Expansion of Applicability for Suspension P-S Logging

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Abstract

The suspension P–S Logging is capable of measuring the P wave and S wave velocity propagating through the layers, without fixing in the borehole the sonde composed of seismic source and geophones. Based on the spacing fixed between the seismic source and the geophone (s) irrespective of the measurement depths, the measurement is conducted with the difference of propagation time between the two geophones, which relieves the time resolution from being affected by the measurement depth. Accordingly, compared to the conventional method in which the seismic source is placed on the ground surface while the geophones being fixed in the borehole, the suspension P–S Logging retains the feasibility for wider application scope.

In respect of the application of the suspension P–S Logging for the layers where propagation velocity of S wave is approximately up to 1,000 m/sec, so far sufficient reliability of the data thus obtained has been confirmed. Yet, in case of its application for the layers where S wave velocity exceeds 1,000 m/sec, the quality aptitude of eventual record indicates deterioration. Especially the deterioration is remarkable with the record on P wave.

For further wider utilization in future of the suspension P–S Logging, it is essential to expand its applicable limit. Additionally, the current method of measurement through suspending the sonde with every 1 m shift involves the factor causing less acceptability of the method among the users in general because of considerable measurement time required.

"Expansion of Applicability" referred to in the title of this paper can only be achieved through both of the enhancement with measurement limit of velocity and the setup of the measurement system easily acceptable by the users in general. In order to make the system easily acceptable for the users in general, the tasks of prime importance have been focused on the two respects, i.e. to conduct continuous logging while moving the sonde on one hand and to lift the restriction with the cable for use on the other hand.

As of June, 1988 the author and his collaborators are convinced of the applicability for the suspension P–S Logging system having been expanded to cover up to 3,000 m/sec with S wave velocity. Additionally, different from the conventional measurement job that required suspension of sonde at each measurement depth, positive prospect has now been foreseen on the measurement continuously conducted while moving the sonde at the speed of 6 m/min and on the system in which any armored cable for logging can flexibly be used, out of the available varieties constituted by those of 1–conductor, 4–conductor, 5–conductor, 7–conductor etc.

With reference to the gain through the measurement system constituted by the source and the geophones, through the augmentation of the radiation impedance with the source and by the enhancement of the sensitivity with the geophone, the improvement has successfully been made to the aptitude 15 to 20 times higher than that the conventional measurement system could reach, thereby the innovated measurement system having been found appropriately applicable for the layer with S wave velocity at 3,000 m/s. In addition, the improvement could be achieved with the measurement of P wave velocity through the use of the hydrophone.

Furthermore, various improvements have been realized through utilization of electronics technology to make application of any of the available armored cables for logging feasible and to conduct flexible change with parallel/serial arrangement with data for continuous logging, by the determination on the optimal length of the filter tube after consideration of its performance characteristic, by establishing the countermeasure against noise in view of the continuous logging and so forth.

This paper serves to summarize the basic concept for the development of the above respects, the test results and so forth.

1 Introduction

Our presentation so far made on the occasion of SEG and our reports made from time to time through OYO TECHNICAL REPORT have proved the suspension P–S Logging to be quite an effective method. However, what clarified simultaneously with above occasions was the quality ambiguity with the data in case of S wave velocity *Vs* of the specific layer exceeding 1,000 m/s. As one of the solutions of this matter, the development has successfully been made with H–S source of cylinder type in respect of the source, that has anyhow enhanced the measurement aptitude to cover *Vs* in the vicinity of 3,000 m/s.

Concerning P wave, conventional method of survey through the horizontal as well as vertical components with the geophones of suspension type results in obtainment of extremely ambiguous record, in case of *Vs* reaching once the level of 3,000 m/s. Despite the successful improvement till now made with the sonde durable against the hydraulic pressure of 100 kgf/cm^2 (in the depth of 1,000 m), the conventional measurement method through suspending the sonde from time to time, for conducting the logging work with the depth of 1,000 m, requires so long time as 17 hours, suppose one minute is required for a depth and providing based on 1 m spacing, and such long spell of time is practically the one not acceptable for the seismic crew.

The above orientate us in what manner the practical acceptability could be sought after in respect of the suspension P–S Logging. In brief, the overall considerations are essential into each of the source, the geophone, the filter tube, the signal transmission system, the gain system and so forth. From such angles, the report summarizes below on how we have proceeded with the relevant development based on the specific concept and on the results we thus have obtained.

2 Application Limit and Development Principles

The fact that the higher S wave velocity is, the more remarkable the decrease in the signal from S wave generated is, constitutes the reason why the measurement with faster S wave velocity entails difficulty. Therefore, what conceivable for the improvement are the aggrandizement with the seismic source power, the betterment with transfer efficiency as seismic wave from the source power, enhancement with sensitivity of the geophone. improvement of S/N ratio against S wave through utilization of the filter tube etc. These elements are corelated one another and in brief, the requirements can be centered on the upgrading with the integrated gain of the seismic source and the geophones and further on the separation of S wave from the rest other than S wave.

Regarding the integrated gain, Fig. 1 indicates the relationship between V_s as S wave velocity of the layer and $\dot{U}_0$ as the particle velocity of the medium 1 cm away from the seismic source. Referring to each point plotted out in this figure, by giving variation to the distance r between the seismic source and the geophone in an identical layer and by determining the decay constant α of the layer, the maximum amplitude $\dot{U}$ of the velocity waveform with S wave observed can be calculated according to the following equation.

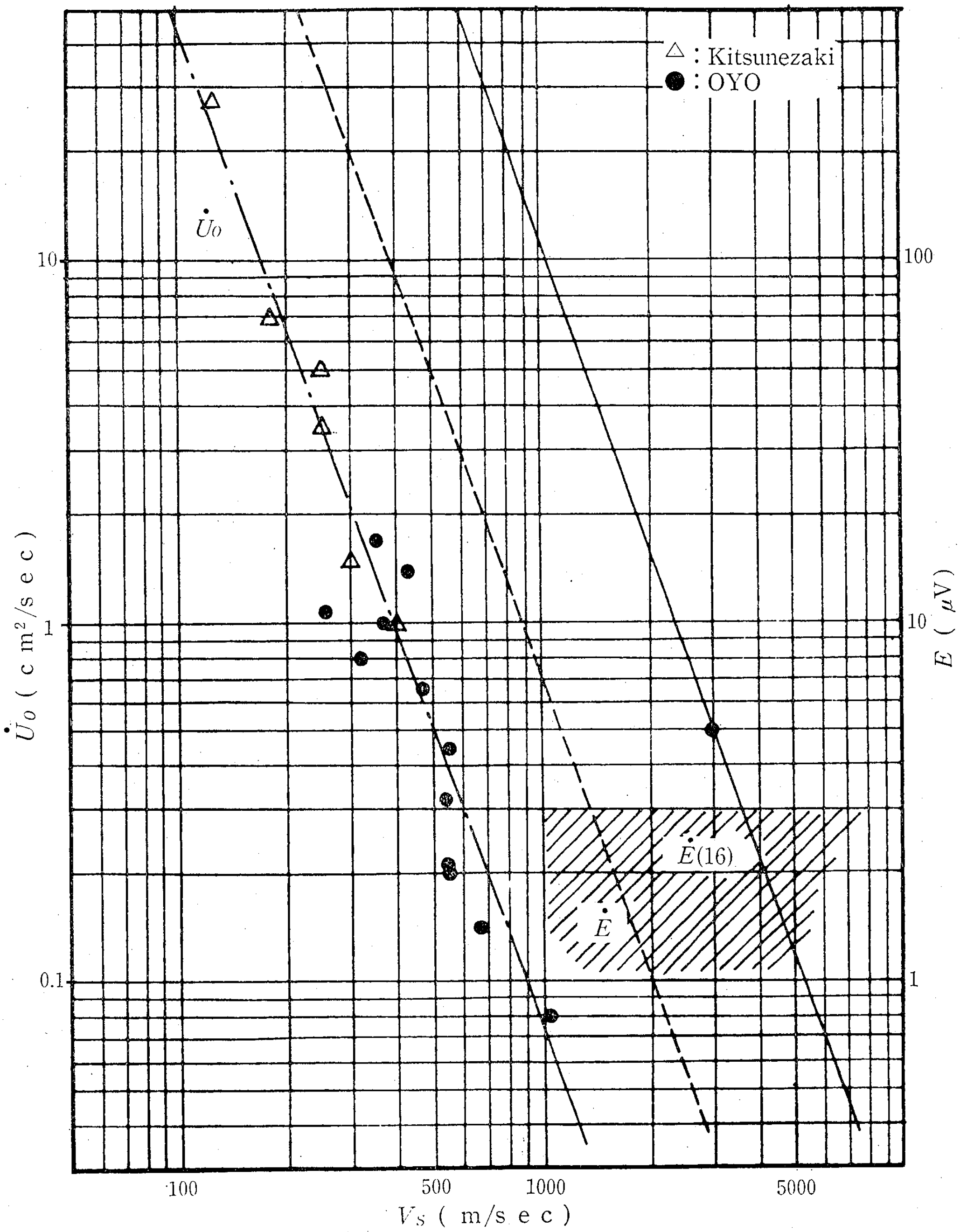


Fig. 1 Amplitude Characteristic of S wave

$$\dot{U}=r^{-1}\,\dot{U}_o e^{-\alpha r} \qquad (1)$$

For converting $\dot{U}$ into the signal voltage $\dot{E}$ of S wave when G expresses the sensitivity of the geophone, the following equation is applicable.

$$\dot{E}=G\cdot\dot{U}_{\,o}r^{-1}e^{-\alpha r} \qquad (2)$$

Suppose "magnitude of seismic source" is defined as the intensity of the wave at the source point generated by the source power, $\dot{U}_o$ signifies just such quantity. Accordingly, the product of G as the sensitivity of geophone and $\dot{U}_o$ as the magnitude of seismic source, in short, $G\times\dot{U}_o$ stands for the integrated gain from the measurement system. To convert $\dot{U}_o$ curve indicated in Fig. 1 into voltage, determination is required on G, r, and α. G as the sensitivity of the geophone being used for the currently utilized sonde is expressed by $G=0.05$ V/kine. The result of calculation based on r being 3 m and $e^{-\alpha r}$ being 0.5 is indicated by broken line in Fig. 1.

This figure deductively signifies that E as the signal voltage in case of $V_s=1,000$ m/sec and in another case of $V_s=2,000$ m/sec respectively result in 7 μV and 1 μV. However, since the current technological aptitude entails difficulty with the detection of the signal voltage at level of 1 μV, the voltage exceeding several μV is required, and such background has been the reason for the application limit till now existing with the suspension P-S Logging system.

The conclusion as to the method for the expansion of the application limit is so simple, being covered by the aggradizement of $G \times \dot{U}_o$, that is, it is centered on the enhancement of the sensitivity of geophone and the magnification of $\dot{U}_o$ as the magnitude of the seismic source.

Nevertheless, to what extent respective enhancement and magnification should be aimed at do make important guiding principles for the designing.

Based on the assumptions of 3,000 m/sec as the measurement limit with S wave velocity and 5 μV as the signal voltage in such a case, the integrated gain eventually required should be the one approximately 16 times as high as the gain level from the current system, as indicated by $\dot{E}$ (16) in Fig. 1. Next, reference is made to the current measurement method in which the practices have been the repetition of moving the sonde by 1 m, suspending it temporarily and then proceeding to measurement, in case of conducting the measurements with the section of 100 m at each position of 1 m interval. Naturally, for the measurement with 100 m section, the sonde is needed to be shifted and be suspended, each 100 times. Suppose the measurement at a measurement depth takes 1 minute, the measurement with 100 m section requires so long time as 1 hour 40 minutes, quite slow compared to the measurement time for usual geophysical logging. Furthermore, the cable workable is restricted to 7-conductor armored cable. In other words, being the system inclusive of the cable, the winch and even the particular control method with winch, the suspension P-S Logging System is different from other geophysical logging systems that can manage to conduct various measurements by mere replacement of sonde while using winch and cable for common purposes, and thus is unable to deal with those measurements in such simple manner as above other geophysical logging systems. Moreover, to conduct the intermittent operation with the usual winch for every 1 m shift accurately and quickly entails extreme difficulty. Though deviating from the fundamental matters with the measurement method, the above are those of prime importance from practical standpoint.

Viewing the above, reconsideration has now been given to the current measurement system as per the following details, in both achievement aspects of enhancement of the measurement limit with S wave velocity to 3,000 m/sec on one hand and the upgrading of the system to the one capable of conducting the logging work using the usual 4-conductor armored cable without necessity to suspend the winch on another hand.

3 Designing the Source

At time of radiation of the acoustic wave into the mass, the vibration body receives the reaction from the mass. In other words, in order to vibrate the vibration body at same speed as if it were in vacuum, the equivalent to the force through the reaction by the mass is required in addition to the force needed to vibrate the vibration body in vacuum. To represent the extent of this reaction, the following equation to define the radiation impedance is applicable.

$$\text{Radiation Impedance} = \frac{\text{over vibration body at time of radiation}}{\text{vibration speed}} \qquad (3)$$

The value of radiation impedance per unit area of radiation plane of vibration body corresponds to radiation impedance density. Being literally representing a concept of impedance, radiation impedance is generally expressed in complex number. Radiation impedance Z_r can be expressed by the following equation.

$$Z_r = r_r + jx_r \tag{4}$$

where r_r is resistance component and x_r is reactance component. In respect of the work actually exercised by the vibration body over the mass, as the reaction force in identical phase with vibration body is effective, the estimation on the acoustic power actually radiated can be made earmarking the real part of radiation impedance, i. e. radiation resistance r_r.

The imaginary part of radiation impedance corresponds to x_r as radiation reactance, which is the ineffective reaction from vibration concerning the radiation of sound wave. x_r divided by ω as angular frequency is so-called "additional mass" as expressed below.

$$x_r/\omega = m_r$$

This additional mass is treated to be the mass adhered to the vibration body. Therefore, radiation reactance should be understood to exercise influence over the frequency characteristic of the vibration body.

W as acoustic power radiated into the mass can be determined through radiation resistance as r_r multiplied by the square of the velocity of vibration body, as expressed below.

$$W = r_r \cdot V^2$$

When the radiation resistance density is expressed by r_r, the total radiation acoustic power should naturally be worked out through r_r multiplied by the area.

As evident from the above, radiation impedance makes the criterion to estimate the source in respect of its capacity as the electrical acoustic converter and from such viewpoint, reconsideration is given on the source as follows:

First of all, in case of suspension P-S Logging, one condition essentially required is that the borehole diameter be sufficiently smaller compared to the wavelength. Since the source is to be placed in the borehole, naturally the source is to be dimensionally smaller enough compared to the wavelength.

3·1 S Source and P-S Source

The sources developed by the author and his collaborators by 1985 were outlined as follows:

S source: Reciprocating movement alternated like piston while no volume change indicated.

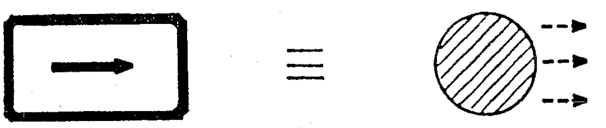


Fig. 2 S source

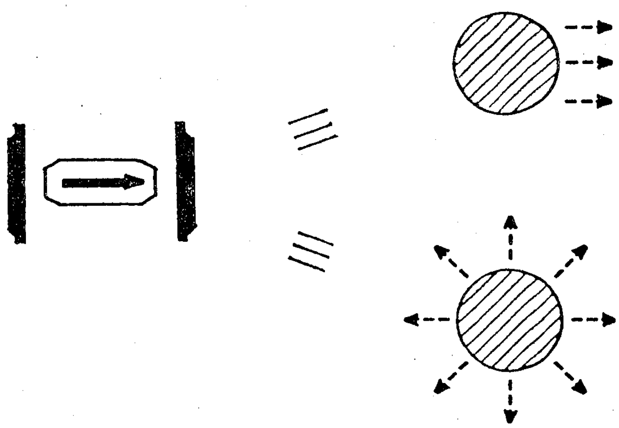


Fig. 3 P-S source

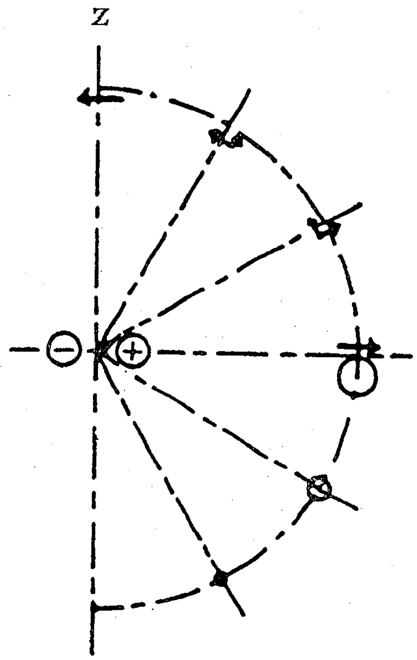


Fig. 4 Radiation pattern by vibration sphere

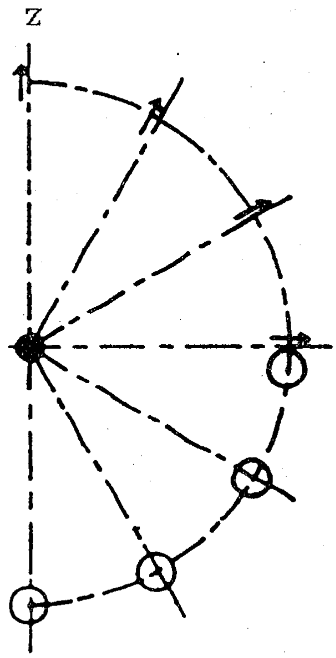


Fig. 5 Radiation pattern by pulsation sphere

P-S source: Single side movement recognized like piston while volume change indicated.

As the working area of these sources is sufficiently smaller compared to the wavelength dimensionally, simplified interpretation on their movement as the vibration of sphere is permissible.

S source is understood to be the vibration sphere to indicate no change with radius during the vibration of the sphere as time function. On the other hand, as for P-S source, it is provided with both the vibration mode as noticed with vibration sphere mentioned above and the different vibration mode as noticed with pulsation sphere that accompanies expansion/contraction with its radius during the course of time. The relevant conditions are indicated in Fig. 2 and Fig. 3. In Fig. 2, the behaviour by the left vibration piston is equivalent to that by the left vibration sphere. In Fig. 3, it causes the behaviour equivalent to the vibration sphere and the one equivalent to pulsation sphere exercise translational movement jointly when the hammer with arrow mark in left strikes the side board.

Fig. 4 and Fig. 5 delineate the acoustic radiation patterns with the vibration sphere and the pulsation sphere. The upper and the lower respectively show the particle velocity and the sound pressure. The particle velocity constituted by radius as well as transverse bearings, is indicated in vector, while the sound pressure is indicated by circumference scale. In respect of the vibration sphere, it is represented as the model in which 2 sound sources with positive/negative phases inversed are configurated symmetrically away from each other with distance small enough compared to the wavelength and is referred to as dual sound source (doublet sound source) in the acoustic engineering. This typically retains directional characteristic of figure-eight type and to supplement, provided that Z axis in Fig. 4 represents the direction of borehole axis, it implies that the sound pressure is not generated to this direction. This verifies the fact that in case of S source, the recognition of P wave is very difficult by the observation of the output of vertical component from the geophone unit. Next, consideration is given below to the radiation impedance density with these models.

On the other hand, Z_{r1} as the radiation impedance density of the pulsation sphere is given as follows:

$$Z_{r1} = \rho c \left\{ \frac{(kR)^2}{1+(kR)^2} + j\frac{kR}{1+(kR)^2} \right\} \tag{5}$$

Z_{r2} as the radiation impedance density of the vibration sphere is given by the following equation.

$$Z_{r2} = \frac{\rho c}{3} \left\{ \frac{(kR)^4}{4+(kR)^4} + j\frac{2kR+(kR)^3}{4+(kR)^4} \right\} \tag{6}$$

where the unit of Z_r is N•sec/cm³

R : radius of sphere (m)

ρ : density of mass (kg/m³)

c : sonic velocity of mass (m/sec)

λ : wavelength (m)

k : $k=2\pi/\lambda$

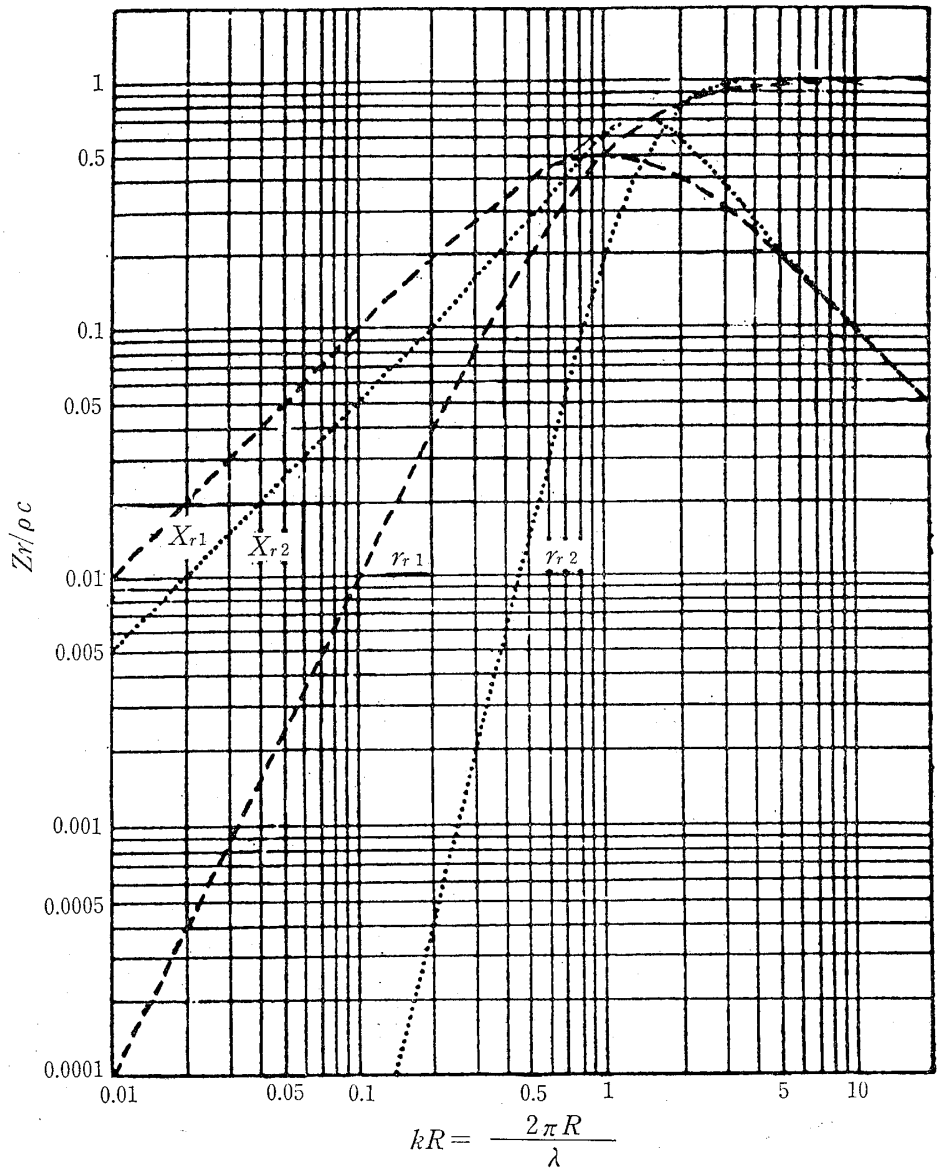


Fig. 6 Relation between Zr/ρc and kR

Fig. 6 shows the result of calculation according to the above equation. Relating to radiation impedance density, its resistance in r_r and its reactance in X_r after divided by ρc as the acoustic impedance of mass, are expressed in the function of kR.

The figures "1" and "2", both added as suffixes to Zr, respectively signify the pulsation sphere with R as its radius and the vibration sphere with R as its radius, and the scale on the axis of ordinates with the curve of the vibration sphere should be multiplied by 1/3. The value of kR in case of the suspension P–S Logging is required to be within the range $kR \leqq 1$ on the condition of $R \ll \lambda$. In respect of the radiation resistance density of the vibration sphere in this range, the smaller the kR value is, the more remarkably the relevant radiation resistance density gets lower. Therefore, to make the radiation acoustic power magnified, it is essential to have the largest possible kR, which means nothing but rendering the radius of the sphere large, along with making the frequency high. Comparing r_{r1} of the pulsation sphere to r_{r2} of the vibration sphere while referring to Fig. 6, the conclusion is $r_{r1} \gg r_{r2}$ as for the range satisfying $kR < 1$. The vibration of the pulsation sphere relates to the generation of P wave. Accordingly, in comparison with the generation of S wave, the generation of P wave requires the energy extremely less.

3.2 H–S Source

Since the commencement of its development in 1978 for S wave logging, the continuous interest has been kept by the author in the simultaneous measurement of P wave and S wave and chronologically such development has led to the introduction of P–S logging system currently utilized. Meantime, it is recalled that the prime tasks to be achieved during the

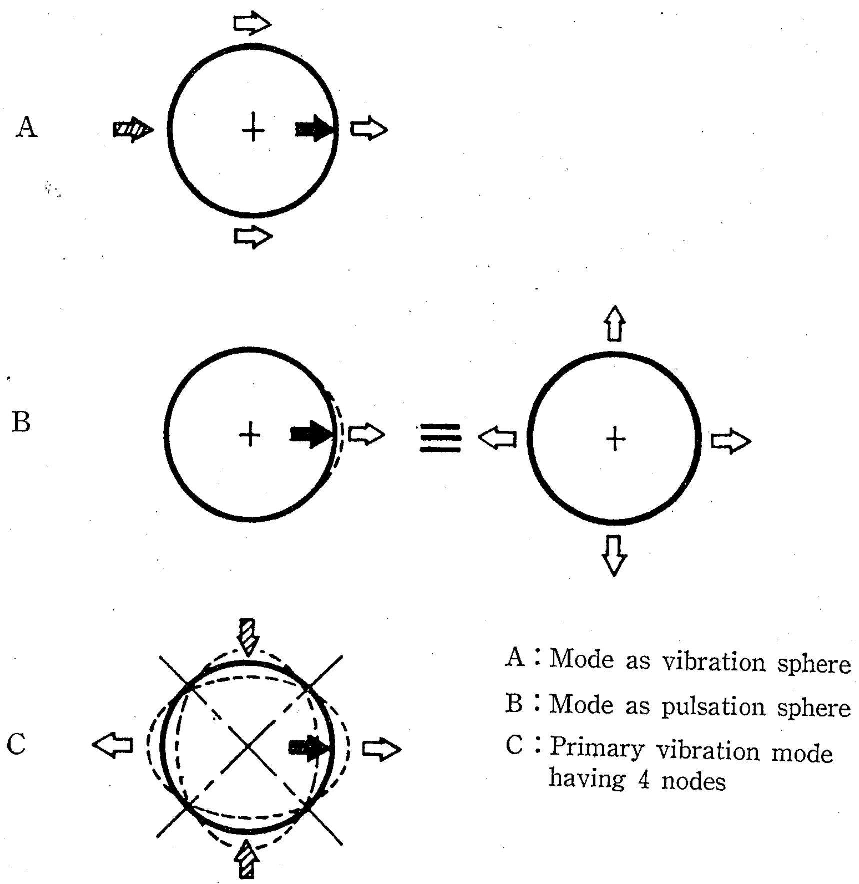


Fig. 7 Vibration generated when inside the cylinder is hammer-struck

course of designing the source constantly consisted in generation of both P wave and S wave and further in the control of the amplitude ratio between P wave and S wave. Of course, such concept as above has been embodied as well in H-S source.

In 1986, the development was made with P-S source of cylinder type satisfying such requirements as large dimension with the source, magnification with radiation impedance, and the function to generate the wave with high frequency. Viewing the feasibility of its application to the high velocity layer, the device thus developed was decided to be referred to as "H-S source". Relevant cylinder is made of stainless steel dimensionally 52 mm with outer diameter, 46 mm with inner diameter and 100 mm with height. Structurally, the center of such height is to be struck by the solenoid hammer.

Fig. 7 indicates the mode of the vibration generated in consequence of striking the inside of the cylinder. "A" mentioned in the figure denotes the vibration mode by vibration sphere to generate S wave, while "B" mentioned in the same figure denotes the different vibration by pulsation sphere to generate P wave and tube wave. "C" in the figure denotes the primary vibration mode conceivable to be equivalent to the result from the configuration in which 4 vibration spheres be placed adjacent one another and so long as the source is placed in the center of the borehole, this vibration mode can be considered as the one entailing no problem with the measurement of P wave and S wave.

Fig. 8 indicates the result of actual measurement with the vibration waveform at each section of the cylinder when struck with its inside in groundwater. Observation was effected through placement of a sensor at each observation station. Since the measurement was conducted on non-contact basis through the use of laser displacement meter, no load was exercised on the cylinder. The waveforms observed at the measurement points I and II directionally identical to the striking axis, do directionally coincide with that of the cylinder acting as vibration sphere and do involve all the components related to the different vibration as pulsation sphere as well as the primary vibration by the cylinder. In respect of the

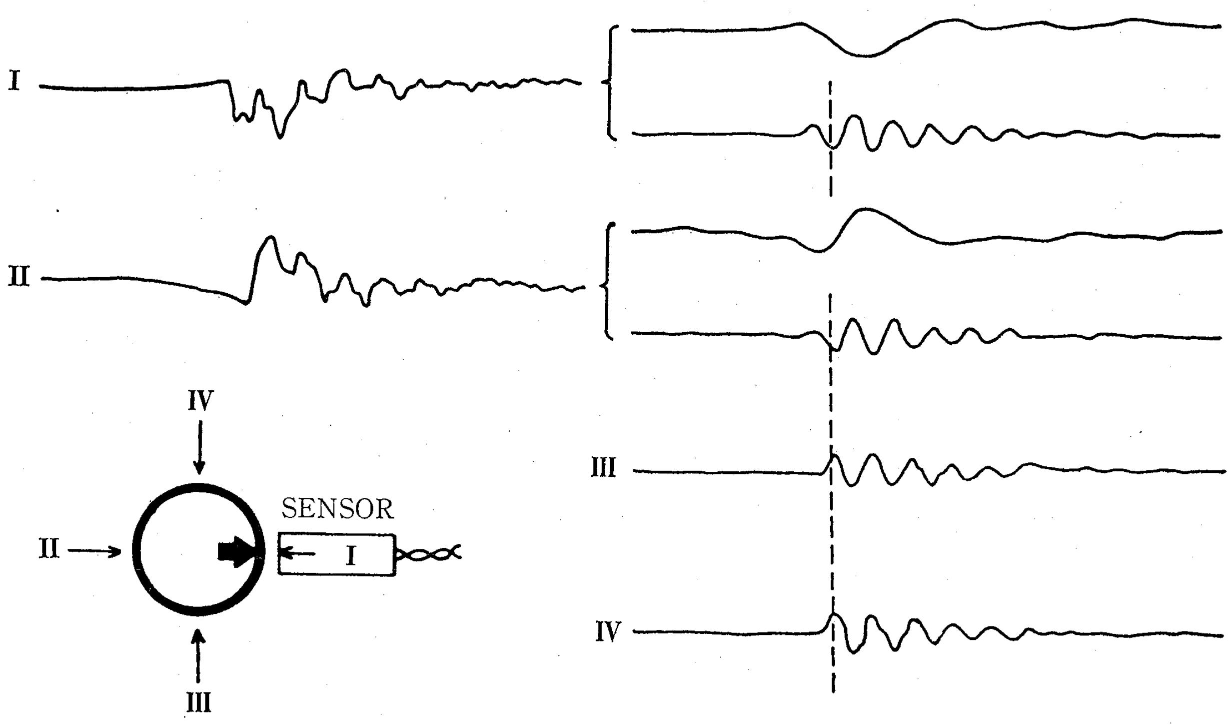
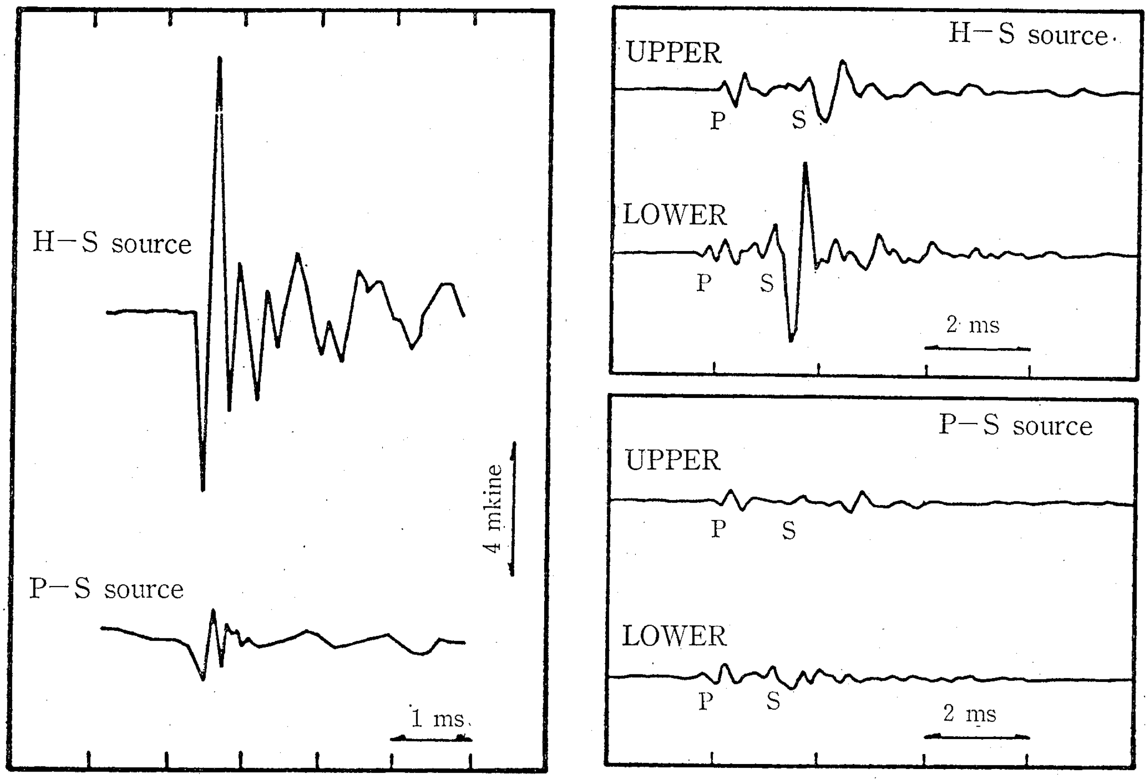


Fig. 8 Vibration waveforms from each section of the sonde when inside the cylinder is hammer-struck. I, II, III, and IV indicate observation stations

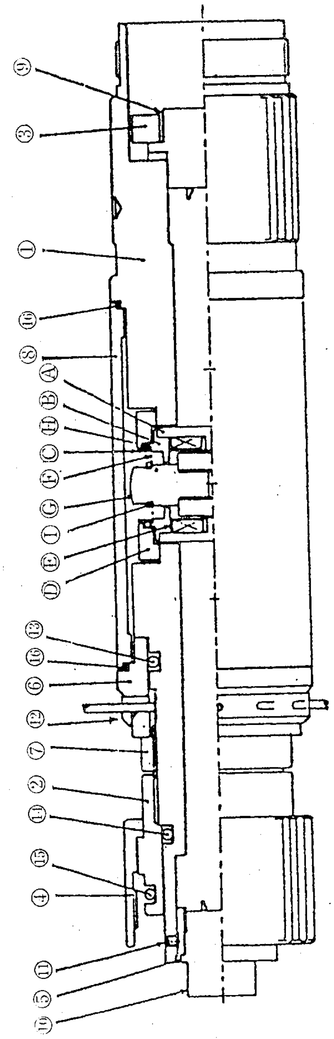


(a) Comparison of waveforms obtained by H−S suurce and P−S source.

(b) Example of waveforms.

Fig. 9 Comparison of the result with P-S source versus H-S source obtained from the test borehole prepared in tuff layer

waveforms III and IV observed perpendicular to the striking axis, their equal phase and their amplitude almost equal have led us to conclude that they only consisted of the primary vibration of the cylinder. Therefore, suppose only the frequency component with the primary vibration is derived from the waveforms I and II, the same correspond to the waveforms indicated in the right side of Fig. 8 deviating by 180° in phase from III and IV while showing no difference in phase between I and II. This proves that the same is the primary vibration of the cylinder as the one marked with "C" in Fig. 7. Concerning the waveform in the right side of Fig. 8, its low frequency component represents the waveform of low frequency component resulted from the cylinder acted as vibration sphere. The frequency of the primary vibration in groundwater with the cylinder, dimensionally 52 mm (outer diameter) × 46 mm (inner diameter) × 100 mm (height) was 3,300 Hz, consistent with the theoretical value. To be deductive, the radiation energy ratio with P wave and S wave can be controlled by giving variation to the thickness of the cylinder or by giving slit to the side of the cylinder. This constitutes another feature with the source of cylinder type. Fig. 9 (a) indicates the waveform obtained from the square-columnar shaped tuff with P wave velocity 2.4 km/sec, S wave velocity 1.0 km/sec, and density 1.7 g/cm^3 and dimensionally 0.7W (m) ×0.7W (m) ×1.4H (m) into which test hole was drilled for insertion of the source, and by placement of the geophones opposite to the source. On the other hand, Fig. 9 (b) is the record example obtained on the job site, showing the comparison of record through H-S source with that through P-S source at the identical location and on identical conditions. From this figure, remarkable improvement with H-S source can be seen. The magnitude of H-S source can be estimated at the aptitude approximately 5 times as high as that of P-S source. Fig. 10 indicates the structure of H-S source.



① Housing
② Connecting ring
③ Connecting adapter
④ Coupling ring
⑤ Inner conecter ring
⑥ Cylinder retainer ring
⑦ Centralizer fixing ring
⑧ Strike cylinder (373g)
⑨ Connecter NJW−2012−RM
⑩ Connecter NJW−2012−PF
⑪ Setscrew M3×0.5×3
⑫ Centralizer
⑬ O ring P−28
⑭ O ring P−24
⑮ O ring P−34
⑯ O ring A−031
Ⓐ Outer core
Ⓑ Side core
Ⓒ Retainer ring
Ⓓ Holder
Ⓔ Coil
Ⓕ Spring
Ⓖ Plunger
Ⓗ O ring A−018
Ⓘ O ring P−9

Fig. 10 Structure of H-S source

4 Designing the Geophone

To upgrade $G\times\dot{U}_0$ that stands for the integrated gain of the measurement system results in the enhancement of the upper limit with the measurement capacity and meantime, as for $\dot{U}_0$, the same is as described above.

Being constituted by geophone units and the housing to store them, the geophone in particular is the one of so-called suspension type designed to have the apparent specific gravity in the vicinity of 1. To be suited for the application into the usual borehole for the survey, its outside diameter is restricted to approximately 50 mm. As mentioned above, the apparent specific gravity of the geophone has been set at 1 as its target at time of its designing. Since the geophones are to be arrayed with 1 m interval, each of them is desired to be within 0.2 m in its length.

In a geophone, two geophone units composed of the one with horizontal component and another with vertical component are housed. Accordingly, to have the geophone of suspension type with approximate specific gravity at 1 and to let the geophone units stored in the housing dimensionally with 50 mm (outer diameter) by 0.2 m or less (length) entail difficulty with selection of the geophone units large and highly sensitive.

Fundamentally, the geophone unit with horizontal component is sufficient for capturing

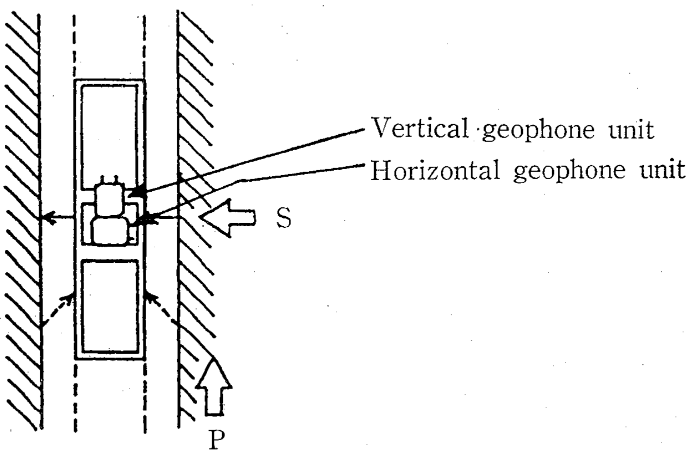


Fig. 11 Schematic diagram of Geophone

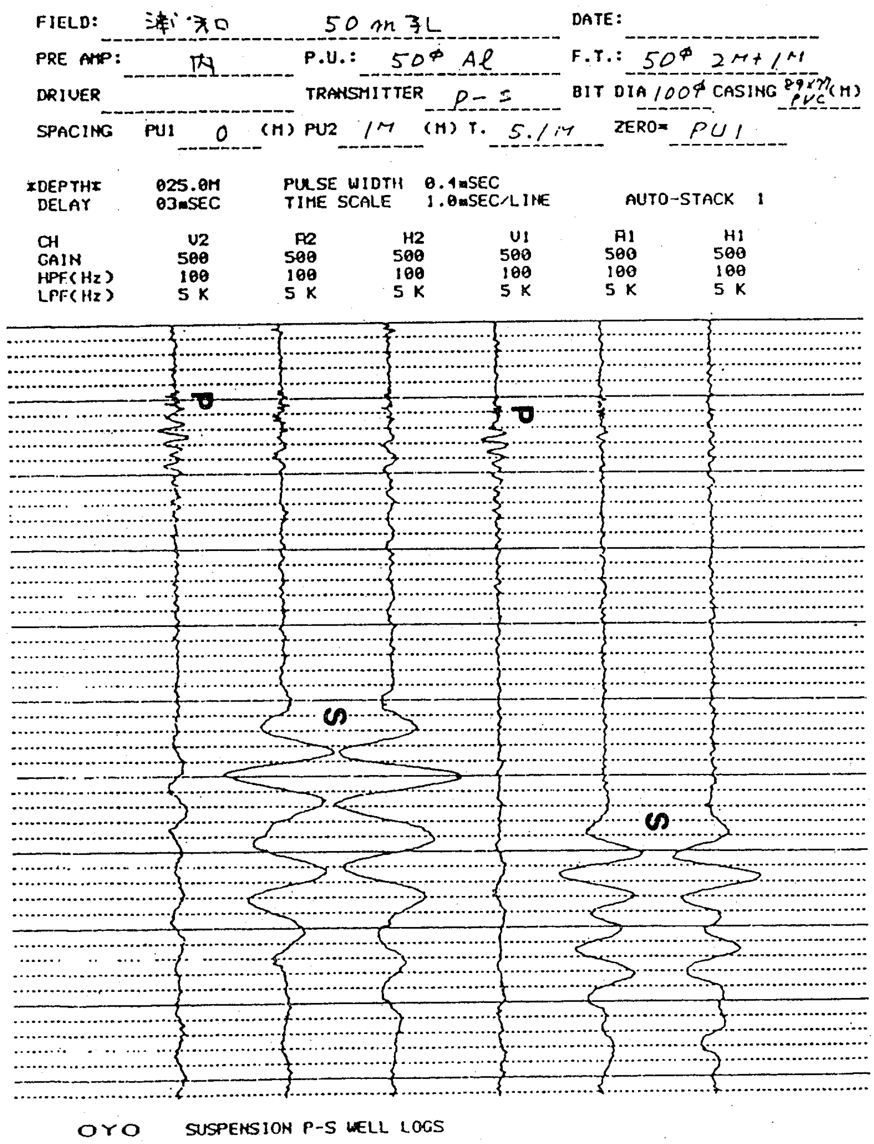
S wave. However, the following reason constitutes the background for the necessity to have the vertical component additionally incorporated.

In the initial stage of the development, the concern was to monitor whether P wave or tube wave might cause disturbance with S wave signal, but the development target was subsequently enhanced to render P–S logging feasible through the use of P–S source and H–S source with respective sources given slight volume variation, and through the change of the interval between the source and the geophone to the range of 3 to 4 m thereby improving the time separation with P wave from S wave.

In respect of S wave, the existence of its measurement limit is evident for the confirmed foundation and the improvement for higher sensitivity with the geophone unit has at least been orientated. As such, consideration is given below on P wave instead.

Referring to the source, the radiation resistance of P wave represents the mode of pulsation sphere, extremely larger in value compared to that of the vibration sphere of S wave. Therefore, the source is provisionally put aside out of the consideration here. Fig. 11 indicates the block diagram of the geophone. Providing the apparent specific gravity of the geophone be approximately 1, the influence exercised by the rubber tube serving for the vertical combination of the sonde, over the response to S wave with lateral incidence towards the geophone, can be the one negligible. Nevertheless, because of the weight of sonde working as load via the spring in case of vertical movement, the eventual apparent specific gravity rendered exceeding 1 results in inferior sensitivity. Moreover, in respect of the cross section of geophone, vertical geophone does not exceed circular cross section of geophone in its maximum case and is much smaller compared to the horizontal geophone that can be expressed by diameter by length. For the above reasons, the survey of P wave through the use of geophone unit with vertical component incorporated into the geophone, entails disadvantage. Fig. 12 indicates a record example through the use of vertical and horizontal geophone units with identical sensitivity to each other and through arrangement to have identical gain between the two. In contrast to S wave clearly observed, P wave entails difficulty with reading of its first break due to its amplitude being minor and though it can be recognized as wave group.

In the homogenous layer, affected by the volume variation with the source, P wave is featured as the spherical wave propagating around the source as its propagation center. Therefore, the measurement of sound pressure leads naturally to the determination on P wave velocity. Sound pressure can be measured through the use of hydrophone. As the geophone unit with vertical component retains sensitivity to the vibration of the geophone itself,



Fiig. 12 An example of record from P-S logging

complex response is expected with various elements involved such as suspension condition with the geophone, its delicate contact with the borehole wall etc, while in case of hydrophone, its sensitivity retained exclusively to sound pressure might bring about its considerable merits.

4·1 Hydrophone Structure

The sensor in the hydrophone for logging purpose has been the one of piezoelectric ceramic of cylindrical shape in many cases. With inner surface and outer surface of the cylinder respectively treated as electrodes, polarization has been effected to the direction of the thickness of the cylinder.

The cylinder with polarity thus given retains its sensitivity to the stress to respective directions of its expansion, its thickness and its height. For the use as hydrophone, the designing is required to let it have the utmost sensitivity to the expansion of the cylinder i.e. its pulsating vibration.

Fig. 13 shows the output waveforms that vary depending on the methods for mounting

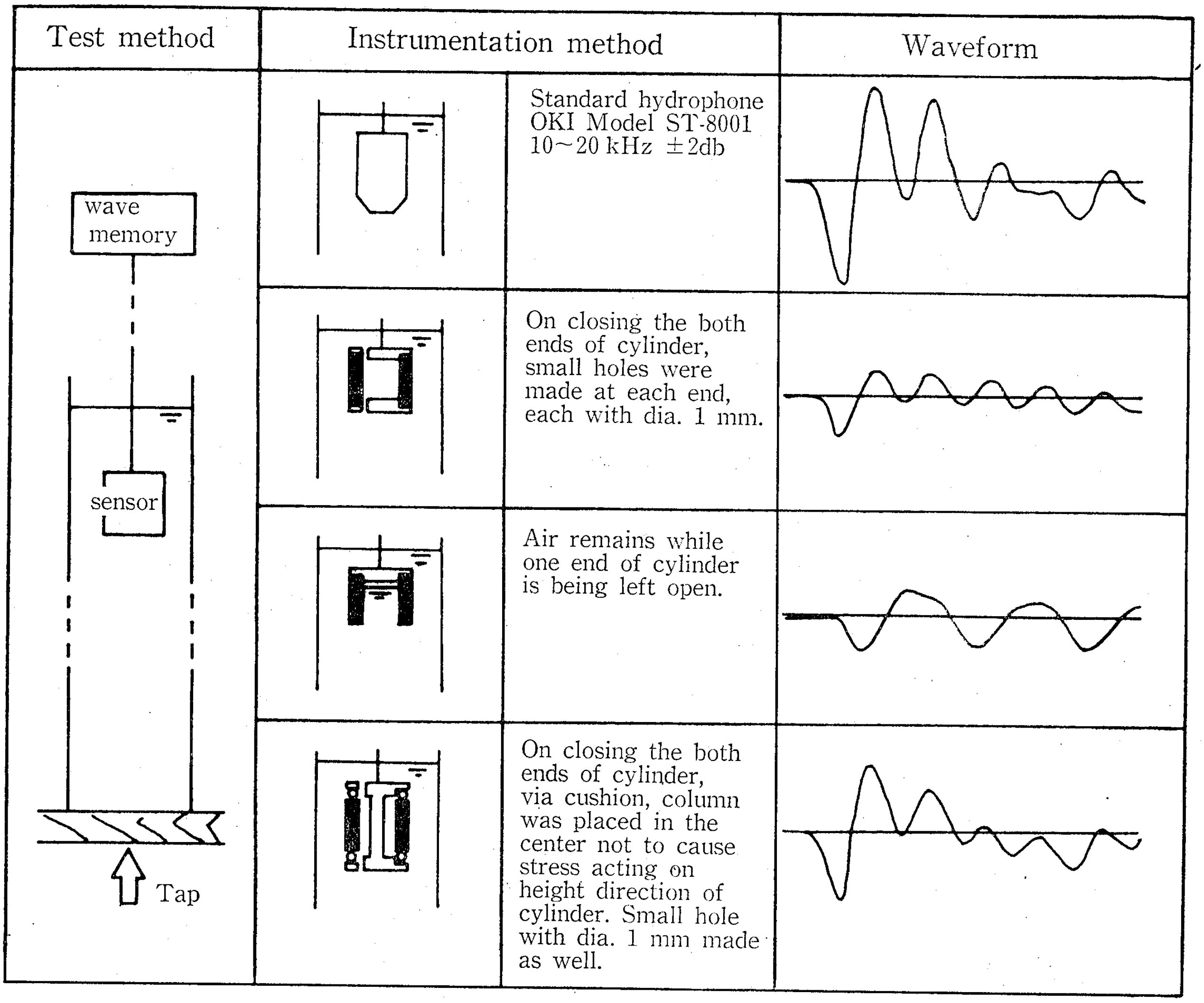


Fig. 13 Influence exercised depending on mounting methods with voltage ceramic of cylindrical type

the piezoelectric ceramic of cylindrical shape (38mm×34mm×30mmH). The structure of this piezoelectric ceramic arranged not to exert stress on the direction of the height of cylinder has proved to output the waveform most similar to the one through the use of the standard hydrophone (the one with flat frequency characteristic guaranteed).

4·2 Designing the Geophone Housing

In respect of S wave, the housing of suspension type shaped cylindrical with horizontal geophone unit incorporated is proved to be the one having the highest sensitivity and capable of obtaining the good frequency characteristic. On the other hand, despite the various tests given through the use of the converter of so-called sound cell type structured to convert directly into electrical signal, the movement of the vibration sensors mounted opposite to each other via air chamber small enough compared to the wavelength, such converter has been found to have demerit of hardly obtaining flat frequency characteristic especially. Relating to designing of the housing, as for the pressure proof, suppose 1,000 m is the target depth, 200 kgf/cm^2 is the level required when safety factor is taken into consideration. In addition, the tare of the housing is desired to be as light as possible from the requirement to render the apparent specific gravity, with the geophone unit involved as well, approximately as low as 1. Viewing the necessity of designing through fairly careful consideration, the relevant summary is given below :

Discussion on housing is just equivalent to the discussion on thin walled closed section involving thin thickness compared to outer diameter. While the internal pressure can be covered depending only on the rigidity of the material and accordingly the countermeasure for the solution is rather simple, in case of the external pressure, flat collapse or triangular collapse might happen. Critical pressure P_o beyond which the collapse is to arise can be determined according to Southwell's equation as follows:

$$P_o=\frac{2Et}{d}\{(n^2-1)\times\frac{m^2}{3(m^2-1)}\times(\frac{t}{d})^2+\frac{\pi^4}{16n^4(n^2-1)}\times(\frac{d}{l})^4\} \tag{7}$$

where d : diamter of cylinder (cm)

E : elasticity modulus (kgf/cm²)

n : arising times of collapse (The minimum value of P_o is in case n = 2)

$\frac{1}{m}$: Poisson's ratio (In case of steel, aluminium, brass etc, within ±5% providing m = 3)

l : length of cylinder (cm)

t : thickness of cylinder (cm)

Above equation (7) is converted as follows, by putting above specific figures of n and m into the same.

$$P_o=2E(\frac{t}{d})\{1.125(\frac{t}{d})^2+0.127(\frac{d}{l})^4\} \tag{8}$$

Providing the target depth be 1,000 m, tentative calculation with thickness t of the cylinder in case of steel, aluminium are given below, on assumptions of safety factor =2, d =5.2 cm and l =20 cm.

P_o	d	l	E	t
200 kgf/cm²	5.2 cm	20 cm	2.2×10^6 kgf/cm² (steel)	0.15 cm
200 kgf/cm²	5.2 cm	20 cm	0.72×10^6 kgf/cm² (aluminium)	0.24 cm

From the above, thickness 3 mm is understood to be enough in case aluminium is used.

The guiding principles to design the geophone can be summarized as follows:

For S wave, the geophone of suspension type is required. With the geophone unit, only horizontal component is to be incorporated. Accordingly, the geophone unit with higher sensitivity is needed. With U_o upped to 5 times, suppose the sensitivity G of the geophone unit is to be rendered 4 times, 0.2 V/kine should be the required specifications, which level can easily be secured from the market. Thus, $G\times U_o$ as the integrated gain can achieve the level of 20 times.

As for P wave, hydrophone is the device to be utilized.

5 Filter Tube and Tube Wave

Fig. 14 shows the result of test conducted to observe the behaviour of filter tube. From this figure, it can be understood that the filter tube functions to retard the velocity of tube wave on one hand and to attenuate the amplitude of tube wave on the other hand.

In case of usual logging work, filter tube has not been inflated through pressurization according to the depth. Since grasping beforehand of the approximate tendency with the functional change of filter tube in the courss of depth variation is important to observe the record in proper manner, consideration is given below into this matter.

The velocity V_B of the tube wave to propagate inside the borehole is given by the following

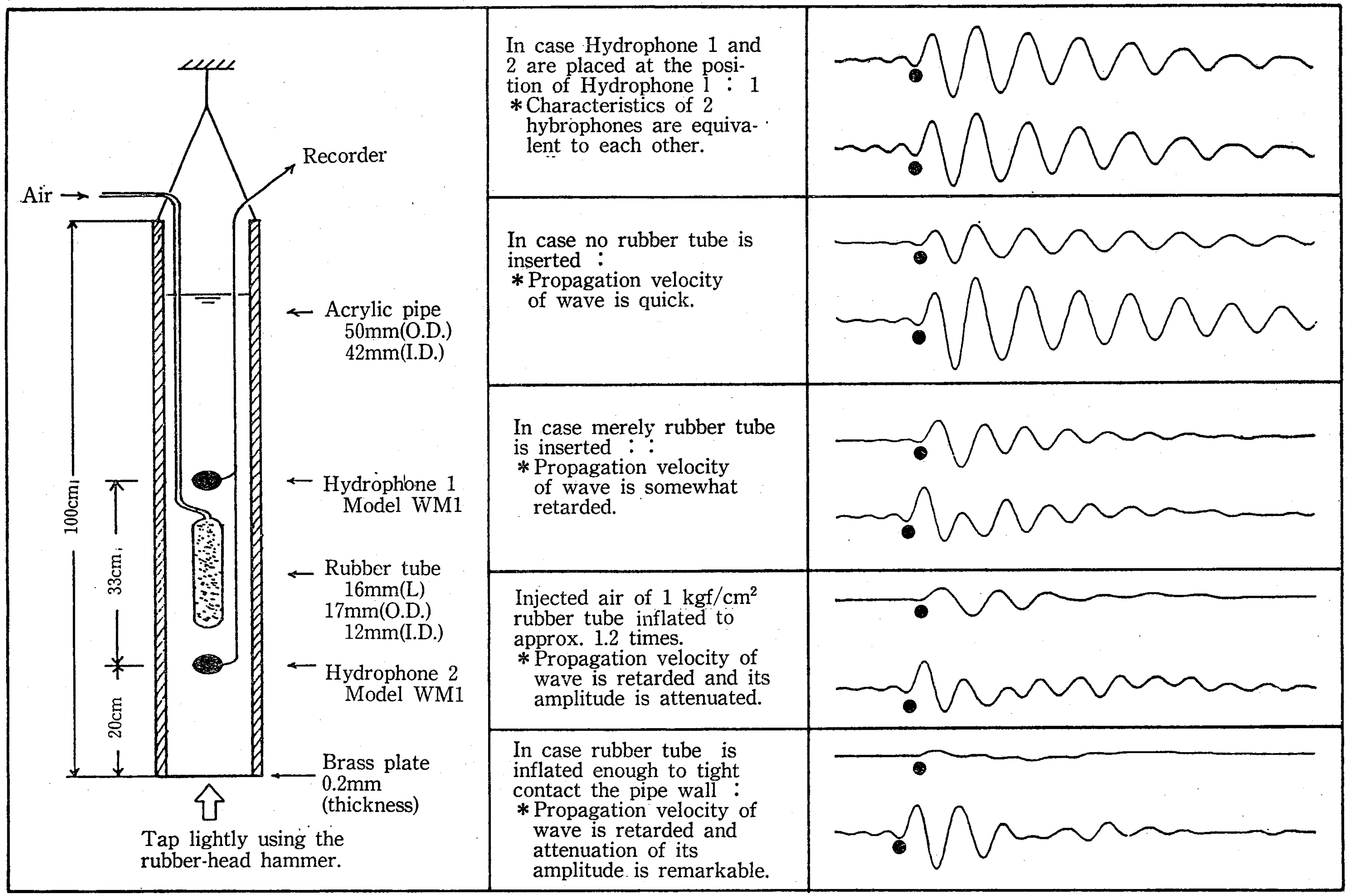


Fig.14 Simulation test with filter tube curve

equation

$$V_B=\frac{1}{\sqrt{\frac{\gamma}{g}\left\{\frac{1}{K}+\frac{2(1+\alpha)}{E}\right\}}} \quad \text{(m/s)} \tag{9}$$

where γ : specific gravity of fluid rendering borehole saturated
K : bulk modulus of elasticity of fluid rendering borehole saturatsd
E : elastic modulus of rock
g : acceleration of gravity

Filter tube can be interpreted as equivalent to its being put in water as the fluid saturating the borehole, into which air is mixed. Suppose the gross volume with the section where the filter tube is existing is represented by V, and the volume of air occupied by the filter tube is represented by V_a, V_a/V should indicate the mixing ratio of air. γ as the specific weight of water into which air is mixed can be determined according to the following equation, where γ_W represents the specific weight of water and γ_a represents the specific weight of air.

$$\gamma=\gamma_w-(\gamma_w-\gamma_a)\frac{V_a}{V} \tag{10}$$

The bulk modulus of elasticity K of water into which air is mixed can be given by the following equation, where K_W represents the bulk modulus of elasticity of water and K_a represents that of air.

$$K=\frac{K_w}{1+(\frac{K_w}{K_a}-1)\frac{V_a}{V}} \tag{11}$$

The following equation gives the relationship between S wave velocity V_s of the layer and relevant elastic modulus E, where the density of the layer is expressed by ρ and Poisson's ratio by σ.

$$V_S=\sqrt{\frac{E}{\rho}\cdot\frac{1}{2\ (1+\sigma)}} \tag{12}$$

Both γ_W as the specific weight of water and K_W as the bulk modulus of elasticity of water are to be extremely less varied by borehole pressure, compared to air. Though provisional, interpretation assumed here is that neither γ_W nor K_W be affected to vary by the borehole pressure. The specific weight of air γ_a and the bulk modulus of elasticity K_a can respectively be determined by the following equations, where the pressure is expressed by P.

$\gamma_a=1.2\ P$ kgf/m^3

$K_a=1.4\times10^4\ P$ kgf/m^2

By putting the above into equation (9), the following equation can be deduced,

$$V_B=\frac{1}{\sqrt{\frac{\gamma_w-(\gamma_w-1.2P)V_a/V}{g}\left[\frac{1+\{K_w/1.4\times10^{10}P-1\}V_a/V}{K_w}+\frac{g}{\rho V_S^2}\right]}} \tag{13}$$

The above equation (13) shows the relationship among tube wave velocity V_B, air mix ratio V_a/V, pressure P, and layer S wave velocity V_s. Based on this equation, and treating air mix ratios V_a/V at respective pressures of 10 kgf/cm^2 (depth 100 m), 50 kgf/cm^2 (depth 500 m), and 100 kgf/cm^2 (depth 1,000 m) as parameters, Fig. 15 shows the relationship between V_s and V_B. Meantime, note that the calculation is based on the layer density being 2.5. From

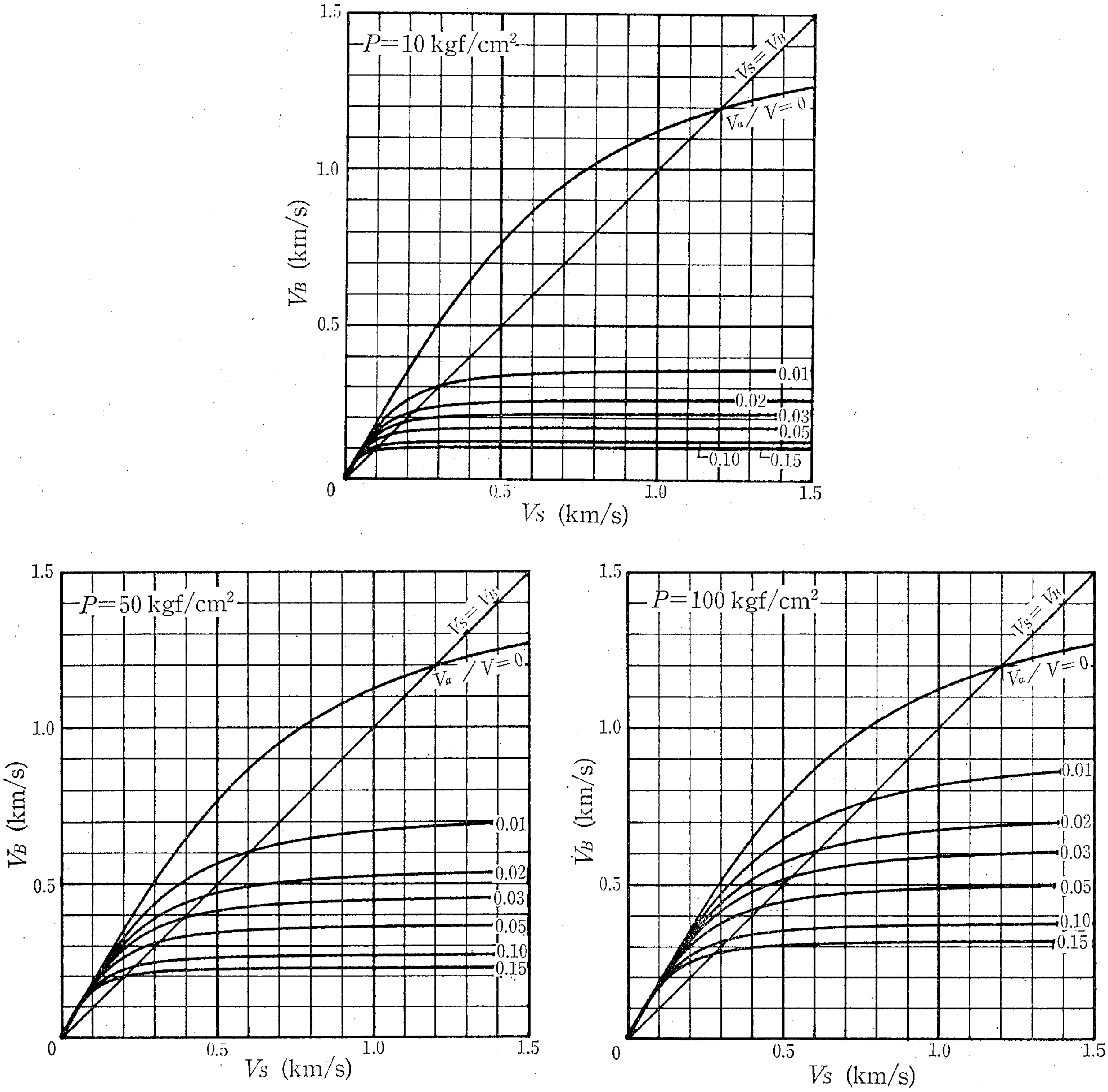
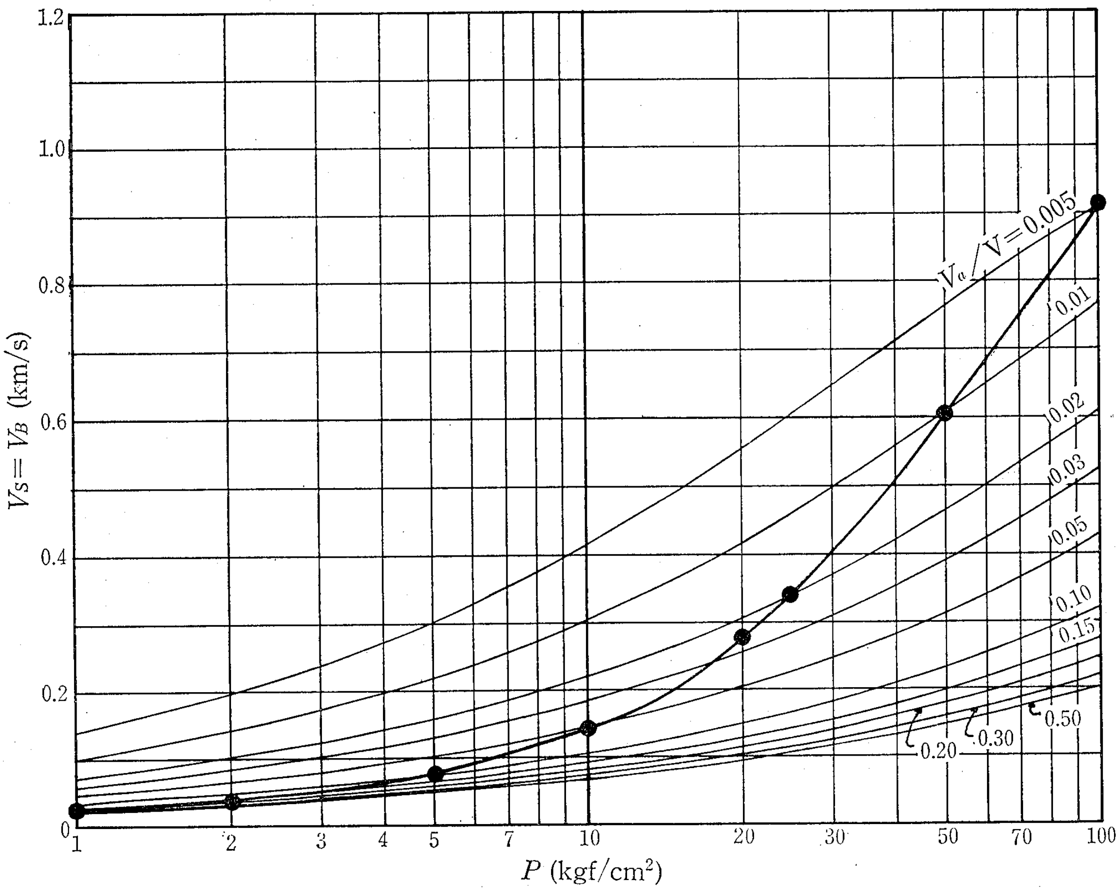


Fig. 15 $V_S \sim V_B$

the figure, it can be understood that the more the depth increases, the quicker the velocity to indicate $V_s = V_B$ becomes, even if V_a/V is identical.

Treating V_a/V as the parameter, Fig. 16 delineates the point to indicate $V_s = V_B$, against the pressure. This figure offers us easy access to understand how the $V_S = V_B$ velocity would show its variation in case of the usual filter tube that once kept 0.5 as to V_a/V at depth of 10 m and that subsequently showed the gradual decrease with V_a/V as the depth went deeper. The curve formed through connecting the points marked with (●) in the figure corresponds to this indication, that is, the deeper the depth goes down, the more remarkably accelerated the $V_S = V_B$ velocity is. To bear in mind this point might facilitate to read the S wave record adequately. Fig. 17 shows the relationship of V_a/V versus V_B through fixing the layer S wave velocity V_s and treating the pressure as the parameter. Specifically, three examples are cited for the cases of $V_s = 3,000$ m/sec, $V_s = 1,000$ m/sec, and $V_s = 200$ m/sec. This figure is effective to judge approximately the adequate level of the air mix ratio. The figure clarifies



Fjg. 16 $P\sim$ $(V_S\sim V_B)$ curve

that even if V_a/V is 1, i.e. even if total replacement by air is actual, V_B velocity tends to be bigger on the contrary. To supplement, as far as V_B velocity is concerned, it can be said to have V_a/V secured in approximate range of 0.1~0.2 is sufficient for the matter. In case of depth considerably distant from surface and V_s indicated slow, depending on the circumstances sometimes it might be desired to have V_a/V at high level and further to keep V_a/V relation fixed irrespective of change with depth. For such case, utilization of gas filter tube as indicated in Fig. 18 is recommendable. (Patent No. 1400376, OYO)

Once this filter tube is inserted into the borehole, borehole water passed through small hole contacts the dry ice to cause fierce vaporization, to saturate inside of rubber bag with CO_2 gas, and to push down the borehole water to the level of the small hole. Under the condition where the borehole water is thus pushed down, thermal supply to dry ice lowers its pace, followed by slowdown with vaporization. Passing through the small hole, surplus CO^2 gas is then released inside borehole. Further increase with the depth leads to borehole water lifted and to vaporization accelcrated with dry ice. Accordingly, above processes repeat themselves.

Therefore, the gas pressure inside the rubber bag is always kept balanced with the hydraulic pressure, with V_a/V rendered unchanged despite eventual change with depth. The concept of gas filter can be taken place by such idea of combined use of other gas with pressure valve, not necessarily sticking to dry ice. Nevertheless, note that the most simple and convenient method is to use dry ice. In respect of CO_2 gas, with its critical temperature at 31.3°C and its critical pressure at 72.9 atmospheric pressure, it can be used down to approximate depth of 1000 m providing the change with V_a is within range of 1 to 0.5.

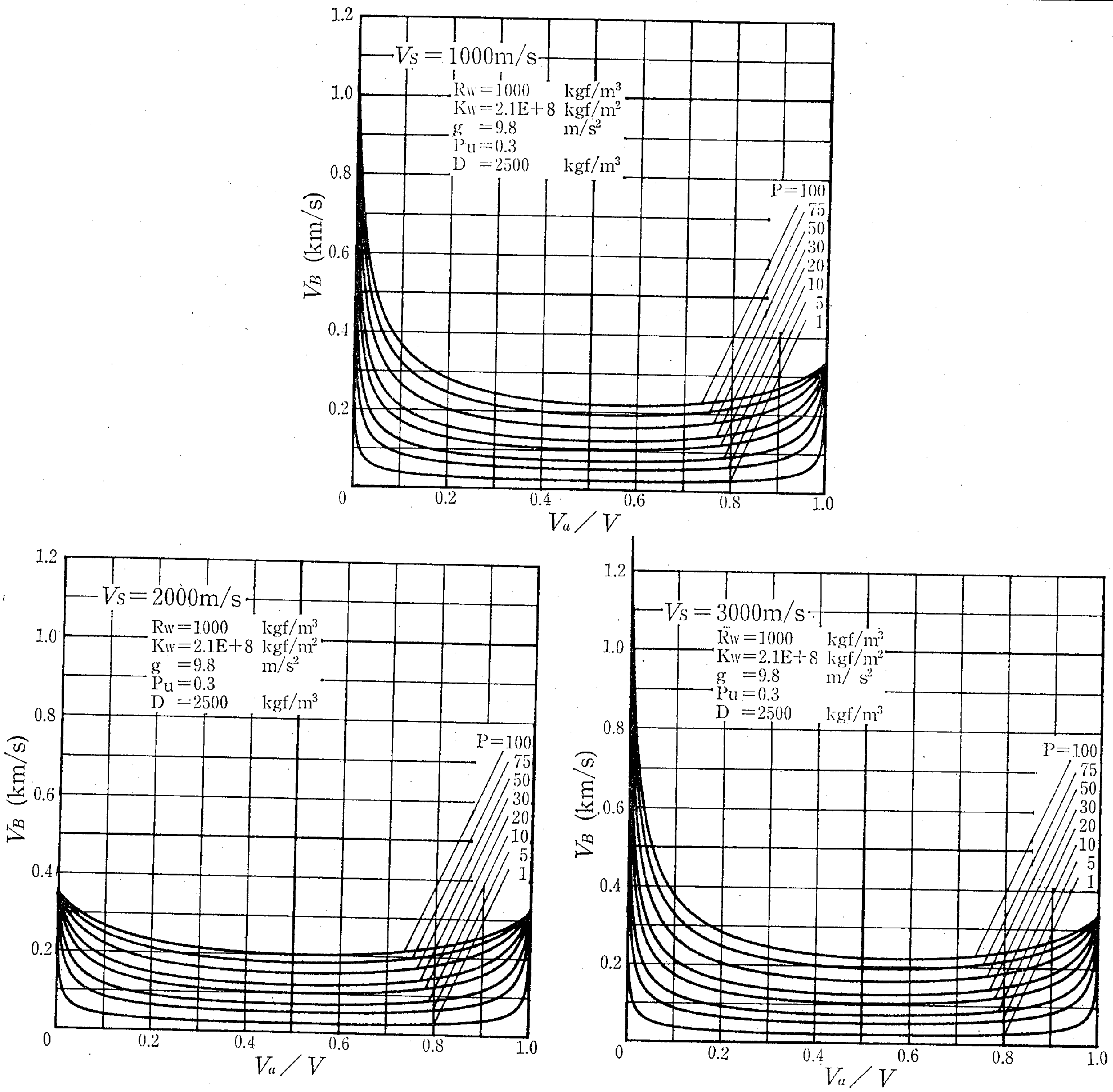


Fig. 17 $V_a/(V\text{-}V_B)$ curve

Referring to attenuation, tube wave is the acoustic wave appearing where borehole water, filter tube and borehole wall are, and is understood to proceed to the direction of borehole axis. Accordingly, consideration is given below to tube wave, on understanding that it can be clarified from the viewpoint similar to reflection and transmission of plane acoustic wave.

Suppose the acoustic impedance of water is expressed by Z_w (density × propagation velocity) and the acoustic impedance in the section L where filter tube is located is expressed by Z_f, the transmission factor T of the wave when Z_f exists sandwiched in Z_w, can be determined according to the following equation.

$$T=\frac{4}{4\cos^2 kL+(Z_w/Z_f+Z_f/Z_w)^2\sin^2 kL} \qquad (14)$$

where $kL=2\pi L/\lambda_f$, in which λ_f represents the wavelength in the section of filter tube. Fig. 19 indicates the curve representing the transmission factor of tube wave in the section of filter

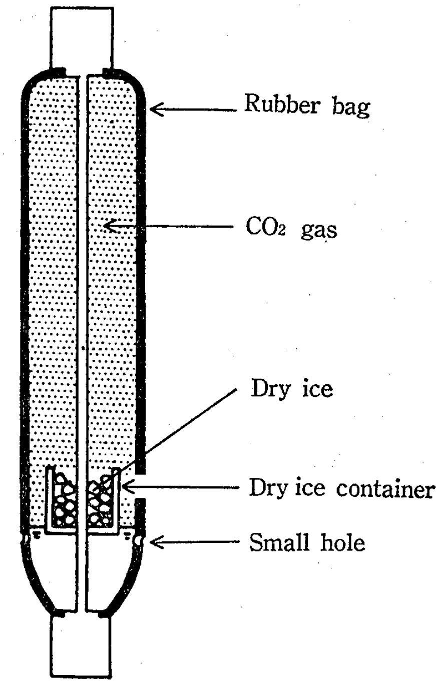


Fig. 18 Gas filter tube

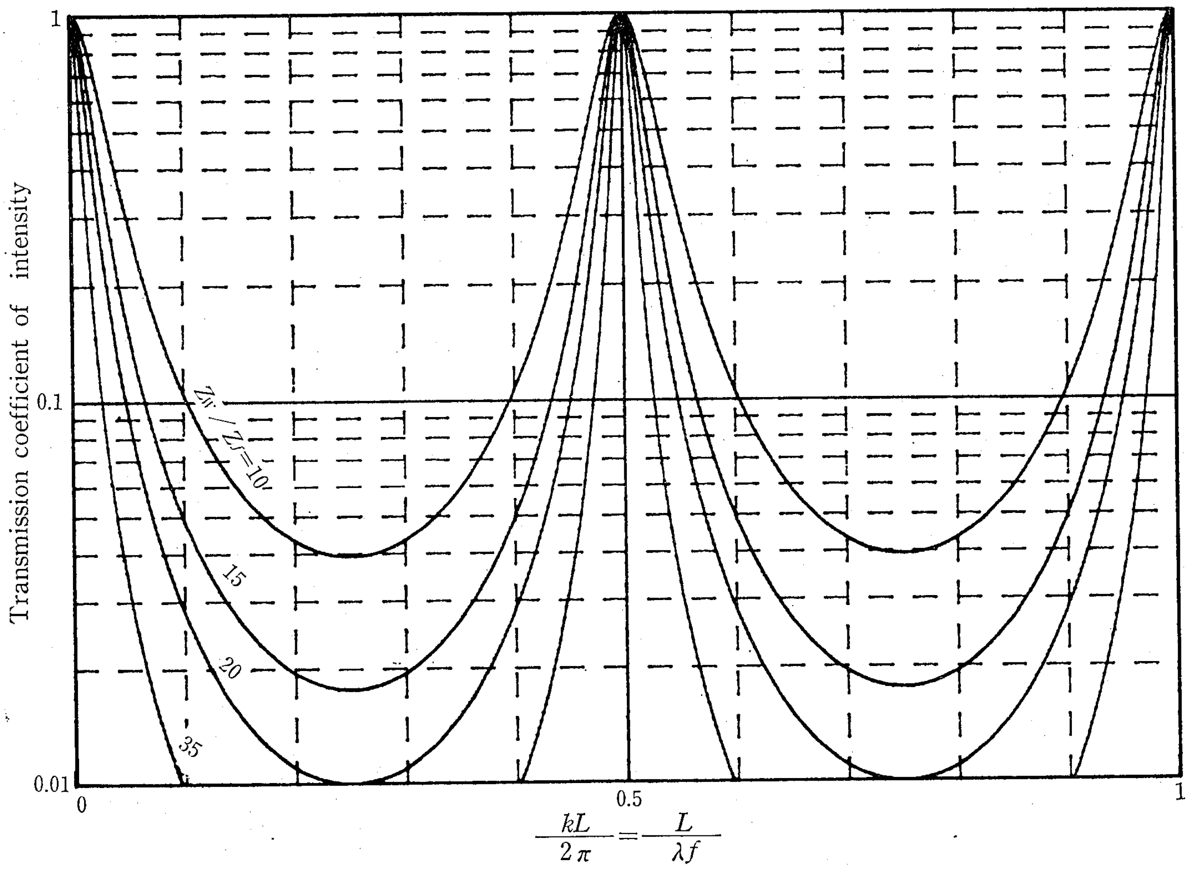


Fig. 19 Transmission coefficient of tube wave in the section of filter tube

tube, while treating Z_w/Z_f as the parameter.

From this figure, what can be deduced are the transmission of the wave without loss in case of L being the integral times of the half-wavelength and the transmission factor rendered minimum in case of L being the odd number times of 1/4-wavelength. To supplement, this means the transmission factor of the wave to vary according to the wavelength and further the frequency characteristic ratained by the wave. In addition, in respect of the frequency involving L to be the integral times of the wavelength, the wave is to transmit resonantly, and the larger Z_w/Z_f is, the more acutely resonance is enhanced. The curve of $Z_w/Z_f=35$ in the figure represents the value in case the rubber occupies its position in the

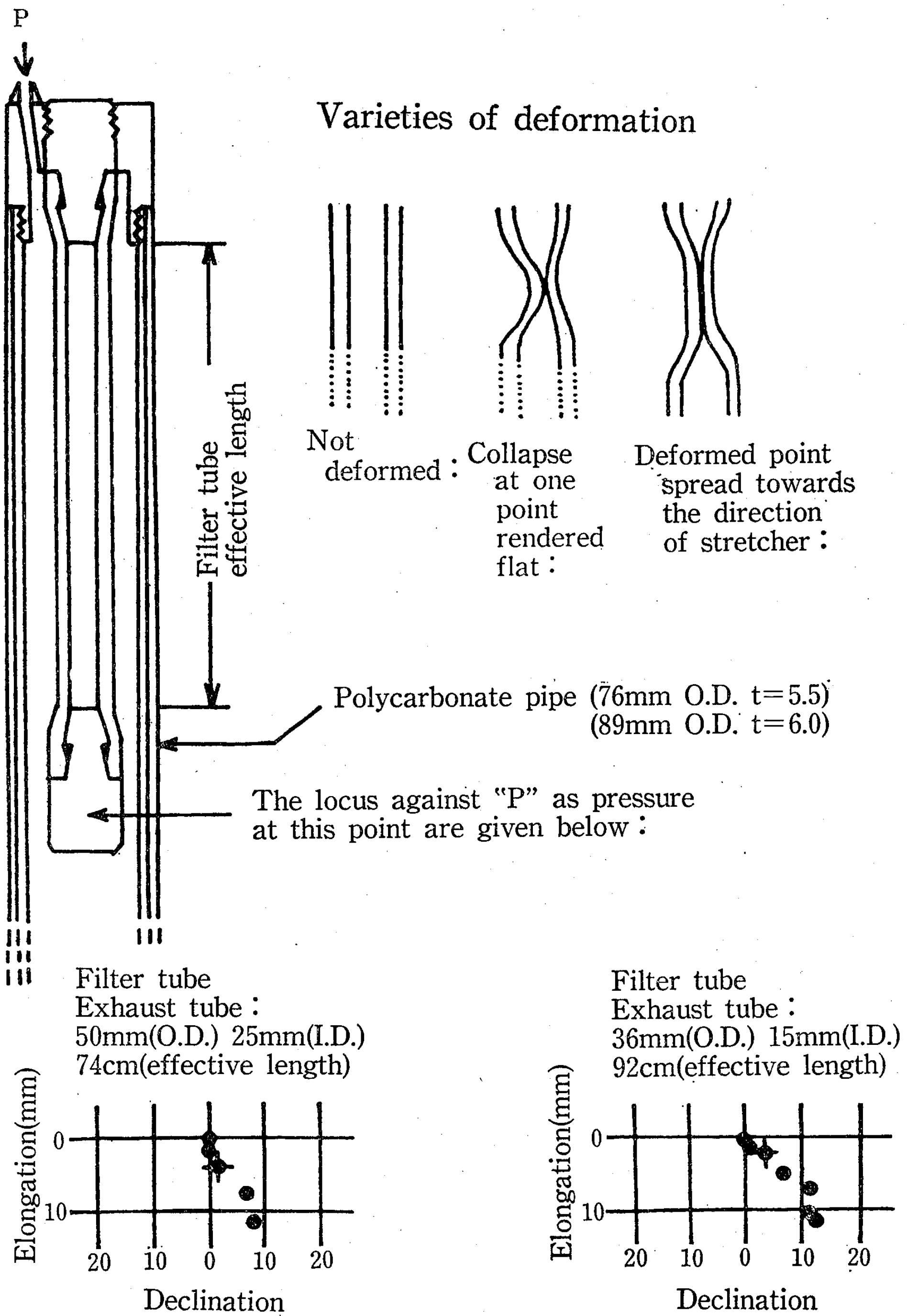
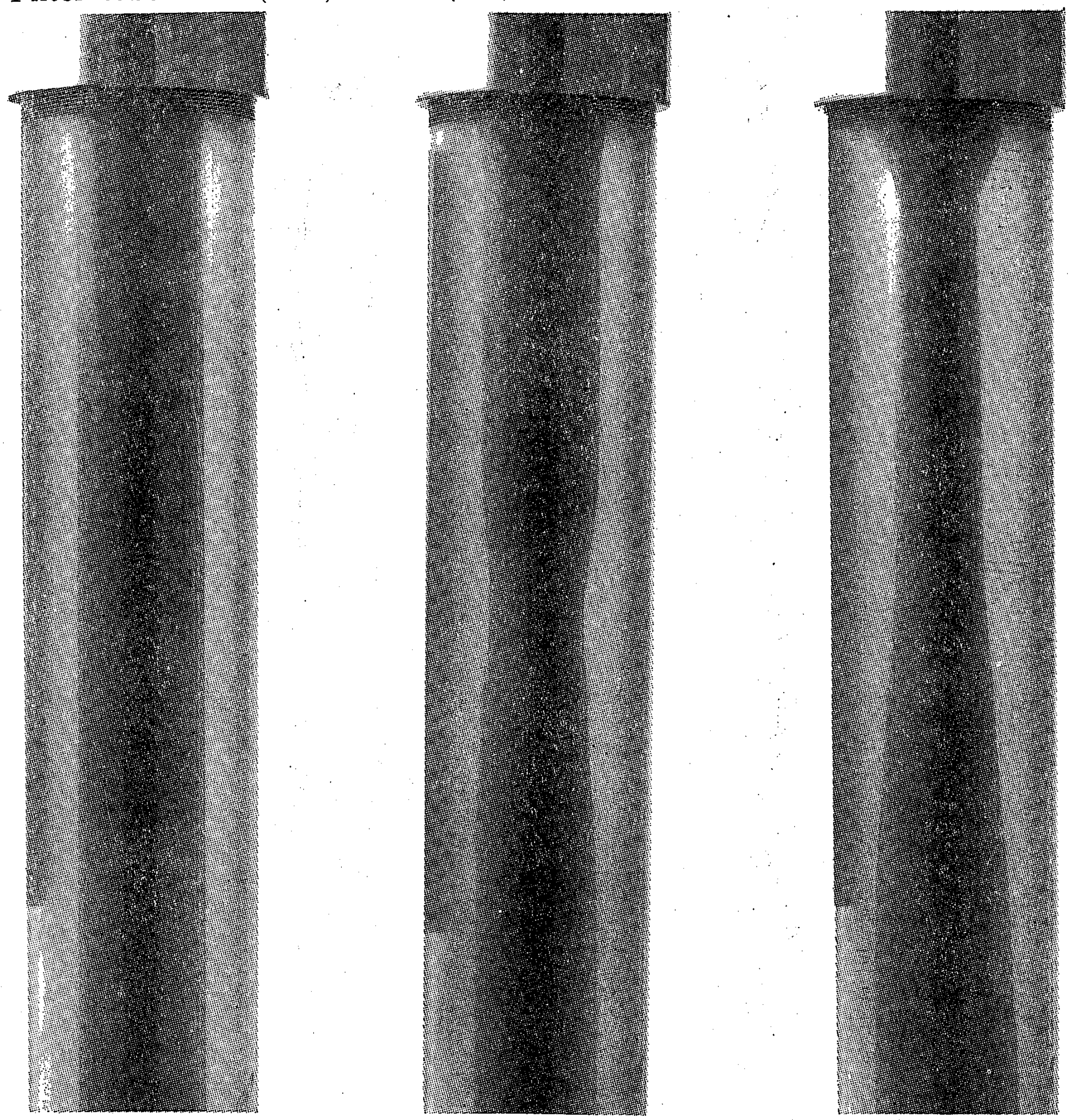
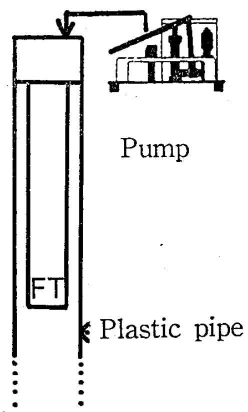


Fig. 20 Deformation and torsion of filter tube

Filter tube 36mm(O.D.)×15mm(I.D.)



0 (kgf/cm^2) ⇨ 4.5 (kgf/cm^2) ⇨ 6.0 (kgf/cm^2)



The weakest part is found collapsed flat to the direction perpendicular to the paper. Observation of this phenomenon begins approximately at 4 kgf/cm^2.

Collapsing area spreads from the part which collapsed first. Simultaneously, another collapse spreads with different part as its starting point. The lower part of the picture indicates the collapse with different part as its starting point. Collapse rendered flat can be recognized parallel to the paper.

Fig. 21 Deformation of filter tube

section of the filter tube, and actually, it is not conceivable to have Z_w/Z_f smaller than 35. Since the filter tube 0.7m long and another 1.7 m long are used practically for sonde, the passage of the wave goes through $Z_w \rightarrow Z_f$ (1.7 m) $\rightarrow Z_w$ (0.3 m)$\rightarrow Z_f$ (0.7 m) $\rightarrow Z_w$, which structure hardly causes resonance.

Relating to the deformation and the torsion with filter tube, Fig. 20 indicates the result of the deformation test conducted on 2 varieties of the filter tube, composed of one with O. D. 50 mm, I. D. 25 mm and another with O. D. 36 mm, I. D. 15 mm.

Once the filter tube is exposed to external pressure, collapse begins with its weakest part to be eventually rendered flat. Further pressurization, if given, results in the development of this deformation, the spread with the flat area, and further simultaneously the development of another collapse with other weak part as its subsequent starting point. Fig. 21 shows the picture that recorded such progress of the phenomenon.

In respect of the torsion with filter tube, as shown in Fig. 20, 10°~12° was the level observed when maximum pressure in range of 0~8 kgf/cm² was given. Though the test has not been conducted giving pressure exceeding 8 kgf/cm² in consideration of the pressure durability with the tester, judging from the flat area spread almost over the entire filter tube affected even by the pressure at 8 kgf/cm², the torsion beyond the above is hardly conceivable. As such, the estimate required to be taken into account with the torsion would be max. 15°. For the review on the amplitude of S wave, this point should especially be noted.

6 Continuous Logging System

In the suspension P–S Logging, the spacing between the source and the geophone is max. 5 m. Accordingly, even on the assumption of S wave velocity of the layer being 100 m/sec, the time appropriated for measurement would be 50 ms at best. If the moving speed of sonde is arranged at 6 m/min, one measurement finishes while moving the sonde by 5 mm, which is synonymous with the measurement conducted with sonde left almost static and which does not make the hindrance against the continuous logging.

The problems to be pondered over are nevertheless the control of the source, the disposal of the signal from sonde, and further the designing of the system for which any of the armored cables used for usual loggings can be effectively applied.

Currently, both the control of source and the power supply to source have been covered from the surface. In respect of the signals from sonde, in brief the 6 signals are dealt with for measurement while moving the source 3 times in total, and those are composed of (a) 2 signals, upper and lower, from the horizontal geophone unit when the source is moved to normal direction, (b) 2 signals likewise when the source is moved to reverse direction, and (c) 2 signals, upper and lower, from the vertical geophone unit when the source is moved to normal direction. Since minimum 2 seconds are required as time for moving the source from one location to another, the current system cannot be fitted for the continuous logging, unless fundamental change is embodied with it.

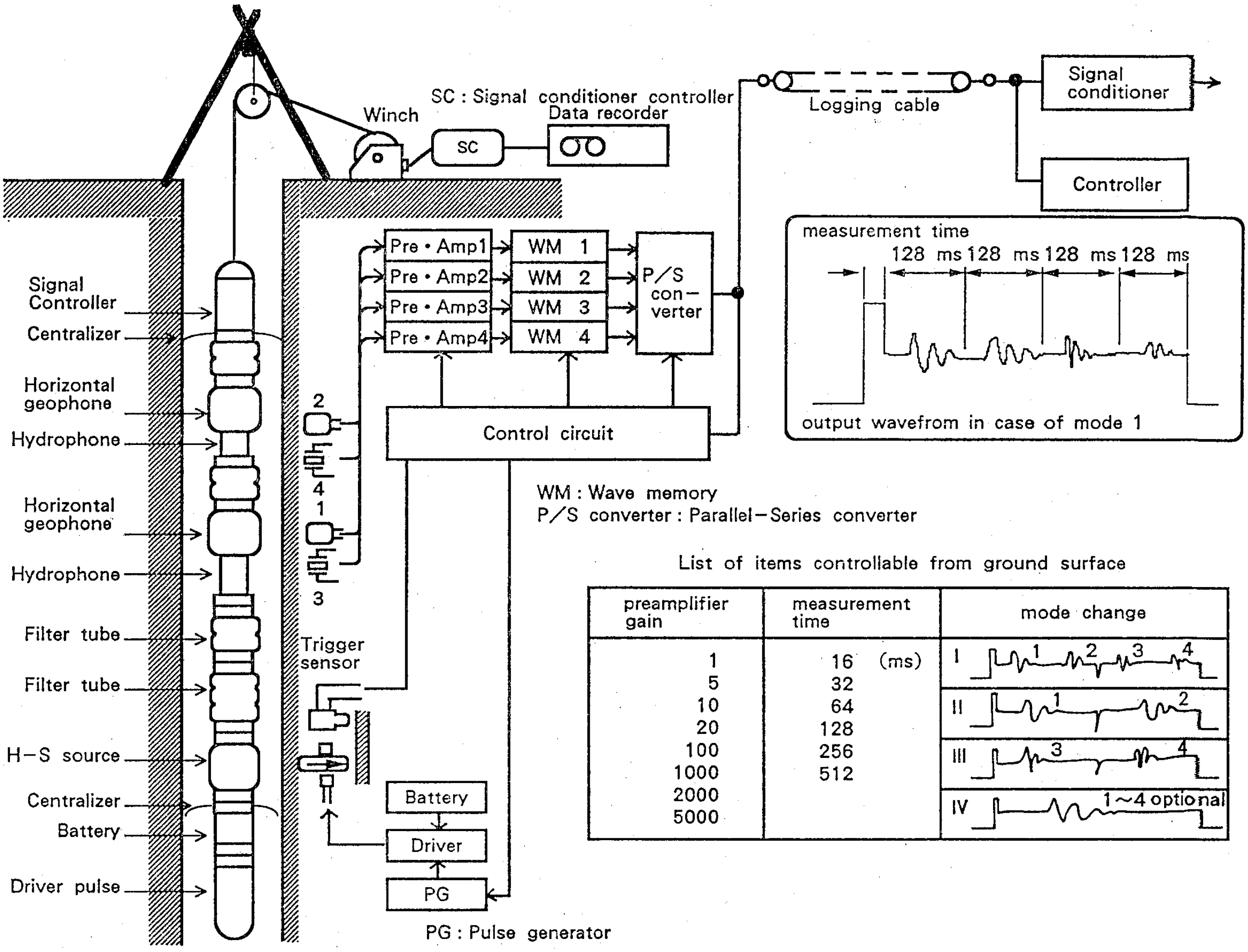
With above background taken into consideration, the following principles have been set up for conducting continuous logging.

(1) In respect of the cable, single–conductor armored cable was decided to be the choice in preparation for the desirable situation where any cable could suit the purpose.

(2) In respect of the movement with source, in place of such conventional rotation as normal →reverse → normal, to stick only to normal was decided.

(3) In respect of the geophone, choices were made to the one of suspension type for S wave and to hydrophone for P wave.

(4) In respect of the configuration with source and geophones, same as in case of the



preamplifier gain	measurement time	mode change
1	16 (ms)	I 1 2 3 4
5	32	
10	64	II 1 2
20	128	
100	256	III 3 4
1000	512	
2000		IV 1~4 optional
5000		

Fig. 22 Block diagram of continuous suspension P-S logging system

conventional placement, the interval between source and first geophone was decided to keep 3~4 m, while the interval between first geophone and second one 1 m.

(5) In respect of the filter tube, two varieties composed of the one with total length of 1 m (the rubber length = 0.7 m) and another with total length of 2 m (the rubber length = 1.7 m) were used.

(6) In respect of total 4 component signals transmitted from the geophone and composed descriptively of 2 component ones from the geophone unit and additional 2 component ones from the hydrophone, they were decided to be put under simultaneous measurement.

Fig. 22 shows the block diagram with the test system prepared according to the above principles. Through preamplifier, the signals are firstly to be amplified and then stored for a while. While effecting the frequency conversion by the conversion with the clock frequency, the signals thus stored are then to be read out in such order as 1, 2, 3, and 4 and be transmitted to the cable. The reason for conducting the frequency coversion is that because of the transmission characteristic with the armored cable being not on excellent aptitude anyhow, this step is to let the signal frequency be below 1 KHz. Since simultaneous passage of signals more than one through the cable is not actual, no fear entails with crosstalk.

The words on wave memory count are 1024 and the resolution is equivalent to 8 bit. Accordingly, obtainment of the dynamic range with great magnitude can never be expected, due

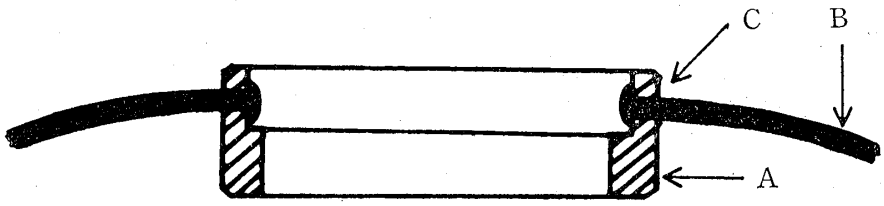


Fig. 23 Diagram of section of centralizer

to which the control from the surface with the gain of preamplifier is required. Additional requirements are for the conversion with measurement time, readout mode etc. Viewing as such, 3-channel selecting device is integrated into the system, through the use of piezoelectric tuning fork. The list of control items is referred to in the figure, which tells that total 21 steps are those under control.

In respect of the source, with the sonde housing all of battery, high pressure power source, driver, and pulse generator, the system is designed to commence its performance, when connected to H-S source. As the battery working hours last 4 hours, suppose the speed for lowering sonde down into the borehole is 15 m/min and the measuring speed while lifting up sonde is 6 m/min, the mere arithmetical calculation works out the measurement feasible with 1028 m.

H-S source is structurally to strike the cylinder by solenoid hammer. A certain time is essentially required from the commencement of current conduction to the solenoid hammer till striking the cylinder. To be specific, the particular time required is various depending on the source pressure, pulse width, status with spring etc. and in an extreme case, might approximately reach 1 ms. With the wish to treat the time when such striking is conducted as the criterion, trial was given on converting the output signal into the trigger one while the vibration sensor of piezoelectric ceramic was put in solderless contact with the cylinder.

Next, reference is made to the function of prime importance that should never be forgotten for conducting the continuous logging. It is easily conceivable that the movement of the source and the geophone while scraping the borehole wall would make the cause for noise. To avoid such unwanted disturbance, the development was successfully made with the centralizer, the structure of which is specified in Fig. 23. Ring A split into two can be united by the setscrews. 12 pieces of whisker B radiantly spread out from the ring, are merely loosely inserted into the hole C on the ring, and can rotate free. The unit of centralizer is used being mounted on the connector section of the sonde. Materialwise, the whisker is made of nylon or the like that retains high toughness. Flexible application to various borehole diameters is feasible by changing the length of whisker. The centralizers, some in number, are to be fitted to the connector section of sonde for the practical use.

Though quite simple in structure, it realizes soft contact with borehole wall, causes less resistance at time of moving the sonde, and is applicable for the boreholes various with diameters by the exchange of whiskers. Though seemingly related to the matter extremely simple, the particular technology involving centralizer in it does play an instrumental role in the embodiment of continuous logging. To have the sonde kept placed in the center of the borehole is the matter of theoretical importance as well that works to curb the generation of tube wave.

7 In Situ Test

Fig. 24 shows the example of the logging record from the borehole with depth 50 m drilled on the premises of Instruments Division, OYO, into which PVC pipe with I. D. 77 mm

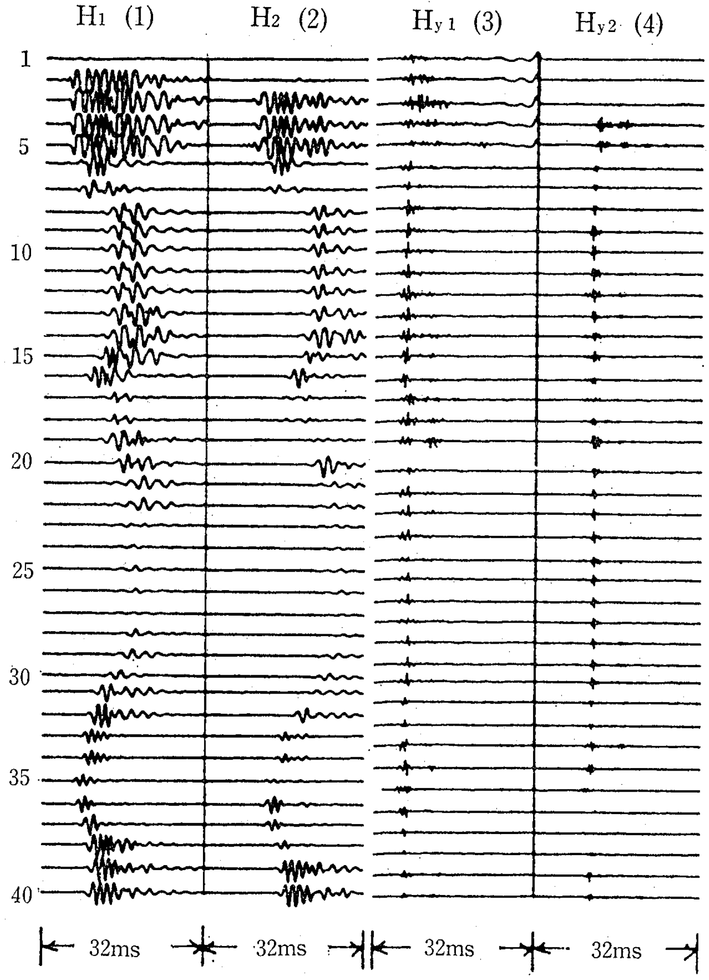


Fig. 24 An example of record from soft ground

and O. D. 89 mm was inserted. The measurement was extended through placement of the sonde as indicated in Fig. 22. $H_1(1)$ put in Fig. 24 signifies the output from the horizontal geophone unit to Channel 1. Likewise, $H_2(2)$ stands for the output from the horizontal geophone unit to Channel 2, while the output from the hydrophone was directed to Channels 3 and 4, respectively marked with $Hy_2(3)$ and $Hy_2(4)$. Based on the location of the source T being zero, the intervals of $T \leftrightarrow H_1$, $T \leftrightarrow H_2$, $T \leftrightarrow Hy_1$, and $T \leftrightarrow Hy_2$ were 2.7 m, 3.9 m, 2.65 m, and 3.85 m respectively. With the mode for storage set to II, respective data were collected by the data recorder.

Being indicative of the result according to the gain fixed and through the playback at every 1 m, the figure delineates well the variation status between propagation time and amplitude. For reading out the propagation time in particular, appropriate adjustment with the gain at time of playback makes it feasible to unify the aptitude of readout accuracy with time. Logging speed at 6 m/min resulted in covering the logging with the depth down to 40 m only in 7 minutes. While the figure indicates the waveforms at every interval of 1 m, the more descriptive data at every interval of 0.2 m are stored on the relevant tape, which means that additional data not indicated in the figure but actually available count 4 times as much as those indicated in the figure. The system capable of acquiring substantially more data with quicker speed compared to the aptitude conventionally achieved has now been embodied, it might be said.

Geological distribution with the test pit proved to be approximately consisted of humic soil with depth range of 1～5 m, alternation of strata of silty clay and silty fine-grained sand with 5～15 m, silty clay, sandy silt, and medium-grained sand distributed in such order with 15～20 m, silty clay with 20～30 m, and gravel and fine-grained sand with 35～40 m. S wave

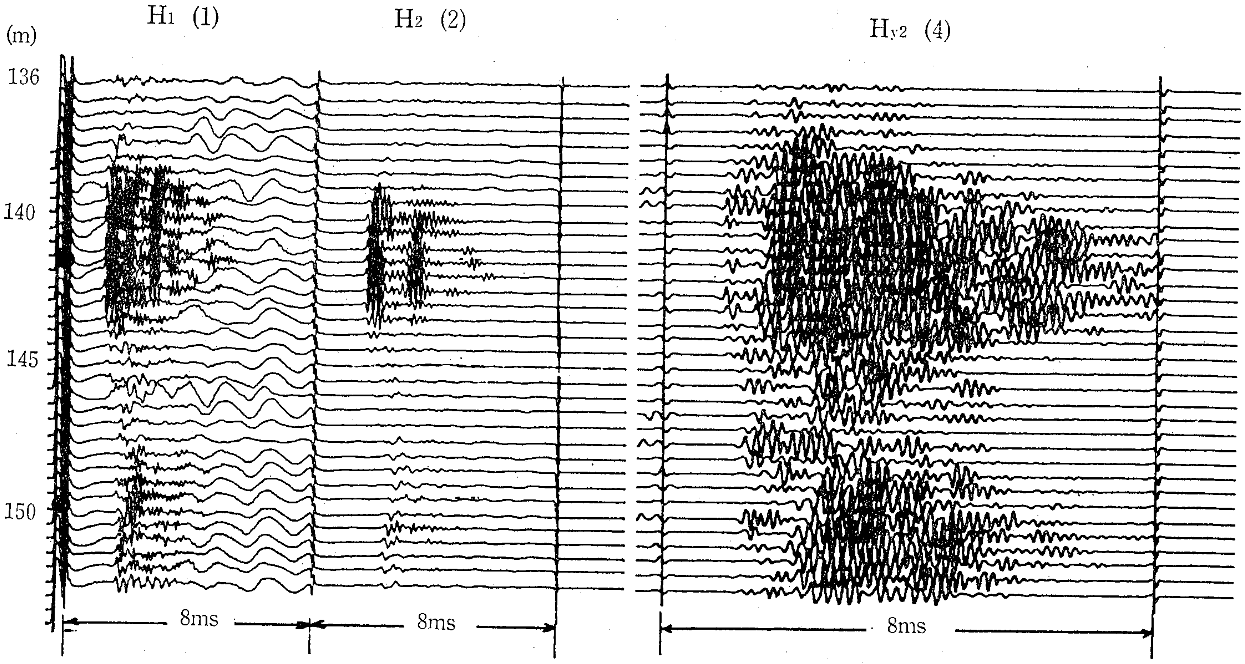


Fig. 25 An example of record from rock ground

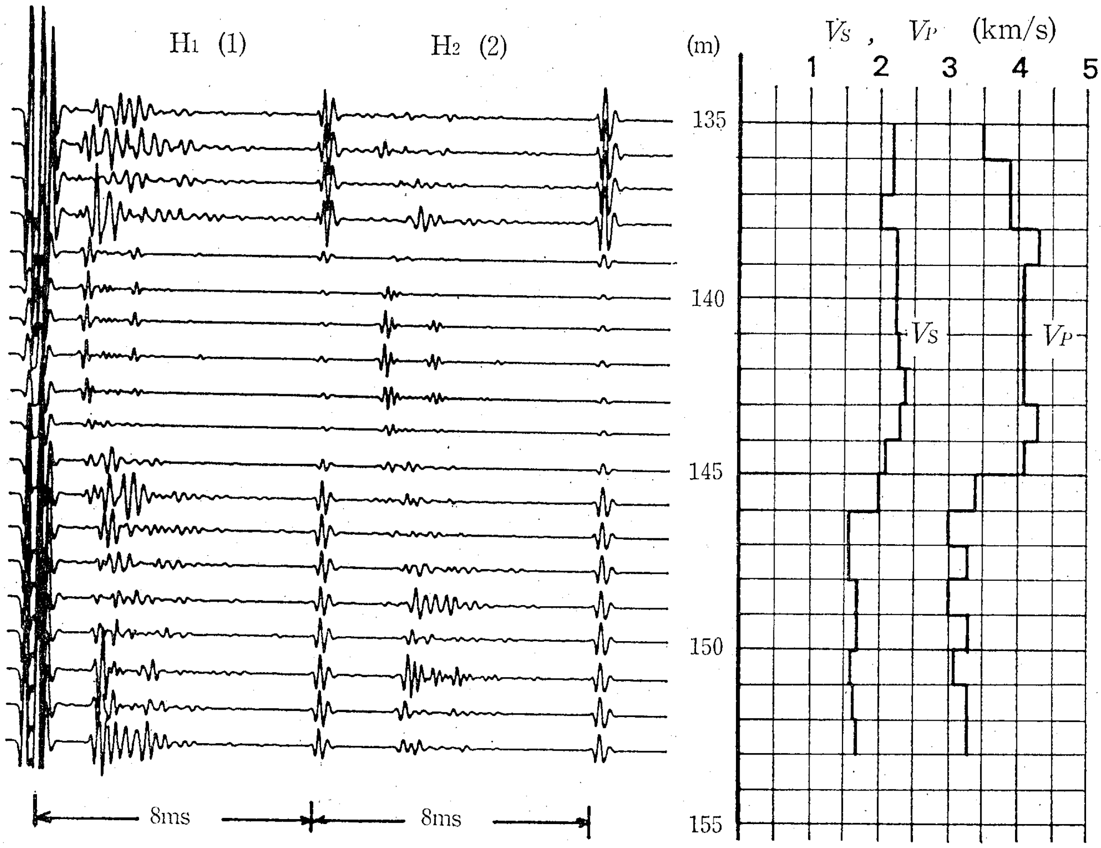


Fig. 26 Relationship between the record for various gains and V_S or V_P

velocity V_s is 150~380 m/sec.

Fig. 25 and Fig. 26 indicate the record examples from the rock layer. The logging speed was 6 m/min and the data are stored on the tape. The waveform stored on the tape is indicated as it is in Fig. 23. Geologically, the measurement depth was composed only of pyroxene andesite. The conditions offered by the depth spanning 136 m to 153 m for the measuring system were those quite uniform and the variation with the amplitude over there really attracted our interest. At time of readout with the propagation time, arrangements were made to change the gain and to utilize filter for easier readout. This example is shown in Fig. 24, while additionally, to the right of Fig. 24, the velocity distribution resulted from such readout is indicated. The values thus obtained have been turned out not contradictory to those as the results from sonic logging and rock sample test, and therefore the judgement on appropriateness with the measurement can be made. As the maximum velocity V_p of P wave was 4, 300 m/sec while V_s was 2, 400 m/sec, the successful measurement has been proved made with the velocity layer till now entailed difficulty with its proper measurement. Judging from the record on the specific area showing the maximum velocity in the approximate depth of 140 m being quite excellent, it might be reasonable to trust the feasibility of the appropriate measurement even with further faster velocity layer.

8 Conclusion

The development has been extended by us to achieve such targets as the application of the suspension P-S Logging for the layer with S wave velocity at 3, 000 m/sec, the performance of continuous logging in same manner as in case of usual geophysical logging, and the embodiment of the instrument that can be integrated as a variety of the tools into the other logging system.

As the result of the field tests, the feasibility of measurement with the velocity at such levels of V_s =2, 400 m/sec and V_p = 4, 300 m/sec has now been confirmed. Additional confirmation has successfully been made with the extension of the continuous logging at the speed of 6 m/min and with the applicability of any cable for such particular practical use.

Through the field tests intended to be given by us in succession to the above in future, exertion of further efforts is promised by us to make the method established relating to expansion of applicability with the suspension P-S Logging on one hand and to clarify the improvement respects required with the instrument trially manufactured to be embodied into its betterment on the other hand. While the discussion done so far on amplitude has been insufficient admittedly, what conceivable for tackling S wave and P wave would be extensive inclusive of such matters as to make the geophone smaller, to shorten the geophone spacing, to place sources in place of a source etc. Speaking about Q value, sometimes there might be the cases where satisfactory results would not be obtainable from the sonde currently available, unless the analyses are made through minute consideration into the layers distribution, the condition of the sonde etc.

In respect of tube wave, there might be some room or other for its utilization, however, the factors for determination on the layer velocity are rendered too many when the filter tube is used, and accordingly, the concept of utilizing tube wave is put aside by us at the moment.

The instrument trially manufactured is the one intentionally prepared to rely on the single-conductor cable tentatively for its daring challenge to overcome the most difficult conditions, and therefore, if 4-conductor cable is used instead, versatile functions could affirmatively be integrated into it, accompanying extensive application scope to open for it.

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サスペンションP–S検層の適用域の拡大

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概 要

サスペンションP-S検層は，振源と受振器を一連のゾンデとして，このゾンデを孔井中に固定することなく地層のP波およびS波の速度を測定するものである。振源と受振器の間隔は，測定深度にかかわりなく一定であり，2個の受振器の間の伝播時間の差を計測するものであるから，時間分解能は測定深度の影響を受けることはない。したがって，振源が地表にあり，孔中固定型受振器を孔井中に配置する従来の方法に比較して，より広い利用の可能性を有している。

しかし，S波の速度が1,000m/s程度までの地層へのサスペンションP-S検層の適用に関しては，これまでのデータでは十分信頼することができることを示しているが，S波の速度が1,000m/s以上になると記録の質が劣化してくる。

今後更に，サスペンションP-S検層が広く利用されるためには，この適用限界を拡大しなければならない。また，現在の1mごとにゾンデを止めて測定を行う方法は，多くの測定時間を必要とするので，一般に受入れられにくい要因になっている。

標題に示した「適用域の拡大」は，測定限界速度を高くすること，一般に受入れやすい測定システムを構築することの両者があって初めて果たせるものである。一般に受入れやすいシステムにするために，ゾンデを移動させながら連続的に検層を行うこと，使用ケーブルが限定されないことの2点を最重点課題とした。

1988年6月現在，サスペンションP-S検層システムの適用範囲は，S波速度で3,000m/sまで拡大できたと確信することができるまでになった。また，従来測定深度ごとにゾンデを止めて行っていた測定作業が，6m/分の速さで連続的にゾンデを移動させながらできるようになり，かつ，ケーブルには，1芯，4芯，5芯，7芯など種々のものがあるが，どのような検層用アーマードケーブルでも使用することができるシステムにすることについて見通しが得られている。

振源と受振器で構成する観測系の利得は，振源の放射インピーダンスを増加させ，受振器の感度を上げて従来の観測系に比較して15～20倍向上させ，S波速度が3,000m/sの地層への適用を可能にした。ハイドロフオンの使用によってP波速度の測定の改良も行った。また，どのようなアーマードケーブルでも使用することができ，かつ，連続検層を行うために，データの並直変換を行うエレクトロニクス，フイルターチューブの動作特性を考慮した最適長さの選択，連続検層のためのノイズ対策などの数々の改良がなされている。

この報文は，これらの開発を行う上での考え方，実験結果などについて取り纏めたものである。