layers in a region. Studies of this kind have been made with encouraging results, amongst others, by Oliver and Ewing (1958), Shurbet (1961), and McEvilly and Stauder (1965). In an earlier paper, Chaudhury (1967) has given the results of a study of such waves (of Rayleigh type) across the Gangetic Basin. Sutton (1968) has also applied the method in the central Californian region and has discussed its usefulness and its limitations. Of help in the use of the technique in different regions with different crustal layering is a paper by Mooney and Bolt (1966) in which they have given computed dispersion curves for Rayleigh waves for different models. This report presents the results of a study of both Rayleigh and Love waves as recorded at Delhi from a number of earthquakes in West Pakistan.

2. Data, Method and Results

On February 7, 1966 an earthquake of magnitude 6·0 occurred in West Pakistan. Its epicentre and other parameters as given by the USC and GS are reproduced here.

Epicentre	:	29·83°N, 69·68°E
Origin Time	:	$04^h\ 26^m\ 13{\cdot}9^s$ GMT
Depth	:	Normal
Magnitude	:	6·0

This earthquake was followed by a large number of aftershocks, many of which had magnitudes exceeding 4·0 and gave fairly good records of short period surface waves at the Delhi Observatory by the Long Period Seismographs of the WWNSS. In addition the East-West component Sprengnether Microseismograph at Delhi also gave some good records.

The location of the epicentres and the observing station together with some other geographical features are shown in Fig. 1. The details taken from the *Earthquake Data Reports* issued by the USC and GS are given in Table 1. It may be seen from this data that the azimuth of Delhi from the epicentral region of the shocks is close to 90°. The Vertical and the East component Seismograms therefore gave the Rayleigh waves while the North component recorded the Love waves. This was an advantage in the study. A few typical records are shown in Figs. 2 and 3.

In the case of Rayleigh waves, the wave periods decreased from about 15 to 5 sec. In the Love waves on the other hand the train usually started with a higher period, about 16 to 18 sec and continued to periods of about 8 seconds. Since in this range of period, the instrumental phase correction is small, it was ignored and the periods of the waves were measured directly from crest to crest and trough to trough. The group velocities were computed in all cases by the usual method. No smoothing of data was done for individual shocks. Instead, all the group velocity values were plotted and a final smoothing by eye estimation was done in drawing the group velocity curves against periods. These are shown in Fig. 4 for Rayleigh

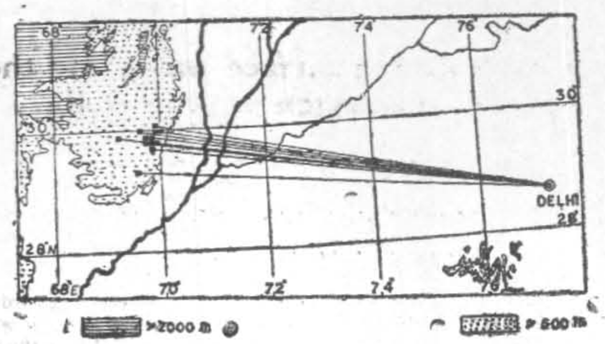

Fig. 1. Index map showing epicentres and observing stations

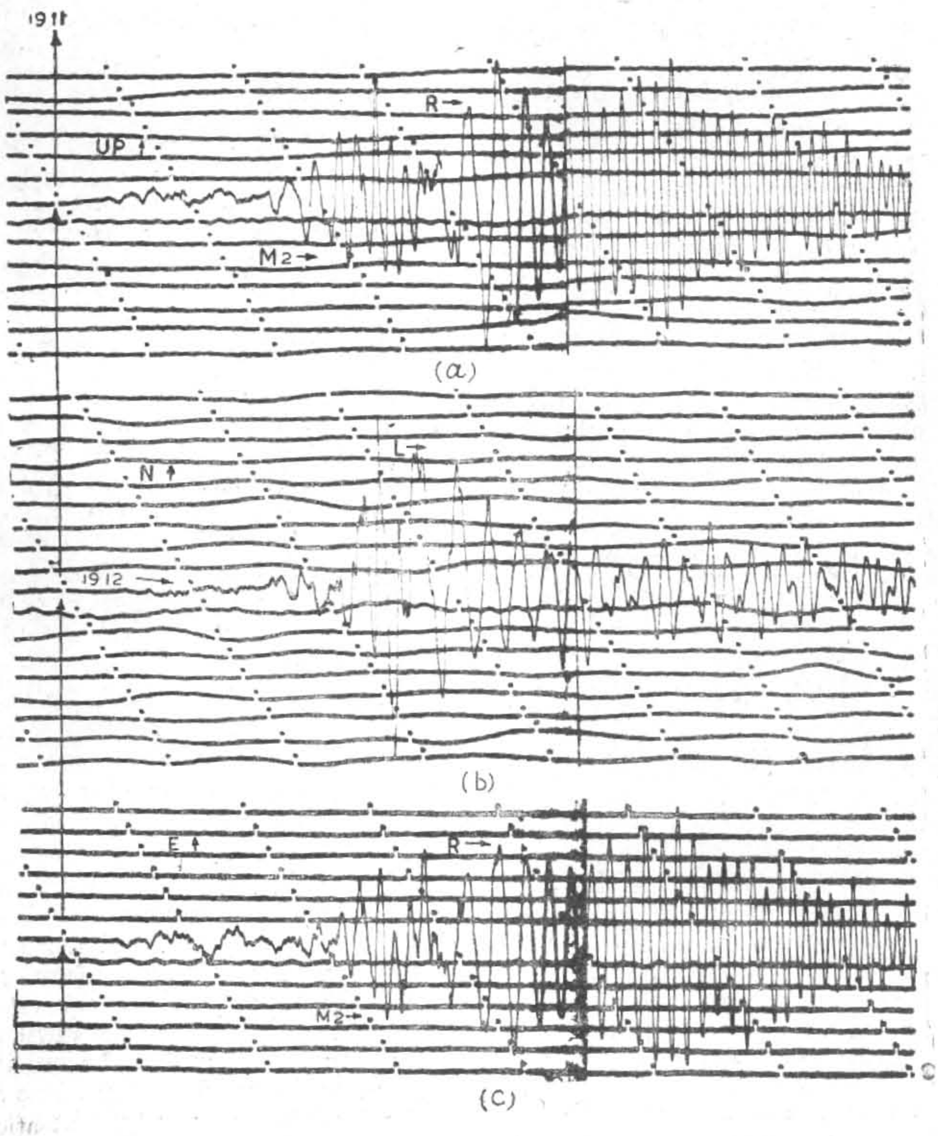

Fig. 2. Long period Seismograph records of 13 February 1966 (Earthquake No. 6)

TABLE 1

Date (1966)	Origin Time (GMT)			Epicentre		Depth (km)	Mag. (CGS)	Distance from Delhi (Degree)	Azimuth of Delhi	Waves Recorded		
	h	*m*	*s*	Lat (°N)	Long (°E)					Ray-leigh	Love	M_2
Feb 7	05	21	44·6	30·0	69·9	10	5·4	(6·5)	99·7	Yes	Yes	
	05	30	19·2	30·0	69·6	48	5·3	(6·8)		Do.	Do.	
	08	38	11·3	30·0	69·9	15	4·8	6·5	99·7	—	Do.	
Feb 9	08	22	17·9	29·8	69·8	29	5·2	6·6	99·8	Yes	Do.	
	22	26	06·6	30·0	69·9	6	4·6	6·5	98·1	—	Do.	
Feb 13	19	09	47·4	29·8	69·7	33	5·1	6·7	98·1	Yes	Do.	Yes
Feb 14	05	41	06·5	29·3	69·5	44	4·8	6·8	93·3	Do.	Do.	Do.
Feb 16	09	44	21·5	29·9	69·7	34	4·6	6·6	98·4	Do.	—	
Feb 17	18	26	17·7	29·9	69·8	22	4·4	(6·6)		—	Yes	
Mar 4	06	01	05·0	30·0	70·0	33	4·4	6·4	99·8	—	Do.	
Mar 11	04	20	20·6	30·1	69·9	32	4·4	6·5	100·6	—	Do.	
Mar 15	09	14	29·3	29·9	69·7	36	4·7	6·7	98·9	—	Do.	
Mar 16	17	40	30·1	29·7	69·8	33	4·7	6·6	97·3	Yes	—	
Mar 18	10	44	09·4	29·8	69·9	33	4·4	6·5	98·0	—	Yes	
Aug 2	09	18	57·6	29·9	69·2	21	5·1	7·1	97·8	Yes	Do.	Yes

waves and in Fig. 5 for Love waves. The Rayleigh wave velocities range from 2·8 to 1·6 km/sec as against 3·0 to 1·8 km/sec for Love waves. Though on first sight it appears that the Love waves are faster, it is seen to be different. In fact right upto a period of 15 sec, the Rayleigh waves appear to travel faster than Love waves of the same period.

The results were compared with standard dispersion curves for a single layer model. Since the wave periods are small, the effect, if any, of the deeper layers (*viz.*, the basaltic layer and the mantle) on their velocities is expected to be small. Thus an attempt was made to estimate the overall sedimentary layer thickness along the path. For purposes of this comparison the deeper medium (the half-space) was taken as the granitic layer and the shear wave velocity in this motion was assumed to be 3·5 km/sec. This is roughly the value obtained in nearby regions from the study of earthquake travel-times. The corresponding velocity in the sedimentary layer is, however, not known. Since the velocity in this layer would effect the conclusions profoundly, the observed results were compared with a number of models in which the sedimentary layer velocity was changed from 1·5 to 2·3 km/sec. In order to make full use of both Rayleigh and Love wave dispersion curves, identical models were tried for both these waves. For Rayleigh waves the models were chosen from Mooney and Bolt (1966) and for Love waves the group velocities for the models were calculated by using the nomograms given by Sato (1953 a, b). These are shown in Figs. 6 and 7. A curve for a slightly different model from Kanai (1951) has also been included in Fig. 6(b).

In Table 2, the inferences from the comparison of the data with the models have been shown. A look at this table as well as the above figures shows that as far as the Rayleigh waves are concerned, the observed dispersion curve could be taken as having fair agreement with a number of models, *viz.*, those in Figs. 6(b), 6(c) and 6(d). Thus on these observations alone, the region under consideration could be taken as having a sedimentary layer with any one of the following properties:

(*i*) Thickness 5 km with *S* velocity 2·0 km/sec

(*ii*) Thickness 3 km with *S* velocity 1·75 km/sec (with density contrast of 1 : 1·1)

(*iii*) Thickness 3 km with *S* velocity 1·5 km/sec (with density contrast of 1 : 1·5).

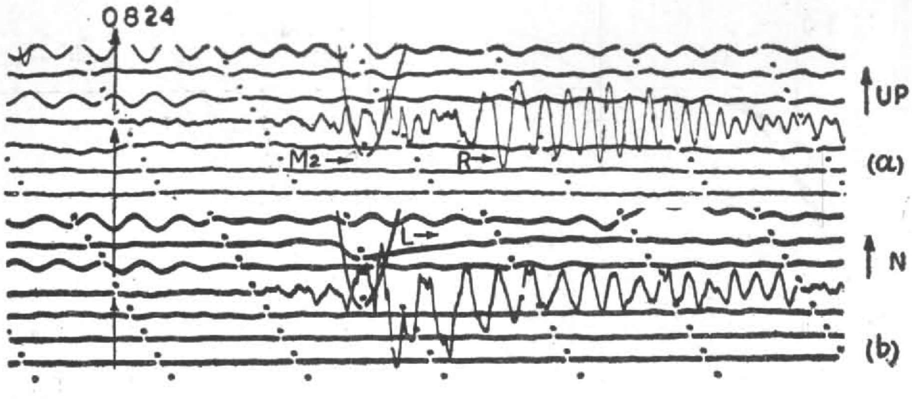

Fig. 3. Long Period Seismograph records of 14 February 1966 (Earthquake No. 7)

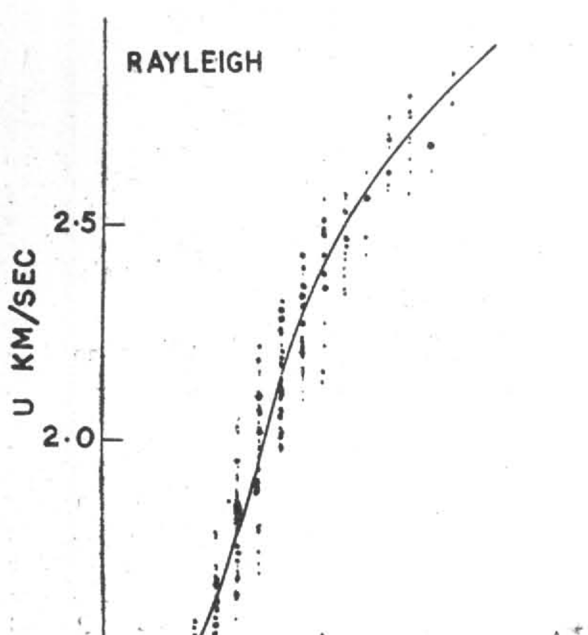

Fig. 4. Rayleigh wave dispersion

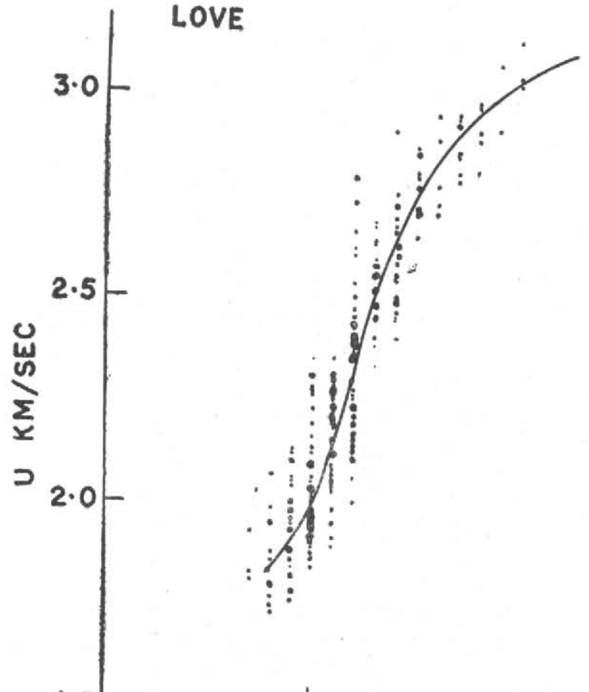

Fig. 5. Love wave dispersion

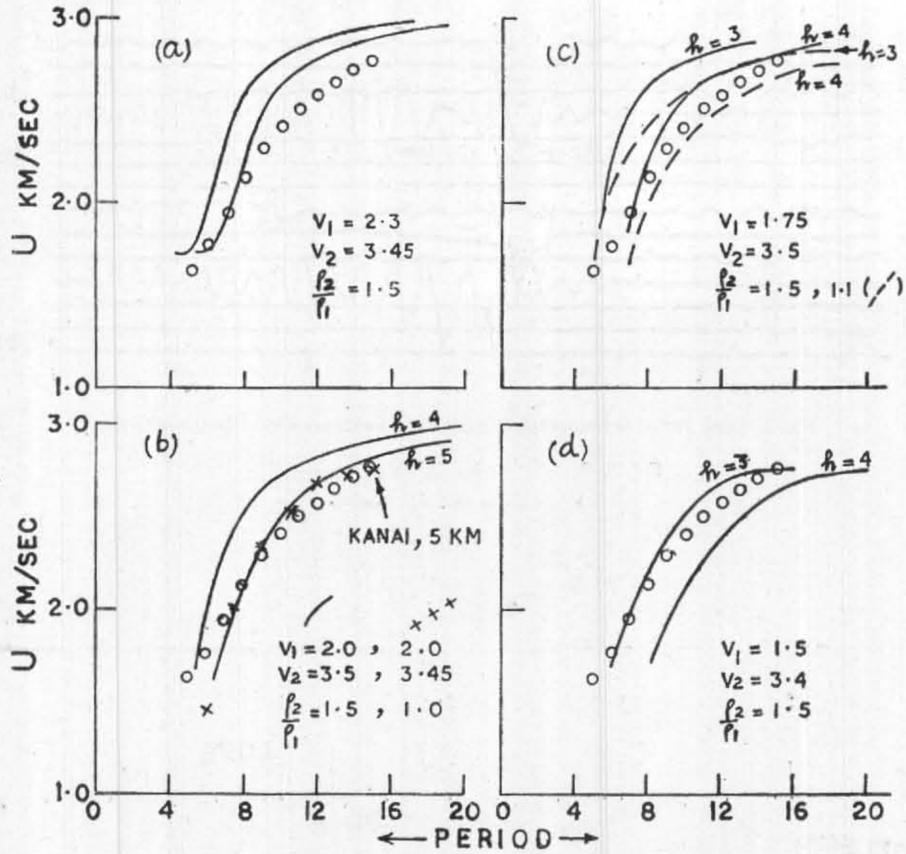

Fig. 6. Comparison of observed Rayleigh wave dispersion with theoretical models

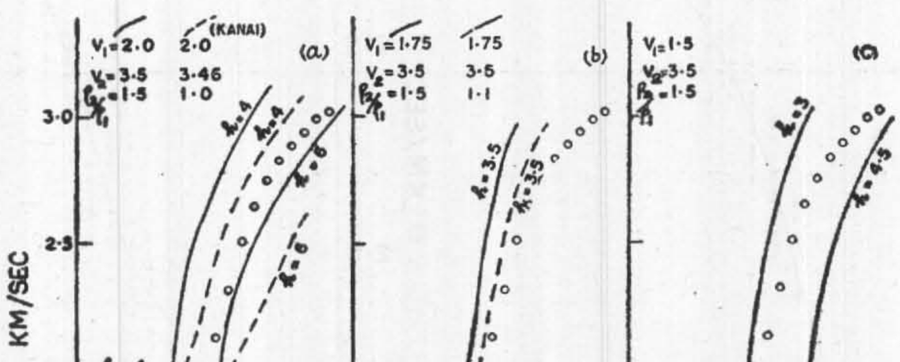

Fig. 7. Comparison of observed Love wave dispersion with theoretical models

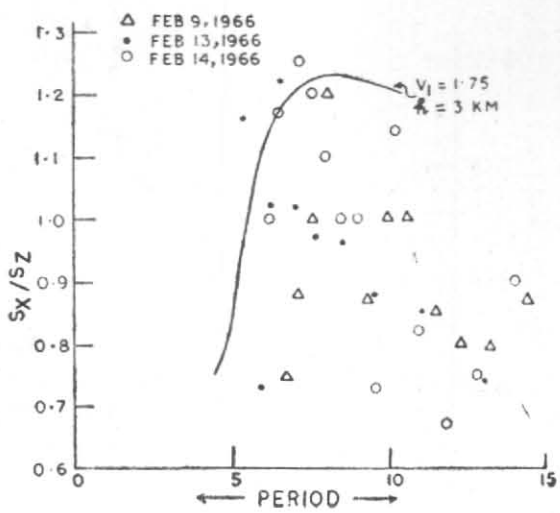

Fig. 8. Ratio of horizontal to vertical motion observed in Rayleigh waves.

TABLE 2

Model	V_1 =	2·3		2·0		2·0		1·75		1·75		1·5	
	V_2 =	3·45		3·5		3·45		3·5		3·5		3·4	
	P_2/P_1=	1·5		1·5		1·0		1·5		1·1		1·5	
		R	L	R	L	R	L	R	L	R	L	R	L
Agreement		No good	—	Fair	Fair	Fair	Good	No good	No good	Fair	No good	Fair	No good
Inferred thickness (km)		X	—	5	5½	5	4½	X	—	3½	X	3	X

The Love wave dispersion curves, however, do not agree with all the above models. Figs. 7(b) and 7(c) show clearly that the models (*ii*) and (*iii*) mentioned earlier are not applicable. Thus only the model with a shear velocity of 2·0 km/sec appears to be in reasonable agreement with the observations of both Rayleigh and Love waves. We may therefore, conclude that the thickness of the sediments in the region is about 5 km.

Mooney and Bolt (*loc cit.*) have also given curves for the ratio of horizontal to vertical ground displacements in Rayleigh waves for various models. As the wave paths in the case under study were very close to East-West, an attempt was also made to compare observations with their calculated curves. For this purpose only records from three events on 9, 13 and 14 February were taken, as the amplitudes on record were good. The ratio of the East/Vertical was plotted against the wave periods. These are shown in Fig. 8. As is expected from earthquakes records, the above data show considerable departure from a smooth variation but they do show on the average a maximum value of about 1·2 around a period of 8 sec. The ratio falls on either side to a value of 0·75 at both shorter and longer periods. For comparison a theoretical curve from Mooney and Bolt is also drawn in the figure. Despite the considerable departure of the data from this curve, it shows broad agreement in features and indicates a shear velocity ratio of about 2 between the sedimentary layer and the underlying half-space. This is close to the ratio 1·75

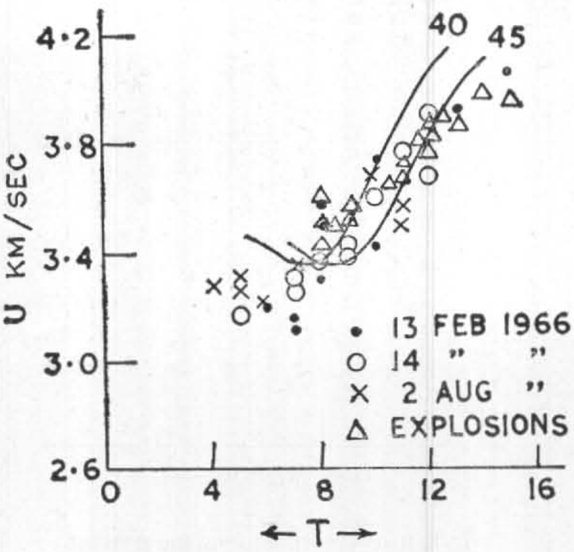

Fig. 9. Observed M_2 wave dispersion together with theoretical curves

obtained from dispersion data. No further conclusions appear to be justified because of the considerable scatter in the dates and their consequent smoothening.

On some of the records, the Rayleigh wave train was proceeded by another train of normally dispersed waves. These had periods ranging from about 15 to about 6 sec. Calculation of their group velocities gave values from 4·0 km/sec at the higher period decreasing to 3·1 km/sec at the lower periods. This dispersion curve is shown in Fig. 9. The values of the velocities, the wave periods and the nature of the records show that these are M_2 waves. Such waves, though of short period, are known to be influenced by deeper layers. Therefore no attempt has been made to use these observations inferring the properties of the sediments.

A comparision of the present results with those obtained from records from atmospheric explosions (Tandon and Chaudhury 1963) as well as with the theoretical curves for Darman's model 8043 have been made in the above figure. This indicates a fair agreement of the velocities in both the observed cases and leads one to conclude that the total thickness of the crust is around 45 km.

3. Discussion and Conclusion

The study, within the limitations imposed by various errors as mentioned above, broadly indicates a thickness of about 5 km of low velocity sediments in the area between Delhi and the epicentres. It may be seen from the map in Fig. 1 that the intervening space could be called a basin, similar to the Gangetic basin between Delhi and the Himalayas. It is known that Delhi lies on the northern tip of the Aravallis and compact bedrock is exposed there. The thickness of the sediments is, therefore, small in this part. The average sedimentary thickness of 5 km obtained in the study would therefore imply that the sediments become thicker towards the west and attain a thickness greater than 5 km just near the hills. No observations either of actual drilling or of any geophysical exploration in this area are known. The gravity anomalies, however, show that these are near zero or slightly positive near Delhi and become increasingly negative as one goes west, attaining the maximum negative values near the epicentral region. This feature is similar to the picture in the Gangetic basin where it is known that the surface of the bedrock is sloping towards the Himalayas. On this analogy the gravity anomalies appear to be consistent with the above observations.

Another point of interest appears to be the success of Kanai's model (shear velocity 2·0 km/sec) in explaining the results. In the study of the Gangetic Basin (Chaudhury 1967) also it was found that the final results agreed better with Kanai's model for Rayleigh waves. It would thus appear that the nature of the surficial layers is similar in the two regions.

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