Studies on Direct Measurement of the Shear Wave and Methodological Comments

Choro Kitsunezaki
Emeritus Professor of Akita University
Akita, Japan

1. Introduction: What Is Intended in This Paper?

In this paper my works on the shear-wave(S-wave) are introduced with some comments on their background and applications. They may have some meaning as a short review on a field of applied geophysics to people in geo-science and -technology, though materials are not so new. However, emphasis is put on rather methodological thought, which are obtained through my research works, than research details. In other words I will present my thought using my own research as materials.

In the section 2, concept of S-wave and its practical significance are described for people who are not familiar in this field of applied seismology. Research history of S-wave is also sketched. In the section 3, my researches are introduced focussing on direct measurements of S-wave in drifts and boreholes. In the section 4, supplementary reviews on the related developments are presented. Some thoughts are emphasized through description of the above matters, and some others in Section 5.

2. General Introduction to S-wave

2.1 What Is S-wave?

The most basic type of seismic waves is the body wave which propagates in an unbounded elastic medium. The body wave consists of P- and S-waves. P and S mean "primary" and "secondary" in arrival order of the waves on seismograph. In elastic dynamics S-wave is the shear wave, which is characterized as shear deformation of the medium accompanied by the wave propagation. In this meaning P-wave is the dilatational wave.

The most clear indication of S-wave is the fact that displacement is perpendicular to the propagation direction. This is practical base of S-wave detection. Otherwise, displacement of P-wave is parallel to the propagation direction.

Propagation velocities of P-wave and S-wave (V_P and V_S, respectively) are given as:

$$V_P=\sqrt{(k+4\mu/3)/\rho}\,, \quad \text{and} \quad V_S=\sqrt{\mu/\rho}\,, \qquad (1)$$

where k,μ,and$\rho$are bulk moduls, modulus of rigidity, and density of the medium, respectively(White,1965, p.15-24). V_S is necessarily slower than V_P from the above relations.

2.2 Practical Significance of S-wave.

S-wave does not propagate in fluid, but solid. This property has important meaning to estimate internal material of the earth in geophysics. In applied geophysics it may be limited to apply this property to actual conditions in pure form. However, soils and rocks in shallow subsurface contain fluid as liquid or gas in pores and fissures. Elastic properties of them are controlled by such conditions. Combination of V_P and V_S provides important means to evaluate condition of pore and contained fluid in reservoir evaluation especially for oil and gas. Though applications to rock and soil mechanics are also on similar trend of the idea., it is the aspect proper to these fields that V_S is regarded as indicator of material strength.

In some cases elastic moduli estimated from P- and S-waves are used as design parameters for civil engineering constructions. In this case the dynamic moduli in small strains obtained from seismic velocities must be converted to static moduli in large strain (Kitsunezaki, 1965).

Direct application of S-wave which has been confirmed most successfully in Japan was evaluation of ground conditions for preventing earthquake disasters. The most of vibration damages are caused by horizontal motion of the ground. In real geological conditions horizontal motion is mainly caused by S-wave, because body waves are incident almost perpendicularly to the ground surface. Such a propagation is a result of refraction of the waves from higher velocity layers in deeper subsurface to lower velocity layers in shallower ground. Transfer factor of the ground motion from the base to the surface is estimated from the observed shear wave data (Shima,1962). In strict discussion the relation of the modulus between small strain in S-wave measurements and large strain in real earthquakes must be considered.

In hard rocks in sound condition, the V_P/V_S ratio is almost constant, 1.5 to 2. In soil, V_P is almost the same as sound velocity of water(1.5 km/s) in water saturation, but it decreases very much with small gas inclusion. V_S is almost independent of contained fluid, but depends on coupling strength of solid particle. V_S is good indicator of geological facies in soil and sedimentary rosks. Seismic prospecting by S-wave is effective for detailed structure survey in soft ground.

2.3 Continuing Interest in S-wave

S-wave is not new as a scientific concept. Seismologists paid attention to the secondary wave as well as the primary wave on seismographs since almost beginning of seismological observation at Japan in the 1880's. After some discussions the secondary wave was widely recognized as the shear wave in elastic dynamics until the end of the 19th century. The elastic theories which served as theoretical base of seismic waves preceded the confirmation of real events on seismograms by about 70 years (Bullen and Bruce, 1985, p1-3).

At the beginnings of the 20th century, European scientists observed teleseismic waves and use the data to estimate internal structure of the earth. The same idea was applied to a method for prospecting relatively shallow geologies by artificial earthquakes. This was the birth of seismic prospecting. This new technology was rapidly developed in the United States for oil exploration with other methods of applied geophysics after the first world war (Weatherby, 1949).

Explosion of dynamite was the most usual source of seismic waves for long time. P-waves which are easily generated by explosions are exclusively used for the seismic prospecting. After all for long time, many people considered that only P-wave should be used for the seismic prospecting.

However, interests in potential applications of S-wave are continued. For Japanese seismologists who felt prevention of earthquake disasters as the most serious subjects , evaluation of S-wave properties in the ground was the important subject to be studied. As application of traditional seismology, some of them believed potential usefulness of S-wave in evaluation of geological properties. Research effort of S-wave was kept by some of applied geophysicists related to oil exploration in the United States and others. Now applications of S-wave have been popular (Dansom and Domenico, 1986). They are not only research subjects but practical means in exploration.

I think that new development on the surface has deep roots under the ground. The roots are sometimes old, but essential. In the conventional science and technology, the aspects easily handled are respected. Other aspects were omitted. Such kind of simplification makes the development easy, but in a limited range. In the conventional flow people apt to forget essential meaning of the omitted aspects. At a certain stage of history, use of the omitted aspects becomes possible by help of scientific and technological development in other areas (electronics and computer technology in this case), and change of social condition creates new demand for the advanced method. The old principle revives as a new method in such conditions. The development is accelerated theoretically and practically, after the new possibility has paid attention to by many people.

3. Direct Measurements of S-wave

3.1 S-wave Measurement in drifts

My research started as a seismic experiment to prospect metal ore in mine drifts in the late 1950's. Though it was not so successful for the original objective, I got useful experiences which served as bases of studies thereafter. I recognized that S-wave is predominantly generated by a small explosion in a short drill hole made at a drift wall (Kitsunezaki, 1971). It is difficult to identify S-wave on conventional records at the ground surface, because shear wave is masked by predominant surface waves. In drifts with small diameter the record is almost free from effect of surface waves.

The same method was applied to the site evaluation in engineering projects. Empirical relation of the V_P/V_S ratio and V_P is measured as indication of weathering effect of granitic rocks. In these experiments borehole-geophones were designed to extend observation points into inside of rock (Kitsunezaki, 1965).

3.2 Down-hole Measurement of S-wave

Ideal condition to observe the direct S-wave is achieved in boreholes. Boreholes are favorable experimental sites as close approximation to the unbounded media, rather than drifts. Seismic observations in boreholes are useful for experiments of wave characteristics and for measurement of real medium properties. Down-hole method consisting of a borehole-geophone fixed to hole-wall and a hammer source on the ground surface was developed by me as a practical method to measure P- and S-wave velocities in the ground in later half of 1960's. An example of records is demonstrated in Fig.1, with auxiliary figures and explanatory comments (Kitsunezaki, 1971).

In relation to the above description, the wave proper to the borehole should be mentioned. Borehole is a cylindrical hole in an elastic solid, which is usually filled with liquid. This condition produces the tube wave propagating along the hole (White,1965,p.148-151). This is a kind of boundary wave propagating along the boundary between solid and liquid (Stoneley wave; Biot,1952). The tube wave is the most important noise in S-wave observation. But it can be used as useful signal for some purposes (Kitsunezaki,1971,p.124,p.151).

3.3 Suspension Type S-wave Logging

My final goal in the above trend was to create a method to measure S-wave with such a utility as sonic log for P-wave. I thought that S-wave logging should be widely applied not only to engineering but to oil exploration and other geophysical projects. In sonic log a probe consisting of a source and receivers is inserted into a borehole (Paillet and Cheng,1991). In this case there is not limitation in applicable depth in the principle.

In hard rocks S-wave is detected as a later phase (refracted wave) on sonic log record. This method, however, is limited in its applicability. V_S should be higher than sound velocity of the boehole liquid (Chen, 1988)

I wanted to get a record of pure S-wave in any rocks and soils, with a probe hanging in the borehole liquid. Many people felt that this idea has contradiction because S-wave can not propagate in liquid.

The base of my idea was the long-wave approximation which was kept at the downhole method. In such a condition that wavelengths of waves are sufficiently longer than the hole-diameter, the effect of hole to wave propagation in the solid can be neglected.

In the following expression the borehole is assumed as vertical.

Displacement of S-wave propagating along the borehole axis is horizontal. Horizontal motion of the hole-wall causes the same horizontal motion of the liquid contained in the hole-wall. Hence, the S-wave can be observed by detecting horizontal motion of the liquid. The liquid motion can be detected by a geophone whose body moves together with the liquid. Hence I designed the suspension type receiver whose body has the same apparent density as the liquid. The liquid motion can be also detected as pressure gradient.

The next problem was how to excite S-wave. The most basic source of S-wave is a simple single force acting in a certain direction (White,1983,p.193-197). Predominant S-wave is propagated in a direction perpendicular to the force direction. For the S-wave propagating (vertically) along the hole-axis the source force should be horizontal force. The horizontal force is applied to the hole wall by a horizontal set of positive and negative pressures in the borehole liquid, which means a dipole source. Such a pressure set was excited by horizontal motion of a rigid body suspended in the liquid. The actual source designed by me was excited by electromagnetic force. This type source was called by me as the indirect type source because the hole-wall is excited through the liquid.

A probe for the S-wave logging was constructed by combining the indirect type source and the suspension type receivers. After some experiments beautiful records of S-wave were obtained in 1977 (Kitsunezaki,1980). An example of the records is demonstrated in Fig.2, with some explanatory comments. This system was called by me as the suspension type S-wave logging. The similar method is now widely used in Japan and the world. Supplementary comments will be given to the related researches and the system in the next section.

4. Supplementary Review of the Related Developments

4.1 Whit's Idea of Shaker Source

J.E. White (professor of Colorado school of mines) proposed the idea of the shaker source with theoretical simulation in 1967. He called the wave produced by it as the flexural wave (White, 1967; 1983,p.144). In long wavelength this wave approaches to S-wave. This condition corresponds to the case of the suspension-type S-wave logging mentioned above. His idea preceded my experiment by about 10 years. He also wanted to prove his idea by experiment, but it was not successful. Hence his work in this subject was not remarked widely. I also did not know his work until I met him in1978 at the SEG meeting where I presented my paper on the suspension type S-wave logging. These methods are also called as White -Kitsunezaki's method based on our recognition that both methods are the same in principle.

The rock condition was different between both experiments. Rock was very hard in White's case, but very soft in my case. In a soft medium S-wave with sufficient amplitude is excited by a small force. Theoretical base of my experiment was the long-wavelength approximation. It made quantitative evaluation of the phenomena easy at every experimental step. In elementary stage of researches, the experimental conditions should be so simple as to permit application of idealized theories.

4.2 Developments in Practical Uses and Theoretical Aspects

Some companies and persons developed practical tools of my method. Suspension P-S Log by OYO Corp. has been widely used for engineering fields in Japan and other countries in past 20 years. In this system a modification was made in the source mechanism to add P-wave component for simultaneous measurement of P- and S-waves (Tanaka and Ogura, 1986).

Schlumberger Co. developed a logging tool called as the dipole shear imager, in which a particular electromagnetic mechanism is used as the source(Hoyle etal, 1989). This has been used mainly for oil exploration since 1990 (Harrison etal, 1990). As the base of this system, researchers in this company intensively investigated detailed wave phenomena in a borehole by theoretical simulations and model experiments (Kurkjian and Chang,1986; Chen,1988). The theoretical simulations were developed from White's work in the shaker source.

Through these researches important characteristics of waves propagated from the dipole source were clarified on the effect of rock hardness (namely V_S) and frequency, in comparison with the monopole source. According to them the flexural wave is dispersive in higher frequency. Hence a correction is made to the observed flexural wave velocity in higher frequency to convert into S-wave velocity. If the ratio of wavelength to the hole-diameter is larger than 10, the long-wavelength approximation is justified (Kurkjian, 1986). The idealized approximation simplifies the theory, but its limitation can not be deduced from the simplified theory.

5. Supplementary Comments on Research Development

Natural and social conditions proper to a country act as a key factor for creations in science and technology especially at their infant stage. Applied geophysics was borne in scientific tradition of Europe and developed mainly in the United States especially for oil exploration. Japan is poor in oil resource. Its geological conditions seemed to be too complex for application of geophysical method which was successful in continental countries. What would be the base to my work? This was a serious problem for me. After all earthquake was a kind of resource for me. In Japan, there is consistent interest in ground conditions related to earthquake disasters, and also tradition of seismology kept interest in S-wave.

Development from shortsighted application studies is limited. Interest in essential aspect of old theory must be kept somewhere in society together with effort to see demands in future. It may be one of roles of universities.

Actual fields are the most important source of our knowledge in geo-technology. But sometimes they are too much complex to basic experiment in an infant stage. Rapid requests to application prevent sound growth of creative works. In the basic experiment we should select such simple condition that we can understand the phenomena by application of idealized simple theories.

Geo-science and -technology are peculiar in such point that they have close relation to "geo". Science and technology have tendency to generalize methods and principles. Geo-science and -technology are also so. But geological knowledge should not be separated from places as source of information. The information obtained for one purpose can be used for multiple purposes, if we know name of the place. Important part of its value would be lost, if we omit the place from geological information. Geological information is fundamentally common property of people in the country. Actually the problem is not so simple in relation to industrial activities. Some rule may be necessary to adjust the different interests. For sound development of geo-technology, we should not easily give up effort to keep proper names in our research reports even in possible range. I very well know the difficulties through my research experiences.

6. Summary and Conclusion

In this paper the concept of S-wave is introduced at first. Usually S-wave should be applied in combination with P-wave. Different responses of P- and S- waves to liquid are a base of applications. The S-wave measurement is now necessary means in site evaluation for earthquake disaster.

Historical background of S-wave research was sketched. S-wave was omitted in efficient development of seismic prospecting. Interest in it was kept in tradition of seismology. Especially in Japan it was connected with serious concerns to earthquake disaster. In some cases new development was borne from old (but essential) principle.

My researches in direct measurement of S-wave were outlined. Long-wavelength approximation was a consistent base of my researches from experiments in drifts at the earlier stage to the suspension type S-wave logging at the final stage. The suspension type S-wave logging was introduced somewhat in detail with review of the related methods.

Based on my experiences, some comments were given on methodological problems which I believe to be important for development of geo-science and -technology.

Reference

Biot, M. A. (1952): Propagation of elastic waves in a cylindrical bore containing a fluid ;
Journal of Applied Physics, Vol.23, pp.997-1005.

Bullen, K.E. and Bolt, B.A. (1985): An introduction to the theory of Seismology, Cambridge University Press, 4th ed.

Chen, S.T.(1988): Shear-wave logging with dipole sources, Geophysics, Vol.53. pp.659-667.

Dansom, S.H. and Domenico, S.N.(1986): Shear wave Exploration, Geophysical Developments No.1, SEG.

Harrison, A.R.,etal(1990): Acquisition and analysis of sonic waveform from borehole monopole and dipole source for the determination of compressional and shear speeds and their relation to rock mechanical properties and surface seismic data; 65th Annual Technical Conference, Society of Petroleum Engineers, SPE20557.

Hoyle, D.C., Wignal, A.H., and Walulik, J.J.(1989): Sonic well logging tool transmitter, U.S. Patent No.4869991.

Kitsunezaki, C.(1965): In situ determination of variation of Poisson's ratio in granite accompanied by weathering effect and its significance in engineering projects, Bulletin of the Disaster Prevention Research Institute, Vol.15, Part 3, No.92, p.19-41.

Kitsunezaki, C.(1971): Field-experimental study of shear waves and the related problems, Contribution of Geophysical Institute, Kyoto University, No.11, pp.103-177.

Kitsunezaki, C.(1980): A new method of shear wave logging ; Geophysics, Vol.45, pp.1489-1506.

Kitsunezaki, C.(1982) : Some basic problems of shear-wave logging by means of the suspension – type sonde: Jour. of Mining College, Akita University, Ser. A, Vol.16, No.2, pp.93-108.

Kitsunezaki, C.(1983): Receivers and sources in the suspension type shear wave logging: Butsuri-tanko(Jour. of SEG of Japan),Vol.36,pp.336-381.

Kurkjian, A. L. and Chang, S. (1986): Acoustic multipole source in fluid filled borehole; Geophysics, Vol.51, p.148-163.

Kurkjian, A. L.. (1986): Theoretical far-field radiation from a low frequency horizontal acoustic point force in a vertical borehole; Geophysics, Vol.51, p.930-939.

Paillet, F.L and Cheng, C.H.(1991): Acoustic Waves in Boreholes, CRC Press, Inc.

Shima, E.(1962): Modification of seismic waves in superficial soil layer as verified by comparative observations on and beneath the surface, Bull. Earthquake. Res. Inst., Vol.40, pp.187-260.

Tanaka,T. and Ogura, K.(1986): Development of suspension P-S logging System (Part 3), OYO Technical Report, p.59-72.

Weatherby, B.B.(1949): The history and development of seismic prospecting; Nettleton, L.L.(ed.): Geophysical Case Histories, p.7-20, SEG.

White, J.E.(1965): Seismic Waves , Application of Seismic waves: McGraw-Hill, New York.

White, J.E.(1967): The Hula log, A proposed acoustic tool; Transcript, Soc. Professional Well Log Analyst, Paper I , 8th Annual Logging Symposium , Denver.

White, J.E.(1983): Underground Sound , Application of Seismic Waves: Elsevier, New York.

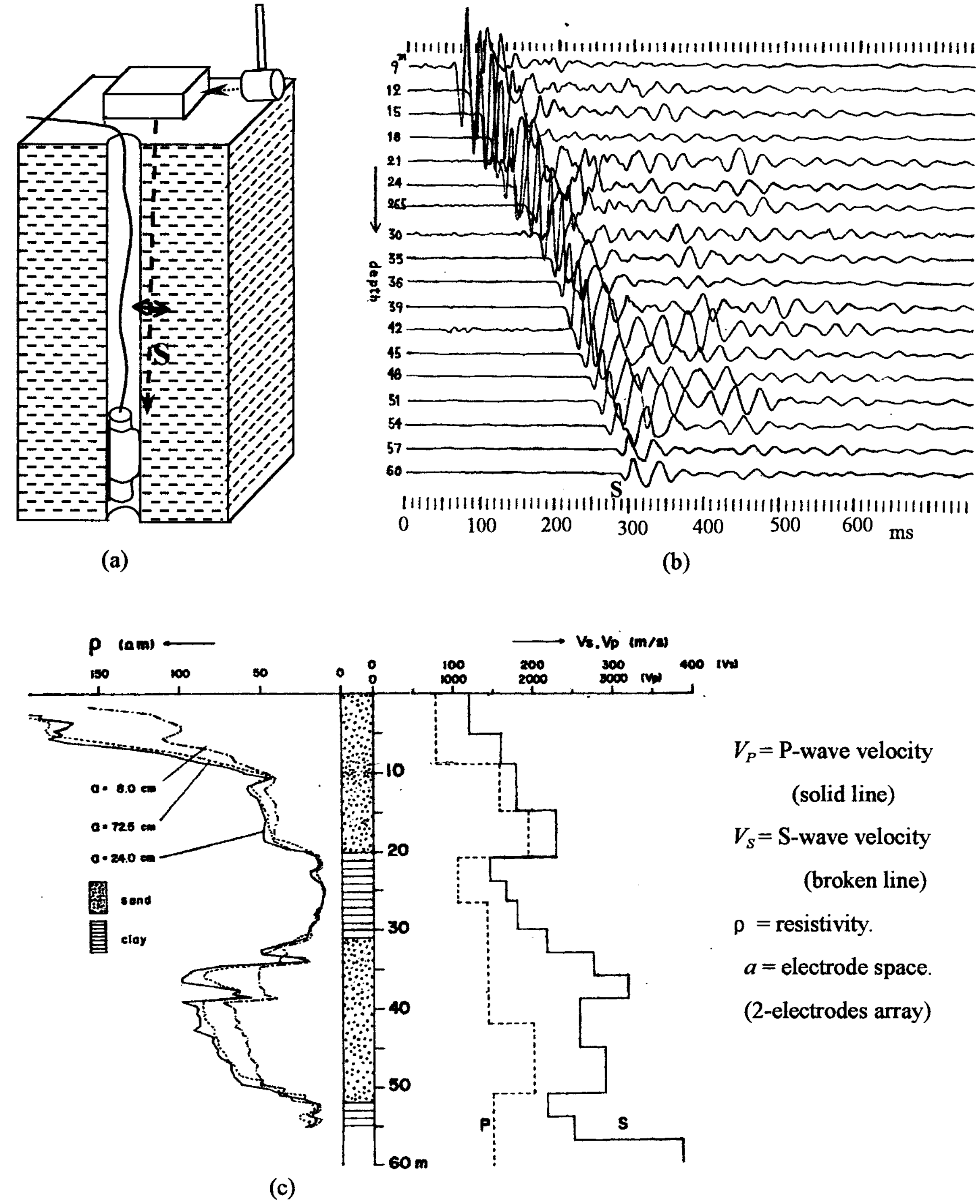

Fig.1 An example of experimental records at earlier stage (1968) and the corresponding logs, which verified availability of the down-hole method using the borehole geophone.

(a) Illustration of observation procedure. S-wave propagated from a horizontal source force on the ground surface was detected by a borehole geophone fixed to the hall-wall.

(b) S-wave record compiled from individual trace at every depth.

(c) Logs corresponding to (b). S-wave velocity clearly corresponds to geological facies.

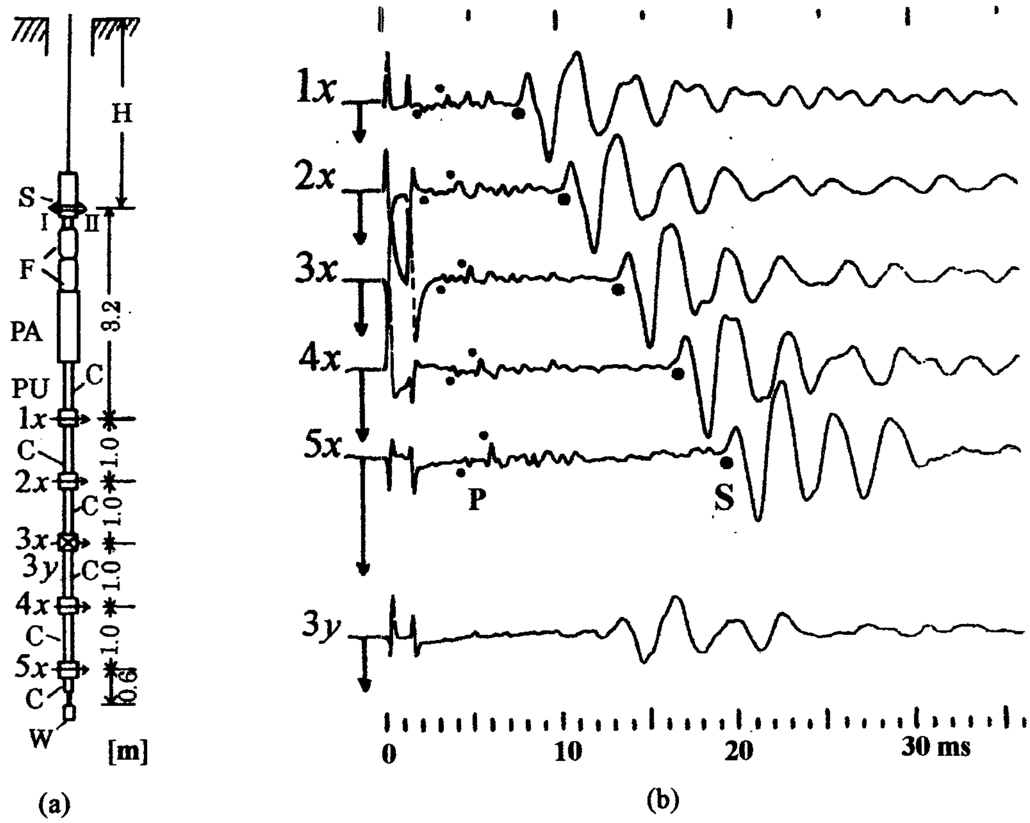

Fig.2 Historical record which verified availability of the suspension-type S-wave logging.

(a) A probe consisting of a source (S) and 5 receivers (PU:1x-5x). Source force is directed toward I ($-x$). Detection axis of PU is in x -direction except the 3 rd one which has x- and y-components (3x and 3y). C = flexible coupling tube. F= filter tube (air-filled rubber tube) for eliminating the tube wave noise. PA= preamplifier. W= weight.

(b) Record obtained by the probe of (a) suspended within 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 polarity corresponding to the initial motion toward the positive direction of detection axis(namely, x or y). Their lengths express relative sensitivity. Comparing with the arrow directions, We can confirm that the initial motion of S-wave is directed toward -x -direction consistent with the direction of source force. The small amplitude of S-wave in 3y which should be ideally zero is attributed to deflection of the detection axis and irregularity of medium conditions. (See Kitsunezaki(1980))