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Basic Aspects of Shear Wave Measurement in a Borehole

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요약 / ABSTRACT

The dipole method is now popular means for S-wave logging. Essential features of this method are explained, emphasizing basic concept based on approximation of the long-wavelength and the far-field. History of my researches concerned is shortly reviewed as background to reach the idea of this method. Short wavelength behavior of the dipole method is simply reviewed. Methods to reject tube wave noise are commented.

Introduction

Objectives of borehole measurements

Idealized target of geophysical prospecting is to evaluate underground geology by remote observation of physical phenomena on the ground surface (or on the sea and in the sky). Geophysical observations in boreholes seem to contradict this formal idealism. However, it is the most important for us to get the best result by using all possible means. By use of boreholes, we can considerably extend ability of geophysical prospecting.

Main roles of borehole observations are the followings :

(1) Direct measurement of geological properties. Typical example is well logging.

(2) Extension of observation spread. Typical examples are seen in geotomography and vertical seismic profiling.

They are very familiar for today's geophysicists. Hence, farther comments are omitted.

Applications of S-wave

S-wave is well known as a basic type of the body waves together with P-wave since the earlier stage of seismology. Seismic prospecting depended on use of P-wave for long time since its beginning, because stable measurement of S-wave by artificial means was difficult. Usefulness of S-wave, however, has been remarked since the earlier stage. Now practical use of S-wave is not so novel topics.

Utility of S-wave is mainly classified to the following three points :

(1) Evaluation of geological facies and reservoir. Some combinations of V_P and V_S are served as diagnostic of them. This

property is used in oil prospecting and others (Tatham and McCormack, 1963).

(2) Estimation of elasticity and strength of rock and soils. This is useful for site evaluation in engineering projects (Kitsunezaki, 1965). Combined use of V_S and V_P is usual for such purpose.

(3) Evaluation of the ground vibration characteristics for preventing earthquake disasters. In this case S-wave properties are almost exclusively important as the parameter for its characterization (Shima, 1962).

The above applications were in my scope through my researches. Actually my research, however, was helped specially by sincere interest in the term (3), which is proper to Japan. This condition was completely different from the major trend in geophysical prospecting which has been developed for oil prospecting.

My research history concerned

My research carrier started in seismic experiments in mine drifts for prospecting metal ores in the later 1950s. Accidental finding of S-wave, which was generated by a small explosion in the experiments, developed to the method of S-wave measurement for rock evaluation in engineering drifts. In the next stage, I developed downhole method with a combination of the borehole geophone and the surface source. The final target was set to create the new method by which S-wave can be measured in the manner similar to the conventional sonic log for P-wave in any kind of rocks. When this target was fundamentally achieved in 1977, I called the method "the suspension type S-wave logging", which will be also called the dipole method as general terminology afterward. Origin of names will be explained there. In the section 4, some comments on every historical stage will be added to reveal technical background of the dipole method.

Scope of this paper

In this paper I totally describe essential features of the dipole method, as well as some elementary base which seems to be important for seismic observation in a borehole. The unidirectional single point force, has been kept continuously as a base of S-wave source through every stage of my researches. Properties of this type of force and the related comments are described in the section 2 and 5.

The development of this research was closely related to social and natural environments proper to Japan. Such kind of methodological discussion is included in another related paper (Kitsunezaki, 2000), as well as comments on practical developments, which are almost omitted in this paper.

THE SOURCE OF S-WAVE GENERATION

Unidirectional single point force

In this paper the medium will be assumed as isotropic homogeneous, if the condition is not particularly specified.

It is very clear fact that the source force with spherical symmetry in the infinite medium can not generate S-wave, but P-wave only. In my belief the most effective source in practical sense is the unidirectional single point force, which is simply called the point force hereafter, if the source is located in the homogeneous medium. In the direction perpendicular to the force axis, the S-wave predominates without the P-wave, otherwise in the direction parallel to the force axis the P-wave dominates without the S-wave. In this case the source force $Gg(t)$ generates displacement u at distance r from the source point O and at the direction ψ with the force axis :

$$u_P = u_r = \frac{G\cos\phi}{4\pi r\rho V_P^2}\, g(t - r/V_P) \text{ for P-wave.} \quad (1a)$$

$$u_S = u_\phi = -\frac{G\sin\phi}{4\pi r\rho V_S^2}\, g(t - r/V_S) \text{ for S-wave.} \quad (1b)$$

In these relations the subscripts P and S mean P-wave and S-wave respectively. The subscripts r and ϕ mean components in the spherical coordinate with the origin at O. The z axis is coincident with the force axis (Fig.1(a)). In the above equation, r is assumed to be sufficiently longer than the related wavelength. Hence, Eq.(1a) and Eq.(1b) are the relation in "the far field approximation".

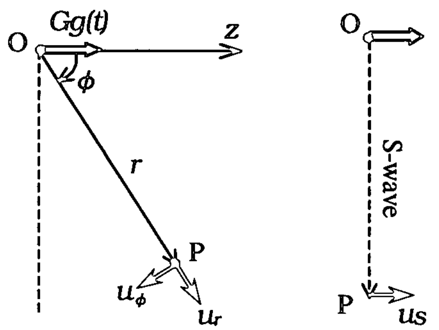


Fig. 1. Wave field of unidirectional single point force.
⇨ Force, ⇨ displacement
(a) Configuration for Eq.(1).
(b) Configuration for S-wave observation.

In normal case S-wave should be detected on a line perpendicular to the force axis (Fig.1(b)) This simple idea was the central base through all my methods for the direct measurement of S-wave.

A horizontal point located on the horizontal ground surface generates the same S-wave displacement as Eq.(1b) except that 4π in the denominator is changed to 2π. But P-wave expression becomes more complex, and completely different from Eq.(1a). It is neglected here.

Single vertical force on the horizontal ground surface generates SV-wave, but not SH-wave. In semi-infinite homogeneous medium it is the most clear fact that the vertical force on the horizontal surface cannot generate S-wave in the vertical direction.

Heterogeneity of medium near source

Sometimes in actual fields we experience S-wave generation which can not be expected in the ideal condition of the medium and the force. In some cases we observe clear SH-wave propagated from the vertical force on the horizontal ground. Such kind of phenomenon is attributed to heterogeneity of the medium close to source in many cases. Based on Kitsunezaki (1994), a case to prove this fact is demonstrated in the following.

Fig.2 demonstrates P- and S-waves generated by the vertical force (weight drop) close to (32m away) the vertical borehole in which the waves are observed with a fixed geophone. In this case the S-wave was not SV-wave but SH-wave. This fact was confirmed by auxiliary experiments, though the phenomenon itself was found accidentally. By excavation we found that the source point was accidentally located almost at the edge of buried pit filled with very soft mud. SH-wave (polarized in direction perpendicular to the pit edge line) predominated at the source point close to the pit edge. We call this phenomenon the pit effect. The configuration of the pit effect is schematically illustrated in Fig.3. A pair of vertical forces (F_A and F_B) propagates SH-wave in the plane containing D and -Z0 axis. Polarities of the SH-wave by F_A and F_B at the opposite edges are reversed mutually.

In this paper detailed discussion on this aspect of S-wave generation is omitted.

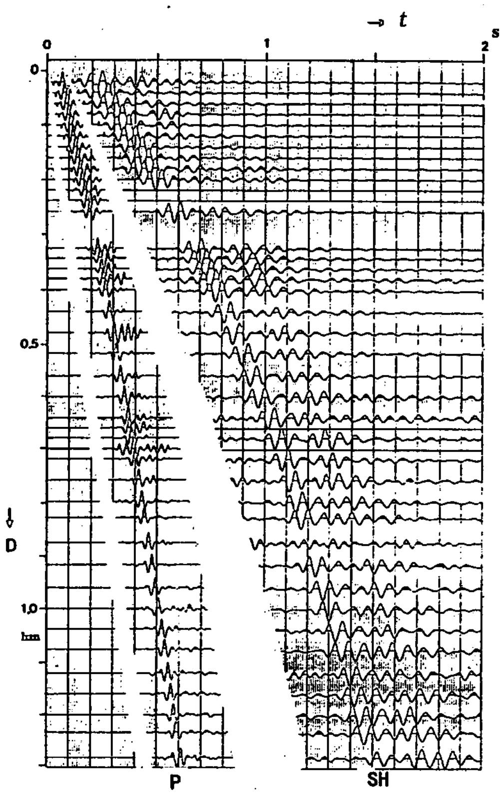


Fig. 2. Demonstration of P- and SH-waves resulting from vertical force. Recorded components: vertical for P-Wave; horizontal for SH-wave. D=depth, t=time.

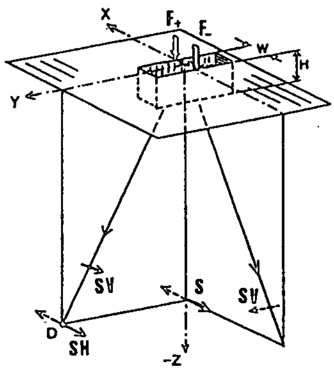


Fig. 3. Typical configuration of a pit and the forces (F_+ and F_-) which causes the pit effect.
Polarities of SH waves at D resulting from F_+ and F_- are reversed mutually. (After Kitsunezaki, 1994).

THEOREM OF RECIPROCITY

I think that it is very important to get clear insight in physical process. The theories used in the main frame of this paper are so simplified as to give the clear concept, by using two major assumption :

(1) the long-wavelength approximation and (2) the far-field approximation.

Theorem of reciprocity provides very useful means to get physical insight of source behavior when these conditions are accompanied. This idea was emphasized by J. E. White(1965). According to him (White, 1983, p.211) the statement of this theorem is as follows :

If, in a bounded, inhomogeneous, anisotropic, elastic medium, a transient force $f(t)$ applied in some particular direction α at some point P creates at a second point Q a transient displacement whose component in some direction β is $u(t)$, then the application of the same force $f(t)$ at point Q in the direction β will cause a displacement at a point P whose component in the direction α is $u(t)$.

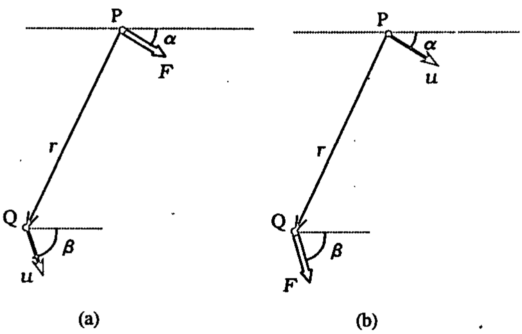


Fig. 4. Illustration of the theorem of reciprocity.
(a) and (b) are equivalent:
u/F is the same in both cases.
F=force.
u=displacement.

Essential idea of this theorem is illustrated in Fig.4, where the force is expressed as F. If the case of (a) is fact, the case of (b) is also fact. The reversed statement is also true. Usually interpretation of source located at some boundary is not easy. Displacement behavior at the same boundary can be rather easily analyzed, if the long wavelength approximation is hold. The source behavior in the inside of the homogeneous medium is simple as expressed in Eq.(1a,b) if the far field approximation is hold. The problem of (a) can be solved by solving that of (b). Actual application of this theorem will be seen in the section 5.

PROGRESSIVE STAGES IN MY RESEARCH

Typical stages are illustrated in Fig.5(a)(b)(c). Explanations are given to every stage :

(1) In the seismic experiment in mine drifts in the later 1950s, I found predominant generation of S-wave by a small explosion in a short drill hole made in the drift wall. The small explosion is considered to behave as the point force acting on the drill hole bottom. The force perpendicular to the drift axis was the source of S-wave which was observed along the same drift (Fig.5(a)). This configuration was directly applied for site evaluation of engineering projects.

(2) In the next stage, boreholes were selected as observation site. The borehole was considered to be more ideal site for wave observation because ratio of hole diameter to wavelength is smaller than that in drift. The geophone fixed to borehole wall was designed for this purpose in 1967. Horizontal force on the ground surface was used as the source of S-wave, which was detected in the borehole (Fig.5(b)). Such a downhole method has been widely used in Japan thereafter especially for ground evaluation related to earthquake disaster.

(3) Final goal of my research in this trend was to create a new method for the S-wave logging, with which we can directly measure S-wave properties of any rock (from soft to hard) in any depth with a suspended probe, as well as sonic log for P-wave. This was the suspension-type S-wave logging, which is described in the following section.

Details of these researches were described by Kitsunezaki (1971).

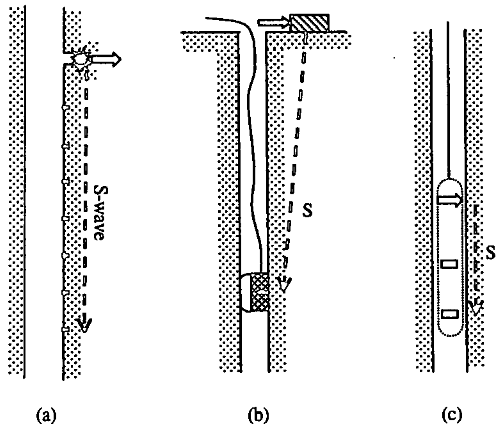


Fig. 5. Typical development stages of my method for S-wave measurement.
(a) Measurement in a drift.
(b) Down-hole measurement.
(c) Probe measurement.

SUSPENSION-TYPE S-WAVE LOGGING (DIPOLE METHOD)

Basic assumption and idealized condition

The essential principle of this new method is conceived as extension of the downhole method. Two kinds of approximation (the long-wavelength and the far-field) were kept as the theoretical base. The source force is the horizontal point force. If the wavelength is sufficiently longer than the hole diameter, we can neglect effects of the borehole to S-wave propagation in the solid. The source force should be perpendicular to the hole axis so that S-wave is observed along the same hole. The borehole is assumed to be vertical in the above expression, and also hereafter.

How to generate S-wave

Direct excitation of the hole wall by a kind of hammer is easily conceived. But this was not the source system to be wanted in the new method. The horizontal force was to be applied to the hole wall through particular set of liquid pressure distribution. I called this source system "indirect excitation type source". Its principle is illustrated in Fig.6(a), where a rigid body is suspended in the liquid contained in a borehole. Direct horizontal force is applied to the rigid body, whose horizontal motion produces positive and negative pressures in the front and rear sides of the motion respectively. The horizontal force is applied to the hole wall through this pressure set.

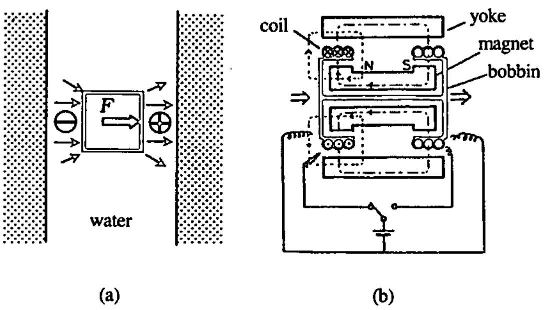


Fig. 6. Dipole source.
(a) Principle.
(b) Mechanism.
A short large current pulse applied to one of two coils causes motion of the bobbin.

Actual mechanism used in the source system is illustrated in Fig.6(b). Two coil bobbins connected at the both ends of a rigid bar, which are set in the strong magnetic field of the permanent magnet, correspond to the rigid body mentioned above. Current applied to any one of the coils produces a horizontal piston-like motion by the electromagnetic force. The motion direction can be reversed by changing the activated coil. Outside of the whole mechanism is covered by a rubber tube for water proof. The same source mechanism was used in the experiment for Fig.8, which will be explained afterward.

The above source mechanism itself is tentative one for the first stage of the experiment. In the elementary stage, every experimental component was to be selected so that dynamic analysis and manufacturing were easy.

The indirect excitation type source is similar to the shaker source by proposed by White(1968). He demonstrated the similar idea in theoretical simulation of many kinds of excitation method. His advanced idea was not so interested, because his experiment was not successful to prove his idea. I knew his work concerned, after I had reported the result of my experiment.

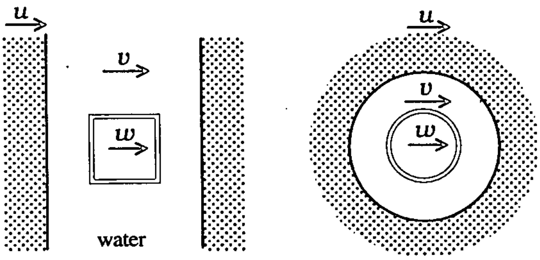
The dipole source in DSI tool of Sclumberger company which has been commercially used since 1990 is the same as the shaker source (Hoyle et al.,1989). Further explanations of this system will be given afterward.

The naming of the dipole source is generally used, because it expresses physical essence of this source system. A set of positive and negative pressure is called the dipole. Hence this name will be used hereafter.

How to detect S-wave

In the wanted system the S-wave should be detected in the liquid contained in the borehole. Many people have a feeling of contradiction, because S-wave can not propagate in liquid. In very strict expression, the phenomenon closely related to the S-wave in the solid is detected in the liquid.

As far as the long-wavelength approximation is kept, horizontal displacement of the borehole wall is the same as that of S-wave itself. And then, horizontal displacement of the liquid contained in the borehole is coincident with the horizontal displacement of the hall wall. As a means for detecting the liquid motion, I proposed the suspension type detector, whose body has property of the neutral buoyancy. The neutral buoyancy means that the apparent density of the body equal to the liquid density. In this condition output of horizontal component of the detector surely corresponds to the horizontal displacement of the liquid and to S-wave displacement as a result. This concept is illustrated in Fig.7. Actually it is not necessary that the condition of the neutral buoyancy is kept so strictly.



(a) Side view. (b) Top view.

Fig. 7. Principle of the Suspension-type detector. If the detector body has property of neutral buoyancy, $u=v=w$, where u, v, and w are horizontal displacements of the hole wall, the water, and the detector.

An alternate method is to detect horizontal pressure difference of the liquid. The liquid motion is caused by pressure gradient. It is only a problem of technical convenience to detect either motion or pressure. Both are the same in the basic principle.

In the DSI tool the pressure difference is detected.

Experiment on the suspension probe

The above source and detectors were connected to construct a probe as shown in Fig.8(a), after utilities of both elements were confirmed by individual tests. A typical example of experimental records is demonstrated in Fig.8(b), where S-wave is very clear. P-wave is very faint. Explanations on experimental condition are given in the caption of these figure.

The maximum displacement of the S-wave was expected in the x-component which is the source force direction. Minor vibration of the y-component ($3y$) may be attributed to deflection of detector directions and (or) by heterogeneity of the medium including hole condition.

Predominant period of the S-wave is about 3ms. S-wave velocity V_S is about 0.35km/s, therefore the predominant wavelength λ is about 1.05m. The hole diameter d is 6.6cm, therefore $\lambda / d \fallingdotseq 16$. The condition that permits the long-wavelength approximation will be discussed in the section 6.

Interpretation of the source principle by the theorem of reciprocity

The physical essence of the indirect-excitation type source or the dipole source is represented in the principle that this type source behaves as the point force in the solid. This principle can be confirmed by applying the theorem of reciprocity as follows :

(1) Fig. 9(a) expresses the concept of the whole probe system. A is the rigid body which behaves as the source. B is another rigid body corresponding to detector. S-wave generated by applying the force F to A is detected at B as its displacement

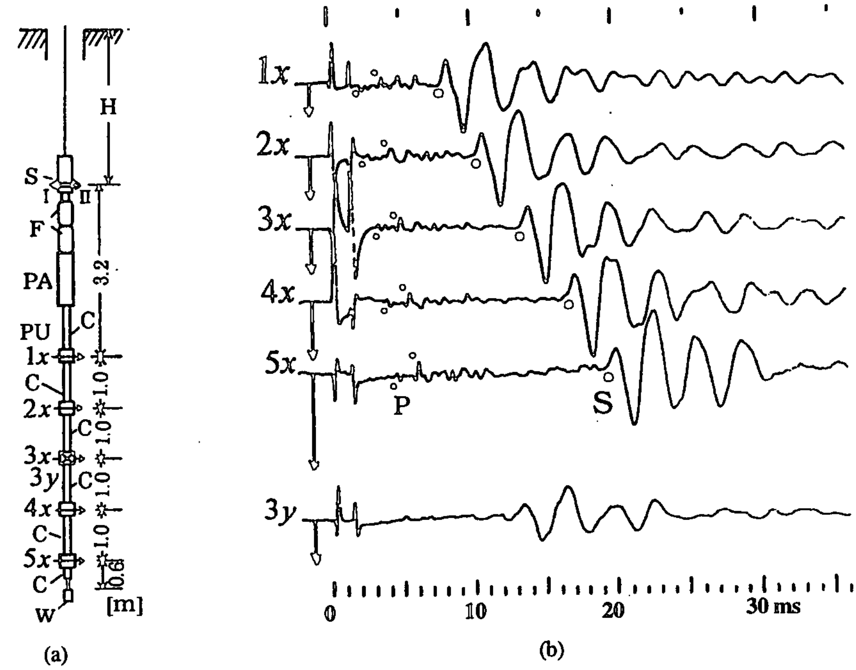


Fig. 8. Historical record which verified availability of the suspension-type S-wave logging.
(a) A probe consisting of a source (S) and 5 receivers. Source force is directed toward (-x) in case of (b). 1x~5x, and 3y=x- and y-component horizontal detectors.
C=flexible coupling tube. F=filter tube, PA=preamplifier. W=weight.
(b) A record obtained in a borehole (6.6cm in diameter) in Pliocene mudstone (V_S =0.35km/s).
S-wave is predominant, but P-wave is very faint. Directions of arrows on left of traces represent the initial motion polarity for x or y direction. Their lengths express relative sensitivity.
(See the text.) (After Kitsunezaki(1980))

u.

(2) A_0 is an auxiliary point assumed in the solid, close to A in such a limited way that its motion is not affected by existence of the borehole wall. In this condition the horizontal separation between A_0 and the hole wall may be almost the same order of the hole diameter. B_0 is the point assumed to B, in the same manner as the relation of A_0 to A.

(3) If the force F is applied to A_0 (Fig.9(b)), this force behaves as the point force in the homogenous medium. Therefore, our problem is to prove that both forces at A and A_0 produce the same effect in the far field. When we observe the waves at B_0 in the far-field, the theorem of reciprocity transfers the original problem to the following form:

Both horizontal displacements at A and A_0, which are produced by the force F applied to B_0, are the same mutually. The former is u'' and the latter is u''_0 in Fig.9(c). If the body A has property of the neutral buoyancy, horizontal displacements of A and A_0 are completely the same for S-wave. In any buoyancy, a transfer factor can be defined as a ratio of the horizontal displacement of A to that of A_0.

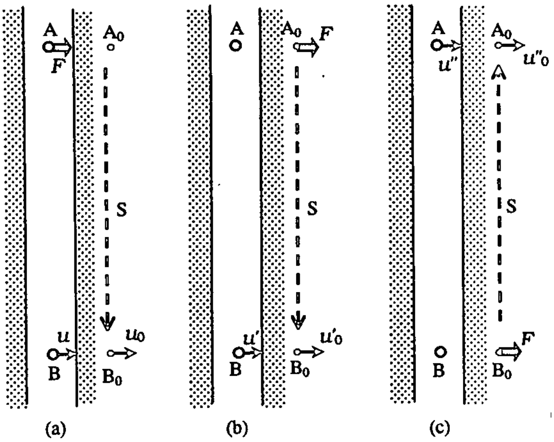


Fig. 9. Interpretation of the far-filed behavior of the dipole source.
Configuration of (a) represents the normal observation condition. The force F acts on A_0 in (b), and on B_0 in (c). In these cases, $u_0=u''$, and $u'_0=u''_0$ according to the theorem of reciprocity. If the body A has the property of neutral buoyancy, $u''=u''_0$, therefore $u_0=u'_0$.

(4) When returning to the original problem, the far-field wave propagated from the source A is the same as that from A_0, if A has property of the neutral buoyancy. Even in general case that A has some property different from neutral buoyancy, the far-field wave propagated from A is not essentially different from the above case, except that the amplitude of the wave field is shrunk or magnified by the above transfer factor. Strictly speaking, frequency characteristic may be introduced in the above modification.

Relation of horizontal displacements at B and B_0 is, of course, controlled by the property of B as the suspension type detector.

A remark on the source design

In the above discussion we implicitly assumed that sufficient magnitude of force F can be applied to A. This is the problem to be considered carefully. When the body A is very small, it may be easily moved in the liquid even by a small force. The mechanical impedance of the body surface is defined as a ratio of its motion velocity to the total force acting on it. Light motion corresponds to low mechanical impedance. In analogy to electric circuit (Fig.10), we can understand that large output force (corresponding to output voltage) is hardly produced at the small output impedance. For increasing the mechanical impedance of the source body, effective volume of the source should be sufficiently large within possible limit. Increase of the force frequency also increases the mechanical impedance.

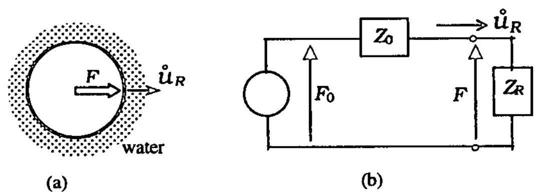


Fig. 10. Effect of mechanical impedance of the source .
(a) Definition of mechanical impedance (radiation impedance) of the outside surface Z_R.
$Z_R=F/\dot{u}_R$; $\dot{u}_R$=particle velocity of the surface, F=force applied to the surface.
(b) Equivalent circuit of (a). The internal mechanism related to Z_0 and F_0 is omitted in (a).

CONDITIONS THAT THE DIPOLE SOURCE CAN BE REGARDED AS THE POINT FORCE IN SOLID

We have confirmed that the dipole source in the borehole liquid is regarded as the horizontal point force in the solid under the conceptional definite conditions. For the actual application it was wanted that these conditions were specified in concrete form. The answer was given by Kurkjian's simulation (Kurkjian, 1986).

My experiment (Kitsunezaki, 1978, 1980) described in the section 5 stimulated interest of people related to well logging. Many advanced researches were made by researchers in Schlumberger company in process to produce their own dipole system which is called DSI (dipole shear imager). Kurkjian's work is one of them.

He computed the displacement waveform for two cases. One of them is the "hole model" in

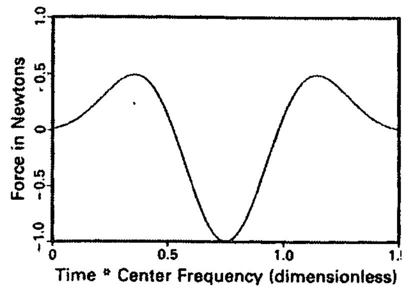
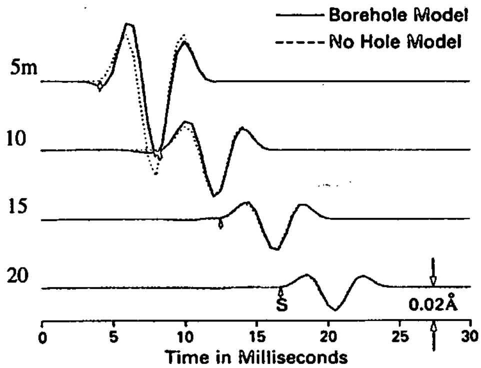
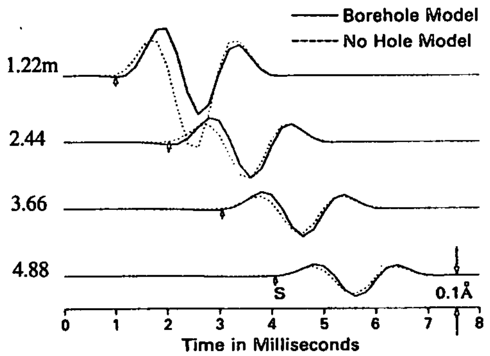


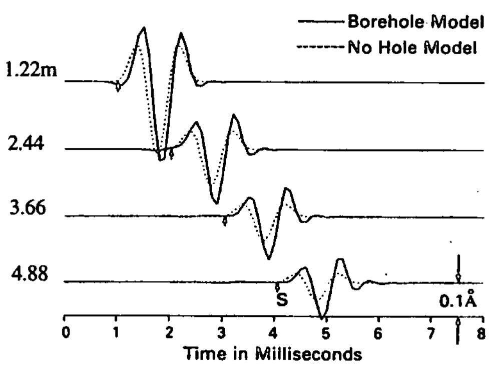
Fig. 11. Waveform of the source force assumed in the simulation of Fig.12 (After Kurkjian (1986)). The center frequency f_0 means the center of spectrum band of this waveform.



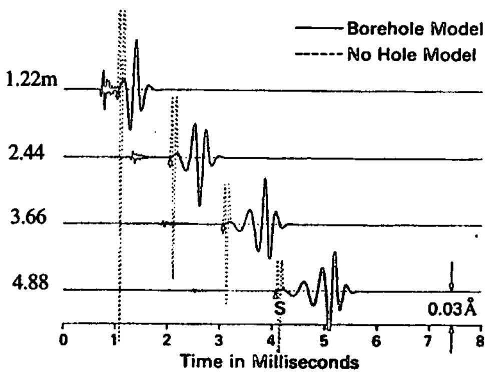
(a) f_0 = 200Hz, λ_0=6m, λ_0/d = 30.



(b) f_0 = 500Hz, λ_0=2.4m, λ_0/d = 12.



(c) f_0 = 1kHz, λ_0=1.2m, λ_0/d = 6.



(d) f_0 = 10kHz, λ_0=0.12m, λ_0/d = 0.6.

Fig. 12. Synthetic waveforms associated with the "borehole model" and the "no hole model". S-wave velocity V_S=1.2km/s; borehole diameter d=0.2m; f_0=source center frequency; λ_0=wavelength of S-wave corresponding to f_0. (After Kurkjian(1986).)

which the horizontal point force and the horizontal detectors are set on the hole axis in the borehole liquid. Another is the "no hole model", in which horizontal point force and the horizontal detectors are located in unbounded medium. Other conditions are the same in the both models. The results of his theoretical simulation are cited in the Fig.12, which is arranged from the original figures. Distance of each receiver from the source, r, is written at the left end of each trace by me only for explanatory convenience.

He assumed parameters as follows :

S-wave velocity V_S=1.2km/s,

hole diameter d =0.2m.

The assumed waveform of the source force is shown in Fig.11. The central frequency of its spectrum band is f_0. The wavelength of S-wave is λ. The λ corresponding to f_0 is λ_0. A key factor characterizing wave features is the ratio of λ_0 to d. They are written in each figure caption. We can directly compare the wave features of two cases in each figure, in which waveforms of the "hole model" and the "no hole model" are drawn by solid line and broken line, respectively. (a) of Fig.12 corresponds to very large λ_0/d, while (d) to very small one as another extreme. In order of (a),(b),(c) and (d), λ_0/d decreases. In (a), waveforms in two cases are identical except the first trace. Almost the same features are recognized also in (b). The differences become remarkable in order of (b) to (c). Both wave features are completely different in (d).

Based on these facts, Kurkjian concluded as follows :

The far field displacements associated with a horizontal point force in an infinite solid are the same as those associated with a horizontal point force (dipole source) in a borehole liquid, provided the source frequency is sufficiently low. The condition of λ/d>10 and r/λ>1 should be at least satisfied for it. (The original statement is simplified by me using the present symbols.)

SHORT WAVELENGTH CHARACTERISTICS AND OTHERS

λ/d is not so large in actual oil wells, whose diameters are fairly large compared with those of engineering boreholes. In short wavelength, wave feature of the dipole source is complex as shown in Fig.12(d). Systematic simulations by Kurkjian and Chang (1986) provide us with comprehensive concept on the related problems. This work covers effects of several factors including S-wave velocity and source force frequency. According to their naming, the fast formation is a solid having V_S higher than the sound velocity of borehole liquid, V_W, while the slow formation has V_S lower than V_W. Whether the formation is slow or fast is an important key factor controlling propagation characteristics.

Monopole source and quadrupole source are also simulated for comparison with the dipole source. The monopole is source of the conventional sonic log. The quadrupole is one of multipole sources. In the concept of multipole source the dipole is the lowest order of multipoles.

Full discussion of these aspects are problems beyond the range of this paper. Some comments are added only for supplementary purpose in the following. Fig.12 is a case of the slow formation. This figure itself demonstrates clear evidence that S-wave is recorded by the dipole system in the slow formation. Fig.8 is a demonstration by field record on the same evidence.

In favorable condition S-wave is detected by the actual monopole system. This wave is the refracted wave propagating the solid wall. Therefore S-wave can not be detected in the slow formation by the monopole system.

In higher frequency as demonstrated in Fig.12(d), feature of predominant wave in the dipole system becomes dispersive. This wave is called the flexural mode, which belongs to the surface mode according to the naming by Kurkjian and Chang(1986). The surface mode is the wave propagating along the boundary between the solid and the liquid. The flexural mode is dominant in frequency f higher than a definite frequency f_C. f_C is the critical frequency at which the flexural mode has the same phase velocity as the S-wave velocity Vs. In $f > f_C$, the phase velocity is lower than V_s (Fig.13). The wavelength of S-wave corresponding to f_C is several times diameter. In frequency range higher than f_C in some degree, the flexural mode is predominant in wave train. Some field tools are designed to observe the flexural mode at frequency near f_C. And then if necessary, the detected velocity is corrected to V_s, considering dispersion characteristics.

If frequency range is considerably higher than f_C and then the solid is the fast formation, trapped mode is dominant rather than the surface mode (Kurkjian and Chang, 1986). In this case, the refracted S-wave exists as well as the refracted P-wave, though their amplitudes are not dominant. Hence, apparent feature of waves in the dipole system is not so different from those of the monopole system. Dipole system is not usually operated in such frequency range.

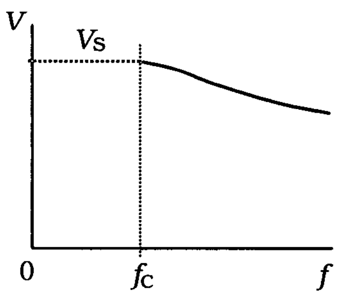


Fig. 13. Conceptional dispersion curve of the flexural mode. V=phase velocity, f=frequency.

The trapped mode mainly consists of waves which propagate in the liquid multiply reflecting between opposite sides of hole wall.

TUBE WAVE

Usually at seismic observations in a borehole, the most important noise is tube wave. This is true also for S-wave measurement by the dipole system. However, in some cases the tube wave can be used as useful signal. Some comments will be added in these points.

What is tube wave?

Tube wave is the dilatational wave propagating along borehole liquid. This wave has nature of axial symmetry and its characteristics is affected by elasticity of solid wall. It propagates in any range of frequency. In high frequency limit this wave approaches to Stoneley wave propagating along a plane boundary between the liquid and the solid. Hence the tube wave is sometimes called Stoneley wave. In long wavelength limit, tube wave velocity V_T is expressed as :

$$V_T = \sqrt{K/\rho_W};\ K = \frac{1}{1/\kappa_W + 1/\mu}, \qquad (2)$$

where ρ_W and κ_W are density and bulk modulus of the borehole liquid. μ is modulus of rigidity of the solid.

How to eliminate tube wave

(1) Tube wave velocity is controlled by apparent bulk modulus of the liquid column K. If we insert air pocket in the borehole liquid, we can considerably decrease the apparent bulk modulus of this portion. Tube wave is reflected at the air pocket (Fig.14). Transmitted tube wave is attenuated. In borehole observations we

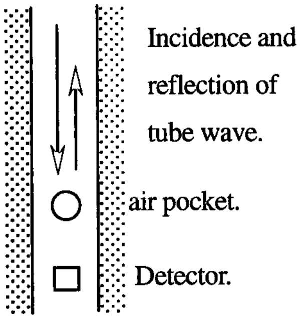


Fig. 14. Conception of tube wave filter.

can get good result sometimes even by small volume of air pocket. In Fig.8(a), the filter tube is a compressible rubber tube containing air for this purpose. The experimental record was completely hopeless before inserting the filter tube.

(2) Tube wave has axial symmetrical nature. The ideal dipole source does not produce tube wave. Tube wave is caused by deflection of the probe center from the hole axis. It is important to keep the center exactly. This is necessary for both; source and receiver.

(3) Force of dipole source can be directed to either directions: "plus" or "minus". Polarities of dipole mode waves are completely reversed with reversion of the force polarity. However, monopole component associated with actual dipole source not always has such a property of polarity reversion. The monopole component corresponds to the tube wave. In this case the monopole component can be extracted by subtracting the "minus" record from the "plus" record, while the dipole component becomes twice of each one.

Tube wave as useful signal

Character of tube wave is affected by property of hole wall. Hence, tube wave has been interested as means to measure such properties of wall solid as modulus of rigidity and permeability. In earlier stage of my experiment in borehole, I found that predominant tube wave was excited by incidence of P-wave at a fracture which intersects the borehole (Kitsunezaki, 1971). The same phenomenon has been remarked as a means to evaluate permeability of fracture in rock since 1980s.

Further discussion of these problems is omitted in the range of this paper.

CONCLUSIONS

Now S-wave logging using the dipole source has been popular. Almost pure record of S-wave is obtained by this method. As means of S-wave logging the dipole method is superior to monopole method generally, and especially in applicability to slow formations.

The first proposal of the dipole method was theoretical simulation by J. E. White. I got an the idea of this method based on series of my experiments in mines and engineering boreholes, independently from his idea. The physical base of the source in my method was the unidirectional point force, which radiates S-wave in the direction perpendicular to the force axis. Other base was simplification of theories by approximation of the long wavelength and the far-field. The wave observed in these conditions can be regarded as the direct S-wave. The wavelength should be more than 10 times diameter, to secure the long wavelength approximation. Basic principles on the source and detectors of my system were reviewed.

Essential features of the short wavelength characteristics are described. Flexural mode is predominant in the frequency range higher than a critical frequency. Hence in this case, the flexural mode is commonly observed instead of "direct

S-wave"

Tube wave was the most important noise in any seismic observation in a borehole. An air pocket inserted in the borehole liquid behaves as an effective filter to eliminate the tube wave noise. Use of this filter was a key factor in success of my experiment on the dipole method, which was called the suspension type S-wave logging.

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