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Analyses of Seismic Waves Generated by Small Explosions

— Experiment at Wakino-machi, Niigata Prefecture —

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Abstract

In order to study the seismic waves generated by small explosions, a field experiment was carried out.

In this experiment, a hole shot method was adopted specially for studying the generation of several kinds of waves. The records thus obtained are shown in Figs. 2,5,6 and 7.

Each of the refraction waves composed of P or S waves or waves which contained both was distinctly observed when the shots were fired at the depth favorable to the appearance of them.

The existence of four types of single reflection waves to be considered on the given structure was also confirmed on the records. The P_1S_1 phase among them, being observed most remarkably, seems as though it contributes most effectively to the generation of wave group II which is considered as a kind of surface wave group.

Surface waves obtained in this experiment were not identified with any modes of dispersive RAYLEIGH waves. It was found, however, that an S wave energy was the most important element in the generation and the predominance of the waves.

1. Introduction

During the past several years studies on seismic waves from explosions have been carried out by members of the Seismic Exploration Group of Japan.

In the experiments, three remarkable surface wave groups have been generally observed. The analyses of these wave groups by TAZIME[1),2)], have been published showing that the waves might be classified respectively as three different modes of dispersive RAYLEIGH waves.

For the past five or six years, in order to make clear the physical properties of the waves, the investigation concerning the propagation of these waves has been both theoretically and experimentally carried out by many members of this group. However, the relation between the structure or nature of the earth and the mechanism of generation of waves has not been completely interpreted; it has not yet been made clear why these wave groups alone have been recorded remarkably and what modes of dispersive RAYLEIGH waves would be observed in the field experiments. This is all true because the actual conditions are more complex than those assumed in the theoretical treatments, of which results are too insufficient to be widely applied for interpreting the observed data and besides, in practice, it is difficult even to obtain experimentally the required data for the theoretical analyses of this problem.

The above problem of physical properties has remained uncertain because there have been very few experiments designed to investigate systematically the observed surface waves.

The present experiment was carried out in cooperation with Hiromu SIMA, Matsushiro Seismological Observatory.

The purpose of the experiment was to study the surface waves generated by small explosions.

The investigation concerning several wave groups carried on as here described has been made also by SIMA and already described in his paper[3]. But his investigation, inferring constructions of observed wave groups, has not yet been authenticated.

Many authors have respectively various viewpoints on the interpretation of observed data.

The present author will again investigate the same data as those used by SIMA, hoping to find some more definite explanation of seismic waves generated by small explosions, independent of SIMA's description. Therefore, on treatment of data, some parts of the present paper will overlap with SIMA's and other parts may contradict his opinions. But, it is not the present aim to discuss the conflict in interpretations, although it must be settled somewhere.

The experiment was made in summer 1959 on the ground of the Wakinomachi Primary School in Niigata Prefecture.

In this paper, the discussion is confined largely to consideration of the propagation of P and S waves, specially to see how these waves contribute to the generation and propagation of surface waves.

2. Classification of observed wave groups

The vertical component of ground motion was recorded by twelve geophones disposed every 1 m along a straight line about 70 m long. In this problem, it is necessary to observe the horizontal component too, but, in this experiment, that could not be carried out.

The instrumental system adopted here is similar to that used in refraction survey. Frequency-response curve of the system, including the geophone, amplifier and galvanometer, is shown in Fig. 1.

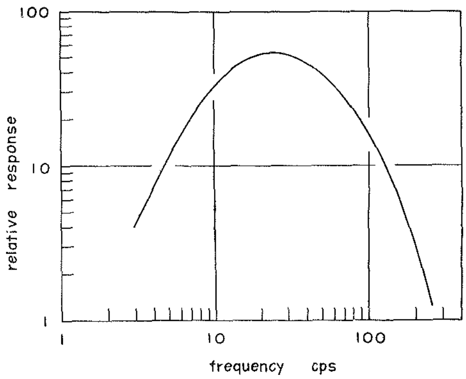


Fig. 1. Frequency-response curve for overall system, including geophone, amplifier and galvanometer.

Each spread corresponding to a single record was 11 m long. Providing shot holes are at 2 m, 10 m, 20 m, 30 m, 40 m, 50 m and 60 m distance from the nearest geophone, the dynamite explosions at depth of 1 m were observed

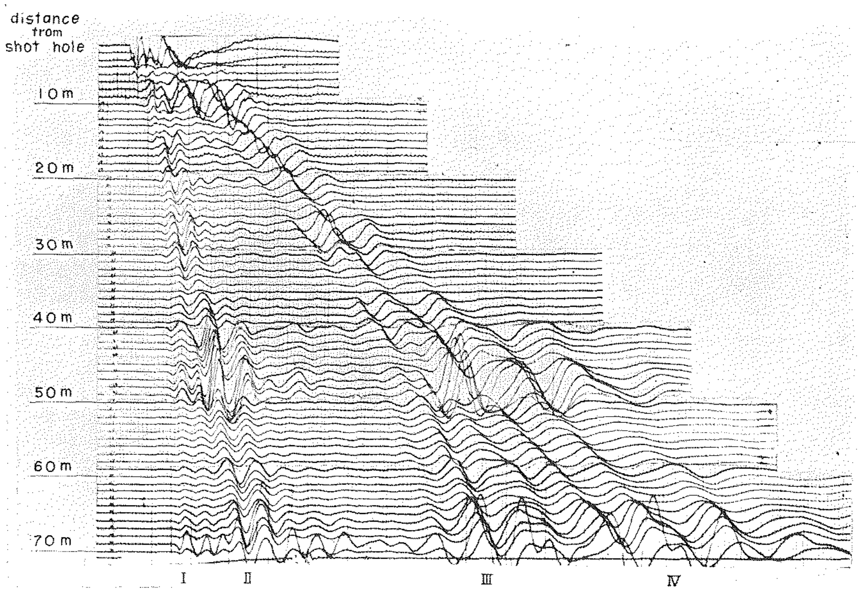
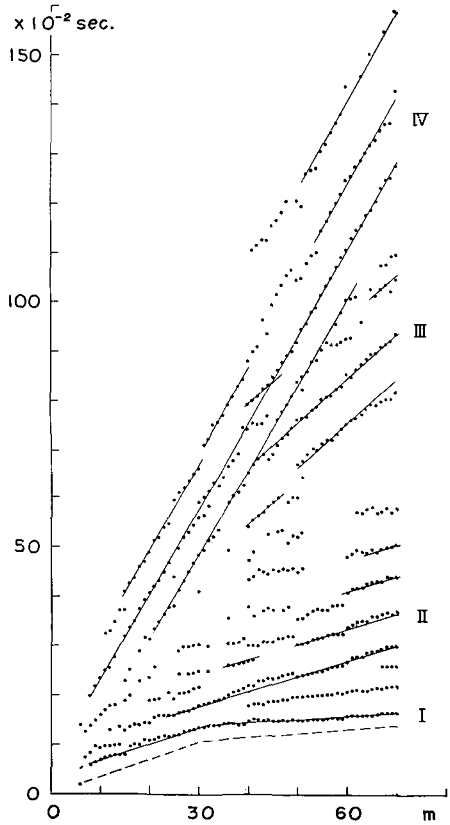


Fig. 2. Seismic records by shot whose depth is 1 m. Time marks indicate 1/100 s.

leaving the disposition of geophones unchanged.

Seismic records thus obtained are exhibited in Fig. 2, being reproduced so as to show the ground motion resulting from one shot.

Fig. 3 shows time-distance plots of all individual peaks of every record in Fig. 2, where dotted lines indicate the first arrival.



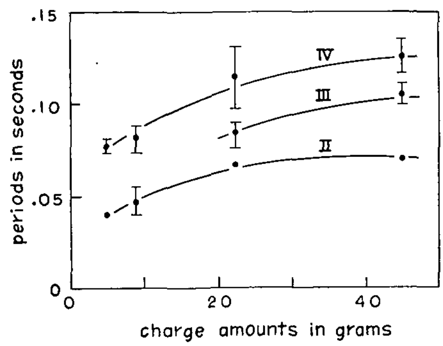


Fig. 4. Relation between periods and charge amounts.

Fig. 3. Time-distance plots of every peak, shot depth being 1 m.

Table 1.

wave group	phase velocity	period
I	3.0 and 12×10^2m/s	
II	3.8	7×10^{-2} s
III	1.2	10
IV	0.6 or 0.7	13

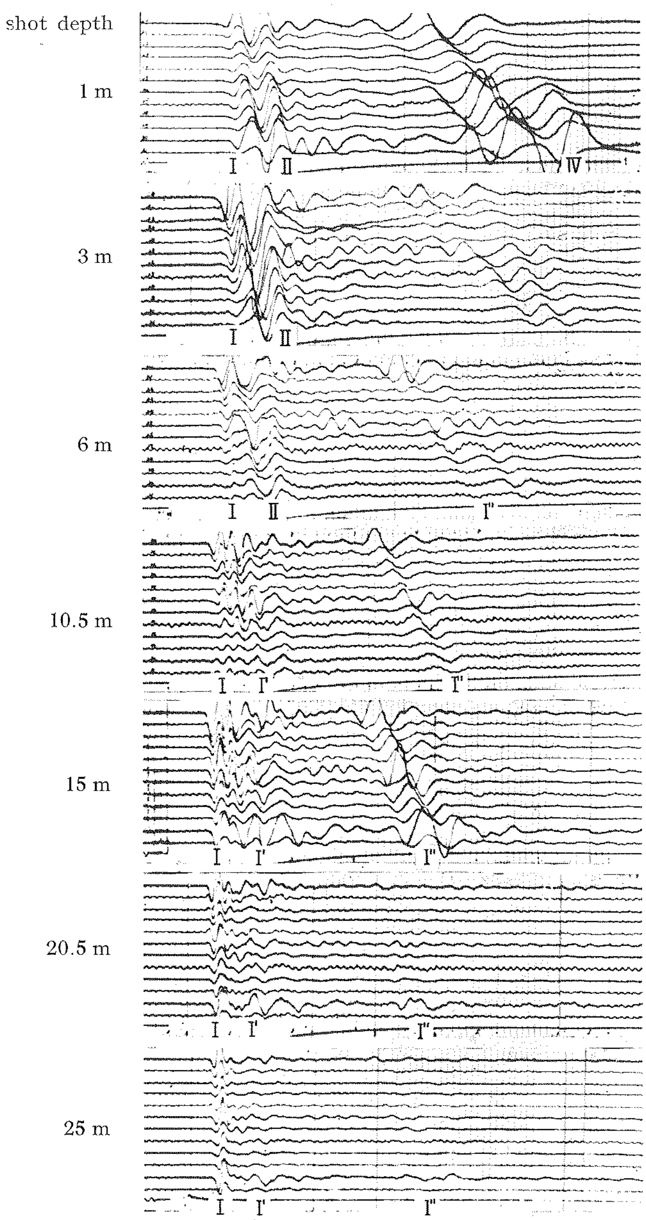


Fig. 5. Seismic records at 20 to 31 m distance from shot hole, charge amounts being 9 grs. of dynamite. Shot depths are 1, 3, 6, 10.5, 15, 20.5 and 25 m.

Several wave groups can be classified from Figs. 2 and 3, by differences of periods and phase velocities. That is similar to the events observed hitherto. The classification is presented in Table 1, where I means the first arrival and for the period of each wave group the largest one is adopted since it is generally changed by charge amounts as shown in Fig. 4.

In order to make clear the property of each wave group, a series of hole shots was made at depths of 1 m to 35 m at 20 m, 40 m and 60 m distance from the nearest geophone, by keeping the charge amounts constant in the same borehole. In this paper, the data obtained when shots are fired at 1 m to 25 m depth are adopted, specially to investigate the propagation of waves in stratified two layers. Seismic records thus obtained are exhibited in Figs. 5 to 7.

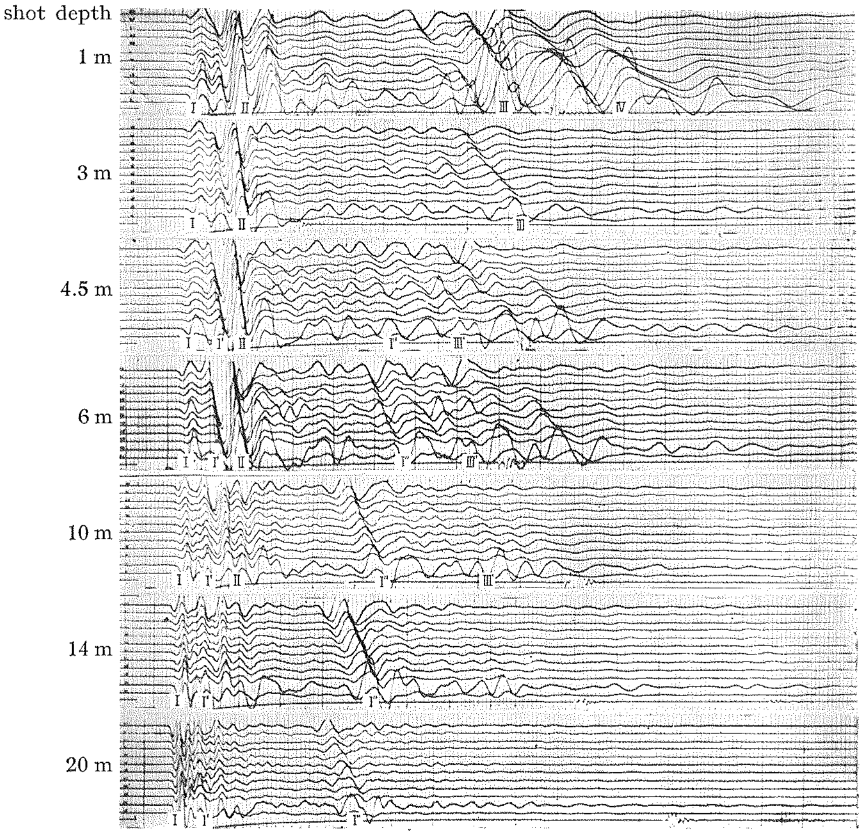


Fig. 6. Seismic records at 40 to 51 m distance from shot hole, charge amounts being 22.5grs. Shot depths are 1, 3, 4.5, 6, 10, 14 and 20 m.

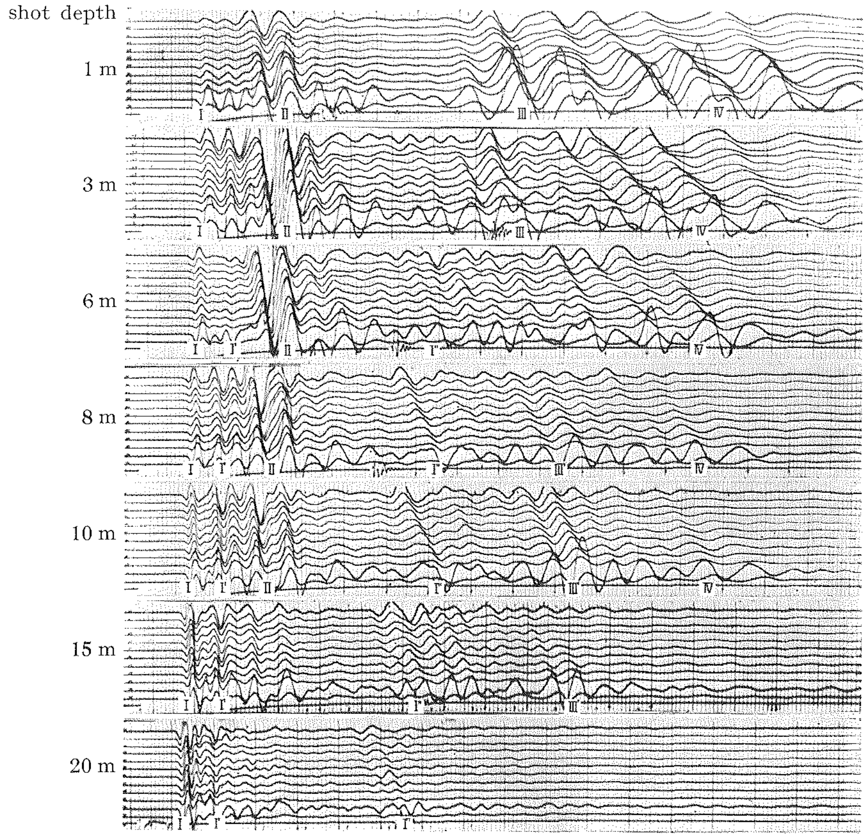


Fig. 7. Seismic records at 60 to 71 m distance from shot hole, charge amounts being 45 grs. Shot depths are 1, 3, 6, 8, 10, 15 and 20 m.

One will see in these figures that some groups, designated III and IV in Table 1, have gradually disappeared and several new wave groups, which are marked I′, I″ and III′ in Figs. 5 to 7, have appeared with increase in shot depth.

Time-distance plots for all wave peaks of every record in Figs. 5 to 7 are shown in Fig. 8, where the shot depths of 10.5 m and 14 m in these figures are treated as the depths of 10 m and 15 m respectively, as though each of the recrods were obtained from one shot.

Phase velocities and periods for new wave groups obtained from Figs. 5 to 7 or 8 are presented in Table 2.

In order to see these events more clearly, certain traces have been picked out from Figs. 5 to 7 and are illustrated in Fig. 9, being rearranged in each distance from shot hole. Since the period for each wave group is little changed, it is almost possible to follow the individual wave groups in the figure.

One will see in this figure that the time of an appearance for all of wave

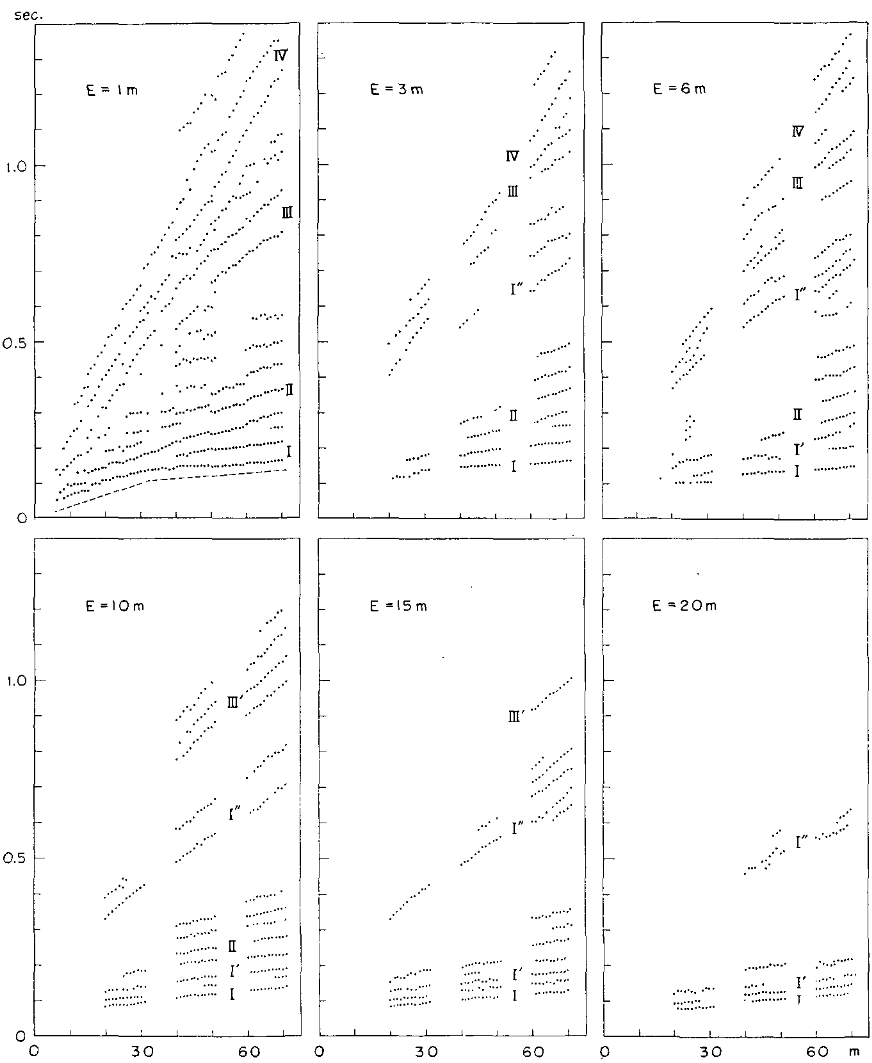


Fig. 8. Time-distance plots of every peak for various shot depths.

Table 2.

wave group	I′		I″		III′	
shot depth	phase velocity	period	phase velocity	period	phase velocity	period
3 m	1200 m/s	4.8×10^{-2}s	130 m/s	$6\sim7\times10^{-2}$s	—	—
10 m	1200～1400	4.1～4.3	130～140	6～7	100～120 m/s	7×10^{-2}s

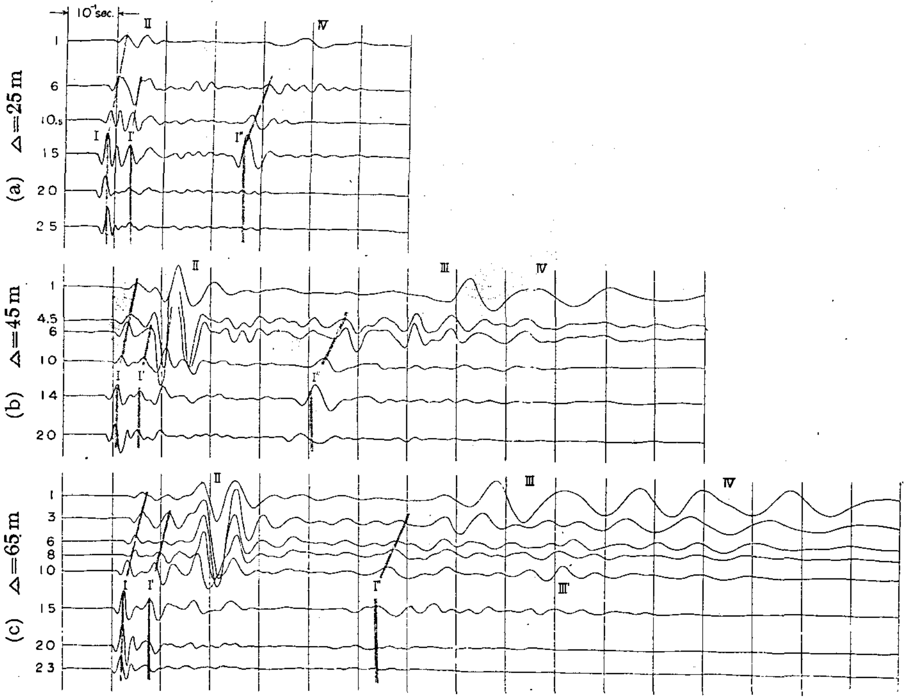


Fig. 9. (a) Seismic records at 25 m distance from shot hole.
(b) Seismic records at 45 m distance from shot hole.
(c) Seismic records at 65 m distance from shot hole.

groups I, I′ and I″ varies in the same way, which will be discussed later, and the time of that for wave groups II, III and IV is invariant with respect to the shot depth. From these facts, it is supposed that wave groups I, I′ and I″ are composed of direct or refraction waves and that wave groups II, III and IV of surface waves.

3. Variations of amplitude and period

The variation of the maximum amplitude for each wave group with shot depth was obtained from Fig. 9 as illustrated in Fig. 10. One of the important

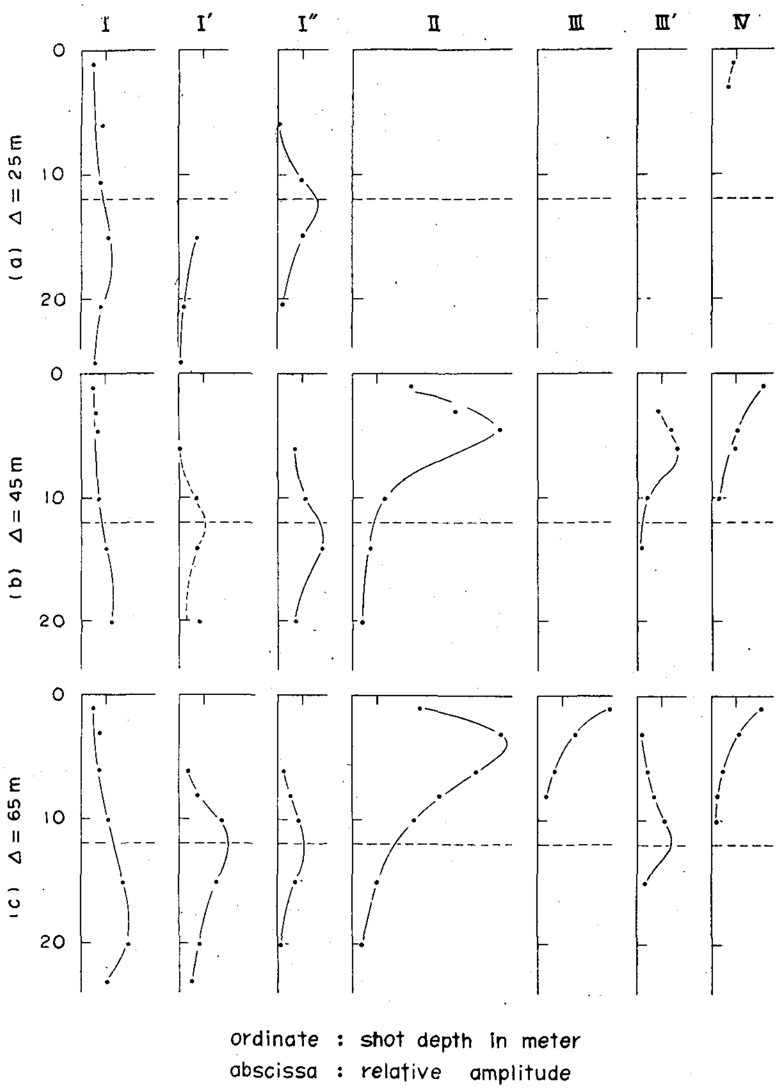


Fig. 10. (a) Amplitude variation at 25 m distance from shot hole.
(b) Amplitude variation at 45 m distance from shot hole.
(c) Amplitude variation at 65 m distance from shot hole.

facts in this figure is that wave groups I, I′, I″ and III′ are similar to each other in the variation of amplitude with shot depth and have the larger amplitudes when the shot is fired between 10 m and 20 m depth in the medium.

In the case of wave group II, the variation of the amplitude seems to be a sine type in the upper medium, but, in the lower, such an exponential type as that vanishing with increase in shot depth.

As to wave groups III and IV, the maximum amplitude decreases exponentially with shot depth.

For the variation of the period for each wave group, in wave groups I, I′ and I″, it is almost the same as shown in Fig. 11, that is, the period decreases gradually with increase in shot depth. On the other hand, the period for wave groups III and IV is strongly affected by the shot depth whereas that for wave group II is almost constant even though the shot depth is changed.

It is a noteworthy fact that each of the wave groups has an individual variation type for the period with shot depth.

The period for each wave will be probably affected by the mechanism of the source, the property of the medium and the size and amount of the charge, and, as the result, will yield effects upon the propagation of surface waves.

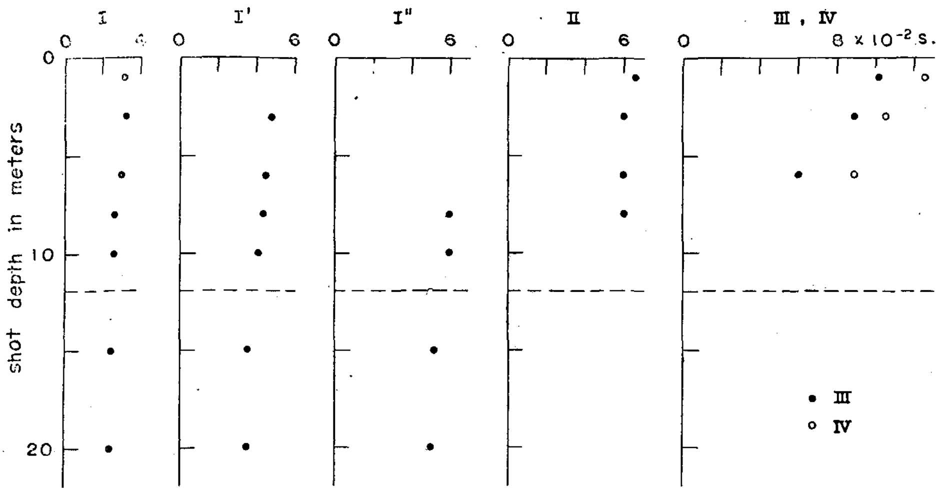


Fig. 11. Period variation for each wave group with shot depth.

In order to obtain the data for the elastic properties of the medium and the subsurface structure, refraction shootings were made on two spans as longs as 300 m at the present experimental site. However, the data thus obtained were not coincident with those from the velocity longgings which were made in boreholes down to 42 m depth. One of the data is shown in Fig. 12.

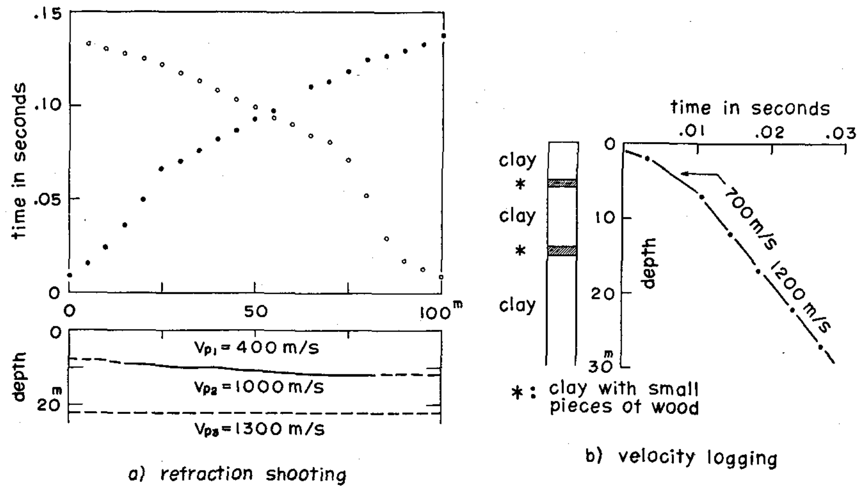


Fig. 12. Subsurface structure deduced from refraction shooting and velocity logging.

Assuming the superficial layer to be horizontal, the following results were obtained from time-distance plots of the first arrival in Fig. 3:

$$v_{p1} = 3\times10^2\,\mathrm{m/s},\ v_{p2} = 12\times10^2\,\mathrm{m/s}\ \text{and}\ H = 12\,\mathrm{m} \tag{1}$$

where v_{p1}, v_{p2} are respectively the velocities of P waves in the superficial layer and substratum and H is the thickness of the superficial layer.

The value of the thickness thus obtained is correspondent with that of the depth where wave groups I, I′ I″ and III′ have, as seen in Fig. 10, maximum amplitudes.

4. Refraction arrival

1) Wave group I

The travel time of the first break is decreased with increase in shot depth as far as about 10 m depth. That is shown in Fig. 13 which shows the relation between travel time and shot depth. This means that the first break is not caused by direct P waves but by refraction waves. Therefore, the travel time curve with shot depth must be a straight line when the shot is fired within the superficial layer, since a decrease in time $-\Delta t$ can be expressed by an increase in shot depth ΔE as

$$-\Delta t = \Delta E/(v_{p1}/\cos \widehat{P_1P_2}) \tag{2}$$

referring to Fig. 14 (a), where $\widehat{P_1P_2}$ is the critical angle concerning P waves in the superficial layer and the substratum.

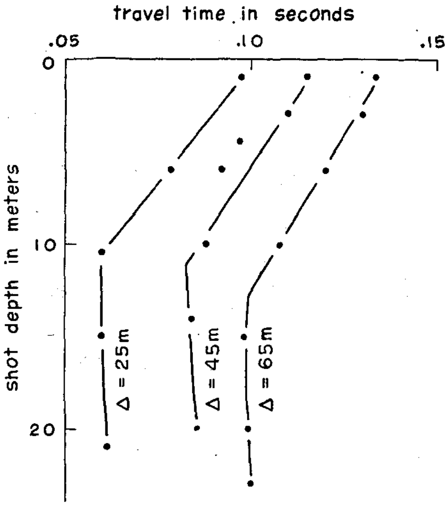


Fig. 13. Relation between travel time and shot depth. Δ indicates distance from shot hole to observation point.

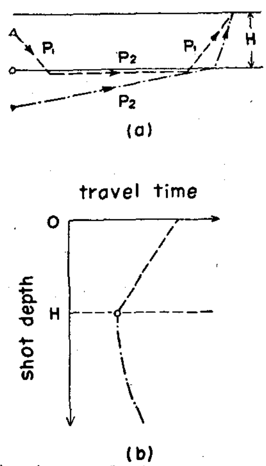


Fig. 14. (a) A model of seismic ray paths where P_1 means a wave in the superficial layer and P_2 in the substratum.
(b) Schematic relation between travel time and shot depth.

If the shot depth E becomes larger than the thickness H of the superficial layer, the travel time of the first break will be parabolically increased with shot depth. The schematic relation of Fig. 14 (b) is satisfactorily consistent with the observed relation of Fig. 13.

Accordingly, it is considered that the thickness of the superficial layer obtained at Eq. (1) is the appropriate value to explain the above events.

If the shot is fired at 10 m depth, the required travel time of the first break at 65 m distance from shot hole will be calculated by using Eq. (1) as

$$t = \frac{2}{v_{p1}} \cos \widehat{P_1P_2} + \frac{65}{v_{p2}} + \frac{12}{v_{p1}} \cos \widehat{P_1P_2} = 10.0 \times 10^{-2}\,\mathrm{s} \tag{3}$$

which is nearly equal to the observed value 10.8×10^{-2} s. Such small differences as produced here are considered to be negligible, because the velocity of P waves is not always constant in actuality throughout the superficial layer.

Thus, wave group I can be recognized P_1 or $P_1P_2P_1$ waves when $E < H$

and as P_2P_1 waves when $E \geqq H$, where $P_1P_2P_1$ waves designated here mean the waves which are propagated along the path of the dotted line and P_2P_1 waves of the chain line shown in Fig. 14(a).

The nearer the location of shot point on the interface, the larger the energy which should be delivered to refraction waves $P_1P_2P_1$. On the other hand, if the shot is fired under the interface, the energy of the P_2P_1 waves coming up to the surface of the earth becomes smaller with increase in shot depth. Therefore, if the amplitude observed at the surface depends only on the intensity of the wave energy, the variation of the amplitude with shot depth must show its maximum on the interface. However, the amplitude at the surface will depend not only on the intensity of the energy but also on the emergent angle of the waves at the observation point. That is, the smaller the emergent angle, the larger the vertical component of the amplitude of P waves.

As to refraction waves $P_1P_2P_1$, since the emergent angle must be constant even though the shot depth increases within the superficial layer, the variation of the amplitude must depend only on the energy intensity. Therefore, the maximum amplitude should be uniformly increased with shot depth.

On the other hand, when the shot is fired within the substratum, the amplitude of the P_2P_1 waves must depend on both the wave energy and the emergent angle. With increase in shot depth within the sbustratum, the energy intensity decreases, but the emergent angle becomes small so as to contribute to the development of the vertical amplitude. Therefore, the resultant amplitude variation must have its maximum when the shot is fired not on the interface but within the substratum as shown in Fig. 10.

2) Wave group I′

Phase velocity of this group is almost the same as that of wave group I. As found in Fig. 8, travel time plots for peaks of wave group I′ are parallel to those for wave group I. Therefore, the waves for wave group I′ are considered again to be some kind of refraction waves which are propagated with P wave velocity in the substratum.

Taking account of the travel time difference of the first breaks I and the remarkable troughs designated above as wave group I′, one finds that wave group I′ should be taken as $P_1P_2S_1$ waves, since the travel time difference considered here is almost invariant to the shot depth as presented in Table 3. $P_1P_2S_1$ waves designated above mean the waves which start as P waves with the velocity v_{p1} from the source in the superficial layer, strike the interface at

Table 3. (unit: 10^{-2} s)

Δ \ E	1 m	3 m	6 m	8 m	10 m
60m	11.0	11.0	10.2	9.8	9.8
61	10.9	11.0	10.0	9.8	9.8
62	10.6	10.9	10.1	9.4	9.8
63	10.4	11.0	10.1	9.4	9.8
64	10.2	10.9	10.1	9.3	9.7
65	10.2	10.8	10.2	—	9.5
66	10.3	10.9	9.8	9.5	9.6
67	10.1	10.7	9.8	9.4	9.8
68	10.3	10.7	10.0	9.4	9.7
69	10.2	10.5	9.5	9.4	9.5
70	10.4	—	9.8	—	—
71	10.1	10.6	9.3	9.3	9.3
mean value	10.4	10.8	9.9	9.5	9.7

the critical angle, travel close to it as P waves with v_{p2} in the substratum and are refracted upward as S waves as velocity v_{s1} in the superficial layer.

If the arrival time difference between one $P_1P_2P_1$ wave and another $P_1P_2S_1$ wave is given, by using Eq. (1), the S wave velocity is essentially calculated as

$$\Delta t = \frac{H}{v_{s1}} \cos \widehat{\mathrm{S_1P_2}} - \frac{H}{v_{p1}} \cos \widehat{\mathrm{P_1P_2}} \tag{4}$$

where Δt is the arrival time difference and $\widehat{\mathrm{S_1P_2}}$ is the critical angle concerning the S wave in the superficial layer and the P wave in the substratum.

If the travel time difference ($\approx 10\times 10^{-2}$ s) obtained from Table 3 instead of the arrival time difference Δt is used in Eq. (4), at least, the lower limit of the S wave velocity in the superficial layer must result from calculation. The value thus obtained is about 0.9×10^2m/s. Therefore, the real value of the S wave velocity must be larger than that value.

Fortunately, the travel time for the break of wave group I′ at 65 m distance from shot hole could be obtained as 17×10^{-2}s. If this value is equated as

$$t = \frac{2}{v_{p1}} \cos \widehat{\mathrm{P_1P_2}} + \frac{65}{v_{p2}} + \frac{12}{v_{s1}} \cos \widehat{\mathrm{S_1P_2}} = 17\times 10^{-2}. \tag{5}$$

then, since the values of v_{p1} and v_{p2} are already known, the S wave velocity in the superficial layer can be obtained. The result thus calculated is

$$v_{s1} = 1.1 \times 10^2 \text{ m/s} \tag{6}$$

which is, of course, identical with the value calculated by using Eq. (4).

On the other hand, the S wave velocity very near the surface has been obtained as

$$v_s = 70\,\mathrm{m/s} \tag{6'}$$

from other experiments[4] at the same site on the propagation of SH waves. However, this value seems to be limited to the vicinity of the surface.

For the case of a shot in the substratum, the phase P_2S_1 becomes more clear on the records as is to be seen in Fig. 7.

The amplitude variation of wave group I′ together with the P_2S_1 phase is shown in Fig. 10. The maximum occurs when the shot is fired near the interface, because the amplitude of the vertical component of the S wave decreases, contrary to that of the P wave, as the emergent angle becomes smaller.

3) Wave group I″

The phase velocity of this group can be estimated from Fig. 8 as 1.4×10^2m/s. The amplitude variation shown in Fig. 10 is similar to that of wave group I′. Therefore, wave group I″ may generally be taken as $S_1S_2S_1$ waves when $E<H$ and as S_2S_1 waves when $E\geqq H$, by considering that this wave group is slow in appearance after the explosion. $S_1S_2S_1$ waves designated here mean the waves which start as S waves with the velocity v_{s1} from the source in the superficial layer, strike the interface at the critical angle, travel close to it as S waves with v_{s2} in the substratum and are refracted upward as S waves in the superficial layer.

If wave group I″ is taken as $S_1S_2S_1$ waves, the required S wave velocity in the substratum can be estimated. When the shot is fired at 10 m depth, the observed travel time of the break at 65 m distance from shot hole is about 60×10^{-2}s, which will be equated as

$$60\times 10^{-2} = \frac{2}{v_{s1}} \cos \widehat{\mathrm{S_1S_2}} + \frac{65}{v_{s2}} + \frac{12}{v_{s1}} \cos \widehat{\mathrm{S_1S_2}}$$

where $\widehat{\mathrm{S_1S_2}}$ is the critical angle concerning S waves in the superficial layer and the substratum, then one has

$$v_{s2} = 1.3\, v_{s1} = 1.4\times 10^2\,\mathrm{m/s} \tag{7}$$

which coincides with the phase velocity of this wave group.

For S_2S_1 phase, the required travel time of the break can be calculated by means of Eqs. (6) and (7). Some examples thus calculated are presented in Table 4 together with the observed values, resulting in satisfactorily coincidence. The above identification of wave group I″ has been checked and justified by these results.

Table 4.

distance from shot hole	shot depth	calculated travel time	observed travel time
60 m	15 m	53.2×10^{-2}s	53.0×10^{-2}s
	20	53.7	54.0
	23	53.9	54.2
70	15	56.6	55.8
	20	57.3	56.5
	23	57.5	57.0

Use being made of the P and S wave velocities, which are obtained from Eqs. (1), (6) (6′) and (7), in the superficial layer and the substratum, the Poisson's ratio in each of the media has been obtained as follows:

$$\left.\begin{array}{ll} \text{near the surface:} & 0.47 \\ \text{in the layer:} & 0.44 \\ \text{in the substratum:} & 0.49 \end{array}\right\} \qquad (8)$$

4) Other wave groups

For stratified two layers, there are nine wave groups to be considered, excepting direct and reflection waves. The schematic ray paths for these wave groups are shown in Fig. 15.

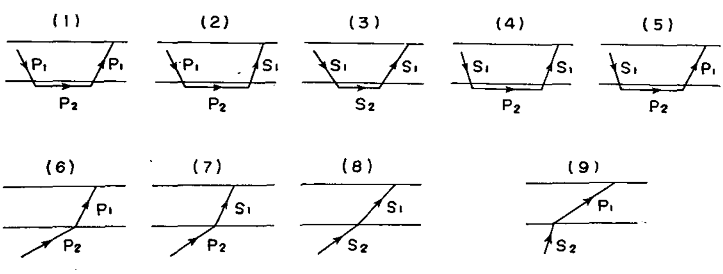


Fig. 15. Schematic ray paths to be considered for stratified two layers obtained by Eq. (1).

The waves for cases (1) and (6) have been designated as wave group I, those for cases (2) and (7) as wave group I′ and those for cases (3) and (8) as wave group I″.

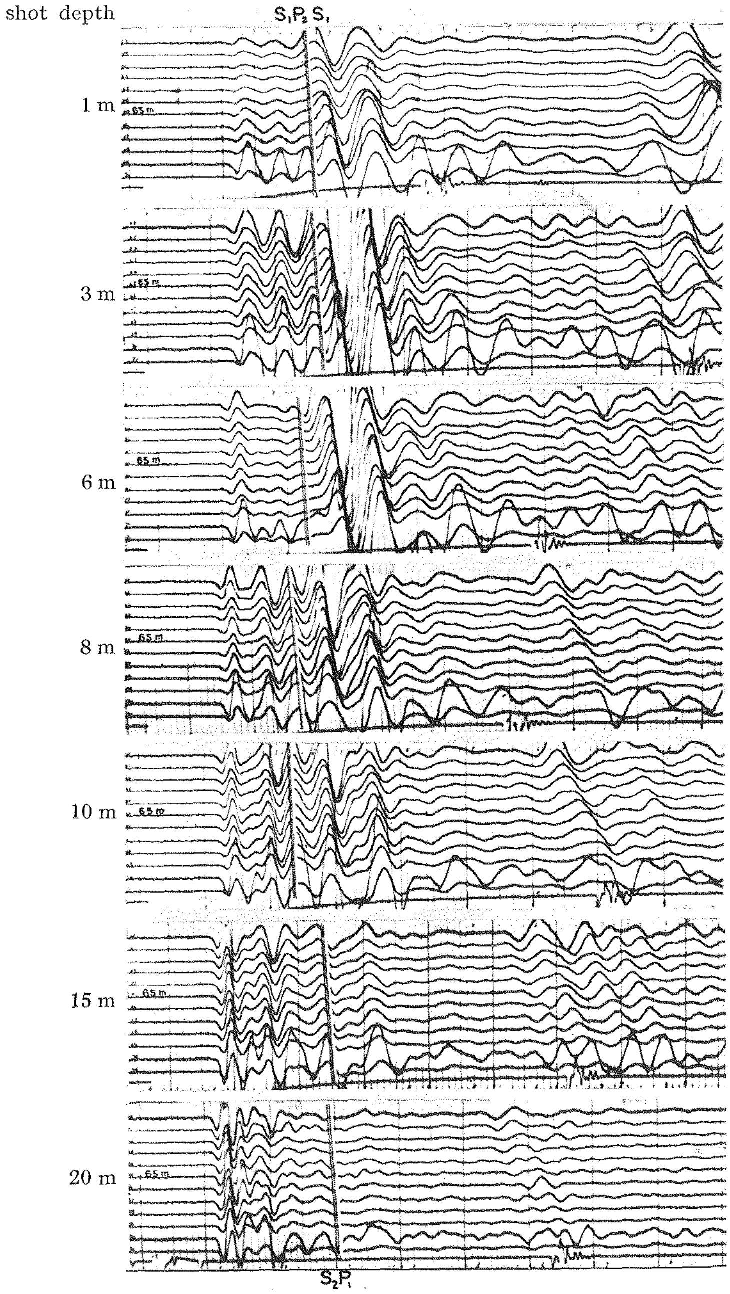


Fig. 16. Observed waves under consideration and their required travel time lines for cases (4) and (9) in Fig. 15.

The waves for these cases have been fairly well observed as described above, however, it is difficult to point out exactly the designation for other cases on the records.

In order to see whether these other waves could be observed in this experiment, the required travel time for each of these waves has been calculated and the result compared with the observed data.

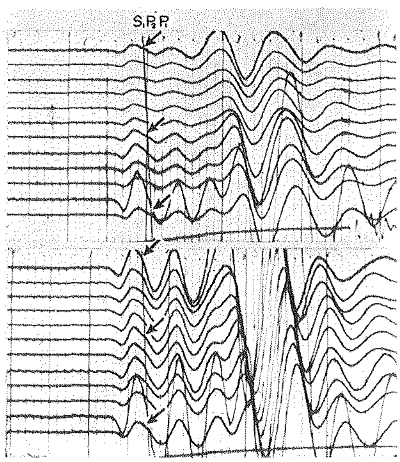
For case (4), the required travel time for the several shot depths and distances from the shot hole have been calculated with the observed values. The results are drawn on the records at 1 m to 10 m shot depth in solid lines as shown in Fig. 16.

As seen in this figure, when the shot point is 3 m deep, the waves for case (4) are not clearly found until the distance of 65 m from the shot hole, since the disturbance of wave group II has already reached the point when the waves arrive. But, with increase in the distance over 65 m, case (4) becomes gradually isolated from wave group II.

On the other hand, when the shots are fired at 6 m and 8 m depth, the waves for case (4) are observed clearly since they are not disturbed by wave group II, as shown in Fig. 16.

For case (5), the waves must arrive at nearly the same time as wave group I reaches the point concerned, when the shot is fired near the interface. The required travel time of the break for the waves of case (5) has been calculated. Thus, it is found on some traces in records that its time corresponds fairly well

shot depth



1 m

3 m

Fig. 17. Required travel time line of the break for the wave of case (5) and time of disturbed part in the wave of group I.

with a time of a disturbed part in the waves of group I, as indicated with arrows in Fig. 17. This event is more remarkable, specially when the shot depths are 1 m and 3 m.

For case (9), the travel time to be required for S_2P_1 waves has been calculated. The results are drawn on the records at 15 m and 20 m shot depth in Fig. 16 in solid lines, which are in good accord with the remarkable phase observed when the shot is fired at 15 m depth.

The amplitude of the waves of case (9) is abruptly diminished with increase in shot depth. The greater the shot depth, the larger the emergent angle for the waves, therefore, the amplitude may diminish with increasing the shot depth.

5) Reflection waves

There may be four types for single reflection waves to be considered in the case of stratified two layers. Namely, they are P_1P_1, S_1P_1, P_1S_1 and S_1S_1, written in order of their arrival. The schematic ray paths for these single reflection waves are shown in Fig. 18.

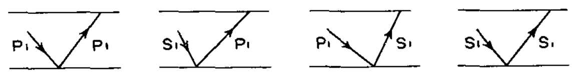


Fig. 18. Schematic ray paths for single reflection waves.

In order to see whether these waves have been recorded in this experiment, the required travel time of the waves for each type on Fig. 18 has been calculated. The results are drawn as solid lines with attached respective marks on the records in Fig. 19.

As found in this figure, some phases obtained from the calculation do not coincide with remarkable phases observed when shots are fired at 1 m and 3 m depth.

For S_1P_1 and P_1S_1 phases, the waves have not appeared as isolated ones but appeared just as the same instant as wave group II, when the shot depths have been 1 m, 3 m and 6 m, respectively.

The generation of wave group II should be affected by these waves, but, in this case, that has not been verified.

The time of appearance of these phases is gradually changed with shot depth as might be expected, although that for wave group II is scarcely changed. Therefore, these phases must separate from wave group II as shot depth is changed.

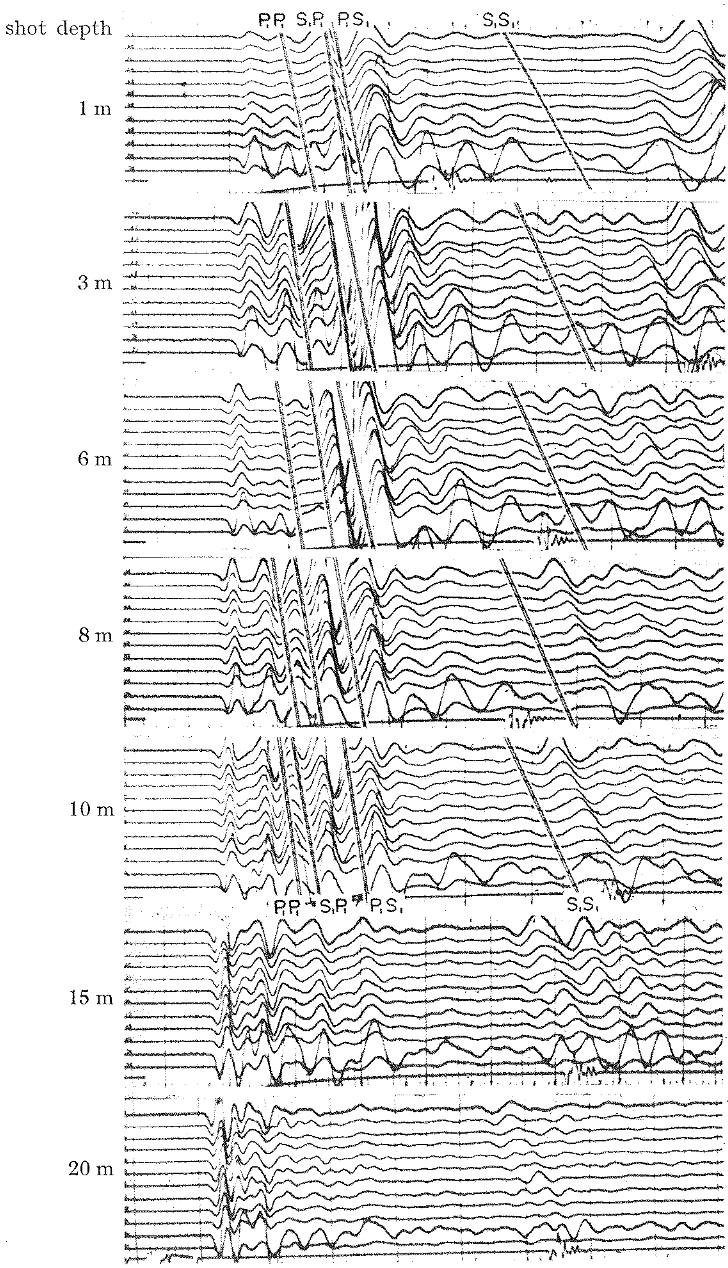


Fig. 19. Required travel time lines for single reflection waves.

When the shot depth is 8 m, P_1S_1 phase in some observation points corresponds to disturbed parts of waves which are isolatedly recorded near the time 35×10^{-2}s. When the shot depth is 10 m, P_1S_1 phase is completely coincident with the isolated phase which is recorded near that time.

The horizontal component of P_1S_1 phase has been observed and discussed in more detail in the paper by RICKER and LYNN.[5)]

For P_1P_1 phase, the travel time for some observation points is correspondent with that of the disturbed part of the waves of group I when the shot is fired at 6 m or 8 m depth. However, in this experiment, it was found that this phase could not be clearly observed.

For S_1S_1 phase, the waves must follow wave group I″ which has been taken as $S_1S_2S_1$ waves. For a region between 60 m and 70 m distance from shot hole, the phase velocity for S_1S_1 waves is almost as great as that for wave group I″. Therefore, it is considered to be caused by the coincidence in phases for S_1S_1 waves and wave group I″ that wave group I″ has been strongly recorded within the range of 60 m and 70 m distance from shot hole when the shot has been fired at 8 m or 10 m depth.

Accordingly, it is concluded that the reflection waves which can be distinctly observed represents not always P_1P_1 phase, but P_1S_1 or S_1S_1 phase. Dependent upon circumstances, the S_1P_1 phase may be observed more strikingly as reflection waves.

It was found in this experiment that the shot depth of 8 m or 10 m was favorable for observation of the reflection waves specially P_1S_1 waves at the Wakino-machi site.

5. Surface waves

1) Wave group II

Waves belonging to wave group II, which have been observed most strongly in this experiment, are identified as surface waves which are probably some mode of the dispersive RAYLEIGH waves, since the time of its appearance is invariant with respect to the shot depth, as shown in Fig. 9, and the variation of the maximum amplitude for wave group II is not similar to that for the refraction wave group.

On the appearance of wave group II when the shot is fired at 1 m depth, the waves for this group can not be seen clearly since the direct P waves are stronger near the shot hole, but wave group II becomes distinguishable at about 40 m distance from the shot hole, where the refraction P waves appear earlier than wave group II, and the predominance in amplitude is gradually transferred to a later phase with the further increase in the distance from the shot hole.

A dispersive characteristic of wave group II is found in this event. Accordingly, wave group II may be distinguished from the refraction wave groups, but it is difficult to identify this wave group with some mode of dispersive RAYLEIGH waves from the results observed as above.

The phase velocity of wave group II is estimated as 380 m/s from the slope of the time-distance curve in Fig. 3, however, it is varied a little with shot depth; that is, it being difficult to identify this wave group because of the distortion of the wave shape, the phase velocity seems to be increased as the depth of shot becomes larger than 8 m.

2) Wave group IV

This wave group is taken to be a surface wave group since the time of its appearance is almost invariant even though the shot depth is changed.

The variation of the maximum amplitude is, differing from that of wave group II, decreased exponentially with shot depth as might be expected in the theory of RAYLEIGH wave propagation in a semi-infinite medium.

The variation of maximum amplitude at a point 65 m distance from shot

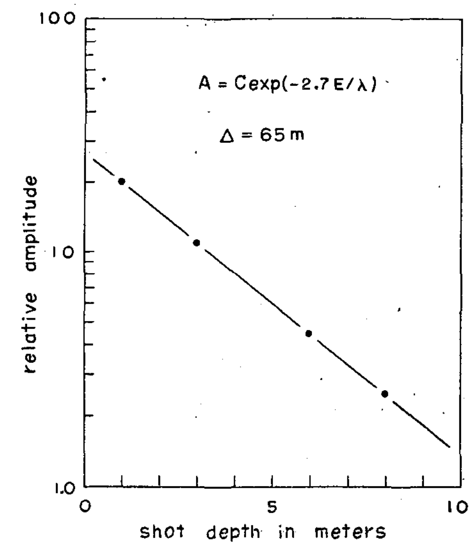


Fig. 20. Maximum amplitude variation of wave group IV at a point 65 m distance from shot hole.

hole with the depth of shot is again illustrated in Fig. 20 rearranged on the semi-log scale.

JEFFREYS[6] has shown that the amplitude of the RAYLEIGH waves in a semi-infinite homogeneous medium should decrease with shot depth E as $e^{-\alpha E}$ for a compressional source disturbance, and $e^{-\beta E}$ for a distortional one when the original disturbance was periodic with wave length λ, where

$$\alpha = \frac{2\pi}{\lambda}\sqrt{1-(c/v_p)^2} \quad \text{and} \quad \beta = \frac{2\pi}{\lambda}\sqrt{1-(c/v_s)^2} \tag{9}$$

in which c is the RAYLEIGH wave velocity

In this experiment, the wave length for wave group IV is about 7~9 m, which is smaller than the thickness of the superficial layer. Accordingly, if it is not considered that the waves of group IV have been governed by any interface in the medium, that is, if these waves is regarded as RAYLEIGH waves in a semi-infinite medium, by applying the relation of the wave amplitude and the shot depth: $A=Ce^{-KE}$ to Fig. 20, it is found that the maximum amplitude of wave group IV decreases according to the relation

$$A = C\, e^{-0.3E} \tag{10}$$

or, when the wave length is taken as 9 m,

$$A = C\, e^{-(2.7/\lambda)E}\ . \tag{11}$$

The phase velocity of this group is estimated as 60~70 m/s from the slope of the time-distance curve in Fig. 3. But it is fairly smaller than the surface wave velocity given by use of Eqs. (1) and (6) when this wave group is taken as RAYLEIGH waves in a semi-infinite medium. That is, since POISSON's ratio in the superficial layer is 0.44, $c/v_{s1}=0.949$ where c is the surface wave velocity, hence, the required wave velocity for this wave group should be 100 m/s.

Such a discrepancy in the velocity between the actually observed and the calculated value often arises, because the property of medium must, in actual fact, not always be homogeneous.

As already mentioned in the preceding section, in another experiment at this site on the propagation of SH waves, the S wave velocity in the upper part of the superficial layer was observed as $v_s=60\sim70$ m/s; however, the layer thickness has not been measured.

Therefore, the above surface waves, of which the velocity is smaller than the required one, may occur in this case because of the upper part of the superficial layer with low velocity, and if an inhomogeneity is taken into account on the superficial layer, the existence of these waves may be explained more clearly.

In order to investigate what Eq. (11) means, the coefficients α and β in (9), which are related to the type of source disturbance, have been calculated in such cases as

i) $v_{p1} = 300\ \text{m/s}$ and $v_{s1} = 110\ \text{m/s}$

from which the POISSON's ratio is obtained as 0.44. Hence, the velocity 100 m/s is given as the RAYLEIGH wave velocity, and

ii) $v_{p1} = 300\ \text{m/s}$ and $v_{s1} = 70\ \text{m/s}$

from which the POISSON's ratio is obtained as 0.47. Hence, the velocity 67 m/s, which is almost equal to the observed one, is secured.

In the case of i), the coefficients are as follows

$$\alpha = 5.9/\lambda \quad \text{and} \quad \beta = 2.0/\lambda \tag{12}$$

and in the case of ii),

$$\alpha = 6.1/\lambda \quad \text{and} \quad \beta = 2.3/\lambda \tag{13}$$

As found in (12) and (13), the coefficient $2.7/\lambda$ in the power of the exponent in Eq. (11) is between the values of α and β.

Anyway, it is a noteworthy fact that the obtained coefficient $2.7/\lambda$ has been near the coefficient for the distortional source disturbance rather than for the compressional one.

From this argument, it will be concluded that the original disturbance generates more strongly the distortional type of movement.

In this stage, it is also difficult to clarify whether the compressional or the distortional waves contribute more effectively to the generation of these surface waves, when the problem concerning such a wave generation is considered ray-theoretically.

To understand wave group IV, one must also notice such facts as that this group appears, differing from other surface wave groups, near the shot hole as shown in Fig. 2, and that it is propagated with the large amplitude, indicating a slight dispersive phenomenon which is one of the important facts in considering the surface waves.

3) Wave group III

This wave group appears near the point of 50 m distance from shot hole when the shot is fired at 1 m depth, as though it were produced from wave group IV, as seen in Fig. 2.

The amplitude near the place where these waves appear is fairly small compared with that of wave group IV, but it becomes gradually great and becomes large enough to be comparable to wave group IV, with being propagated farther from the shot hole.

Another remarkable fact in this wave group is that its amplitude variation as shown in Fig. 10 is similar to that of wave group IV, that is, the maximum amplitude decreases exponentially with shot depth, hence this wave group has been considered as a surface wave group.

Taking account of its period variation, of which the period decreases abruptly with shot depth, together with its amplitude variation, it must be considered that this wave group is more sensitive to the source conditions than to the layer thickness.

It seems to be a useful thing to investigate the generation of these surface waves that, for wave group III, the phase velocity is almost equal to the S wave velocity in the substratum and that, for wave group IV, equal to that in the superficial layer.

Thus, it is considered that the generation of these surface waves may depend much on a distortional wave energy. Therefore, the distortional waves would be produced from a dynamite explosion or transferred from compressional waves on the interface.

4) Wave group III′

The maximum amplitude variation of this group is quite similar to that of refraction wave groups. Nevertheless, since the appearance of this wave group is too late to be interpreted by the ray paths for such refraction waves as already given, it is not considered that this wave group, of which the phase velocity is between the S wave velocity in the superficial layer and that in the substratum, consists of refraction waves.

As seen in records in Fig. 9 obtained when the shot is fired near the interface, these waves are distinctly isolated and the wave shape is not very disturbed. Hence, this wave group would be taken as some kind of reflection waves. However, as far as the single reflection waves are concerned, the occurrence of this wave group is not interpreted by that supposition, because, as mentioned above, the appearance of this wave group is later than that of S_1S_1 reflection waves which arrive latest at the surface of all of the single reflection waves.

Therefore, assuming that wave group III′ is a multiple reflection wave group, then one has a new contradiction between the energies in single and multiple reflection waves, that is, it comes to that the amplitude for multiple reflection waves will be recorded as a larger one compared with that for single reflection waves.

Thus, since there are several reasons for not taking this wave group as a refraction or reflection wave group, it may be perhaps best to consider it as a surface wave group, such as, for instance, "the second surface wave" so called by CAGNIARD[7] or "the STONELEY wave".

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