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On Forms of Seismic Waves Generated by Explosion, II

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Abstract

The form of waves generated by a detonation of a cap is discussed from the result of the special observation by the Seismic Exploration Group of Japan. The law of propagation concerning the waves in the 4th wave group is quite similar to those of the preceding wave groups. It is established that the wave motion consists of several regular wave groups, which are governed by a simple law of propagation, and that the irregular part in the seismograms is an apparent result of the superposition of such regular waves. The difference between the present law and the results of mathematical treatment on the propagation of elastic or visco-elastic waves is also discussed.

1 Introduction

The seismograms actually obtained in seismology or explosion seismology are usually too complicate and irregular to be compared quantitatively with the result of mathematical studies on the generation and propagation of elastic or visco-elastic waves. Some efforts to fill up this gap have been made by Ricker (1), (2), (3), Tazime (4), and also by the present authors, based on the seismograms specially obtained for this purpose (5). Further progress is given in this paper.

One of the difficulties in such studies consists in the fact that the wave-to-wave correspondence is not always found in the two seismograms, even when they are observed at two stations separated from each other by a distance of only one wave-length, which is determined from the period and velocity of the predominant waves. Hence the observation is available for the present study, only when the wave motions are registered at many stations within the distance range of one wave-length. The special observation of this kind was carried out in 1953 by the Seismic Exploration Group of Japan.*

An outline of the observation is described here again. Transducers used are of the electro-magnetic type designed by Sassa and are called the C-type transducer. The pendulum of the transducer has a natural frequency of 15 c/s, and is damped in an almost critical state by an air damper. A galvanometer with a natural frequency of 50 c/s is directly connected with the transducer, but no amplifier is used. The transducers are

* This group was provisionally called the "Group for Experimental Research of Seismic Exploration" in the previous paper, but is recently named the "Seismic Exploration Group of Japan".

placed at intervals of 50 cm within the extent of an epicentral distance of 11.25 m -- 25.25 m. Eleven seismograms are recorded simultaneously on a photographic paper, together with shotmark by another element of the oscillograph. Time marks at each 1/100 sec are also recorded in the paper. A cap is detonated as a wave-generating source at the depth of 75 cm. The registered seismograms are shown in Fig. 1 of the previous paper.

The ground motions registered in the present seismograms consist of two parts, i.e., the regular and irregular part. In the regular part, the ground motions have very simple and regular forms and contain no higher harmonics. The wave-to-wave correspondence is evident in this case, and therefore the law concerning the change of amplitude of each wave can easily be obtained. On the other hand, in the irregular part, the forms of the motions are complicated with regard to both amplitudes and periods, the wave-to-wave correspondence being never found. Four regular parts are seen in the present seismograms. Each regular part consists of several waves regularly undulated, is called the 1st, 2nd, 3rd, or 4th wave group, according to the order of the appearance.

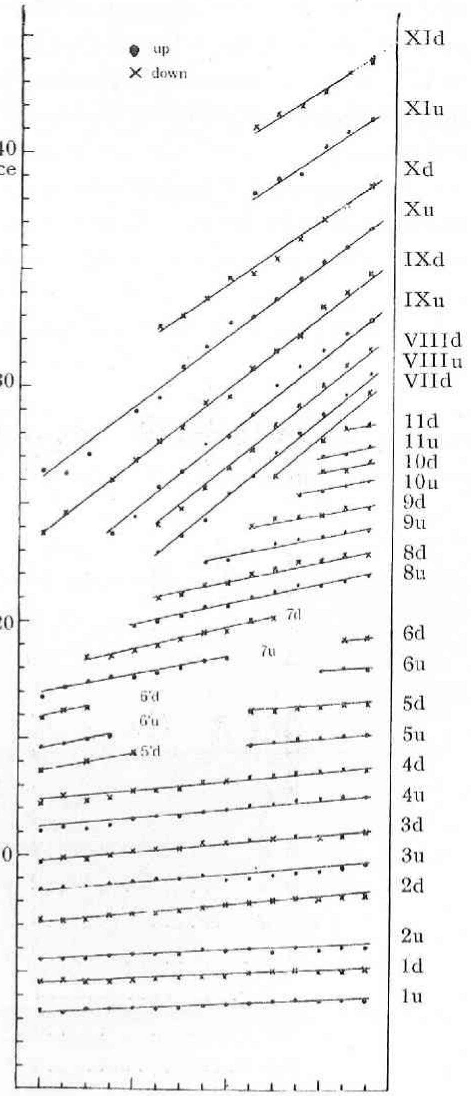

Fig. 1. The travel-times of peaks and troughs.

Without regard to the irregular parts, we superpose the forms of each wave group, which are estimated for any desired epicentral distance after the law of propagation determined from the data in the regular part. Thus we obtain an artificial seismogram at any distance, which is provisionally called an "expected seismogram" in this study. It has been established in the previous paper that the expected seismograms closely resemble to the observed ones, even for the waves in the irregular part between the 2nd and 3rd wave groups. From this fact we can infer that the wave motions generated by explosions consist essentially of several wave groups, which are very simple and regular in regard to their forms and laws of propagation, and that the irregular part is an apparent result of the superposition of such regular waves. The validity of this inference will be examined in the next pages for the irregular parts not treated previously.

2 Travel Times of Peaks and Troughs

The procedure of study is similar to that in the previous paper. At first the travel times of all the peaks and troughs are taken into consideration, and are plotted as ordinate against the epicentral distance as abscissa (Fig. 1). The peaks and troughs are denoted by the symbols, VIId, VIIIu, VIIId, and so on, according to the order of their appearance at the epicentral distance of 11.25 m. The irregular part naturally remains blank in this figure. As shown in Fig. 1, the travel time of a peak or trough increases linearly with epicentral distance, at least within the range of distance in the present observation.

The equations of travel times of each peak and trough determined by the least square method are given below. They include the equations for peaks and troughs belonging to the 1st, 2nd, and 3rd wave groups. Some equations are corrected by the addition of new data.

1 *u*	$t = 0.021 + \Delta/1020$	
1 *d*	$t = 0.035 + \Delta/1080$	1st Wave Group
2 *u*	$t = 0.043 + \Delta/\ 950$	
2 *d*	$t = 0.050 + \Delta/\ 520$	
3 *u*	$t = 0.065 + \Delta/\ 570$	
3 *d*	$t = 0.077 + \Delta/\ 530$	
4 *u*	$t = 0.093 + \Delta/\ 570$	
4 *d*	$t = 0.102 + \Delta/\ 490$	2nd Wave Group
5 *u*	$t = 0.117 + \Delta/\ 490$	
5 *d*	$t = 0.137 + \Delta/\ 600$	
6 *u*	$t = 0.149 + \Delta/\ 570$	
6 *d*	$t = 0.158 + \Delta/\ 510$	
5′ *d*	$t = 0.091 + \Delta/\ 250$	
6′ *u*	$t = 0.096 + \Delta/\ 230$	
6′ *d*	$t = 0.110 + \Delta/\ 230$	
7 *u*	$t = 0.115 + \Delta/\ 210$	
7 *d*	$t = 0.127 + \Delta/\ 220$	
8 *u*	$t = 0.142 + \Delta/\ 230$	3rd Wave Group
8 *d*	$t = 0.155 + \Delta/\ 240$	
9 *u*	$t = 0.168 + \Delta/\ 250$	
9 *d*	$t = 0.181 + \Delta/\ 260$	
10 *u*	$t = 0.192 + \Delta/\ 270$	
10 *d*	$t = 0.202 + \Delta/\ 280$	
VII *d*	$t = -0.021 + \Delta/\ 57$	
VIII *u*	$t = -0.002 + \Delta/\ 60$	
VIII *d*	$t = 0.021 + \Delta/\ 62$	
IX *u*	$t = 0.032 + \Delta/\ 61$	
IX *d*	$t = 0.063 + \Delta/\ 63$	4th Wave Group

X u .... $t = 0.089 + \Delta/65$
X d .... $t = 0.111 + \Delta/66$
XI u .... $t = 0.171 + \Delta/75$
XI d .... $t = 0.213 + \Delta/80$

It is apparent from Fig. 1, that the present irregular part has some features different from those treated previously. The waves in the 4th group show an evident nature of dispersion, while the preceding ones have a constant period. Another feature lies in that the range of the superposed parts of the 3rd and 4th groups is far larger than that in the previous case, e.g., each half of the two groups is superposed to the other. Moreover, the range of the superposed part varies very rapidly with epicentral distance, because of the great difference between the velocities of the two groups. Hence the matter is further complicated in the present case. This complication, however, is rather favourable to check the validity of our inference, because the discrepancy between the expected and observed seismograms will be evident, if the inference is not correct for the actual cases.

3 Variation of Wave Forms with Distance

Amplitudes of all the peaks and troughs in the 4th wave group are divided for each trace by a standard amplitude, which is taken to be the peak 4u in this study. The amplitude ratios thus obtained are plotted as ordinate against the epicentral distance as abscissa (Fig. 2). It is apparent from this figure that there is a linear relation between the two variables. The amplitude ratios of waves in the head part of 4th group decrease with increasing distance, while those in the tail part increase with distance. These circumstances are quite similar to the waves in the preceding groups.

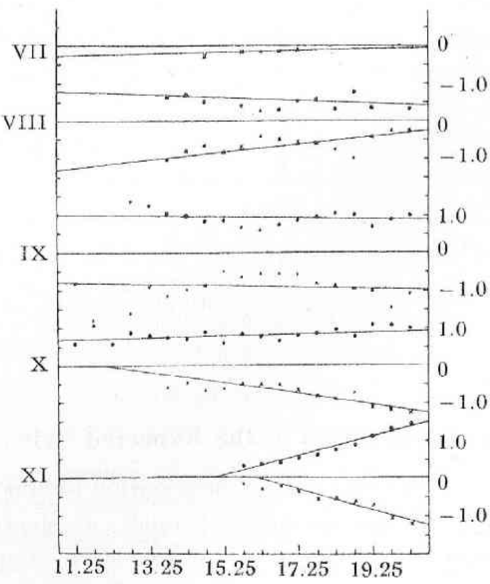

Fig. 2. The amplitude ratios for the peaks and troughs in the 4 th group.

As a result of the amplitude variation stated above, it seems as if the wave belonging to the tail part of a group is generated at a certain critical epicentral distance. Therefore the number of waves in a wave group increases with distance. It is a remarkable fact that the form of a wave group varies so much even within the extent of epicentral distance in the present observation.

The gradients of straight lines representing the variation of amplitude ratio are called the "growing rate" of each peak and trough in this paper, and are plotted as ordinate in Fig. 3 against the order of appearance of peaks and troughs as abscissa. The growing rates for waves in the 1st, 2nd, and 3rd wave groups, which are given in the previous paper, are reproduced here.

As seen in Fig. 3, the change of the growing rate is very regular for every wave group. It is noteworthy that the mode of the variation is similar for all groups except the 1st one, though the periods and the velocities of the groups are quite different from each other. The mode of the variation for the 1st group is entirely different from the other. The facts are of much interest and will give an important clue to the study of wave propagation.

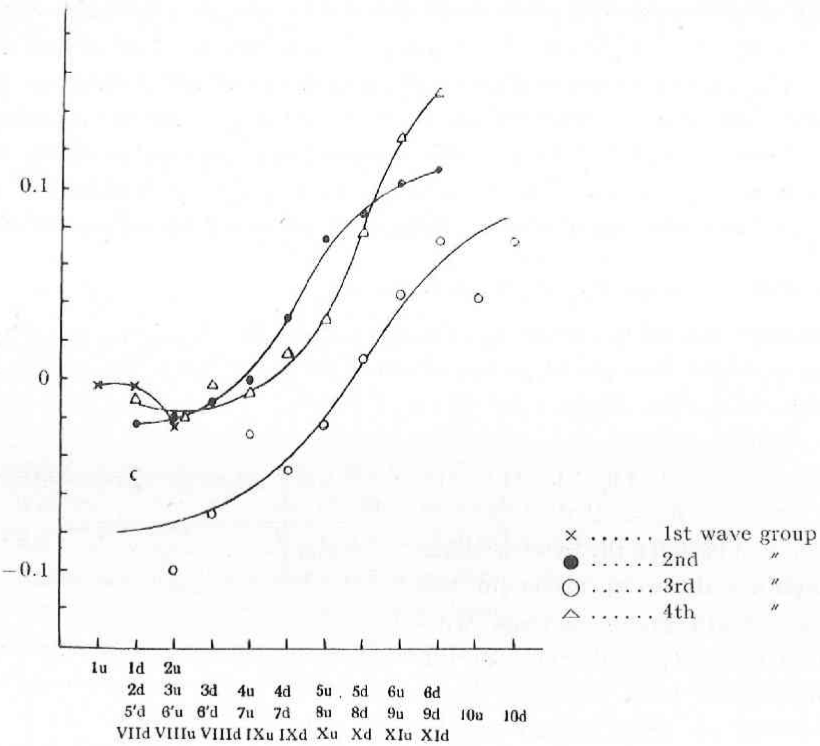

Fig. 3. The "growing rate" of each wave group.

4 Comparison of the Expected Seismograms with the Observed Seismograms

After the laws of propagation obtained above, the wave form can be estimated for any desired epicentral distance, as shown in Fig. 4 separately for each wave group. Superposing the forms of the wave groups, we obtain the expected seismograms, for example, as shown in Fig. 5. The observed seismograms corresponding to the expected ones are shown in Fig. 6 in the same scale as Fig. 5 with regard to both time and amplitude. These figures show that the two seismograms coincide well with each other, not only in the regular parts, but in the irregular parts, although the expected seismograms are based exclusively on the data in the regular parts.

Some typical examples are also given in Fig. 7 in a larger scale. In the uppermost example in the figure, the observed wave marked by single star has a very large amplitude than those of the preceding and the following waves. Sometimes such phenomenon may be misconstrued to be due to an instrumental or accidental cause. However, this can be completely explained as the result of superposition of two regular wave groups as shown in the expected seismogram. In the second example, the wave marked by double star undulates irregularly and has a different aspect from the nieghbouring ones. This circumstance is also explained by the superposition.

From the above discussion it is concluded that the observed ground motion consists exclusively of several wave groups, which are governed by a simple law of propagation, and that the irregular part of the seismograms is an apparent result of the superposition of such regular waves.

5 Discussion

One of the most remarkable facts in this study, is that the wave forms of the 2nd, 3rd, and 4th wave groups vary widely even within the distance range of 14 m concenred in the present observation. The wave-lengths are estimated from the periods and velocities of peaks and troughs at 15 m, 13 m, and 5 m for the 1st, 2nd, and 3rd wave groups respectively, while the wave length of the 4th group cannot be determined owing to its dispersive nature. Hence it is apparent from the above stated fact that the wave form varies widely even within the distance range of one or two wave-length. This is not immediately accepted from the results of mathematical studies on elastic or visco-elastic waves, unless an unreasonable large value of viscosity is assumed.

Of course, the conception of wave-length is concerned only with a coherent sine waves with constant amplitude : Therefore, in the strict sense, the wave-length cannot be determined for such waves with a finite duration of time as well as the varying amplitude as discussed in the present study. However, no higher harmonics is expected to be predominant in our wave groups, as easily understood from the simple form of each group as shown in Fig. 4. Consequently the value of wave-length estimated for each group is considered as the smallest one among those of predominant harmonics, which appear in the expression of wave forms by Fourier's integral. Thus the discrepancy between the observation and the mathematical studies still remains unexplained.

The form of a wave group obtained in the present study is different from that of "wavelet" defined by Ricker(1). The wavelet of the 1st order in his definition consists of two peaks and one trough, when observed by a seismometer of velocity type. As the present observation is made at so small epicentral distances as one or two wave-length from the origin, it is not necessary that a wave group is exclusively expressed by the wavelet of lowest order. However, this circumstance is not enough stop to fill the discrepancy between the form of wave groups under discussion and that of wavelet. The wavelet theory shows that the form of a wave group should approach to that of the wavelet of 1st order as the distance increases, because the wavelets of higher orders should attenuate more rapidly with distance than that of 1st order. The number of waves in the present wave group on the contrary, increases with epicentral distance. After the recent study by Tazime (6) a wave group, when observed at an epicentral distance far less than the case under discussion, has a form similar to the 1st wavelet. This is quite contrary to the inference deduced from the wavelet theory. Further study is expected to explain the discrepancy.

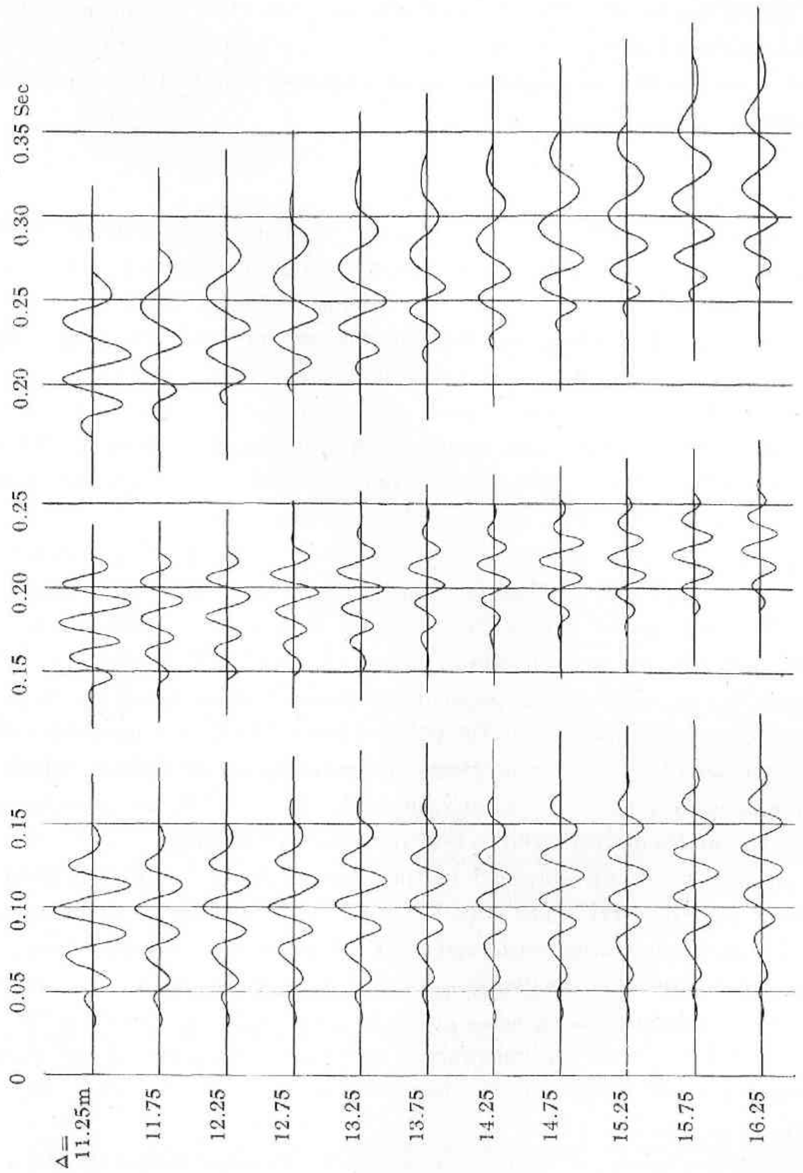

Fig. 4. The forms of each wave group: 1st and 2nd wave groups on the left, 3rd wave group on the middle, and 4th wave group on the right.

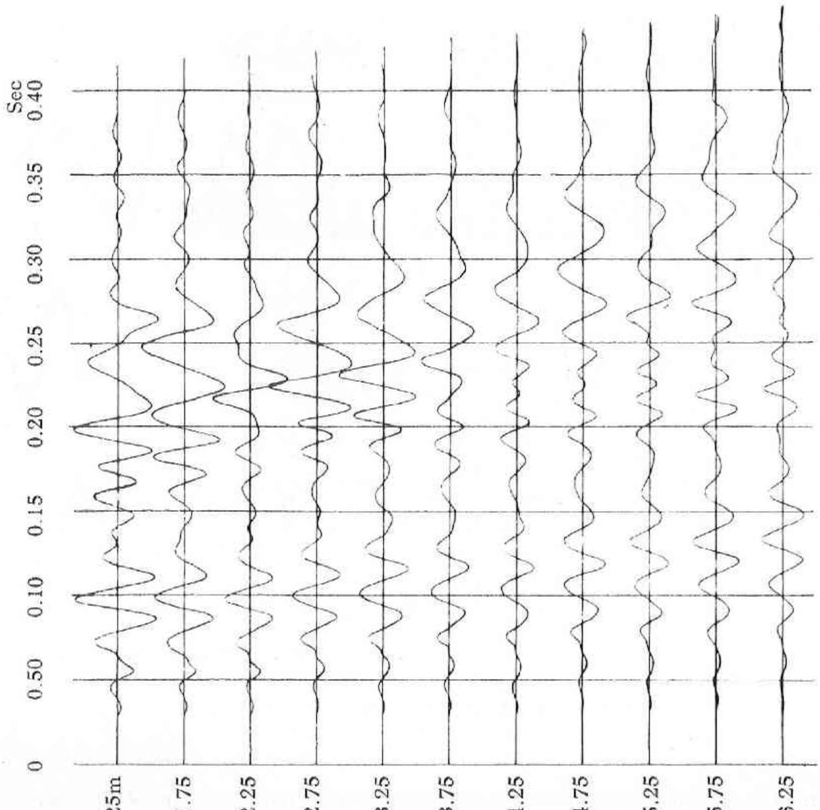

Fig. 6. The observed seismograms.

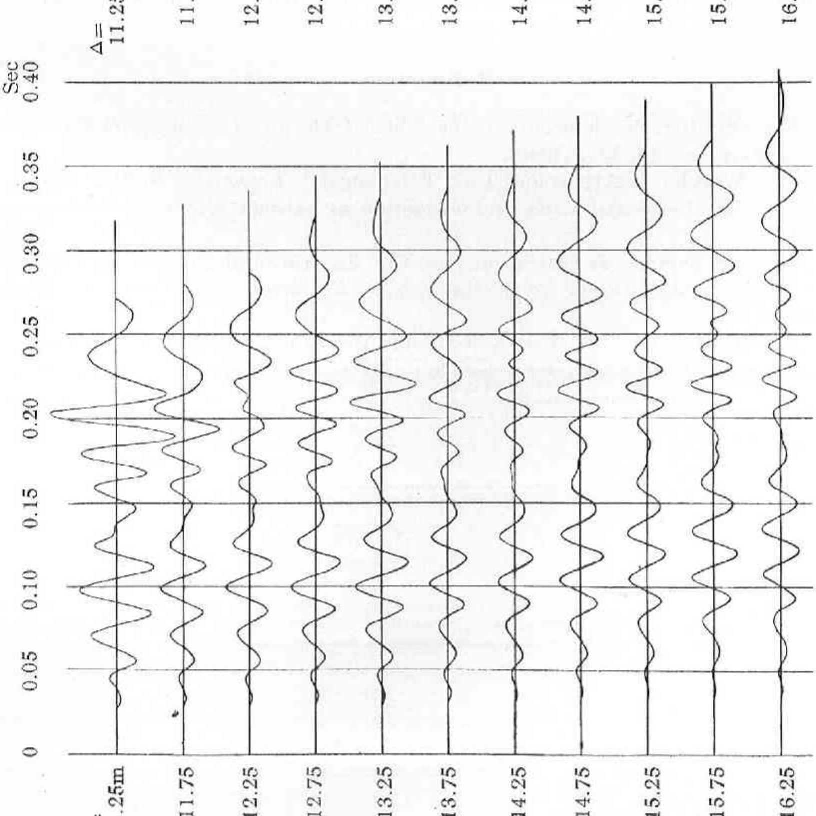

Fig. 5. The expected seismograms.

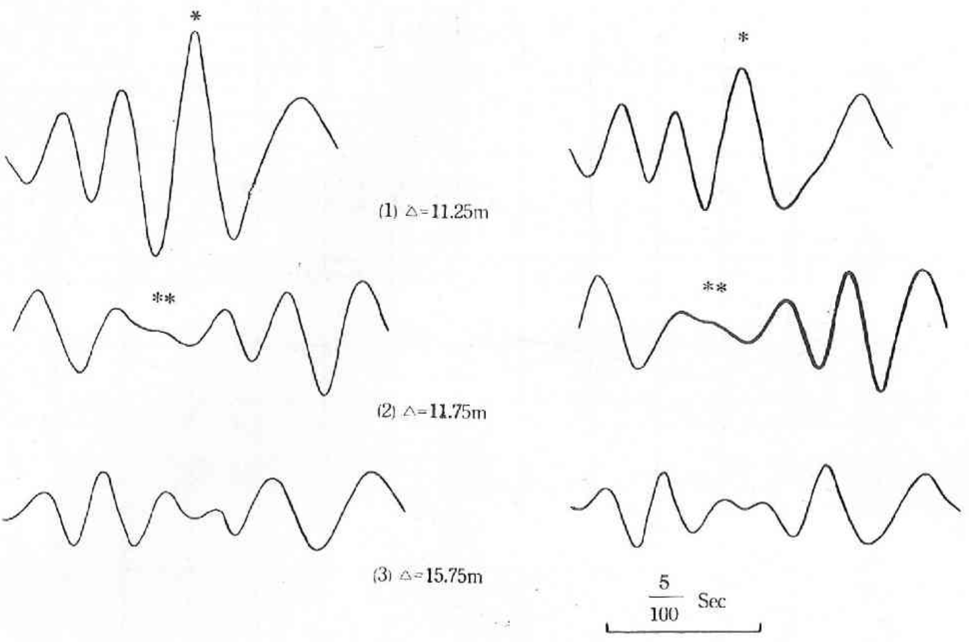

Fig. 7. The enlarged forms of the observed seismograms (on the right), and the expected seismograms (on the left).

This study is a contribution of the Seismic Exploration Group of Japan.

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