On the Surface Waves of Kamchatka Earthquakes

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Abstract

To avoid the effect caused by the inclination of discontinuity within the crust, the surface waves propagated along the boundary of continent and ocean are studied. As the first step of this study, Kamchatka earthquakes observed at Sendai are taken into consideration. A Formosa earthquake is also investigated for reference.

The dispersion curves indicate that the crustal layer from Kamchatka to Japan has a continental feature but the thickness of the crust is as thin as about 20 km.

The waves having a Love-type orbit and a lower group velocity than that of the fundamental Love waves are found in many cases.

No Lg waves is distinguished in every case.

1 Introduction

Many papers (for example, BRILLIANT and EWING, 1954, EWING and PRESS, 1950 and 1952, PRESS and others, 1952 and 1956, SANTO, 1950, etc.) have been published on the estimation of the crustal structure from the dispersion curves of surface waves. Most of these studies were based on the theory for the surface waves in a horizontally stratified medium. However, one of the present authors (SUZUKI, 1959) recently pointed out that the waves along the surface of a medium having an inclined discontinuity show some different features of dispersion from those for a horizontal structure. For instance, the phase velocity of these waves depends not only on the structure just below the observation point but also on the whole structure through which the waves have travelled from the source to the observation station. Moreover, the difference in the dispersive features for horizontal and non-horizontal structures is conspicuous even when the slope of the discontinuity is very gentle. Such effect of a sloping boundary were also established by recent model-experimental (TAKAGI, 1959 and OLIVER, 1960) and theoretical studies (NAGUMO, 1960).

The difficulties mentioned above are rather essential when the observation station is located in the boundary area between a continent and an ocean, such as in Japan. As well-known, the oceanic crust is far less in its thickness than the continental one, and hence, the crustal structure in the boundary area is reasonably considered to be inclined at least in the direction perpendicular to the margin of the continent. Therefore, the studies of surface waves in such cases should be re-examined under the light of new knowledges.

It is one of the ways avoiding the difficulties that the surface waves propagated

only in the boundary area are taken into consideration. In such cases, the structure along the path of propagation is taken to be approximately horizontal, although it has an inclination in the direction perpendicular to the path. Hence the theoretical results for a horizontal structure can be safely compared with the observations.

As the first step of the investigations under these considerations, some Kamchatka earthquakes observed at Sendai, Japan, are studied in this paper.

2 Materials and method

The earthquakes listed in Table 1 are used as the materials of the present study. Data for dispersion curves are based on the seismograms registered by a long period electromagnetic seismograph at the Seismological Observatory of the Tôhoku University, Sendai, Japan. The exact location of the Observatory is 140° 51′30″ E and 38°14′32″ N.

Table 1. Data for the selected earthquakes. "No." indicates the serial number of the earthquakes in the "List of earthquakes of IGY" published by JMA.

No.	Date	Origin Time (GMT)	Epicenter	Epicentral Distance
150	1957 12 17	05 10 11	Near east coast of Kamchatka 53.5N. 162E.	21°
222	1958 4 13	12 29 07	Near east coast of Kamchatka 53N. 161E.	20.5°
295	1958 8 15	19 55 39	Near east coast of Kamchatka 53N. 160.5E.	20° (depth 60 km)
104	1957 10 19	18 28 50	Near east coast of Formosa 23.5N. 122E.	21.5°

The long period electromagnetic seismograph, which has been operated for IGY program, consists of a pendulum of 25 sec period and a galvanometer with a natural period of about 50 sec. The frequency reponse for each NS and EW component of the

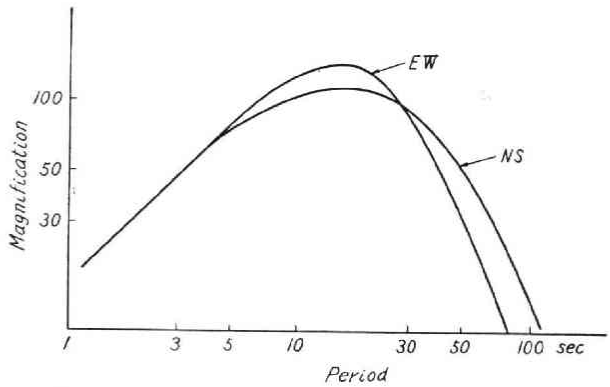

Fig. 1 Frequency response curve of long period electromagnetic seismograph. (Date of calibration : Apr. 15, 1958)

seismograph is given in Fig. 1.

In some cases, the records detected by shorter period seismographs or the seismograms observed at other IGY stations in Japan are available for reference's sake, especially for the recognization of phases.

Fig. 2 shows the locations of epicenters and the observation station together with the great-circle paths between them. As is seen in this map, the surface waves of every earthquake are propagated along the continental margin. These earthquakes, therefore, are appropriate for the purpose of the present study.

The following procedure is adopted in this study to obtain a dispersion curve from a seismogram. The arrival time t_i of i-th wave in a wave group is measured as illustrated in Fig. 3. Then the period of the wave, T_i, is

$$T_i = t_{i+1} - t_i \,,$$

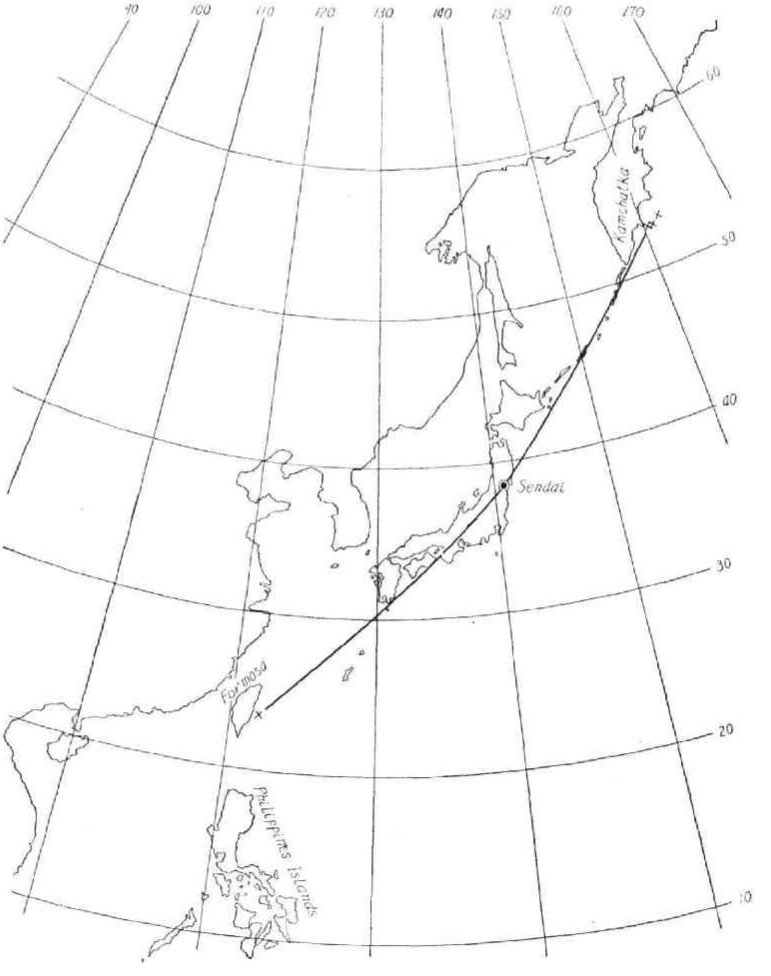

Fig. 2 Geographical map showing the epicenters of earthquakes, location of observation station and paths of wave propagation.

and the group velocity $U_i(T_i)$ is calculated as

$$U_i(T_i) = \Delta/(t_i - t_\varepsilon)\,,$$

where Δ and t_ε are the epicentral distance and the origin time, respectively.

Strictly speaking, this method does not always give the exact value of the velocity, although it is very simple in practical procedure. R. SATO (1958) made a discussion on the form of dispersive waves and concluded that the best formula to calculate the group velocity is

$$U_i(T_i) = \frac{\Delta}{2}\left(\frac{1}{t_i - t_\varepsilon} + \frac{1}{t_{i+1} - t_\varepsilon}\right)$$

$$T_i = 2\,(t'_{i+1} - t'_i)\,,$$

where t_i' is the time of i-th crest (or trough). Fig. 4 is the illustration of the method.

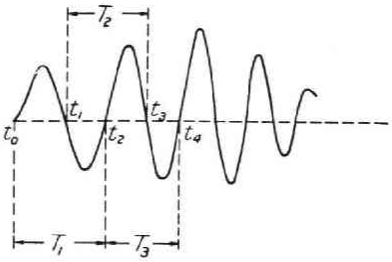

Fig. 3 Illustration of the method adopted in the present study.

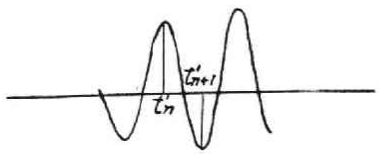

Fig. 4 Illustration of the Sato's method.

However, the difference between the two values according to our method and the SATO's is so slight as to cause no essential change in the conclusions.

Several other methods were also proposed for this purpose but there is substantially little to choose among them.

3 Description of surface weves of each earthquake

Fig. 5 shows the seismogram (E-W component) of the Kamchatka earthquake on April 13, 1958. Two groups of surface waves denoted by L_R and L_3 are distinguishable

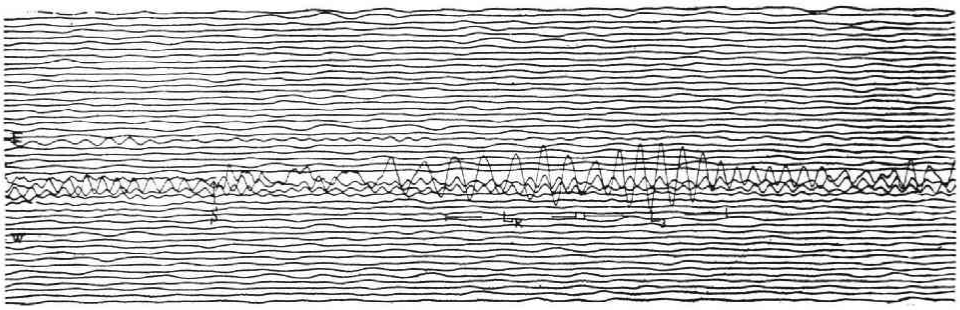

Fig. 5 Seismogram of the Kamchatka earthquake on April 13, 1958.

on the seismogram. The orbit of ground motions for the two groups are obtained from the seismograms in E-W and N-S components. As is seen in Fig. 6 (a) and (b) ,the first group L_R represents a Rayleigh-type orbit and L_3 has a Love type one.

The group velocities for both groups are plotted in Fig. 7 against the period of each wave in abscissa. The figure shows that the groups have dispersive characters. L_R waves are obviously identified to be the fundamental Rayleigh waves from their velocities as well as their orbit in Fig. 6 (a). However, the velocities of L_3 waves cannot be taken as that of the fundamental Love waves, though the waves have a Love-type orbit as seen in Fig. 6 (b).

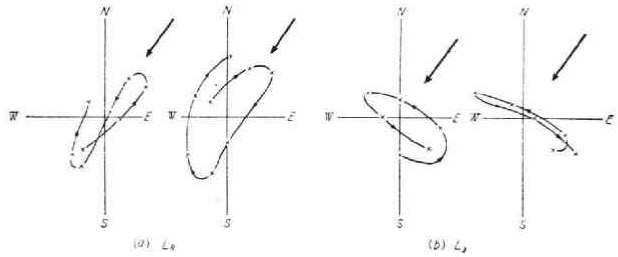

Fig. 6 Orbit of surface waves of the earthquake on April 13, 1958. Arrow shows the direction of epicenter.

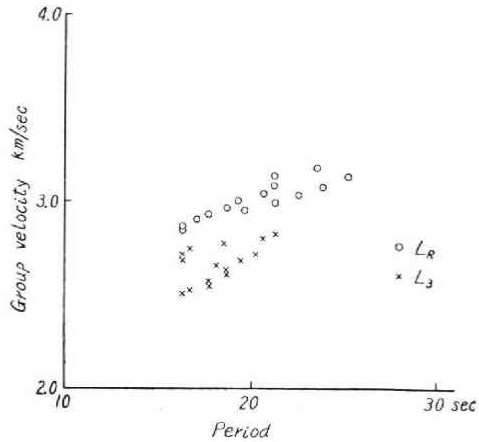

Fig. 7 Dispersion of surface waves of the Kamchatka earthquake on April 13, 1958.

The similar description is made in the case of the earthquake on Aug. 14, 1958. In this case, three wave groups are found on the seismogram. Orbital motions for these groups are shown in Fig. 8 (a), (b) and (c). The second group L_R has the Rayleigh type orbit and the other have the Love-type character. The relations between the group velocities and periods indicate that the first group L_Q is the fundamental Love waves, the second one L_R is the fundamental Rayleigh waves, and the third one L_3 corresponds to the waves L_3 in the former case.

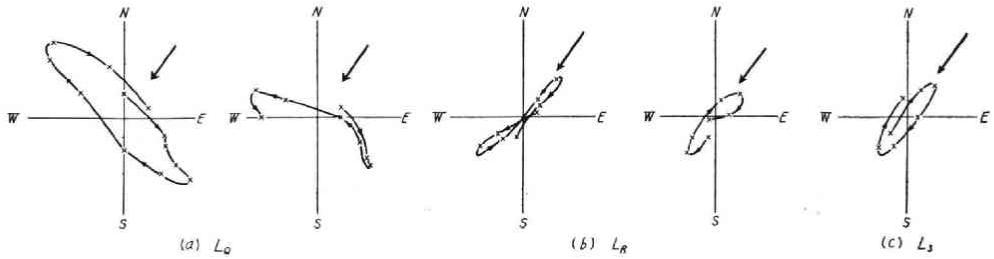

Fig. 8 Orbit in the case of the earthquake on Aug. 15, 1958.

In the case of the earthquake on Dec. 17, 1957 only one wave group corresponding to L_3 is distinguished and the fundamental Rayleigh and Love waves are not clearly found. Moreover, the orbit for L_3 group are not so distinctly Love-type as in the former earthquakes.

4 Synthetical results and the crustal structure

The synthesis of the above three cases indicates that there are three groups of surface waves, i.e., L_R, L_Q and L_3. All the plots of group velocities in the three earthquakes are given in Fig. 9. Now these dispersion data are compared with the theoretical curves calculated for various structures.

A typical dispersion curve for oceanic crust was obtained by M. EWING and F. PRESS (1954). Their result is the curve marked by (a) in Fig. 9. As is clearly seen,

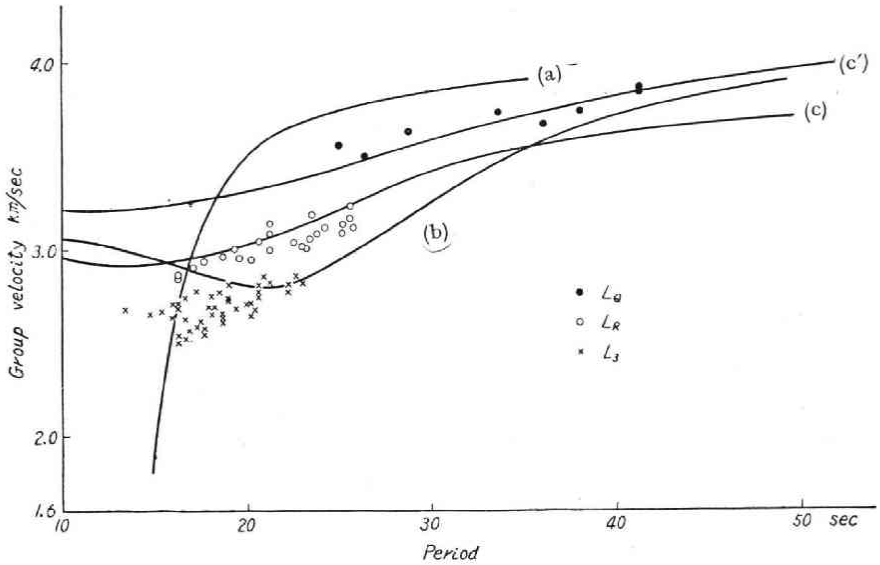

Fig. 9 The dispersion of surface waves obtained from three Kamchatka earthquakes and theoretical curves.
(a) theoretical curve for oceanic crust
(b) theoretical curve for continental crust
(c),(c') theoretical curve for thin continental crust

this curve can not explain the present data.

The dispersion for a continental path calculated also by F. PRESS and M. EWING (1956) is shown by the curve (b) in the same figure. This is not suitable for our data, although the discrepancy between the calculation and the observation is less than in the above case.

T. NAGAMUNE (1956) computed another dispersion curve. The structure adopted in his computation was rather continental but the thickness of the crust was taken to be far less than that in the EWING and PRESS' case. The comparison of the structures in the above three cases is elucidated in Fig. 10.

The curves (c) and (c') represent the NAGAMUNE's curves for Rayleigh and Love waves respectively. The present data of the Kamchatka earthquakes are well explained by these curves.

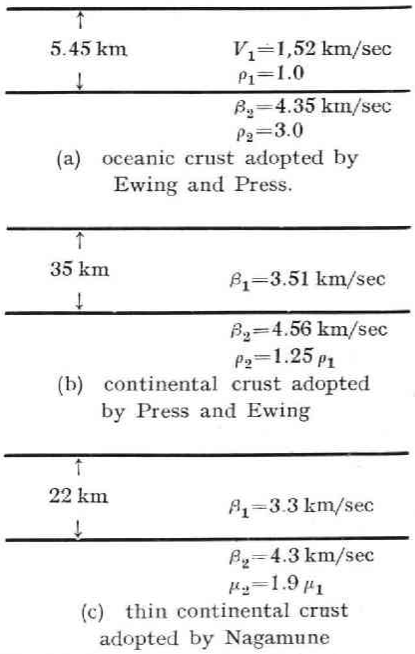

Fig. 10 Structures adopted in the calculations of the curves (a), (b) and (c) in Fig. 9.

It is concluded from the above considerations that the crustal structure along the path from Kamchatka to Japan is rather continental but the crustal layer is much thinner in comparison with the perfectly continental areas. The thickness of the layer is estimated to be roughly 20 km.

This conclusion is reasonably accepted by some other seismometrical data. For example, T. MATUZAWA and the Research Group for Explosion Seismology, Japan (1959) reported that the thickness of the crust in northeastern Japan was estimated to be 20–25 km from the explosion seismological observations. This value is quite consistent with the present conclusion.

5 The Formosa earthquake on Oct. 19, 1957

The Kamchatka earthquakes have the epicentral distances of about 20° at Sendai. Formosa is situated at about the same distance from Sendai in the opposite direction to Kamchatka. Furthermore, the great-circle path from Formosa to Sendai is also along the boundary of the continental and the oceanic areas. For these reasons, the Formosa earthquake on Oct. 19, 1957, which was observed by the same seismograph as in the cases of Kamchatka earthquakes, is similarly studied for reference's sake.

In this case the ordinary L_R and L_Q waves are distinguished. The dispersions of these waves are seen in Fig. 12. Comparing this figure with Fig. 9, it is concluded that the two surface waves indicate the continental feature of the crust concerned, although the thickness of the crust may be slightly larger than that in the case of

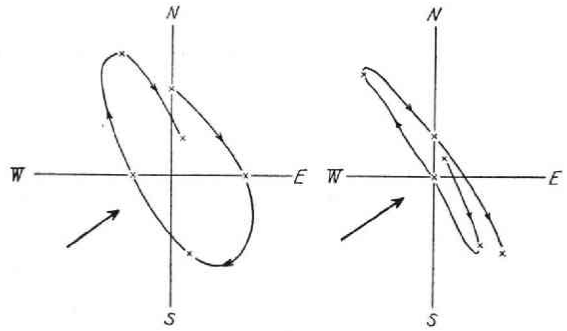

Fig. 11 Orbit of L_3 waves in the case of Formosa earthquake on Oct. 19, 1957

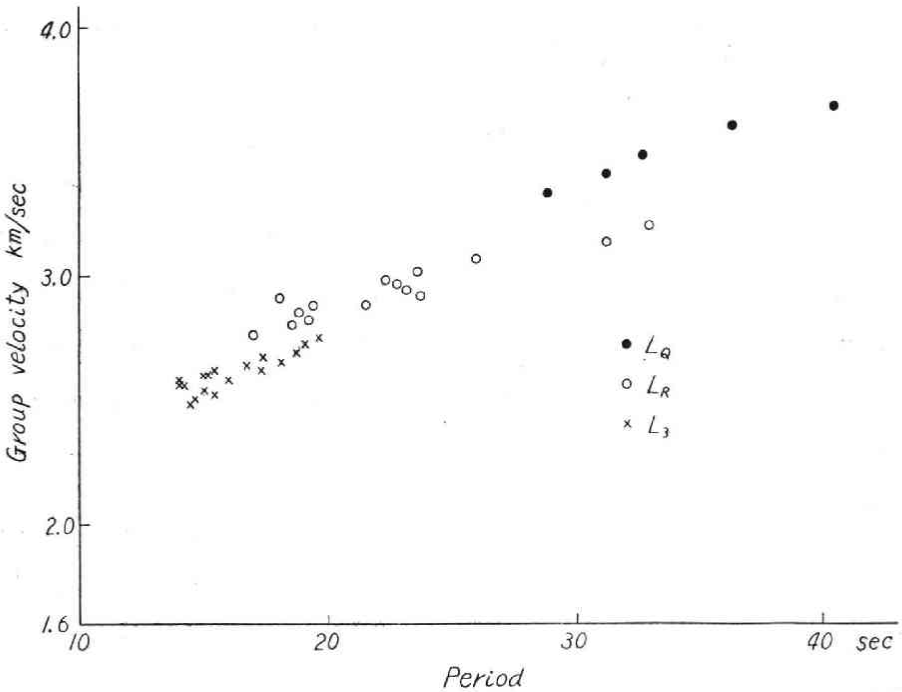

Fig. 12 Dispersion of surface waves in the case of Formosa earthquake on Oct. 19, 1957.

the Kamchatka earthquakes.

Besides L_R and L_Q, the third wave group L_3 is clearly found. The ground motions of these waves show the Love type orbit as seen in Fig. 11. Fig. 12 shows that the group velocities of the waves are lower than those of the fundamental Love waves. Accordingly these waves are of the nature similar to the L_3 waves in the case of the Kamchatka earthquakes.

6 Additional results

The wave group of L_3 were clearly distinguished in many cases stated above. These waves have an orbit similar to that of Love waves but they are propagated with a lower group velocity than that of the fundamental Love waves. In order to make sure of the existence of the waves, the seismograms of the studied earthquakes at some other Japanese stations, where the long period seismograph was operated, are also examined. A distinct wave group is found at every station corresponding to L_3 group. Hence the existence of these waves is fairly ascertained. They might be a higher mode of Love waves but the definite identification will be reserved for a future study.

It was sometimes reported that the Lg phase was seen on the seismograms, when the path of waves was perfectly continental. However, no Lg waves is found in the present cases, although the path belongs entirely to the continental crust. The examination of seismograms by shorter period seismographs make sure of the above fact. This is presumably in some relation to the thin crustal layer.

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