12 Mar 1991, 10:30 am - 12:00 pm

Degradation of Saturated Clays after Cyclic Loading

Tamotsu Matsui
Osaka University, Osaka, Japan

Mohamed A. Bahr
Osaka University, Osaka, Japan

Nobuharu Abe
Osaka University, Osaka, Japan

Proceedings: Second International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, March 11-15, 1991, St. Louis, Missouri, Paper No. 1.18

Degradation of Saturated Clays after Cyclic Loading

Tamotsu Matsui
Professor of Civil Engineering, Osaka University, Osaka, Japan

Nobuharu Abe
Associate Professor of Civil Engineering, Osaka University, Osaka, Japan

Mohamed A. Bahr
Doctoral Researcher of Civil Engineering, Osaka University, Osaka, Japan
[Formerly, Assistant Lecturer of Civil Engineering, Al-Azhar University, Cairo, Egypt]

SYNOPSIS This paper presents a part from a series of tests performed to evaluate the static shear behavior of normally consolidated and over-consolidated clays after cyclic loading effect. The results demonstrated that the static undrained stress-strain behavior of these types of clays was affected by their relative stiffness. Based on the equivalent over-consolidation hypothesis and the experimental results it was able to construct the shear characteristics degradation relationships for the normally consolidated clays. The predicted results were compared with the measured test data and their well agreement was confirmed.

INTRODUCTION

The cyclic loading usually generates an excess pore pressure in saturated clayey ground. As consequence, the shear characteristics degradation of clays occurs, being followed by the effective stress reduction. Summary of the previous studies involves a variety of clays and different modes of shearing reported by some investigators such as Thiers and Seed (1968), Castro and Christian (1976), Andersen (1976,1988), Matsui et al (1977,1980), Matsui and Abe (1981), Koutsoftas (1978) , Yasuhara (1982,1985) , Hicher and Lade (1987), Vucetic and Dorbry (1988), and Azzouz et al (1989), showing that undrained cyclic shearing of normally consolidated clays causes an equivalent over-consolidation in their subsequent response to undrained monotonic shearing.

In this paper, first the static undrained stress-strain behavior of both normally consolidated (NC) and over-consolidated (OC) remolded and natural undisturbed clays after cyclic loading effect is investigated. Secondly, the cyclic stress-strain history and the equivalent over-consolidation hypothesis are mentioned and the equivalent over-consolidation hypothesis is established. Thirdly, based on the experimental results and the equivalent over-consolidation hypothesis, the relations for estimating the shear characteristics degradation by cyclic loads are proposed for the NC remolded and undisturbed clay specimens. Finally, the predicted shear characteristics degradation relationships are analyzed and compared with the test data points, and its reliabilities are discussed.

PROPERTIES OF TESTED CLAYS

The clay used for NC and OC remolded clay specimens is a commercial clay known by Crown clay. The natural NC undisturbed clay specimens are obtained from thin-walled tube samples of alluvial marine Osaka clay deposit known by Ma13, while the natural slightly OC undisturbed specimens are obtained from two saturated block samples of diluvial marine Osaka clay deposit known by Ma12. The physical properties of the tested clays are summarized in Table 1. From the characteristics of the natural clay layers, the alluvial Ma13 clay is classified as inorganic medium to soft silty clay, and the diluvial Ma12 clay is classified as inorganic silty clay with over-consolidation ratio of 1.3. Both Ma13 and Ma12 clays showed consistency limits plotting over the A-Line of the plasticity chart.

Table 1 Physical Properties of Tested Clays

Test Items		Tested Clays		
		Crown	Ma13	Ma12
Specific Gravity		2.70	2.67	2.75
Clay (<2μm)	(%)	60.0	57.9	48.0
Liquid Limit	(%)	99.8	72.5	94.1
Plastic Limit	(%)	43.3	27.9	25.5
Plasticity Index		56.5	44.6	68.6

EXPERIMENTAL PROCEDURE

Test Equipment

The apparatus used is a servo controlled electro-hydraulic triaxial apparatus. Both cyclic and static loading tests can be carried out, independently controlling the axial load and cell pressure. Out lines of the system and a special triaxial cell are shown in Figs.1 and 2, respectively. The top of the cell is always fixed by three supports inside the cell, of which the cylindrical side wall can move up and down. The construction of the whole cell is performed by fixing the bottom of its side wall with one-touch joint ring. A specimen having a 50 mm diameter and a variety of height up to

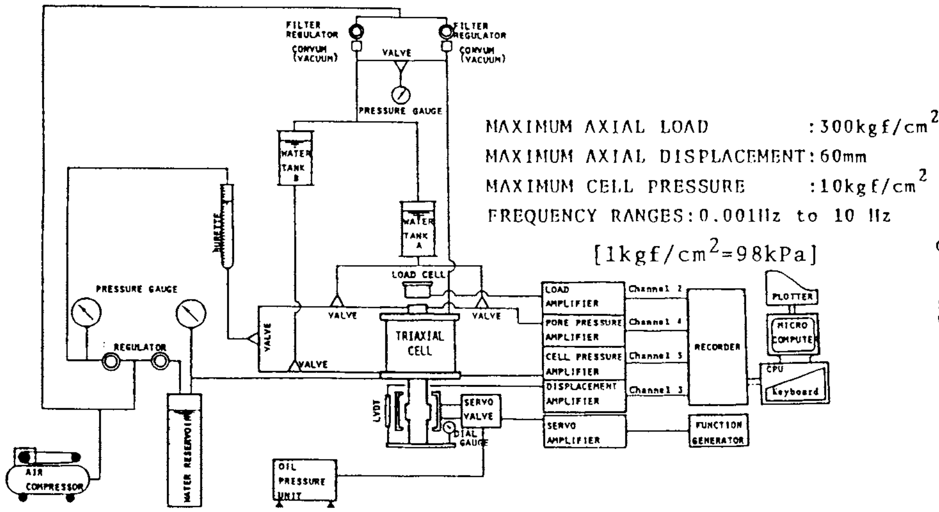

Fig.1 System of Servo Controlled Electro-Hydraulic Triaxial Apparatus

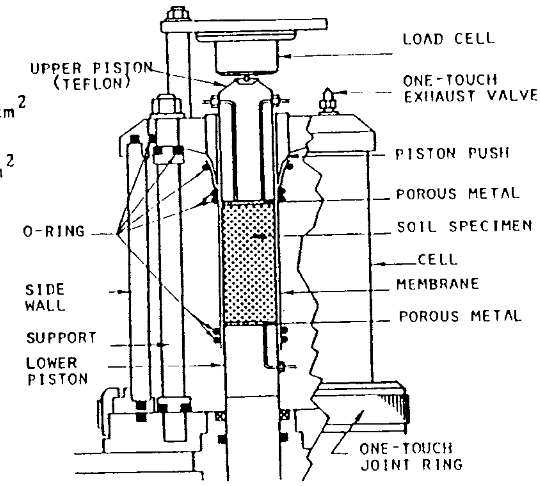

Fig.2 Triaxial Cell

125 mm can be set between the upper and lower pistons. The upper piston reacts against a fixed load cell. The cell water around the upper piston is sealed by stretching a membrane upwards to the piston bushing, and fixed it by O-rings. Advantages of this type of triaxial cell are minimal disturbance of the specimen during its placement in a cell, and negligible friction between the upper piston and the piston bushing, which leads to the accurate measurement of axial load.

Samples and Testing Technique

The samples for the NC remolded Crown clay are prepared at initial water content greater than twice the liquid limit by remolding in a large container under consolidation pressure of about 1.0 kgf/cm^2 (98 kPa). The specimens of 50 mm in diameter and 125 mm in height are normally consolidated for about 24 hours under the maximum effective consolidation pressure of 2.0 kgf/cm^2 (196 kPa). The OC remolded clay specimens are obtained by firstly consolidating the specimens to the NC state and then swelling to a final consolidation stress of 0.5 kgf/cm^2 (49 kPa) to induce OCR of 4.

The NC undisturbed Ma13 clay specimens are trimmed by 50 mm in diameter and 80 mm in height from the undisturbed samples. A procedure for consolidating specimens being similar to that suggested by Ladd and Foott (1974) is followed. That is, the specimens are isotropically consolidated to the maximum stress of 2.0 kgf/cm^2 (196 kPa), which is about two times the maximum past consolidation stress on the in-situ clay samples.

The slightly OC undisturbed Ma12 clay specimens are trimmed by 50 mm in diameter and 125 mm in height from the two block samples taken from 42.5 m below the ground surface. A special process is performed to ensure the fully saturation of specimens. After the saturation process, the specimens are consolidated isotropically for about 24 hours to its mean effective stress of 2.5 kgf/cm^2 (245 kPa).

A back pressure of 1.0 kgf/cm^2 (98 kPa) is used during the consolidation process for the Crown and Ma13 clay specimens, while a back pressure of 3.0 kgf/cm^2 (294 kPa) is selected for Ma12 clay specimens, which is about 75% of the in-situ hydrostatic pressure on the undisturbed Ma12 clay samples.

After consolidation, the specimens in undrained condition are subjected to sinusoidally strain controlled cyclic loading of frequency 0.5 Hz in the axial direction for a number of cycles up to 100 and different cyclic axial strain amplitudes ε_c. At the end of cyclic loading, the specimens are left to cure for one hour under zero shear stress.

After curing, the specimens are monotonically sheared to failure in the undrained condition with axial strain rate of 0.5 %/min. For one test of each group, the consolidated undrained static shear test is performed without cyclic loading effect, and the results obtained are used as a basis for comparison. The test conditions are summarized in Table 2.

ANALYSIS OF TEST RESULTS

STRESS-STRAIN BEHAVIOR AFTER CYCLIC LOADING

Behavior of NC Clay After Cyclic Loading

Fig.3 represents the effect of undrained cyclic loading on the undrained stress-strain behavior during the subsequent static loading for both NC remolded Crown clay and NC undisturbed Ma13 clay. The figure includes three test results for the monotonic static loading tests after

Table 2 Summary of Test Conditions

Sample Type	Consolidation: Over Consolidation Ratio OCR	Consolidation: Consolidation Pressure σ'_c (kgf/cm^2)	Consolidation: Back Pressure (kgf/cm^2)	Cyclic: Frequency f (Hz)	Cyclic: Cyclic Axial Strain ϵ_c (%)	Cyclic: Number of Cycles N	Static: Axial Strain Rate $\dot{\epsilon}_a$ (%/min)	Equivalent OCR OCR_{eq}
Remolded NC Crown Clay	1.0	2.0	1.0	0.5	0.320	100	0.5	3.345
	1.0	2.0	1.0	0.5	0.495	100	0.5	4.158
	1.0	2.0	1.0	0.5	1.030	100	0.5	6.536
	1.0	2.0	1.0	0.5	0.000	Without	0.5	
Remolded OC Crown Clay	4.0	2.0	1.0	0.5	0.490	100	0.5	
	4.0	2.0	1.0	0.5	1.021	100	0.5	
	4.0	2.0	1.0	0.5	0.000	Without	0.5	
Undisturbed NC Ma13 Clay	1.0	2.0	1.0	0.5	0.486	100	0.5	1.358
	1.0	2.0	1.0	0.5	0.991	100	0.5	2.002
	1.0	2.0	1.0	0.5	1.922	100	0.5	2.759
	1.0	2.0	1.0	0.5	0.000	Without	0.5	
Undisturbed OC Ma12 Clay	1.3	2.5	3.0	0.5	0.107	100	0.5	
	1.3	2.5	3.0	0.5	0.299	100	0.5	
	1.3	2.5	3.0	0.5	0.000	Without	0.5	
	1.3	2.5	3.0	0.5	0.658	100	0.5	
	1.3	2.5	3.0	0.5	1.013	100	0.5	
	1.3	2.5	3.0	0.5	1.983	100	0.5	
	1.3	2.5	3.0	0.5	0.000	Without	0.5	

[1kgf/cm^2=98kPa]

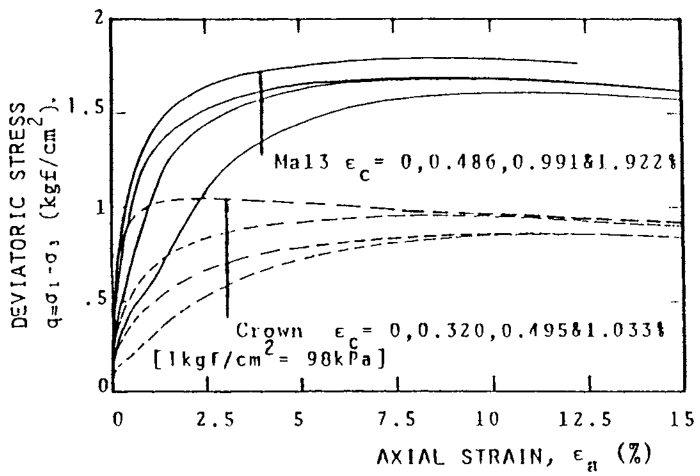

Fig.3 Effect of Cyclic Loading on Undrained Stress-Strain Behavior of NC Remolded Crown Clay and Undisturbed Ma13 clay

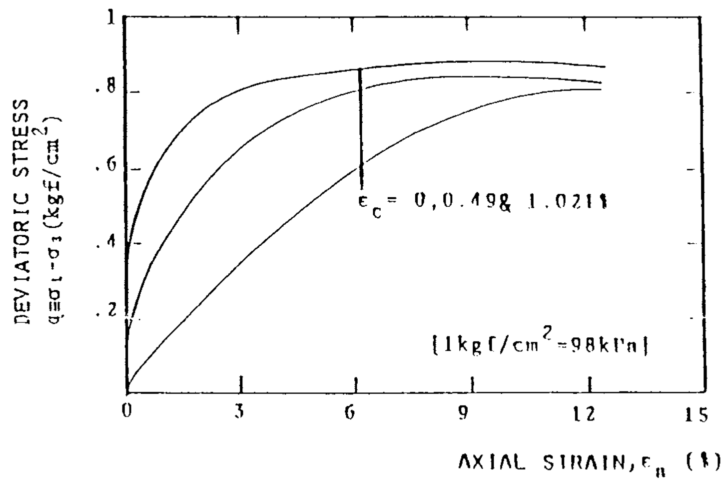

Fig.5 Effect of Cyclic Loading on Undrained Stress-Strain Behavior of OC Remolded Crown Clay

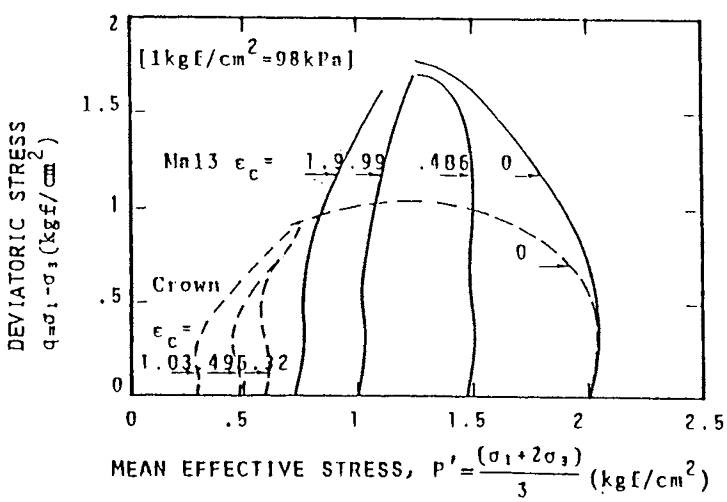

Fig.4 Effect of Cyclic Stress-Strain History on Effective Stress Path of NC Remolded Crown and Undisturbed Ma13 clay

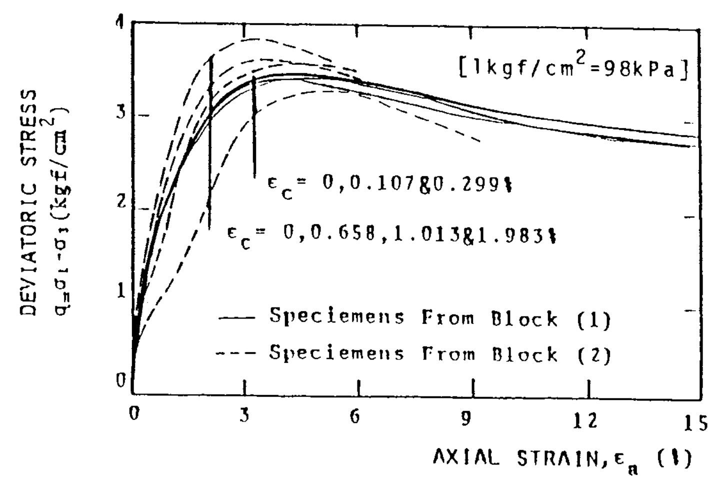

Fig.6 Effect of Cyclic Loading on Undrained Stress-Strain Behavior of OC Undisturbed Ma12 Clay

cyclic loading with number of cycles up to 100 at different ε_c and one test result for the monotonic static test without cyclic loading effect. From the inspection of the result it can be noticed that the undrained shear strength decreases as the cyclic axial strain increases, and cyclic loading has a significant effect in decreasing the tangent and secant deformation moduli. Also, it can be observed that the strain at failure may increase due to cyclic loading.

Degradation rates of such shear characteristics as shear strength, deformation modulus and failure strain depend on the imposed ε_c. It can be observed that the degradation rates increase as increasing ε_c.

Comparison of the results obtained for remolded Crown clay to that obtained for undisturbed Ma13 clay indicates that the degradation rates are less for Ma13 clay than those for Crown clay, and this may be attributed to their relative stiffness.

Fig.4 shows the effective stress paths for the static part of the tests shown in Fig.3 . The relations in this figure indicate that the effective stress paths seem to behave in a similar way as those of OC specimens. The reason of this may be that, even if no drainage has been permitted, the effective stress reduction during the undrained cyclic loading corresponds to that by a real unloading and swelling. In other wards, as discussed by some investigators, the cyclic loading has caused an apparent over-consolidation to the clay.

Behavior of OC Clay After Cyclic Loading

Figs.5 and 6 show the stress-strain behavior relationships obtained in similar tests on OC specimens of remolded Crown clay of OCR 4 and undisturbed Ma12 clay of OCR 1.3, respectively. Also inspection of the results indicates that the undrained strength after cyclic loading decreases and the strain at failure increases as ε_c increases. At all stress levels the tangent and secant deformation moduli decrease significantly as increasing ε_c. It is remarkable that there is no significant effect of the cyclic loading on the strength degradation of specimens from block (1), as represented by the solid lines in Fig.6. This observation can be attributed to the low cyclic axial strain used for these tests. For higher ε_c a significant effect can be observed for the results concerning the specimens from block (2), as shown by the broken lines in Fig.6. However, this degradation is not so large, comparing to those for OC remolded Crown clay, because of their relative stiffness differences.

CYCLIC STRESS-STRAIN HISTORY AND EQUIVALENT OVER-CONSOLIDATION HYPOTHESIS

Fig.7 illustrates a schematic diagram of the relation between the void ratio ,e, and the logarithmic effective stress ,logσ', in which the part (AB) represents NC and the part (BC) represents OC. First, if we consider that a NC specimen at point (A) is subjected to undrained cyclic loading , point (A) moves to point (C) in parallel to the abscissa, having its mean effective stress ,σ'_m. The specimen at this point represents one kind of OC state identified by the equivalent over-consolidation ratio OCR_{eq}. Secondly, if we consider that a NC specimen at point (B) is allowed to swell until point (C), being reduced to its σ'_m, the specimen at point (C) represents another kind of OC state identified by the ordinary over-consolidation ratio OCR. Thus among the specimens at point (C), there can be two types of specimens which have different stress-strain histories, namely the cyclic stress-strain history and the ordinary OC history. The OCR of respective history can be defined by:

$$OCR_{eq} = \frac{\sigma'_e}{\sigma'_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

$$OCR = \frac{\sigma'_c}{\sigma'_m} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

where σ'_e = Equivalent consolidation pressure
σ'_c = Consolidation pressure at point (B)

Based on the algebraic relations in Fig.7, the following relation between OCR_{eq} and OCR can be easily derived.

$$\log\ OCR_{eq} = \left(1 - \frac{Cs}{Cc}\right) \log\ OCR \quad \ldots\ldots\ldots\ldots (3)$$

in which Cc and Cs are compression and swelling indices, respectively. Using Eq.3, OCR can be converted to OCR_{eq} when necessary.

This similarity in the behavior of NC clay subjected to cyclic loading effect to that of the ordinary OC clay will establish the basis of the OCR_{eq} hypothesis, in which the shear characteristics degradation of NC clays after cyclic loading can be represented as a function of OCR_{eq} from the behavior of the NC clay.

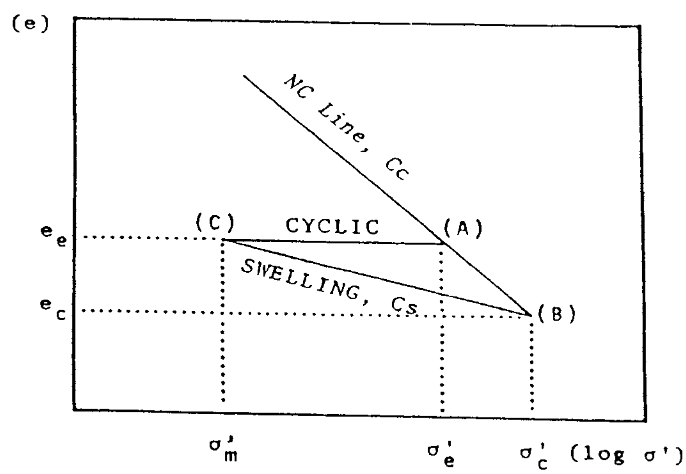

Fig.7 Schematic Diagram of (e) - (log σ')

PROPOSED DEGRADATION RELATIONS OF NC CLAY AFTER CYCLIC LOADING

Fig.8 shows the test results for the undrained strength degradation τ_f/τ_{f0} for the NC Crown clay specimens, being subjected to such different numbers of cycles as 1, 10, 30 and 100, versus the inverse of OCR_{eq}. Fig.9 shows the test results for the secant deformation modulus degradation $E_{50}/(E_{50})_0$ versus OCR_{eq}, while Fig.10 represents the failure strain degradation $\varepsilon_f/\varepsilon_{f0}$ versus OCR_{eq}. In Figs. 8, 9 and 10, the test results for the NC Ma13 clay are also included.

From the inspection of the results, it can be observed that all test data points at different number of cycles are located within a certain narrow band , indicating that there is no significant effect by increasing the numbers of cycles. Therefore, the test results can be fitted and expressed by the following relations:

$$\frac{\tau_f}{\tau_{f0}} = \frac{1}{[\ \alpha_\tau + (1-\alpha_\tau)\ OCR_{eq}\ ]} \quad \text{..........(4)}$$

$$\frac{E_{50}}{(E_{50})_0} = [\ OCR_{eq}\ ]^{\alpha_E} \quad \text{....................(5)}$$

$$\frac{\varepsilon_f}{\varepsilon_{f0}} = 1 + \alpha_\varepsilon \ \mathrm{Log}\ (OCR_{eq}) \quad \text{.............(6)}$$

Eqs. 4,5 and 6 represent the suggested relations for estimating the degradation of the strength, deformation modulus and failure strain of NC remolded Crown and undisturbed Ma13 clays. As shown by the solid and broken lines in Figs.8, 9 and 10, well agreement of data points and fitting results are confirmed.

The predicted degradation parameters α_τ, α_E and α_ε are found as 0.93, -1.86 and 4.42 for remolded Crown clay (OCR_{eq} = 3.3~6.5) and 0.94, -1.73 and 1.39 for undisturbed Ma13 clay (OCR_{eq} = 1.35~2.76), respectively. Analysis of these parameters indicates that the reduction in the undrained strength due to cyclic loading effect is not significant as increasing the OCR_{eq}, while the reduction in the deformation modulus and the increase of failure strain are significant. This observation agrees with the previous investigation by Castro and Christian (1976), Koutsoftas (1978), and Matsui and Abe (1981), that there is no significant effect on the strength within the low values of OCR_{eq}, while there is significant reduction in clay stiffness. Comparison of the obtained degradation parameters for NC remolded Crown and undisturbed Ma13 clays shows that similar values are obtained for both strength and

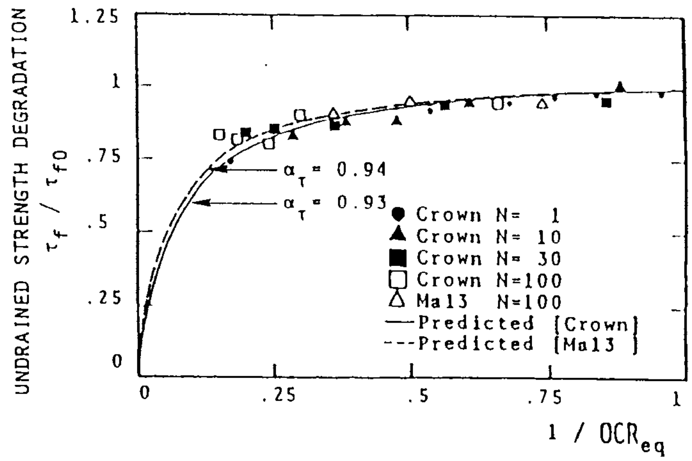

Fig.8 Undrained Strength Degradation τ_f/τ_{f0} Versus Inverse OCR_{eq} for NC Remolded Crown Clay and Undisturbed Ma13 Clay

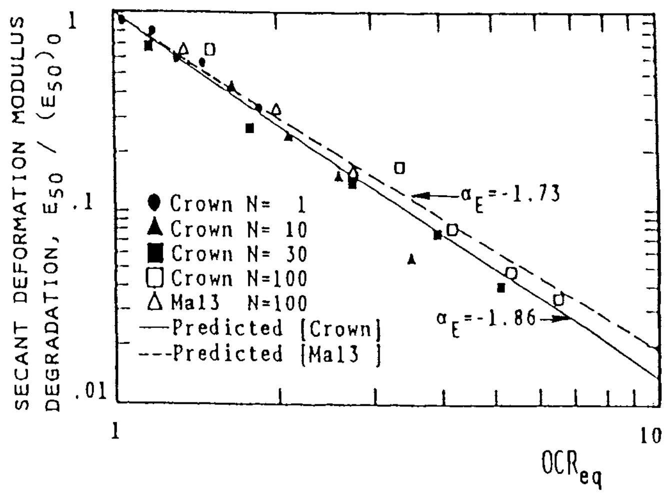

Fig.9 Secant Deformation Modulus Degradation $E_{50}/(E_{50})_0$ Versus OCR_{eq} for NC Remolded Crown Clay and Undisturbed Ma13 Clay

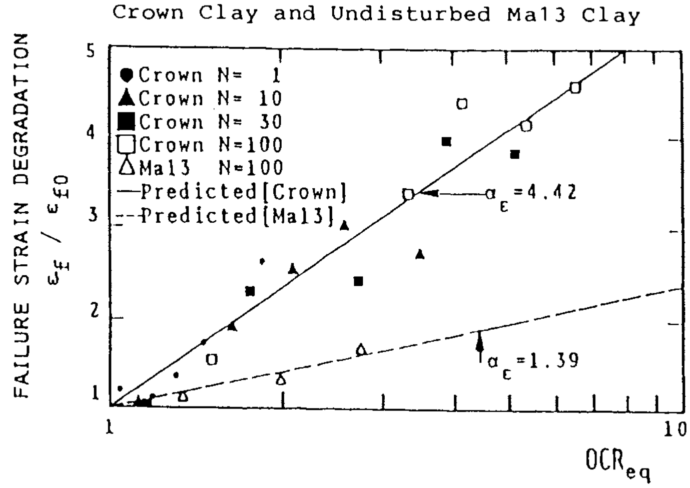

Fig.10 Failure Strain Degradation $\varepsilon_f/\varepsilon_{f0}$ Versus OCR_{eq} for NC Remolded Crown Clay and Undisturbed Ma13 Clay

deformation degradation parameters, while a large difference for failure strain degradation parameter can be observed. This also can be attributed to the difference of their relative stiffnesses.

CONCLUSIONS

In this paper, the undrained static shear degradation of saturated clay after cyclic loading have been discussed and clarified, based on the experimental results and the OCR_{eq} hypothesis. The main conclusions can be summarized as follows:

(1) The degradation response of saturated clays to cyclic loading mostly depends on their relative stiffness.

(2) From the similarity in the behavior of NC clay subjected to cyclic loading to that of the ordinary OC clay, the base of the equivalent over-consolidation hypothesis has been established.

(3) Based on the experimental results and the OCR_{eq} hypothesis, it has been able to construct the degradation relations of shear characteristics after cyclic loading for both NC remolded and NC undisturbed clays.

REFERENCES

Andersen, K.H., (1976), "Behavior of Clay Subjected to Undrained Cyclic Loading," Proc., Conf. on Behavior of Offshore Structures, Trondheim, Norway, V(1), 392-403

Andersen, K.H., (1988), "Properties of Soft Clay Under Static and Cyclic Loading", Proc., International Conf. on Engineering Problems of Regional Soils, Beijing, China.

Castro, G., and Christian, J.T., (1976), "Shear Strength of Soils and Cyclic Loading", J. Geotech. Engrg. Div., ASCE, 102(9), 887-894.

Hicher, P.Y., and Ladd, P.V., (1987), "Rotation of Principal Direction in K_0-Consolidated Clays", J. Geotech. Engrg. Div., ASCE, 104(5), 609-620.

Koutsoftas, D.C., (1978), "Effect of Cyclic Loads on Undrained Strength of Two Marine Clays", J. Geotech. Engrg. Div., ASCE, 104(5), 609-620.

Ladd, C.C., and Foott, R., (1974), "New Design Procedure for stability of Soft Clays", J. Geotech. Engrg. Div., ASCE, 99(7), 763-786.

Matsui, T., Ohara, H., and Ito, T.,(1977), "Effect of Dynamic Stress History on Mechanical Characteristics of Saturated Clays", Proc. JSCE, V(257), 41-51 (in Japanese).

Matsui, T., Ohara, H., and Ito, T., (1980), "Cyclic Stress-Strain History and Shear Characteristics of Clay", J. Geotech. Engrg. Div., ASCE, 106(10), 1101-1120.

Matsui, T., and Abe, N., (1981), "Behavior of Clay on Cyclic Stress-Strain History", Proc. 10th. Int. Conf., SMFE, Stockholm, V(3), 261-264.

Thiers, G.R., and Seed, H.B., (1968), "Cyclic Stress-Strain Characteristics of Clay", J. Soil Mech. Found. Engrg. Div., ASCE, 94(2), 555-568.

Vucetic, M., and Dobry, R., (1988), "Degradation of Marine Clays Under Cyclic Loading", J. Geotech. Engrg. Div., ASCE, 114(2), 133-149.

Yasuhara, K., Yamanouchi, T., and Hirao, K., (1982), "Cyclic Strength and Deformation of Normally Consolidated Clay", J. Soils and Foundation, JSSMFE, Vol.22, No.3, 77-91.

Yasuhara, K., (1985), "Undrained and Drained Cyclic Triaxial Tests on a Marine Clay" Proc. 11th ICSMFE, San Francisco, V(2), 1095-1098.I