On Forms of Seismic Waves Generated by Explosion,?

著者	Suzuki Ziro, Sima Hiromu
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On Forms of Seismic Waves Generated by Explosion, 1

By Ziro SUZUKI
Seismological Observatory, Faculty of Science, Tôhoku University
and
Hiromu SIMA
Geophysical Institnte, Faculty of Science, Tôhoku University

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Abstract

The seismic waves generated by the detonation of explosives consist of several wave groups. Each wave group has rather simple form with constant period and with amplitude varying regularly with the distance and the order of appearence. The irregularly undulated part of the seismogram is interpreted as the superposition of these regular wave groups. The superposed form of the groups at any distance fairly coincides with the observed seismogram. The law of propagation of the wave groups and the variation of their forms are studied basing on the seismograms observed by "the Group for Experimental Research on Seismic Exploration". A remark on the initial motion of later phases is noted in addition to the above results.

1 Introduction

Recent development of mathematical investigations on the generation and propagation of elastic waves has made it possible to calculate the form of waves at any distance generated by a detonation of explosives. At the present state of seismology, however, the mathematical results do not directly connect with seismograms, except the qualitative property that the seismic waves consist of several wave groups, i.e., direct waves, refracted and reflected waves, and surface waves. Actual seismograms are too complicated to be compared quantitatively with what is obtained mathematically, and the cases mathematically treaed are restricted to very simple ones.

More recently, several attempts to stop the gap have been made by some authors. N. Ricker (1) has introduced the "wavelet theory", and found several "wavelets" in explosion seismograms. K. Tazime (2) has studied some empirical laws basing on many seismograms. The present writers take a stand point of view, as Tazime, to find the empirical laws phenomenologically at first, without any consideration in mathematical theory. As the first step of this study, they will show in this paper that the seismograms are expressed, even quantitatively, as a superposition of several regular and simple wave groups. The law of propagation of these groups is also studied.

2 Materials

The materials used are based upon the observations carried out by "the Group for Experimental Research of Seismic Exploration" in Feb., 1953, in the grounds of

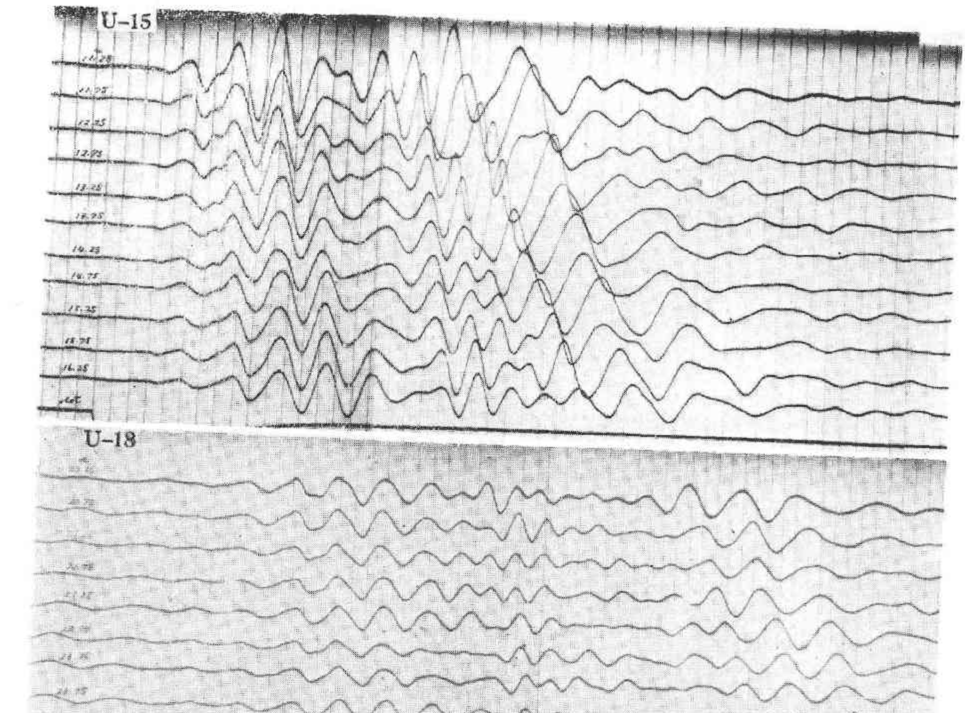

Fig. 1 (A). The seismograms used.

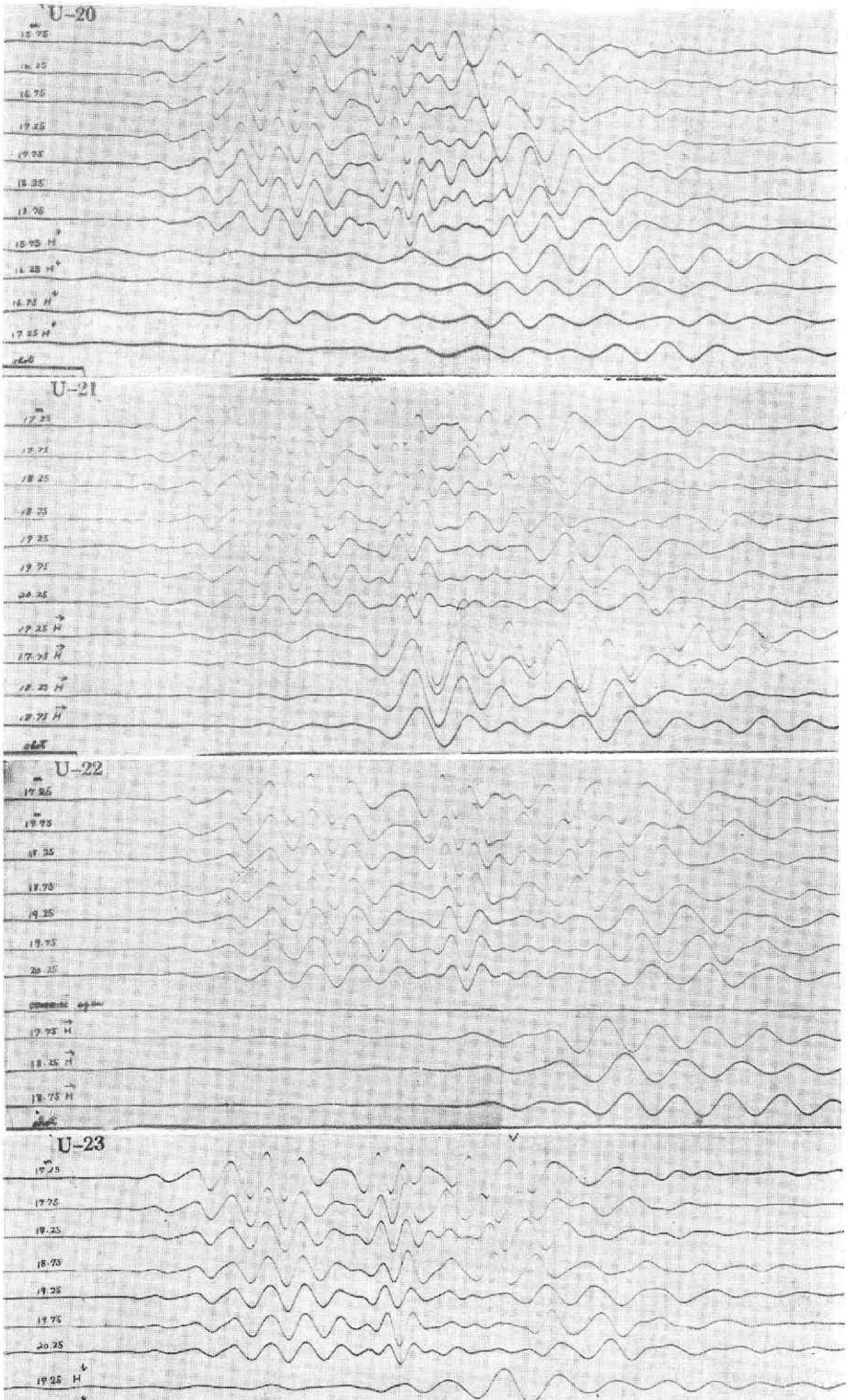

Fig. 1 (B). The seismograms used.
(The downward motion on the seismograms represents the upward motion on the ground.)

the Geoplogical Survey of Japan, Kawasaki, Kanagawa Pref. For the sake of simplicity, the present discussions are concerned exclusively in the seismograms obtained by means of the seismometers with no electric amplifier. (The record numbers of them are U–15, U–18, U–19, U–20, U–21, U–22, ard U–23). These seismograms are obtained by S. Hayashi and T. Miyajima.

The transducers are of the type designed by K. Sassa (called C type), the natural frequency being 20 cycles/sec., and the damping being adjusted to be about critical by a air damper. The galvanometers have a natural frequency of 50 cycles/sec., and are critically damped. Each galvanometer is directly connected with a transducer, no grouping and mixing being operated.

The oscillograph used has 12 elements, one of which is used for shot mark and others for seismic records. Time signal is marked every 1/100 sec. on the recording paper.

The observation points are set every interval of 25 cm. from the source. The spreads of the seismograms are as follows:

U–15 : 11.25 m. — 16.25 m.	U–21 : 17.25 m — 20.25 m.
U–18 : 20.25 m. — 25.25 m.	U–22 : 17.25 m — 20.25 m.
U–19 : 15.75 m. — 18.75 m.	U–23 : 17.25 m — 20.25 m.
U–20 : 15.75 m. — 18.75 m.	

The sensitivity of the seismometer is kept constant for every spread, hence the ground motion at the station nearer than 11.25m. is too large to be recorded within the scale of oscillograph paper. For this reason, these seismograms cannot be used for the present discussion.

A detonating cap is fired at the depth of 75 cm. under the ground surface. The conditions of detonation are similar for every observation. Tazime* has reported that the same ground motion is observed at the same station for repeated explosions, provided the conditions of explosion and the instrument of observation are kept the same. In our case also, this is ascertained ; the record U–19, for example, is quite the same as U–20. This fact shows that the differences of wave forms on each trace are due to the effect of propagation of the waves.

The seismograms obtained are shown in Fig. 1. As seen in Fig. 1, the seismogram consists of two parts : regularly undulated part and irregularly disturbed part. In the regular part, simple and regular waves continue and make a wave group, the wave-to-wave correspondence being easily found for every trace, while in the irregular part, which appears between two regular parts, no clear correspondence is seen. These circumstances will be interpreted to be the result of the superposition of regular wave groups, as described later.

3 Travel Times of Peaks and Troughs

At first the travel times of all the peaks and troughs of seismograms are plotted on a graph, the epicentral distance being taken as abscissa, as shown in Fig. 2. The first peak is denoted by $1u$, and the first trough by $1d$. In the similar way, the n *th* peak and trough are written by nu and nd respectively, in order of their appearance.

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* dictated at the meeting of the Seismological Society of Japan, in May, 1951.

The travel times of each peak and trough in the regular part increase linearly with epicentral distance within the range of present observation. In irregular part, however, the travel-time-distance curve connot be drawn, becaus the wave-to-wave correspondence for each trace is difficult. In Fig. 2, this part is lacked. Concretely speaking, the peaks and troughs from the initial motion to 4d correspond each other for the whole range of epicentral distance. For both 5u and 5d following 4d, the correspondences are clear exclusively for traces having the epicentral distance larger than 15.75 m., and moreover the velocities determined by their time-distance curves are nearly the same as that of the preceeding 4d. In other words, the tail part of the wave group appears clearly at the distance $\Delta > 15.75$ m., while this part is disturbed by the head of the following wave group at the distance smaller than 15.75 m. The conditions for 6u and 6d are also the same as these of the above 5u and 5d. At the distance smaller than 13.25 m., the travel times of the peaks and troughs following 4u are plotted, but these points diffe from those of 5u and 5d in their velocities of propagation, and rather belong to the following wave group. Namely, it may be reasonably accepted that the head of the following wave group appears at this distance. Hence these points are called 5'd, 6'u, and 6'd discriminatively from 5u and 5d. At the middle distance, the wave-to-wave correspondences are not clear, and the wave trains is of the disturbed part, hence this part is lacked in this figure.

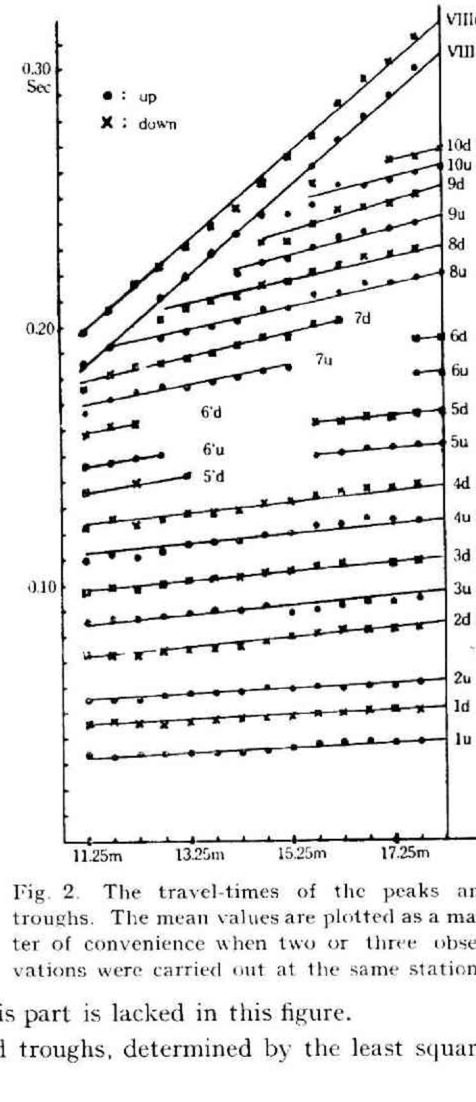

Fig. 2. The travel-times of the peaks and troughs. The mean values are plotted as a matter of convenience when two or three observations were carried out at the same station.

The variation of travel times of peaks and troughs, determined by the least square method, is expressed as follows :

$$\left.\begin{aligned} 1\,u \cdots\cdots t &= 0.021+\Delta/1020 \\ 1\,d \cdots\cdots t &= 0.035+\Delta/1082 \\ 2\,u \cdots\cdots t &= 0.044+\Delta/\ 950 \end{aligned}\right\}\ \text{1st Wave Group}$$

$$\left.\begin{aligned} 2\,d \cdots\cdots t &= 0.050+\Delta/\ 520 \\ 3\,u \cdots\cdots t &= 0.064+\Delta/\ 570 \\ 3\,d \cdots\cdots t &= 0.076+\Delta/\ 530 \\ 4\,u \cdots\cdots t &= 0.093+\Delta/\ 570 \\ 4\,d \cdots\cdots t &= 0.102+\Delta/\ 490 \end{aligned}\right\}\ \text{2nd Wave Group}$$

$$
\left.\begin{array}{l}
5\,u \cdots\cdots t = 0.117+\Delta/490 \\
5\,d \cdots\cdots t = 0.136+\Delta/600 \\
6\,u \cdots\cdots t = 0.149+\Delta/570 \\
6\,d \cdots\cdots t = 0.158+\Delta/510
\end{array}\right\}
$$

$$
\left.\begin{array}{l}
5'\,d \cdots\cdots t = 0.091+\Delta/250 \\
6'\,u \cdots\cdots t = 0.096+\Delta/230 \\
6'\,d \cdots\cdots t = 0.109+\Delta/230 \\
7\,u \cdots\cdots t = 0.115+\Delta/210 \\
7\,d \cdots\cdots t = 0.127+\Delta/220 \\
8\,u \cdots\cdots t = 0.142+\Delta/230 \\
8\,d \cdots\cdots t = 0.155+\Delta/240 \\
9\,u \cdots\cdots t = 0.151+\Delta/200 \\
9\,d \cdots\cdots t = 0.150+\Delta/170 \\
10\,u \cdots\cdots t = 0.176+\Delta/210 \\
10\,d \cdots\cdots t = 0.208+\Delta/300
\end{array}\right\}\text{3rd Wave Group}
$$

$$
\left.\begin{array}{l}
\text{VIII}\,u \cdots\cdots t = 0.021+\Delta/60 \\
\text{VIII}\,d \cdots\cdots t = -0.008+\Delta/60 \\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots \\
\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots
\end{array}\right\}\text{4th Wave Group}
$$

where t is the travel time in seconds and Δ is the epicentral distance in meters.

According to the velocity of propagation, the peaks and troughs may be classified into four groups. The groups are called 1st, 2nd, 3rd, and 4th "wave group" in order of their appearance. For the last group, which consists of peaks and troughs denoted by VII u, VIII d, and the followings, the expression is omitted, because this group does not come into consideration in the present discussion.

The time intervals between each travel time curve show the period of respective waves. The period is kept constant for 1st, 2nd, and 3rd wave groups, as seen in the above expression, that is, the dispersion is not recognized at least within the range of the present observation.

Sometimes small peaks are evidently recorded between 2u and 2d, and 3u and 3d,

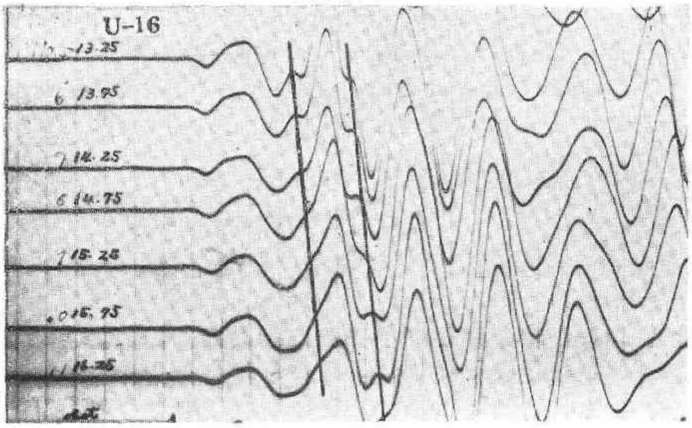

Fig. 3. An example of sound waves.

an example being seen in Fig. 3. The travel times of these peaks also increase linearly with distance. The velocity of propagation is determined to be about 340 m/sec., and they seem to be the sound waves in air. Hence the travel times of them are also omitted in the present discussion.

4 Variation of the Form of Wave Groups with Distance

The peak $4u$ is the most clear and regular wave in the whole range of observation, hence the amplitude of this peak is taken to be the standard. Amplitudes of peaks and troughs are divided by this standard amplitude of 4u in respective traces. The amplitudes of the waves decrease with increasing distance. By the above operation, the effect of the general amplitude decrease is canceled, which reasonably assumed to be uniform for all the wave group, and also the effect of the difference in frequency response of each seismometer is eliminated. Hence the amplitude ratio thus obtained is considered as a factor indicating the variation of the wave form eliminating the general decrease.

The amplitude ratios for all peaks and troughs are seen in Fig. 4, and the variation of the standard amplitude against the epicentral distance is also seen in Fig. 5. As seen in Fig. 4. the ampitude ratio is expressed by a straight line against the distance. The full lines in Fig. 4 show the straight lines determined by the least square method. The gradients of these lines may be taken as a measure indicating the rate of growth of respective waves, and called by "the growing rate" of the wave in this paper.

The values of the growing rate are arranged in order of the appearance of peaks and

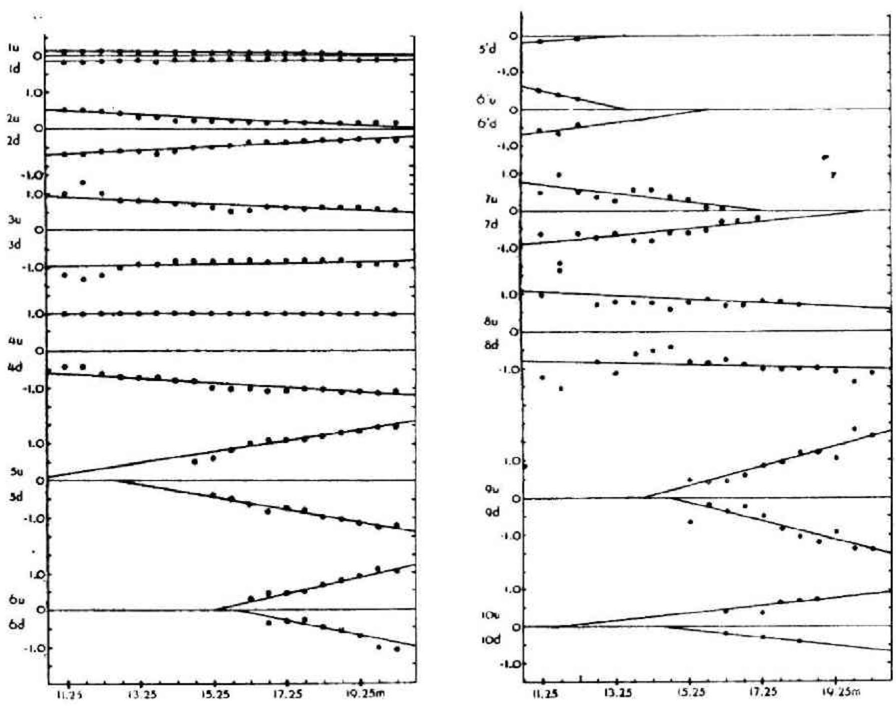

Fig. 4. The amplitude ratios for the peaks and troughs. The mean values are plotted as a matter of convenience when two or three observations were carried out at the same station.

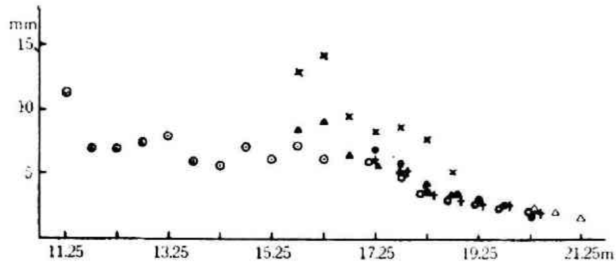

Fig. 5. The variation of the standard amplitude of 4u with the epicentral distance on each record The trace amplitudes on the oscillograph paper are shown in m.m. as ordinate.

(•) U-15 △ U-18 × U-19 ▲ U-20
● U-21 + U 22 ○ U-23

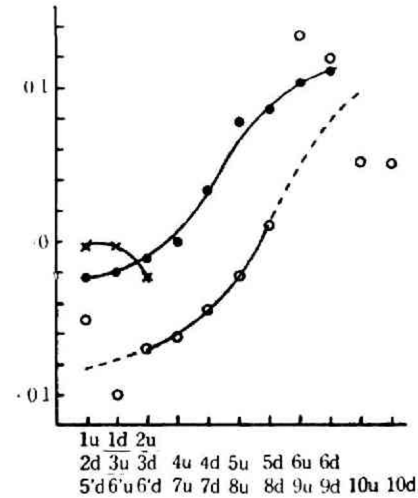

Fig. 6. The values of "the growing rate" in each wave group. The growing rate is expressed by the gradient of the full line in Fig. 4.

× ····· 1st wave group
● ····· 2nd wave group
○ ····· 3rd wave group

troughs as shown in Fig. 6. The rate is regularly increased with the order of appearance, as seen in the figure. This regularity will give a interesting clue to the law of propagation of seismic waves, and this problem will be discussed in the next paper.

Fig. 6 shows that the amplitude of the head of the wave group diminishes with increasing

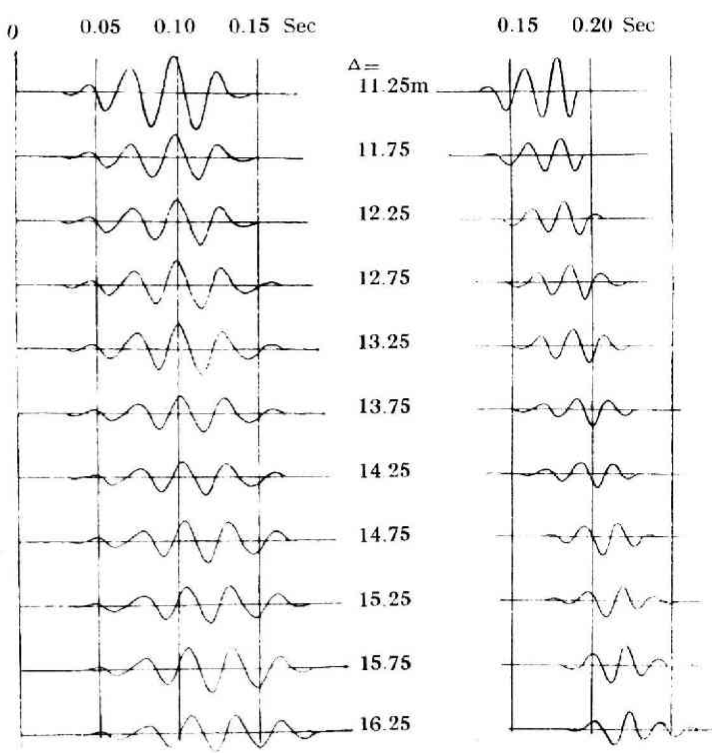

Fig. 7. The form of each wave group: 1st and 2nd wave groups by the left side, and 3rd wave group by the right side.

distance, while the amplitude of the tail grows up. As the growth of the tail is larger than the decay of the head in our case, the number of waves in a group increases with distance, and, at certain distance, the head of the wave group is overlapped by the tail of the preceding wave group. This is the resaon of occurrence of irregular part in seismograms, as studied in next paragraph quantitatively.

5 Interpretation of Irregular Part

The regular part in the present seismograms consists of some wave groups as stated above. The form of the wave group is very simple ; the period is constant, the amplitudes of peaks and troughs vary regularly with distance and order of appearance, and, moreover, no higher harmonics are contained. Then the superposed form of these wave groups can be calculated at any distance, under consideration of the velocity of propagation of each wave determined previously. The expected forms of each group and the superposition of them are shown in Fig. 7 and by the left side in Fig. 8 respectively. The observed seismograms are also shown in the same scale by the right side in Fig. 8. The seismograms observed and expected coincide fairly well with each other even in the irregular part. This fact means that the irregular part of the observed seismogram is the apparent result due to the superposition of some regular wave groups. In other words, the seismogram is composed of the superposition of some regular and simple wave groups only, and the properties on the propagation of wave groups, discussed above, are valid for the whole part of seismograms.

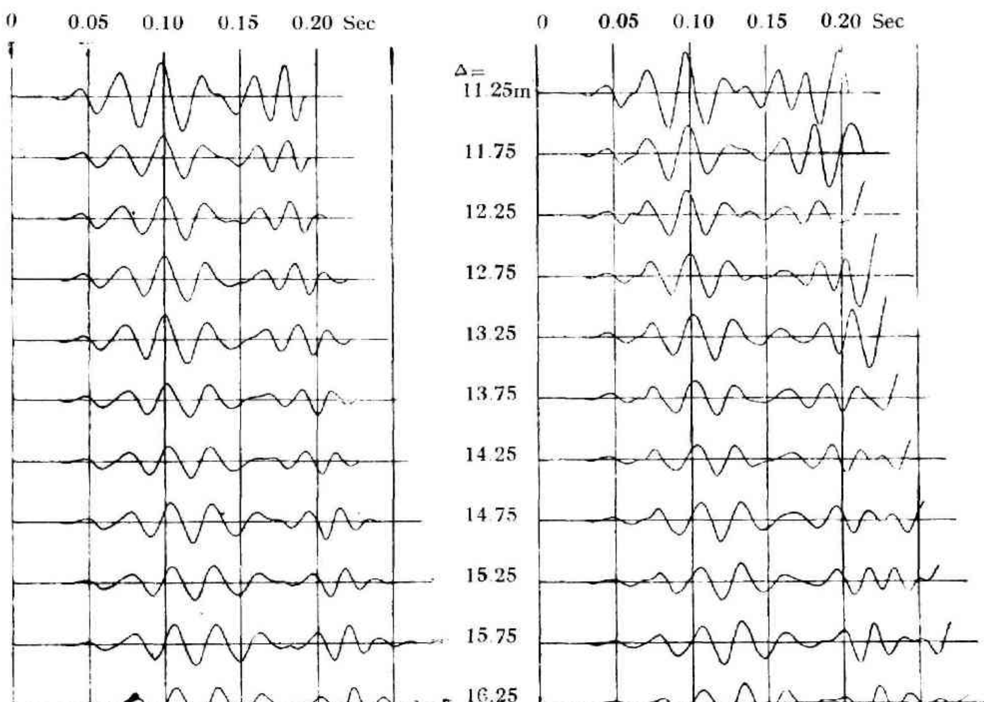

Fig. 8. The comparison of the seismograms expected and observed. The former, by the left side, and the latter, by the right side.

6 Remark on the Initial Motion of Later Phases

As a result of the decrease of the head and the increase of the tail of wave groups with distance, the initial motion of later phases is sometimes misread. For an example, the two traces in U-15 are given in Fig. 9. A and B in Fig. 9 may be taken to correspond to the initial motion of following wave group on each trace, provided no other observation is given. The true initial motion of this group, however, is to be at the point C in the lower trace, according to the process described above, although any symptom of initial motion is not found there. This difficulty in finding the initial motion must be noted, when the wave-to-wave correspondence cannot be established, as in the case when the interval of observation stations is too large.

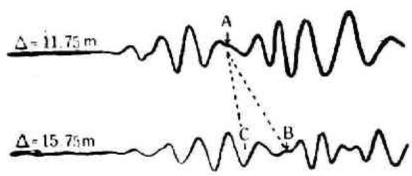

Fig. 9. The initial motion of the later phase.

7 Summary

Summarizing the above stated results, the followings are obtained :

(1) The ground motion generated by the detonation of explosives consists of some simple and regular wave groups, and the irregular part of the motion is an apparent results of the superposition of the wave groups.

(2) The period of waves in a group is kept constant at least within the range of present observation.

(3) The amplitude ratio to the standared amplitude in a wave group varies linearly with distance.

(4) The growing rate of waves varies regularly in order of their appearance in the group. The head of the group decays with increasing distance, while the tail increases rapidly.

(5) As the result of the property stated above, the inital motion of later phases is sometimes misread.

Acknowledgement

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