

16. *Seismic Prospecting on a Sea Bottom.*

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Introduction.

For examining the geological structures of a coal field, seismic prospecting was attempted on a sea bottom in two places, namely, in the bay of Ariake-Sea and in the offing of a sea in Yamaguti Prefecture. In the case of the former, the prospecting was over a length of about 9 km from the seashore towards the offing, one observation point being set on the islet and another on the shoal in the bay. A mechano-optical seismograph was used at the point on the islet, while an electromagnetical seismograph of moving coil type was used at the point on the shoal. In the case of the offing, Yamaguti Prefecture, in which the prospecting was entirely in the sea from 10 to 20 m deep, an electromagnetical seismograph of changing flux type was used, a transducer being set on the bottom of the sea, and the record obtained on a boat.

In this paper, the seismographs used will first be briefly described, followed by descriptions of the field work and the observational results.

Seismographs.

1) *An Electromagnetical Seismograph of Moving Coil Type.* For the purpose of seismic prospecting, an electromagnetical seismograph with a transducer of moving coil type was constructed. The instrument consists of three parts, namely, a transducer, a valve amplifier, and a galvanometer. The transducer, as shown in Fig. 1, is constructed similar to the dynamic cone for a radio set. A brass circular disk D , to which a circular coil of enamelled wire is attached, and which is suspended by a metal plate P , forms a pendulum of vertical component with a period of 0.1 sec. For reducing the restitutive force, the metal plate is cut into the shape shown in the figure. Since, when the pendulum moves, the coil cuts the magnetic field that is produced by the electromagnet E , electromotive force is induced in the coil. The transducer is made water-tight. The electromotive force induced in the transducer is amplified by a three-tube amplifier, containing input and output transformers, specially designed to keep a fairly constant

characteristics for frequencies larger than 10 cycles per sec.

The galvanometer used here has a sensibility of 2×10^{-4} ampere/mm, with a period of 1/10 sec, being strictly overdamped by oil. The equation of motion of a galvanometer is, usually, written

$$\frac{d^2\theta}{dt^2} + a \frac{d\theta}{dt} + b\theta = ci,$$

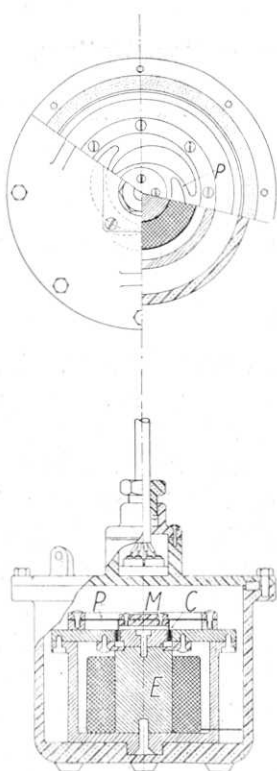


Fig. 1. Schematic diagram of the moving coil type transducer.



Fig. 2. Moving coil type transducer.

where θ is the deflection angle of the galvanometer coil, i the current, and a, b, c are constants. When the galvanometer coil is strictly overdamped, constant a is very large, so that the foregoing equation may be written

$$a \frac{d\theta}{dt} = ci,$$

or

$$\theta = \frac{c}{a} \int_0^t i dt + \text{Integral constant}.$$

That is, the deflection of the galvanometer coil is proportional to the integrated value of the current, neglecting the integral constant. Since the current produced by the transducer is proportional to the displacement of the earth ground once differentiated by time when the vibration is more rapid than the period of the transducer, the deflection of the coil in this case is proportional to the displacement of the ground

itself. Thus, the instrument is a displacement recorder for vibrations with period of a certain range shorter than 0.1 sec.

Magnification of the instrument, which is varied by a potentiometer that is attached to the grid circuit of the third valve in the amplifier, may be had up to 500,000. Fig. 11 is a reproduction of a record by this seismograph, and of the mechano-optical seismograph with magnification 40,000, which latter was installed in the same place for comparative tests.

2) *An Electromagnetical Seismograph of Changing Flux Type.* The electromagnetical seismograph with a transducer of changing flux type, in which the air gap in a magnetic circuit is changed by the motion of the pendulum, the resulting change in magnetic flux producing the electromotive force in a coil, was first constructed by H. Benioff,^{1,2)} its theory being discussed by E. C. Bullard³⁾ and J. J. Devlin, S. J.⁴⁾ Instruments of this type have the advantage that they are easily constructed and are most suitable for field use, such as in seismic prospecting. They have been in extensive use for a number of years, especially in America.

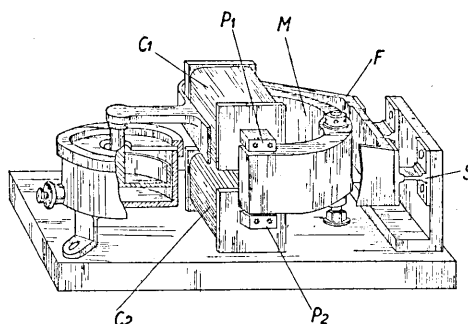


Fig. 3. Schematic diagram of the changing flux type transducer.

The seismograph used in the present case is an instrument constructed by one of the writers on the same principle, a schematic diagram and a photograph reproduction of it being shown in Figs. 3, 4. A permanent horseshoe magnet *M* is fixed to the platform of the instrument. The armatures *P*₁ and *P*₂, made of permalloy, are attached to an aluminium frame *F* that is suspended by two flat springs *S*. Enamelled copper wire *C*₁ and *C*₂ is wound around the armatures. This system forms a pendulum of vertical component, the coils and armatures acting as a pendulum mass. For damping the pendulum, an air damper *D* of piston type is attached. There are small air gaps between the armature and the pole of the magnet. Since, when the pendulum moves, the distance of the air gaps on one side is increased and that on the other side decreased, the magnetic flux through the armatures may be varied, whence electromotive force is produced in the coils, which are combined

1) H. BENIOFF, *Bull. Seism. Soc. Am.*, 22 (1932), 155.

2) H. BENIOFF, *Bull. Seism. Soc. Am.*, 25 (1935), 283.

3) E. C. BULLARD, *Mon. Not. Roy. Astron. Soc., Geophys. Suppl.*, 4 (1938), 336.

4) J. J. DEVLIN, S. J., *Bull. Seism. Soc. Am.*, 28 (1938), 255.

in series to aid each other, and connected to a socket. Provided the distances of the air gaps are kept equal, and the displacement of the armature is sufficiently small, the electromotive force of output is given by⁵⁾

$$E = k \frac{\phi_m}{x_0} \frac{dx}{dt}, \dots \dots \dots (1)$$

where k is the total number of turns in the coil, x_0 the length of air gap, ϕ_m the total flux through the permanent magnet, x the displacement of the armature, and t the time.

The constants of the instrument are

Natural period	k	ϕ_m	x_0	Resistance of the coils in series
1/20 sec	1000	3.5×10^4 Maxwell	0.2 cm	5.0×2 ohm

The leading wire goes from the socket of the transducer direct to the terminals of an oscillograph, an electric circuit in series being formed by the coils, the leading wire, and the vibrator of the oscillograph. For this purpose, a portable electromagnetic oscillograph with three elements (Yokogawa N-3 Type) was used, the constants of which are as follows.

Sensibility (when shunted)	Period	Resistance of vibrator	Shunt resistance for damping the vibrator critically	Resistance of oscil- lograph circuit when shunted
1.5×10^{-6} $\frac{\text{amp}}{\text{mm}}$ (3.6×10^{-6})	$\frac{\text{sec}}{1/150}$	$\frac{\text{ohm}}{8.5}$	$\frac{\text{ohm}}{6}$	$\frac{\text{ohm}}{3.5}$

Putting the numerical values into equation (1), we get $E = 1.8 \times dx/dt$ (in volts), so that the electric current passing through the oscillograph circuit is $I = E/R = 0.13 \times dx/dt$ (in amperes), where R is the resistance of the circuit that is made by the vibrator of the oscillograph and the coil of the transducer, both in series, neglecting the resistance of the leading wire. A deflection of 1 cm on the record therefore corresponds to $3.6 \times 10^3 \times dx/dt$. Since the magnitude of x , neglecting detailed figures, is of the same order as the amplitude of the earth movement, if, for example, we assume that the period of vibration of the ground is 1/20 sec, the maximum value of dx/dt (which is expressed by $2\pi x/T$, T being the period) is approximately equal to $126 \times x$, consequently a deflection of 1 cm on the record corresponds to $4.5 \times 10^5 \times x$, so that the amplitude of the vibration is magnified 4.5×10^5 times. Actually, it is necessary to take into consideration the leakage of the magnetic flux, the resistance of the leading wire, the inductance in the coil of the trans-

5) J. J. DEVLIN, *loc. cit.*

ducer, and the dynamical effect of the pendulum, etc., all of which reduce somewhat the magnification from that of the foregoing rough calculation. But a magnification of the order of 10^5 can be obtained for vibrations with periods ranging from $1/20$ to $1/100$ sec, which are frequent in earth movements, those caused by explosions, for example. By experiment, for a period of $1/20$ sec the magnification of this instrument was found to be 2×10^5 . A reproduction of a record obtained by three transducers of this type is shown in Fig. 5.

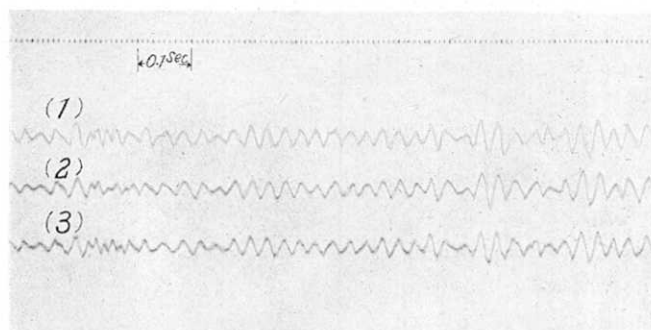


Fig. 5. Records obtained by three transducers of like type.
(Microseism due to street traffics.)

Field Work.

1) *Field Work in the Ariake-Sea.* For examining geological structures with the aid of artificial disturbances, the choice of the line along which the explorations are to be made must be carefully made. In the case of prospecting at the Ariake-Sea, since it was expected that a soft Alluvial layer about 300 m thick and a Tertiary stratum, about 500 m thick overlie the Paleozoic stratum, in order to use the refraction method, it was necessary to take a seismic traverse 4000 m long. As the area to be explored was under sea-water from 10 to 30 m deep, the seismograph was at first set up in the lighthouse that stands on a small islet, 2000 m distant from the shore. At a distance of 4000 m from the lighthouse, there was a shallow, 10 m below the M. S. L., upon which a tower has been built to serve as a footing for future boring operations. Since, in this place, the mechano-optical seismograph was no more available, an electromagnetical seismograph was used, namely, a moving coil type transducer, enclosed in a water-tight brass container, was placed on the sea bottom, 30 m away from the tower, a wire being led from this to the galvanometer fixed on the tower. The transducer was set up in a small hole dug previously into the top of a big concrete block, in order to prevent it from being swept away by the tidal current.

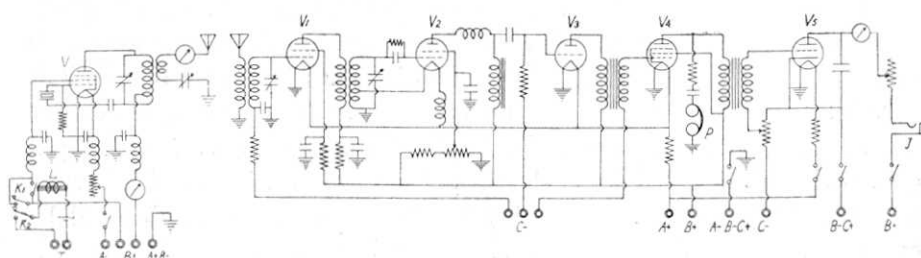


Fig. 6. Wiring diagram of the wireless apparatus.

V_1 —Transmitting tube (UY47), V_2, V_3, V_4 —Receiving tubes (UX32, UX32, UX30, UY33), V_5 —Thymotron relay tube (TY16G), L —Electromagnet, K_1 and K_2 —Keys, P —Phones, J —Electromagnet.

The needed shock was caused by a dynamite blast. The dynamite with an electrical detonator inserted was loaded in a water-tight tin can, and submerged at the sea bottom. The lead wire of the detonator and another wire wound around the outside of the can reached a boat. A transmitter and receiver for a short wave wireless, a mechanical relay for controlling the key of the transmitter, and a blasting machine were kept in readiness on the boat. Wireless is used not only to communicate between the boat and the observation point, but also to time the instant of explosion. The circuit of the wire that is wound around the outside of the can, which is closed before the explosion, is cut off by the explosion, thus interrupting the work of the wireless transmitter. Since, in this process, owing to the low electrical resistance of the sea-water, it is not suited for leading the high voltage current to the wire that is wound around the can, a mechanical relay is used for controlling the key

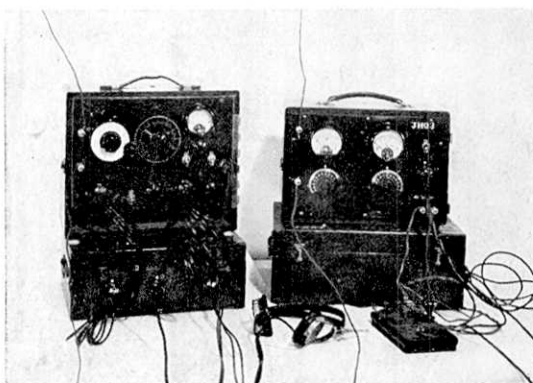


Fig. 7. Wireless apparatus (Right—Transmitter, Left—Receiver).



Fig. 8. Preparing to set up the transducer on the sea bottom (Ariake-Sea).

of the transmitter.

The shot points were placed every 200 m along a straight line. Upon receiving signals from the two base points of the survey on the shore, where the transits are set up, the boat proceeds to the shot point. The dynamite is dropped into the sea when it is judged that the boat has arrived at the point where the shot is to be fired. The position of the boat at this instant is determined exactly by the transits on the shore. As the dynamite reaches the sea bottom, the boat recedes several tens of meters, and as soon as everything is ready for taking the seismic record at the observation point, the dynamite charge is fired.

The elastic disturbance thus generated spreads out in every direction from this point of origin until the transducer, which is set up at the observation point, is excited. The electric current that is induced by the transducer is led by wire to the galvanometer after it has passed through the amplifier. In order to record the instant of explosion, the receiver, which is set up side by side with the galvanometer and amplifier, catches the wireless signal emitted from the shot point. This high frequency wave, which is converted into a low frequency current of several thousands of cycles, is then amplified. The amplified current is detected by the ear-phones and at the same time works the relay. For the relay, a thymotron valve is used. In short, during the signal emitted from the shot point, the relay works and the circuit, which contains a coil of electromagnet, is closed, deflecting a flat iron bar placed in front of the coil. The moment emission ceases, the relay ceases to function, so that the iron bar detaches itself from the coil, recording a discontinuity in the time line to be recorded. In these processes, one explosion gives one record.

2) *Field Work in the Yamaguti Field.* Upon conducting seismic

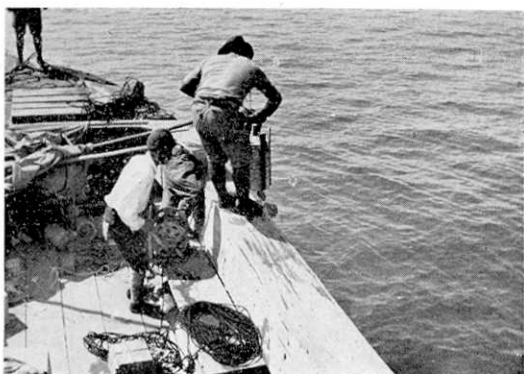


Fig. 9. Dropping the explosive into the sea (Ariake-Sea).

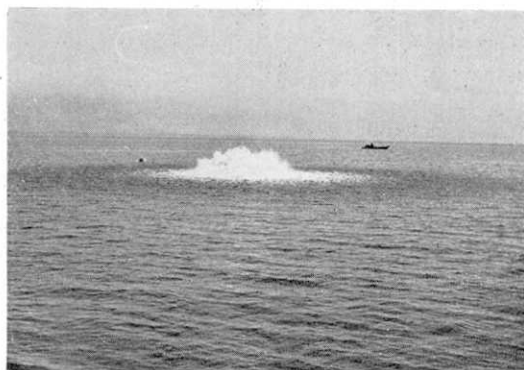


Fig. 10. Explosion.

prospecting at the offing of a certain city in Yamaguti Prefecture, there was no shallow place, such as the shoal of the Ariake-Sea. Besides, as the area to be explored was much more extended, it was impossible to build a tower for every observation station. For the transducer in this case, a changing flux type seismograph, which was placed in a water-tight container, was let down to the sea bottom from the boat. The container, in addition to being perfectly water-tight, is also heavy, so that it will not be swept away by the tidal current, a heavy zinc mass filling the space in it. The wire leading from the transducer to the oscillograph set up on the boat, which is anchored in the neighbourhood of the transducer, records the movement of the ground. The position where the transducer is to be located must be surveyed by the intersection method of using two transits set up on the seashore.

The changing flux type transducer used here being sufficiently sensitive to give a direct magnification of the degree desired, the amplifier was dispensed with, so that field difficulties were lessened to a large extent.

The area covered in the foregoing observations amounts to about 50 sq. km, and 10 lines of observations. The analysis of the time-distance curves that follows is concerned with only one of these 10 lines of observations.

Analysis of the Time-distance Curves.

1) *Observational Results in the Ariake-Sea.* The time-distance curves obtained by the foregoing observations are shown in Fig. 12. As will be seen from the figure, there are three phases, namely, that of the direct surface wave (P_1), that of waves totally refracted in the second layer (P_2), and that of waves totally refracted in the third layer (P_3).

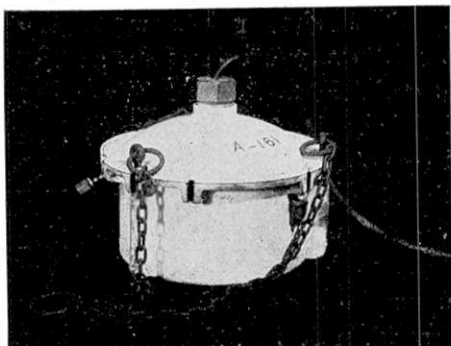


Fig. 13. Water-tight container to hold the transducer.

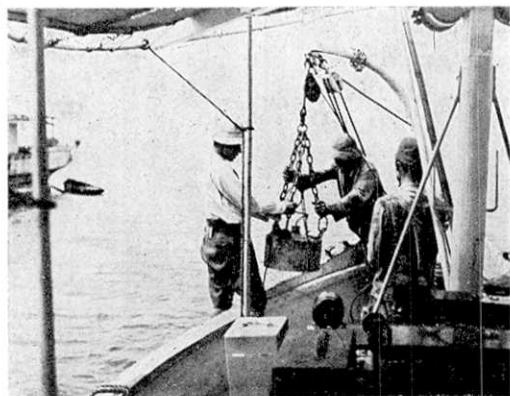


Fig. 14. Sending the transducer to the sea bottom.

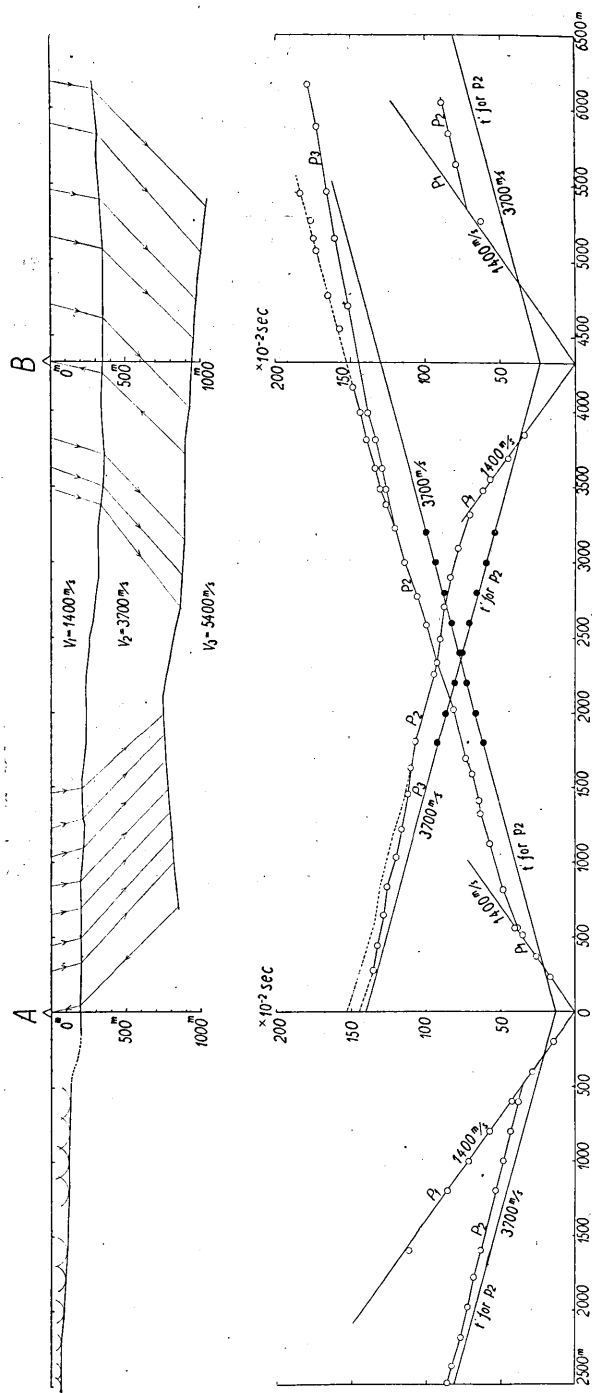


Fig. 12. Time-distance curves (Ariake-Sea).

The propagating velocity of the direct surface wave was determined direct from the time-distance curve to be $V=1400$ m/s. Next, the propagating velocity in the second layer and the depth of that layer at each point must be determined. Here the depth of the second layer is given by⁶

$$h_s = \frac{V_1(t_{SA} + t_{SB} - t_{AB})}{2 \cos i},$$

where h_s is the depth of the second layer at a point S between stations A and B , t_{SA} the travel time of P_2 from S to A , t_{SB} and t_{AB} having also the same meaning, and $\sin i = V_1/V_2$ (V_2 is the propagating velocity in the second layer). The value of V_2 is obtained by considering a quantity, t'_{SA} , that is given by

$$\begin{aligned} t'_{SA} &= t_{SA} - \frac{(t_{SA} + t_{SB} - t_{AB})}{2} \\ &= \frac{h_A \cos i}{V_1} + \frac{x}{V_2}, \end{aligned}$$

where x is the distance of S from A .

The above equation being linear for x , if we take x as abscissa and t'_{SA} as ordinate and plot the corresponding points, a sort of time-distance curve is obtained, the inclination angle of which gives the velocity V_2 . For convenience, we call this the " t' -curve". This procedure cannot be used at points in the neighbourhood of A or B , where the travel time is not for the refracted wave but for the direct surface wave, in which case t' is read off from an extension of the " t' -curve", when h_s is given by

$$h_s = \frac{V_1(t_{SA} - t'_{SA})}{\cos i} \quad \left(\text{or } \frac{V_1(t_{SB} - t'_{SB})}{\cos i} \right).$$

The actual values are shown in Table I.

As to the P_3 phase, since the foregoing procedure cannot be used, the graphic method was resorted to, in which the travelling time of the refracted wave is calculated with the aid of a model of the assumed underground structure, and then compared with the observed value. The model is gradually altered until the values, both calculated and observed, are the same within an error of 1/100 sec. In this case, the propagating velocity through the third layer (granite) was assumed to be 5500 m/s, according to the result of previous seismic prospecting on land near the present prospecting site, in which former place the depth of the third layer was very shallow.

6) T. HAGIWARA and S. OMOTE, *Bull. Earthq. Res. Inst.*, 17 (1939), 118.

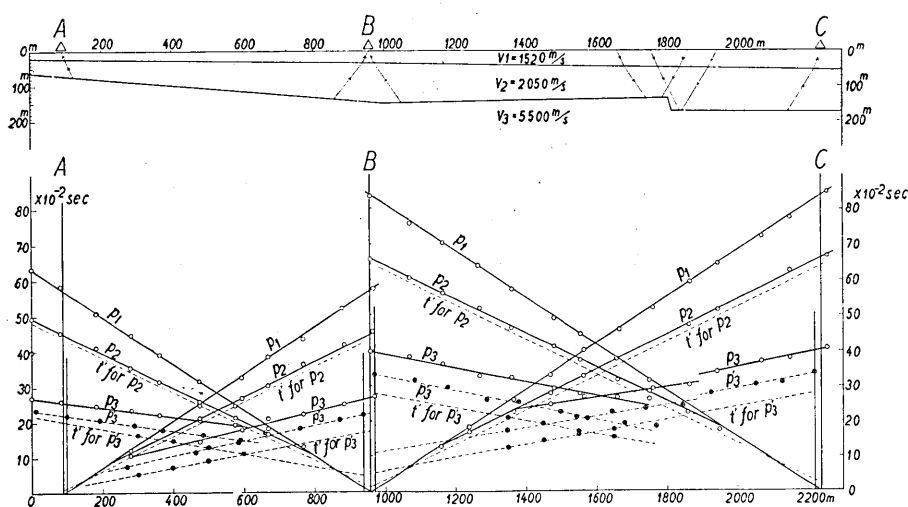


Fig. 16. Time-distance curves (Yamaguti field).

Besides, it had to be assumed that the depth of the third layer at one point is known, namely, that the depth of the third layer at the point near *A* is 840 m, based on the results of boring at the point "—160 m".

1) *Observational Results in the Yamaguti Field.* One of the time-distance curves obtained by the exploration in the Yamaguti field is shown in Fig. 16. Three phases P_1 , P_2 , and P_3 are found in the seismograms (Table II). P_1 is the direct wave in the first layer (Alluvium), P_2 the refracted wave in the second layer (Tertiary), and P_3 the refracted wave in the third layer (Palaeozoic). In the present case, the P_2 phase appears behind the P_3 phase. The propagating velocity of P_1 is 1520 m/s. We determined first the depth of the second layer by means of the travel time of P_2 , for which the " t' -curve" method just mentioned was used. After the depth of the second layer was determined, the travel time of P_3 was changed by calculation to the travel time, for which the observation points and the shot points lay, as it were, on the upper surface of the second layer. The time-distance curves for such an imagined case are shown in the figure by P_3' , from which we may regard the matter as a case of a two layered structure, so that the " t' -curve" method could be applied in determining the depth of the third layer and the velocity through it.

Table I, a.

$$V_1 = 1400 \text{ m/s, } \sin i = V_1/V_2 = 0.379, \quad V_1/\cos i = 1515 \text{ m/s,}$$

$$V_2 = 3700 \text{ m/s, } \cos i = \dots\dots 0.925, \quad T_{AB} = 153.0,$$

Distance	1800 ^m	2000 ^m	2200 ^m	2400 ^m	2600 ^m	2800 ^m	3000 ^m	3200 ^m
t_{SA}	76.0	80.9	87.9	94.3	100.0	106.7	114.4	119.8
t_{SB}	108.1	101.9	96.2	91.9	88.8	85.6	80.8	74.0
h_S	237 ^m	226 ^m	237 ^m	252 ^m	272 ^m	300 ^m	321 ^m	310 ^m

$$\text{Unit of time} = 1/100 \text{ sec, } h_A = r_A \times \frac{V_1}{\cos i} = 197 \text{ m, } h_B = r_B \times \frac{V_1}{\cos i} = 350 \text{ m}$$

Table I, b.

Distance	600 ^m	800 ^m	1000 ^m	1200 ^m	1400 ^m	1600 ^m	....	2400 ^m	3600 ^m	3800 ^m	4000 ^m
t	40.0	47.6	53.8	59.8	64.2	70.0	....	127.0	133.3	139.0	143.4
t'	29.0	34.6	40.0	45.3	50.8	56.2	....	104.8	110.0	115.5	121.0
h_S	167 ^m	198 ^m	210 ^m	220 ^m	204 ^m	210 ^m	....	337 ^m	354 ^m	357 ^m	340 ^m

Distance	4200 ^m	4400 ^m	4600 ^m	4800 ^m	5000 ^m	5200 ^m	5400 ^m	5600 ^m	5800 ^m	6000 ^m
t	149.1	154.0	158.0	161.9	166.5	171.3	178.9	78.0	82.7	87.3
t'	126.4	131.7	137.0	142.4	148.0	153.2	158.6	57.5	62.9	68.1
h_S	345 ^m	338 ^m	319 ^m	296 ^m	281 ^m	275 ^m	309 ^m	312 ^m	301 ^m	292 ^m

Table I, c.

Distance	-600 ^m	-800 ^m	-1000 ^m	-1200 ^m	-1600 ^m	-1800 ^m	-2000 ^m	-2200 ^m	-2500 ^m
t	38.3	43.6	48.2	53.8	63.9	68.7	72.9	77.5	86.7
t'	30.0	35.5	40.9	46.2	57.1	62.4	67.3	73.2	81.3
h_S	126 ^m	123 ^m	110 ^m	115 ^m	103 ^m	95 ^m	85 ^m	67 ^m	67 ^m

Table II.

Travel time of P_1 , P_2 , and P_3 .

(The distance was measured from the base point, the unit of time being 1/100 sec.)

Observation point = A (88 m), unit of time = 1/100 sec.

Shot point	280 ^m	474 ^m	596 ^m	670 ^m	770 ^m	885 ^m	967 ^m
P_1	12.2	24.7	32.7	38.4	43.4	52.2	58.0
P_2	10.7	20.6	26.8	30.4	36.2	41.8	45.5
P_3	—	14.5	17.8	21.0	22.0	24.9	27.1

[T. HAGIWARA and S. OMOTE.] [Bull. Earthq. Res. Inst., Vol. XVIII, Pl. VII.]

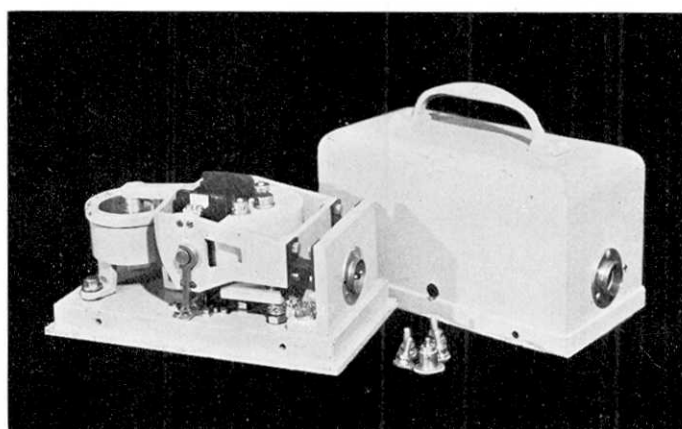


Fig. 4. Changing flux type transducer.

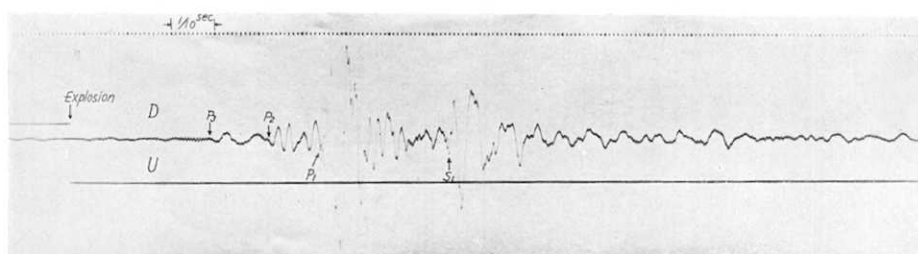


Fig. 15. Record obtained in the Yamaguti field.

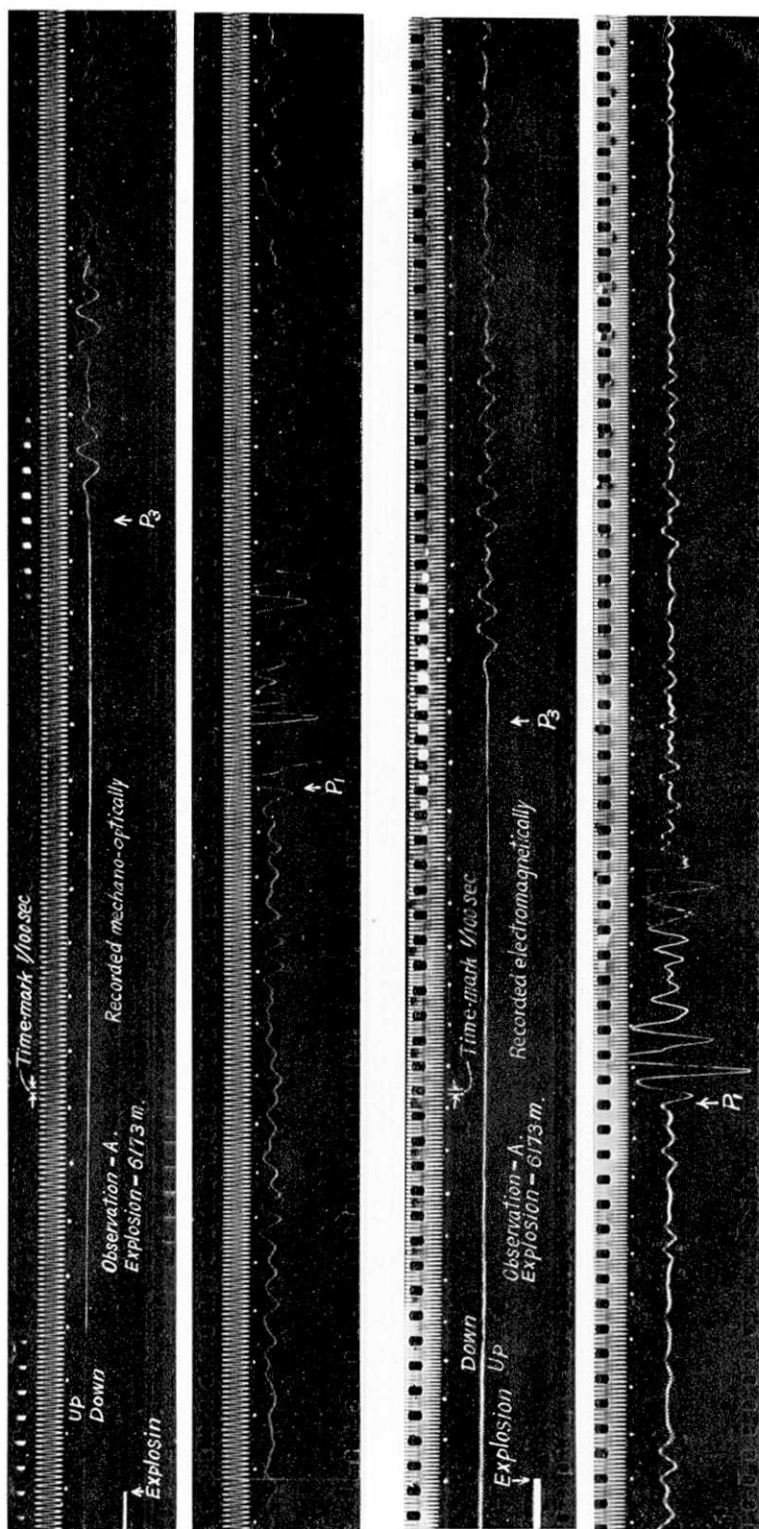


Fig. 11. Comparison of records obtained by the mechano-optical seismograph and the electromagnetical seismograph (Ariake-Sea).

Observation point = B (958 m)

Shot point	0 ^m	83 ^m	182 ^m	282 ^m	362 ^m	475 ^m	577 ^m	673 ^m	764 ^m
P_1	63.1	58.3	50.7	44.7	39.2	31.7	25.8	18.2	12.8
P_2	49.4	45.3	41.2	35.5	31.5	25.9	21.2	16.5	—
P_3	27.2	26.0	24.7	23.5	22.0	20.6	19.2	—	—

Observation point = B (958 m)

Shot point	1163 ^m	1240 ^m	1366 ^m	1469 ^m	1565 ^m	1665 ^m	1758 ^m	1864 ^m	1944 ^m	2072 ^m	2150 ^m	2255 ^m
P_1	12.7	18.1	26.1	33.0	40.0	45.8	52.0	59.4	64.5	72.3	77.5	84.9
P_2	—	16.7	22.6	27.9	32.7	—	—	47.2	51.5	—	62.5	66.9
P_3	—	—	—	24.8	26.9	28.2	29.2	30.2	34.0	36.8	37.8	40.5

Observation point = C (2238 m)

Shot point	963 ^m	1070 ^m	1165 ^m	1271 ^m	1360 ^m	1478 ^m	1557 ^m	1660 ^m	1751 ^m	1859 ^m	1951 ^m
P_1	83.7	76.0	70.4	63.9	57.2	49.0	43.0	37.5	31.5	—	—
P_2	66.0	60.5	56.3	52.0	45.7	41.0	37.2	31.6	28.5	22.5	17.5
P_3	39.9	38.4	36.1	32.9	32.2	29.0	27.6	26.7	26.2	—	—

16. 海底に於ける弾性波地下探査

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最近、有明海及び山口縣某市沖合に於て海底の Seismic prospecting を實施した。海底に於ける微動観測には、新たに製作せられた電磁型高倍率地震計を使用した。有明海に於ては動線輪型、山口縣に於ては變磁束型の Transducer を使用した。是等の Transducer は何れも耐水容器の中に收められて、海底に置かれた。有明海に於ては、海中の適當な場所に淺瀬があつたため、この上に塔を組み記録装置は此處に置かれたが、山口縣沖合に於ては記録操作は全部船の上で行はれた。振動源としては、海底にダイナマイトを吊下げ、これを爆發せしめた。調査の結果は、海底下數百米に於ける地層（沖積層、第三紀層、古生層等）の境界を判然と知ることが出來た。