Model Seismology (Part 3), Wave Propagation in the Step-shaped Structure and on the Cliff

著者	Kato Yoshio, Takagi Akio
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*Model Seismology (Part III)**
Wave Propagation in the Step-shaped Structure and on the Cliff

By Yoshio Kato and Akio Takagi

Geophysical Institute, Faculty of Science, Tôhoku University

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Abstract

Model experiments by means of ultrasonic technique are carried out on the elastic wave propagation over a semi-infinite medium, especially when the medium has a surface with some kinds of discontinuity of which the dimension is in comparative order of magnitude with one wave-length. Experimental results demonstrate some interesting behaviours on wave conversion by collision of waves with the discontinuity. When the source is on the upper part of a step-shaped surface and obserivng point is on the lower surface, the amplitude of Rayleigh waves decreases exponentially with the step size, as it does with the depth of observing point in case of a flat surface. Another outstanding fact is that a new pulse is secondarily generated from the step point when a body or surface wave passes through the discontinuity. The generation of the new pulse may be caused by a conversion phenomenon of waves, that is, a surface wave of Rayleigh type is newly generated by the incidence of a body or surface wave to the discontinuity point. The experiments lead us to the validity that there is efficient conversion of the body wave energy into the surface wave as much as the surface wave into the surface wave. To confirm this further, the propagation of pulse over the surface of a rectangularly shaped plate is studied. In the latter experiment, two waves are observed to be propagated along the side plane of the medium with velocity of Rayleigh wave and a new wave, apparently originating from the corner point. These are due to the conversion by the incident P and L_R waves respectively. Finally, we study the case where an original impulse is applied on the surface instead of the embedded source adopted in the former experiments, and similar results are obtained except the conversion from P to L_R. An interpretation for this exceptional case is attempted.

1 Introduction

A theoretical study on the propagation of elastic waves in a semi-infinite medium was studied by H. Lamb, applying a vertical force is on the surface of an elastic solid. H. Nakano, E. R. Lapwood and others developed the study on the source lying in the interior of the medium. The experimental verification of their results have been carried out by many other authors (T. D. Northwood and D. V. Anderson, H. E. Tatel, and Y. Kato and A. Takagi, [1, 2, 3,]).

Recently, H. E. Tatel [4] studied the effect of surface irregularity on the propa-

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gation of elastic waves, and he concluded that the complex seismograms were in a form of scattering, most of which were related to surface and not to the interior of the medium. More recently, R. SATO [8] studied theoretically the similar problem.

In this paper we report the results of experiments on the propagation of the pulse when the medium is a semi-infinite elastic solid with a step-shaped surface as an example of complex case. The propagation of waves near the corner of the medium is investigated. This is an extreme case of the step-shaped surface, and is provisionally called the "cliff problem" in this paper. Since the transmitting source is embedded in the medium just below the surface in the former cases, we finally take the case in which the source is placed on the surface, in order to know the effect of the state of the source situation.

2 Experimental Procedure

The apparatus and the procedure of this experiment is similar to those in the former studies in connection with the present work [3]. A thin plate of bakelite (100 $\times 50 \times 0.3$ cm in size) is taken as a model material. The transmitting source is a small disk made of $BaTiO_3$ whose dimensions are 5 mm in diameter and 2 mm thick. The source is burried in the plate, the center of disk being located at 0.5 cm beolw the surface, then its location is just below the surface. The embedding method is the same as reported in the previous paper [9], to keep the uniform condition in wave radiating intensity. The receiver is a rectangular plate of $4 \times 2 \times 1$ mm made of barium titanate ceramic. The above-stated procedure serves a model of wave propagation in two dimensional cases with a line source. To avoid undesirable effects of reflexions on the side or the bottom plane, the source and the receiver are always set at points at least 30 cm apart from the edge, except the time when the cliff problem is concerned. The fixed source and removing receiver system is adopted, the source being fixed at a point 30 cm apart from the side plane and the receiver at intervals of 2 cm in epicentral distance.

3 Wave Propagation in Step-shaped Structure

As the first example of complex cases about which the theoretical treatment is too complicated to be carried out, the effect of a step-shaped surface as a scattering center on progressive waves is investigated. The case treated in the present investigation is of a sort of the rough surface problem. The surface of the medium treated has a step-shaped form as illustrated in Fig. 5. Hence the free surface is divided by the step into two parts, which are called the upper surface and the lower in this paper. The horizontal distance between the step and transmitting sources is 20 cm, and the dimension of the step size is variable. The transmitter is always placed on the upper surface.

The effect of surface step on the observed motions is clearly seen in Fig. 1, which reproduces the seismograms at a fixed distance in case of the range of various step sizes, from 0 cm to 5 cm.

As seen in the records, seismograms obtained within the distance range between the step and the source are not so different from ones observed for the medium without step, when the receiver is placed at points appreciably apart from the step. However, when the receiver comes near the step, surface irregularity is found to alter the simple wave pattern. The two new phases are recorded, i.e., P and Rayleigh wave reflected by the step. The identification of these waves is based on the relation between their travel times and distances.

At distances beyond the step, the seismograms obtained are appreciably altered in comparison with those for the simple model without step. Though some disturbances appear before and after the proper Rayleigh wave, we are "at first" concerned only with the law of amplitude decrease of the proper Rayleigh wave. An important characteristic of the decreasing amplitude with the increasing step size is seen for Rayliegh waves observed on the lower surface. Fig. 7 shows the relation between the step depth and the amplitude. The amplitude at any depth of the step is represented in its percentage value to that presenting no step.

As seen in Fig. 7, this amplitude ratio decreases exponentially with the increasing step depth, as it does with the depth when the medium has no step structure.

The major effect of a surface discontinuity is the production of some converted waves. Some examples of these waves appearing before and after the proper Rayleigh pulse are fairly seen in Fig. 1. The travel time of the initial motions of these phases are plotted in Fig. 5. Within the range between the source and the step, there are only two straight lines corresponding to the travel time curve of P and Rayleigh pulse, except the two straight lines corresponding to the travel time curve of the reflected P and Reflected L_R pulse by the side plane of the step. At the distance beyond the step, there appear various kinds of travel time curves which are expressed in straight lines, besides those of ordinary P and L_R. All these straight lines are parallel to that for the ordinary Rayleigh waves. From these results we may conclude that these phases are the surface waves of Rayliegh type converted from the incident P and L_R waves, and that the complex nature of seismograms are mainly attributed to the existence of these converted pulses caused by the discontinous surface. Five phases are observed in our seismograms obtained on the lower surface, each of which is identified to be the following type of waves from its time-distance relation.

(a) is a direct P pulse.

(b) is a wave which starts from the source as P, and converts into a new phase at the lower corner of the step and travells along the lower surface with the same velocity as the proper Rayleigh wave.

(c) is a wave which is propagated on the upper surface as P, converts into a new phase on the upper corner of the step and travells along the side plane and the lower surface with the velocity of the proper Rayleigh wave.

(d) is a wave which is propagated over the whole distance with the velocity of the proper Rayleigh wave irrespective of the existence of the step.

(e) is a wave which starts as the Rayleigh pulse, converts into new Rayleigh pulse at the upper corner and travells along the side plane of the step and the lower surface with the same velocity as the proper Rayleigh wave.

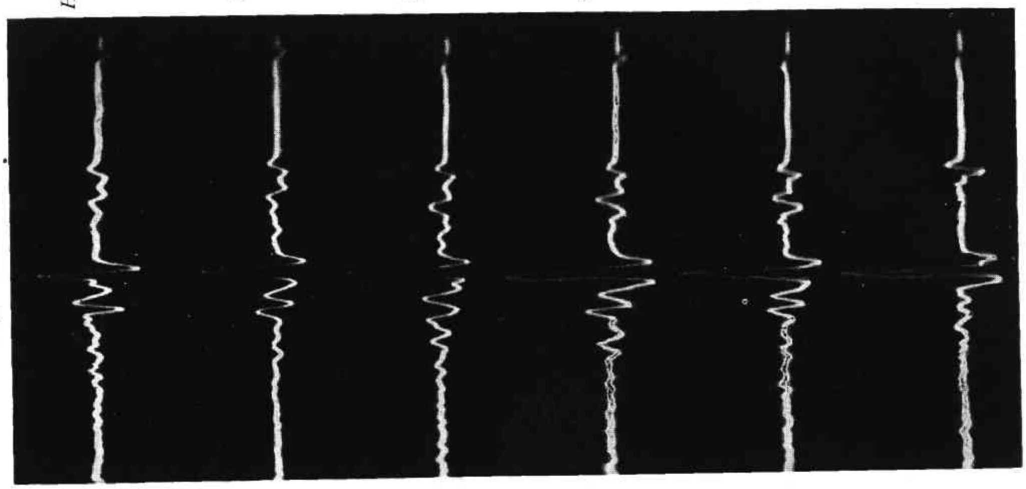

Fig. 1a $\Delta=18$ cm

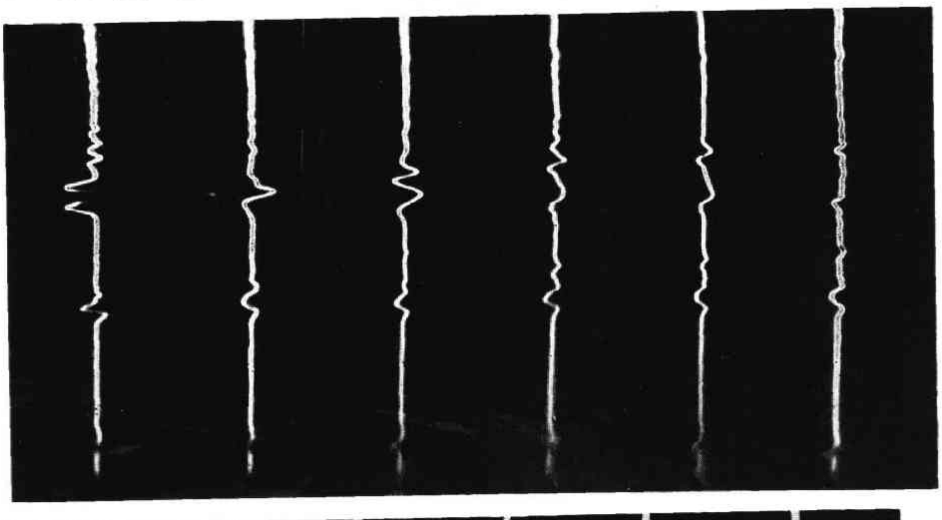

Fig. 1b $\Delta=22$ cm

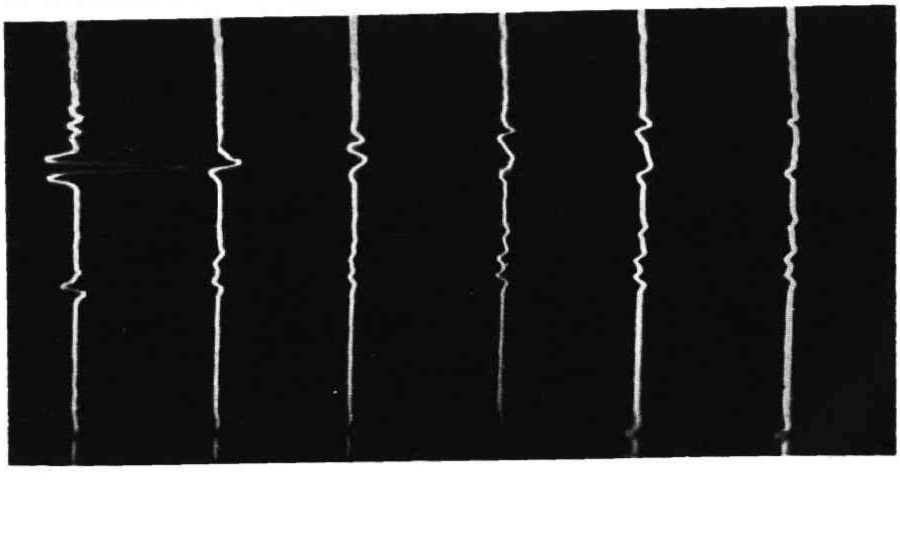

Fig. 1c $\Delta=24$ cm

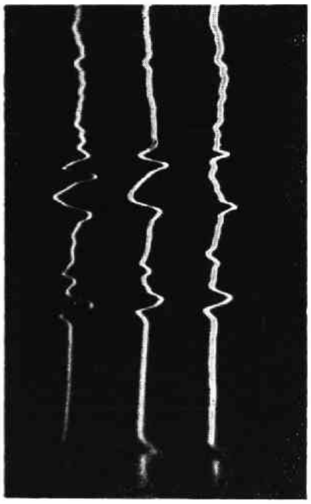

Fig. 2a Δ=22 (amp)

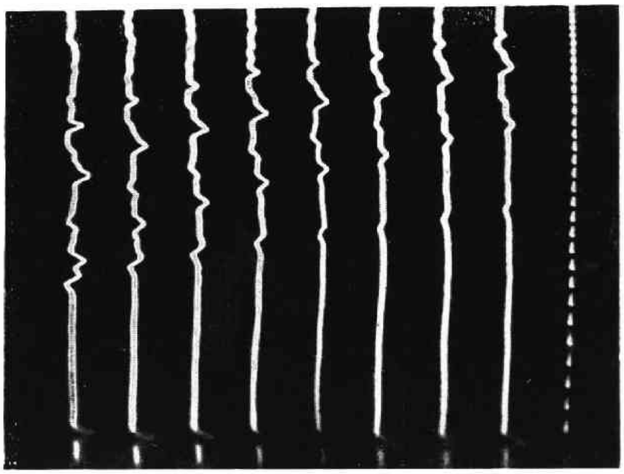

Fig. 2b $H=5$ cm (amp)

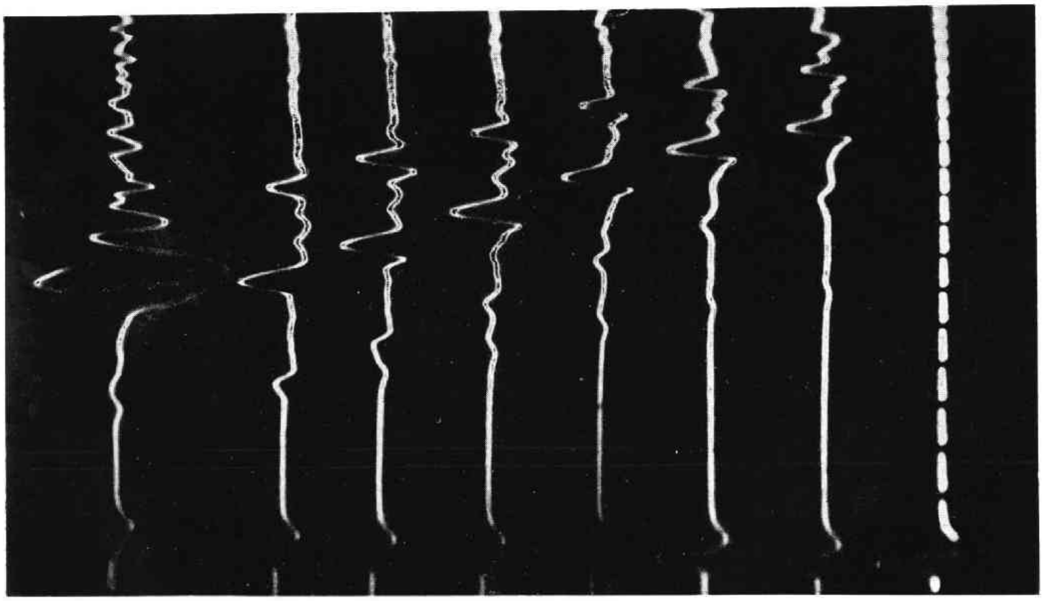

Fig. 3 $H=5$ cm

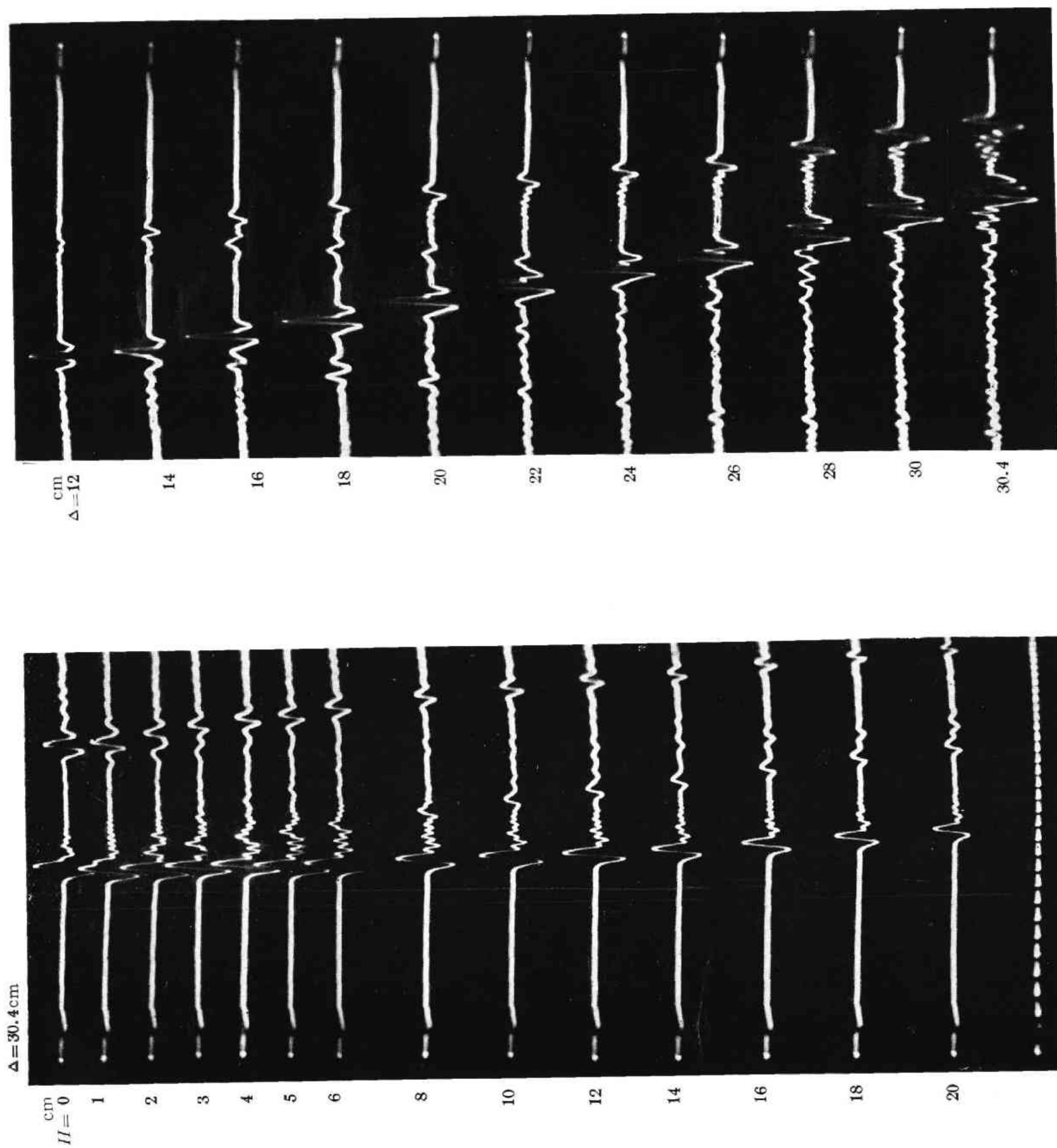
Δ = 12 cm
14
16
18
20
22
24
26
28
30
30.4
Δ = 30.4 cm
H = 0 cm
1
2
3
4
5
6
8
10
12
14
16
18
20

Fig. 4

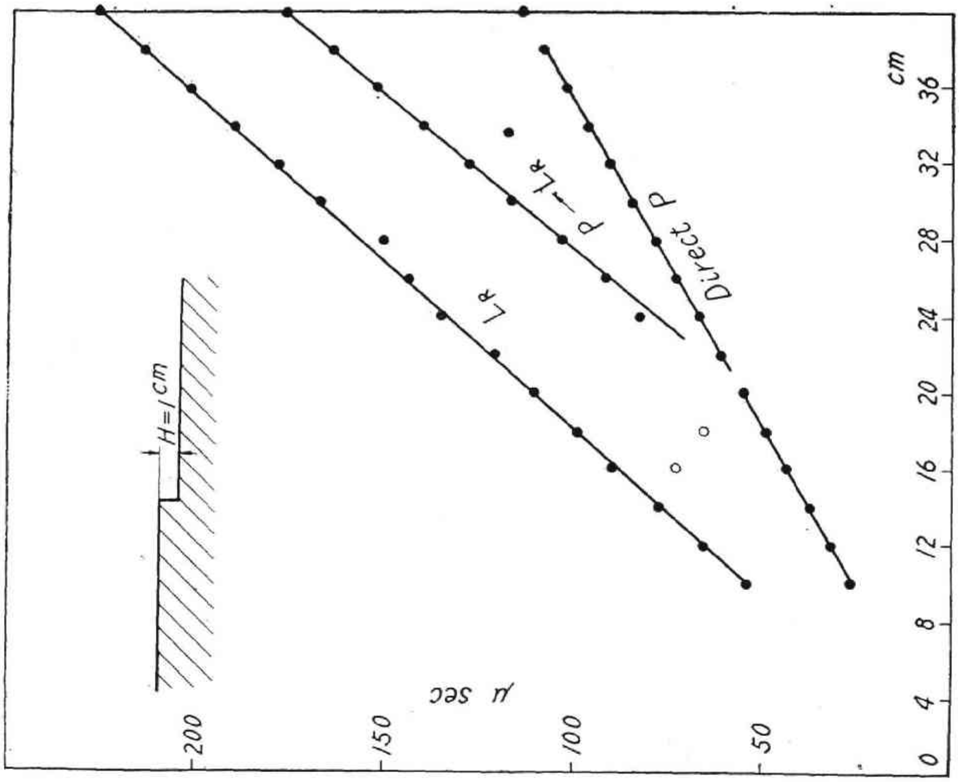
H=1cm
μ sec
cm
L^R
P → L^R
Direct P
200
150
100
50
0
4
8
12
16
20
24
28
32
36

Fig. 5 a

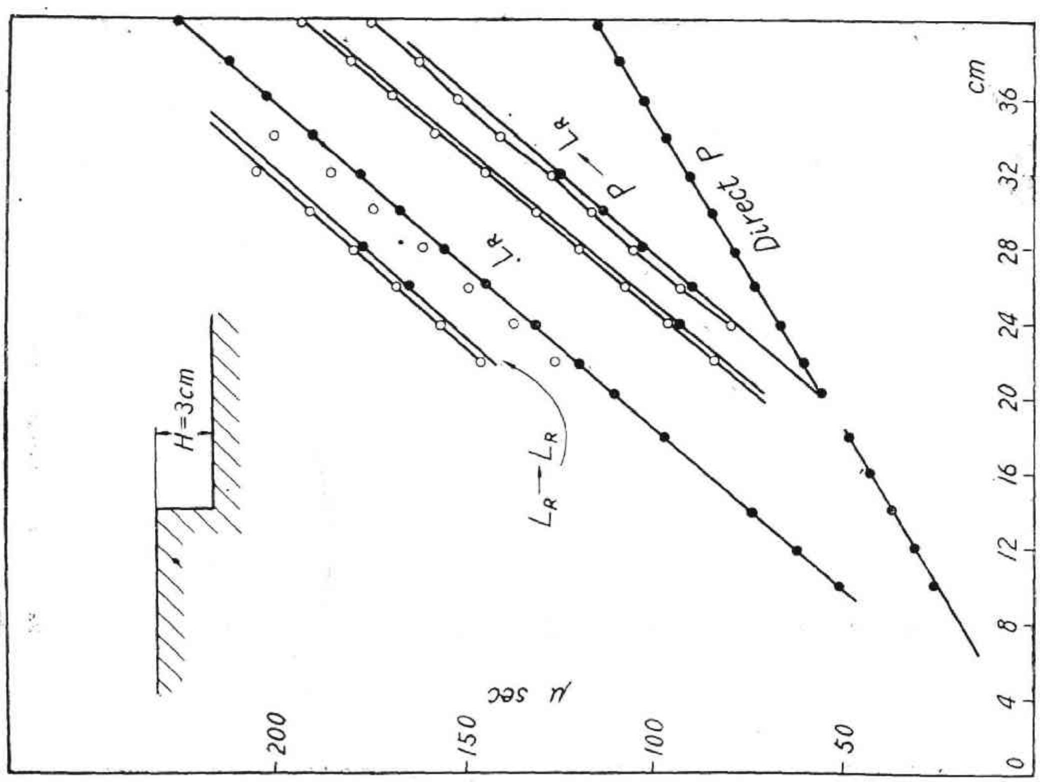
H=3cm
μ sec
cm
L^R
L_R → L_R
P → L^R
Direct P
200
150
100
50
0
4
8
12
16
20
24
28
32
36

Fig. 5 b

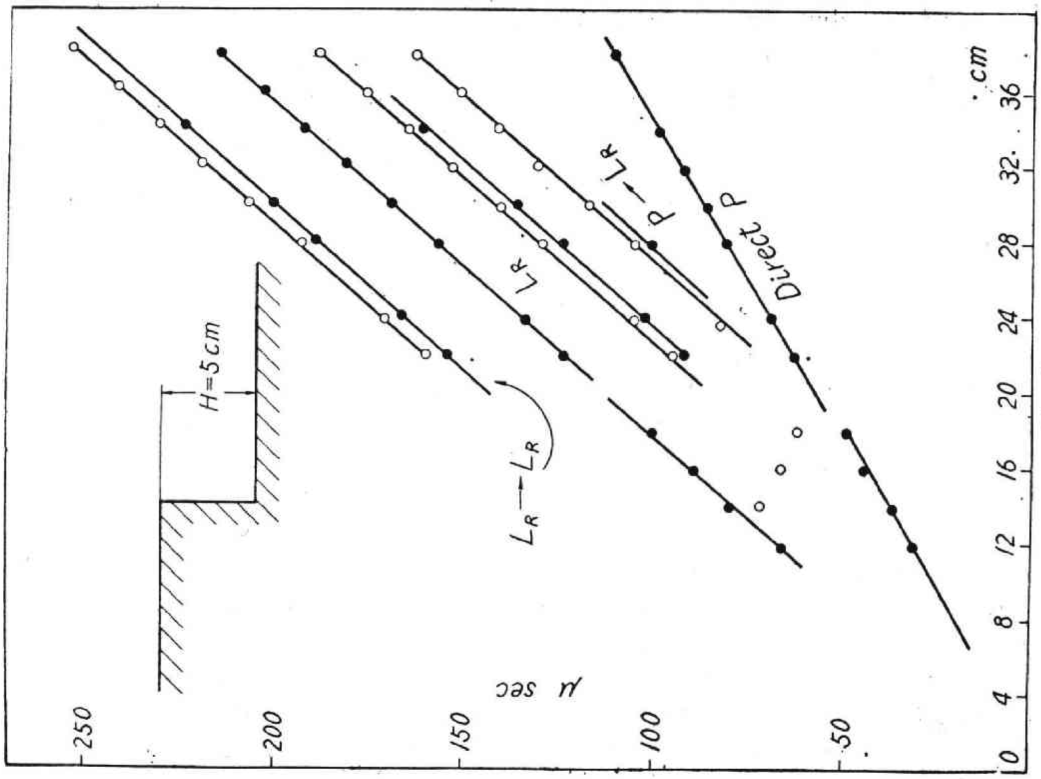
H=5 cm
$L_R \rightarrow L_R$
L_R
$P \rightarrow L_R$
Direct P
μ sec
cm
0
50
100
150
200
250
4
8
12
16
20
24
28
32
36

Fig. 5 c

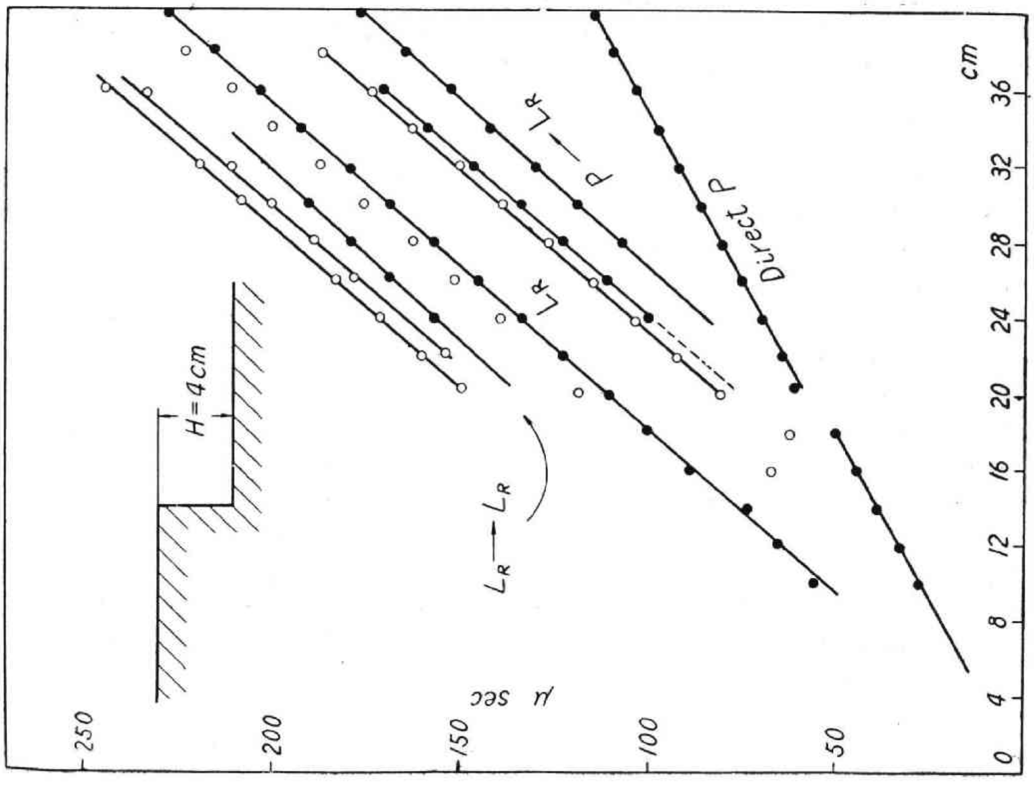
H=4 cm
$L_R \rightarrow L_R$
L_R
$P \rightarrow L_R$
Direct P
μ sec
cm
0
50
100
150
200
250
4
8
12
16
20
24
28
32
36

Fig. 5 d

These results lead us to the conclusion that the conversion of waves can occur not only in the way $P \rightarrow L_R$ but also $L_R \rightarrow L_R$. The conversion of the former type was suggested by H. E. TATEL and the later conversion type is newly found in the present investigation.

It is noted, moreover, that the beginnings of the pulses can not be clearly recognized seperately from the ordinary P or L_R waves, when the step size is small enough. The resaon of this fact may due to the following circumstances. If the step size is small, the discrepancy in travel times of the incident and the converted waves is also small, and the two phases are overlapped with each other. When the step becomes large, each wave becomes to seperate and to take such a characteristic form as in the present seismograms, because both the incident and converted waves have a wave form of shock type with a short duration time. Since the identifications of converted waves are based only on the travel time relation, as already stated, the behaviour of converted pulses in the cliff case will be discussed in the next paragraph.

It is expected from the present interpretation of pulses that the time interval between the travel time of (b) and (c) must coincide with that between (d) and (e). As seen in Fig. 5, no agreement is found in the results of observation, in other words, the time interval of the travel-time curves of Rayleigh waves produced by the incident P wave on the upper and lower corners of the step, seems to be smaller than that expected from our deduction. However, it may be explained as follows. The source from which the cylindrical pulse is emitted into the medium, is burried just below the surface and, therefore, the effective path of the wave (c) is reasonably considered to be smaller than that when the source is on the surface.

4 The Cliff Problem

In the preceeding paragraph, model seismological experiments show that a surface discontinuity in the path of body or surface waves act as a scattering center, which produces converted Rayleigh waves. For further investigations, we carry out the studies mainly concerned with the recognization and identification of various phases in a simpler case. This problem is treated at the time when the scattering center to proceed the conversion or scattering of wave components is in the form of cliff, i.e., the free boundary of the medium is consisted of two planes, perpendicular to each other, one of which is horizontal and the other vertical. The horizontal distance between the corner and the transmitting source which is embedded just below the surface is also kept at 30 cm. The receiver is placed vertically to the surface within the distance range between the source and the corner, and is placed perpendicularly to the side plane for the distance beyond the corner. Measurements are carried out at intervals of 2 cm. The largest distnace is 20 cm from the corner for the observation on the vertical side plane. Seismograms are shown in Fig. 4. As seen in the records, seismograms obtained within the range between the corner and the source are not so different from the one obtained on the upper surface in the preceeding experiment. On the side plane of the medium, we obtain many interesting seismograms in which the converted waves with the velocity of the proper Rayleigh wave is found to be originated from the corner point at the moment of the arrival of incident pulses. It is clearly seen in the seismograms that in the vicinity of the corner, the amplitude of the original Rayleigh wave along the side plane of the medium diminishes with the increase of distance from the corner. This indicates that the amplitude variation of the incident Rayleigh wave is the same as that in the case of the semi-infinite medium, without regards to the existence of the cliff.

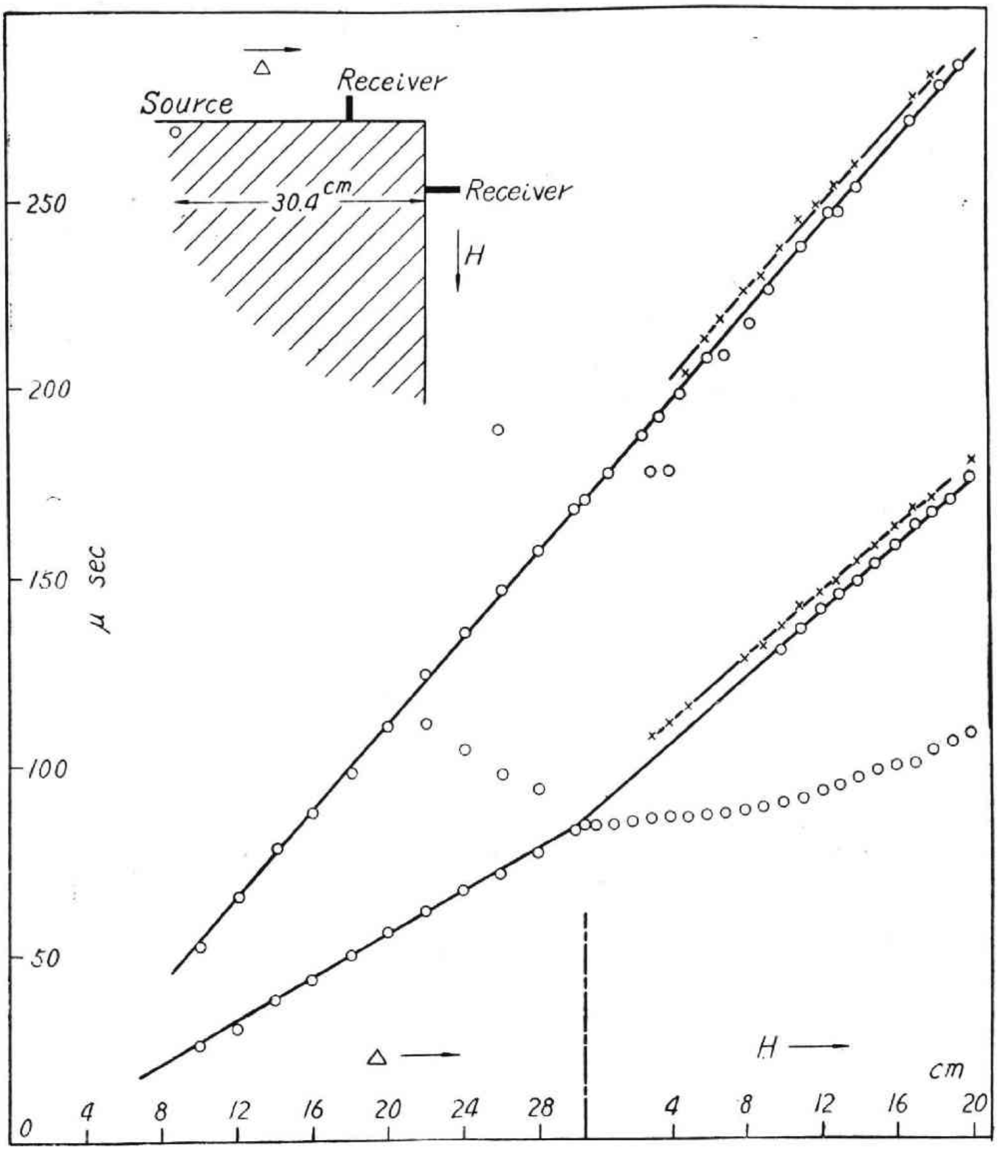

Fig. 6

When the distance from the corner becomes large, the original Rayleigh wave diminishes and the converted Rayleigh wave develops a marked and isolated form, as the distance from the point of the corner increases. For the identification of these phases, travel-time curves are taken in the Fig. 6, in which the sum of the two distances from the source to the corner and that from the corner to the receiver is taken as abscissa for the measurements beyond the corner, while the ordinary epicentral distance is taken for the points on the horizontal surface. From this figure, we safely conclude that, when the P pulse which is propagated over the surface, come to the corner of the medium, the converted Rayleigh pulse is generated from the corner point and is propagated along the cliff and that the similar conversion of $L_R \rightarrow L_R$ is also recognizable.

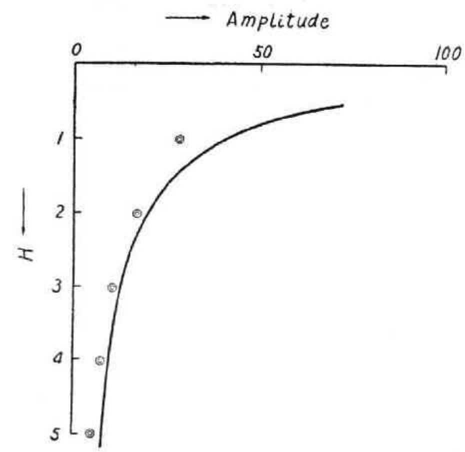

Fig. 7

5 Wave Propagation in a Step-shaped Structure by an Impulsive Source is applied Vertically on the Surface

Finally, we study the case where an impulse is applied vertically to the suraface

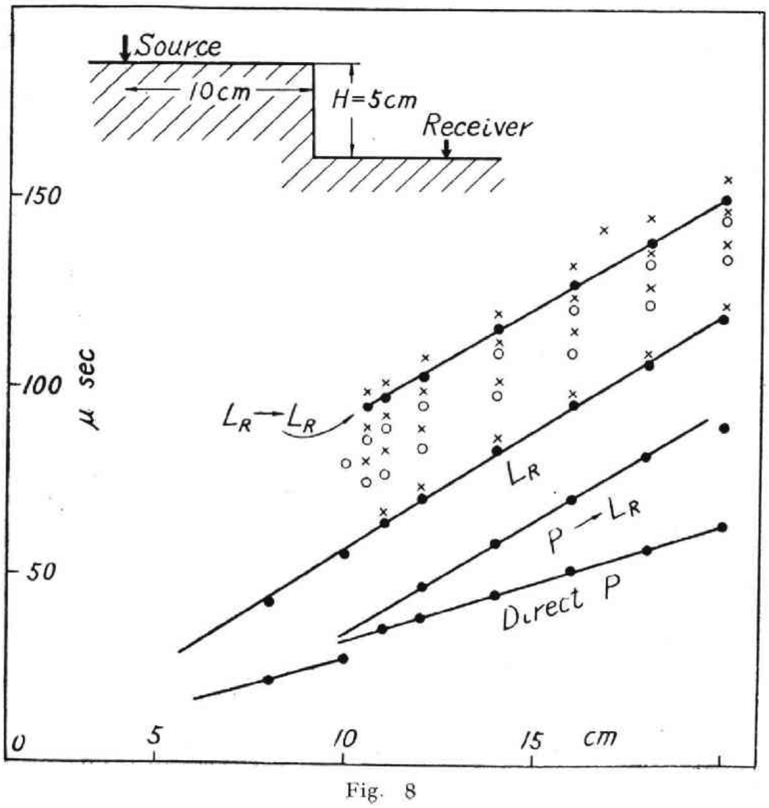

Fig. 8

in the step-shaped model, instead of a source embedded in the medium. The horizontal distance between the step and the transmitting source is 10 cm and the step depth is 5 cm. The seismograms thus obtained are not so different from those obtained in the former case. As seen in the seismograms in Fig. 3 and the travel time curves in Fig. 8, two new phases are generated before and after the Rayleigh wave respectively. The wave corresponding to (c) in the previous paragraph, is absent in the present experiment. This is due to the fact that the energy of direct P wave is small in this case, as is expected from theoretical and experimental studies. [7].

6 Conclusion

The model experiment of wave propagation in the medium with complex structure is carried out. The experimental results are summarized as follows.

1 The wave propagation in the medium with a step-shaped surface is studied as a kind of rough surface problem. The amplitude decrease of the ordinary Rayleigh wave with the increase of depth is similar to that in case of a semi-infinite medium.

2 When the body and surface wave collide to the step, two kinds of new pulses are generated there; one is due to a conversion of $P \rightarrow L_R$ and the other to the conversion of $L_R \rightarrow L_R$. From these experiments, it is deduced that the complex features recorded on a seismogram may be mainly attributed to the waves converted and scattered at the surface discontinuity.

3 We attack the cliff problem in the two-dimensional model. At the corner of the cliff, two new phases are originated ; one is propagated along the vertical plane with the velocity of Rayleigh wave and is considered to be the converted wave of $P \rightarrow L_R$, the other is due to the conversion $L_R \rightarrow L_R$.

In conclusion, the present writers wish to express their hearty thanks to Prof. S. TANAKA, Institute of High Speed Mechanics, Tôhoku University and Mr. T. ANZAI, Research Institute for Scientific Measurement, Tôhoku Universtiy who kindly constructed the measuring apparatus by which present studies were carried out. The authors also express their thanks to Prof. H. HONDA for his kind suggestion and encouragement throughout the course of this investigation.

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