SEISMOLOGICAL STUDY OF THE CRUSTAL LAYERS IN INDIAN REGION FROM THE DATA OF NEAR EARTHQUAKES

By

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Introduction

Seismologists investigated the various aspects of crustal structures in different parts of the earth from a study of near earthquakes and other methods. Those studies have revealed that the earth's crust in many regions consists of two or three layers of total thickness of 30 to 50 Kms, each layer being associated with characteristic velocities of P and S waves. Jeffreys on the basis of the data of European earthquakes deduced velocities in the granitic layer, the intermediate layer and the material just below as follows:

P_g = 5.57 ± .02 km/sec. S_g = 3.36 ± .01 km/sec.

$P*$ = 6.50 ± .03   " $S*$ = 3.74 ± .03   "

P_n = 7.76 ± .03   " S_n = 4.36 ± .02   "

He gave the P and S velocities in an overlying sedimentary layer in European region as 4.7 and 2.8 km/sec. respectively. Gutenberg's study of Southern Californean earthquakes led to the velocities in different layers as:

P_g = 5.58 ± .01 km/sec. S_g = 3.26 km/sec.

P_y = 6.05 km/sec. S_y = 3.65   "

P_m = 6.95 ± .18 km/sec. S_m = 4.10   "

P_n = 8.06 ± .11   " S_n = 4.45   "

His analysis for regions under and near the Alps gave the following results regarding the thickness of different layers and the depth of Mahorovicic discontinuity:

Region	Thickness (km) Upper granitic layer	Intermediate layer	Depth of Mohorovicic discontinuity (km)
North Western Europe	30	10	40
Schwefische Alb	25-30	20-25	50
Northern Alps	35	20-25	55-60

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Southern Carnic Alps	40	20-25	60-65
Yugoslavia	15	25	40

Rozova and Matuzawa arrived at the undermentioned figures in respect of Central Asia and Japan respectively:

	Velocity in km	
	Central Asia	Japan
P_g	5.54	5.0
P_*	5.99	6.20
P_n	7.82	7.5
S_g	3.29	3.15
S_*	3.79	3.7
S_n	-	4.5

Rozova deduced a thickness of 20-25 kms for the first layer (granitic) and a depth 45 kms for the Mohorovicic discontinuity in Central Asia. Roy on his study of Great Bihar earthquake of 15. 1. 1934 (Epicentre 26°.18' N 86°.18' E) gave the following velocities of P and S waves for Gangetic valley (India)

$$P_g = 7.80 \text{ km/sec.} \qquad S_g = 4.38 \text{ km/sec.}$$

$$P_* = 6.21 \text{ "} \qquad S_* = 3.71 \text{ "}$$

$$P_n = 5.26 \text{ "} \qquad S_n = 3.29 \text{ "}$$

His calculations of thickness of granitic layer and basaltic layer in Bihar area were 14.8 kms and 25.4 kms respectively. Banerjee on an examination of the after shocks of the Great Assam earthquake of 15. 8. 1950 indicated that the depth of the Mohorovicic discontinuity under the foot hills of the Himalayas is some what greater than 60 kms. Chakravorty in his Presidential Address, Mathematics Section, Indian Science Congress expressed the view that the depth of the Mohorovicic discontinuity under the Himalayas might be of the order of 70 kms. It is seen from the results described above that the crustal aspects of different parts of the earth are far from being identical. Depths of crustal layers and the wave velocities in the layers vary from one region to the other. One of the authors of this paper in his routine study of Seismograms relating to near shocks in India noticed at times that some of the phases in the Seismograms did not tally well with the standard Travel Time tables which are based on average values of wave velocities. With due regard to the personal errors and errors in time determinations which may be responsible for the anomaly observed, one has to examine critically whether the discrepancies are real and if so, whether it is

possible to explain them. Apart from this question, it is interesting to examine how the crustal aspects in Indian areas compare themselves against those of other areas which were studied from extensive data. It has, therefore, been considered worthwhile to make an attempt to find out the velocities of P and S waves in different crustal layers and the thickness of these layers from a study of a large number of near earthquakes of shallow focal depths recorded at Indian Stations and to find out the actual focal depths of the earthquakes. The object of this paper is to describe the results obtained from this study and to discuss the interesting features.

Selection of data

For the purpose of the present analysis 19 near earthquakes of shallow focal depths recorded by the Seismological observatories in India during the period June 1950 to February 1954 were selected on the following considerations (vide Tables 1 & 2):

(a) The epicentres of these earthquakes were determined by the India Metereological Deptt. from a study of all available observations and the relevant data were published in the Seismological Bulletins. Many of the selected earthquakes were felt.

(b) Most of the desired phases (viz. P_g, P_*, P_n, S_g, S_*, S_n) in these cases were available from the records of at least two stations.

(c) The epicentres in question were fairly well distributed over Indian area and its immediate neighbourhood.

In regard to near shocks Macalwane pointed out that a phase is real if it can be followed from station to station in such wise that the respective arrival times when plotted against epicentral distances are isolated and lie on or very close to a continuous curve. Due consideration was given to this point in selecting out the above data from a large number of earthquake records.

Analysis of data

Seismologists have accepted the view that in the regions close to the epicentre i.e. when the epicentral distances from the recording stations are within 10 degrees or so, the additional pulses P_*, P_g, S_* and S_g are due to waves which travel through layers near the earth's surface. If these pulses along with normal P_n and normal S_n are recognised on the Seismograms of a few near stations and if the epicentre of the earthquake and its "O" time are determined correctly, it is possible to find out the velocities of P_g, P_* etc. in different layers and the corresponding delay times, from which the focal depth of the earthquake as well as the thickness of the individual layers can be calculated from the following formulae due to Jeffreys:

$$d = \frac{\beta_g}{(1 - \frac{\beta_g^2}{\alpha_g^2})^{\frac{1}{2}}} \cdot t_{P_g-S_g},$$

$$2\,H_g = d + \frac{\alpha_g}{(1 - \frac{\alpha_g^2}{\alpha_*^2})^{\frac{1}{2}}} \cdot t_{P_* - P_g},$$

$$2\,H_B = d + \frac{\alpha_*}{(1 - \frac{\alpha_*^2}{\alpha^2})^{\frac{1}{2}}} \cdot t_{P - P_*}$$

when α_g, α_* and α are the velocities of P waves in different layers; β_g, β_* and β are the velocities of S waves in different layers;

$t_{P_g} - S_g$, $t_{P_* } - P_g$; $t_{P} - P_*$ are the delay times;

d is the depth of focus

H_g is the thickness of the first layer (granitic)

H_B is the thickness of the second layer (basaltic)

In the present investigation, the time data for all available phases in respect of each earthquake were treated in a way similar to Geiger's method of eliminating the errors in order to find out the correct "O" time and the epicentral distance. After this treatment final time distance curves were drawn and the corresponding delay times were calculated. The Sample Curves drawn in respect of one earthquake (29. 8. '53) are shown in Figure 1. The delay times calculated from the curves are also shown as inset in this figure. From the time distance curves thus drawn for each of the 19 earthquakes, the depth of focus, velocities of the different types of waves characteristic to individual layers and the thickness of the layers were calculated. The results are given in Tables 1 & 2 attached. The values of velocities and layer thickness shown in the Tables are, no doubt, appropriate to the regions covered by a distance of 1000 kms. or so round each epicentre. The locations of the Seismological stations which recorded the earthquakes and the epicentres of all the 19 earthquakes studied are shown in Figure 2. In this figure the layer thicknesses obtained from the data relating to each earthquake are also shown for ready reference.

Discussion on the results

It will be seen from Table 1 that the depths of foci of almost all the earthquakes under consideration are below 20 kms and that the foci lie either near the bottom of the first layer (granitic) or at the top of the second layer (basaltic). The latter characteristic is exhibited particularly by the earthquakes whose epicentres are in Tibet. Roy identified the focus of the Great Bihar earthquake of 15. 1. 1934 at the bottom of the granitic layer. Banerjee discussed the mechanism of the shallow-focus earthquakes in India. According to him materials at a depth of 20 kms or more apparently exist in a state of cohesion under the confining pressure and in producing earthquakes of the type under examination, nature breaks a block of large dimension (say 200 kms long, 100 km

broad and 10 kms thick) and not a large no. of rocks. If the upper surface of this block be 15 or 20 kms below the surface, the material will be under high pressure and high temperature. The depths of foci obtained from the present analysis are quite consistent with the idea put forward by Banerjee. It is interesting that the depths of foci for epicentres to the north of Lat. 28° N in India and neighbourhood are in some cases slightly less than those to the south. The enhanced pressure under the Himalayan region may be responsible for this feature. Apparent existence of foci at the top of the second layer in the cases discussed is interesting in the light of Banerjee's discussion regarding the mechanism of shallow focus earthquakes, because it will be noticed from the note which will follow that the thickness of the first layer in the areas where the foci lie at the top of the second layer is comparatively small. It is to be mentioned here that the existence of foci at the top of the second layer does not materially affect the time distance curves used for the calculation of thickness etc. of different layers.

According to Jeffreys the "P" usually observed in a near earthquake is a wave which originated from the focus as a shear wave and was transformed to a "P" wave at incidence on the surface and travelled along the surface to the station. Byerly, however, recognised both the secondary P of Jeffreys and also a weaker direct P_g. Gutenberg opined that P_g travels directly from the focus to the station and P_g on incidence with the surface sets up a shear surface wave which travels faster than S_g. While it was difficult during the present study to verify whether the Indian earthquakes revealed anyphases other than P_g, P_*, P_n, S_g, S_* & S_n, it was confirmed from all the travel time curves that S_g cuts the time axis at the epicentre earlier than other pulses.

The calculated values of thickness of layers as given in Table 1 and shown in Fig. 2 present an interesting picture. While the thickness of the first layer (granitic) varies between 13 and 20 kms, it shows a characteristic change from one region to another. To the north of Lat. 30° N the thickness is 13 or 14 kms; it increases southwards to 20 kms. The thickness of the second layer (basaltic) is 17 to 19 kms in southern part of Central Himalayan region and 22 to 27 kms in Assam Kutch, Arakan and the rest of Himalayan region. The values of total thickness for the two layers gives an uneven picture of the depth of the Mohorvicic discontinuity.

The total thickness varies between 35 and 42 kms, the southern parts of Central Himalayan region showing slightly smaller values than other regions. The maximum crustal depth occurs over Eastern Himalayan region. The values thus obtained fixes the Mohorvicic discontinuity at a depth not exceeding 42 kms. While this result agrees fairly well with that obtained by Roy in his study of Great Bihar Earthquake, it is difficult to conceive a depth of 60 or 70 kms of the discontinuity as suggested by some workers. Airy's theory of isostasy requires that the Himalayas should have deep roots.

The results obtained from the present analysis do not in any way go against the above requirement because a difference of 7 kms in the total crustal thickness from one region to the other is revealed by this

analysis. In this connection one should not lose sight of the fact that the elevation of the Himalayan region varies considerably from one place to the other. Gutenberg's value for depth of Mohorvicic discontinuity under and near the Alps exceeds 50 kms. The question, therefore, remains to be examined critically how the Himalayan region, at least at places, shows a less depth for the discontinuity.

In regard to the velocities for the different types of waves it will be seen from Table 2 that the values vary widely from one region to the other. S waves being slower show smaller variation than P waves. Then again the amplitudes of variations of other waves are less prominent than those of P_g and P_*. It is fairly clear that the physical properties of crustal layer near the surface are widely different, and this difference is responsible for varying velocities. It is interesting that velocities in lower latitudes are generally less than those in the Himalayan region. Such variations in velocities were observed in other parts of the earth by many Seismologists.

In different parts of Asia itself the velocities were found to vary considerably, for P_g 3.56 to 5.54 km/sec., for P_* 5.99 to 6.30 km/sec., for P_n 7.5 to 8.48 km/sec., for S_g 2.22 to 3.29 km/sec., for S_* 3.7 to 3.79 km/sec. and for S_n 4.4 to 4.8 km/sec. In the light of the above findings the variation of velocities in different parts of Indian areas is not unusual.

Conclusion

In view of the varying aspects of the crustal layers and the respective velocities in the Indian areas as discussed in the preceding paragraphs one can appreciate the difficulty which a Seismologist is likely to experience to find out the correct epicentral distances etc. of near shocks in India on the basis of the standard Travel Time Tables computed from extensive data collected from all parts of the earth. If it is possible to work out Travel Time Tables on the basis of regional data over India and neighbourhood the task of analysing the near earthquakes becomes easier. It is quite probable that the discrepancies in the determination of correct phases of near earthquakes as pointed out before, lie to some extent in the lack of information regarding the correct parameters of the waves travelling in the crustal layers in Indian areas.

One of the authors had the opportunity of having a short discussion on this point with Sir Harold Jaffreys during his visit to Banaras Hindu University in November, 1959. Sir Jaffreys apparently realised the difficulty discussed above. In recent years much information on the structure of the outermost layers in the Indian region has been obtained by reflection and refraction methods of seismic prospecting besides from a large volume of data relating to near earthquakes. It is hoped that the question of finding out correct parameters for the Seismic waves in Indian region will get proper consideration by the Indian Seismologists in due course. The findings from the present study may be helpful in that connection.

Acknowledgement

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Figure 2

Notations

THICKNESS OF 1st LAYER (KM)
THICKNESS OF 2nd LAYER (KM)

● EPICENTRES
▥ RECORDING STATION
= THICKNESS COULD NOT BE DETERMINED

Figure 1

DATE - 29 - 8 - 53
σ TIME - 01ʰʳ 58ᴹᴵᴺ 30ˢᴱᶜ

Sg - Sn = 9·5ˢ
Sg - Pn = 9·0ˢ
Sg - Pɴ = 7·0ˢ
Sg - Pg = 5·0ˢ
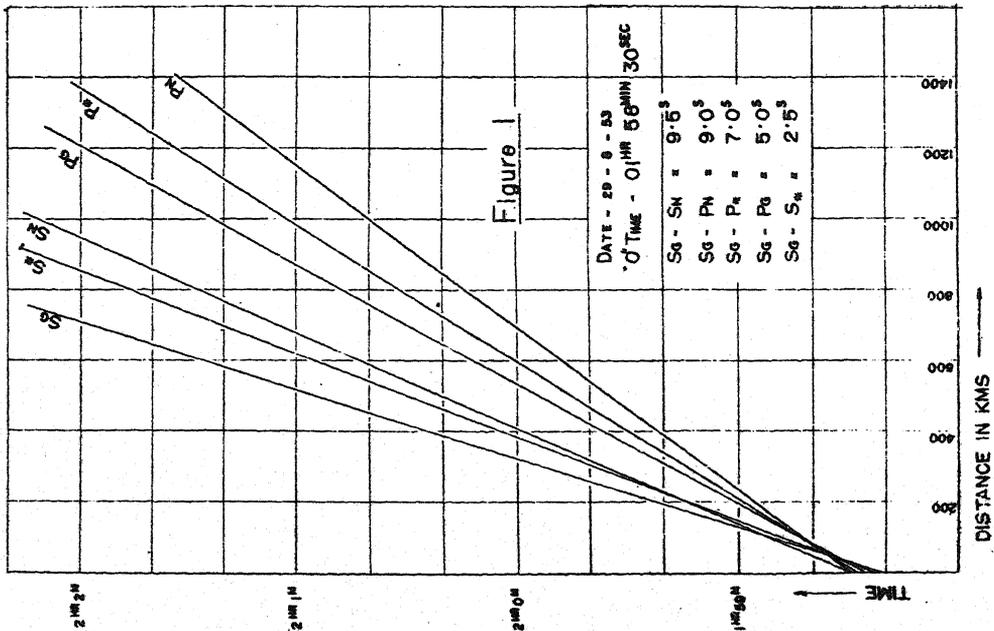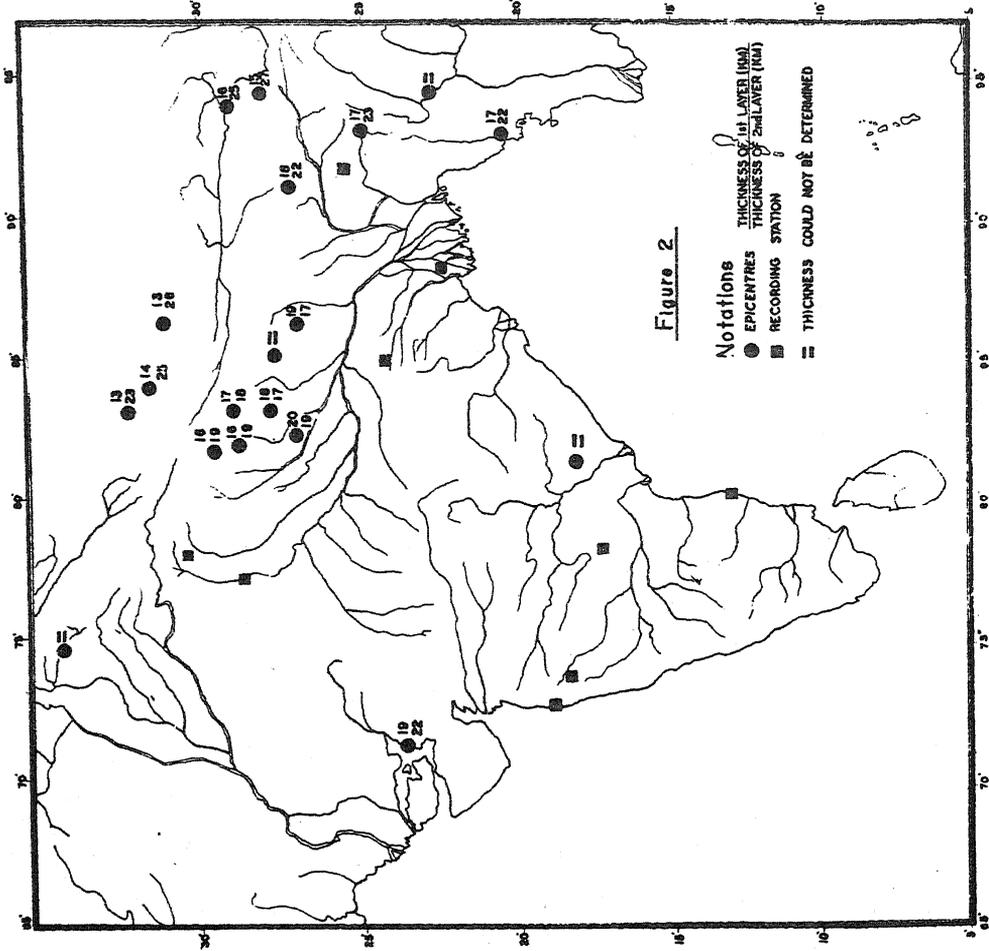Sg - Sₙ = 2·5ˢ

DISTANCE IN KMS

TIME

Table 1

Epicentres and focal depths of earthquakes and thickness of crustal layers

S.No.	Date	Epicentre		Focal depth in km	Thickness in km		
		Lat (N)	Long(E)		1st layer	2nd layer	Total
1.	14.6.50	24.0	71.2	19	19	22	41
2.	14.4.51	29.0	94.0	16	16	25	41
3.	22.4.51	28.7	94.4	16	15	27	42
4.	28.5.51	27.6	85.0	-	-	-	-
5.	9.7.51	20.5	93.0	16	17	22	39
6.	16.1.53	25.0	93.0	17	17	23	40
7.	27.1.53	23.0	94.5	-	-	-	-
8.	16.2.53	29.5	81.5	16	16	19	35
9.	20.2.53	27.0	86.0	21	19	17	36
10.	23.2.53	28.7	81.8	14	16	19	35
11.	27.2.53	29.0	83.0	16	17	18	35
12.	1.3.53	34.0	74.5	-	-	-	-
13.	23.4.53	28.0	83.0	16	18	17	35
14.	29.8.53	27.3	82.2	19	20	19	39
15.	8.10.53	31.5	84.0	16	14	25	39
16.	11.10.53	32.0	83.0	14	13	23	36
17.	3.12.53	31.0	86.0	16	13	26	39
18.	5.1.54	18.0	81.3	-	-	-	-
19.	23.2.54	27.0	91.0	18	18	22	40

Table 2

Velocities of P and S waves

S.No.	Date	Epicentres of earthquakes		Velocities in km/sec. for					
		Lat (N)	Long(E)	P_g	P_*	P_n	S_g	S_*	S_n
1.	14.6.50	24.0	71.2	5.5	6.4	7.9	3.5	3.9	4.5
2.	14.4.51	29.0	94.0	5.1	6.3	7.7	3.4	3.8	4.3
3.	22.4.51	28.7	94.4	5.2	6.2	7.7	3.3	3.8	4.4
4.	28.5.51	27.6	85.0	-	-	7.8	3.5	-	4.5
5.	9.7.51	20.5	93.0	5.5	6.5	7.8	3.5	3.9	4.5
6.	16.1.53	25.0	93.0	5.5	6.4	7.8	3.3	3.8	4.5
7.	27.1.53	23.0	94.5	-	6.4	7.8	-	3.8	4.4
8.	16.2.53	29.5	81.5	5.3	6.3	7.7	3.3	3.7	4.3
9.	20.2.53	27.0	86.0	5.3	6.2	7.6	3.3	3.7	4.3
10.	23.2.53	28.7	81.8	5.2	6.2	7.6	3.3	3.7	4.4
11.	27.2.53	29.0	83.0	5.1	6.3	7.6	3.3	3.7	4.4
12.	1.3.53	34.0	74.5	-	6.4	7.7	-	3.8	4.4
13.	23.4.53	28.0	83.0	5.4	6.4	7.8	3.2	3.7	4.4
14.	29.8.53	27.3	82.2	5.6	6.5	7.7	3.2	3.9	4.4
15.	8.10.53	31.5	84.0	5.1	6.2	7.6	3.2	3.8	4.4
16.	11.10.53	32.0	83.0	5.2	6.3	7.6	3.2	3.7	4.3
17.	3.12.53	31.0	86.0	5.3	6.4	7.6	3.3	3.8	4.3
18.	5.1.54	18.0	81.3	-	-	7.9		-	4.5
19.	23.2.54	27.0	91.0	5.5	6.5	7.8	3.4	-	4.5