Dynamic Shear Tests of Soils for Seismic Analyses

Essai de Cisaillement Dynamique du Sol

A.HARA Research Engineer,
Y.KIYOTA Research Engineer, Kajima Institute of Construction Technology, Tokyo, Japan

SYNOPSIS Many excellent analytical procedures to evaluate the earthquake effects on soil deposits have been developed recently. In order to apply these analytical procedures to the designing of actual buildings, it is necessary to experimentally grasp the stress-strain relationships of soil in a soil deposit at small to large strain amplitudes. Under such a necessity, we have developed a Kjellman-type dynamic simple shear apparatus. This paper introduces an outline of this apparatus and examples of tests of clay, sand and mudstone samples. These tests showed that results of the in-situ tests and the dynamic simple shear tests were generally coincidental. They also revealed shear modulus, damping strain-dependency and frequency-dependency of the above-mentioned three kinds of soil. In conclusion, this paper shows hysteresis curves of typical samples, and indicates that the stress-strain relationships of soil are simpler that they have been considered.

INTRODUCTION

The designing seismic load for a plant to be built on the soft ground or nuclear power stations, of which high-degree safety is required, has a tendency to be determined by soil-structure interaction.

Excellent analytical procedures to find relationships of soil-structure interaction have been developed. For application of these procedures to the designing of aseismic structures, it is necessary to experimentally grasp the soil dynamic characteristics of in-situ soil deposits at small to large strain amplitudes.

The soil dynamic characteristics at small strain amplitudes can be obtained by in-situ tests for geological survey and earthquake observation. However, it is difficult to conduct an in-situ test using large energy artificially. Therefore, it is more realistic to grasp dynamic characteristics of soil at large strain amplitudes in a laboratory test. Two major requirements for the laboratory tests are:

1) Reproduction as faithful as possible of the stress condition during an earthquake in-situ soil deposits.

2) Practicality of being able to test soil from in-situ soil deposits at any strain amplitude in an easy method.

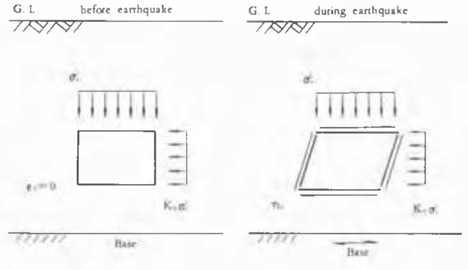


Fig. 1 Stress Condition in a Soil Deposit

Under such circumstances, authors aimed at an apparatus having the above-mentioned two functions, and succeeded in the development of a new dynamic shear apparatus.

Using this test apparatus, the authors conducted tests on clay, sand and mudstone samples taken from in-situ soil deposits and extensively examined results of the tests.

OUTLINE OF DYNAMIC SIMPLE SHEAR APPARATUS

The stress condition in a soil deposit during an earthquake, strictly speaking, is complicated. However, the major cause for seismic damages is considered to be shear waves. Therefore, we aimed at faithfully reproducing the stress condition that affects soil elements in a soil deposit as shown in Fig. 1. The simple shear test method is practical because the shape of sample to be used is simple. For this reason, we examined the stress condition inside sample for the simple shear test as follows:

The stress condition in case of shearing deformation of circular samples as shown in Fig. 2(a) was analyzed by the three-dimentional FEM method (Iso-Parametric Element Method) refering the studies made by Lucks et al. The shape of sample have a radius of 5.4 cm and height of 3.0cm. Its Young's modulus E was assumed to be 200kg/cm^2 and its Poisson 's ν 0.49.

When shearing displacement of 0.06cm was given to the sample as shown in Fig. 2(a), the distribution of normal stresses on the vertical section and on the top surface was as shown in Fig.2 (b,c).

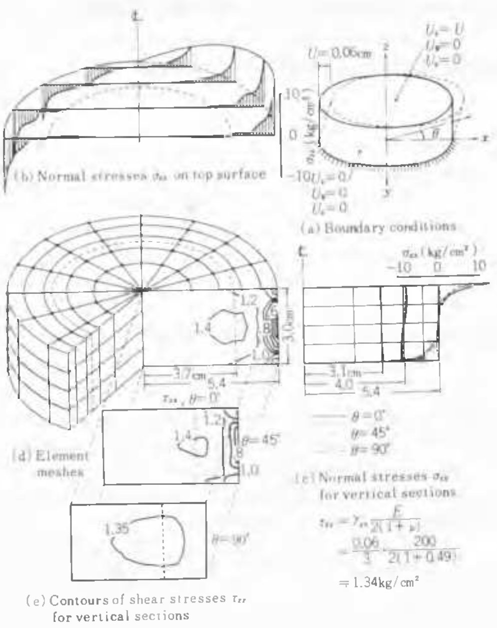


Fig. 2 Normal Stresses and Shear Stresses of Simple Shear Sample

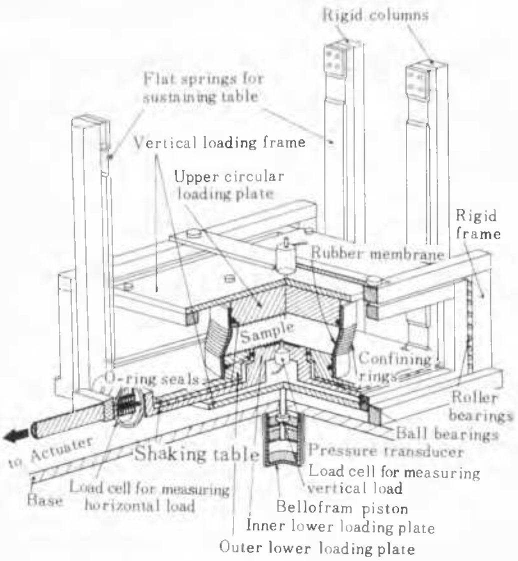


Fig. 3 Cubical View of Dynamic Shear Apparatus

Moreover, contours of shear stresses on vertical sections at $\theta = 0^{\circ}$, 45°, and 90° inside the sample were as shown in Fig.2(e).
Averaged shear stress of the sample can be obtained by the following equation:

$$\tau=\gamma\frac{E}{2(1+\nu)}=\frac{0.06}{3}\cdot\frac{200}{2 \times 1.49}=1.34\text{kg/cm}^2 \quad \cdots(1)$$

According to Fig.2(e) depicting contours of shear stresses, stresses are concentrated in the peripheral part of the sample, and the distribution of shear stresses in the entire sample is different from that of soil elements during an earthquake as shown in Fig.1. However, the distribution of shear stresses inside of a radius of 3.7cm as shown by a dotted line in Fig.2(e) is almost equal to the average shear stress of 1.34 kg/cm². And the normal stress on the vertical section and on the top surface are almost zero.
Accordingly, if the sample shown in Fig.2(a) can be deformed by shearing and the shear stress in the central region of the sample within a radius of 3.7cm can be measured, it is ideal. However, it is difficult to strictly measure the shear stress generated in the central region of the sample. Therefore, we decided to approximately measure the shear stress in the central region of the sample by the method mentioned below:
Firstly, the plate on which the sample is mounted is divided into the inner and outer parts as shown in Fig.3. As ball bearings are inserted between them, the two parts structurally do not interact upon each other. And the two parts have the same area of contact with the base of the sample. Therefore, if one end of two load cells with identical spring constant is linked to each of the two parts, and the other end of the cells is fixed to a piston rod is put into motion, the inner and outer parts are deformed by shearing approximately the same. Thus, the shear stress in the central region of the sample can be measured by a load cell linked to the inner plate. Fig.3 is a three-dimentional figure of a dynamic shear apparatus designed on the basis of results of the above-mentioned analysis. There are three types of a shear apparatus--NGI-type, Cambridge Univ. -type and Kjellman-type. The above-mentioned apparatus is of Kjellman type.
Salient features in structure and function of this apparatus are summarrized as follows:

1) The shaking table is supported on four 50 cm-long flat springs so that the frictional force acting between the parts supporting the shaking table in the vertical direction and the shaking table may be made negligibly small.
2) As the shear apparatus is driven by the electro-hydraulic testing system, tests can be subjected to strain or stress control according to the program.
3) Usually tests are conducted according to the test programs shown in Fig.4. In accordans with the test programs shown in Fig. 4, soil dynamic characteristics ranging widely in shearing strain amplitude from 0.001% to 1.0% and in frequency from 0.1Hz to 10Hz can be obtained.

TEST EXAMPLES

The shape of the samples is circular, with a diameter of 108mm and height of 30mm.
The sample was fixed to the test apparatus shown in Fig.3, and consolidated for 24 ~ 48 hours by adding consolidation stress by the Bellofram piston.
In this case, the sample was in a plane strain condition, as confining rings were fixed to its side surface. The consolidation stress was made equal to effective overburden stress at the depth of soil from which the sample was extracted.
All tests were performed under undrained condition.

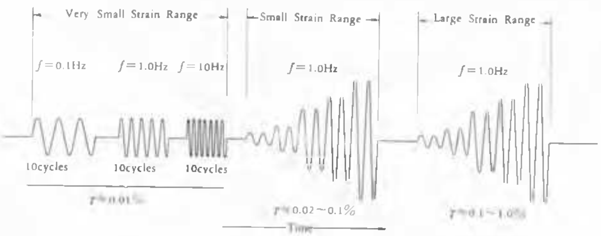


Fig. 4 Testing Program

Properties of each samples and consolidation stress are shown in Table 1.

Table 1 Properties of Each Samples and Consolidation Stress

Sample No.	Soil type	Unit weight γ g/cm³	Void ratio e	Water content w (%)	Degree of saturation Sr (%)	Plasticity index Ip (%)	Consolidation Stress σ_c (kg/cm²)
1	Clay	1.46	2.09	71.2	89.4	51.3	1.8
2	〃	1.74	1.17	43.2	97.1	32.6	2.15
3	〃	1.71	1.31	52.5	100.0	51.7	2.45
4	〃	1.67	1.43	57.3	100.0	65.0	2.8
5	〃	1.63	1.54	61.7	100.0	78.9	3.15
6	〃	1.61	1.63	64.8	100.0	74.6	3.5
7	Sand & Gravel	1.8	0.65	14.4	59.0	—	1.1
8	〃	1.78	0.72	15.5	55.5	—	1.2
9	Sand	1.721	0.666	6.9	28.0	—	0.15
10	〃	1.717	0.669	6.9	28.6	—	0.31
11	Mudstone	1.72	1.225	44.3	91.0	—	1.8
12	〃	1.72	1.15	29.0	96.0	—	2.1
13	〃	1.72	1.27	50.0	97.5	—	2.7
14	〃	1.73	1.27	50.0	97.5	—	2.8
15	〃	1.72	1.33	54.2	98.5	—	2.9

Since it is known that in case of soil, shear modulus depends largely on the strain amplitude, the results of the test were arranged as follows:

1) In any of the tests, when the shear strain amplitude was 0.001%, the shear modulus was regarded as initial shear modulus Go.
2) The value of shear modulus G at a certain shear strain amplitude was determined by measuring the slope of the line connecting the extreme points of the hysteresis curves.
3) The damping factor was calculated by the same method as that used by Seed et al.

Clay

The samples No.1~6 shown in Table 1 were extracted from the soil deposit shown in the boring log of Fig.5.

Fig.5 shows comparison between shear modulus obtained by the Down hole method, which is an in-situ test method, and initial shear modulus Go obtained by the dynamic shear test. The values of the both moduli are fairly identical. The relationship between the shear modulus at a certain strain amplitude normalized by the above-mentioned initial shear modulus G/Go and the shear strain amplitude of damping factor h is shown in Fig.6.

Moreover, the hysteresis curves of small amplitude range and large amplitude range for the sample No.5 is shown also in Fig.7.

Sand

Results of the grain size accumulation curves for the samples No.7, 8, 9 and 10 are shown in Fig.8.

Like the test example for clay, the relationship between G/Go~ γ and between h~ γ for sand is shown in Fig.9.

In order to make it clear that in case of sand samples, grain size distribution affects the damping factor to a large extent, the number of samples is attached to the value of h.

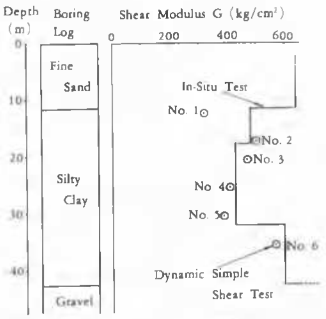


Fig. 5 Comparison of G Determined by In-situ and Laboratory Test

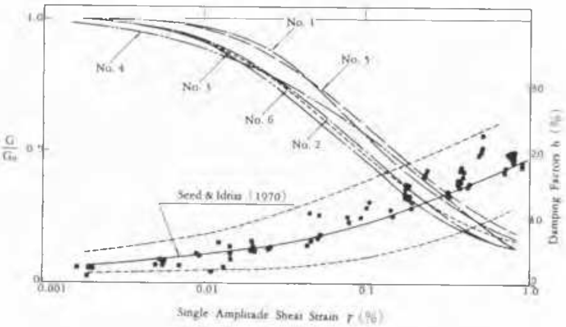


Fig. 6 Shear Modulus and Damping Factor Versus Shear Strain for Clays

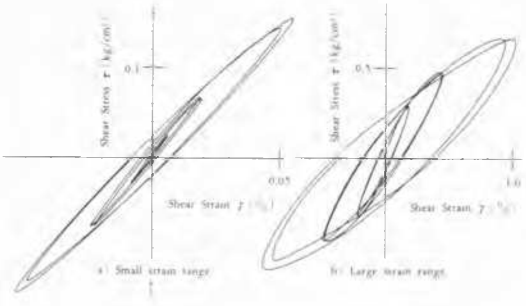


Fig. 7 Dynamic Hysteresis Curves of Clay

As an example of a test of the sample No.10, the hysteresis curves for all the test programs listed in Fig.4 are shown collectively in Fig.10.

Fig.10(a) shows hysteresis curves for a test conducted by keeping the strain amplitude constant and varying frequency to three steps of 0.1, 1.0 and 10.0Hz. As the hysteresis curves are very similar with one another, it is conceivable that effects on G and h are small at such a small strain amplitude.

Fig.10(b,c) presents the hysteresis curves in the small and large amplitude ranges.

They show that the values of G and h depends largely on strain amplitude.

Mudstone

In testing mudstone samples, we used epoxy adhesives to prevent the occurrence of slide between the sample and the upper and lower plates.

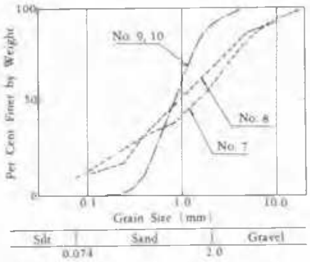


Fig. 8 Grain Size Distribution of sand

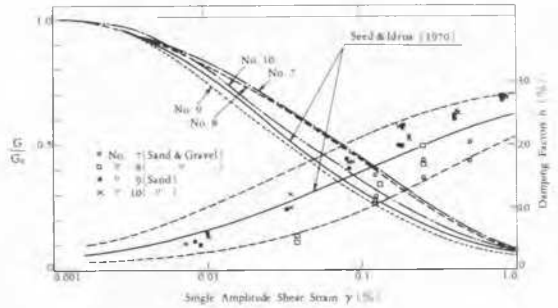
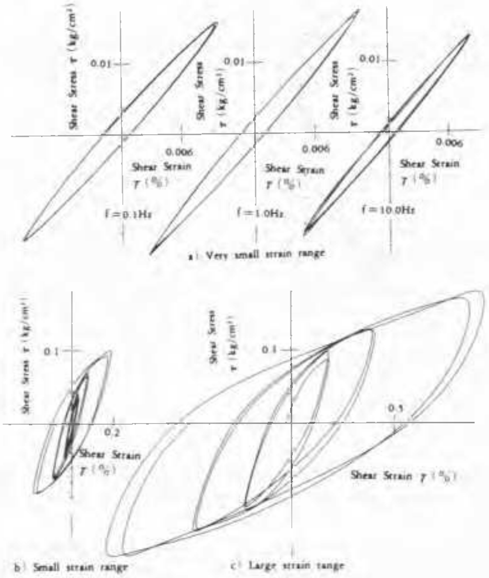


Fig.9 Shear Modulus and Damping Factor versus Shear Strain for Sands



a) Very small strain range

b) Small strain range

c) Large strain range

Fig.10 Dynamic Hysteresis Curves of Sand

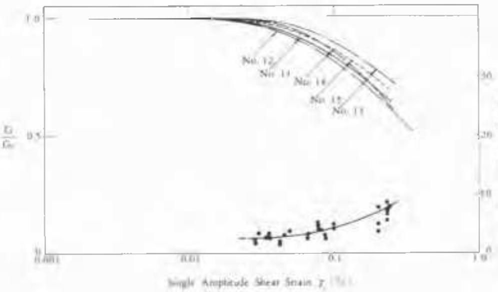


Fig.11 Shear Modulus and Damping Factor versus Shear Strain for Mudstone

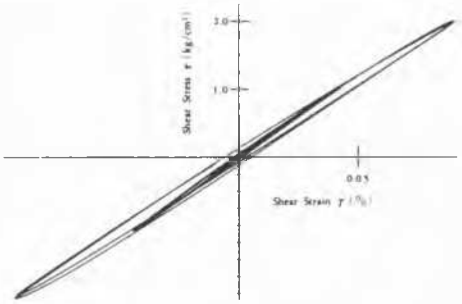


Fig.12 Dynamic Hysteresis Curves of Mudstone

Fig.11 collectively shows the relationships between $G/G_o \sim \gamma$ and between $h \sim \gamma$ for the samples No.11 ~ 15.
Fig.12 shows the hysteresis curve for the sample No.12. From these figures, it was found that a mudstone has a wider elastic region than a sand and a clay.

CONCLUSION

1) The value of shear modulus obtained from the in-situ test was approximately coincidental with the value of initial shear modulus obtained from the dynamic simple shear test. In view of this, it is conceivable that the test apparatus we have developed can reproduce the stress condition in the soil deposit fairly faithfully.
2) Examples of results the tests on samples of clay, sand and mudstone extracted from the soil deposits, shown above, indicate that the test apparatus is highly practical.
3) Soil is matter strong in nonlinearity. Sand is stronger in nonlinearity than clay, which is stronger than mudstone. They are in reverse order in case of elasticity.
4) An effective way to accurately grasp the dynamic stress-strain relationship of soil is the illustration of such a relationship by a hysteresis curve.
Such hysteresis curves indicates that the stress-strain relationship of soil is simpler than it has been considered to be.

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REFERRENCES

Kjellman, W. (1951), "Testing the Shear Strength of Clay in Sweden," Geotechnique, June, Vol.2, No.3, pp225-235.

Lucks, A. S., et al. (1972), "Stress Condition in NGI Simple Shear Test," Journal of the Soil Mechanics and Foundations Division, ASCE, Vol.98, No. SM1, Jan., pp155-160.

Seed, H, B., and Idriss, I. M. (1970), "Soil Moduli and Damping Factors and Dynamic Response Analysis," Report No.EERC 70-10, University of California, Earthquake Engineering Center, Berkeley, Calif., Dec.