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ON SEISMIC WAVES GENERATED BY SMALL EXPLOSIONS

By

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Abstract

The problem related to seismic waves generated by small dynamite charged explosions has been investigated based upon the experiment carried out by the Exploration Group of Japan at Shirane City, Niigata Pref. in 1965.

There are four different types of wave groups; namely, wave groups of I, II, III and IV. On the wave groups III and IV, the comparative investigations were made both theoretical and experimental by several authors.

Consequently, in the present paper, characteristics of the wave groups I and II have been mainly treated.

The wave group I is concluded to be composed of various kinds of converted waves generated from the interfaces under the surface. While, in the wave group II, three different kinds of waves are found; a kind of surface waves having the longest wave length among the wave groups, a wavelet of direct P wave and refracted SV waves. Among these three kinds of waves, the main part of the wave group II having a surface wave type is more interest. Its wave form and characters are equivalent for the normal mode wave in the liquid-liquid layers. Namely, its phase velocity is lying between the propagation velocities of the P waves in the surface layer and half space, its amplitude distribution in depth shows the same form as the surface wave having a loop on the surface, one node in the layer and its amplitude decreases with depth.

Moreover, Poisson's ratio of our experimental field is almost 0.5, then it resembles closely to the liquid state. Therefore, it is quite possible that among the wave groups generated by the explosions, there is a suface wave having a type similar to the normal mode wave in liquid-liquid layers.

1. Introduction

The problems concerned with the seismic waves generated by small charged explosions were investigated by the members of the "Seismic Exploration Group of Japan" (Tazime [1956, 1957], Kubotera [1955, 1957], Sima [1963 a, b], Okada [1963, 1965], Iida and Ohta [1966]).

From these investigations, the seismic waves were characterized by four different types of waves, that is, the wave groups of I, II, III and IV respectively. They concluded that the wave group I is the initial motion of direct or refracted P waves; the wave groups III and IV are the normal mode Rayleigh waves (M_{21} and M_{11}) which have been guided in the layered structure. Nevertheless, a satisfactory conclusion has not yet been reached for the wave group II. The main part of the wave group II has the characteristics resemble to the usual surface waves having one node in the surface layer and has the longest wave length among the wave groups observed. The phase velocity is lying between the propagation velocities of P waves of the surface layer and substratum. In the wave group II, however, reflected or refracted P waves and also direct P phase which appears succeeded the wave group I are included.

Moreover, Hatakeyama [1966] found that there is a new phase between signal and noise zone on the records of the reflection method of seismic exploration, and he concluded that this new phase is the refracted SV waves. This newly revealed phase is also included in the wave group II. Therefore it is necessary to separate the wave group II into above two parts (surface wave group and refracted P or S waves).

The wave group II corresponds to $\left\{\frac{\overline{SS}}{ES}\right\}$ type if adopting Sato's [1953] classification concerned with the amplitude distribution of surface waves in a solid layer over solid half space[1]. But this type of waves can not satisfy the definition of normal mode Rayleigh waves, therefore, the main part of the wave group II was supposed to be a kind of bodily wave, leaking mode in the solid-solid layer or wave analogous to P-P mode in the liquid-liquid layer.

In response to the demand for examining the above mentioned problems, we have carried out the experiments on the seismic waves generated by small explosions using a somewhat longer spread than the previous ones.

2. Experimental procedures and sub-surface structure at the experimental site

The experiments were carried out by the "Seismic Exploration Group of Japan" in cooperation with the "Section of Geophysical Prospecting, Japan Petroleum Exploration Company" in 1965 at Shirane City, Niigata Pref.

The instruments employed in our experiments are those used in usual seismic prospectings. The seismometer is of the electromagnetic type with a vertical component, the natural frequency being 4.5 cps; 30 seismometers were used; 21 of them were set up on the ground every 5 m on an array (horizontal spread), remaining 9 were set up at various depths (0 m, 2 m, 5 m, 10

[1] The notation $\left\{\frac{\overline{SS}}{ES}\right\}$ means that amplitude distribution has sinusoidal forms in the surface layer in both its compressional part and distortional part, and further means that in the solid half space the compressional part is exponential and the distortional part is sinusoidal.

m, 15 m, 20 m, 25 m, 30 m and 40 m) into the bore-holes which had been made collectively near the base point (vertical spread). On the base point, a horizontal longitudinal component having a natural frequency of 4.5 cps was placed. Above sets are illustrated in Fig. 1. The shooting points used were the holes of 5 m in depth, their distances from the base point being 50 m, 150 m, 250 m, 350 m, 450 m, 550 m, 650 m, 750 m, 850 m and 930 m respectively. A constant dynamite charge of 500 g was fired throughout the experiment.

The sub-surface structures of the experimental field have been determined by means of the refraction method of P and SH waves, and have been reported by several authors, these results being summarized in Fig. 2.

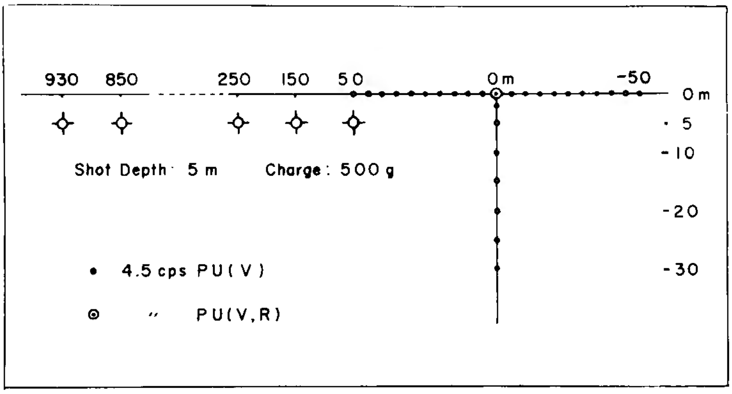

Fig. 1. Spreads of the seismometers and shooting points.

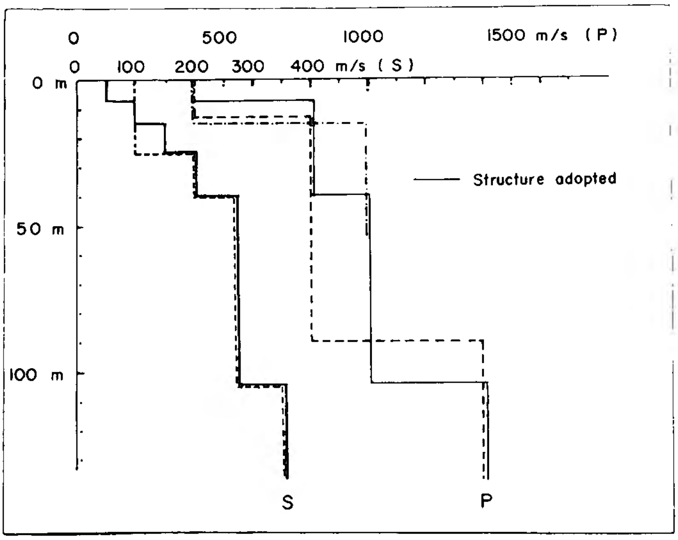

Fig. 2. Seismic profiles of P and S waves at the experimental site.

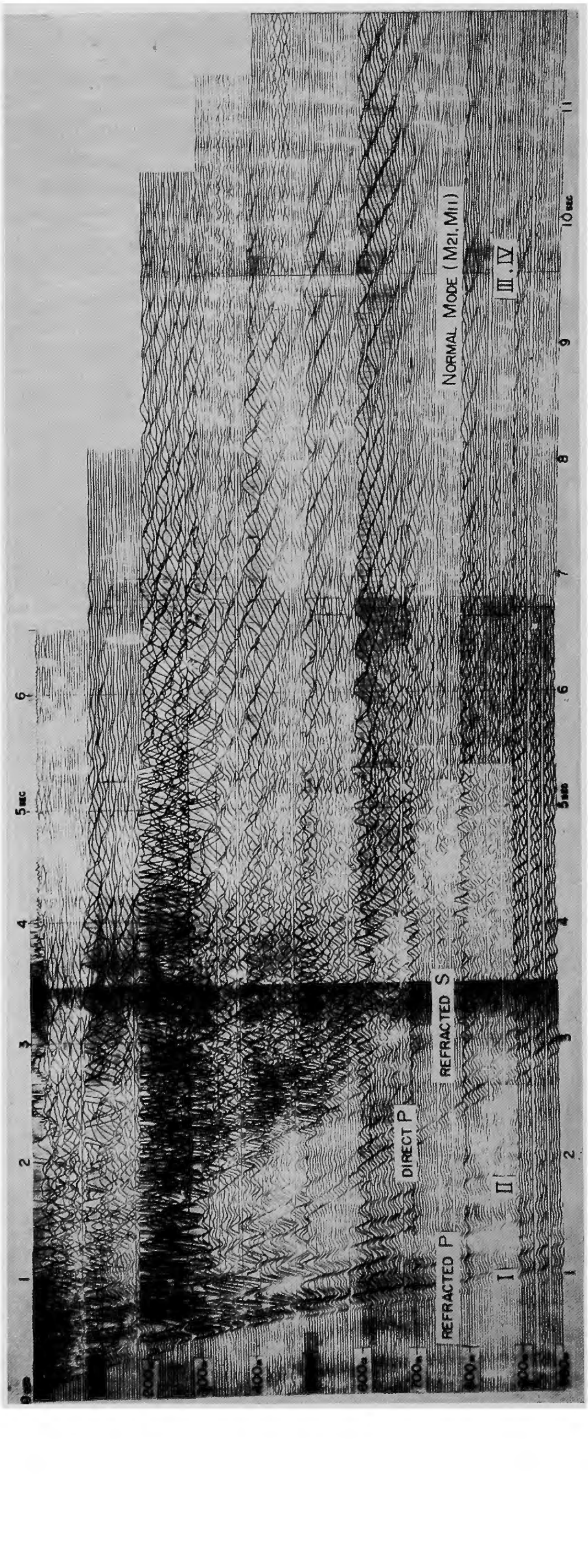

Fig. 3. Paste-up of the seismograms.

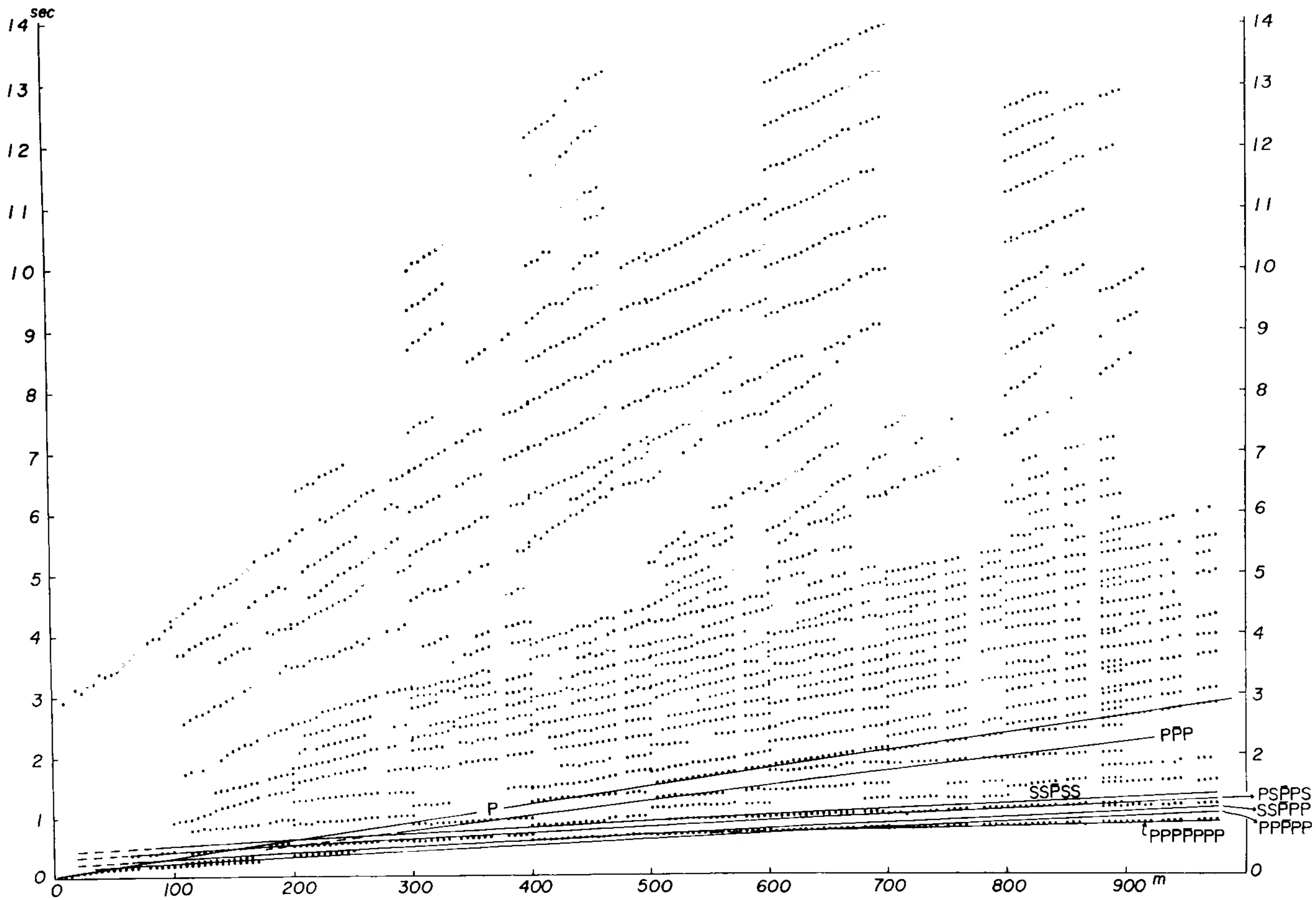

Fig. 4. Travel time plots for every peaks.

3. Analysis of seismic records

(1) *General view of the seismograms*

Array seismograms obtained from the horizontal spread have been shown in Fig. 3 and travel time plots for all peaks have been presented in Fig. 4.

From the seismograms or travel time plots it is easy to classify the observed waves into four wave groups named I, II, III and IV. And each wave group has its own characteristic period and phase velocity. The separation of wave group I from II becomes clearer beyond a distance of 500 m.

Recent investigation by Iida and Ohta [1966] says that the wave group I is the initial motion of direct or refracted P waves. According to the computation of the travel times of the various converted waves generated from the subsurface structure of this field, however, it is found that these curves coincide with any one of the travel time curves of the wave group I (See Fig. 4). Therefore, saying more accurately it is concluded that the wave group I is to be composed of the various kinds of converted waves from the interfaces under the surface.

In the wave group II the series of wavelet having 2 or 3 peaks is presented. Its phase velocity is 380–400 m/sec. and equals to the propagation velocity of the direct P wave derived by use of the refraction method. The travel time curve of the direct P wave corresponds to this wavelet's one. Therefore it is confirmed that the direct P wave mixes in the wave group II, taking the form of the series of wavelet.

Between bodily waves of group I and the direct P wave above, there exists a wave train having the long period (0.1–0.13 sec.) and high phase velocity (1000–1300 m/sec.). This wave train is the main part of the wave group II.

After the direct P wave ceasing, there is no phase notable until the onset of the noise zone, the wave groups III and IV having long periods and low velocities are appeared.

(2) *Using the rectified wave forms*

For the purpose of examining the wave groups rather clearly we modified the original waves into the so-called rectified waves. The procedure is somewhat resemble to the variable area method usually employed in the field of seismic prospecting. In Figs. 5 and 6 rectified wave forms of vertical and horizontal components have been drawn. The corresponding period has been also plotted under each wave.

As shown in Figs. 5 and 6, it is easy to discriminate the variation in amplitude or period of the wave groups. For example, the amplitude and period

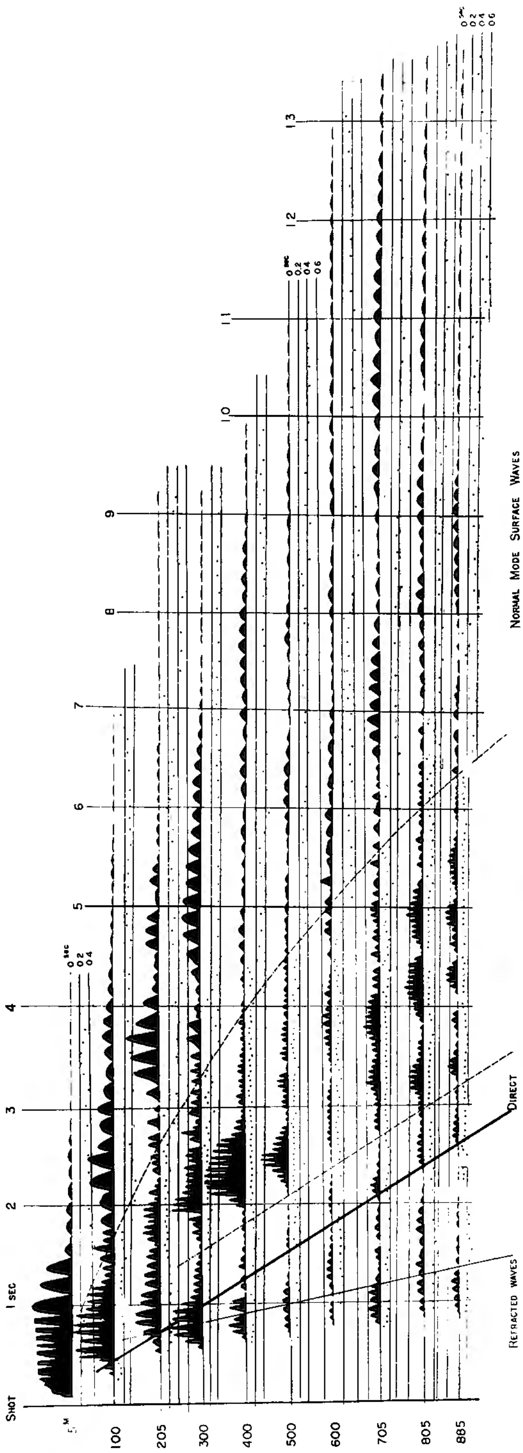

Fig. 5. Rectified wave forms of the vertical component.

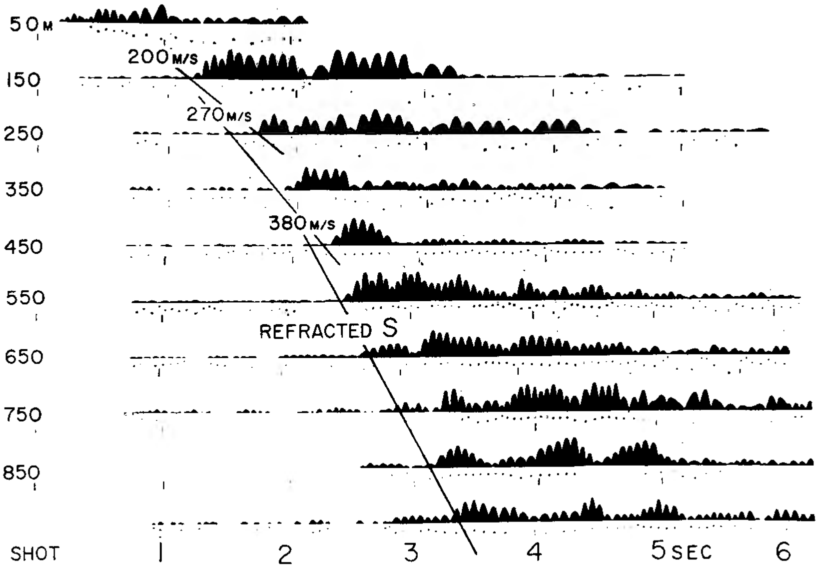

Fig. 6. Rectified wave forms of the horizontal component.

of the wave groups suddenly increased right after the dashed line (in Fig. 5) written between the wave groups II and III. Hence, the classification between the wave groups II and III is made clear by using this method. A thin line shows the threshold of the converted waves above mentioned. The initial phase of the direct P wave is shown with a thick line.

Before and after these two lines, sudden changes in amplitude and period are found. In the region bounded by the above two lines, there is a wave packet having a long period. This wave packet is the main part of the wave group II.

After the several cycles from the direct P waves, waves having a large amplitude are seen. These waves correspond to the refracted S phases. Similar result is more distinctly closed up in Fig. 6.

As shown in Fig. 6 there is not any remarkable phase in the region between the wave group I and the direct P waves, however, after the "S refracted line" remarkable phases having a large amplitude are existing. The lines binding the initial phases of this predominant wave groups coincide with the travel time curves of the refracted S phase which have been estimated from the prescribed structure. For this reason, it is likely concluded that before this lines there is the region essentially concerned with the P wave only, while, after the S-lines there is the region concerning with both the P and S waves.

From the analysis described above, it is found that the wave group I is to be composed of the various kinds of converted waves from the interfaces under

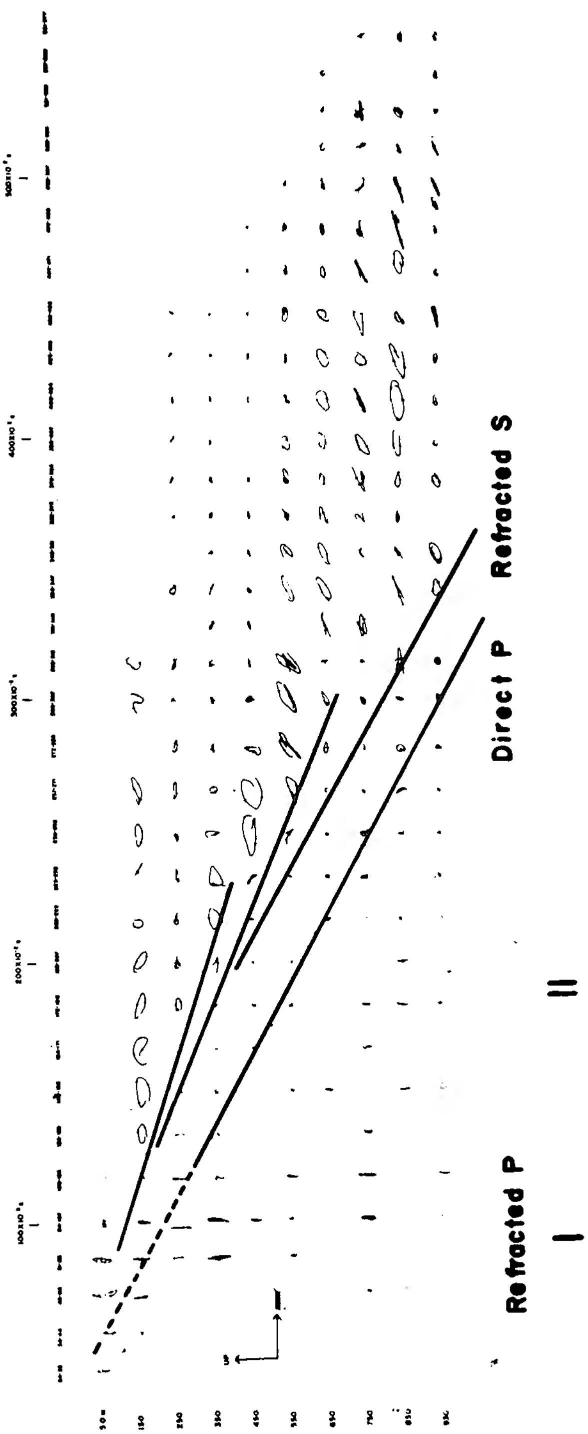

Fig. 7. Particle motions of the wave groups and their general view.

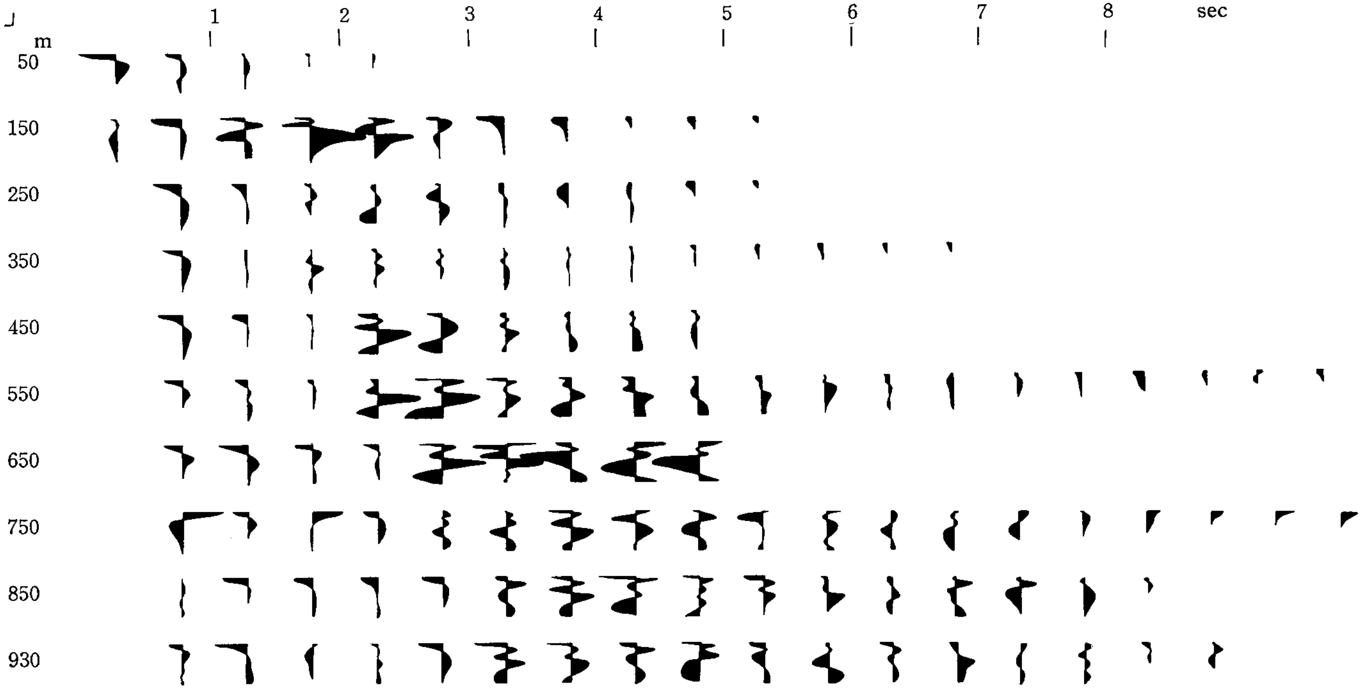

Fig. 8. Amplitude distributions in depth, arranged in order of times and distances.

the surface, while the wave group II includes the surface wave having the long period and high phase velocity, the wavelet of the direct P waves and the refracted S waves.

4. Particle motion and amplitude distribution with depth

The particle motions related to "up and away" and the amplitude distributions with depth have been drawn in Figs. 7 and 8. In both figures pictures of trajectories have been arranged in order of times and distances.

As shown in Fig. 7 the main part of the wave group II is of predominant vertical motions, direct P waves of small circular motions and refracted S waves of elliptical motions. The wave groups III and IV have been omitted in the figure, since similar problems had been discussed by many authors and hence well known.

The figures of amplitude distribution with depth (Fig. 8) of the main part of the wave group II show that they have a loop on the surface, one node in the layer and their amplitudes decrease with depth. The S phase's are very complicated and the wave groups III and IV's show the form which have been presumed by the theory of normal mode Rayleigh waves in the layered structure.

5. Phase and group velocities and amplitude-period relations of the wave groups III, IV

On the wave groups III and IV the comparative investigations were made both theoretical and experimental by several authors (Ohta [1964], Okada [1965], etc). And satisfactory conclusions, both qualitatively and quantitatively, were obtained by regarding the wave group III as M_{21} waves and the wave group IV as M_{11} waves respectively (Iida and Ohta [1966]).

In this section similar investigations have been made. The phase

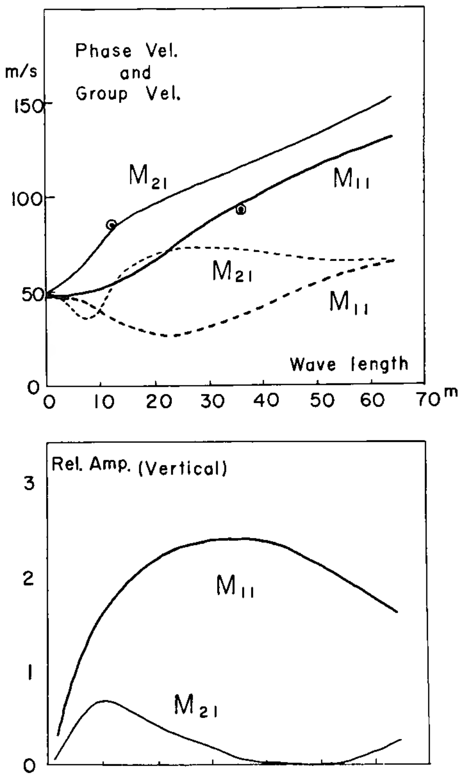

Fig. 9. Theoretical dispersion curves and amplitude-period relations; their comparison to the observation.

and group velocities and amplitude-period relation of M_{21} and M_{11} waves have been computed theoretically by using the data of this experiment. These results have been shown in Fig. 9. Phase velocities of the predominant phases in the wave group III or IV have been also plotted in Fig. 9. The observed results show a good agreement with the theoretical one.

6. Proposal in connection with the mechanism of the wave group II

As yet few investigations have been made in connection with the generation and propagation mechanism of the wave group II, in this section an attempt is made to propose the explanation of this problems based upon the results derived from the experiments which have been continuously carried out at various places every year since 1953 by the Seismic Exploration Group of Japan.

The phase velocities of the wave groups II, III or IV and seismic profiles both for P and SH waves have been always obtained throughout the above experiments. When the stratified double layer is taken into consideration as a representative of the experimental sites, the following relations are generally deduced except for 1958's experimental site

$$V_p > C_{II} \geqq V_p' \gg V_s \geqq C_{III} > C_{IV} \doteqdot V_s',$$

where C_{II}, C_{III} and C_{IV} are the phase velocities of the wave groups II, III and IV, respectively. V_p, V_s, V_p' and V_s' are the propagation velocities of P and SH waves of lower and upper layers. Thus the wave group II has the wave type $\left[\frac{SS}{ES}\right]$, while the wave group III or IV has $\left[\frac{ES}{EE}\right]$ or $\left[\frac{EE}{EE}\right]$ type. Hence, the wave group III or IV satisfies the definition of the normal mode Rayleigh waves, but the wave group II does not satisfy.

When our consideration is restricted to P wave only, the characteristics of the main part of the wave group II bear resemblances to the normal mode wave in the liquid-liquid layers. Namely, its phase velocity is lying between the velocities of P waves in the surface layer and half space, and its amplitude in depth shows the distribution having a loop on the surface, one node in the layer and its amplitude decreases exponentially with depth.

On the other hand, the Poisson's ratios of our experimental fields are almost 0.5, thus the medium under consideration can be approximated with those in the liquid state. Therefore, it is quite possible to propose that in the wave group II there is a surface wave just equivalent to the normal mode wave in the liquid-liquid layers. The investigation of this possibility will be made in future.

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