EVALUATION OF Q VALUE USING S–WAVE LOGGING RECORDS

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Abstract

Damping factor of the ground is just as important as *S*-wave velocity in the investigation of ground behavior during earthquakes. This paper reports our findings concerning the damping of *S*—waves (the dimensionless quantity, *Q* value is generally used to express wave damping). It is based on records obtained from in-situ *PS* and Suspension *S*-wave logging.

Conventional *PS* logging consists of the measurement of waves generated by plank hammering on the surface, at one point in a borehole. However, in the *PS* method used by the authors, a fixed base of measurement was established in the vicinity of the source in order to normalize source energy. Suspension *S*-wave logging is still in the initial process of development. The *SS* method is used by authors, with measurements taken at 2 depths at a time.

Measurements were taken at 2 sites. At Site **A**, only the *PS* method was used. *Q* value was determined for 2 layers, a sandy soil layer in which S-wave velocity was 270 meters per second, and a clayey soil layer in which *S*-wave velocity was 180 meters per second. *Q* value for the former layer was found to be 10, and for the latter, 30. Also, *Q* values were determined for intervals of 2, 4 and 6 meters. However, no overall pattern of differences corresponding to degree of interval was apparent. If it is assumed that the medium is uniform, *Q* value of that medium should be independent of the degree of interval. Thus, it can be said that this result is reasonable.

At Site **B**, both the P*S* and *SS* methods were used. Again, measurements were taken in 2 different layers. The layer were classified as fine sand ($Vs=330$ m/sec; Layer I) and sandy silt ($Vs=410$ m/sec; Layer II). Using the *PS* method, *Q* value for Layer I was determined to be 30, while the *SS* method gave a somewhat different value of 50. For Layer II, the *PS* method gave a *Q* value of 20, while the SS method set *Q* at a very close value of 25. It will be noted that in both layers, the *SS* method yielded a greater value for *Q*.

In the results of measurements taken by the two methods, there is a great difference in the frequency ranges. Frequencies in the *PS* method are in the range from 30 to 50 Hz, while for the *SS* method, frequencies range from several hundred to one *KHz*. One theory has it that damping factor in a certain medium depends on frequency. As mentioned above, the fact that *Q* values obtained differ according to the logging method used could perhaps be a confirmation of this theory.

It is said that strain level at the time of in-situ measurement such as those described above is around 10^{-6}. In the laboratory where conditions can be controlled, it is possible to conduct testing in areas of high strain level. Various testing methods are available, including the popular dynamic triaxial test. The authors used this method on samples taken from Site **B**, and damping factor h defined to be $1/2\,Q$ was obtained. There is a relatively good correlation between this value and the one determined by in-situ testing.

While, about the geometrical factor, strictly speaking, it has to take into consideration that waves are reflected and refracted at layer boundaries. However, from a practical standpoint, it is more convenient to use the geometrical factor to be the inverse of distance from the vibration source.

Finally, taking into consideration measurement error, it appears that apart from *SS* method, *Q* value as determined by *PS* method is somewhat less reliable. However, When consideration is taken of the fact that the frequency ranges during testing are much higher compared to the ranges found during earthquakes, the desirability of carrying out in-situ testing at earthquake level ranges becomes apparent. This is a problem that must be taken up in the future.

1 INTRODUCTION

In order to predict ground behavior during earthquakes and to provide for effective aseismic design, it is important to grasp the various dynamic qualities of the ground. Fundamentally indispensable data concerning soil includes *S*-wave velocity, rigidity and damping. Of these, in-situ *S*-wave logging procedures, for example, *PS* logging, has been perfected to the point where it can be readily carried out, and a great volume of data has been accumulated throughout Japan. Examples of reports on *S*-wave velocity measurements include papers by Imai, et al. (1972, 1975) and Imai (1977).

However, little data on field measurements of damping is yet available. what data is available is mostly based on laboratory testing of samples for damping that have been carried out in recent years. Naturally, there is a limit to the applicability of data based on laboratory experiments.

This paper investigates the degree of damping represented by the quality factor designated *Q*, based on records obtained from *PS* and suspension *S*-wave logging conducted in the field.

It is well known that the fundamental research on visco-elastic bodies was carried out by Maxwell in the design of the Maxwell model, and by Voight, Kelvin and Mayer, who produced the Voight model. Since this basic research was presented, many indidviduals have made their contributions. With the exception of the earliest research, most of the more recent work in the field of wave propagation in visco-elastic bodies (i. e., attenuation of wave motion) has concentrated on the deep structure of the earth. In this area, startling advances have been made.

In comparison to this, however, very few field experiments on damping in soft ground surface layers have been carried out. Such work in Japan has only been conducted by the Seismic Exploration Group of Japan. A paper by Kudo (1976) examines this work in detail. We needn't go into the subject here. Research by Kudo and shima (1970) represents the only information available which, like the present paper, is concerned with practical considerations. It should be noted, however, that as a response to needs in the field of earthquake engineering, there has been a modest increase in reports on this problem. [for example, Kusano, et al. (1978)]

2 MEASURING METHODS

The authors employed two methods of measurement, a technique based on *PS* logging (hereafter referred to as the *PS* method) and Suspension *S*-wave logging (hereafter referred to as the *SS* method). The techniques are illustrated in Figures 1 and 2 respectively.

The *PS* method does not differ basically with ordinary *PS* logging. However, in order to normalize energy from the plank hammering vibration source, fixed measuring points were established at ground surface. The seismograph used in the measurements is equipped with a direction detector, and consists of 3 orthogonally arranged geophones whose natural frequency is 28 *Hz*. Called the Borehole Pick (OYO Model 3320), this instrument may be fixed to the borehole wall at any desired depth. A magnetic data recorder was employed in the measurements.

The *SS* method is based on a concept advanced by Kitsunezaki (1979) which was developed into a model Suspension *S*-wave logging system by Ogura(1979). Suspension S-wave logging is a method that employs a sonde which consists of its own indirect vibration source and two floating type geophones, connected by an isolator. Measurements are conducted in a free floating state, without the sonde being fixed to the borehole wall. The two free-floating

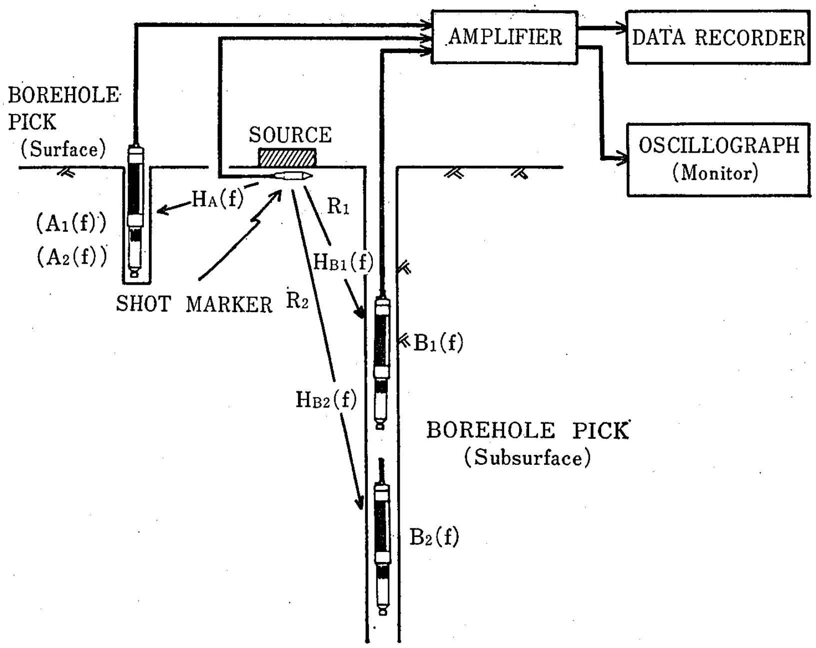


Fig. 1 *PS* method measurement system

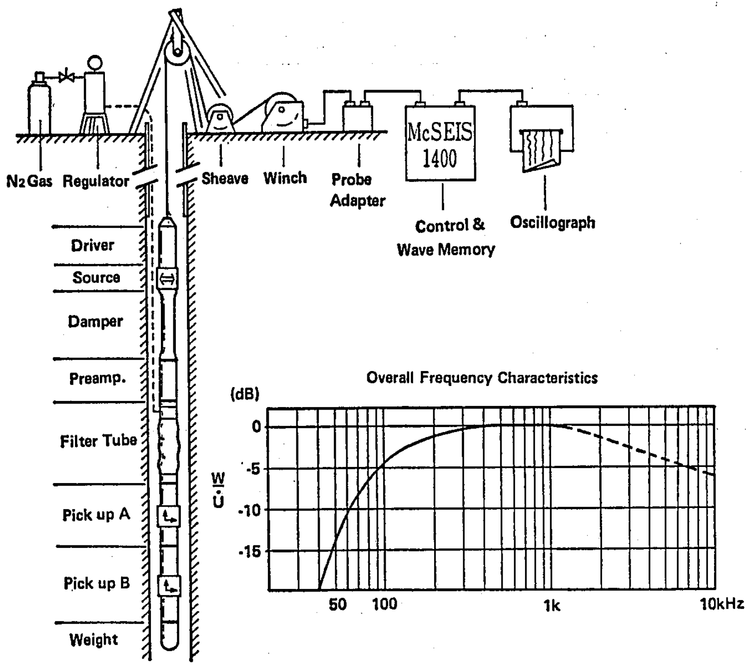


Fig. 2 *SS* method measurement system

geophones also built into the sonde are spaced 1 meter apart. In this way, *S*-waves from the built-in vibration source are measured simultaneously for two depths. The recording equipment has a "wave memory"function that can perform addition of waveforms. When one recording has been made, the direction of the wave source can be reversed, and the resulting two opposing waveforms stored for later readout. Then, signals are simultaneously channeled into an oscillograph.

3 ANALYSIS METHODS

In the *PS* method, the terms $A(f)$ and $B(f)$, which fall within the frequency domain obtained by applying Fourier transformation to records of measurements taken below and on the surface, may be expressed in the following way:

$$A(f)=H_A(f)\cdot P_A(f)\cdot S(f) \tag{1}$$

$$B(f)=H_B(f)\cdot P_B(f)\cdot S(f) \tag{2}$$

where f: frequency (Hz)
$H(f)$: transfer function of medium between source and geophone
$P(f)$: frequency characteristics of measuring instrument, and
$S(f)$: frequency characteristics of vibration source

If the medium is homogenous, the transfer function $H(f)$ is expressed as the following:

$$H(f)=G\cdot e^{\alpha(f)\cdot R} \tag{3}$$

where G: geometrical factor
$\alpha(f)$: attenuation coefficient (m^{-1}), and
R: distance in meters between vibration source and geophone

If Formula (3) is rewritten, substituting the two transfer functions for the two depths shown in Figure 1, attenuation coefficient $\alpha(f)$ may be expressed as follows:

$$\alpha(f)=\frac{ln\left\{\left(\frac{H_{B_1}(f)}{G_1}\right)\Big/\left(\frac{H_{B_2}(f)}{G_2}\right)\right\}}{R_2-R_1} \tag{4}$$

The *PS* method used that plank hammering method, which is conducted by hammering the edge of a plank. Since the distance between the vibration source and the geophone is sufficiently greater than the size of the plank, the waves generated may be thought of as spherical waves. Furthermore, if the ground has a homogenous character, the geometrical factor G may be approximated as $G=1/R$. Although in reality the ground is usually more complex than this, due to such phenomena as reflection and refraction of waves at layer boundaries, let us for the moment proceed on the assumption of homogeneity, leaving a detailed analysis of geometrical factors for later.

Also, because the same instrument was used in conducting measurements both on the surface and underground, the terms $P(f)$ and $S(f)$may be cancelled from Formulas (1) and (2), and solved for H_B as follows:

$$H_B(f)=\frac{B(f)}{A(f)}\cdot H_A(f) \tag{5}$$

Here, because the point of measurement on the surface is fixed, $H_{A_1}(f)=H_{A_2}(f)$. Thus, if we substitute Formula (5) into Formula (4), we find that $\alpha(f)$ may be expressed by the following formula:

$$\alpha(f)=\frac{ln\left\{\left(R_1\cdot\frac{B_1(f)}{A_1(f)}\right)\Big/\left(R_2\cdot\frac{B_2(f)}{A_2(f)}\right)\right\}}{R_2-R_1} \tag{6}$$

Generally, the relationship between viscosity coefficient η and the ratio of energy E for one cycle and the resultant energy loss $\triangle E$, is defined:

$$\eta=\frac{\triangle E}{2\pi E} \tag{7}$$

Q is often used to express wave attenuation. The relationship of Q to the above Formula is $\eta=1/Q$.

Now, if wave phase velocity c is used with $\alpha(f)$ from Formula (6), Q may be expressed as follows:

$$Q=\frac{2\pi f}{c\cdot\alpha(f)} \tag{8}$$

Records from two depths are taken according to the *PS* method, and $\alpha(f)$ is determined using Formula (6). This value is used in Formula (8) to determine Q.

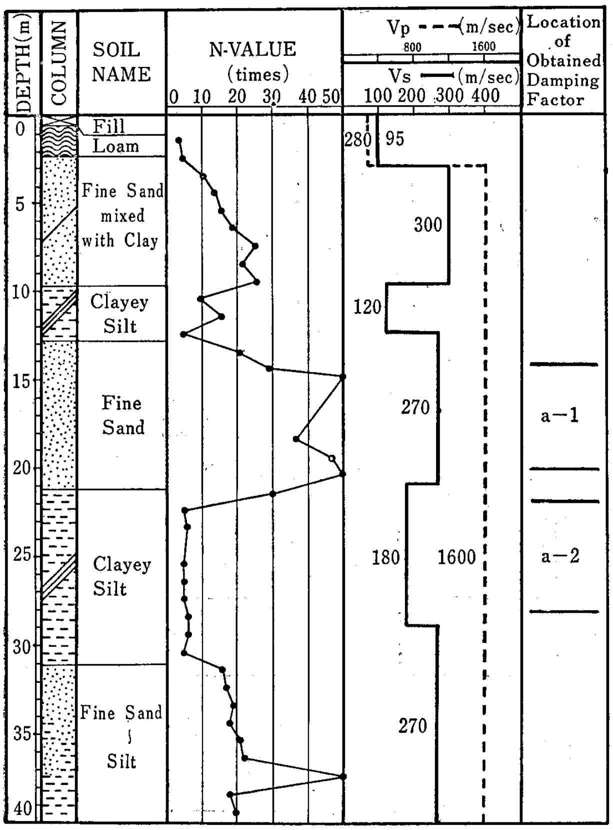


Fig. 3 Ground conditions at Site A

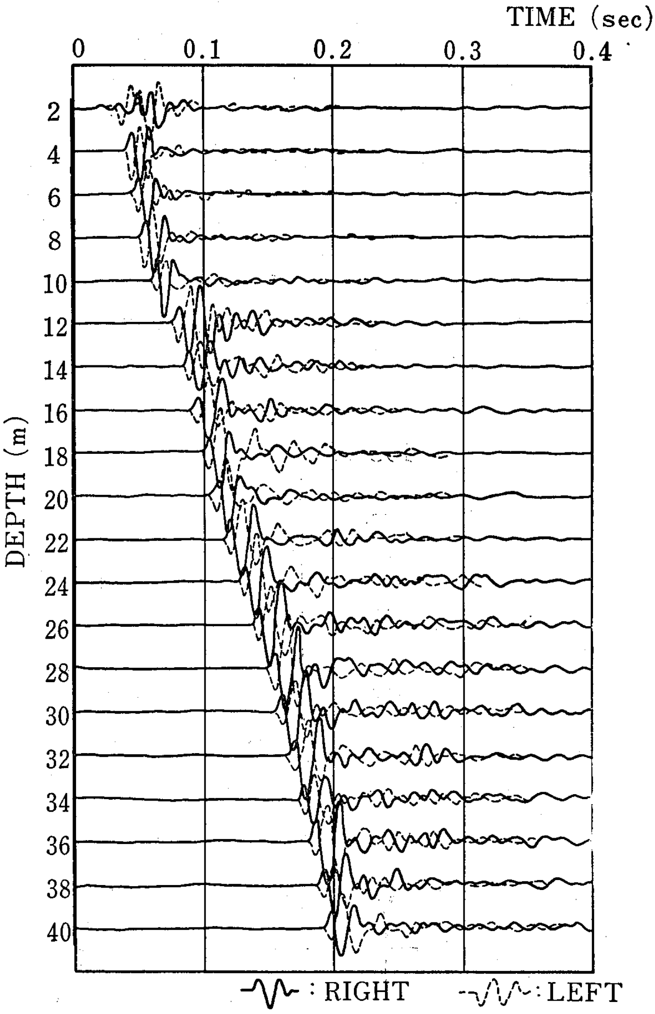


Fig. 4 *S*-Wave records taken at Site **A**

If the *SS* method is used, simultaneous measurement at two depths of waves produced from a single vibration source is carried out, so $A_1(f)$ and $A_2(f)$ are cancelled out from Formula (6), simplifying the formula.

Note that *S*-wave velocity is used as phase velocity in Formula (8).

4 RESULTS

Measurements were conducted at two sites. Following are the results obtained at each site.

(1) Site **A**

At this site, only the *PS* method was used. The ground at this site consisted of a

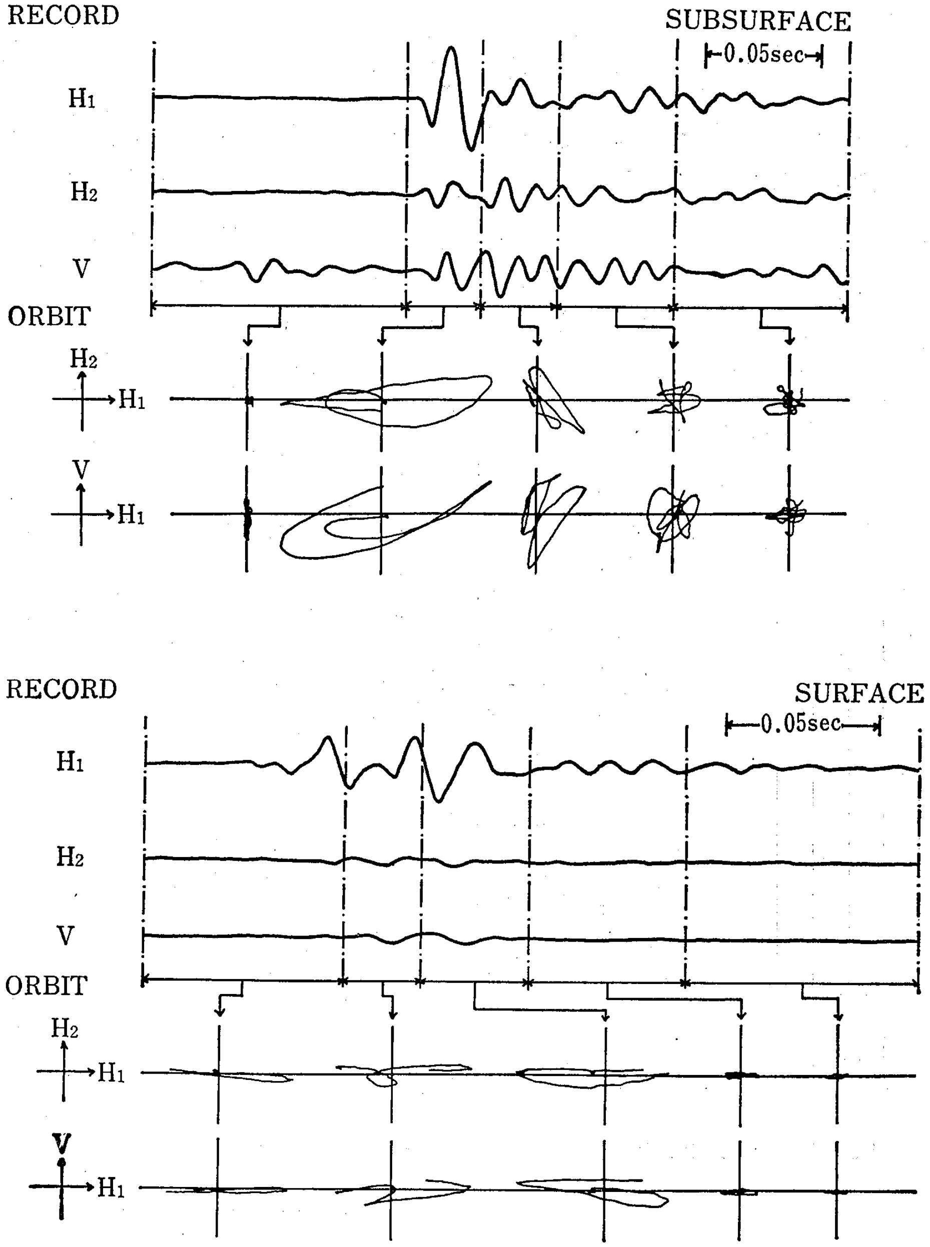


Fig. 5 Example of particle orbit (to verify *S*-phase)

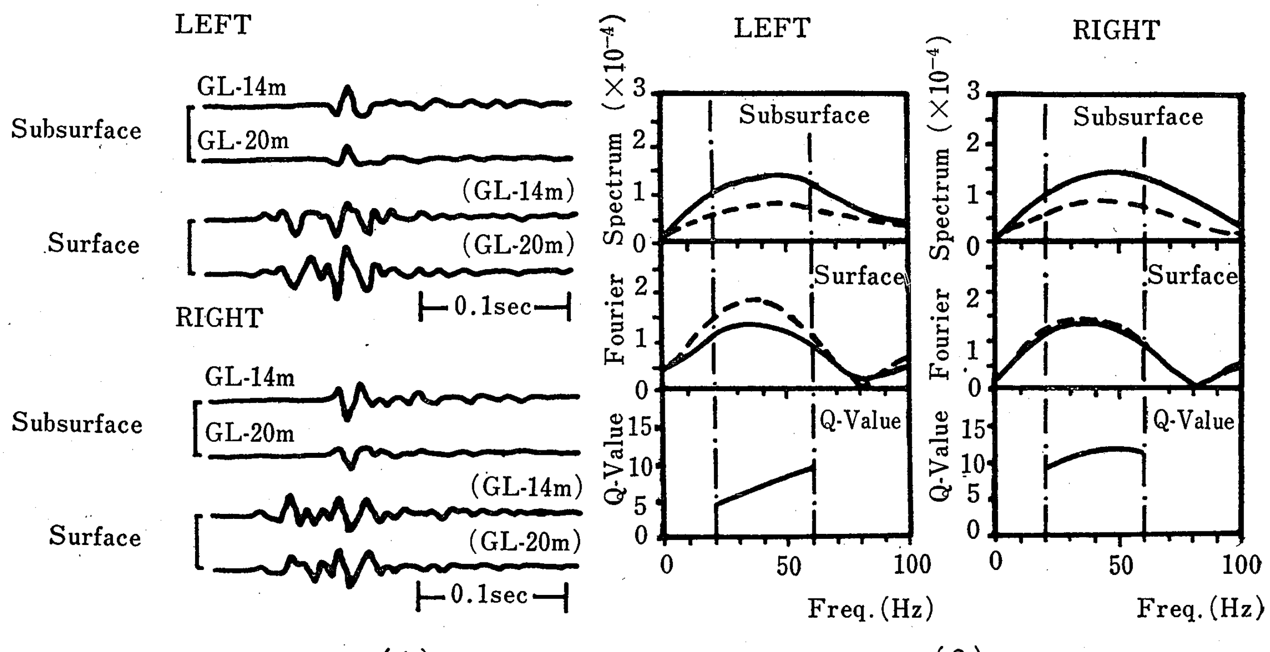
layers of sandy soil alternating with clayey soil layers. Figure 3 shows the velocity distribution, soil types and N-values for each layer.

Figure 4 shows S-wave recordings with shot times aligned and arranged according to depth of measurement. Figure 4 includes waves recorded when both the left and right sides if the plank were struck. Clearly, these waves are the reverse of one another, confirming them to be SH waves.

The two layers that were thought to be relatively homogenous were chosen for analysis: a sandy layer (S-wave velocity$=270$ m/sec) extending between 13 and 21 meters deep, and a clay layer (S-wave velocity$=180$ m/sec) immediately below this.

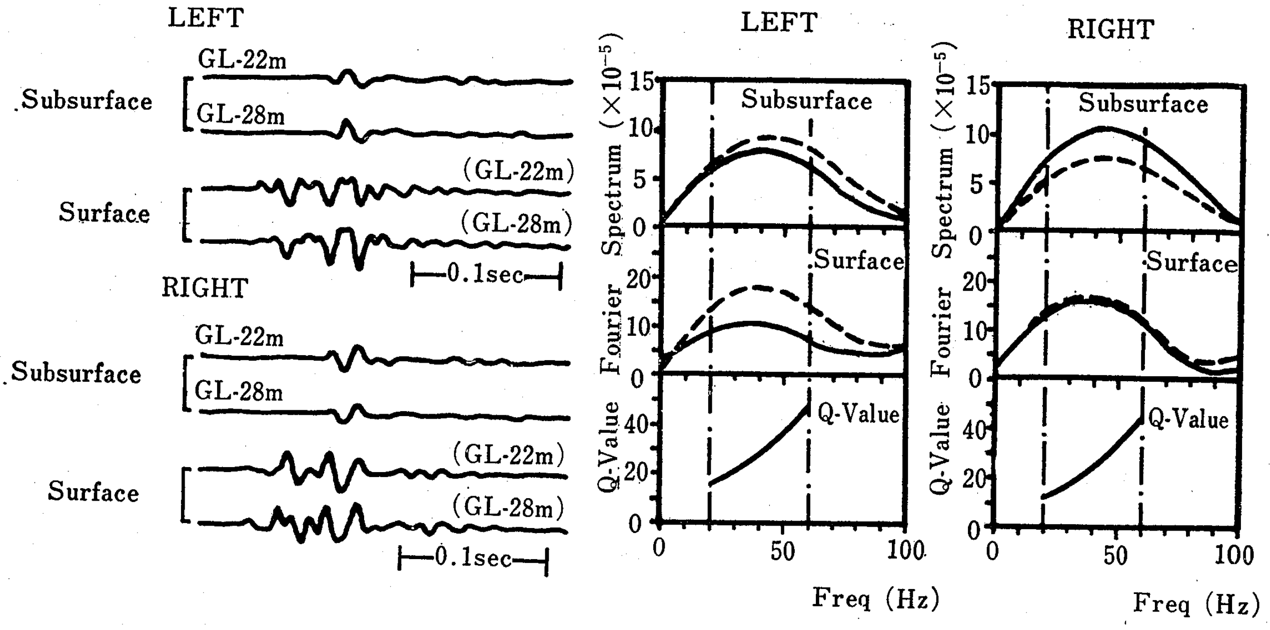
According to the S waveform shown in Figure 4, those waves which reverse phase according to direction of hammer blow are SH waves. However, before proceeding to calculate the value of Q, the authors sought to confirm that this is indeed the case by using another method. Records obtained with a 3-component orthogonally arranged measuring instrument at successive detphs and one fixed measuring point on the surface were used to determine particle orbits. Figure 5 shows one example of the results obtained. The example shows results of measurements taken at the depth of 22 meters. The top part of the figure shows a record taken below the surtace. The bottom half shows a record taken on the surface simultaneously. In this example, in the respective maximum amplitude regions of H_1 component, the vibration of the H_1 component (direction of blow to the plank) predominates, thus confirming the phase to be that of an S-wave.

In this way, the confimed S-wave record was used to calculate the value of Q. Figure 6 shows the results of analysisis of records taken in a sandy soil layer. In Figure 6, Graph 1 consists of waveform records used in analysis. The upper half of the graph shows results obtained when the plank was struck on the left end, while the lower half of the graph consists of waves produced when the plank was struck on the right end. Both waveform records taken at two depths and for two directions, along with surface waveform records taken



(1) (2)

Fig. 6 Example of sandy layer analysis



(1)

(2)

Fig. 7 Example of clayey layer analysis

simultaneously are shown. In the graph, the X (time) axis has been adjusted so that the corresponding phases if each wave are aligned under one another in order to facilitate comparison of phases. Graph 2 shows the analysis results. The Fourier spectra indicated correspond to the waveforms in the chart on the left. The values Q are obtained from these two spectra and Formulas (6) and (8), given above. Analysis results of records taken in a clayey soil layer are shown in Figure 7.

As mentioned above, all geophones used in taking measurements had a proper frequency of 28 *Hz*. Also, as made clear by the Fourier spectra in Figure 6, the recorded waveforms also peak between 30 and 50 *Hz*. consequently, the characteristics of the geophones and the wave form records were taken into account, and the value of Q calculated for frequencies of 20 to 60 *Hz*. In the case of the sandy layar, while differences in direction of the blow to the striking plank give slightly different values for Q, the value can nevertheless be thought of as the same. In the case of the clayey layer, this difference is not seen, for the most part, and the value for Q tends to be somewhat larger than for the sandy layer. we find that Q values at the point (frequency) where Fourier spectra reach their peak are approximately 10 for the sandy layer, and 30 for the clayey layer.

(2) Site **B**

At Site **B**, measuring was carried out by both the *PS* and *SS* methods. Figure 8 shows the ground conditions at this site. The authors selected as objects for analysis two layers which could be regarded as relatively uniform mediums: a layer of fine sand at a depth of around 70 meters (S-wave velocity=330 m/sec) and a layer of sandy silt at a depth of around 110 meters (S-wave velocity=410 m/sec).

Figure 9 shows some examples of the waveforms and Fourier spectra used in analysis. These represent records obtained in the sandy silt layer. The top half of Figure 9 shows waveforms and Fourier spectra obtained by the *PS* method. Tow sets of records, each taken simultaneously on the surface and at a certain depth, are shown.

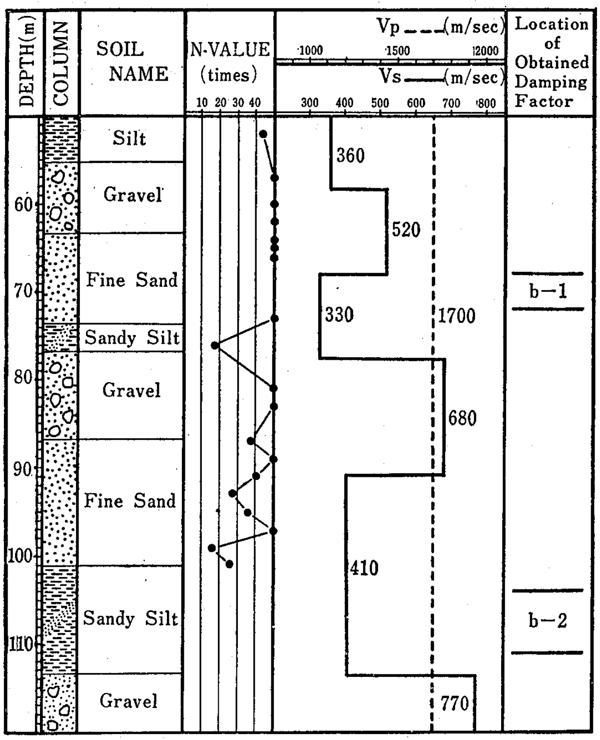


Fig. 8 Ground conditions at Site **B**

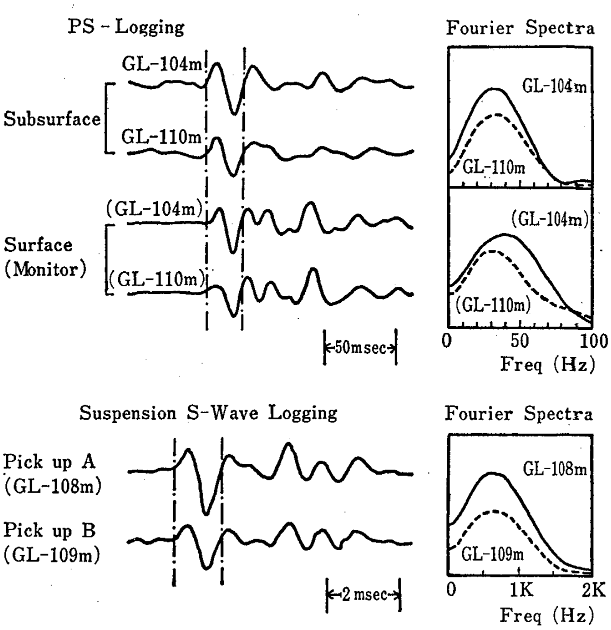


Fig. 9 Example of waveforms and spectra used in analysis of Site **B**

The bottom half of Figure 9 shows results obtained using the *SS* method. Because measurements are taken at two depths simultaneously, there is no necessity to normalize source energy. Thus, no fixed measuring points on the surface, as in *PS* logging, are necessary.

As the example in Figure 9 clearly shows, the frequency of waveform records obtained by the *SS* method is on the order of several hundred *Hz*, which is 20 to 30 times that of the *PS* method.

Using the same procedure for determining Q as described above for Site **A**, Q was found to approximately equal 30 in layer *b*-1 (find sand) by using the *PS* method, while the value of Q was about 50 by the *SS* method, showing somewhat of a difference. For layer *b*-2 (sandy silt), the *PS* method yielded $Q \fallingdotseq 20$, and the *SS* method, $Q \fallingdotseq 25$, showing fairly good agreement.

Thus, we see that different logging methods give somewhat different Q-values for a each layer, and that there is a tendency for the values obtained by the *SS* method to be bigger than those obtained by the *PS* method. This difference might be attributable to the above-cited difference in frequency range between the *PS* and *SS* logging systems.

5 DISCUSSION

Let us make two or three observations concerning the results we have obtained. First, Figure 10 shows the relationship between, Q and S-wave velocities. This graph was borrowed from Kudo's 1976 paper on his independent research, to which has been added the results from the authors' research. As mentioned in the beginning of this paper, there is not much data on Q-values obtained by in-situ measurement. In fact, Figure 10 represents most of what is available.

A paper by Vassilev, et al. (1962) determined Q for ground types ranging from rock to soil on the premise that α is proportional to frequency. A paper by McDonal, et al. (1962)

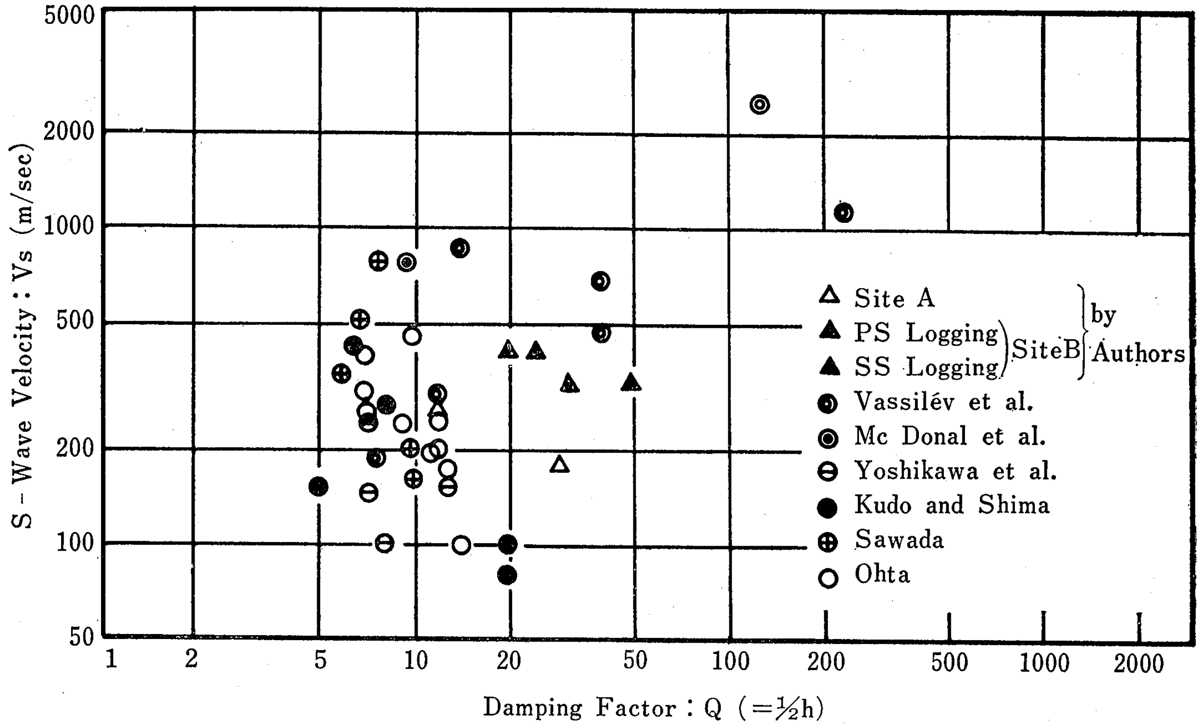


Fig.10 Relationship between Q and S-wave velocity

used records obtained by the crosshole method to express the primary relationship between α and frequency. Yoshikawa,et al. (1965) used records obtained by the refraction method to determine α. They concluded that the lower the S-wave velocity, the bigger the value of α.

Kudo, et al. (1970) and Sawada (1975) used downhole S-wave logging records to determine Q. As a result of this research, Kudo, et al. concluded that Q has no relationship with frequency, but is instead a fixed value. Sawada also reported that even if there is some relationship, it is very small. Ohta (1975) used seismograms obtained from both on the surface and underground to apply the optimization method for determining Q.

Thus, there is a variety of methods for in-situ measurement, even though the number is small. Of the research results summarized in Figure 10–including those of the authors–it may be said that it is unlikely that there is a systematic difference in results due to differences among in-situ measurement methods.

Next, let us discuss two or three problems connected with in-situ measurement.

The first problem concerns the effect of the difference in interval between the two records taken for each measurement by the authors' system. The effect of this difference on the values obtained for Q was investigated. As mentioned above, the values for Q obtained for each layer at Site a were taken by the *PS* method at intervals of 6 meters. Assuming that the medium was homogenous, the Q value should not differ over this interval. To test this, the authors determined Q-value for two different intervals at Site A, at 2 meters and at 4 meters. These results were combined with the measurements taken with an interval of 6 meters to form Figure 11. clearly, there is no recognizable pattern of differences due to differences in intervals. In this study, it was assumed that both the sandy and clayey layers were homogenous mediums. At the least, it can be said that with this assumption, the Q-value that is obtained would not depend on the interval between the two depths at which measurements are taken.

The second problem concerns the comparison of Q values obtained in-situ S-wave records on the basis of various hypotheses, with the values obtained in the laboratory by dynamic soil testing. In conducting in-situ measurement by the *PS* or *SS* methods, it is generally assumed that strain level is around 10^{-6}. However, in laboratory testing, where conditions may be easily controlled, it is possible to conduct testing under greater strain levels. While there are various methods for testing damping factor h ($h=1/2Q$), the triaxial testing method is the most common [See Yokota, et al. (1980), Kokusho, et al. (1979) and Hara (1973)]. At Site **B**, after the authors had determined Q, samples were taken from each of the layers and triaxial testing was conducting to determine damping factor h (Imai, et al. 1979). Figure 12 compares these results, along with those from in-situ measurements (with Q converted to h). Here it can be seen that the values determined dy in-situ measurement agree comparatively well with the extraporated curve based on triaxial test results.

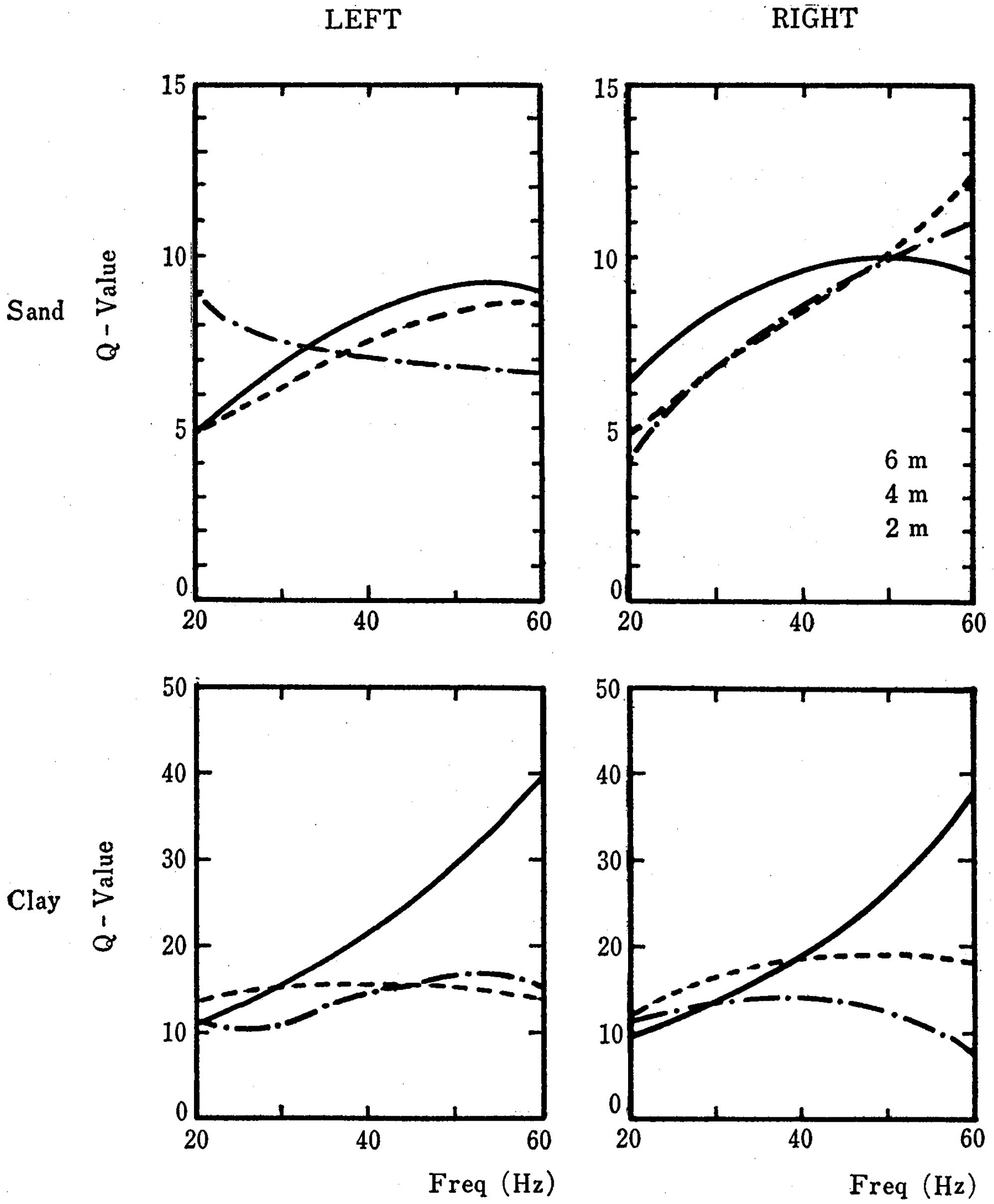


Fig.11 Changes in Q according to changes in interval between receiver

The third problem concerns the accuracy of Q as it is determined by these methods. The value Q in Formulas (6) and (8) may be obtained by the following Formula (In this case, the spectral ratio K between the two depths is designated):

$$Q=\frac{\pi f(R_2-R_1)}{c\cdot ln\left(\frac{R_1}{R_2}\cdot K\right)} \tag{9}$$

Figure 13 uses the constants by which Q-value for Site **B** was calculated to express the relationship between the K value of Formula (9) and Q. This graph makes it clear that Q values obtained by the PS method are a little less reliable than those obtained by the SS method. The explanation for this is that in the PS method, the slope of the K–Q curve is steep in the vicinity determined for the Q values. Thus, even a small change of spectral ratio greatly affects Q values. consequently, considerable accuracy in measurement becomes requisite.

In order to check this concept, let us consider in more detail the error involved in

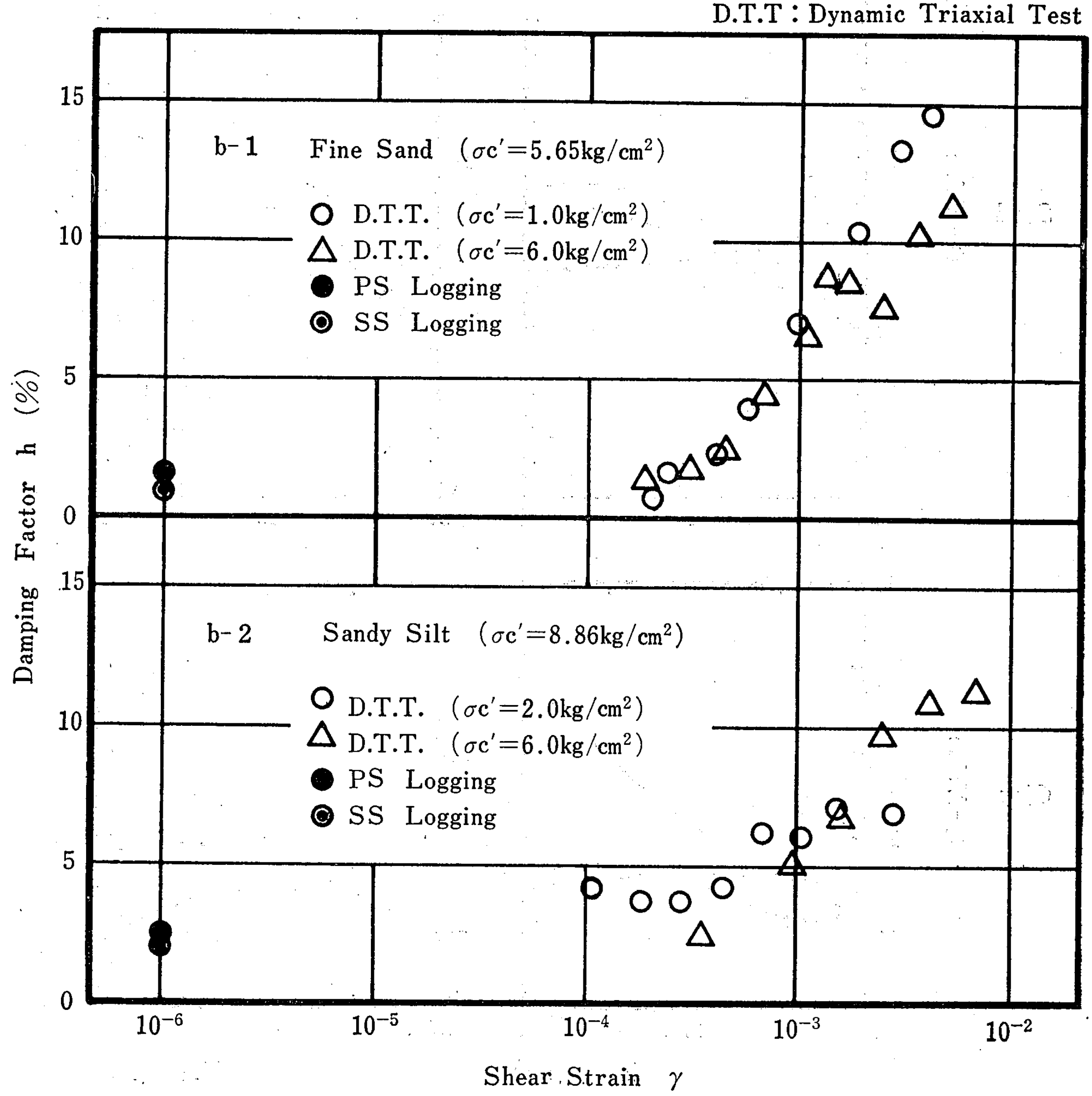
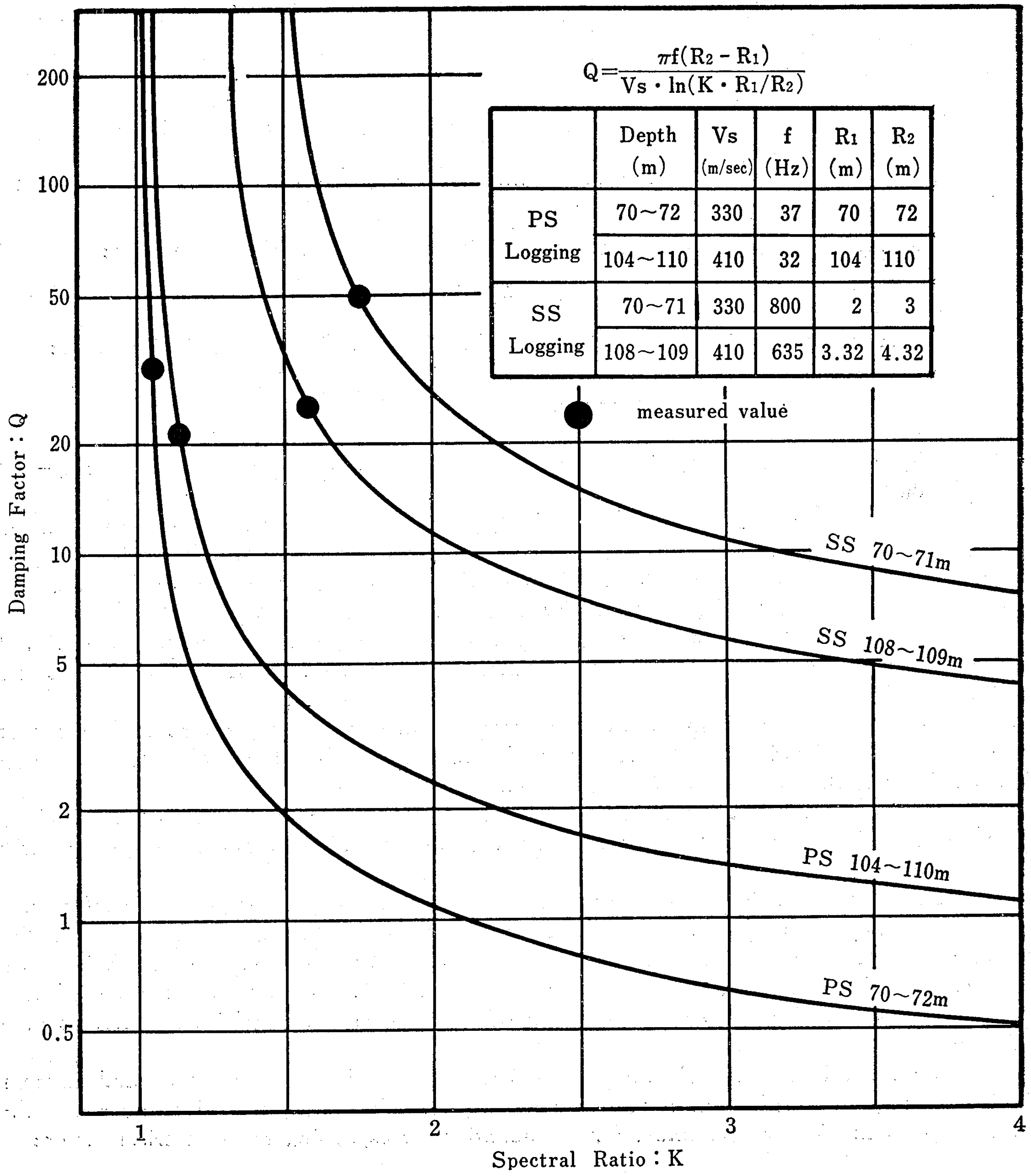


Fig.12 h values obtained in-situ compared with those obtained by dynamic soil testing in laboratory the determination of Q. First, we may rewrite Formula (9) using h:

$$\mathrm{h}=\frac{c\cdot ln\left(\frac{R_1}{R_2}\cdot K\right)}{2\pi f(R_2-R_1)} \tag{10}$$



$$Q=\frac{\pi f(R_2-R_1)}{V_s\cdot \ln(K\cdot R_1/R_2)}$$

	Depth (m)	Vs (m/sec)	f (Hz)	R1 (m)	R2 (m)
PS Logging	70~72	330	37	70	72
	104~110	410	32	104	110
SS Logging	70~71	330	800	2	3
	108~109	410	635	3.32	4.32

Fig.13 Relationship between Q and spectral ratios of two depths

We may designate the change that h undergoes as spectral ratio K changes to ε. K in Formula (10) as $\triangle$h. Thus,

$$\mathrm{h}+\triangle\mathrm{h}=\frac{c\cdot ln\left\{\frac{R_1}{R_2}(1+\varepsilon)\cdot K\right\}}{2\pi f(R_2-R_1)} \tag{11}$$

Consequently, we may use Formulas (10) and (11) to express $\triangle$h:

$$\triangle\mathrm{h}=\frac{c\cdot ln(1+\varepsilon)}{2\pi f(R_2-R_1)} \tag{12}$$

The logarithmic terms of the right side of the Formula may be progressively expanded:

$$ln(1+\varepsilon)=\varepsilon-\frac{\varepsilon^2}{2}+\frac{\varepsilon^3}{3}+\cdots\cdots+(-1)^{r-1}\cdot\frac{\varepsilon^r}{r}+\cdots\cdots \tag{13}$$

Because $\varepsilon \ll 1$, the formula may be approximated using the first term only:

$$ln(1+\varepsilon)\fallingdotseq\varepsilon \tag{14}$$

Consequetly, if we substitute Formla (14) into Formula (12), we get the following:

$$\frac{\triangle\mathrm{h}}{\varepsilon}=\frac{c}{2\pi f(R_2-R_1)} \tag{15}$$

Figure 14 shows the relationship of $\triangle$h/ε to c using the terms f and $\triangle R$ $(=R_2-R_1)$ from Formula (15) as parameters.

Changes in spectral ratio in Formula (15) may be considered to be due to errors in measurement. If we consider this error ε to be 5%, the point in the vertical axis of Figure 14 where $\triangle$h/ε=1 means that $\triangle$h=0.05. That is, if measurement error is equal to 5%, the degree of fluctuation included in the value for h thus determined is 0.05 (Q=10).

Consequently, in order to make the obtained fluctuation value $\triangle$h less than 0.01, if measurement error is assumed to be 5%, a value for f or $\triangle R$ in which $\triangle$h/ε becomes less than 0.2 must be selected.

In this graph, the authors have converted Q values to h. If we assume a degree of measuring error of 5% with the *PS* method at Site **B**, h would include a degree of fluctuation of from 0.02 to 0.04, a range too wide to be considered accurate.

On the other hand, if we assume a measurement error of 5% in the results obtained by the *PS* method at Site a and by the *SS* method at Site **B**, $\triangle$h becomes 0.01 or less, a fairly reliable result.

Finally, the fourth problem we would like to introduce concerns geometrical factor.

Throughout this paper, the authors have postulated geometrical factor to be the inverse of distance from the vibration source. However, as we have mentioned, in cases where the ground consists of a number of layers, as in Figure 15, waves are reflected and refracted at layer boundaries, so that, strictly speaking, G does not equal $1/R$. Let us take up this problem here.

Kitsunezaki (1967) has taken up the problem of amplitude change in waves produed from a single point in ground with a number of horizontal layers. Taking ray intensity into consideration, he derived the following formula for the quantity corresponding to geometrical factor:

$$G=\frac{\overline{K}}{\overline{r}_n} \tag{16}$$

Here, the terms $\overline{K}$ and $\overline{r}$ refer to "synthetic transmitting coefficient" and "equivalent

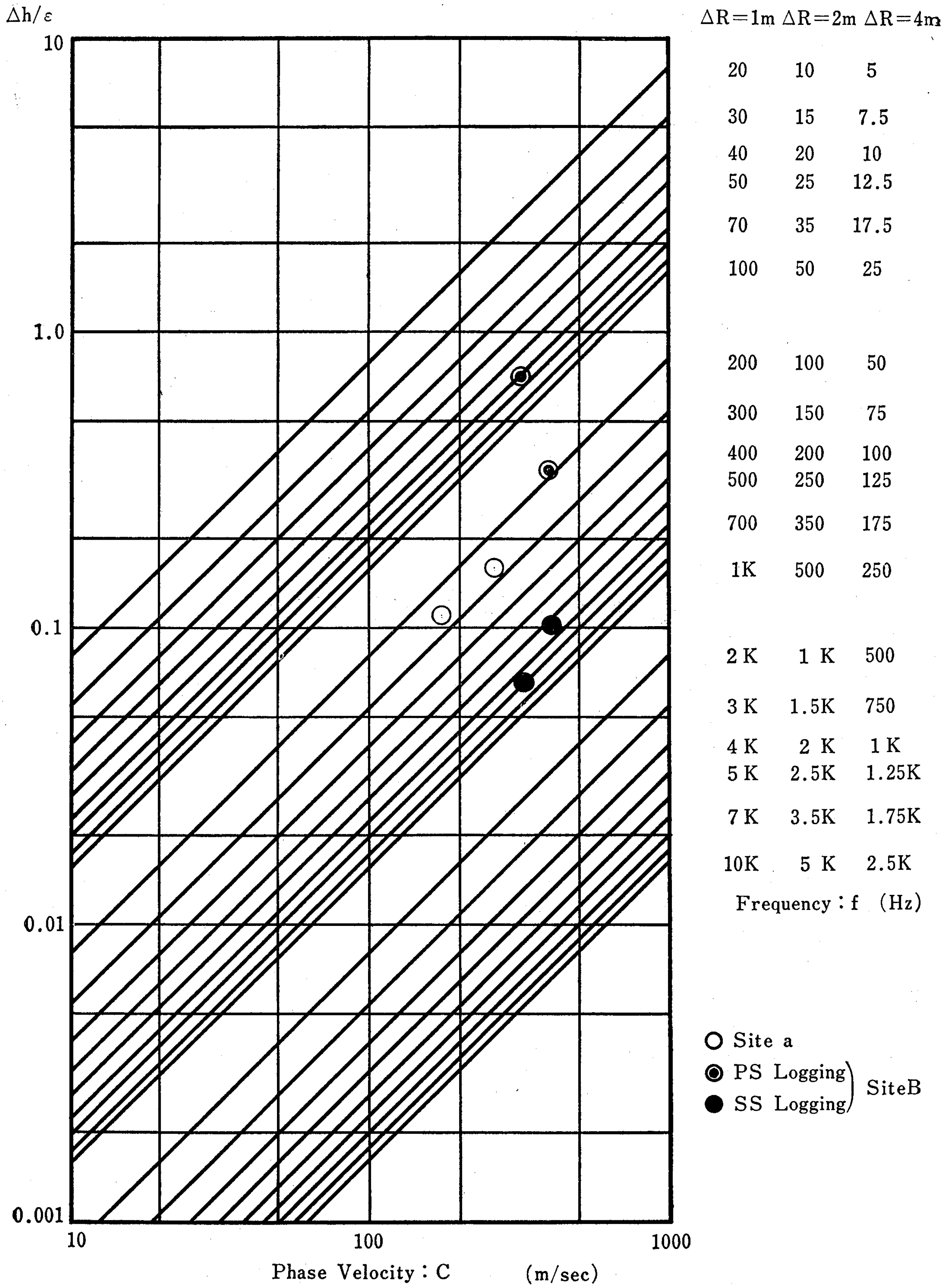


Fig.14 Relationship between $\Delta h/\varepsilon$ (quantity expressing accuracy of obtained *Q* values) and *c* (phase velocity)

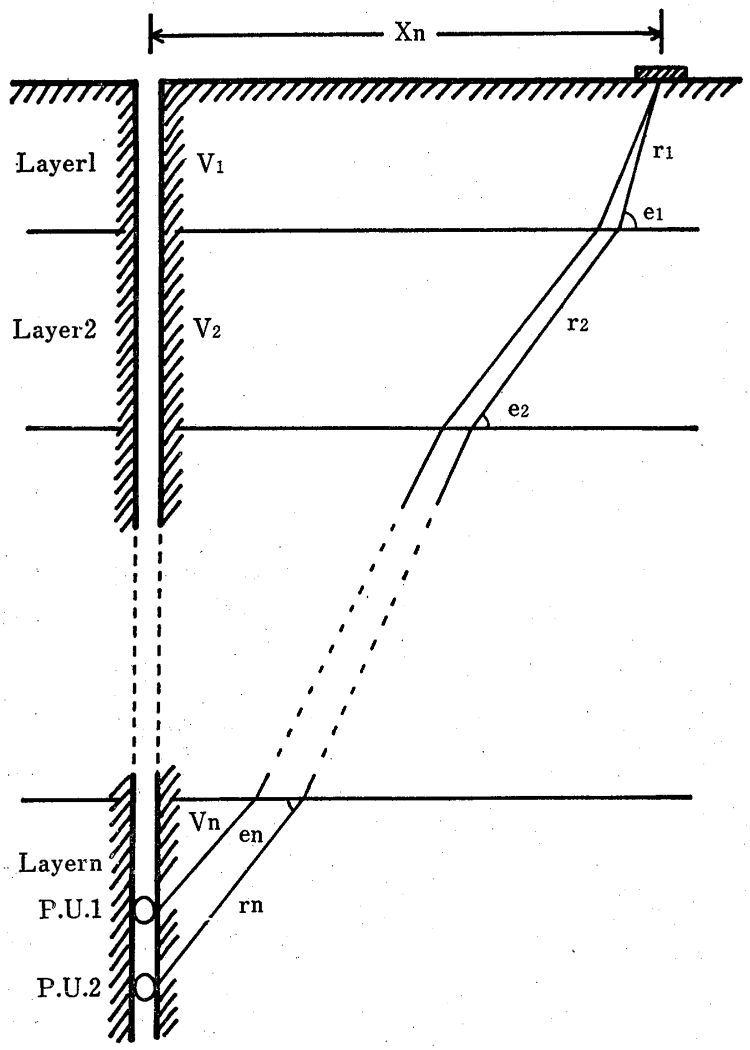


Fig.15 Path of ray as it passes through horizontal layed ground

distance from vibration source" respectively. These terms are defined as follows:

$$\overline{K}=K_{12}\cdot K_{23}\cdot K_{34}\cdots\cdots K_{ij}\cdots\cdots K_{n-1,n} \tag{17}$$

$$\overline{r_n}=\sqrt{\left\{r_1+r_2\frac{V_2}{V_1}\left(\frac{\sin e_1}{\sin e_2}\right)^2+\cdots\cdots+r_n\frac{V_n}{V_1}\left(\frac{\mathrm{Sin}\ e_1}{\mathrm{Sin}\ e_n}\right)^2\right\}\frac{x_n}{\cos e_1}} \tag{18}$$

where K_{ij}: transmitting cofficient from i layer to j layer,
r_i: length of ray passing through i layer (See Fig. 15),
V_i: S-wave velocity of i layer
e_i: angle described by ray passing through i layer as it meets layer boundary (See Fig. 15), and
x_n: horizontal distance between vibration source and borehole (See Fig. 15).

The *PS* method used by the authors was the "downhole method" in which the vibration source is set up on the surface and the receiver is set in the borehole. Because the vibration source is very close to the measuring borehole, rays can be considered to penetrate the layers almost perpendicularly. Consequently, we find that $e_1 \fallingdotseq e_2 \fallingdotseq \cdots\cdots \fallingdotseq e_n \fallingdotseq 90°$, so that Formula (18) changes in the following way:

$$\overline{r_n}=r_1+r_2\frac{V_2}{V_1}+r_3\frac{V_3}{V_1}+\cdots\cdots+r_n\frac{V_n}{V_1} \tag{19}$$

If we substitute Formulas (16), (17) and (19) into Formula (4), we find:

$$\alpha(f)=\frac{1}{R_2-R_1}\left[ln\left\{\left(\frac{H_1(f)}{\overline{K_1}/\overline{r_{n_1}}}\right)\Big/\left(\frac{H_2(f)}{\overline{K_2}/\overline{r_{n_2}}}\right)\right\}\right] \tag{20}$$

Here, as is clearly shown in Figure 15, the records taken at two different depths used in the authors' analysis represent a single velocity layer, that is to say, $\overline{K_1}=\overline{K_2}$. Thus, we may simplify Formula (20) in the following way

$$\alpha(f)=\frac{1}{R_2-R_1}[ln\{H_1(f)\cdot\overline{r_{n_1}})/(H_2(f)\cdot\overline{r_{n_2}})] \tag{21}$$

As an example, Formula (21) was used on the data obtained at Site **B** by the *PS* method to find *Q*. Using Formula (4), the values thus obtained, along with those obtained by the *SS* method are all shown together in Table-1.

Table-1 Comparison of *Q* values obtained according to different computation methods

	by Formula (4)	by Formula (21)	by *SS* method
b-1 Layer	32	43	49
b-2 Layer	21	24	25

Looking at the table, we see that the values for *Q* obtained by using Formula (21) are somewhat larger than those obtained by using formula (4), and that they are close to those values obtained by using the *SS* method. As we have mentioned above, investigation has shown results obtained by the *SS* method to be relarively accurate. From this, we may that values obtained by using Formula (21) are more suitable. However, it is argued that this is based on the assumption that *Q* does not depend on frequency. At the same time, there is now the view that it does depend on frequency, so that no final conclusion can be reached. We will conclude our discussion at this point. We will note, however, first, it is clear that Formula (21) best reflects the actual phenomena, but, second, the simplier Formula (4) shows no particular theoretical difficulties, and, from a practical standpoint, is more convenient to use.

6 AFTERWORD

As we have pointed out, the value *Q* is one of the quantities that may be used to express the dynamic nature of the ground. This paper has considered the determination of *Q* by in-situ measurement. It has become clear that *Q* values change according to the medium. However, when a number of samples were taken from the same medium, triaxial testing showed good correspondence between *Q* values obtained. This investigation conducted in-situ measurements with the easy and practical *S*-wave logging method. However, it must be noted here that there is a limit to the accuracy of this method, and that we have not at this time dealt with the matter of changes in *Q*-value due to fine differences between mediums.

It must be noted that the amount of data on the demping determined by in situ measurement is far less than sufficient. Thus the future accumulation of such data is necessary. This study has pointed out several problem areas involved in the measurement of *Q* value. In order to meet this need, it will be necessary to develop a system for determining *Q* value that is simple, practical and yet accurate.

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S波検層記録を用いた土の“Q”の評価

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概 要

地盤の地震時挙動を解明していく上で，地盤を構成する土の減衰定数はS波速度同様重要な要素の1つである。

本論文は，原位置測定としてPS検層およびサスペンションS波検層を行ない，その際得られる記録をもとに，S波の減衰（波動の減衰を表わす量として一般に無次元量Qが用いられる）について検討したものである。

通常のPS検層は，地表の板叩き振源からの波動を孔中の一深度で受振するものであるが，今回のPS方式では，1回の測定ごとの振源エネルギーを規準化するために，振源付近に固定の測定点が設けられている。一方，サスペンションS波検層システムは，現在開発途上のものであるが，今回用いたSS方式は，1回の測定で同時に2深度の記録が得られるものである。

今回，2つのsiteで測定を行なった。まず，site **A** では，PS方式のみの測定であるが，S波速度が270m/secの砂質土層と180m/secの粘性土層の2つの層についてQを求めた。その結果，前者については$Q \div 10$，後者については$Q \div 30$との値を得た。また，ここでは，地中2深度の間隔が2，4，6mの3とおりの場合についてQを求めたが，これらの間隔の違いによる特徴的な差は認められなかった。このことは，媒質が均質であるならば，その媒質のQは2点間の間隔によらないはずであり，当然の結果といえる。

つぎに，site **B** では，PS方式の他に，SS方式も併せて用いた。ここでも，site **A** 同様2つの層について検討した。その結果，S波速度330m/secの細砂層では，PS方式で$Q \div 30$，SS方式で$Q \div 50$と若干差があるのに対し，S波速度410m/secの砂質シルト層では，PS方式で$Q \div 20$，SS方式で$Q \div 25$とかなり近い値を示した。いずれの層でも，PS方式よりSS方式から求めた値の方が大きい。

今回の測定に用いた2つの方式の周波数領域は，PS方式では30〜50Hzであるのに対し，SS方式では数100〜1kHzと大きな差がある。媒質の減衰定数は周波数に依存するといった考え方もあり，上述のように，方式の違いによって，求めたQに差があるのは，あるいはそういった理由によるのかも知れない。

また，site **B** では，サンプリング試料を用い，振動三軸試験によって減衰定数$h\,(=1/2Q)$を求めたが，上述の原位置測定から得た値と比較的良い対応を示している。

一方，幾何学的な拡散係数に関する検討結果によると，厳密な意味では層の境界面での反射および屈折を考慮しなければならないが，簡単で実用的といった見地からは，拡散係数を振源距離の逆数と置いても特に問題はなさそうである。

最後に，得られたQ値の精度については，SS方式はともかく，PS方式から求められる値はやや信頼性に欠けることが明らかとなった。しかし，実際の地震時に問題となる周波数域としては，高々10Hzまでの低周波数域であることを考えると，原位置測定はできるだけこれに近い周波数域で行なわれることが好ましく，今後，検討していかなければならない問題である。