STONELEY Waves Generated by Explosions.

By

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Abstract

Using three components seismometers, field measurements of under ground motions within bore-holes were carried out.

In this experiment, boundary waves which could be considered as STONELEY waves were obtained. The boundary surface is between layers of clay and sand and is of about 9 m depth from the ground surface.

The characteristics of this wave are as follows:

The wave velocity is 430 m/sec.

The period of motion is about 0.06 sec.

The particle trajectories are elliptical and retrograde.

The amplitude of the wave is large at the boundary surface and is decreased rapidly on leaving this surface.

These results are in good agreement with those predicted by the classical theory on the STONELEY waves.

§ 1. Introduction

Putting seismometers at various depths within bore-holes, and varying the depth of shot-hole, explosive waves were recorded by vertical and horizontal seismometers.

The most interesting result obtained in these experiments was that the STONELEY wave could be observed by explosions, at the boundary surface between two different layers.

In 1924, R. STONELEY found that it was theoretically possible for RAYLEIGH-type waves to be transmitted along the boundary surface of two elastic solids. Later on, K. SEZAWA and K. KANAI (1938 and 1939) studied mathematically the way of generation of the boundary waves. K. SEZAWA and K. KANAI (1939) and J. G. SCHOLTE (1947) calculated the possible existence range of the STONELEY wave.

Many theoretical studies on the STONELEY wave have been carried out since then. However, there have been no reports on the direct observation of this wave or the opportunities of doing so. (Y. SATO 1953).

In the present experiment, the seismograms recorded a phase which seems to correspond to the boundary wave. This phase could clear-

ly be recorded on the trace of seismograms only when the seismometers were placed at or near the boundary surface of the two different layers.

In view of many other results obtained it seems that this wave corresponds to the STONELEY wave.

§ 2. Experimental Procedure.

Instruments

The instruments employed in these experiments are those used in usual prospecting operations. The seismometers are of the E.T.L. type (Electro-Technical Laboratories' Seismic Detector, Model EVS-3D) with three components (one vertical and two horizontal), the natural frequency being 10 cycle/sec., and the damping being critical. The galvanometers have a natural frequency of 30 cycle/sec., and are critically damped. Each galvanometer is directly connected to a seismometer, with no amplifiers but sometimes with attenuators.

Figure 1 shows a response curve of the entire system, including the seismometer and the galvanometer. The magnification of this system is about 2500 at 20 cycle/sec.

Fig. 1. Frequency-magnification curve for over all system including seismometer, galvanometer and occillograph.

Fig. 2. Geological profile of the test field.

Fig. 3. Time-distance curves by the refraction test. (after T. KAMETANI)

Location

The observations were carried out by the "Seismic Exploration Group of Japan" in Feb. 1954 and March 1955, on the ground of the agricultural field of Tokyo University, Tanashi, Tokyo.

The geological profile here is shown in figure 2. The upper layer is a clay, called "Kanto Loam," under which is a sandy layer beginning 9 m below the surface. The STONELEY wave was observed at the boundary surface between the clay and sand layers.

A seismic prospecting test by the refraction method was carried out in this field by our group, and the result was reported by T. KAMETANI (1954). The time-distance curves in this report are copied in figure 3. The longitudinal wave velocity is gradually increased with the depth. This velocity distribution may be represented by the following formula:

$$(1) \quad v(z) = v_0 + az$$

where z is the depth in meter. Using the time-distance curves, the constants v_0 and a are determined as follows:

$$v_0 = 1411.5 \pm 3.7 \text{ m/sec.}$$

$$a = 32.1 \pm 1.1 \text{ sec.}^{-1}$$

Shooting procedure

Two types of tests were made as follows:

1) The ground motion resulting from dynamite explosions in a bore-hole of 15 m depth was recorded by seismometers placed at bore-hole bottoms of varying depths. The depths of the seismometer holes were 2 m, 7.5 m, 9.0 m and 10 m in the first test, and 1.5 m, 5.0 m, 8.5 m and 11.5 m in the second test, the shot-receiver distances being 60 m and 45 m in the first and second tests, respectively. (Figure 4)

2) In order to determine the propagation velocity of this wave, three component seismometers (vertical, horizontal radial and horizontal transversal components) were placed at three shot-receiver distances, namely $\Delta = 20$ m, $\Delta = 60$ m and $\Delta = 100$ m along the boundary surface of the clay and sand layers, which is at about 9 m depth. An additional instrument was placed at the up-hole 100 m away. A

Fig. 4. Maps of disposition of seismometers and shot-holes in the experiment.

dynamite charge was fired at the depth of 15 m under the ground surface.

By using an attenuator, the sensitivity of each seismometer was kept constant in each experiment. The sensitivity of seismometers were changed, however, according to the distance as follows;

Shot-Receiver Distance.	Sensitivity Ratio	
	Vertical	Horizontal
100 m	1	1
60 m	1/3	1
20 m	1/10	1/10

§ 3. Experimental Results.

The seismograms obtained in experiments I and II are shown in figures 5, 6 and 7.

As is seen in figures 5 and 6, there is a remarkable later phase in traces A-1, A-2, B-1 and B-2, but no such phase in trace C, D, E-1 and E-2.

Our conclusion is that this clearly distinguishable later phase is due to a boundary wave, on the ground that it is found near the boundary surface between the clay and sand layers and its amplitude is decreased rapidly on leaving the surface.

Is this wave progressive or not? As shown in figure 7, we found in experiment II that

Fig. 5. Seismograms obtained by the 1st test in 1) experiment.

Trace Number	Types of Seismometer	Disposed Depth	Shot-Receiver Distance	Sensitivity Ratio	Notation
1	Vertical $10\infty/s.$	10 m	60 m	1	A-1
2	" "	9 m	"	"	B-1
3	" "	2 m	"	"	E-1
4	" "	$7\frac{1}{2}$ m	"	"	C

(Shot-hole depth; 15 m)

Fig. 6. Seismograms obtained by the 2nd test in 1) experiment.

Trace Number	Types of Seismometer	Disposed Depth	Shot-Receiver Distance	Sensitivity Ratio	Notation
1	Vertical $10\infty/s.$	$1\frac{1}{2}$ m	45 m	1	E-2
2	" "	5 m	"	"	D
3	" "	$8\frac{1}{2}$ m	"	"	B-2
4	" "	$11\frac{1}{2}$ m	"	"	A-2

(Shot-hole depth; 15 m)

this wave was recorded by the vertical and horizontal radial components of the seismometers at every distance on or near the boundary surface, but not recorded by the up-hole seismometer. Thus, we may safely conclude that this wave propagated along the boundary surface.

In the following paragraphs, some of the characteristics of these boundary waves will be studied.

1) Propagation velocity

The time-distance curves for the initial motions and boundary waves obtained from figure 7 are shown in figure 8. From these time-distance curves, we see that the propagation velocities of the boundary wave and the

initial motion are 430 m/sec. and 1800 m/sec., respectively. The propagation velocity of 1800 m/sec. corresponds to the longitudinal wave by the following reason:

By equation (1), the propagation velocities of the longitudinal wave at 9 m (the boundary surface) and 15 m depth (the depth of explosion point) are estimated to be

$$v(z=9)=1728 \text{ m/sec.}$$

$$v(z=15)=1920 \text{ m/sec.}$$

The velocity of 1800 m/sec. lies between these two values.

2) Trajectories of Particle Motions.

Figure 9 shows the particle motion trajectories obtained by the vertical and horizontal

Fig. 7. Seismogram obtained by 2) experiment.

Trace Number	Types of Seismometer	Disposed Depth	Shot-Receiver Distance	Sensitivity Ratio
1	Vertical $10^\infty/s$.	9 m	20 m	1/10
2	" "	9 m	60 m	1/3
3	" "	$8\frac{1}{2}$ m	100 m	1
4	" "	0 m	100 m	1
5	" $27^\infty/s$.	0 m	100 m	—
6	Horizontal $10^\infty/s$.	9 m	20 m	1/10
7	" "	9 m	60 m	1
8	" "	$8\frac{1}{2}$ m	100 m	1
9	" "	0 m	100 m	1
10	" $27^\infty/s$.	0 m	100 m	—

(Shot-hole depth; 15 m)

radial seismometers at a point of 8.5 m depth from the ground surface and 100 m distance from the firing point. Three successive cycles are shown in the figure. The motion is retrograde in the first two cycles and is roughly elliptical, but not so in the third cycle. It seems that the first two cycles correspond to the STONELEY wave but that the third one re-

presents some other type of wave.

At a point of 9 m depth from the ground surface and 60 m from the firing point two cycles can also be seen in trajectories.

3) Period and Dispersion

The period of this wave is about 0.06 sec., but the time intervals between successive peaks and troughs become longer as time

Fig. 8. Time-distance curves for underground test.

goes on. This time increase may be due to the abnormal dispersion of the wave. The STONELEY wave is not dispersive, if the elastic

constants and densities of the two layers are constants. Thus the wave dispersion obtained above may be explained by the complexities of the structure in this region.

4) Amplitude.

The amplitude distribution in a vertical column is shown in figure 10. On the other hand, the amplitude distribution versus shot-receiver distance along the boundary surface is shown in figure 11. It is rather difficult to determine the attenuation formula of the STONELEY wave from this figure, because at $\Delta=20$ m, the STONELEY wave is not clearly separated from other waves.

§ 4. Conclusions and Remarks

In this section, the existence conditions and the excitation conditions of the STONELEY wave derived theoretically will be discussed.

K. SEZAWA and K. KANAI (1938) and F. G. SCHOLTE (1947) determined the range of the density ratio (ρ/ρ') and the elastic constant ratio (μ/μ') of two separated layers within which STONELEY waves can be existed. Some of the results obtained are shown in figure 12. From figure 12, we see that the range of

Fig. 9. Particle trajectories of successive STONELEY wave recorded at 8.5 m deep and 100 m shot-receiver distance.

$\left(\frac{\mu}{\mu'}, \frac{\rho}{\rho'}\right)$ within which the STONELEY waves can be existed is quite narrow. When $\left(\frac{\mu}{\mu'} \middle| \frac{\rho}{\rho'} \approx 1\right)$,

Fig. 10. Effect of depth upon the vertical component of the amplitude of STONELEY waves.

Fig. 11. Effect of shot-receiver distance upon the vertical component of the amplitude of STONELEY waves.

i.e., when the velocity difference of two separated layers is quite small, the STONELEY wave can be existed.

In the present experiment, there was hardly any velocity difference between the two separated layers as was shown in figure 3, although the layers are clearly distinguishable in the bore-hole tests.

Thus it may safely be concluded that in this field, the existence conditions for the STONELEY wave are satisfied.

Next we shall consider the generation condition of the STONELEY wave: K. SEZAWA and K. KANAI (1938 and 1939) showed mathematically that dilatational wave origins or distortional origins of SV type can generate the

Fig. 12. The range of existence of STONELEY waves. (after K. SEZAWA & K. KANAI and F. G. SCHOLTE.)

boundary wave. In the present experiment, the origin is of dilatational type, because, in general, dynamite explosions initially generate spherical dilatational waves.

The propagation velocity of the observed STONELEY wave was measured as 430 m/sec. The propagation velocity of the STONELEY wave is shown to be nearly equal to that of the transversal wave in the same solid. In the present experiments, the transversal wave velocity was not obtained, but assuming Poisson's ratio of about 0.45, we get the transversal wave velocity of 430 m/sec. This value of 0.45 is not so unnatural for clay or sand fields.

Unfortunately, the attenuation formula for the STONELEY wave could not be determined experimentally by the reasons given above.

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