DETERMINING DYNAMIC DEFORMATION CHARACTERISTICS OF SOILS BY IN-SITU MEASUREMENTS AND LABORATORY TESTING

BY

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SUMMARY

Rigidity (G) and Damping (h) factors of soils from soft ground were tested using in-situ and laboratory methods. The in-situ methods included PS logging and Suspension S-wave logging, while the laboratory tests included dynamic soil testing, dynamic triaxial testing, and resonant column testing of soil samples. Strain levels by in-situ measurement were approximately 10^{-6}, which corresponds to initial strains of dynamic deformation characteristics produced by laboratory testing. At the same strain level, both types of testing show a very good correlation between G and h.

INTRODUCTION

The identification of the seismic behaviour of soft ground is important in helping to prevent damage from earthquakes. Accordingly, many different types of analyses of ground models have been carried out recently with this end in mind. The actual behaviour of the ground is, however, complex and successful testing of models depends on how each ground constant is determined, regardless of the type of testing used. Of especial importance is the determination of dynamic deformation characteristics, namely, Rigidity (G), Damping (h) and their variations depending on strain level.

This study constitutes a reexamination of G and h of soils in soft ground. In-situ measurement as well as laboratory dynamic soil testing of smaples was used. Dynamic deformation characteristics of soil include not only the factors G and h, but also Young's Modulus, Poisson's Ratio, etc.. Fig. 1 shows the procedures and conditions involved in measuring soil dynamic deformation characteristics in the field by seismic methods and in the laboratory by dynamic soil testing.

IN-FIELD SEISMIC MEASUREMENTS

We are able to deribe the dynamic moduli and Poisson's ratio of soil by knowing the P-wave velocity and the S-wave velocity. For this purpose, in Japan, the PS logging technique, developed by the authors in 1967, has been widely used. Seismic methods, however, as shown in Table 1, are primarily based on the measurement of velocity of wave propagation without dealing with the problem of damping.

As a regular practice, the authors take damping factor measurements when PS logging is conducted. As shown in Fig. 2, in order to normalize source energy from wooden plate hammering, a fixed type measuring point is established on the surface and S-waves generated are measured simultaneously

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on and beneath the surface. The data is all stored magnetically in a data recorder, which is useful afterwards for spectral analysis. The seismograph is a 3-component borehole pickup (OYO product, Model 3320).

The results of simultaneous measurement at the surface and certain given depths, A(f) and B(f) may be expressed as frequency domains:

$$\left.\begin{aligned} A(f) &= Ha(f).Pa(f).S(f) \\ B(f) &= Hb(f).Pb(f).S(f) \end{aligned}\right\} \qquad (1)$$

where

f: frequency (Herz)
H(f): transfer function from source to pickup
P(f): frequency characteristics of measurement system
s(f): source characteristics

If the medium is homogeneous, the transfer function H(f) may be represented:

$$H(f) = K.\exp\{-\alpha(f).R\} \qquad (2)$$

where

K: geometrical diffusion coefficient
$\alpha(f)$: attenuation coefficient (m^{-1})
R: distance from source to pickup

According to Eq. (2), if we apply the transfer function derived between 2 points in the borehole (Fig. 2), the attenuation $\alpha(f)$ may be expressed as Eq. (3):

$$\alpha(f) = \frac{\ln\{(H_{b1}/K_1) \;/\; (H_{b2}/K_2)\}}{R_2 - R_1} \qquad (3)$$

Since the distance between the wooden plate being used as a vibration source and the pickup is sufficiently large in comparison to the size of the plate, the waves can be taken to be spherical, so the diffusion coefficient can be approxmiated as K = 1/R. And, as the same kinds of instruments are used on the ground level as well as below the surface, we may eliminate B(f) and S(f) from Eq. (1) and solve for H(f) and, by substituting in Eq. (3), we find that $\alpha(f)$ may be found according to the following equation:

$$\alpha(f) = \frac{\ln\{(R_1 \times \frac{B_1(f)}{A_1(f)}) \;/\; (R_2 \times \frac{B_2(f)}{A_2(f)})\}}{R_2 - R_1} \qquad (4)$$

Using the value for $\alpha(f)$ from Eq. (4) and phase velocity C, we may find damping factors h according to the following equation:

$$h = \frac{C \cdot \alpha(f)}{2\pi f} \qquad (5)$$

The value for h that is thus determined, has the following relation to be dimensionless quantity Q, which is used frequently in seismology and indicate attenuation:

$$Q = \frac{1}{2h} \qquad (6)$$

Recently, Kitsunezaki (1978) and Ogura (1979) have developed the Suspension S-wave logging system (Fig. 3), in which a float type receiver that does not adhere to the sides of the borehole is used together with an electromagnetic underwater hammering source. In this system, two pickups are placed one meter apart. Both monitor S-waves from the same source. This system is a much simplier way of finding h than by using PS logging.

Fig. 4 shows one example of an analysis made using PS logging and Suspension S-wave logging. The upper portion of the figure shows simultaneous PS logging on the surface and underground. Fourier spectra at two points in the boreholes and spectra at the surface are shown for normalization. h is determined according to the highest frequency peak. The lower portion shows the records of Suspension S-wave logging, where two pickups record vibrations from the same source. The respective Fourier spectra are also shown.

Fig. 5 incorporates the results of various research in the past, with the Damping factor (Q), derived by the procedures described above.

The techniques for finding the damping factor when measuring S-waves as a system of analysis still have many points that can be improved. But it is nevertheless one step more advanced than the other technics, which are only usable for determing velocity. It is thus important as a means of finding out more information concerning the dynamic properties of soils.

DYNAMIC SOIL TEST IN LABORATORY

There are several kinds of dynamic soil tests to determine the deformation characteristics of soil under dynamic loads (see Fig. 6). The one in most general use is the dynamic triaxial test. Besides this, the dynamic simple shear test, dynamic torsional test and the resonant column tests are frequently used.

The greatest fundamental difference among these test methods involves differences in external forces,that act as a dynamic load. Thus, the testing method is classified according to whether compression type, shear type or torsion type procedures are used. However, with the exception of the resonant column test, the other three tests all yield a stress-strain hysterisis loop as a result of a cyclic load, as shown in Fig. 7. The dynamic modulus is obtained as the gradient of the loop. The loop's area ratio gives the damping factor. Also, by varying the amount of cyclic load and obtaining G, h, etc. for each different strain level, a pattern of deformation due to strain may be described. The results of this kind of test are reliable down to the 10^{-4} level. Strain levels smaller than this are at present covered by the resonant column test.

The resonant column test takes a cylindrical specimen with a fixed based and applies cyclic torsion to the top. It gives the resonant frequency (fo), corresponding to the dimensions and shear modulus (G) of the specimen. For this, the shear modulus for strain in the range of 10^{-6} can be obtained.

COMPARISON OF DYNAMIC DEFORMATION CHARACTERISTICS

As we have seen, each of the dynamic characteristics of soil can be independently found, either by seismic methods in the field or by dynamic soil testing in the laboratory. With a range of differing conditions such as stress conditions, strain levels, frequencies, etc. at the time measurements are taken, a few theoretical assumptions may be made in order to derive some constants. In this way, a variety of values are obtained, and the appropriate ground characteristics must be decided on in order to conduct whatever types of simulations are required by the job. Following is an account of the authors' experience in this regard. We will give some examples from measurement data that we have gathered.

First shear modulus (G) is shown in Fig. 8. The strain level is 10^{-6}, and it is a comparison between the values Gd, obtained by seismic methods, and G_T, obtained in the laboratory either by the dynamic traxial test or the resonant column test. This relation agrees well, but, generally speaking, the values obtained by seismic methods are somewhat larger than those obtained by laboratory testing.

Next, let's present one example of a comparison between damping factors (h) obtained in the laboratory and by seismic methods. Fig. 9 shows the positions from which comparative measurements were taken and the types of soil tested. These measurements were taken in an experimental well at OYO's Urawa Research Institute.

In it, the damping factor of S-waves was figured both by PS logging and Suspension S-wave logging for a diluvial soil layer at about 70 meters, diluvial sand layer at 90 to 100 meters and a diluvial silt layer at 104 to 111 meters. Then, using soil samples from each of these three layers, a dynamic triaxial test to determine h was conducted.

Fig. 10 shows the results of these tests. The value h, determined in the laboratory, increases rapidly with increases in strain. Differences in confining pressure exert a big influence. In small levels of strain, h decreases, and with a strain of 10^{-6}, h seems converge on the value by about 1 to 2%. It is little different from the damping factor obtained by seismic methods.

AFTERWORD

In order to establish a well-balanced model of soil, geophysical methods should henceforth go hand in hand with geotechnical methods. We expect the former type of investigation to make substantial contributions in the future. We also believe that the improvement of measuring techniques and the greatest understanding of the true properties of soil will become a major goal.

Finally, we would like to express our deep appreciation to the President of OYO Corporation, Dr. Kunio Suyama, for his continued guidance in the pursuit of our research. In addition, we are greatly indebted to many OYO members who have greatly assisted our work both in the field and in the laboratory.

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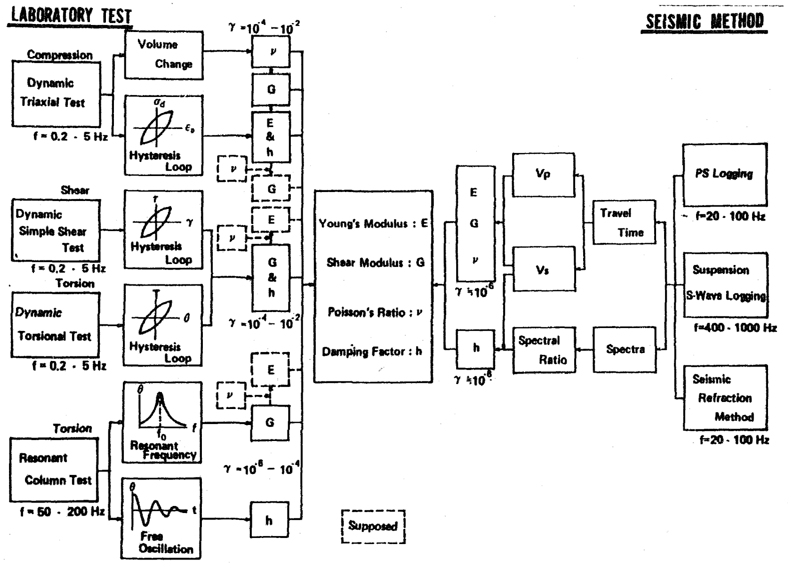


Fig.1 The procedure and conditions of laboratory test and seismic method for estimation of dynamic moduli.

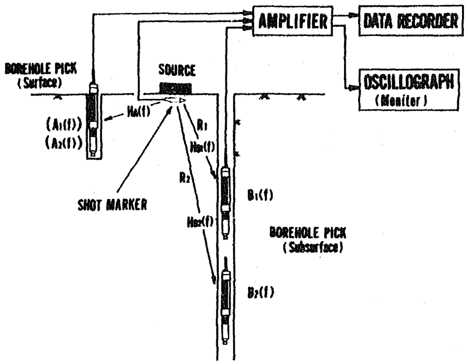


Fig.2 Measuring system for obtaining damping factor with PS logging.

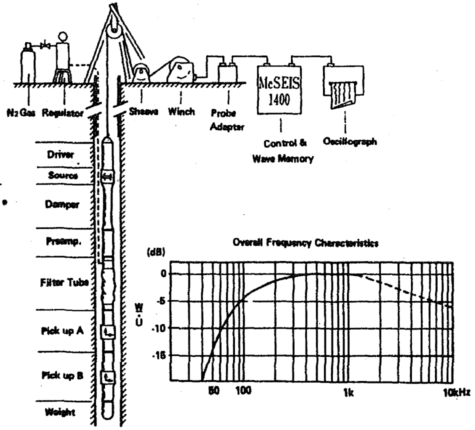


Fig.3 Measuring system in outline Suspension S-wave logging.

Table 1 Comparison of seismic methods for estimation of dynamic moduli.

Method	Practice	Wave Source	Frequency (Hz)	Available Depth(m)
Refraction	Line Observation on Surface	Wooden Plate Hammering Weight Dropping Blasting	20 ～ 100	Subsurface
PS Logging	Well Shooting (downhole or uphole)	Wooden Plate Hammering Weight Dropping Blasting	20 ～ 100	0～200
Suspension S-wave Logging	Logging (in bore hole)	Electromagnetic Vibration Source	400～1000	0～1000

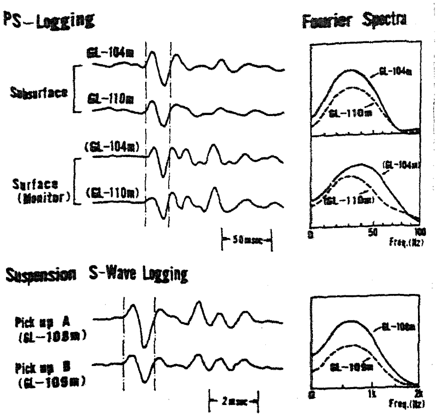


Fig.4 One example of S-wave records and their Fourier spectra.

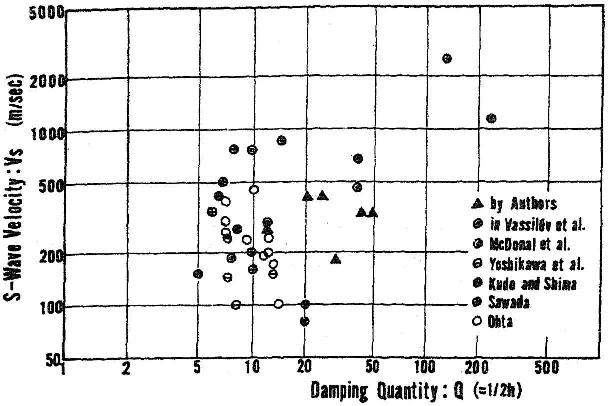


Fig.5 Relationship between Damping Quantity(Q) and S-Wave Vel.(Vs).

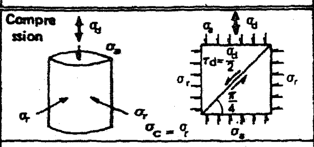
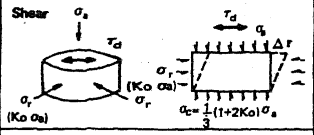
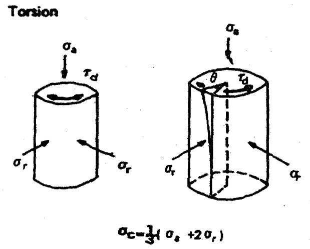
Method	Stress Condition	Item of Measurements (for Dynamic only)	Obtained Dynamic Moduli	Strain Level	Cyclic Frequency (Hz)
Dynamic Triaxial Test	Compression  $\sigma_c = \sigma_r$	Axial Load : L Axial Stress: q_d Axial Displacement : Δa Axial Strain : ϵ_a Porewater Pressure : Δu Volume Change : ΔV	Young's Modulus : E Shear Modulus : G Poisson's Ratio : ν Damping Factor : h	10^{-4} - 10^{-2}	0.2 - 5
Dynamic Simple Shear Test	Shear  $\sigma_c = \frac{1}{3}(1+2K_o)\sigma_a$	Shear Load : S Shear Stress : τ_d Horizontal Displacement : Δr Porewater Pressure : Δu	Shear Modulus : G Damping Factor : h	10^{-4} - 10^{-2}	0.2 - 5
Dynamic Torsional Test	Torsion 	Torque : T Shear Stress : τ_d Torsional Angle : θ Shear Strain : γ Porewater Presure : Δu		10^{-4} - 10^{-2}	0.2 - 5
Resonant Column Test	$\sigma_c = \frac{1}{3}(\sigma_a + 2\sigma_r)$	Acceleration : Ah Resonant Frequency : f_0		10^{-6} - 10^{-4}	50 - 200

Fig. 6 Comparison of laboratory tests for estimation of dynamic moduli.

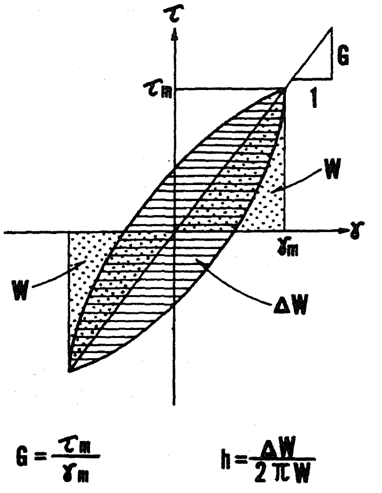


Fig. 7 Definition of shear modulus and damping factor.

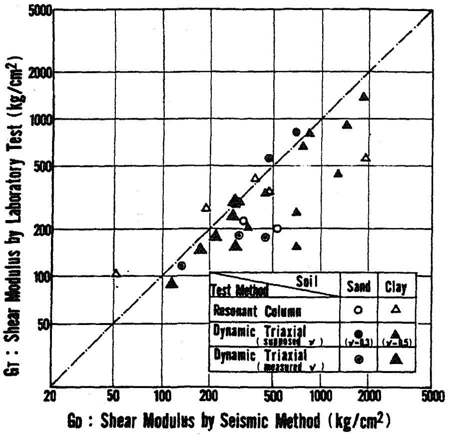


Fig. 8 Comparison of shear modulus obtained by seismic method and laboratory test.

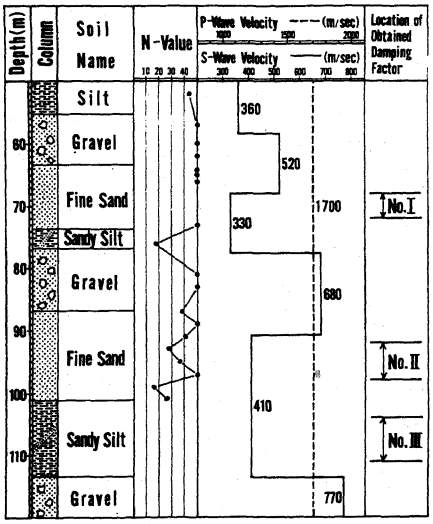


Fig.9 Geological column and distribution of wave velocity where damping factors measured.

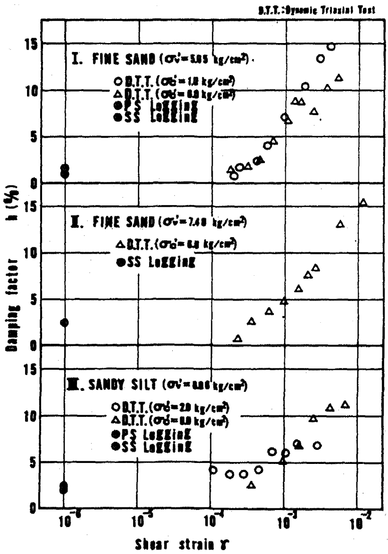


Fig.10 Damping factor obtained by seismic method and dynamic triaxial test.