週期的 反復荷重에 의한 軟弱粘土의 強度特性

Cyclic Strength Characteristics of Soft Clay

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要　旨

軟弱粘土(방콕)의 週期的 反復荷重에 依한 擧動을 糾明하기 위하여 不攪亂試料에 對한 一連의 反復荷重을 利用한 三軸壓縮試驗을 試圖했다. 本試驗은 拘束壓力 및 初期剪斷應力을 變化시켜 가면서 粘土의 剪斷變形, 强度變化 等을 調査・比較한다. 그 結果 初期剪斷應力이 增加함으로써 應力一變形曲線은 적은 變化를 보였고, 反復荷重에 依한 强度變化는 應力比로 表現될 때 拘束壓力이 1.0 kgf/cm^{2}이었을 때 더 컸으며, 逐差應力으로 表現될 境遇는 拘束壓力이 1.5 kgf/cm^{2}이었을 때 크게 나타났다.

Abstract

A series of cyclic triaxial tests were carried out on undisturbed samples to clarify the cyclic behavior of Bangkok(Ransit) soft clay. Based on the test results obtained from the cyclic tests employing different initial shear stress and different confining stress, the cyclic properties of clay such as shear strain development and cyclic strength were investigated. The results showed that with increase in the initial shear stress, the stress-strain curve was flattened to some extent. The cyclic strength expressed by the stress ratio was higher in the test with 1.0 kgf/cm^2 of confining stress, while the cyclic strength expressed by the deviator stress was higher in the test with 1.5 kgf/cm^2 of confining stress.

I. Introduction

1.1 Objective of the Study

Saturated clays in the ground are often subjectected to cyclic loading caused by earthquakes, waves, traffic, pile driving, etc., and settlements and tiltings of foundations and failure of slopes during cyclic loading are of major concern to engineers. To grasp the cyclic behavior of clay, it is useful to impose the stress state to each sample in the laboratory in accordance with the condition in the field. For this purpose, cyclic triaxial tests are adopted as well as cyclic simple shear or hollow cylindrical tortional shear tests. Although the number of previous studies on the cyclic properties of clay is not so small, further investigations are still needed to clarify

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the cyclic properties more realistically based on tests employing undisturbed samples. Hence, the objective of this study is to identify dynamic strength of Bangkok clay which is necessary for understanding the cyclic behavior of the ground subjected to earthquakes, waves, traffic loads or other cyclic loads.

II. Literature Review

2.1 Types of Cyclic Loading

To determine the dynamic strength of soils, several types of cyclic loading tests have been employed, and these may be classified into four types according to whether the loading speed is rapid or slow and monotonic or repetitive. Four types of cyclic loading commonly employed to determine the cyclic strengths of soils comprise monotonic loading, monotonic cyclic loading, cyclic monotonic loading, and monotonically increasing cyclic loading.

2.2 Failure Criterion for Clay under Cyclic Loading

The definition of the failure criterion in cyclic loading has not been clearly established and some early publications are vague about failure criterion they employed. It is, however, agreed with to avoid defining failure in terms of effective stress because pore water pressure measurements during triaxial cyclic loading tests are inaccurate. And failure is usually defined in terms of cyclic strain amplitude in the case of cohesive soils. Various strain magnitude ranging from about 2.5% single amplitude of cyclic strain to 20% double amplitude of cyclic strain has been used as a failure criterion. On the other hand, in other investigations, the failure has been defined as the point when the rate of deformation starts to increase. Fig. 2.1 shows a typical example of the cyclic triaxial test result to illustrate the failure criterion(8).

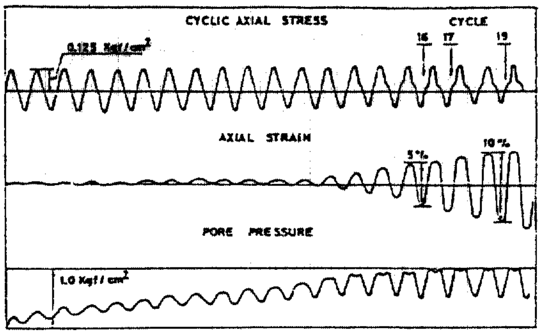

Fig. 2.1 A Typical Example of Failure Criterion (after Ishihara, 1982).

2.3 Factors Affecting Cyclic Strength

To explain the factors affecting the cyclic strength characteristics of cohesive soils, many constitutive relations have been proposed in recent twenty years(e.g., (3), (5), (6), (7), (12), etc.). Some results of their studies are briefed hereafter.

2.3.1. Effect of load frequency

The effect of frequency on the strength of cohesive soils has been studied by Koutsoftas (1978)(13) et al. They showed that the low load frequency tests require longer time to cause failure than the high frequency tests, and that increase in strength in the rapid loading tests as opposed to the slow loading tests may be visualized under monotonic loading conditions.

2.3.2. Effect of number of loading cycles

The effect of load cycle on the cohesive soils has been investigated by Seed, et al.(15) The result of this study consistently revealed that the strength of cohesive soils tends to decrease as the number of load cycles increases.

2.3.3. Effect of initial shear stress

Ishihara(1981)(8), Ishihara, et al. (1982)(9), Ishihara, et al.(1983)(10) have studied on the effect of the magnitude of an initial shear stress. In general, they showed that the strength of cohesive soils was increased with increasing initial shear stress up to a magnitude. Ishihara

(1981)(8) pointed out that for a given number of cycles, the cyclic strength was at least below the static strength when the initial shear stress was not zero, but it was increased to a value over the static strength when the initial shear stress was approximately equal to half the static strength value.

2.3.4. Effect of stress ratio

Ishihara and Ansal(1982)(9) reported that the cyclic deformation tended to increase as the amplitude of cyclic stress ratio increased. Therefore, to repeat the cyclic loading test on an identical specimen, increasing the amplitude of cyclic loads stepwise is desirable.

2.3.5. Effect of confining stress

Ishihara, Nagao and Mano(1983)(10) conducted several series of cyclic triaxial shear tests on a cohesive soil to clarify the effect of confining stress. They reported that the effect of confining stress are significant and can be evaluated in terms of the More-Coulomb type failure criterion. General tendency showed that the cyclic strength somewhat increases with increase in effective confining stress.

III. Experimental Investigations

3.1 General Description of the Site

The soil samples were taken from the site near the test embankment constructed on AIT campus, Rangsit, which is approximately 42 km north of Bangkok along the paholyothin highway.

3.2 Sampling Procedure

The samples used in this investigation were taken from three boreholes at a center to center distance of 2.5 m using a power auger boring machine equipped with a 10 in. diameter and 22 in. long thin walled piston sampler advanced by hydraulic push. In order to keep the bore holes open and to prevent the occurrence of cave-in, a 12 in. inside diameter, 3.3 ft long casing was first driven to a depth of about 5.5 m. The bore holes were then cleared by the auger. The sampler was connected to a sampler head which was in turn connected to the drill rod. There are four vent holes and a ball check valve in the sampler head. The sampler was lowered into the open bore hole and pushed into the soil manually. After the sampler was hoisted and removed from the drill rod, it was sealed with wax and stored in a room where the temperature was maintained at 20±1°C in order to reduce the evaporation of moisture from the sample. The samples were obtained at the depth of 5.5 m to 6.0 m below the ground level (soft clay zone).

3.3 Testing Equipment

3.3.1. Set-up of equipment

The pneumatic cyclic triaxial apparatus was used in this investigation. The equipment com-

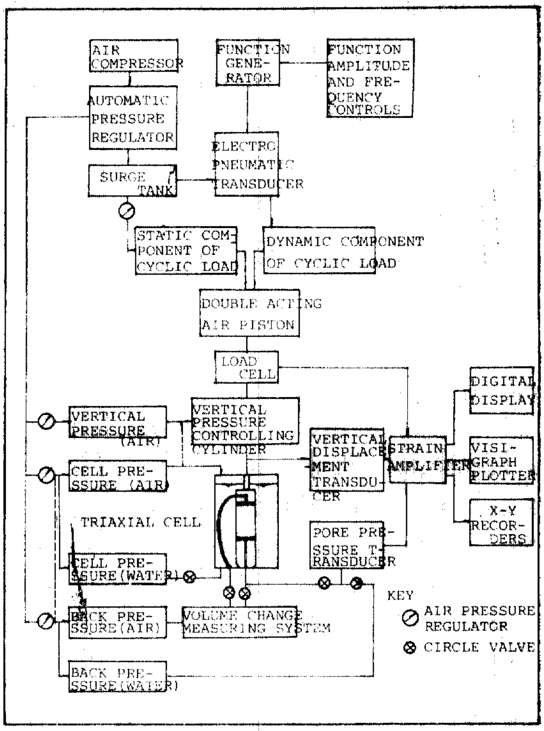

Fig. 3.1 System of Pneumatic Cyclic Triaxial Apparatus

prises two triaxial cells, which can be used for simultaneous consolidation of two specimens, and an air and water control unit, a vertical loading unit, a pneumatic sinusoidal loading unit, and a recording unit with digital display and visigraph plotter. Fig. 3.1 illustrates the system of the pneumatic cyclic triaxial apparatus. A data recorder and a $X-Y$ recorder were used to supplement the recording capacity of the equipment. To supply cell pressure, back pressure, vertical pressure and cyclic stresses, an air compressor was used. And a vacuum pump was employed to make de-aired water and to supply suction pressure to the specimens.

3.4 Isotropic Consolidation of Sample

When the degree of saturation became more than 95%, the back pressure line was connected to the burrette for volume change measurement and cell pressure and axial load were increased to a design value for the isotropic consolidation(1). During the consolidation process, the volume of the water discharged by the specimen and the axial displacement was measured. This consolidation process was continued until the minimum average degree of consolidation of 95% was reached.

3.5 Procedure of Cyclic Loading Test

3.5.1. Test series

After completion of the isotropic consolidation, the specimens were moved to the loading table, where the vertical load was applied by a belloframe cylinder placed on the loading frame. Two series of cyclic loading tests were then carried out, that is, undrained cyclic loading tests without and with initial shear stress. In the former test series, after the isotropic consolidation, the specimens were applied cyclic shear stresses under undrained conditions. In the later test series after the consolidation, the specimens were subjected to an initial shear stress under drained conditions prior to cyclic loading. From a different point of view, this test series can be considered as undrained cyclic loading tests on anisotropically consolidated specimens. After observing the completion of deformation due to the initial shear stress, the specimens were subjected to cyclic shear stresses under undrained conditions.

Table 3.1 Testing Types and Number of Samples Employed

Testing Types		Confining Stress	
		1.0 kgf/cm²	1.5 kgf/cm²
Without Initial Shear Stress		6	5
With Initial Shear Stress	0.4(SS)	7	—
	0.6(SS)	5	—

* SS means static strength

Table 3.1 shows the testing types and number of samples employed in the investigation.

3.6 Stress Controlled Cyclic Loading

Application of cyclic stresses was carried out employing a sinusoidal load of about 1 Hz with a given magnitude. During cyclic loading the cell pressure was kept constant and the back pressure line was closed. After setting the magniutde of cyclic loading and adjusting the measurement equipment, cyclic stresses applied to the specimen. In the tests without initial shear stress, the cyclic stress ratios (that is, cyclic stress/effective confining stress$=\tau_d/2\sigma_0'$), of 0.28, 0.30, 0.35, and 0.40 were applied to the specimen until 5% double amplitude of axial strain was developed. In the tests with an initial shear stress, the cyclic stress ratios, $\tau_d/2\sigma_0'$, of 0.25, 0.30, 0.35 and 0.40 were applied until the samples exhibited 5% double amplitude of axial strain.

IV. Results and Discussions

4.1 Strength Characteristics During Cyclic Loading

4.1.1. Effect of confining stress with number of loading cycles

Fig. 4.1 shows the relationship between the amplitude of cyclic stress ratio and number of cycles causing 5% double amplitude strain. As can be seen in this figure, the number of load cycles causing 5 % double amplitude strain increased with decrease in stress ratio applied to the specimens. The figure also shows the effects of an effective confining stress on the cyclic strength. The number of cycles causing 5 % double amplitude strain increases as the effective confining stress decreases for a given stress ratio.

4.1.2. Effect of initial shear stress

In order to grasp the effect of initial shear stress from the stress-strain data of two test series employing different initial shear stresses, that is, 40 % and 60% of the static strength, the relationship between cyclic stress plus initial shear stress and axial shear strain for several numbers of load cycles, i.e., $n=1, 5, 30, 50$ cycles is presented in Fig. 4.2.

Fig. 4.3 is cited to aid understanding of Fig. 4.2. After consolidation, an axial stress, τi is applied statically to the specimen under drained condition as indicated by point P in Fig. 4.3. A uniform cyclic stress, d_1 is then applied to the specimen until producing a certain amount of axial strain. From the stress-strain curve shown in Fig. 4.3(a), point A is corresponding to the axial strain for the cyclic stress d_1 in the 5th cycle. In the next test, a fresh specimen applied the same initial stress is subjected to an increased cyclic stress, d_2 as shown in Fig. 4.3.(b). Similarly to Fig. 4.3(a), point B represents the strain for the axial stress d_2 in the 5th cycle. Connecting the points A, B and C determined as above, a cyclic stress-strain curve shown in Fig. 4.3(d) is constructed for a loading employing 5 cycles of axial stress

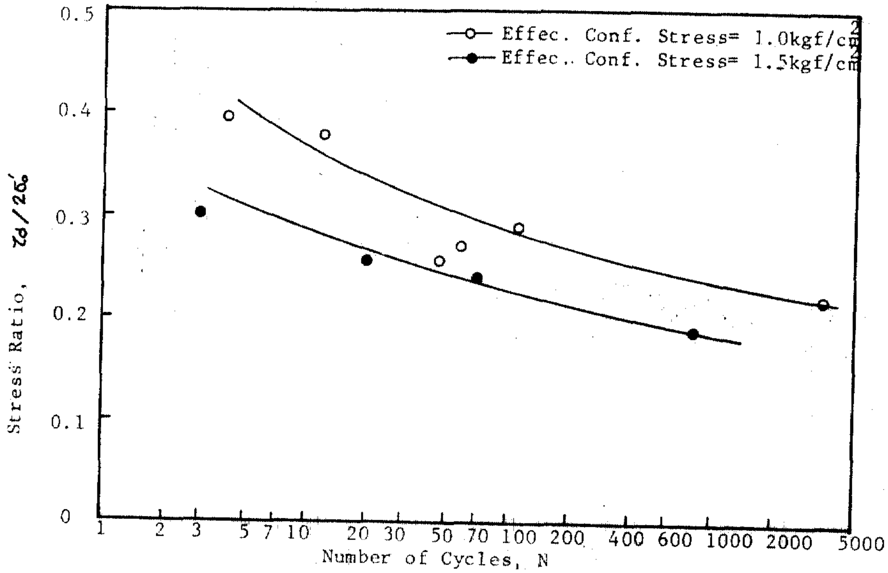

Fig. 4.1 Relationship Between Stress Ratio and Number of Load Cycles Causing 5 % Double Amplitude Strain

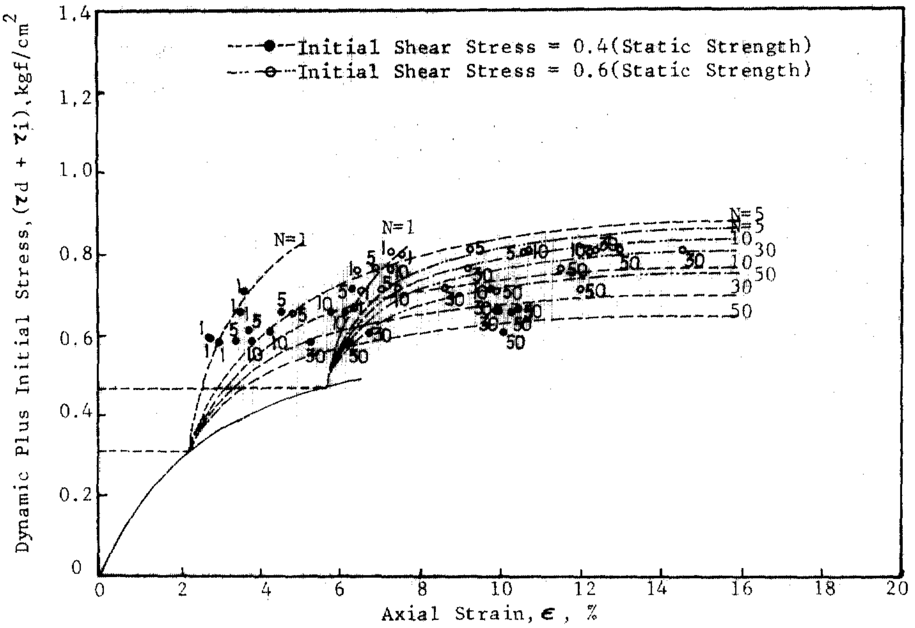

Fig. 4.2 Effects of the Initial Shear Stress on the Shear Stress Versus Shear Strain Curves

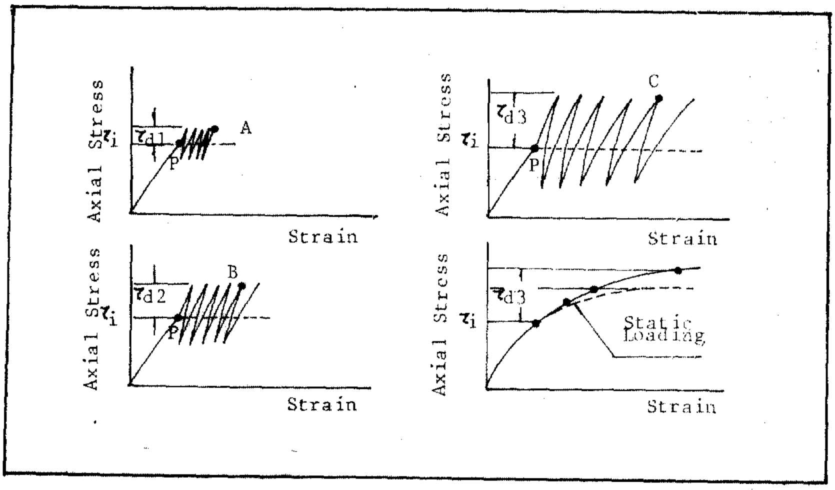

Fig. 4.3 Construction of a Axial Stress Versus Strain Curve from Cyclic Loading Test Results.

application. In a similar manner, cyclic stress-strain curves for loadings employing different number of cycles can also be obtained.

There are good reasons to infer that the stress-strain curves tend to flatten as the number of loading cycles increase. Ishihara, K. (1981)⁽⁸⁾ indicated that the test with one cycle of loading is equivalent in the effect to the test in which a rapid monotonic load is applied to the sample. Therefore, the stress-strain curve is the steepest for the test with one cycle of loading as shown in Fig. 4.2. The set of summary curves in Fig. 4.2. shows that the stress-strain curve tends to flatten to some extent, as the initial shear stress is increased from 40 % to 60 % of the static strength value. This results is in good agreement with the finding of Ishihara, Nagao and Mano(1983)(10).

4.2 Strength under Combined Static and Cyclic Loading Conditions

To grasp the strength characteristics of soil under the combined static and cyclic loading conditions, Fig. 4.4 was obtained from the stress-strain curves shown in Fig. 4.2. In this figure, the cyclic strength defined as the static plus cyclic axial stress causing failure in a test specimen divided by the corresponding static strength(14) was plotted against the initial shear stress divided by the static strength of the specimens. Fig. 4.4 revealed that the cyclic strength deterioration begins to show up as the number of cycles is increased and the strength of the soils is decreased as compared with the static strength. It was also pointed out in the preceding sections that the strength deterioration progressed in cohesive soil as the number of loading cycles increased. It is to be noted that in Fig. 4.4 the cyclic strength is smaller

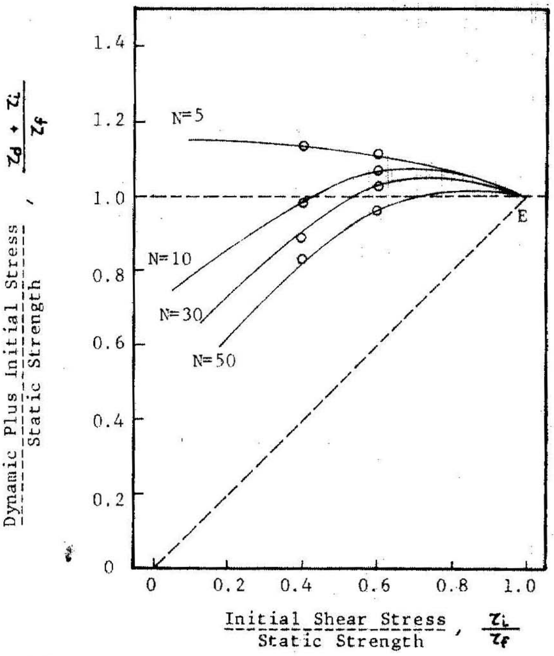

Fig. 4.4 Cyclic Strength Ratio Plotted Versus Initial Shear Stress Ratio

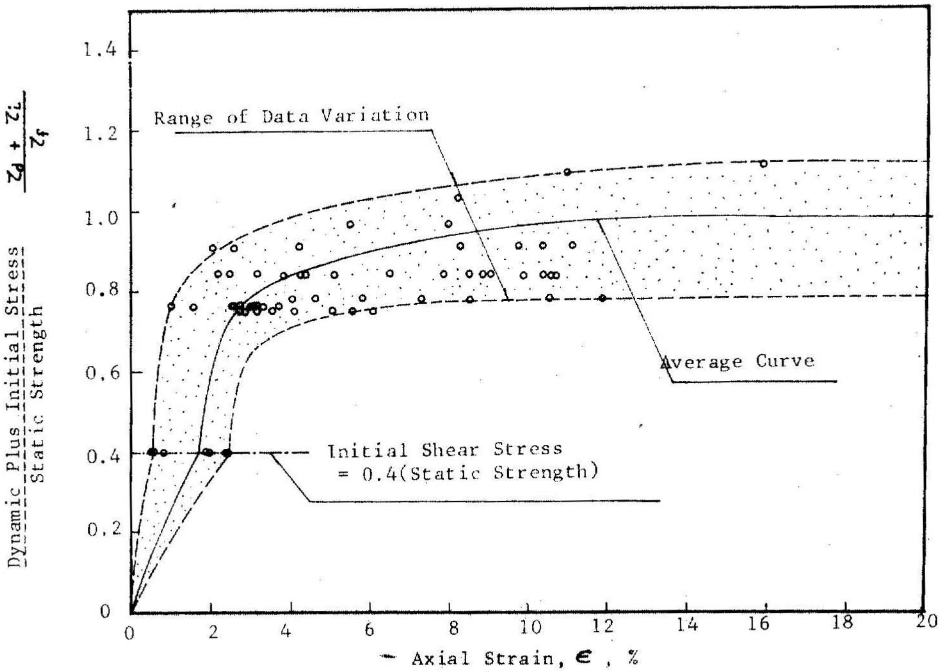

Fig. 4.5 The Variation of Cyclic Strength Ratio Versus Shear Strain

than the static strength when the initial shear stress is zero, but it increased to a value over the static strength when the initial shear stress is approximately equal to half of the static strength value. Ishihara and Yasuda(1980)(11) offered a logical interpretation to the observed test results shown in Fig. 4.4. When the initial shear stress is more than half of the static strength, there may be a few chance for the specimen to be subjected to a high degree of stress reversal. The deteriorating effect is, therefore, outweighed by the rate effect, hence the cyclic loading is in a fully reversing condition with a zero value of initial shear stress, the deteriorating effect becomes greater than the static strength. On the contrary, when the cyclic loading is in a fully reversing condition with a zero value of initial shear stress, the deteriorating effect becomes predominant and a remarkable reduction in cyclic strength is observed. The results of each test series with initial shear stress 40 % and 60 % of the static strength are plotted in Figs. 4.5 and 4.6 respectively. Then a reasonable average curve was drawn using the entire set of test data to establish a axial stress-strain relationship. Although there exist some scatters depending upon the cyclic stress ratio level and the elapsed time, all data points for the case of the initial shear stress of 60 % of the static strength fall in a relatively narrow zone enclosed by dashed lines.

4.3 Stress-Strain Behavior with Number of Loading Cycles

From the stress-strain data of cyclic loading test with and without initial shear stress Fig. 4.7 was plotted to grasp the relationship between the axial shear strain and the number of loading cycles for several stress ratios. As can be seen in Fig. 4.7, the increase in the double amplitude shear strain for log cycle of the number of loading cycles is found to be almost constant at low cyclic deviator stress level, $\tau_d/2\sigma_0'=0.161$, while the increasing rate of the double amplitude shear strain becomes higher

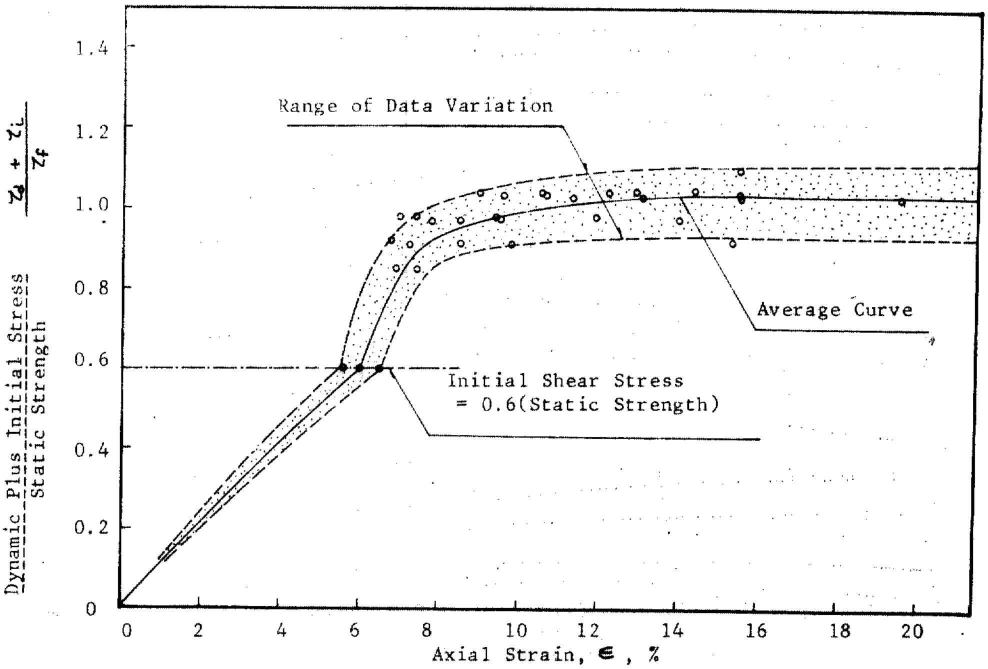

Fig. 4.6 The Variation of Cyclic Strength Ratio Versus Shear Strain

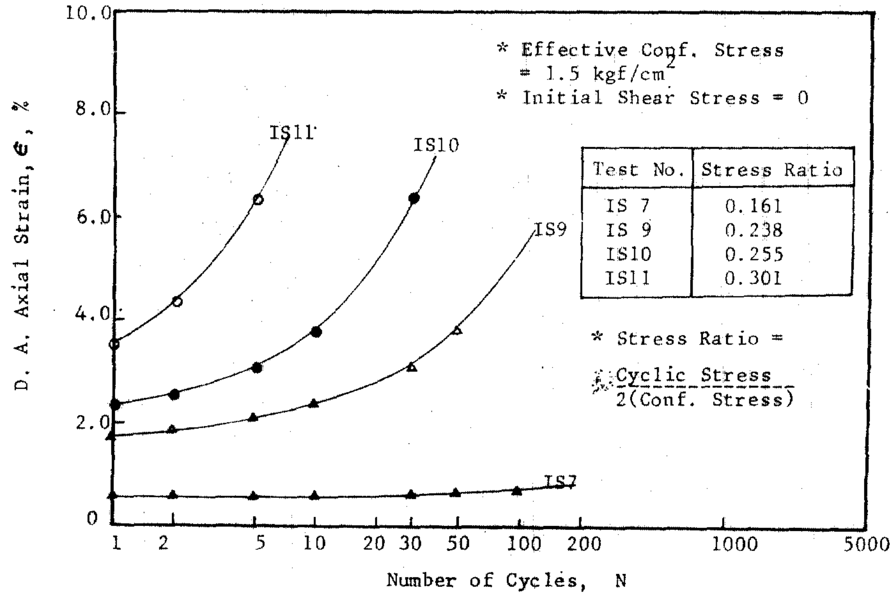

Fig. 4.7 The Variation of Shear Strain with Number of Load Cycles

at higher cyclic deviator stress ratio levels. These findings reveal that there is a critical cyclic deviator stress level below which no failure equilibrium state will be reached when the specimen is subjected to successive cyclic loading. If the cyclic deviator loading above this critical stress ratio level is applied, the double amplitude shear strain increases progressively with the number of load cycles as shown in Fig. 4.7(4). The samples showed an exponentially increasing double amplitude shear strain towards failure under the higher cyclic deviator stress levels($\tau_d/2\sigma_0' > 0.161$). This behavior is in good agreement with the finding of Brown, Lashine and Hyde(1975)(2).

V. Conclusions

A series of cyclic triaxial tests were conducted on the undisturbed samples to investigate the cyclic strength and deformation characteristics of soft Rangsit clay. From the test results the following conclusions are obtained;

(1) In the case of cyclic loading tests without initial shear stress, the cyclic strength expressed by the stress ratio causing 5% double amplitude axial strain was decreased with increase in the number of cycles.

(2) The cyclic strength expressed by the stress ratio was greater in the tests with 1.0 kgf/cm^2 confining stress than in the tests with 1.5 kgf/cm^2 confining stress. While, the cyclic strength expressed by the deviator stress was higher in the tests with 1.5 kgf/cm^2 confining stress than in the tests with 1.0 kgf/cm^2 confining stress. This result is in good agreement with the finding of Koutsoftas(1978)(13).

(3) Considering the relationship between the axial strain and the number of loading cycles for various stress levels, it was revealed that the cyclic strength curves were changed sensitively for higher cyclic stress ratios. When the cyclic stress ratio was smaller than the critical stress ratio, specimens did not cause failure in spite of a large numbers of loading cycles employed.

(4) The ratio of initial shear stress plus dynamic stress to failure strength required to cause failure decreased as the number of loading cycles increased.

(5) When the initial shear stress was increased from 40 % to 60 % of the static strength value, the stress-strain curve is flattened to some extent. This result is consistent with the finding of Ishihara, et al. (1983)(10).

(6) When the strength under combined static and cyclic loading conditions is considered, it was revealed that the effect of the cyclic strength deterioration began to show up as the number of cycles increased, and the strength of the soil decreased as compared with the static strength.

(7) The average stress-strain curve drawn for the entire set of data both for static and dynamic portions of the axial stress-strain curves showed a steeper rise during initial phase of cyclic loading, then eventually converged to a horizontal line corresponding to a dynamic strength value.

VI. References

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