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SEISMIC TRAVEL-TIME TABLES : PART I - EVOLUTION

R. C. Agrawal*

Introduction

Since there is no direct method to discern the interior of the Earth, the seismic waves recorded at seismological observatories are the only source of the more reliably established quantitative information about the Earth's interior. To date, most of the more precisely determined information has come from travel-time tables which give, for various seismic phases, the transit times along the corresponding rays in terms of distances (generally angular distances) travelled.

The complete study of the construction of 'Seismic Travel-Time Tables' is a very long project. The various parts of this project have been divided in three parts, viz. Part I-Evolution, Part II-Methods (used in the analysis of residuals) and Part III-Regional travel-time tables. Materials pertaining to Part I are presented in this paper.

The Early Developments

During the years 1900-1906, the travel-times of P and S waves covering epicentral distances upto 90° were published by Oldham, Milne, Bendorf and others (Bullen, 1967 a and Lehmann, 1967). Zöppritz (1907) from a study of three well recorded earthquakes, gave a new set of travel-time tables for the main and additional phases. These were the best available tables in those days. In 1912, Zöppritz and his fellow workers made some minor adjustments to the times by studying the variation of amplitude with distance. These times were extrapolated by Zöppritz to 117° epicentral distance and were later reduced to tables by H. H. Turner and further extrapolated to 150° epicentral distance. These tables were adopted for use in compiling the Intenational Seismological Summary (I.S.S.) for earthquakes during the period 1918-1929, and were called Zöppritz - Turner tables (Z—T Tables).

In the mean time two important discoveries were made on the seismograms. A. Mohorovičić, in 1910, found at epicentral distances between 300 Km and 700 Km two sets of P phases having diverging time curves and explained this due to an abrupt increase of wave velocity at the bottom of the crust. He constructed travel-time tables for P and S in 1914 for greater distances and improved his tables in 1921 by adding more data (Jeffreys, 1970). The second important discovery was made by Oldham (1906), when he found late arrivals of P near the anticentre, while analysing the seismograms of 1897 Assam earthquake and this, he explained, was due to the drop of P velocity in the central core and thus forming the shadow zone. The unmistakable shadow zone and focal zone effects on the side of the Earth opposite to the earthquake focus indicate the presence of a core or a nucleus in the Earth, which refracts the energy of the earthquake waves. Gutenberg (1914) made a precise determination of the depth of core, by studying the travel-times of the core influenced phases,

* Reader, Department of Earthquake Engineering, University of Roorkee, Roorkee — 247672 (U.P.) India.

to be 2900Km. Later the more elaborate work of Jeffreys revealed the depth of core to be 2898±4 Km. In 1928, Gutenberg published a chart of travel-time curves of the various seismic phases (Macelwane, 1936).

Turner (1922) discovered the existence of deep focus earthquakes during the compilation of I.S.S. Before this, it was a practice to assume that earthquakes originate at almost the same shallow depth and therefore wrong allowance for the depth of focus was made. Wadati, during the period 1927-1931, made convincing efforts to establish that the earthquakes occur at varying depths. In 1931, Scrase identified the various additional phases of deep focues earthquakes on the seismograms. Wadati and his coworkers, during 1933-1934, published tables of the main and additional phases for various depths of focus. In 1937, Macelwane and Dahm made a new set of travel-time tables from a study of three well recorded normal earthquakes. In twenties, many sets of travel-time tables were published by using a few earthquakes by Augenheister and Visser & Hecker ; while Krumbach composed a set of tables by forming the means of the times as given by the then existing tables. This could not be accepted because of the different base-lines chosen in different tables (Lehmann, 1967).

The Jeffreys–Bullen Travel–Time Tables of 1940

Jeffreys (1936) pointed out that the preparation of travel-time tables is not an easy task and travel-times for the various phases are obtained only after recalculating the various parameters of each earthquake with reference to a trial table. The final construction of travel-time tables is, therefore, done only by successive approximation. Systematic work leading to the construction of new and effective travel-time tables was undertaken in the thirties. The Z-T tables were found to contain serious anomalies by Turner (926) because his analysis showed a systematic variation of the residuals. The means of the residuals varied with distance by about 20 s for P and 30 s for S.

The Jeffreys-Bullen travel-time tables of 1940 (J.B. tables) were designed to produce the most probable travel-times for an 'average' earthquake. These were published in 1935 in its first recognised form. The observations were taken mostly from the I.S.S. (Jeffreys & Bullen, 1935).

In the thirties, Gutenberg and Richter also made an extensive study of travel-times and the velocity distribution of various seismic phases, including the ones which travel deep into the interior of the Earth. They published a series of papers under the heading "On Seismic Waves" (Gutenberg & Richter 1934, 1935, 1936 and 1939). Gutenberg and Richter (1933) pointed out the effect of the ellipticity of the Earth and Bullen (1937) calculated the ellipticity corrections.

Miss Lehmann, in the mean time, gave a strong evidence about the existence of an inner core (Lehmann, 1936).

The J.B. tables were updated by making ellipticity correction and adding more data. The velocity distribution in the core was found afresh (Jeffreys, 1939 b, c and d) and the final form of the J.B. tables, giving times for various phases, were published in 1940. Thorough statistical procedures were used to get results for an 'average' earthquake. The tables relate to a spherically symmetrical Earth model which is defined so that each internal spherical surface of constant P and S velocity encloses the same volume as in the actual Earth. The tables correspond to an 'average' earthquake. The regional effects were not taken into consideration while making these tables. It took about a decade to achieve the final form of the J.B. tables. Since then these tables are in constant use for compilation of data at the I.S.S., which has now been renamed as International Seismological Centre (I.S.C.) (infact J.B. tables were in use from 1930 onwards at I.S.S. in provisional forms).

The J.B. tables (Jeffreys & Bullen, 1940) and Gutenberg and Richter tables (Gutenberg & Richter, 1939) agree fairly well except for the short distances.

The lateral inhomogeneities of the Earth's crust and the upper mantle are supposed to be the main cause for correction needed to J.B. tables at short distances. This was pointed out by Jeffreys (1939 b) in his prophetic statement, "......... further development is unlikely to lead to the substitution of any single set of tables for the present ones. It is more likely to lead to the introduction of minor correction, not always with the same sign, that can be applied to the present tables in specified circumstances". Infact, it is still a fairly accurate statement because no new travel-time tables have so far been constructed for an 'average' earthquake which do not make room for regional variations.

Regional Travel-Time Tables

Looking critically, at the data used in the preparation of the J.B. tables, one finds that at small distances the Japanese earthquakes, at intermediate distances the European earthquakes and at large distances the American and a few European earthquakes were used for giving the times upto 105° epicentral distances. A similar treatment was made in finding S-times. Thus, the uneven distribution of selected events makes the J.B. tables look more like a patchwork quilt than a world average.

As soon as the J.B. Tables were published, the regional differences became evident and the consensus of seismologists agreed with Sir Harold Jeffreys's statement of 1939. One of the main reasons for regional differences is the assumption in the J.B. tables that the upper mantle does not vary much from place to place. In the J.B. tables, the Pn velocity, the velocity of P at the base of the crustal layers, was 7.75 Km/sec, corresponding to $dt/d\Delta = 14.3$ sec/deg at zero degree epicentral distance. As pointed out earlier, the Japanese earthquakes were used at short distances, this value of $dt/d\Delta$, therefore, represents only that region. For other regions the value of $dt/d\Delta$ is less than this value (Jeffreys, 1970).

The advent of the use of nuclear explosions as controlled experiments, contributed substantially in the study of travel-times of the various earthquake phases. In explosions, the shot time and location of the source are known to a high degree of precision. Though the depth of the source is not appreciable yet this small depth is even known to make an allowance for the effects of superficial layer. The explosions, if available, are, therefore, generally more suitable for travel time studies of a particular region than the earthquakes. In July 1946, an underwater explosion was carried out near Bikini atoll. For the first time, the information on the shot time and the location of th source were made available to seismologists. The P times were recorded upto 80° epicentral distances and showed that these times were

2s earlier than the predicted times by the J.B. tables. The difference was attributed to the structure beneath the souce. Similar early arrivals were reported by Gutenberg in 1953 from Pacific nuclear explosions. From a study of the hydrogen bomb explosion of 1954 near Bikini, Burke-Gaffney and Bullen concluded several important seismological inferences and most notable of these being the firm existence of early P arrivals at epicentral distances between 137° and 142° (diffracted P.) The existence of these arrivals has thrown more light on the inner core boundary (Bullen, 1967 b).

Jeffreys made several special studies of the travel times for distances upto 30°. From an explosion study, Jeffreys (1947) found a sharp bend in P travel-time curve at 15° epicentral distance indicating a shift in 20°-discontinuity. He also found high Pn velocity for Europe. This result was confirmed by Wilmore (1949) and many others. Pn velocities between 8.0 km/sec and 8.2 km/sec corresponding to dt/dΔ between 13.8 sec/deg and 13.5 sec/deg for Europe were reported in different studies (Gutenberg, 1959).

At the same time, the variation in Šn velocities confirm the systematic difference from the J.B. tables elsewhere in the world. The Table 1 summarises the various studies made by Jeffreys for P & S for the different regions.

Table 1 : P and S Velocities in Different Regions (after Jeffreys, 1970)

	P		S	
	dt/dΔ	Velocity	dt/dΔ	Velocity
J.B. (1940)	14.08	7.90	25.09	4.29
Europe	13.66 ± 0.07	8.140 ± 0.041	24.28 ± 0.15	4.576 ± 9.928
Central Asia	13.64 ± 0.10	8.146 ± 0.060	24.11 ± 0.15	4.608 ± 0.018
West North-America	13.95 ± 0.16	7.966 ± 0.091	—	—
East North-America	13.59 ± 0.10	8.176 ± 0.060	23.66 ± 0.017	4.969 ± 0.033
Pacific	13.654 ± 0.041	—	—	—
Japan	14.13 ± 0.04	7.87 ± 0.024	25.41 ± 0.00	4.373 ± 0.034

These values are the averages between 2° and 10° epicentral distances. The table compiled by Jeffreys (1970) has been reproduced here in order to emphasise the existence of regional differences. The world wide recognition of regional differences makes it essential to construct the travel-time tables for the various seismic phases for the major seismic regions. However, at present, owing to the poor distribution and less number of seismic observatories, it may not be possible to make new tables with any authority for all seismic regions.

The travel-time tables for selected stations were constructed by Båth (1947), Sornes & Sindre (1963) and Enayatollah (1972) among many others. The correction to the J.B. tables were found for different regions by Jeffreys (1954), Carder and Bailey (1958), Kondorskaya (1959), Gogna (1967) and Kaila et al. (1968). They used different materials and methods in their studies. The comprehensive work of Carder & Bailey (1958) containing information on travel-times from more than one thousand seismic records of nuclear explosions pointed the ways to corrections needed to the J.B. tables. The precise work of Husebye (1965) determined the needed corrections to the J.B. tables in a better manner by dividing the deviations between the observed travel-times and those calculated from the J.B. tables into a station and an epicentre corrections. Regional differences in P travel-times across the United States were found large enough to affect seriously the determination of epicentres by the usual routine method.

Gutenberg (1953 and 1954), with the help of a number of studies gave strong evidences about the existence of low velocity layers both in the crust and the upper mantle. At present, his hypothesis has got substantial support from a number of studies conducted by using different geophysical methods and from the study of dispersion of surface waves.

Delays in the arrival times of P have been reported by Herrin (1957), Barr & Robson (1963) and Press and Beihler (1964). Jeffreys (1954), Cleary & Hales (1966), Bolt & Nuttli (1966) and others obtained earlier arrivals than predicted by the J.B. tables.

With the above results and other works as reviewed by Nuttli (1963) and Herrin (1967) in mind, a few leading seismologists, mostly from the United States, taking note of the use of nuclear explosions and the vast improvement in the instrumentation during the last three decades and a substantial increase in the number of observatories distributed nearly uniformly over the whole Earth, decided to reconstruct a new set of tables of P for intermediate and large distances. They published a new set of P travel-time tables for epicentral distances greater than 20° alongwith the times of other P phases influenced b the core (Herrin et al. 1968). Because of regional differences, they did not try to make world 'average' tables for shorter distances. Method of the analysis of the residuals differed. They determined means of residuals for 1° cells and then determined station corrections from the residual deviations. The iterative technique was applied using the data recorded at 300 stations recording 400 earthquakes and 30 explosions. They found the times of P with a standard error of about, 1 s as compared to the standard error of 2 s in the J.B. tables. This result verifies that it is very difficult to achieve a higher accuracy for the world average travel-time tables. In 1971, Randall prepared the tables for S taking the same earthquakes and the crust & upper mantle model as used in the preparation of Herrin et al (1968) seismological tables.

After the firm establishment of the existence of an inner core in 1954 from hydrogen bomb explosion studies (Burke-Gaffney & Bellen, 1957), Bolt made a series of efforts to bring out a true picture of the core from the study of first arrivals through the core (PKP) (Bolt 1959, 1965 and 1968). Bolt (1968) published his finally revised travel-time tables for PKP. In his work of 1965, Bolt remarked that the further revision of PKP was not desirable.

Aims of the Present Study

The Indian region has not yet been studied in detail. The firm existence of regional differences makes it desirable to make a new set of travel-time tables for serious seismological studies of this region. The aim of the present study is, therefore, to analyse the travel-times of the two main body waves, viz. longitudiual & transverse waves, generated by the earthquakes orginating in India and recorded at near and far stations, to give a new set of travel-times for the Indian region. The S-type waves through the core (SKS), could not be studied due to the lack of good observations. For this purpose, the deep focus earthquakes are selected from I.S.S. and I.S.C. bulletins.

Reasons for Using Deep Focus Earthquakes & Bulletin Readings

(i) *Deep focus earthquakes*

While analysing the normal earthquakes, one encounters with certain significant difficulties, which are not faced in the case of deep focus earthquakes. First and quite foremost problem one faces with the normal earthquakes is about the recording of the bodily wave phases on the seismograms. In deep focus earthquakes these phases appear sharper and the seismograms are free from the disturbance of surface waves. The advantage of using deep focus was first noticed by Zöppritz in 1912. Gutenberg and Richter (1939) emphasised further the importance of deep focus earthquakes when they used data from such earthquakes to give times for S phases. Jeffreys (1935) used five deep focus earthquakes for his study of body waves and noticed some of the advantages of deep focus earthquakes over shallow focus ones. Later, Jeffreys (1939 a) studied some Japanese deep focus earthquakes and obtained much better results. He remarked, "It has appeared that analysis of readings in deep focus earthquakes may help to answer a number of questions that can not be adequately treated from normal earthquakes alone". Jeffreys (1959 d) has given complete description of deep focus earthquakes. The deep focus earthquakes are particularly useful in the study of S-phase because in shallow focus earthquakes, the observations of S are generally distributed quite evenly over 20 s or more at short and intermediate distances. In case of P also one finds a better estimate of the standard deviation of one observation for deep focus events than for the shallow focus ones (Arnold, 1965).

The most significant problem one faces with the normal earthquakes is to account for the depth of focus. In the preparation of J.B. tables, the average depth of focus was taken to be 10 km. This assumption is one of the reasons for the anomalies present in the J.B. tables. It is difficult to estimate the standard error in the depth quite accurately in normal earthquakes, because it is very difficult to separate the errors from that in the origin time while recalculating the parameters (Jeffreys, 1966). It is easy to account for the depth, in case of well recorded deep focus earthquakes. For deep focus earthquakes it is quite common to have the estimate of the standard error less than 0.001 R (R being the radius of the Earth from the centre to the Mohorovicic discontinuity). In deep focus earthquakes, the variation of $dt/d\Delta$ with depth at a given distance is considerable so as to enable us to build up a surface focus table by adding surface times for ascending and descending rays for the same $dt/d\Delta$. The normal earthquakes do not give sufficient opportunities to check the existence of a possible low velocity layer (Gutenberg, 1953). But in case of deep focus earthquakes, one can compare times from those above, in and below the possible low velocity layer. Jeffreys has found that for rays originating in a low velocity layer, the times for intermediate distance will be delayed compared to large and small distances than in case of focii above and below (Jeffreys, 1962). This is because rays leaving the focus horizontally have to travel a greater distance in a deeper layer before reaching the surface, whereas in the surface focus case no ray can exist with its deepest point in the layer. Some of the deep focus earthquakes having depth less than 0 01 R have a very good series of both P and S observations at almost all distances.

Most of the workers used normal earthquakes in their study either for finding corrections to the J.B. tables or for finding tables for separate regions but could not meet with the desired success. Arnold (1965), working under the supervision of Sir Harold Jeffreys, modified Jeffreys's Japan times of 1954 by using deep focus earthquakes. It is evident that the use of data from deep focus earthquakes would lead to more precise determination of travel-times. In the light of all these, it was decided to concentrate on deep focus earthquakes for the present study.

(ii) Bulletin readings

Jeffreys (1970) calls the reading of all the seismograms of an earthquake by an individual as the 'special study'. Most of the real advances in seismology have been made by making 'special studies'. Others have used the routine observations compiled by I.S.S. or I.S.C.

The standard deviation of one observation remains essentially the same, no matter whosoever reads the seismograms and the error is porbably due to the small variations in the Earth's structure and not the observer. There are two obvious advantages in using I.S.S. or I.S.C. data over the 'special study'. The first advantage is that the most laborious part of the work, the reading of the records and the computation of approximate parameters of earthquakes, have already been done by the observatory and the I.S.S. staff. Consequently it is possible to use several earthquakes in the study and test the results for consistency in a time that would hardly suffice for one earthquake in a 'special study'. The second advantage is that the routine observations are made in most dispassionate manner and in 'special studies', the observer has in mind what he wants to see and the temptation to see is great. Due to this reason, some seismologists believe that the study based on the routine observations is much more reliable than the one made from a 'special study'.

The methods and techniques used in the analysis of residuals for constructing the seismic travel-time tables have been described in Part II and the results of this study i.e. the travel-time tables for the Indian region have been presented in a concise form in Part III. Parts II and III are being published elsewhere.

Concluding Remarks

The need for preparing a separate set of travel-time tables for the prominent seismic phases for the Indian region has been stressed. In order to achieve the desired accuracy in the construction of these tables for the Indian region, the evolution of the construction of such tables for the world-wide average earthquake has been presented in this paper. Further critical reviews of the works done for constructing travel-time tables for an 'average' earthquake by various authors, from time to time, have clearly brought out the fact that the sound statistical techniques employed for preparing a set of regional travel-time tables for the prominent seismic phases yield more accurate results. Further, the use of deep focus earthquakes provides the opportunity to employ pP phase in determining the allowances for focal depths. This allowance makes the data look more realistic and analysis of residuals gets fair treatment. Similarly the advantages in utilising the bulletin readings instead of making a 'special study' are also brought out clearly.

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