Behavior of Strength and Pore Pressure of Soft Bangkok Clay under Cyclic Loading

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Abstract

The objectives of this research are to study the behavior of cyclic strength and pore pressure characteristics of soft Bangkok clay which were investigated by using the cyclic triaxial apparatus under stress controlled and undrained conditions. The undisturbed samples were collected at the depth of 7.50-8.00 meter at the Faculty of Engineering, Thammasat University. From the physical property test results, it shows that subsoil is silty-clay with 78-95 % of natural water content, LL in the range 75-99 %, PL in the range of 30-42 % and specific gravity in the range of 2.57-2.73. A series of cyclic triaxial tests were conducted on the undisturbed samples to investigate the cyclic strength and deformation characteristics of soft Bangkok clay. From the test results the axial strain and the excess pore water pressure both increase with increasing the number of loading cycles in all cases. But the shear modulus decreases with increasing the number of loading cycles. On the other hand, the damping ratio decreases slightly with increasing the number of loading cycles. The effect of rate of loading on the cyclic properties was also investigated. The loading frequencies adopted for the test were 0.1, 0.5 and 1.0 Hz, respectively. It was found that the cyclic strength increased with increasing of loading frequencies for a given confining stress but excess pore water pressure decreased with increasing of loading frequencies. It was found that effect of loading frequencies on shear modulus was minor. However, when the loading frequencies increase the damping ratio decreases.

Keywords: Cyclic strength, Pore pressure, Soft Bangkok clay and Cyclic Triaxial Test

1. Introduction

At present, traffic congestion has become a way of life in Bangkok because of the growing economy, industry and community. Therefore, it is essential to have roads constructed on this area which originated from the sedimentation at the delta of the Chao Phraya River. Soft Bangkok clay is well know worldwide in the geotechnical field for its high compressibility and low strength. The problem that has been found after construction and during the working period of a road embankment is the very high settlement rate, which shortens the design life of roads. There is much research that suggests that settlement of the road embankment due to traffic loading is greater than those from static loading, i.e. load from the embankment itself [1, 2]. It is necessary to study the behavior of strength and deformation of soft Bangkok clay under cyclic loading.

To study the behavior of cyclic deformation caused by the traffic load a simple test is suitable. The previous results did not agree with the real condition. The test should be more complex such as a cyclic triaxial test, which can simulate the field conditions and permits excess pore pressure measurement so its results can be accepted more than results from other tests. Therefore this study used the cyclic triaxial apparatus to study the dynamic properties such as cyclic shear strength and pore pressure during cyclic loading of Bangkok clay at Thammasat University Rangsit Campus under stress controlled and undrained condition. A series of cyclic triaxial tests were performed on specimens with various initial stress, loading frequencies and stress ratio.

2. Materials

Samples used in the tests are soft Bangkok clay and were collected at a depth of 7.50-8.00 m at the Faculty of Engineering, Thammasat University. The physical property test results show that the subsoil is silty-clay with 78-95 % of natural water content, LL in the range 75-99%, PL in the range of 30-42 % as shown in Fig.1. The specific gravity of the soil is particled is in the range of 2.57-2.73. Fig.2 shows the soil is composed of 5-20 % of sand, 10-40 % silt, and 50-70 % clay.

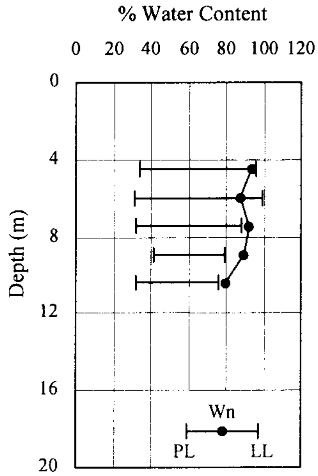

Fig. 1 %PL, %Wn and %LL with depth

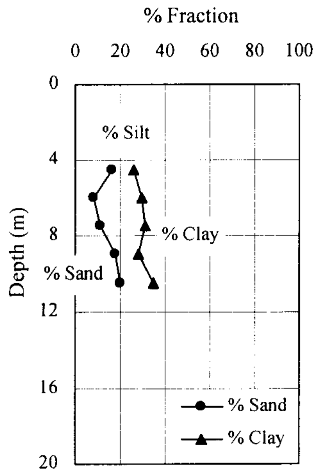

Fig. 2 %sand, %silt and %clay with depth

3. Test Equipment and Procedures

The loading of specimens was carried out using a cyclic triaxial test apparatus. Layout of the system and the special triaxial cell are shown in Figs. 3(a) and 3(b), respectively. The axial load and cell pressure are independently controlled, and both cyclic and static loading tests can be carried out by this apparatus. The axial load, the excess pore water pressure and the axial displacement of specimens are measured by means of a load cell and a linear variable displacement transducer, respectively.

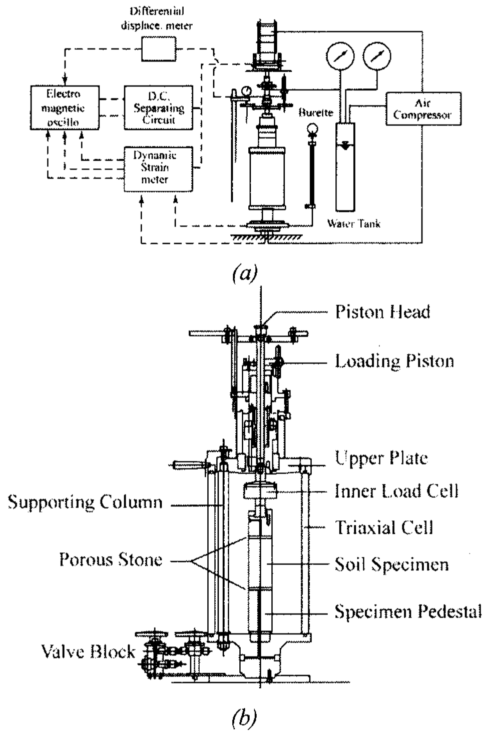

Fig. 3 The cyclic triaxail test apparatus for cyclic loading test. *(a)* Layout of the cyclic triaxial test apparatus. *(b)* Triaxial cell.

An undisturbed specimen about 50 mm in diameter and 100 mm in height was thawed and set between the upper and lower pistons. The specimens were consolidated by isotropic stress for 24 hrs under several effective confining stress. After the completion of consolidation, a back pressure of 2.0 kgf/cm^2 was applied to the sample. The measured B values of the coefficient of pore water pressure were over 0.97 before cyclic loading.

The specimens in an undrained condition were subjected to cyclic loading under a constant mean total principal stress by varying the frequencies at 0.1 Hz, 0.5 Hz and 1.0 Hz and cyclic shear stress ratio at 0.20, 0.25, 0.30, 0.35 and 0.40, as shown in Table 1. Some tests were done with initial shear stress at 40% and 60% of static strength before applying the cyclic loading. Moreover, confining stresses of 0.5 kgf/cm^2 and 1.0 kgf/cm^2 were used in this study in order to make sure that the samples were in normally consolidated condition (σ'_{vo} = 0.48 ksc).

Table 1 Test Conditions and Specimen Descriptions

Test No	σ_c [a] (kgf/cm^2)	σ_s [b] (kgf/cm^2)	f [c] (Hz)	$\sigma_d / 2\sigma'_{vo}$ [d]
CYC 1-1	0.5	-	0.1	0.20
CYC 1-2	"	-	"	0.25
CYC 1-3	"	-	"	0.30
CYC 1-4	"	-	"	0.35
CYC 1-5	"	-	"	0.40
CYC 2-1	1.0	-	0.1	0.20
CYC 2-2	"	-	"	0.25
CYC 2-3	"	-	"	0.30
CYC 2-4	"	-	"	0.35
CYC 2-5	"	-	"	0.40
CYC 3-1	0.5	0.4 (SS [e])	0.1	0.20
CYC 3-2	"	"	"	0.25
CYC 3-3	"	"	"	0.30
CYC 3-4	"	"	"	0.35
CYC 3-5	"	"	"	0.40
CYC 4-1	0.5	0.6 (SS)	0.1	0.20
CYC 4-2	"	"	"	0.25
CYC 4-3	"	"	"	0.30
CYC 4-4	"	"	"	0.35
CYC 4-5	"	"	"	0.40
CYC 5-1	0.5	-	0.5	0.20
CYC 5-2	"	-	"	0.25
CYC 5-3	"	-	"	0.30
CYC 5-4	"	-	"	0.35
CYC 5-5	"	-	"	0.40
CYC 5-1	0.5	-	1.0	0.20
CYC 5-2	"	-	"	0.25
CYC 5-3	"	-	"	0.30
CYC 5-4	"	-	"	0.35
CYC 5-5	"	-	"	0.40

[a] σ_c = Confining Stress

[b] σ_s = Initial Shear Stress

[c] f = Loading Frequency

[d] $\sigma_d / 2\sigma'_{vo}$ = Cyclic Shear Stress Ratio

σ_d = Axial Deviator Stress

σ'_{vo} = Effective Overburden Stress

[e] SS = Static Strength

4. Results and Discussion

4.1 Strength Characteristics During Cyclic Loading

The axial strain and excess pore water pressure responses with loading cycles are shown in Fig.4. It can also be seen that the axial strain increased monotonically with the number of loading cycles, since when a soil is subjected to cyclic loading, a total strain will occur during loading, and a resilient strain will occur during unloading. As a result, a certain amount of plastic residual strain will remain and accumulate almost constantly with number of loading cycles and increase until the specimen fails. At the same time, the excess pore water pressures increase with increasing number of loading cycles until they become equal to the total confining stress under very restrictive stress state.

More and more case histories describing dynamic loading induced failures of soil specimens have been studied and reported [3, 4]. These studies invariably show that excessive dynamic deformation developed in soil specimens is closely related to pore water pressure buildup and corresponding loss of soil strength.

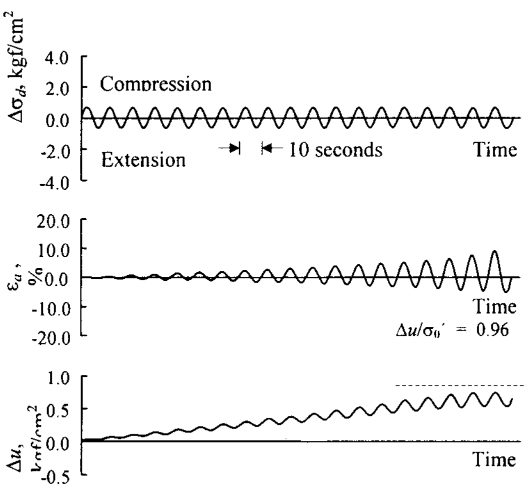

Fig. 4 Typical record of cyclic triaxial test

4.1.1 Effect of Confining Stress with Number of Loading Cycles

Specimens were isotropically consolidated under a confining stress of 0.5 kgf/cm^2 and 1 kgf/cm^2 and were subjected to cyclic loading with loading frequency of 0.1 Hz. Fig. 5 shows the relation between the number of cycles causing 5% double amplitude strain and amplitude of cyclic stress ratio. It is seen in this figure that the number of loading cycles causing 5% double amplitude strain increased with increase in effective confining stress for a given stress ratio.

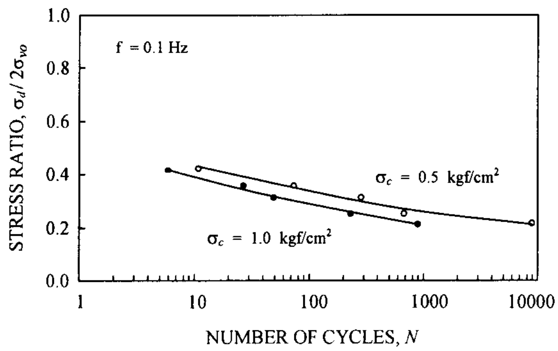

Fig. 5 Relationship between stress ratio and number of load cycles causing 5% double amplitude strain for different confining stress.

4.1.2 Effect of Initial Shear Stress

Specimens, isotropically consolidated at a confining stress of 0.5 kgf/cm^2, were subjected to an initial static axial stress about 40% (CYC 3-3) and 60% (CYC 4-3) of static strength under undrained conditions and then to sequences of cyclic axial stress with stress ratio about 0.30 until the specimen failure. Fig. 6 shows the relation between the number of cycles, N, and the double amplitude axial strain, DA, with the initial shear stress as a variable parameter. It is seen in this figure that the cyclic strength decreased generally as the number of cycles increased. The test results in Fig. 6 also show that the cyclic strength increased substantially as the initial static stress was increased. This is because the clay when subjected to initial static shear stress, such as embankment load, is unstable during cyclic loading [5].

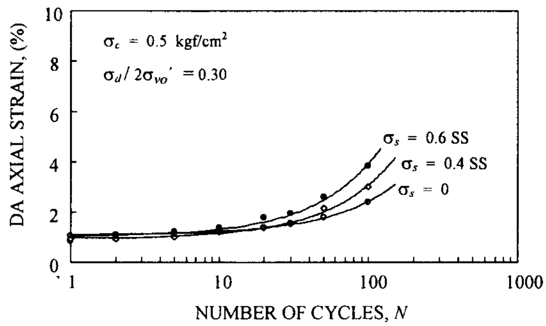

Fig. 6 Relationship between double amplitude strain and number of load cycles for different initial shear stress.

4.1.3 Effect of Loading Frequency on Cyclic Strength

The characteristics of the test results for various loading frequencies of 0.1 Hz (CYC 1-3), 0.5 Hz (CYC 5-3) and 1.0 Hz (CYC6-3) are presented in Fig. 7 in which the logarithm of number of loading cycles is plotted versus the double amplitude axial strain under isotropic consolidated confining stress 0.5 kgf/cm^2 conditions. This figures shows the effect of loading frequency on the cyclic strength, by the number of loading cycles causing 5% double amplitude strain of cyclic strength increased with increase in loading frequency for a given stress ratio. This behavior is in good agreement with [6-8] that a general trend showed that the slow loading tests require longer time to cause failure than the rapid loading test.

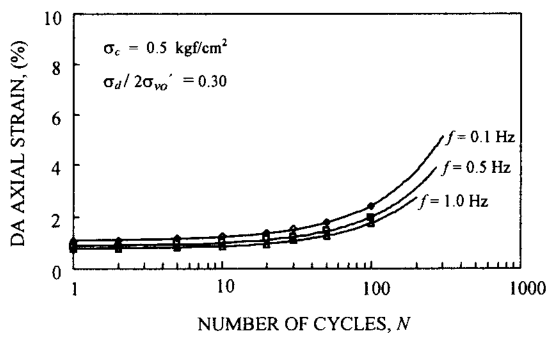

Fig. 7 Relationship between double amplitude strain and number of load cycles for different loading frequency.

4.2 Excess Pore Water Pressure Behavior During Cyclic Loading

Because of saturated clayed subjected to a cyclic loading, excess pore water pressure increased as the number of loading cycles increased. Consequently the shear resistance decreased, at least until the excess pore water pressure dissipated. Thus, it is necessary to clarify the behavior of excess pore water pressure of saturated clays when subjected to a cyclic loading under several number of loading cycles, confining stress and loading frequency. In this study, the excess pore water pressure was measured by pore pressure transducer at the bottom of the sample.

4.2.1 Effect of Number of Loading Cycles on Excess Pore Water Pressure

Fig. 8 show the relation in the excess pore water pressure with the logarithm of number of load cycles in each series of cyclic loading test. It can be seen that the excess pore water pressure increases with increase in the number of loading cycles. Higher excess pore water pressure was generated at higher normalized stress ratio. This tendency is similar to that recognized in the axial strain versus number of cycle's relationship. As can be seen in this figure, the pore water pressure exhibits only a very slight increase for a lower cyclic stress ratio, while the excess pore water pressure increased steeply at higher cyclic stress ratio.

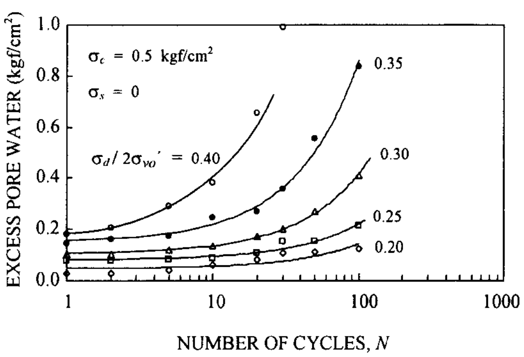

Fig. 8 The variation of excess pore water pressure with number of load cycles for different cyclic stress ratio.

4.2.2 Effect of Confining Stress on Excess Pore Water Pressure

Specimens, isotropically consolidated under confining stress of 0.5 kgf/cm^2 and 1.0 kgf/cm^2, were subjected to cyclic loadings with a frequency of 0.1 Hz and a cyclic shear stress ratio about 0.30. Fig. 9 shows the relation in the excess pore water pressure with the logarithm of number of load cycles in each series of cyclic loading test. It is seen in this figure that for a given cyclic shear stress ratio, the relation in the excess pore water pressure during cyclic loadings shows nearly similar tendency for the different effective confining pressure. The results obtained are in good agreement with the finding of [9].

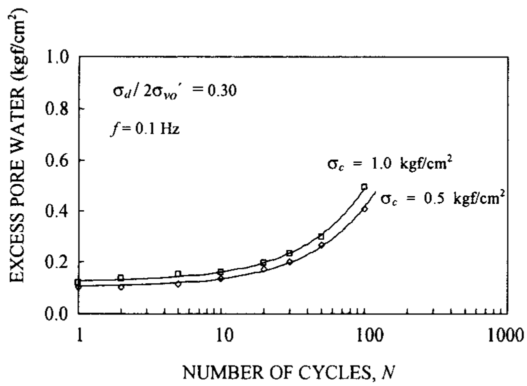

Fig. 9 Effect of confining stress on excess pore water pressure

4.2.3 Effect of Loading Frequency on Excess Pore Water Pressure

Fig. 10 shows the results of cyclic triaxial test by using loading frequencies 0.1 Hz (CYC 1-3), 0.5 Hz (CYC 5-3) and 1.0 Hz (CYC 6-3) under isotropic consolidated confining stress 0.5 kgf/cm^2. It can be seen in Fig. 10 that the excess pore water pressure increasing with increasing number of loading cycles but the excess pore water pressure decreased with increasing loading frequency. For a given number of cycles, higher excess pore pressure and axial strains are generated at lower frequencies. Thus the loading frequency dependencies on both the excess pore pressure and the axial strain are similar. This implies that they are interrelated with each other [9].

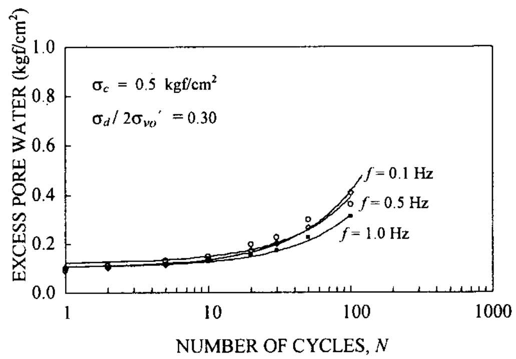

Fig. 10 Effect of loading frequency on excess pore water pressure

4.3 Cyclic Stress-Strain Properties

It is generally known [10-13] that the deformation properties or cyclic stress-strain properties are expressed by shear modulus and damping ratio. The results of our investigation, are shown in Fig. 4. The shape of the stress-strain curve can be adequately represented by a hyperbolic curve. The shear modulus can be defined as amplitudes of cyclic deviator stress and cyclic axial strain, and the damping ratio is defined from a hysteresis loop of the relationship between deviator stress and axial strain. The results of these studies in cyclic stress-strain properties are shown hereafter.

4.3.1 Effect of Number of Loading Cycles on Shear Modulus and Damping Ratio

The shear modulus and the damping ratio at any strain measured from the cyclic triaxial test is plotted in Fig. 11 and 12, respectively. These figures are the results at the confining stress of 0.5 kgf/cm^2 and subjected to cyclic loadings with a frequency 0.1 Hz. In these figure, the shear modulus decreases with increasing number of loading cycles, in contrast, the damping ratio increases with increasing number of loading cycles. Because when the specimen was subjected to cyclic loading, the deterioration of bonding between soil particle and accumulation of strain, damping energy increases. Therefore, the shear modulus decreases and the damping ratio increases with increasing number of cycles. The results confirm the general findings of [3, 4, 5, 8]. All of the results show that damping ratio decreased approximately linearly with the logarithm of the number of loading cycles and shear modulus also decrease with increasing number of load cycles.

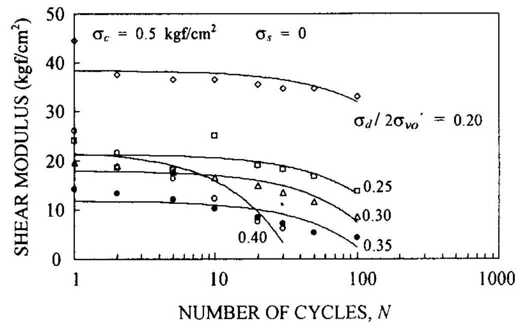

Fig. 11 Relationship between shear modulus and number of loading cycles for different cyclic stress ratio

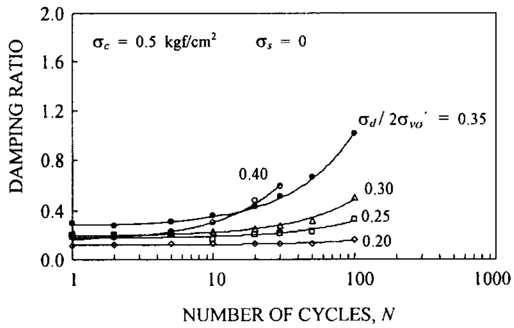

Fig. 12 Relationship between damping ratio and number of loading cycles for different cyclic stress ratio

4.3.2 Effect of Confining Stress on Shear Modulus and Damping Ratio

The specimens, isotropically consolidated under confining stress of 0.5 kgf/cm^2 and 1.0 kgf/cm^2, were subjected to cyclic loading with a frequency of 0.1 Hz. Fig. 13 shows the relation between the double amplitude axial strain on the logarithmic scale and the shear modulus during cyclic loading. It is seen in this figure that shear modulus corresponding to each effective confining stress increases as the effective confining stress becomes higher. This behavior is in good agreement with the findings of [2, 3, 4, 8] and suggest that the dynamic shear modulus increases with increasing confining pressure. Their relationship can be plotted as a straight line on a log-log scale at all levels of treatment and strain amplitude. The relationship between the double amplitude axial strain on the logarithmic scale and the damping ratio are presented in Fig. 14. It can also be seen that the damping ratio decreases with increasing double amplitude axial strain.

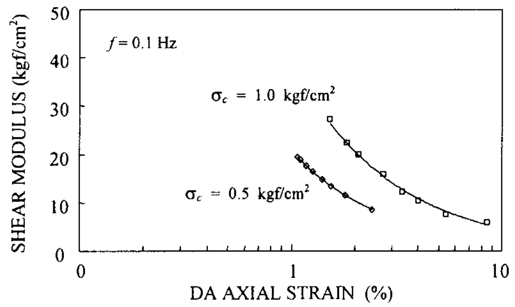

Fig. 13 Relationship between shear modulus and double amplitude axial strain under different confining stresses

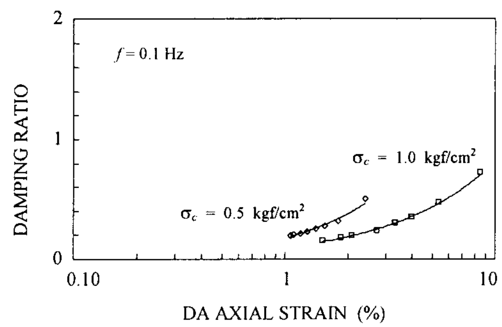

Fig. 14 Relationship between damping ratio and double amplitude axial strain under different confining stresses

4.3.3 Effect of Loading Frequency on Shear Modulus and Damping Ratio

Figs. 15 and 16 show relationships between the shear modulus and the damping ration with DA axial strain due to subjected loading frequencies 0.1 Hz (CYC 1-3), 0.5 Hz (CYC 5-3), and 1.0 Hz (CYC 6-3). It can also be seen in Fig. 15 that at given loading frequency, shear modulus increases with decreasing axial strain, and when given axial strain, the shear modulus decreases with increasing loading frequency. However, the results presented in Fig. 16 show that at given loading frequency, the damping ratio increases with increasing axial strain, and again when given axial strain, the damping ratio increases with increasing loading frequency. When loading frequency increases, the axial strain decreases, damping energies decrease together, or damping ratios increase. The results confirm the general findings by others [2, 3, 4] for undisturbed cohesive soil.

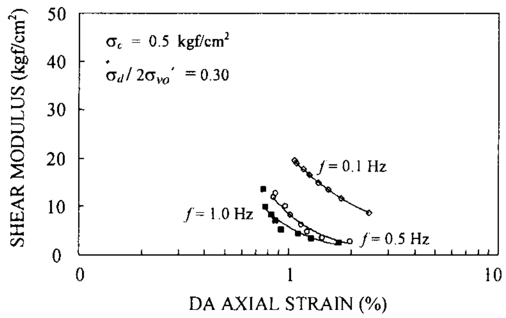

Fig. 15 Relationship between shear modulus and double amplitude axial strain under different loading frequencies

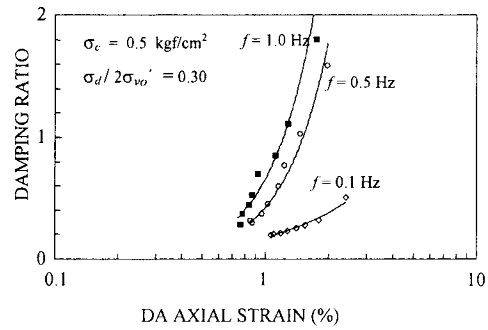

Fig. 16 Relationship between damping ratio and double amplitude axial strain under different loading frequencies

5. Conclusion

From the results of cyclic triaxial tests to investigate the cyclic strength and pore pressure characteristics of soft Bangkok clay, the following conclusions may be drawn:

1. The axial strain and the excess pore water pressure both increase with increasing number of loading cycles in all cases.

2. The cyclic strength tended to increase as the amplitude of cyclic stress ratio increased.

3. The cyclic strength (number of cycles causing 5% double amplitude strain) increases with increase in effective confining stress for a given stress ratio. For a given cyclic shear stress ratio, the variation in the excess pore water pressure during cyclic loadings shows nearly similar tendency for the different effective confining pressure.

4. The cyclic strength increased with increasing of loading frequencies for a given confining stress but excess pore water pressure decreased with increasing of loading frequencies.

5. The shear modulus decreases with increasing number of loading cycles. On the other hand, the damping ratio increases with increasing the number of loading cycles.

6. The shear modulus decreases with increasing stress ratio, which is attributed to the apparent characteristics of the stress-strain curve. The damping ratio increases with increasing stress ratio.

7. The shear modulus corresponding to each effective confining stress increases slightly as the effect confining stress becomes higher. The damping ratio decreases as confining stress increases.

8. The shear modulus decreases with increasing loading frequency. Moreover, when the loading frequency increases the damping ratio increases.

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7. References

[1] Casagrade, A. and Wilson, S.D., Effect of Rate of Loading on the Strength of Clay and Shales at Constant Water Content, Geotechnique, Vol. 2, pp.251-263, 1951.

[2] Hardin, B.O. and Black, W.L., Vibration Modulus of Normally Consolidated Clay, Proc. ASCE, Vol. 94, SM.2, pp. 353-369, 1968.

[3] Hardin, B.O. and Drnevich, V.P., Shear Modulus and Damping in Soils; Design Equations and Curves, Proc. ASCE, Vol. 98, SM7, pp. 667-692, 1972.

[4] Hardin, B.O. and Drnevich, V.P., Shear Modulus and Damping in Soils; Measurements and Parameter Effects, Proc. ASCE, Vol.98, SM6, pp.603-624, 1972.

[5] Humphries, W.K. and Wahls, H.E., Stress History Effects on Dynamic Modulus of Clay, Proc. ASCE, Vol. 94, SM.2, pp. 371-389, 1968.

[6] Ishihara, K. and Yasuda, S., Cyclic Strength of Undisturbed Cohesive Soils of Western Tokyo, Int. Sym. On Soils under Cyclic and Transient Loading, Swansea, pp. 57-66, 1980.

[7] Kawakami, F., Properties of Compacted Soils under Transient Loads, Soil and Foundation, Vol. 1, No. 2, pp. 23-29, 1960.

[8] Kokusho, T., Yoshida, Y. and Esashi, Y., Dynamic Properties of Soft Clay for Wide Strain Range, Soils and Foundations, Vol.22, No.4, Dec. 1982, pp. 1-18, 1982.

[9] Lee, K.L., Cyclic Strength of a Sensitive Clay of Eastern Canada, Canadian Geotechnical Journal, Vol. 16, No. 1, pp. 163-176, 1979.

[10] Matsui, T., Ohara, H. and Ito, T., Cyclic Stress-Strain History and Shear Characteristics of Clay, Journal of the Geotechnical Engineering Division, ASCE, Vol. 106, No. GT10, pp. 1101-1120,1980.

[11] Sakai, A., Samang, L. and Miura, N., Partially-Drained Cyclic Behavior and Its Application to The Settlement of a Low Embankment Road on Silty Clay, Soils and Foundations, Vol. 43, No.1, pp. 33-46, 2003.

[12] Whitman, R.V., The Behavior of Soils under Transient Loading, Proc. 4th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 207-210, 1957.

[13] Yasuhara, K., Consolidation and Settlement under Cyclic Loading, Proc. of the International Symposium on Compression and Consolidation of Clayey Soils, Hiroshima, Japan, pp. 979-1001, 1995.