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A preliminary note on the travel times of *P* and *S* waves in the Indian subcontinent*

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ABSTRACT. Recorded times of *P* and *S* phases as observed in different observatories in India during the period 1955, 1956 and 1957 on account of earthquakes having epicentres in and near the Indian subcontinent were collected from the Seismological Bulletins of the India Meteorological Department. The distances of the epicentres were determined and travel time curves for *P* and *S* waves were prepared. The observed velocities are fairly in good agreement with those determined by other workers for this region.

It is a well known fact in seismology that regional differences are observed in travel times of earthquake waves at epicentral distances shorter than 20 degrees. These differences are partly caused by the structure of the earth's crust in that region and are partly caused by regional anomalies of the crustal and upper mantle wave velocities. Velocities of *P* waves in the upper mantle which are usually observed to vary between 7·9 and 8·2 km/sec have been reported for the apparent velocity just below the Moho. The purpose of this paper is to draw the regional travel-time curves for India from observed data. At present the travel times of Jeffreys and Bullen are widely in use in India. The use of regional travel-time curves obtained from observed data will enable better and more accurate location of epicentres.

Seismically there are three main active regions in India. The first comprises of a narrow belt which runs along the foot hills of Himalayas. This belt also encloses parts of the Rann of Kutch and the adjoining areas of the western coast and Khasi and Garo Hills in Assam in the east. To the south of this belt and running almost parallel to it exists the area of moderate damage, in another belt about 300 km in width. Outside this belt lies an area which is comparatively stable. This region consists of the Deccan plateau. In this paper an attempt has been made to construct local travel time curves for *P* and *S* waves from data of near earthquakes.

Standard travel time tables of Jeffreys and Bullen are constructed for a spherical earth model. This model is defined as the sphere having the same volume as the earth, being concentrically homogeneous where for example the velocity at a given distance from the centre is equal to the corresponding mean velocity of the earth. Jeffreys has tested statistically the standard errors connected with the production of Jeffreys-Bullen Table of 1940. He concluded that for the most important phases of an average earthquake no further improvement can be expected.

By travel time we understand the relation —

$$T = f(\triangle) \qquad (1)$$

where, T is the time of transmission of a seismic wave and $\triangle$ the epicentral distance in degrees or km. For the determination of relation (1) it is necessary to know the values of T_i for a set of $\triangle_i$ since $T = t - H$ where T is the observed time of arrival of a seismic wave at a station and H is the time of origin of the earthquake and since the epicentral distance $\triangle$ is determined by the geographical co-ordinates of the epicentre (ϕE, λE) and those of the station (ϕS, λS), we need for the determination of (1) the following set of six parameters —

$$\phi\text{E},\quad \lambda\text{E},\quad \phi\text{S},\quad \lambda\text{S},\quad H \text{ and } t$$

By means of these parameters travel time curves for any particular region can be constructed emperically.

In the present paper local travel-time curves for *P* and *S* waves were constructed by the emperical method for the region of Indian subcontinent. To verify the accuracy. the results were compared with the standard travel time curves of Jeffreys and Bullen.

Data for the above work was collected from the monthly Seismological Bulletins of India Meteorological Department. As the time at the disposal of the author for writing this paper was very short, only three years' data (1955-1957) were taken. However, in his future work the author intends to take up data for at least 10 years. Altogether 51 earthquakes, were selected, having epicentres in India and the neighbourhood, within a distance

* This study was made while the author was at the International Institute of Seismology and Earthquake Engineering, Tokyo, Japan

TABLE 1

Station	Instruments	Component	Period (sec)	Static magnification	Damping ratio	Paper speed (mm/min)
Bokaro	Wood–Anderson	E	0·8	960	0·8	60·0
	Wood–Anderson	N	0·8	1000	0·8	60·0
	Milne–Shaw	N	12·0	250	20:1	16·0
	Milne–Shaw	E	12·0	250	20:1	16·0
Bombay	Sprengnether	E	$To=Tg=$ 7 sec	—	—	30
	Milne–Shaw	N	12	350	20:1	16
	Milne–Shaw	E	12	350	15:1	8
Chatra	Benioff	Z	$To=0·72$ $Tg=0·45$	—	—	60
	Milne–Shaw	E	12·0	250	20:1	16
	Wood–Anderson	E	1·0	1000	30:1	60
Dehra Dun	Milne–Shaw	N	12	250	20:1	8
	Wood–Anderson	N	0·8	800	60:1	60
	Wood–Anderson	E	0·8	950	60:1	60
Hyderabad	Milne–Shaw	N	12	254	20:1	8
	Milne–Shaw	E	12	254	20:1	8
Kodaikanal	Mine–Shaw	E	10·0	250	20:1	8
New Delhi	Milne–Shaw	N	12	320	20:1	8
	Omori–Ewing	E	30	30	1	12
Poona	Sprengnether	Z	$To=Tg=1·6$	—	2·1:1	30
	Milne–Shaw	N	12	300	20:1	8
	Wood–Anderson	E	4	1100	20:1	16
Shillong	Benioff	Z	$Tg=0.18, T_0=1·0$	—	—	60
	Sprengnether	E	$To=Tg=7·8$	5000	—	30
	Milne–Shaw	N	12	250	20:1	8
	Wood–Anderson	N	4	1000	Critical	30
	Wood–Anderson	E	0·8	1000	Critical	30
	Wood–Anderson	N	0·8	1000	Critical	30

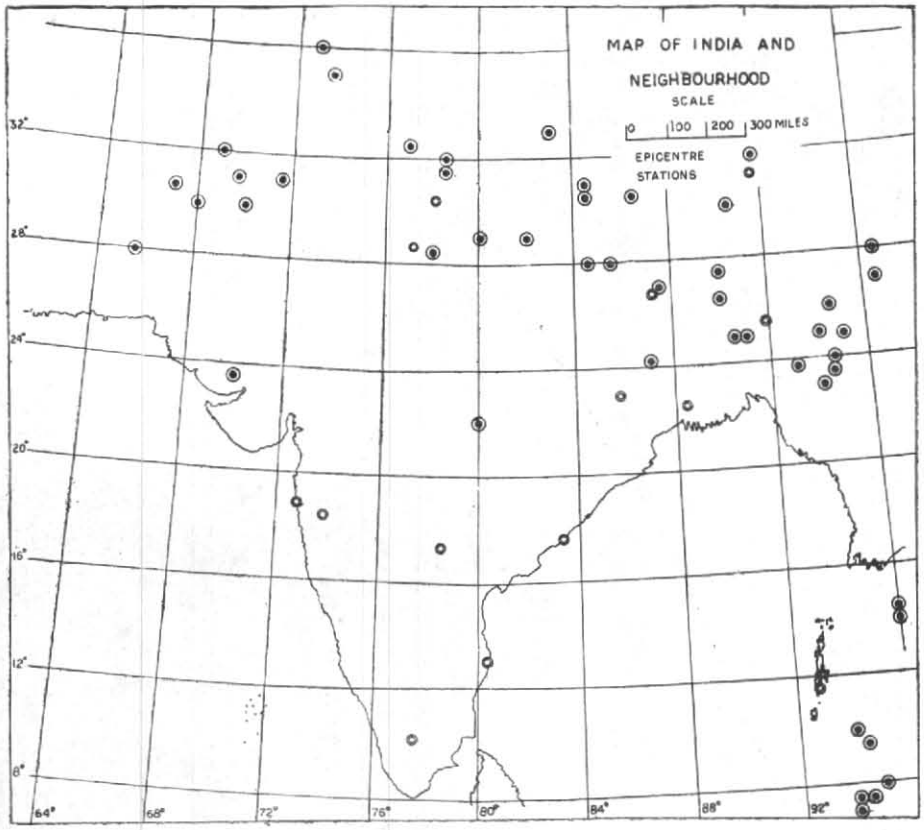

Fig. 1

of 3000 km from any of the stations. The interpretation given in the Bulletins published by the India Meteorological Department had to be accepted as the author did not have access to the original records and as such no critical control of P and S readings were possible. However, in future work original records will be consulted minutely. The selected earthquakes were recorded at the following stations –

(1) Dehra Dun, (2) New Delhi, (3) Shillong, (4) Chatra, (5) Bokaro, (6) Bombay, (7) Poona, (8) Hyderabad and (9) Kodaikanal.

All these stations were equipped with the instruments as shown in Table 1. The epicentres and origin times of the earthquakes are shown in Table 2. From Table 2 it may be seen that the epicentres of most of the earthquakes were considered as determined by the U. S. C. G. S. and incorporated in the India Meteorological Department Bulletins. Epicentres for a few shocks determined at Shillong had to be taken because the same as determined by U. S. C. G. S. were not available for these shocks.

No mention regarding the depth of focus of these earthquakes have been made in the seismological bulletins. But, as all these earthquakes have given rise to Pg and Sg waves, they were considered to be of shallow foci. The epicentres were plotted on a map of India and neighbourhood (Fig. 1). Co-ordinates of all the stations were also plotted on the same map and the epicentral distances were measured according to the map scale.

Average values of the travel times of P and S waves were arranged according to distance as tabulated in Table 3. Average values of P and S times were calculated within each interval of 100 km. These average values were plotted on a graph. The travel-time curves were drawn emperically in order to fit the maximum of the averaged values. The curves thus obtained are shown in Fig. 2. Both the curves are straight lines up to a distance of about 2000 km and after that the slope changes. These changes in the slopes perhaps coincides with the 20° discontinuity.

It was found that the observed time of arrivals both for P and S waves in the region under consideration are a little later than those of Jeffreys and Bullen. The difference in time between the curves drawn from observed data and those of Jeffreys-Bullen as shown in Figs. 3 and 4 are quite significant. From these figures it is evident that the

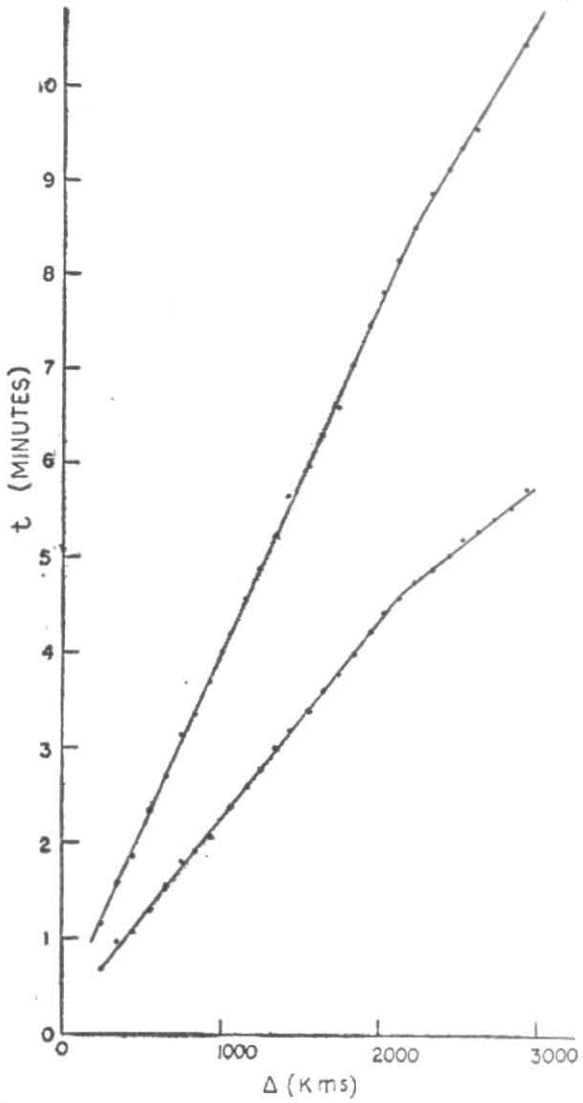

Fig. 2

TABLE 2

			Epicentre		Origin time			
			Lat. °N	Long. °E	*h*	*m*	*s*	
	1955							
1	9	Feb	33	83	10	35	24	U.S.C.G.S.
2	18	,,	30·5	67	22	48	33	,,
3	23	,,	28	85·5	23	13	30	,,
4	10	Mar	32·5	77	21	16	20	,,
5	12	,,	35	73·5	16	42	15	,,
6	15	,,	23·8	93	08	13	18	SHILLONG
7	4	May	28	96·5	00	16	59	U.S.C.G.S.
8	27	Jun	32	78·5	10	14	06	,,
9	27	,,	31·5	78·5	13	46	10	,,
10	1	Aug	9·5	94½	06	50	20	B.C.I.S.
11	4	,,	30·5	86·5	06	40	46	U.S.C.G.S.
12	23	,,	31	71·5	14	09	17	,,
13	20	Sep	27·5	90	20	21	13	,,
14	23	Nov	26·5	90	02	33	37	,,
15	29	Dec	30	90·5	08	25	33	,,
	1956							
16	2	Jan	8	95	01	30	15	,,
17	11	,,	7·5	94	06	10	03	,,
18	11	,,	31	69·5	22	16	18	,,
19	19	,,	30	81	19	50	34	,,
20	21	,,	23	94	17	35	34	,,
21	29	Feb	23·5	94·5	20	51	10	,,
22	29	,,	23·5	94·5	21	25	53	,,
23	3	Mar	23·5	94·5	10	13	44	,,
24	13	May	30	70	07	50	33	,,
25	4	,,	24·2	87	08	35	27	SHILLONG
26	12	Jun	25	91	03	12	37	,,
27	3	Jul	28	84·5	10	17	57	U.S.C.G.S.
28	12	,,	23	94	15	01	17	,,
29	21	,,	23·6	70	15	32	27	SHILLONG
30	29	Sep	7·5	94·5	09	03	37	U.S.C.G.S.
31	10	Oct	28·5	78	15	31	34	,,
32	5	Dec	25	90·5	15	05	08	SHILLONG
33	21	,,	27	96·5	03	27	41	U.S.C.G.S.
34	20	,,	24	94·5	21	59	06	,,
	1957							
35	1	Mar	29·2	80·2	15	40	09	SHILLONG
36	10	,,	36·3	73	03	30	12	,,
37	14	,,	27	87·5	10	03	40	,,
38	14	Apr	31	84·5	07	11	50	U.S.C.G.S.
39	14	,,	31	84·5	16	36	48	B.C.I.S.
40	22	,,	30·5	84·5	00	18	16	U.S.C.G.S.
41	22	,,	30·5	84·5	01	42	15	,,
42	28	May	25·5	95	05	51	30	,,
43	10	Jun	30	68	04	46	12	,,
44	14	,,	32	67	11	36	49	,,
45	18	,,	14·5	96	02	12	12	,,
46	18	,,	14	96	14	48	17	,,
47	25	,,	10	94	10	11	17	,,
48	1	Jul	25	94	19	30	16	,,
49	25	Aug	22	80	21	04	50	SHILLONG
50	30	,,	26	94·5	20	23	05	,,
51	4	Sep	28	65·5	08	07	15	U.S.C.G.S.

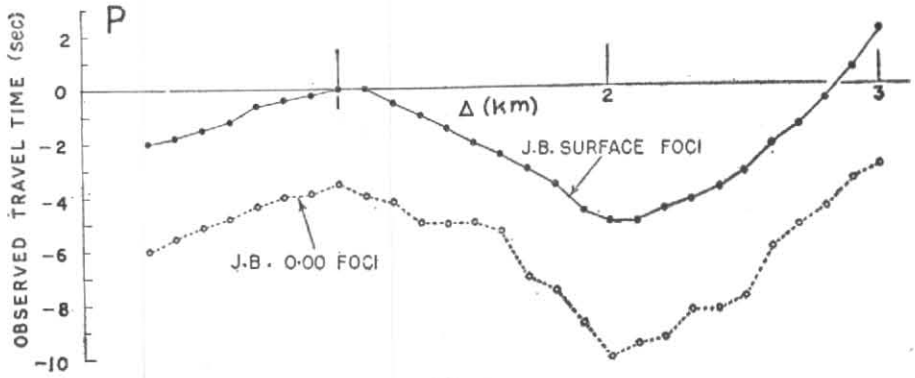

Fig. 3

TABLE 3

Epicentral distance (km)			No. of observations	Mean travel time for *P* wave		Epicentral distance (km)			No. of observations	Mean travel time for *S* wave	
from	to	mean		min	sec	from	to	mean		min	sec
200	299	249	16	00	41	200	299	247	15	01	09
300	399	345	9	00	58	300	399	347	8	01	35
400	499	439	11	01	04	400	499	442	10	01	52
500	599	552	8	01	18	500	599	556	7	02	20
600	699	657	13	01	33	600	699	661	12	02	42
700	799	758	15	01	48	700	799	759	14	03	08
800	899	846	12	01	55	800	899	846	12	03	22
900	999	938	12	02	04	900	999	939	9	03	42
1000	1099	1063	4	02	23	1000	1099	1063	4	04	12
1100	1199	1166	7	02	36	1100	1199	1166	7	04	34
1200	1299	1252	11	02	47	1200	1299	1251	11	04	53
1300	1399	1349	13	03	00	1300	1399	1352	11	05	14
1400	1499	1440	10	03	11	1400	1499	1434	8	05	40
1500	1599	1563	10	03	24	1500	1599	1563	10	05	59
1600	1699	1649	20	03	36	1600	1699	1646	20	06	18
1700	1799	1749	31	03	42	1700	1799	1751	27	06	36
1800	1899	1852	21	04	00	1800	1899	1851	18	07	03
1900	1999	1960	12	04	14	1900	1999	1957	11	07	28
2000	2099	2045	11	04	26	2000	2099	2043	9	07	49
2100	2199	2144	17	04	35	2100	2199	2143	16	08	09
2200	2299	2239	16	04	45	2200	2299	2244	14	08	30
2300	2399	2351	9	04	53	2300	2399	2353	9	08	52
2400	2499	2465	9	05	02	2400	2499	2466	10	09	08
2500	2599	2546	8	05	12	2500	2599	2546	8	09	21
2600	2699	2647	3	05	17	2600	2699	2647	3	09	33
2700	2799	2747	1	05	25	2700	2799	2747	1	09	34
2800	2899	2855	3	05	32	2800	2899	2855	3	10	02
2900	2999	2955	4	05	44	2900	2999	2954	4	10	27
3000	3099	3016		05	55	3000	3099	3016	1	10	38

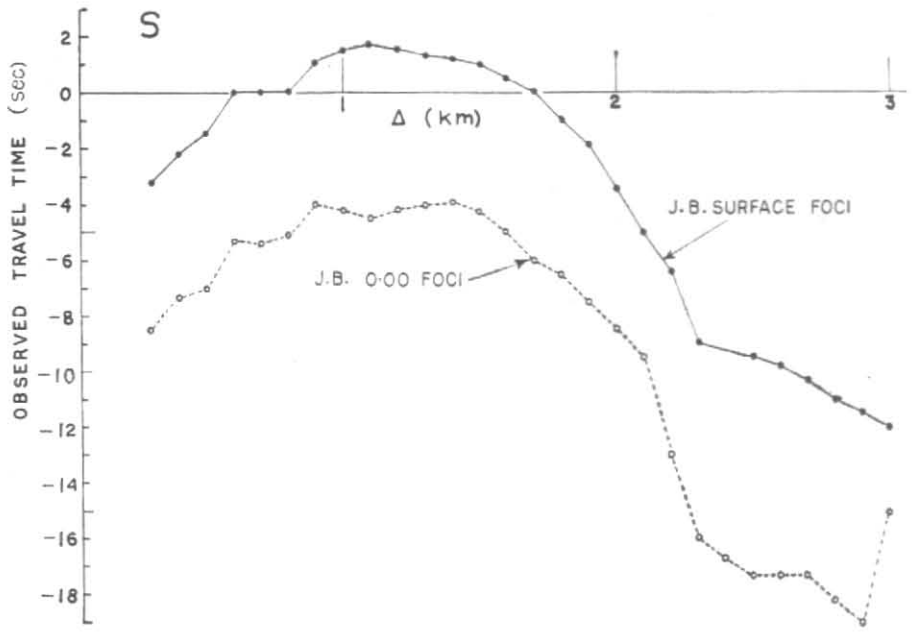

Fig. 4

TABLE 4

Phase	Indian subcontinent (Present author)	Central India (Mukherjee 1942)	Gangetic Valley (India) (Roy 1939)	N.E. India (Tandon 1954)
P	8·0	7·73	7·80	7·91
S	4·54	4·38	4·38	4·46

J-B curve for surface focus fits in better than that of 0·00 *R*. The velocities for *P* waves was found to be 8·0 km/sec and that for the *S* waves was 4·54 km/sec. Tandon (1954) from a detailed study of the great Assam Earthquake of 1950 and its aftershocks determined the velocities of *P* and *S* waves in the northeastern region of India to be 7·91 km/sec and 4·46 km/sec. These values are fairly in agreement with those determined by the author. In the past some other workers also have determined the velocities of *P* and *S* waves in the same region from earthquake records and their findings are given in Table 4 together with those as determined by the author.

From the present preliminary work it has been evident that in the region of Indian subcontinent the observed time of travel of seismic waves differ a great deal with the travel times of Jeffreys and Bullen. In his future work the author intends to draw travel-time curves from observed data collected from a number of years which can be used, for more accurate determination of epicentres in India.

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