16. *On Ground Vibrations Caused by Explosions.*

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1. Introduction.

The seismic waves caused by the detonation of explosives such as dynamite or powder have been utilized for prospecting underground materials, and each phase of the waves has been elucidated. In America, however, a wave new to seismology was found for the first time by L. Don Leet[1] and again by B.F. Howell.[2] Concerning this new wave Leet stated as follows: "It causes a particle in its path to move in a longitudinal-vertical plane, clearly independent of motion on the transverse component at the same time. The unique and significant thing about the motion is that it is the opposite of the Rayleigh wave and the particle at the top of its inclined elliptical orbit moves forward as for a wave on water. For that reason it has been called a Hydrodynamic wave and tentatively labelled H."

It is worth while to ascertain whether this wave can be found in Japan or not.

We recently carried out an experimental investigation of the ground vibrations at Minami-Sunamachi, Kôtôku, Tôkyô, and we have the records obtained on that occasion by us now. The two seismometers used in the present investigation were Kishinouye's horizontal tromometers,[3] and we adjusted their periods of free vibrations to 5 seconds, their magnifications to 480, and the damping to critical. As these seismometers were originally intended for the study of microseisms, the speed of recording bromide-paper is 19 millimeters per second and too slow to distinguish the such quick oscillations as P- or S-wave, and further, these instruments do not carry the equipments to superimpose a mark of shot time on the record. Consequently we can not measure the travel time of the wave directly. Therefore these records are somewhat inconvenient for the purpose of

1) L. DON LEET, *American Scientist, Spring Issue,* **34** (1946), 198.

2) B.F. HOWELL, *Bull. Seism. Soc. Amr.*, **39** (1949), 285.

3) F. KISHIOUYE, *Bull. Earthq. Res. Inst.*, **20** (1942), 215.

studying a new wave.

On the other hand these seismometers have long periods in comparison with those of the ground motion. Therefore we can expect records quite distinct from those recorded by the conventional geophone with short period.

The one seismometer was set to respond to motions toward and away from a shot point and the other perpendicular to this, and the distances from the shot point to the seismometers were varied 40, 48, 70 and 80 meters.

A shot hole with a depth of 3 meters was drilled and shots of 45 grams (1 unit) or 67.5 grams (1.5 units) of 60% dynamite were made at the bottom of the hole.

Time-marks were electrically sent out every second from a chronometer and recorded on the records.

We could obtain five records at 48 and 80 meters distant from the shot point, respectively, but we could obtain only one record at 40 and 70 meters, respectively. Therefore we mainly depend on the records obtained at 48 and 80 meters.

2. Wave Form.

Fig. 1 shows the records observed at the distances of 48 and 80 meters, respectively, and in each distance the two records represent the motions of longitudinal and transverse components. These records are shown as an example at the respective distances and the other records at the same distance have completely similar wave forms. The records observed at the distances of 40 and 70 meters have also similar wave forms, though the records are not shown in the figure.

We will not touch on the parts of P- and S-waves, because both the amplitudes and the periods of these parts are too small and short to be measured clearly. The waves arriving after these parts have large amplitudes and long periods, and at various distances the phases are so similar in longitudinal component that they correspond to one another. The amplitudes of transverse component are remarkably small in comparison with those of loegitudinal component, and each phase hardly corresponds to each other at various distances. This fact suggests that the earth motions of this part predominate in longitudinal component and that these waves have the Rayleigh wave type.

This time we have analysed the waves using longitudinal component.

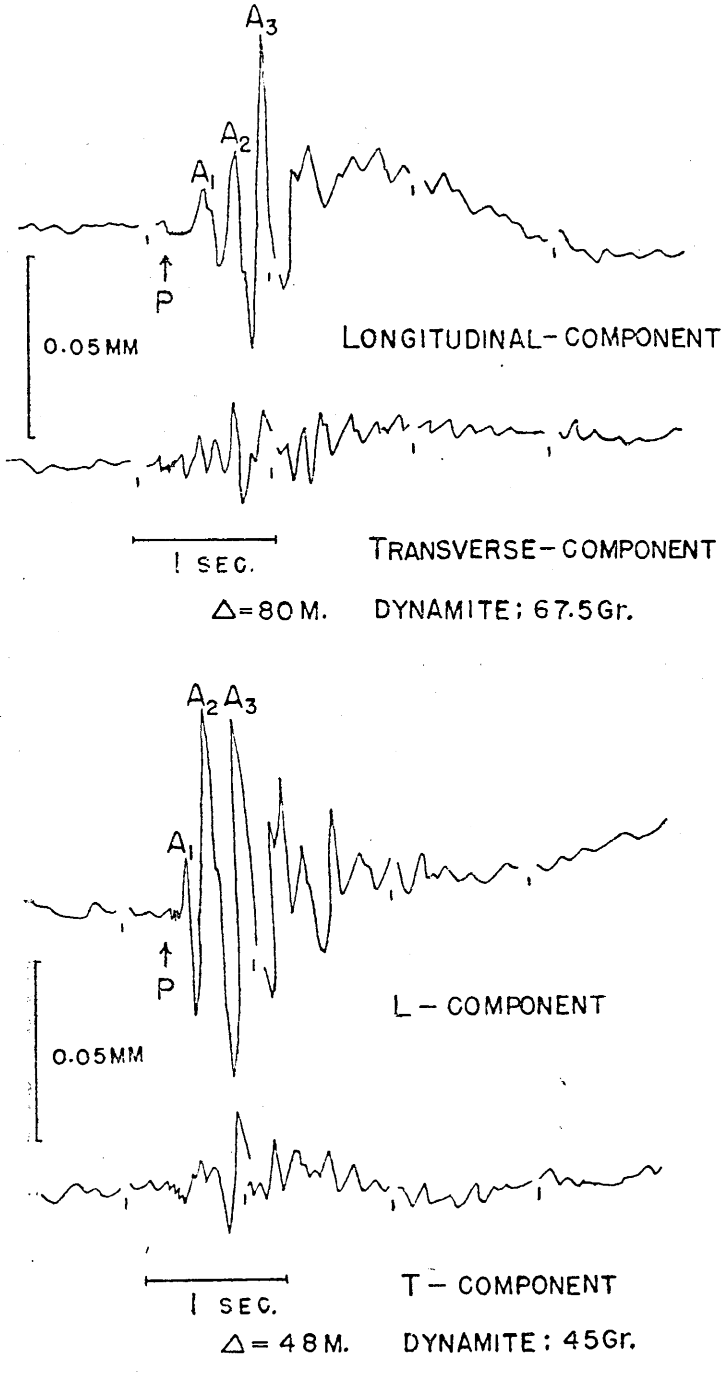

Fig. 1. Records of ground motion at distances of 80 and 48 meters.

3. Wave Analysis.

By the above mentioned reason, we have no intention to touch on the first group of arriving waves, which appears like P- and S-wave. The next group of waves, which starts with the emergent pulse labelled " A_1 " on the records, predominates in longitudinal component, and " A_2 " and " A_3 " follow it. The amplitudes of longitudinal component gradually increases to a maximum, and conspicuous oscillations are repeated about ten times and slowly die out again. In this paper we will analyse the waves, " A_1 ", " A_2 " and " A_3 ".

It is a noticeable fact that these waves predominate in longitudinal component, which we think suggests that these waves may be Rayleigh waves or such waves as the " H "-wave which moves in a longitudinal-vertical plane entirely independent of the motion on the transverse component at the same time. It is necessary to measure the travel time of each wave, but we could not measure directly the travel time on our records since the shot time was not superimposed on our records. Accordingly on every record we measured the times from the beginning of P-phase to the crests of A_1-, A_2- and A_3-wave, respectively, and these intervals in second were marked t_{P-A1}, t_{P-A2} ane t_{P-A3}, respectively. These velues are tabulated in Table I, and the travel time curves plotted by these values are shown in Fig. 2. In Fig. 2 the points of each group seem to lie

Table I.

Distance	t_{P-A_1}	t_{P-A_2}	t_{P-A_3}
meters	sec.	sec.	sec.
40	0.134	0.225	0.462
	—	0.288	0.524
	0.179	0.314	0.596
48	0.172	0.290	0.524
	0.173	0.293	0.527
	0.177	0.295	0.550
70	0.268	0.466	0.705
	0.268	0.490	0.725
	0.273	0.505	0.759
80	0.274	0.489	0.728
	0.275	0.491	0.722
	0.299	0.500	0.774

in a straight line, respectively, and the straight lines computed by least square are as follows;

$$t_{P-A_1} = (0.011 \pm 0.050) + (0.00337 \pm 0.00073)\Delta,$$
$$t_{P-A_2} = (-0.014 \pm 0.080) + (0.00644 \pm 0.00124)\Delta,$$
$$t_{P-A_3} = (0.229 \pm 0.069) + (0.00646 \pm 0.00118)\Delta.$$

On A_1 and A_2 of the three phases, it is asserted that every line passes near the original point of this coordinate. The line of A_3-phase runs

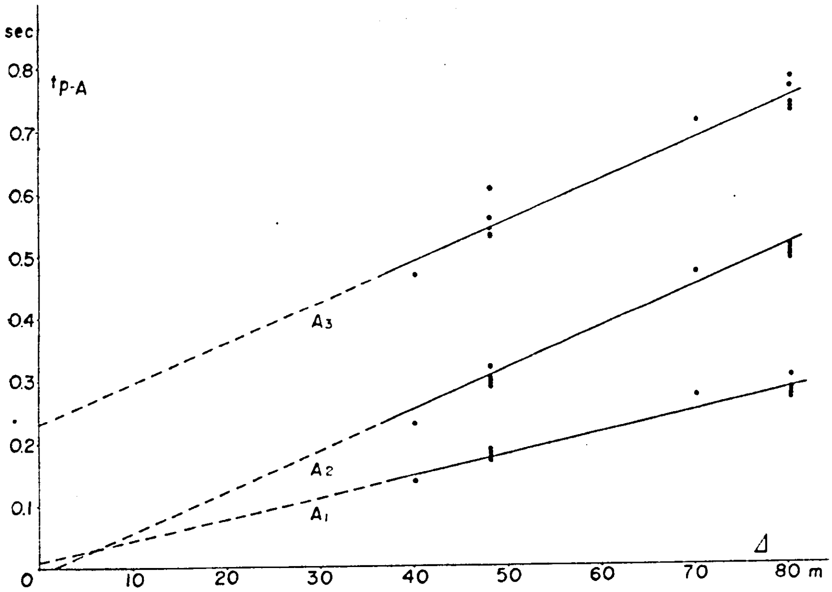

Fig. 2. Travel time curves of A_1-, A_2-, A_3-wave.

parallel with that of A_2-phase. To judge from this figure, A_1 and A_2 seem to be separate kinds of waves with different velocities, and A_3 to be the same kind of wave as A_2.

For the purpose of computing the velocities of A_1 and A_2, we assume that

$$t_{P-A_1} = 0.00337\,\Delta,$$
$$t_{P-A_2} = 0.00644\,\Delta,$$

and put these expressions into the equation

$$t_{P-A_n} = \left(\frac{1}{V_{A_n}} - \frac{1}{V_P}\right)\varDelta,$$

where V_{A_n} is the velocity of the nth wave and V_P the velocity of P-wave.

S. Omote[4] prospected at the same place by geophones and made clear that the velocity of P-wave was 950 meters per second at the surface layer with a thickness of about 10 meters.

Assuming this as the value of P-wave velocity, V_{A_1} and V_{A_2} are computed as follows;

$$V_{A_1} = 226 \text{ m/sec},$$
$$V_{A_2} = 133 \text{ m/sec}.$$

These values of P-, A_1- and A_2-wave are tabulated in the following table together with Leet's values[5] and Howell's values.[6] In Table II Leet's values were calculated by us from the tracing record illustrated in his paper.

Table II.

	P-wave	H-wave		R-wave
	Velocity	Velocity	Period	Velocity
L. Don Leet	665 m/sec.	290 m/sec.	0.14 sec.	187 m/sec.
B.F. Howell	120–750	270	0.22	167.5
R. Ikegami	950	226 (A_1)	0.18	133 (A_2)

On the occasion of Leet's observations, there was a low-velocity layer (p=665 m/sec), with a thickness of about 16.7 meters, and the charge was set off at a depth of about 3 meters. In case of Howell's, there was a "weathered" or "low-velocity" layer with a thickness between 1.2 and 8.4 meters, its P-wave velocity between 120 and 735 meters per second, and the charges were set off at depths ranging from 6.7 to 12.5 meters. In our case, the thickness of a low-velocity layer was about 11.5 meters, according to the result of drilling, (see Fig. 3), and the charges were set off at a depth of 3 meters.

4) S. OMOTE, Read at *Monthly Meeting of the Earthq. Res. Inst. on September*, 1950.
5) L. DON LEET, *loc. cit.*, p. 210.
6) B.F. HOWELL, *loc. cit.*, p. 300.

Comparing these three cases, in every case there were low-velocity layers, and charges were always set off in or near that layer. These may be the conditions necessary for generating "H"-wave, and thereby we think that "A_1"-wave is "H"-wave and that "A_2"- and "A_3"-wave are Rayleigh waves.

The fundamental weakness of our records is that they are wanting in vertical component and that the orbits of the earth particle were not examined. In future we will investigate this problem again by adding the vertical seismometer.

4. Energy.

i) Relation between amplitude of the ground motion and energy of the explosives.

The double amplitudes were measured from the first wave to the 7th wave on the four records observed at 80 meters on the occasion of the explosions of a 1.5 units dynamite (67.5 gr.) and on the record observed at the same distance on the occasion of the explosion of a one unit dynamite (45 gr.). These values are tabulated in Table III. The ratios of the amplitudes between the two cases are shown in the extreme right column of this table, and the mean value of the ratios is 1.33. This result shows that the amplitude of the ground motion is almost in proportion to the square root of the charge (viz. energy transmitted from the focus), and is equal to the results obtained in the past from other data.

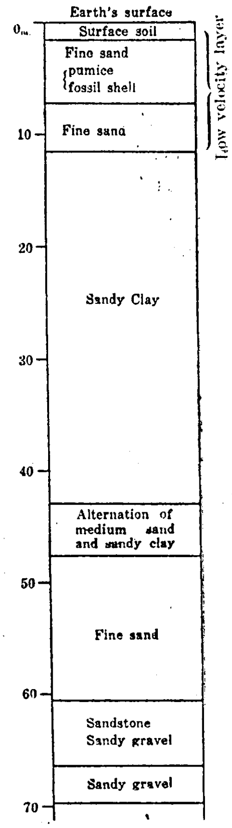

Fig. 3.
Driller's log at the site of the experiments. (By the courtesy of Chiyoda Natural-gas Co. Ltd.)

For the purpose of calculation of the energy, the amplitudes of the third waves, (A_3), observed on the occasion of the explosion of one unit dynamite at the distance of 48 meters are shown in Table IV.

Table III.

$\Delta = 80$ m.

Wave	Dynamite 67.5 gr.					Dynamite 45 gr.	Amplitude ratio
	1	2	3	4	mean		
	mm.	mm.	mm.	mm.	mm.	mm.	
1st (A_1)	—	8.1	9.8	7.5	8.50	6.8	1.25
2nd (A_2)	16.4	14.4	16.9	18.1	16.45	12.3	1.33
3rd (A_3)	42.2	38.9	42.2	44.4	41.90	—	—
4th	17.7	16.7	20.1	13.1	16.80	13.9	1.20
5th	5.9	5.5	7.6	6.0	6.30	4.7	1.34
6th	8.2	7.7	—	7.6	7.80	4.9	1.59
7th	4.0	4.3	5.8	3.3	4.40	3.5	1.25

mean 1.33

ii) Transmission of energy.

In order to establish a way of transmission of energy transferred by the waves treated here, we considered the two cases of three- and two-dimensional transmission and examined to which of the two cases the observed values may be applied.

Table IV.

$\Delta=48$ m. (Dynamite 1 unit)

Record No.	Amplitude of the 3rd wave (A_3)
	mm.
1	54.0
2	50.7
3	40.4
4	52.2
5	32.7

mean 46.0

When the energy is transmitted semi-spherically in the earth, provided that the absorption of energy into the earth is not taken into account, the energy E_1 and E_2 crossing unit surface at right angle to the direction of propagation at distances Δ_1 and Δ_2 are $E_1 = E/2\pi\Delta_1^2$ and $E_2 = E/2\pi\Delta_2^2$, respectively, where E is the total energy spread out from the focus. (See Fig. 4 (a)). Therefore

$$E_1/E_2 = (\Delta_2/\Delta_1)^2 .$$

Taking $\Delta_1 = 48$ meters and $\Delta_2 = 80$ meters,

$$E_1/E_2 = 2.77. \quad \dots\dots\dots\dots\dots\dots\dots\dots(1)$$

When the energy is transmitted two-dimensionally maintaining a constant depth L, E_1 and E_2 are $E/2\pi\Delta_1L$ and $E/2\pi\Delta_2L$, respectively. (See Fig. 4 (b)).

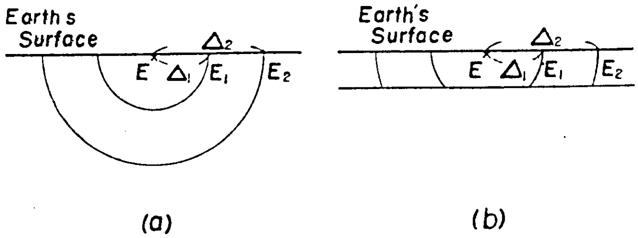

Fig. 4.

Therefore

$$E_1/E_2 = \Delta_2/\Delta_1 .$$

Taking $\Delta_1 = 48$ meters and $\Delta_2 = 80$ meters,

$$E_1/E_2 = 1.66. \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

On the other hand, let M_1 and M_2 be the amplitudes of the third wave at Δ_1 and Δ_2, respectively, and $M_1 = 46.0$ and $M_2 = 41.9$ millimeters on Table IV and Table III.

Considering the difference of charges,

$$E_1/E_2 = \frac{1.5(46.0)^2}{(41.9)^2} = 1.80. \quad \ldots\ldots\ldots\ldots (3)$$

Provided that we compare the values of (3) with those of (1) and (2), we see that the energy of waves treated by us were spread out two-dimensionally. This indorses the fact that the waves treated by us were a kind of surface waves.

Jeffreys[7] showed that the energy in a Rayleigh wave is the same as if there were no vertical motion, and that the horizontal motion has the same amplitude at the surface as down to a depth of 1.12 wave-length. In the subsequent calculation we will use the wave-length as the value of L in the expression in (iii).

iii) Energy of the ground motions.

Let V be the velocity, T the period and M the amplitude of the ground motion at the distance of Δ, and let us suppose that the energy spreads out two-dimensionally from the focus. Then the energy is computed by the following expression.

7) H. JEFFREYS, *Geophys. Supp. Roy. Astro. Soc.*, **1** (1923), 24.

$$E = 4\pi^2 \varDelta L\rho \int \frac{M^2 V}{T^2}\, dt = 4\pi^3 \varDelta L\rho \frac{M^2 V}{T},$$

where ρ is the density.

Taking $\rho = 2.5$ gr./cm³., $\varDelta = 80$ m., $T = 0.20$ sec., $L = 26.6$ m., $V = 133$ m./sec., and $M = 0.008$ cm., we obtain the value 28.1×10^9 ergs. as the energy in the third wave from this expression.

Using this value of the third wave, we computed the energy of each wave from the first wave to the tenth wave. These values are shown in Table V, and the total energy was about 4.0×10^{10} ergs. In the present

Table V.

Wave	Traced amplitude	Energy
	mm.	ergs.
1st	8.50	1.1×10^9
2nd	16.45	4.3
3rd	41.90	28.1
4th	16.80	4.5
5th	6.3	0.6
6th	7.8	0.9
7th	4.4	0.3
8th	4.7	0.3
9th	3.8	0.2
10th	2.4	0.1

Total energy
40.4×10^9
$\fallingdotseq 4.0 \times 10^{10}$ ergs.

case the total energy computed here is only the energy of surface waves, and the energy of the other parts of the wave train is not taken into account, since it is presumed that the energy of the other parts is weak.

The charge consisted of 1.5 units (67.5 gr.) of 60% nitroglycelin, and the total energy of it is about 2.6×10^{12} ergs. Therefore the ratio between the total energy of the ground motion and the total energy spread out from the charge is

$$\frac{4.0 \times 10^{10}}{2.6 \times 10^{12}} = 1.5 \times 10^{-2}.$$

Namely, we see that 1.5×10^{-2} parts of the total energy spread out from the charge were spent as the energy of the wave-motions and the other parts were spent as sound, heat and others.

In closing, I wish to express my appreciation to Prof. F. Kishinouye for his guidance and to Mr. Y. Sato for his advice.

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16. 火薬の爆發によつて起される地動について

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東京都江東區南砂町に於て，ダイナマイトの爆發によつて起される地動を岸上式微動計で観測した。その記象を用ひて解析を行つた處，最近 L. Don Leet[1] によつて最初に發見された H-波 (Hydrodynamic-wave) と同種類の波と思はれるものが存在する事が判つた。

更に地動の振幅は薬量（エネルギー）の略々平方根に比例する事，エネルギーの傳播は我々の取扱つた波については二次元的である事，ダイナマイトが放出する全エネルギーの内約 1.5/100 が地動となつて傳播する事等が判つた。