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34. *Travel Time Curve of Near Earthquakes in Japan Area and Some Related Problems. 1. Procedures and Preliminary Results.*

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Abstract

Recent advancements in the observations of natural and artificial earthquakes and in the improvement in the speed and memory size of electronic computers are sufficient to give us aspiration for the attempt of revising the travel time tables of near earthquakes which have been used in routine works for nearly thirty years in Japan. The Research Group for the Travel Time Curve was thus organized in view of the practical and theoretical applications of the earthquake observations as well as the studies of the crustal structure in this part of our planet. The Group aimed at the determination of travel time curves of earthquakes with different depths best fitted to the observations by the method of least squares for earthquakes originating in and around Japan by simultaneous adjustment of origin times and hypocentral locations of all the earthquakes studied. The station corrections for the arrival times for all the observatories are also to be determined at the same time.

In the present study, our effort was inevitably confined to the study of travel time curves of near earthquakes up to the epicentral distance of 1500 km, owing to the areal limitation of our country and paucity of observing stations in other neighbouring countries and in the oceanic area. But high seismicity in the region concerned allowed us to obtain many data even in the limited interval of eleven years (1954–1964).

Several preliminary attempts and tests were made to select a feasible procedure for the purpose. For the time being, the memory size of an available computer and other factors confined us to the determination, at one time, of a travel time for the earthquakes with a given constant depth of hypocenter. Similar analyses were

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carried out for each earthquake group of respective hypocentral depths.

In view of the practical significance, some preliminary studies and tests are briefly described in Part I, while the results of our final analyses are described in Part II. Major items treated in Part I are as follows; Selection of the formula to express the travel time curve and rejection criterion of inappropriate data (Section 2), dependency of the resulting travel time curve on the assumed epicenter location (Section 3), effect of the starting assumption of the location of the epicenter on the final epicenter coordinates approximated successively by the iterative application of Geiger's method (Section 4), convergency of the epicenter location and the travel time curve in alternate successive determinations of the travel time curve and epicenter location (Section 5), calculation of the travel time curve for epicentral distances less than 170 km (Section 6), method of simultaneous determination of the travel time curve and station correction for the arrival of the P-wave, together with the origin time and epicenter locations of all the earthquakes by means of arrival times of the P-waves of many earthquakes at the stations throughout our country (Section 7).

In Part II, the last procedure reached at in Section 7 is applied, first to a group of earthquakes with a hypocentral depth of 40 km as determined by the Japan Meteorological Agency. Some detailed reviews of the method and the results are given in Section 8. Similar analyses were next made of other groups of earthquakes with hypocentral depths of 0, 20, 60, and 80 km respectively, and the results are shown in Section 9.

In Section 10, a comparison of the travel time curve obtained here for earthquakes of zero km depth is made with the travel times obtained in explosion seismic experiments carried out in Japan by the Research Group for Explosion Seismology.

Contents

Introduction

Exact determination of the origins of earthquakes has recently become one of the key problems in modern seismology. The cause of earthquakes, which is one of the ultimate objects of earthquake study, is presumed to be best solved from the exact knowledge of the distribution of hypocenters in relation to geological and geographical features. The seismicity of a region also forms the essential basis for the practical application of engineering means of the mitigation of earthquake disasters, the largest natural calamity for the human race. This also depends on the distribution of hypocenters and the mean frequency of earthquake occurrences in each locality.

The accuracy of hypocenter determination depends on the arrival time observation of seismic waves at a number of stations and on the travel time curves of these waves. The utility of the accurate travel time curve is not confined to the above problems. It also gives us the best means to elucidate the structure of the interior of the earth.

The studies of the travel time curves of seismic waves date back to the beginning of seismology, and here no complete historical review of them is necessary and possible. It is worth mentioning that most of the travel time tables currently used (Wadati, Sagisaka and Masuda, 1933; Sagisaka and Takehana, 1935; Gutenberg and Richter, 1936; Jeffreys and Bullen, 1940) are derived by taking the means of available travel times at respective distances from the epicenters, which are determined by some standard travel time tables. Principally, therefore, they are not free from the systematic errors in the presently used standard table. Owing to the inhomogeneity in data due to the lack or paucity of seismological stations and epicenters in some regions of the world, the mean travel time tables can never be free from the regional inhomogeneities of the crustal structures, as recently revealed from the studies of surface waves (Aki, 1961; Aki and Kaminuma, 1963; Kaminuma and Aki, 1963; Kaminuma, 1964) and from the results of explosion seismic experiments (Usami *et. al.*, 1958; Matuzawa, 1959; Matuzawa *et. al.*, 1959; Mikumo *et. al.*, 1961; Hotta *et. al.*, 1964).

It is, therefore, necessary to know as exactly as possible the position of the hypocenters of available earthquakes, independently of any assumed travel time curve, which give the best travel time curve to fit the observed arrival times with the least deviations. Recent advances in explosion seismology revealed the existence of very large station corrections (Herrin and Taggart, 1962; Romney *et. al.*, 1962), which calls for the inevitable elimination of their effect in the ensuing analysis.

The next important point of the study would be the possible differences of crustal structures in different parts of the world.

Recent advancement in the observations of natural and artificial earthquakes and the improvement in the capacity of electronic computers gave us impetus for the study of the above problems. We first attempted to determine the travel time curves of earthquakes originating in and around Japan, where available data are abundant owing to the high station density and seismicity.

The object of the present study lies in the calculation of the standard travel time curves of the P wave within 1500 km for shallow earthquakes in the Japan area. The study is characterized by (1) a vast amount of data processed by an electronic computer, which yields a better accuracy than in the past, (2) the coordination of the surface focus travel time curves with the results of explosion seismic observations, and (3) the simultaneous calculation of the corrections to the travel time curve and hypocenter constants, and the station corrections by means of the least squares method.

Earthquakes which have occurred in and around Japan since 1954 are used in the analysis and data are obtained from the Seismological Bulletin of the Japan Meteorological Agency. Hereafter, the Japan Meteorological Agency will be abbreviated to *J.M.A.* and the data prepared and published by *J.M.A.* to *J.M.A. data*. According to Yamakawa (1965), *J.M.A.* data in this period have the best quality in its history since 1883 and can be safely assumed to be homogeneous. Earthquakes having available observations at places farther than 1350 km are adopted.

Since available observations at large distances are few owing to the geographical relationship of the observation network to the seismically active region, the travel times at epicentral distances less than about 1550 km are considered.

Before entering the actual work, the following preliminary tests were made in order to fix the procedures in detail. They are given in Part I.

1) The difference of calculated travel time curves due to the adoption of different formulas and data is examined in Section 2. The cubic formula without a quadratic term as a function of the epicentral distance is adopted finally and the observed data which deviate by more than 2 seconds from the assumed travel time curve will be omitted from the calculation of the travel time curve.

2) The effect of the small shifting of the epicenter location on the resulting travel time curve is examined in Section 3. It is concluded that earthquakes having a probable error of longitude and latitude of the epicenter of less than 1′ would be preferable for this study.

3) The initial epicenter location affects the final location in the process of successive approximations by Geiger's method. This effect is examined in Section 4 and it is found that the effect is negligible if data which deviate by more than 2 seconds from the referred travel time curve are omitted in every step of the successive approximations.

4) A test is made on the convergency of the epicenter location and the travel time curve when they are calculated by alternate successive approximations. The result shows that the convergency is so rapid that we may adopt the first approximation epicenter constants and the second approximation travel time curve as the standards in the procedure described in Section 7.

5) Since most earthquakes adopted in this study occur under the oceanic region and available data at short distances are scanty, the travel time curve calculated from these data cannot be applied to short distances. Therefore, the travel time curve for distances less than about 170 km is considered separately. For this distance range, data of large earthquakes and additional small ones are processed together as is described in Section 6.

6) A method of calculating simultaneously station corrections, corrections to the presumed travel time curve (see Eq. (1-4)), corrections to the time of occcrrence and to the epicenter location is given in Section 7.

Application of the procedures given above to the actual data is developed in Part II. Earthquakes are grouped according to the *J.M.A.* focal depth and the actual work is done for each group. The Wadati-Sagisaka-Masuda travel time curve and the *J.M.A.* constants of hypocenter (latitude, longitude, depth and time of occurrence) are adopted as the starting approximation in this investigation. The processes explained in 1)~6) are reviewed in Section 8 using earthquakes with the *J.M.A.* focal depth of 40 km, and the results for the focal depths of 0, 20, 40, 60 and 80 km are summarized in Section 9.

The travel time curve describing the data of explosion seismic experiments carried out in Japan is calculated for a range less than 300 km. Since for this distance range, this travel time curve is more reliable than that obtained from the analysis of natural earthquake of shallow focus, the latter travel time curve is adjusted to the former one to obtain a travel time curve for the surface origin (cf. Section 10).

Concluding remarks and future problems are given in the last Section.

Part I. Numerical Tests on and Description of the Method

1. General descriptions

With the above-mentioned object in view, the method of least squares is applied in various stages of this study. The results, however, depend principally on the data used, the location of the epicenter, the first approximation travel time curve, the method of data processing, and so on. In order to make clear the contributions of these causes to the final results, several kinds of numerical tests are described in this Part.

In Section 2, the selection of the data and the formula for the travel time curve are considered. In the following Sections, from 3 to 5, the effect of the shifting of the epicenter location on the travel time curve, the effect of the starting epicenter location on the final one in the process of successive approximations by Geiger's method, and the convergency of the travel time curve and epicenter in alternate successive determinations are considered. The method calculating travel time curves for short distances is given in Section 6. A method calculating the β approximation travel time curves (see Section 8) will be explained in Section 7 by which the station correction, corrections to the travel time curve, to the time of occurrence and to the epicenter location can be calculated simultaneously.

2. Formula for the travel time curve and selection of data

The travel time curve can be expressed in a certain range of epicentral distance as a polynomial function of n-th degree of the epicentral distance. An attempt was made (Seismological Section, *J.M.A.*, 1963) to approximate the Wadati-Sagisaka-Masuda travel time table of the P wave by an n-th degree polynomial function in epicentral distance. According to the results, if the degree n is large, this function reveals undesirable fluctuations of small amplitude showing that the derivative of the travel time curve with regard to the epicentral distance $dt/d\Delta$ does not decrease monotonously as the distance increases. On the other hand, when the focal depth is zero, it is known that the coefficients of the even degree terms of the epicentral distance generally vanish (Kawasumi and Yoshiyama, 1934). Considering the results of these investigations, the following two formulas were chosen and tested numerically.

$$\text{a)} \quad t=a+b\Delta+d\Delta^3 , \tag{1-1}$$

$$\text{b)} \quad t=a'+b'\Delta+c'\Delta^2+d'\Delta^3 . \tag{1-2}$$

In the attempt to calculate the travel time curve which best fits to the observed data by the method of least squares, the choice of data is known to have effects on the results. Usually data which deviate by more than a certain value from the assumed travel time curve are omitted before the calculation. In the present study, the two processes (I) and (II) were tested in order to determine the critical value for the rejection of inappropriate data.

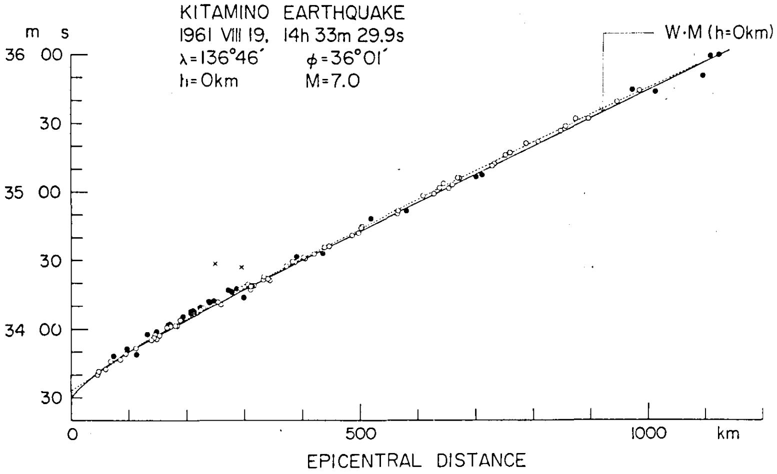
First of all, the travel time of an individual earthquake is plotted, as in Figure 1, referring to the *J.M.A.* constants of the hypocenter.

Process I) Next, all the data which deviate from the average by more than about 5 seconds are omitted and the coefficients of either (1-1) or (1-2) are determined from the remaining data by the method of least squares.

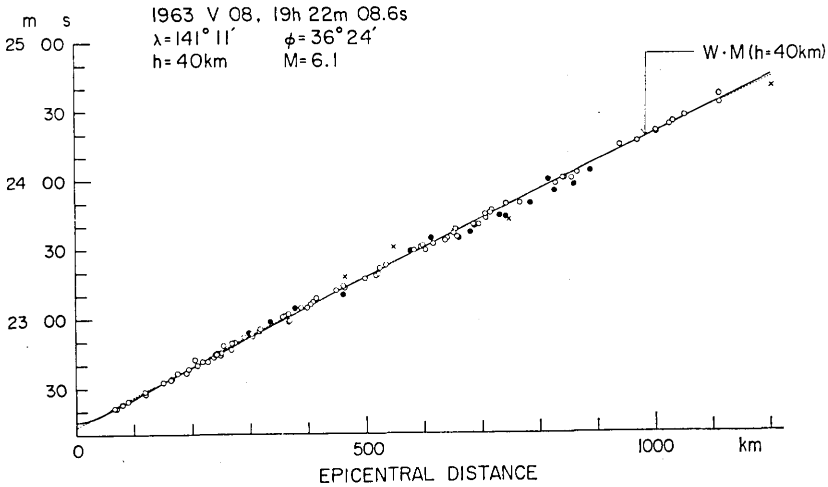
Process II) Then, data which deviate by more than 2 seconds from the derived relation (1-1) or (1-2) are discarded, and the coefficients of relation (1-1) or (1-2) are redetermined from the remaining data.

The value, 2 sec., was adopted referring to the fact that the arrival time of the P wave determined by *J.M.A.* may have inaccuracy amounting to a maximum of 2 seconds, even when the on-set of the wave is undoubtedly identified (Hayakawa, 1949; 1951). Cross marks in Figure 1 are the observations rejected in the process I), solid circles show the data rejected in the process II), and the resultant curve which is shown by the dotted line is calculated using only open circles. In this figure, travel time curves corresponding to the expression (1–2) are shown.

The resultant curve is slightly different from the Wadati-Sagisaka-Masuda curve. This difference is the main subject of the present study.



(a)



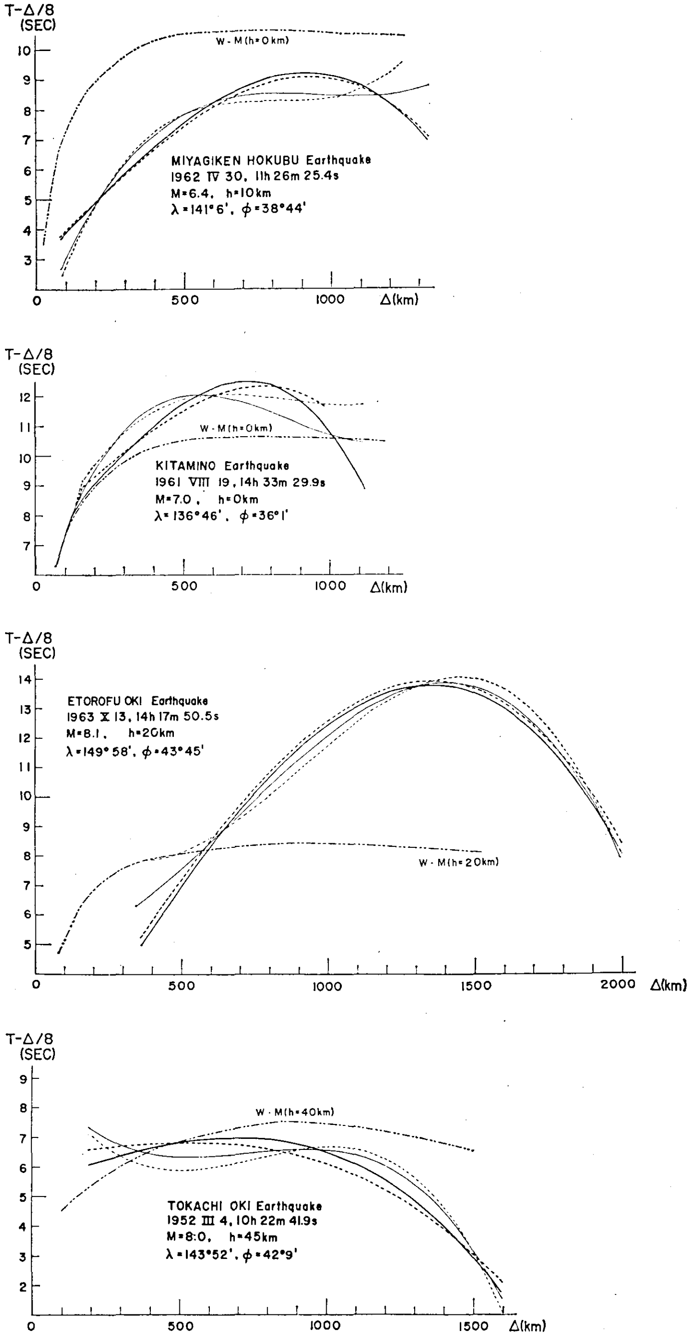
(b)

Figure 1. Examples of the travel time curve of the *P* wave. The solid line shows the Wadati-Sagisaka-Masuda travel time curve. Cross marks are the data omitted before the calculation and solid circles are those which deviate by more than 2 seconds from the travel time curve based on both open and solid circles. The travel time curve shown by the dotted line is calculated using only open circles.

In *J.M.A.*, since 1961, the determination of the hypocenter has been carried out on an electronic computer using the arrival times of P and S waves obtained at about 25 stations nearest to the epicenter. The difference between the resultant curve and the Wadati-Sagisaka-Masuda curve may be partly due to the number of data used and partly due to the different procedures of the analyses. Examples of the processes I) and II) are given in Figure 2. Generally speaking, the differences among the four (thin and thick dotted, thin and thick solid) curves are so small that any of the four can be adopted. In this study, however, considering the investigation by Kawasumi and Yoshiyama cited above, the dotted thin curve, the result of the process II) employing the formula (1-1), is adopted as the standard. For earthquakes with 80 km focal depth, formula (1-2) is employed instead of (1-1). It can also be found from Figure 2 that the calculated curves for earthquakes with a certain focal depth are similar to each other when the focal depth is larger than 40 km.

3. Effect of the shifting of the epicenter location on the travel time curve

The shifting of the epicenter location affects the features of the resulting travel time curve. A test on this point was carried out and the results are arranged in Figure 3. The thick solid curve is the travel time curve referred to the *J.M.A.* epicenter. The other curves are constructed by shifting the longitude and latitude of *J.M.A.* epicenter by 1′ or 3′. For the line denoted by SE, for example, $\Delta\lambda=1'$ (or 3′) and $\Delta\varphi=-1'$ (or $-3'$), where λ is the longitude and φ the latitude of the epicenter. In general, the *J.M.A.* epicenter gives the smallest standard deviation. It is seen from these figures that if the probable error of the *J.M.A.* epicenter is smaller than 1 minute, any shifting of the epicenter within the range of probable error gives little effect on the results, but if it is larger than 3 minutes, the effect of shifting cannot be neglected. This suggests that the earthquakes with an epicenter precision better than the above mentioned amount are desirable. However, most of the large earthquakes in and near Japan occur under the ocean; consequently the earthquakes with such a good precision are rather rare. In order to overcome this disadvantage, a newly developed method (see Section 7) is used in the calculation. Namely, by means of the least squares method the corrections to the travel time curve and hypocenter constants, and the station corrections are simultaneously calculated.


T-Δ/8 (SEC)
W-M(h=0km)
MIYAGIKEN HOKUBU Earthquake
1962 IV 30, 11h 26m 25.4s
M=6.4, h=10km
λ=141°6', φ=38°44'
Δ(km)
T-Δ/8 (SEC)
W-M(h=0km)
KITAMINO Earthquake
1961 VIII 19, 14h 33m 29.9s
M=7.0, h=0km
λ=136°46', φ=36°1'
Δ(km)
T-Δ/8 (SEC)
ETOROFU OKI Earthquake
1963 X 13, 14h 17m 50.5s
M=8.1, h=20km
λ=149°58', φ=43°45'
W-M(h=20km)
Δ(km)
T-Δ/8 (SEC)
W-M(h=40km)
TOKACHI OKI Earthquake
1952 III 4, 10h 22m 41.9s
M=8.0, h=45km
λ=143°52', φ=42°9'
Δ(km)

(a)

(b)

(c)

(d)

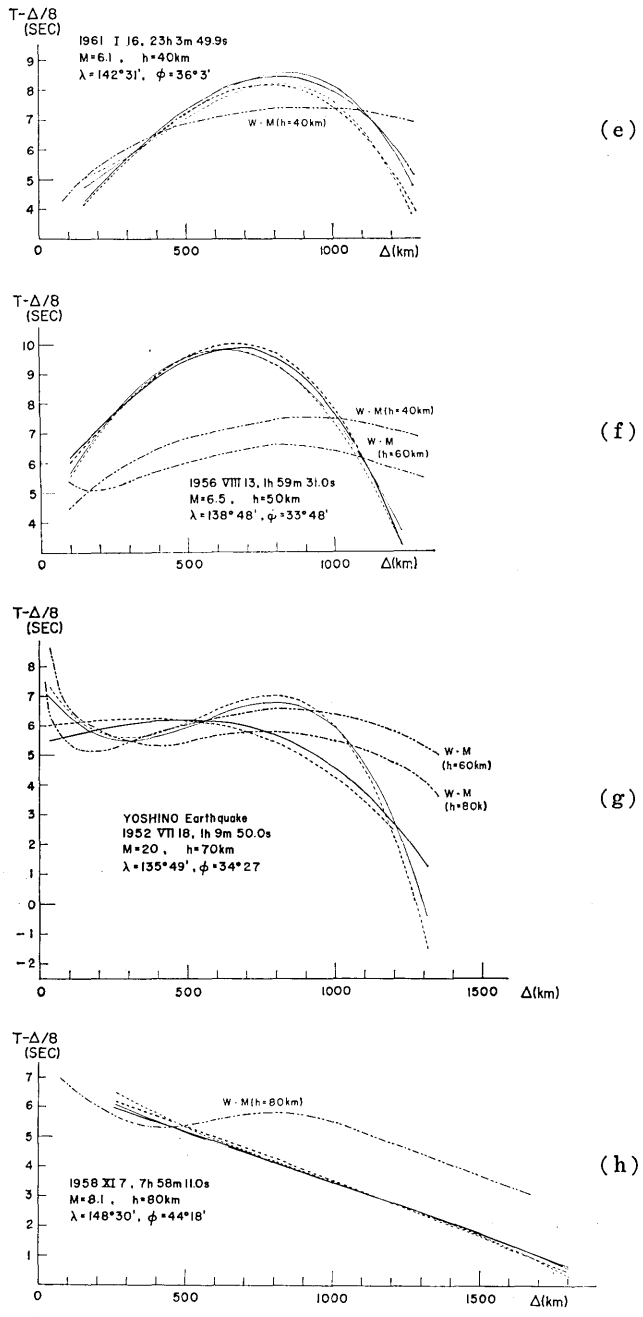


Figure 2. Comparison of travel time curves calculated by the method of least squares. Chain line (W–M) is the Wadati-Sagisaka-Masuda travel time curve. Solid line is the result of the process I) and dotted line that of II). Thick and thin lines show the results calculated using the expressions $t=a+b\Delta+c\Delta^2+d\Delta^3$ and $t=a'+b'\Delta+d'\Delta^3$, respectively.

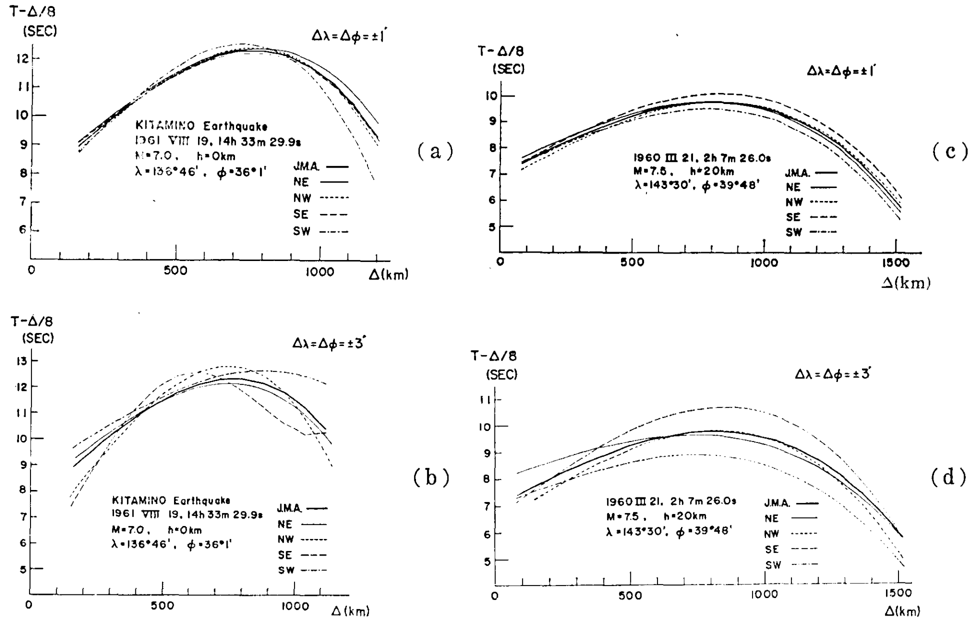


Figure 3. Effect of the assumed location of the epicenter on the calculated travel time curve. Thick solid curve is the result based on the *J.M.A.* hypocenter constants. The other curves are obtained by shifting the epicenter by 1′ or 3′ along the longitude and latitude. The line NW, for example, implies $\Delta\lambda=-1'$, $\Delta\varphi=+1'$.

4. Effect of the initial epicenter location on the final one in the process of successive determinations of the epicenter

Geiger's method of calculating corrections to the epicenter location and to the time of occurrence is adopted. In the successive application of this method, it is empirically known that the final epicenter location and time of occurrence depend on the starting epicenter location and the data used. This effect is shown in Figure 4 by an example. The critical value, C.V., is defined as the largest permissible deviation from the reference travel time curve. The cross mark in each figure is the *J.M.A.* epicenter and the open circles are the starting epicenter locations shifted by ± 5 minutes in angle along both longitude and latitude. Arrow shows the shifting of the epicenter for each iteration of computation, and solid circle is the final location of the epicenter. If the critical value, C.V., is four seconds or more, epicenter locations are obtained elsewhere according to the starting positions of the epicenter. For the critical value of three seconds or less, wherever the starting point may be, the epicenter finally falls in a limited area and this feature is really remarkable

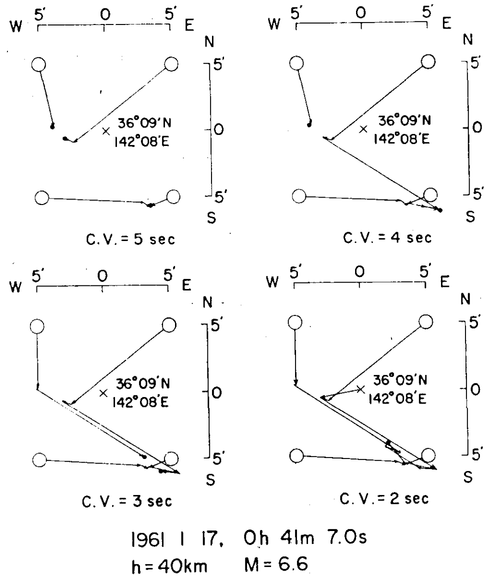


Figure 4. Convergency of the epicenter location by iterative application of Geiger's method. Cross mark: *J.M.A.* epicenter. Open circle: starting point for the iterative determination of the epicenter which is shifted by 5′ along longitude and latitude from the cross mark. Arrow line: movement of the epicenter for each iteration. Solid circle: final location of the epicenter. The data which deviate by more than the value denoted by C.V. from the presumed travel time curve is omitted in each step of the iteration. This example shows that the final epicenter location depends on the position of the starting one. However, for the case in which the C.V. is less than 3 seconds, the final location of the epicenter converges to within a small area independent of the initial location of the epicenter.

for the case of the critical value less than two seconds. Therefore, the value 2 seconds is taken for the subsequent epicenter determination.

5. Convergency of the determination of the travel time curve and epicenter location by alternate successive approximations

In an alternate application of the determination of the travel time curve by the method of least squares and of the revision of the epicenter location and the time of occurrence by Geiger's method, it is tacitly assumed that this procedure will be convergent. If this does not converge, it may be concluded that the observed data adopted are not suitable.

An example of a numerical experiment on this point is demonstrated in Figure 5 using earthquakes of 40 km depth. The process is as follows. Among earthquakes with available data at

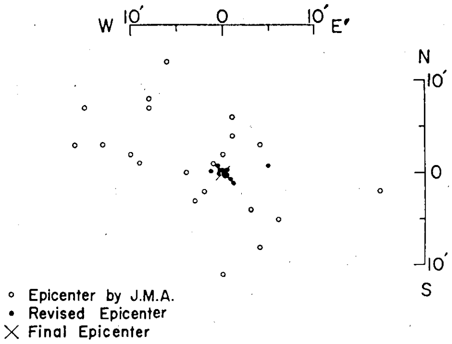


Figure 5. Convergency of the epicenter by alternate determination of the travel time curve and epicenter location. Final epicenters of various earthquakes are superposed on the position of the cross mark. The open circle shows the *J.M.A.* epicenter and the solid circle the epicenter revised once.

distances farther than 1350 km, those having similar travel time curves are adopted. This number of earthquakes is eight. First, introducing the *J.M.A.* constants of the hypocenter, the travel time curve describing the observed data calculated by means of least squares is determined for each earthquake and their average is considered as the first approximation travel time curve. Next, using this travel time curve the epicenter location and time of occurrence of each earthquake are revised by Geiger's method. The epicenter thus revised is called the first approximation epicenter. Following in a similar way, the further approximations of travel time curve and epicenter location are calculated successively by using the lower order approximations.

The travel time curves thus obtained are

$$\left.\begin{array}{ll} t=3.580+0.13284\Delta-0.(8)2998\Delta^3 & \text{1st approx.} \\ t=3.599+0.13288\Delta-0.(8)3096\Delta^3 & \text{2nd approx.} \\ t=3.597+0.13289\Delta-0.(8)3102\Delta^3 & \text{3rd approx.} \end{array}\right\} \qquad (1\text{–}3)$$

In Figure 5, the second approximation epicenters are superposed on the position of the cross mark. The first approximation and the *J.M.A.* epicenters relative to the cross mark are given by solid and open circles respectively. In this figure, the results of thirteen more earthquakes are added. It is clearly seen from this figure and the above formulas that the alternate determination of the travel time curve and epicenter location makes them converge and that the first approximation epicenter and the second approximation travel time curve can reasonably be adopted as standard. The second approximation travel time curve will be called the *α approximation* travel time curve.

6. Method of calculating the travel time curve for short distances

Since earthquakes with available P waves at distances larger than about 1350 km usually occur under the ocean and have few data at short distances, the travel time curve calculated by the method described in the preceding sections shows less accuracy at short distances.

On the other hand, the travel time curve at short distances is much affected by the earth's structure near the surface and displays different features from that at large distances. The travel time curve at short distances less than about 150∼170 km, therefore, is considered separately. In order to cover the scarcity of data at this distance range, small earthquakes having no available P waves at distances farther than about 1350 km were added.

Examples are given in Figure 8 for earthquakes with various focal depths. Data from 32 smaller earthquakes were added to those of the earthquakes listed in Table 1 for the case of 40 km focal depth.

The curve best fitted to these data can be approximated by a linear or a cubic formula using the method of least squares. A quadratic formula was tried, too. The result is numerically very close to the cubic formula and the difference can be neglected. The cubic formula is adopted as the standard in the following analysis.

7. Method of calculating station corrections, corrections to the presumed travel time curve, to the time of occurrence and to the epicenter location

A method calculating simultaneously the station corrections, the corrections to the assumed travel time curve, to the time of occurrence and to the epicenter location is adopted to give the β approximation travel time curve (see Section 8).

Although it may be natural to consider the correction to the presumed travel time curve as a continuous function of the epicentral distance, this correction is assumed, in this study, to be a stepwise function of the epicentral distance.

The difference between the observed and calculated travel times is assumed to depend on (i) the station correction S_i, (ii) the correction to the standard travel time $t_j(\Delta)$, (iii) the correction to the time of occurrence T_k and (iv) the corrections to the location of epicenter, namely,

$$O-C=S_i+t_j+T_k+\frac{\partial t}{\partial\lambda}d\lambda_k+\frac{\partial t}{\partial\varphi}d\varphi_k\ . \tag{1-4}$$

The epicentral distance is divided into regions with an equal interval d except for the region nearest to the epicenter which has the interval $d/2$. $t_j(\Delta)$ is assumed to be constant in each interval. As S_i, t_j and T_k appear only in the form of a sum in the equation (1-4), it can easily be seen that the two of these quantities are indefinite by a constant. This implies that the system of normal equations derived from the observation equations (1-4) has second order degeneracy. Therefore, we assume the values of two unknowns in solving equation (1-4).

Let the solutions be noted by

$$(S_i)_a\ ,\ (t_j)_a\ ,\ (T_k)_a\ ,\ (d\lambda_k)_a \text{ and } (d\varphi_k)_a\ , \tag{1-5}$$

when the station correction of a specific station i_0 is equal to a, namely

$S_{i0}=a$; then the solutions when a is changed to $\bar{a}(=a+a')$ are

$$\left.\begin{aligned}(S_i)_{\bar{a}}&=(S_i)_a+a' ,\\(t_j)_{\bar{a}}&=(t_j)_a ,\\(T_k)_{\bar{a}}&=(T_k)_a-a' ,\\(d\lambda_k)_{\bar{a}}&=(d\lambda_k)_a ,\\(d\varphi_k)_{\bar{a}}&=(d\varphi_k)_a .\end{aligned}\right\}\qquad(1\text{-}6)$$

In a similar way we can calculate the solutions corresponding to the case $T_{k0}=\bar{b}(=b+b')$ from those which were obtained for the assumption $T_{k0}=b$, namely

$$\left.\begin{aligned}(S_i)_{\bar{b}}&=(S_i)_b-b' ,\\(t_j)_{\bar{b}}&=(t_j)_b ,\\(T_k)_{\bar{b}}&=(T_k)_b+b' ,\\(d\lambda_k)_{\bar{b}}&=(d\lambda_k)_b ,\\(d\varphi_k)_{\bar{b}}&=(d\varphi_k)_b .\end{aligned}\right\}\qquad(1\text{-}7)$$

In actual computation, the station correction of a certain station and correction of the time of occurrence of a certain earthquake were put to zero. In order to determine these values finally they should be subjected to additional conditions having geophysical significance, such as the base line corrections (Cleary and Hales, 1966) or the vanishing of average station corrections.

Part II. Application to the Actual Data and Preliminary Results

8. Procedures used

Application of the method and results of various tests given in Part I to the actual data will be explained in this section using earthquakes with the *J.M.A.* focal depth of 40 km. Earthquakes which have magnitudes larger than 5.0 and which occurred during the period from 1954 to 1964 are chosen. The *J.M.A.* constants of the hypocenter are adopted as the starting value. Travel time curves describing the observed data by means of least squares are calculated by equation (1–1) and process (II) in Section 2 and are arranged in Figure 6. The variations of the travel time curves are considerable. About half of the travel time curves, however, show similar features and cluster in a narrow band near the center of the figure. The average travel time curve of these clustered curves is given by the thick solid curve which shows a time delay compared with the Wadati-Sagisaka-Masuda travel time curve in the distance range less than about 1200 km.

As was stated in the Introduction, it is intended in this study to calculate the travel time curve up to 1500 km epicentral distance. In order to attain this goal, earthquakes having available data at distances larger than about 1600 km are to be analysed. Since such earthquakes are rare in the Japan area, earthquakes with usable readings of the initial wave at distances farther than 1350 km are employed in this study. Among such earthquakes, eight events having similar travel time curves are chosen from Figure 6 and their travel time curves are averaged as

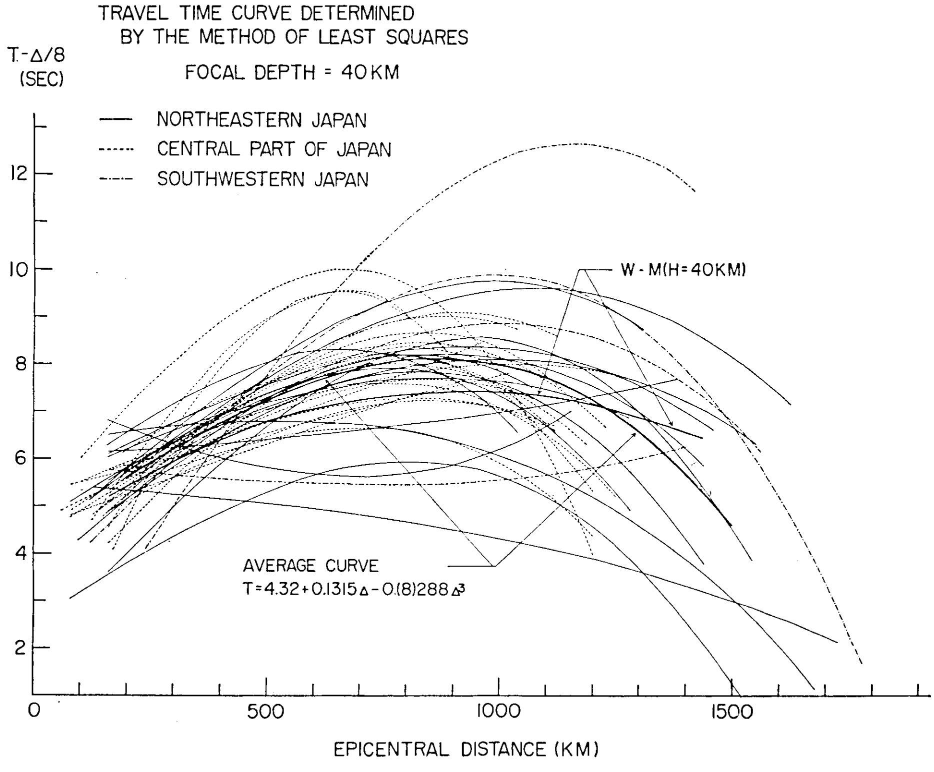


Figure 6. Travel time curves obtained by the process I) using the formula (1-1) for earthquakes having a *J.M.A.* focal depth of 40 km. Travel time curves of about 20 earthquakes showing similar features are averaged, which is shown in the figure as the "average curve". This curve is slightly different from the one given by (2-1), because the former includes smaller shocks, while the latter is the average of 8 large earthquakes with available data at distances larger than 1350 km. *W-M* means the Wadati-Sagisaka-Masuda travel time curve.

$$t=3.580+0.1328\Delta-0.(8)2998\Delta^3,$$
$$150\,\mathrm{km}<\Delta<1500\,\mathrm{km}\,. \qquad (2\text{-}1)$$

Employing this averaged travel time curve, the constants of the hypocenter are re-determined using the method described in Sections 4 and 5. In this stage, earthquakes whose epicenters are moved by more than 50 km from the *J.M.A.* epicenter are omitted. The new travel time curve is calculated for each earthquake using the revised constants of the hypocenter. The average of the travel time curves thus obtained has the expression

$$t=3.599+0.1329\Delta-0.(8)3096\Delta^3\,. \qquad (2\text{-}2)$$

Using this travel time curve as well as data at distances larger than about 150 km, the constants of the hypocenters of 32 smaller earthquakes are revised. The data of these earthquakes are added to those of the larger ones in order to improve the accuracy due to the scarcity of data in the region within 150 km. Travel time curve for short distances ($\Delta<170$ km) best fitted to the observed data is calculated applying a cubic polynomial function of the epicentral distance and the revised epicenters. In this calculation, the data of 40 earthquakes are processed together. The result is given by

$$t=6.346+0.1007\Delta+0.(5)5994\Delta^2+0.(6)5082\Delta^3\,. \qquad (2\text{-}3)$$

Expression (2-2) and (2-3) intersect at the epicentral distance 179 km. The combination of (2-2) and (2-3) is adopted as the standard travel time curve for the process described in Section 7. This is called the α *approximation* and is expressed as

$$\left.\begin{array}{ll} t=3.599+0.1329\Delta \qquad\qquad\qquad -0.(8)3096\Delta^3 & \Delta>179\,\mathrm{km}\,, \\ t=6.346+0.1007\Delta+0.(5)5994\Delta^2+0.(6)5082\Delta^3 & \Delta<179\,\mathrm{km}\,. \end{array}\right\} \qquad (2\text{-}4)$$

Next, the process given in Section 7 is carried out employing the revised epicenter and the α approximation travel time curve. It is assumed that the correction to the travel time curve $t_j(\Delta)$ is constant in each 100 km interval which is measured from $\Delta=50$ km. The first interval covers $0\sim50$ km epicentral distance. Since the data at distances farther than 1550 km are very few, the analysis is performed for the epicentral distances less than 1550 km. The station correction of Tokyo and the correction of the time of occurrence of the 18-th earthquake of Table 1 are preliminarily assumed to be zero. After the computation the modification was made so that the mean of all station corrections vanished, and consequently the corrections S_i and t_j were adjusted according to (1-5) and (1-6). In this analysis, the number of stations, intervals of epicentral distance and earthquakes are 91, 16 and 8, respectively. So a system of 131 linear equations is solved. Corrections to the travel time, being stepwise, are added to the α approximation for epicentral distances from 0 to 1500 km at 100 km intervals. The travel time thus corrected was approximated in the sense of least squares applying a 5th-order polynomial function of distance.

The travel time curve thus obtained is called the β *approximation* curve that has to be shifted by a constant amount which will be determined in the detailed comparison of our results for various depths with the results of the analysis of data given by the explosion seismic experiments in Japan. In Figure 10-(c), the Wadati-Sagisaka-Masuda travel time curve, the α and β approximations and the value subjected to the stepwise correction, which is temporarily taken to be zero at the epicentral distance of 500 km, are given.

Figure 7 is the plot of actual data referred to the *J.M.A.* constants of the hypocenters for 20 large earthquakes having 40 km focal depth. This figure assures the plausibility of the β approximation.

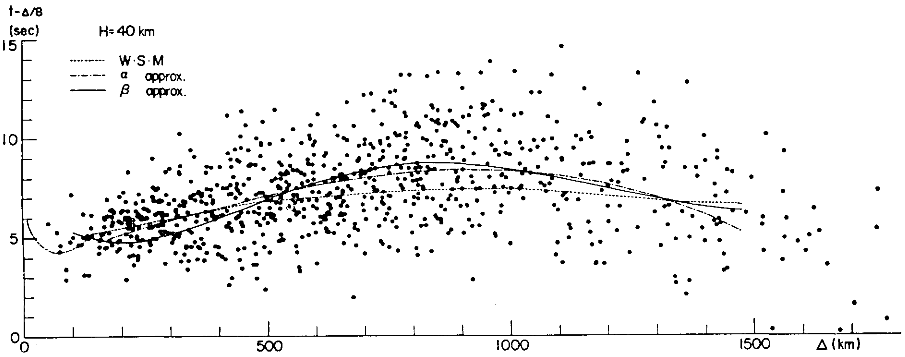


Figure 7. Travel time curves and observed data of 20 large earthquakes having 40 km focal depth. Dots show data plotted for the *J.M.A.* constants of the hypocenter. The solid, chain and dotted curves are the β and the α approximations and the Wadati-Sagisaka-Masuda travel time curve respectively.

9. Travel time curves for various focal depths

Following the process explained in Section 8, travel time curves for various focal depths are calculated. Earthquakes used in this study are listed in Table 1. The number of earthquakes for focal depths 0, 20, 40, 60 and 80 km are 3, 9, 8, 18 and 8 respectively. To determine the α approximation travel time curve for short distances, 15, 20, 32, 24 and 15 earthquakes are added to each earthquake group having focal depths 0, 20, 40, 60 and 80 km respectively. The travel time curves thus obtained are as follows. Units of the travel time and epicentral distance are the

Table 1. List of Earthquakes

Date			Origin Time			Latitude		Longitude		Depth	Magnitude
			h	m	sec	°	′N	°	′E	km	
1960	02	05	01	50	26.0	38	36	143	12	10	6.1
1961	02	23	13	16	10.7	38	16	143	30	00	6.4
1964	05	07	16	58	07.7	40	20	139	00	00	6.9
1958	04	11	09	58	06.0	38	30	144	00	20	6.4
1959	10	26	16	35	04.0	37	36	143	12	20	6.7
1960	03	21	02	07	26.0	39	48	143	30	20	7.5
1960	03	21	18	18	20.0	39	36	143	36	20	5.9
1960	03	23	09	23	19.0	39	18	143	48	20	6.7
1960	03	23	10	07	15.0	39	30	143	24	20	6.1
1960	03	24	07	22	35.0	39	12	143	30	20	6.2
1960	07	30	02	31	38.0	40	12	142	36	30	6.7
1963	10	04	08	24	31.0	31	53	132	09	20	6.3
1955	05	01	22	58	46.	39	45	143	45	40	5.7
1957	06	12	17	28	35.	41	06	142	54	40	6.1
1960	06	16	00	36	53.0	40	06	142	30	40	6.0
1960	08	13	16	11	06.0	40	18	142	30	40	6.2
1961	02	27	03	10	48.1	31	36	131	51	40	7.0
1961	06	19	16	38	20.0	39	09	143	39	40	5.8
1961	11	27	14	57	10.7	31	18	131	33	40	6.0
1964	01	10	13	50	53.8	41	42	142	51	40	6.1
1954	08	30	16	57	23.	43	36	147	48	60	5.9
1955	02	02	04	16	12.	41	54	142	36	60	5.6
1955	03	28	18	12	20.	29	24	130	06	60	6.3
1956	04	23	12	31	39.	42	24	145	00	60	6.1
1957	04	27	00	08	29.	44	00	148	00	60	5.8
1958	02	16	15	04	08.0	38	30	142	12	60	6.1
1960	07	08	21	51	25.0	30	15	130	45	60	6.1
1961	05	17	06	45	26.7	30	27	132	02	60	5.8
1961	07	18	23	03	37.9	29	37	131	46	60	6.6
1961	07	18	23	34	03.9	29	48	131	36	60	5.9
1961	08	12	08	33	49.6	42	49	145	34	60	5.8
1961	11	15	16	17	09.9	42	39	145	34	60	6.9
1962	01	09	21	40	46.2	42	39	145	21	60	6.0
1962	04	23	14	58	11.8	42	14	143	55	60	7.0
1962	07	18	02	20	22.3	42	38	145	10	60	5.9
1962	12	21	18	33	18.5	42	01	142	30	60	6.3
1963	08	21	00	48	09.4	41	05	143	02	60	5.7
1963	10	23	18	47	03.1	41	08	144	35	60	5.3
1958	09	08	23	53	17.0	33	48	131	54	80	
1958	11	07	07	58	11.0	44	18	148	30	80	8.1
1958	11	13	13	04	44.0	43	36	148	12	80	
1960	04	15	20	38	59.0	40	54	141	36	80	
1961	02	13	06	53	45.2	43	13	147	53	80	
1961	08	12	00	51	31.9	42	51	145	34	80	
1963	08	17	20	12	40.9	30	24	131	03	80	
1964	06	23	10	26	34.9	42	59	146	28	80	

second and the km, respectively.

$$
\begin{array}{llll}
 & & \text{critical distance} & \\
t=2.002+0.1844\Delta+0.(4)7226\Delta^2-0.(6)1479\Delta^3 & & \Delta<150\text{ km} & \multirow{2}{*}{$h=0$ km ,} \\
\ \ =7.528+0.1318\Delta-0.(8)3381\Delta^3 & & \Delta>150\text{ km} & \\
t=1.800+0.1377\Delta+0.(3)1942\Delta^2-0.(6)5862\Delta^3 & & \Delta<180\text{ km} & h=20\text{ km ,} \\
\ \ =5.722+0.1314\Delta-0.(8)2424\Delta^3 & & \Delta>180\text{ km} & \\
t=6.346+0.1007\Delta+0.(5)5994\Delta^2+0.(6)5082\Delta^3 & & \Delta<180\text{ km} & h=40\text{ km ,} \\
\ \ =3.599+0.1329\Delta-0.(8)3096\Delta^3 & & \Delta>180\text{ km} & \\
t=8.164+0.07258\Delta+0.(3)1952\Delta^2+0.(7)7330\Delta^3 & & \Delta<150\text{ km} & h=60\text{ km ,} \\
\ \ =4.164+0.1296\Delta-0.(8)1866\Delta^3 & & \Delta>150\text{ km} & \\
t=11.49+0.04974\Delta+0.(3)2484\Delta^2+0.(6)1380\Delta^3 & & \Delta<170\text{ km} & h=80\text{ km .} \\
\ \ =7.487+0.1169\Delta+0.(4)1156\Delta^2-0.(8)5026\Delta^3 & & \Delta>170\text{ km} & \\
\end{array}
$$

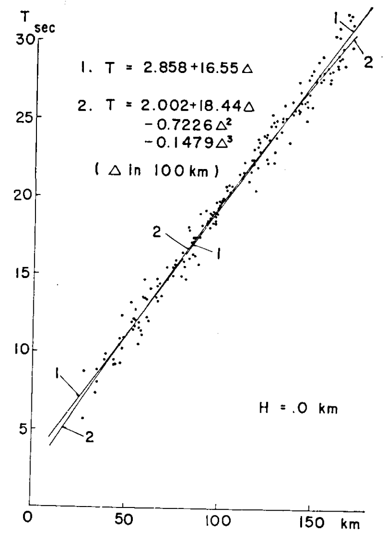
(For example, 0.(4)7226 implies 0.00007226.) (2-5)

The critical distance which separates the applicability range of the travel time formulas for short and long distances is obtained by equating the travel times calculated from the first and second formulas of (2-5) for each focal depth. The approximate value of this distance is given in formula (2-5) as the critical distance. Figure 8 shows the data used and the α approximation travel time curve of linear and cubic forms for short distances. It also indicates that the latter form expresses the plotted data better. The curves of cubic form and the Wadati-Sagisaka-Masuda travel time curve are summarized in Figure 9.

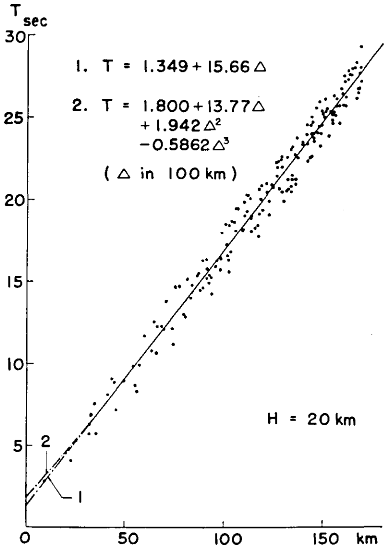
Figure 10 is prepared in order to show the relation among Wadati-Sagisaka-Masuda's curve, the α and the β approximation travel time curves and the one subjected to the stepwise correction. In this figure, open circles are adjusted by a constant so that they coincide with the α approximation curve at the epicentral distance 500 km. Figures 10-(a) ~ 10-(e) are summarized in Figures 11 and 12 which indicate a tendency for the discrepancy between the Wadati-Sagisaka-Masuda curve and the β approximation travel time curves to become larger as the focal depth decreases, whereas the α approximation differs very little from the β approximation.

The travel time curve for short distances, especially for the surface source, will be discussed in the next section in more detail by considering the crustal structure.

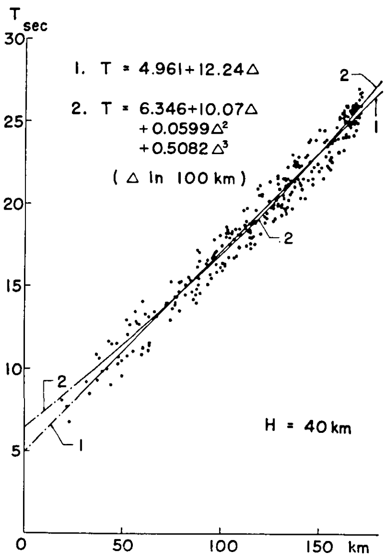
In carrying out the process of Section 7, 90 of the 112 *J.M.A.* routine


T sec
1. T = 2.858+16.55△
2. T = 2.002+18.44△
-0.7226△²
-0.1479△³
(△ in 100 km)
H = .0 km
0
50
100
150 km

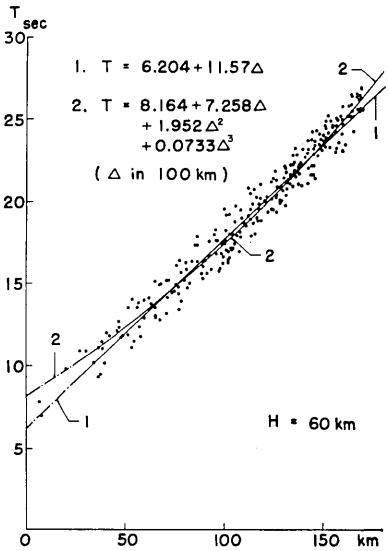
(a)


T sec
1. T = 1.349+15.66△
2. T = 1.800+13.77△
+1.942△²
-0.5862△³
(△ in 100 km)
H = 20 km
0
50
100
150 km

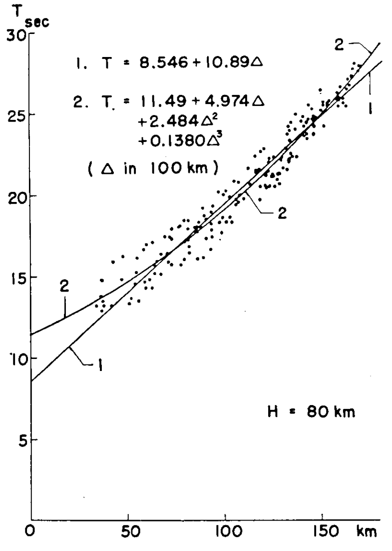
(b)


T sec
1. T = 4.961+12.24△
2. T = 6.346+10.07△
+0.0599△²
+0.5082△³
(△ in 100 km)
H = 40 km
0
50
100
150 km

(c)


T sec
1. T = 6.204+11.57△
2. T = 8.164+7.258△
+1.952△²
+0.0733△³
(△ in 100 km)
H = 60 km
0
50
100
150 km

(d)



(e)

Figure 8. Calculated travel time curve for short distances, and data used. Curves specified by 1 and 2 represent the linear and cubic polynomial function of the epicentral distance.

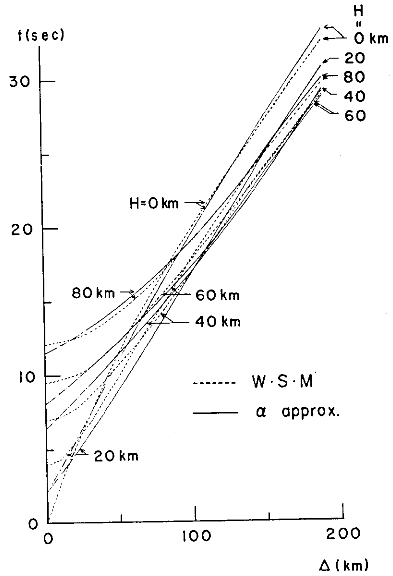
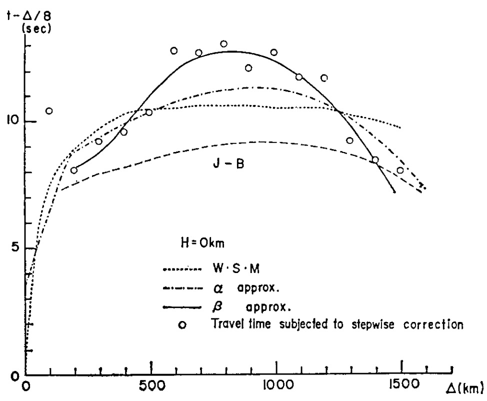
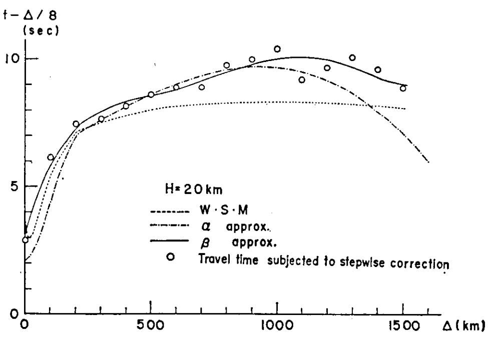


Figure 9. The Wadati-Sagisaka-Masuda and the α approximation travel time curves for various focal depths at short distances. The latter represents the curves specified by 2 in Fig. 8. The chain line means parts where accuracy is relatively low.

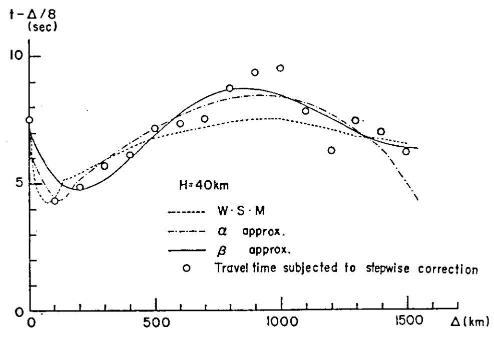
stations are selected and Tsukuba Station of the Earthquake Research Institute is added. Because of the memory size of the computer the number of stations is limited to 91. Station corrections are plotted in



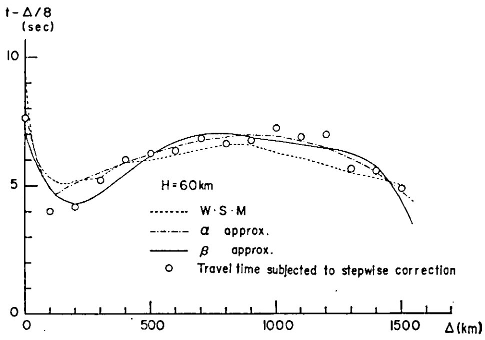
(a)



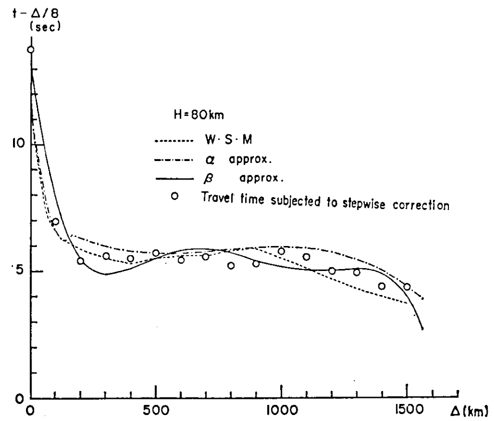
(b)



(c)



(d)



(e)

Figure 10. Comparison among the Wadati-Sagisaka-Masuda, the α and the β approximation travel time curves. Open circle is the travel time subjected to stepwise corrections and adjusted by a constant so that it coincides with the α approximation at the epicentral distance of 500 km. J-B in Figure 10-(a) means Jeffreys-Bullen's travel time curve for a surface focus.

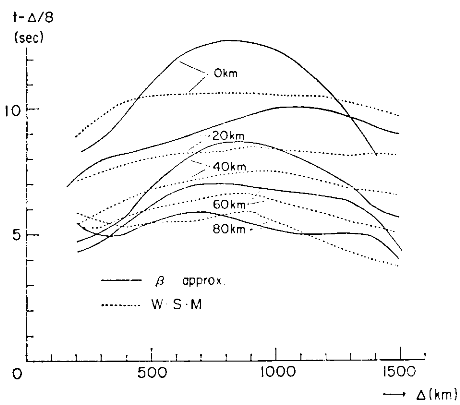


Figure 11. The Wadati-Sagisaka-Masuda and the β approximation travel time curves for various focal depths.

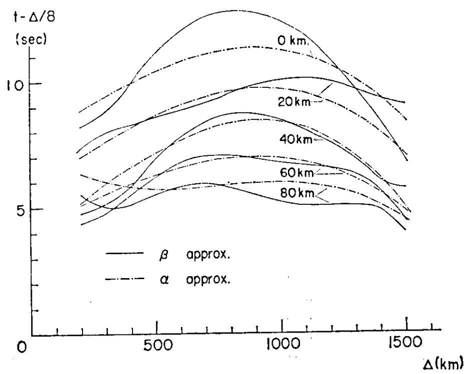
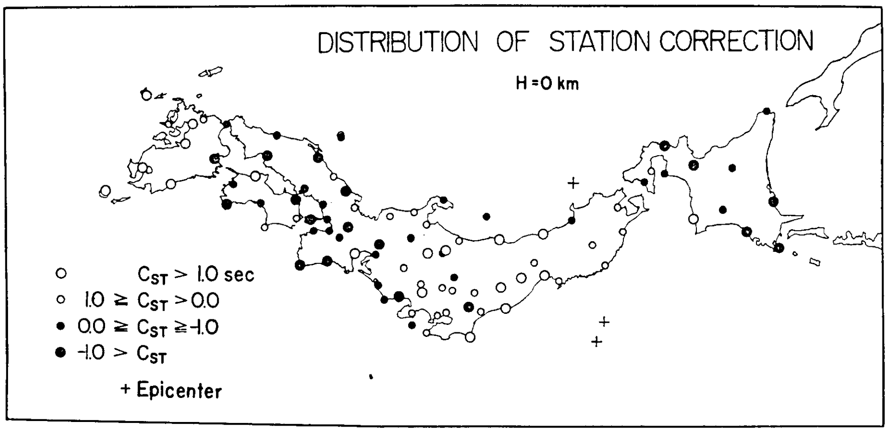
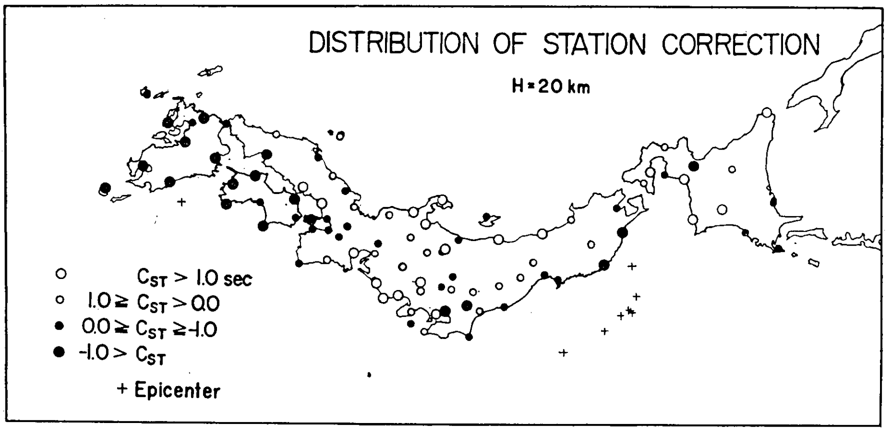


Figure 12. Comparison between the α and the β approximation travel time curves.

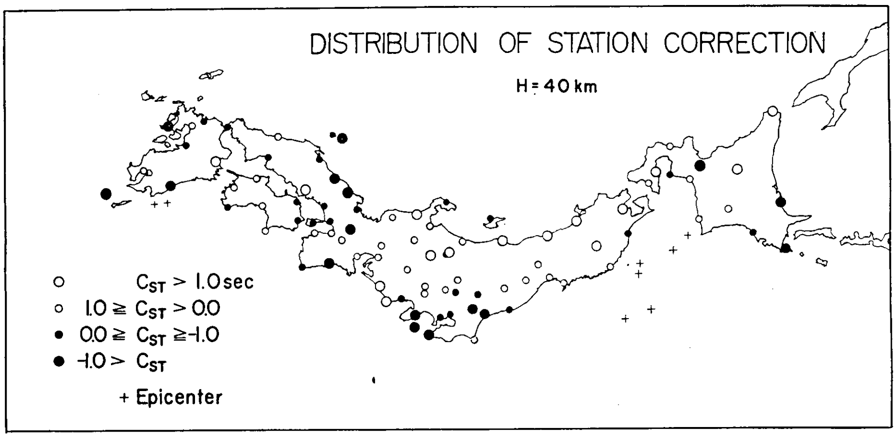
Figure 13, which show, as a rough approximation, little difference between various focal depths, as far as the general pattern of distribution of station corrections is concerned. Figure 13-(f), showing the station corrections averaged over various focal depths, reveals the general tendency of the distribution of station corrections in Japan. Arrival times appear earlier along the Pacific coast of Tōhoku and Hakkaidō districts, Kwantō plain and western Japan; and later in the coastal regions of Hokkaidō and Tōhoku districts facing to the Sea of Japan and the mountain area of central Honshū. The region of earlier arrivals in Tōhoku and Hokkaidō districts coincides with the area of the abnormally sensitive seismic region.



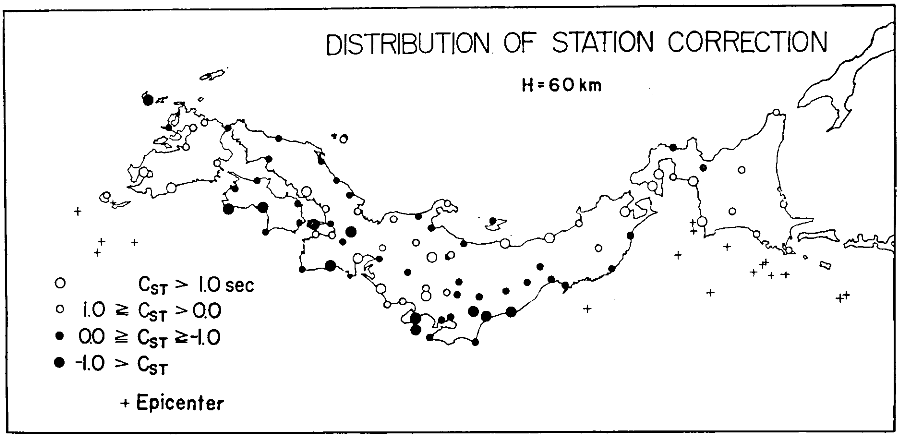
(a)



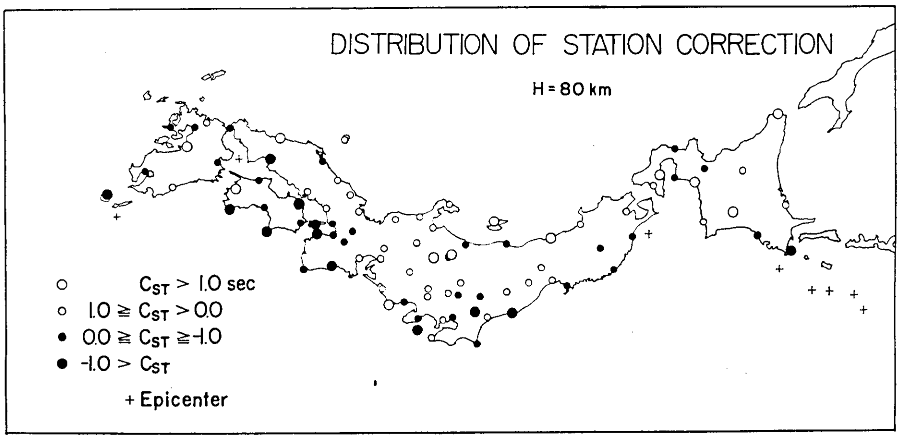
(b)


DISTRIBUTION OF STATION CORRECTION
H=40 km
○ C_{ST} > 1.0 sec
○ 1.0 ≧ C_{ST} > 0.0
• 0.0 ≧ C_{ST} ≧ -1.0
● -1.0 > C_{ST}
+ Epicenter

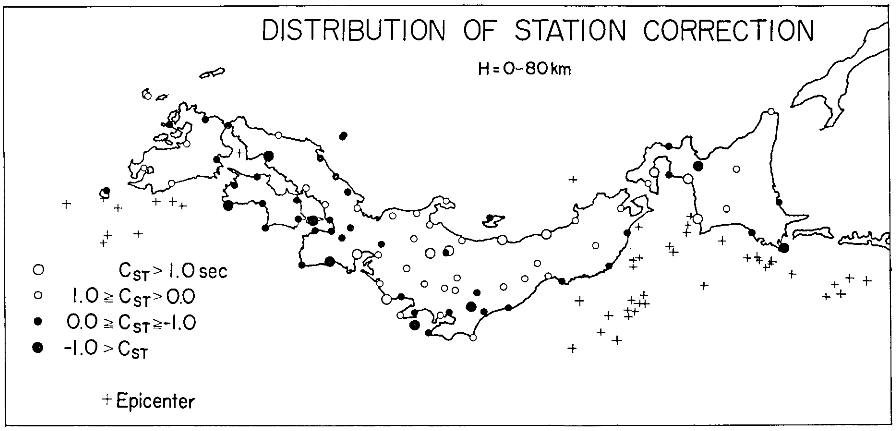
(c)


DISTRIBUTION OF STATION CORRECTION
H=60 km
○ C_{ST} > 1.0 sec
○ 1.0 ≧ C_{ST} > 0.0
• 0.0 ≧ C_{ST} ≧ -1.0
● -1.0 > C_{ST}
+ Epicenter

(d)


DISTRIBUTION OF STATION CORRECTION
H=80 km
○ C_{ST} > 1.0 sec
○ 1.0 ≧ C_{ST} > 0.0
• 0.0 ≧ C_{ST} ≧ -1.0
● -1.0 > C_{ST}
+ Epicenter

(e)



(f)

Figure 13. Distribution of station corrections for various focal depths and distribution of average station correction. Cross mark shows the epicenter of earthquakes used for the calculation of the station correction. C_{ST} means the value of the station correction. Station correction is defined as C_{ST}=average{(observed travel time)−(calculated travel time)}.

10. Comparison between the travel time curves obtained from earthquakes of surface focus and explosion seismic experiments

As is shown in Table 1, the number of earthquakes used in obtaining the β approximation for surface focus earthquakes is too few to deduce a result of impartial character.

The observed data of the explosion seismic experiments carried out throughout Japan by the Research Group for Explosion Seismology are useful in the present study and they are plotted in Figure 14. The open circle means data obtained on the E–W profile across northeastern Japan and the cross mark denotes those obtained on the N–S profile along the 139°E line. These data, however, are omitted from the present analysis, and other data (solid circles), which are obtained along the profile parallel to the Island Arc of Japan, are used. These solid circles suggest a uniform crust lying on the mantle with a discontinuity of velocity. If so, the slope of the travel time curve of the explosion data representing the velocity of the uppermost part of the mantle must be close to that of the α approximation of ours at about the same epicentral distance. Under this guiding principle the data represented by solid circles are divided into two groups at the epicentral distance 170 km and a linear function is fitted to each group. Curves thus determined are drawn by the thick solid line in Figure 14. The slope of the α approximation at an epicentral distance a little larger than the critical distance is nearly equal to that of the explosion experiment at the same epicentral distance. This slope, 7.61 km/sec, indicates the velocity of the upper mantle. The α approximation for shorter distances in Figure 14 is reduced by 0.6 sec. from the curve shown in Figure 8-(a), so that the cross-over distance may coincide with that determined from the explosion seismic data.

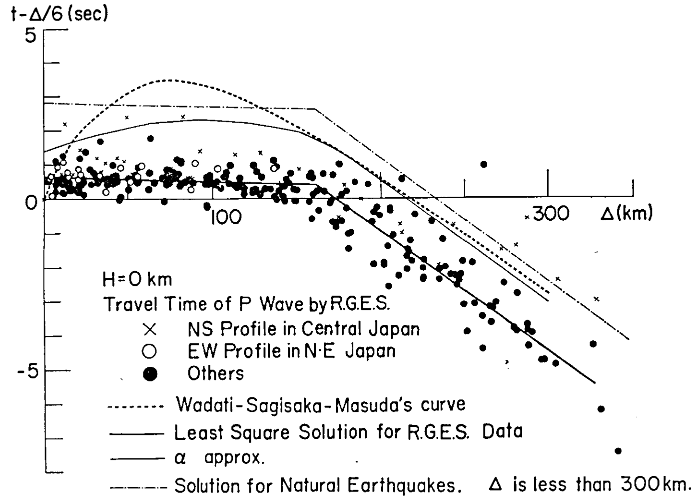


Figure 14. Travel time of the P wave based on the data of explosion seismic experiments carried out by the Research Group for Explosion Seismology (RGES). The thick solid line is obtained by the method of least squares from the solid circles representing data on the profile parallel to the Island Arc of Japan. Chain line is the travel time curve calculated from the data of natural earthquakes. These curves suggest a homogeneous crust with a P wave velocity of 6.07 km/sec and a thickness of 28.5 km lying on the mantle. The P wave velocity at the uppermost part of the mantle is obtained as 7.61 km/sec.

The data of the earthquakes of surface focus at distances less than 300 km are divided into two groups at the distance 170 km and a linear function is adopted for each group. The obtained travel time is drawn in Figure 14 by a chain line. This is parallel to and about 2 seconds later than the curve determined from the explosion data. The 2 seconds difference means that *J.M.A.* determined the time of occurrence around 2 seconds earlier than the real one. The difference seems to arise from the process of hypocenter determination at *J.M.A.*, in which the Wadati-Sagisaka-Masuda travel time curve is referred to as the standard and data at about 25 stations nearest to the epicenter are used. Moreover, even for earthquakes with surface focus, available data within 30 km epicentral distances are usually very few. Therefore, the epicenter determination is mainly affected by the Wadati-Sagisaka-Masuda travel time curve farther than 30 km. It can be easily seen from Figure 14 that these circumstances lead to the determination of the time of occurrence about 2 seconds earlier than expected.

The travel time curve of the β approximation at distances larger than about 170 km is parallel to and about 0.9 seconds later than that determined from the explosion data. Since the data of the explosion seismic experiments are more reliable than those of natural earthquakes for shorter distances, the β approximation for farther distances is reduced by about 0.9 seconds so that it coincides with the travel time obtained from the explosion experiments in the range farther than the critical distance. This reduction of 0.9 seconds may be considered as the constant correction which should be added to the β approximation owing to the uncertainty originating in the process in Section 7. The travel times for shorter distances obtained from the explosion experiments and the β approximation for larger distances reduced by 0.9 seconds are combined to construct our standard travel time curve for the surface focus. This curve suggests a crust with a 28.5 km thickness and a P wave velocity of 6.07 km/sec. overlying the mantle having a P wave velocity of 7.61 km/sec. just below the boundary.

11. Concluding remarks and future problems

The travel time curves of near earthquakes in the Japan area are studied in the present paper and those best fitted to the observed data for earthquakes with focal depths of 0, 20, 40, 60 and 80 km were obtained based on the method of least squares. They are given in Figure 9 as the α approximation for short distances and in Figure 10 as the β approximation for farther distances. Those curves at distances farther than the critical distance show the tendency of approaching to the Wadati-Sagisaka-Masuda travel time curves as the focal depth increases. Referring to the travel time curve obtained from the data of the explosion seismic experiments in Japan, the curve of the natural earthquakes for surface focus was modified, so that the latter coincides with the former at distances within about 300 km.

It is found in this study that the *J.M.A.* time of occurrence for earthquakes of surface focus is given, in general, about 2 seconds earlier than is to be expected.

The station correction was modified in this study so that the average over all stations in Japan will vanish, and they are given in Fig. 13. The region in northeastern Japan where the travel time of the initial motion appears earlier than expected coincides well with the abnormally sensitive seismic region.

The travel time curve for a surface focus suggests, as a rough approximation, a crust with a thickness of 28.5 km and a V_P of 6.07 km/sec. overlying the mantle, the velocity of the latter being 7.61 km/sec. near the boundary. This crustal structure will be employed as the standard in the near future in the synthetic investigation of the travel time curve for various focal depths and for explosion seismic experiments in relation to the crustal structure. Such crustal structure must satisfactorily fulfill all the travel time curves for various focal depths and be consistent with the results derived from other investigations such as explosion seismology and surface wave studies (Aki, 1963; Aki and Kaminuma, 1964; Kaminuma and Aki, 1963; Kaminuma, 1964).

The numerical computation was carried out on an IBM 7090. The work was done partly through the project UNICON to which our sincere thanks are due.

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34. 日本付近の走時曲線
1. 方法といろいろな深さの地震に対する結果

地震研究所　走時曲線研究グループ

最近の地震観測網の整備・観測精度の向上・地殻構造に関する知識の増大，大型高速電子計算機の発達等を考えると，日本近付の近地々震に対する走時曲線を再検討する機運が熟しつつあると考えられる．そこで，観測資料に出きるだけ忠実に *P* 波の走時曲線を見直してみた．

和達・鷺坂・益田の走時曲線に見合うように震央距離 1500 km までの走時曲線を作ることを目標とした．

資料は 1954 年～1964 年の 11 年間に日本付近に起きた地震のうち震源の深さが 80 km 以浅で震央距離 1350 km 以上に有効な観測資料のあるものに限つた．初動のよみとり値は気象庁の地震月報所

載のものを採用し，月報所載の震源要素と和達・鷺坂・益田の走時曲線を出発値とした．

計算に先だち，その方法と資料を取捨選択する基準を決めるために次のようなテストを行なつた．

a） 最小自乗法で走時曲線を決めるのに，走時を震央距離のどのような函数としたらよいか．

b） 震源の位置の精度は，どの程度走時曲線の形に影響するか．

c） ガイガーの方法により逐次近似で震源を決めるとき，初めに仮定する震源の位置が最後に得られる震源位置に及ぼす影響はどうか．

d） 逐次近似で走時曲線と震源を交互に決めるとき，その収斂の様子はどうか．

テストの結果を考慮して次のように手順を決めた．

a′） 震央距離 ($\varDelta$) ≧ 約 170 km では $t=a+b\varDelta+d\varDelta^3$, $\varDelta$ ≦ 約 170 km では $t=a'+b'\varDelta+c'\varDelta^2+d'\varDelta^3$ を採用し，とくに震源の深さ 80 km のときには，$\varDelta$ の全域に亘つて $t=a+b\varDelta+c\varDelta^2+d\varDelta^3$ を採用することにした．また基準にとる走時曲線から ±2 秒以上外れている資料は取除いて計算することとした．

b′） 震央の緯度および経度の誤差が ±3′ 以下のものを理想とする．しかし実際には，この条件に合う地震は少なく，ことに海上の地震では皆無になるので，とくにこの条件に固執しないこととした．

c′） 逐次近似の各段階で標準の走時曲線から ±2 秒以上ずれている資料を除けば，始めの震央位置にかかわらず最終的に求められる震央はほぼ一致することがわかつたので，この方法を採用することとした．

d′） 走時曲線・震央とも収斂がよく，震央は第1近似で，走時曲線は第2近似で十分なことがわかつた．

以上のテストの結果をとり入れて，次の順序で，深さ 0, 20, 40, 60, 80 km の地震について別々に走時曲線を求めた．

1) 個々の地震について気象庁の観測資料と震源要素を使つて最小自乗法により走時曲線を $\varDelta>150$ km について求める．

2) こうして求めた走時曲線のうち，考える震央距離の範囲内でお互いに傾向の似ているものを選んで平均する．

3) 2) で求めた走時曲線を使つて震央定数を決め直し，その改訂震央定数を使つて，もう一度 1), 2) の操作により走時曲線を作る．

4) $\varDelta$ ≦ 約 170 km については資料が少ないので，選定基準に達しなかつた小さい地震を追加し，3) に求めた走時曲線を使つてその震央定数を決め直す．こうして手続 3) で使わなかつた地震の資料も加え，それらの改訂震央定数を使つて近距離の走時曲線を最小自乗法で求める．

5) 3) 4) とで求めた走時曲線をつなげて α 近似とする．

6) α 近似の走時曲線と観測値との差は，各観測点個有の補正値・各地震の緯度，経度，震源時の補正，α 近似の走時曲線に対する補正等に起因するものと考え，最小自乗法により各深さ別に，上記補正値を一挙に求める．この補正を加えた走時を β 近似の走時曲線とした．

7) とくに深さ 0 km の地震については爆破地震動研究グループの資料から得られた結果と比較し，$\varDelta$ ≧ 約 170 km の範囲では β 近似の走時曲線から一律に 0.9 秒差引いたものを採用し，また $\varDelta$ ≦ 約 170 km の範囲では，爆破グループの資料から得た走時を採用して，これを結びつけたものを β 近似とした．

その結果，次のようなことがわかつた．

I) β 近似走時曲線は深さが深くなるほど和達・鷺坂・益田の走時曲線に似てくる．

II) 気象庁で決めた震源の深さ 0 km の地震の震源時は綜合すると約2秒早く与えられている．

III) 観測所固有の補正値の分布は，東北，北海道の太平洋側（いわゆる異常震域）および中国，四国，九州で負（観測値が早くでる），中部地方，東北，北海道の日本海側で正（観測値が遅くでる）になる．

β 近似の走時曲線は各震源の深さ別に求めたもので，それを地下構造を介して，お互いに矛盾が少なくなるように調整しなければならないが，これは第2報にゆずる．