Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Prediction of shear characteristics of undistributed clays after cyclic loading and consolidation

Tamotsu Matsui
Department of Civil Engineering, Osaka University, Suita Osaka, Japan

Mohamed A. Bahr
Department of Civil Engineering, Al-Azhar University, Nasr City, Cairo, Egypt

ABSTRACT: This paper presents the experimental and analytical results for series of static tests performed after cyclic loading without and with subsequent consolidation in triaxial apparatus. The tested clay was a normally consolidated undisturbed clay taken from a shallow alluvial clay layer in Osaka area in Japan. The tests were conducted to predict the post cyclic response based on the rise in pore water pressure associated with cyclic loading effect and it causes an apparent overconsolidation to specimens. As a result, the prediction of shear characteristics degradation was suggested, and reliable predicted relations were confirmed through the test data.

1 INTRODUCTION

Cyclic loading usually generates an excess pore water pressure in clayey ground. As a consequence, the deterioration of clay structure skeleton occurs followed by the shear characteristics degradation of clayey layers (Matsui et al. 1991,1992). Also the consolidation due to pore water pressure dissipation during and after cyclic loading occurs and it may play an important role on the subsequent static behavior of clayey layers. Within the last two decades studies on the effect of consolidation during or after cyclic loading have been focused by some researchers such as France and Sangery (1977), Matsui et al. (1980), Ohara and Matsuda (1988) and Yasuhara and Andersen (1991). The laboratory evidences and proposed analytical relations in the previous studies made an attention to the importance of research subject on natural clays to get useful correlation for the practical purposes.

In this paper the effect of both cyclic loading and consolidation on the subsequent static response of a natural undisturbed clay is presented comparing with a pre-cyclic static test result. Then, the relations of shear characteristics are constructed. Finally, the relation obtained are compared with the experimental data and their reliability is discussed.

2 TESTED CLAY AND EXPERIMENTAL WORK

Saturated undisturbed clay samples were selected from a shallow alluvial marine clay layer in Osaka area in Japan. The Physical properties of the natural clays indicate that the clay samples are in the normally consolidation state (NC) and contain 41% of clay particles. Their basic index properties are: Liquid, Limit of 67%, Plastic Limit of 44.5% and 22.5 Of Plasticity Index.

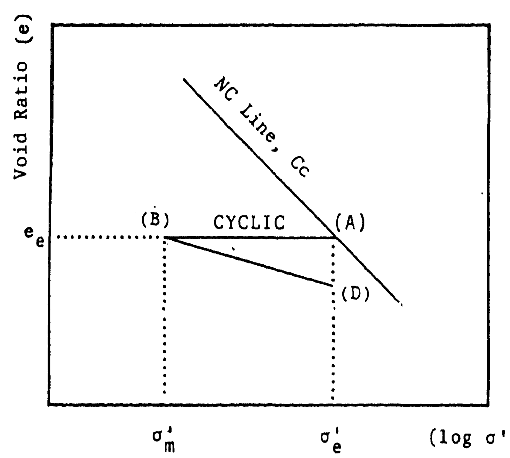

Fig. 1 Schematic diagram of (e) - Log σ' relationship

Three groups of the clay samples were tested using an instrumented servo-controlled electro-hydraulic triaxial apparatus (Matsui et al.,1991). A summary of test program is illustrated on Fig. 1 of a schematic diagram of (e) - (log σ') plane.

Table 1 Summary of test groups and test conditions

Group Number	Over-consolidation Ratio, OCR	Consolidation Pressure σ_c' (kgf/cm^2)	Back Pressure (kgf/cm^2)	Cyclic: Frequency f (Hz)	Cyclic: Cyclic Axial Strain Ranges ε_c (%)	Cyclic: Number of Cycles N	Static: Axial Strain Rate $\dot{\varepsilon}_a$ (%/min)
1,2	1.0	2.0	1.0	0.5	0.5-3.0	1,10,100	0.5
3	1.0	2.0	1.0	...	....	....	0.5

Table 1 shows a summary of test groups and test conditions. In the experimental work, all specimens were consolidated isotropically under an effective consolidation pressure, σ_c' of 2.0 kgf/cm^2 represented by point (A) in Fig.1. Then, specimens of Groups 1 and 2 were subjected to constant cyclic axial strain loading in undrained condition up to point (B) in Fig.1 for different numbers of cycles and different cyclic axial strains. The mode of loading was symmetrical uniform loading in extension and compression with sinusoidal wave pattern excited at a frequency of 0.5 Hz. Afterwards, the developed pore water pressure was allowed to equalize throughout the specimens mass for about one hour under zero shear stress. After curing, specimens of Group 1 were monotonically sheared to failure in undrained condition, while specimens of Group 2 were firstly allowed to consolidate before being subjected to static loading. The consolidation was performed by allowing drainage from the bottom end of specimens until the equilibrium state before cyclic loading was reached as represented by point (D) in Fig.1. Finally, a specimen of Group 3 was subjected to a consolidated undrained static shear test without cyclic loading and the result of this test was used as a basis for comparison.

3 TEST RESULTS AND DISCUSSIONS

3.1 Static stress-strain behavior and effective stress paths

Figure 2 represents the effect of cyclic loading and consolidation on the undrained shear behavior during the subsequent static loading. The figure includes the test result for the monotonic static test without cyclic loading effect.

From the inspection of the results it can be noticed that the cyclic loading without consolidation further degrades

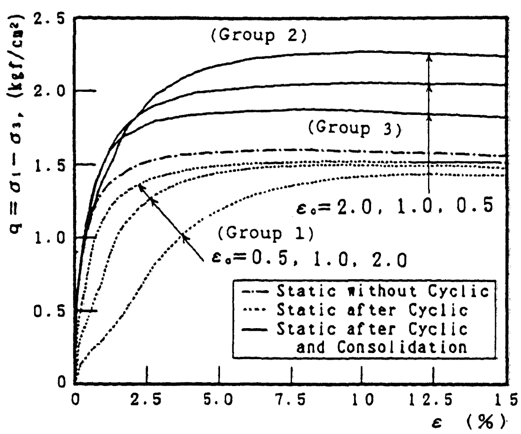

Fig. 2 Effect of cyclic loading and consolidation on the undrained stress-strain behavior of NC undisturbed clays

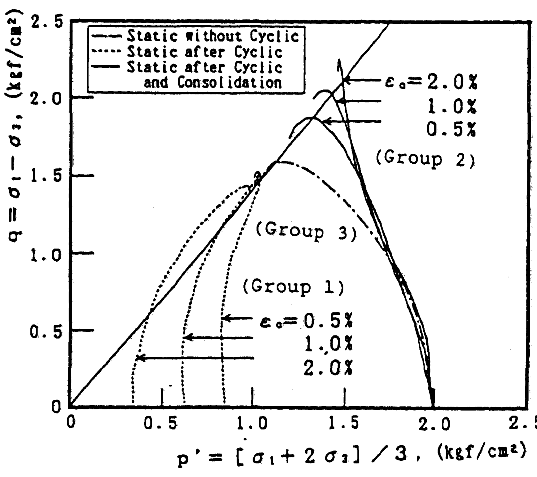

Fig. 3 Effect of cyclic loading and consolidation on the effective stress path of NC undisturbed clays

such shear characteristics as strength at failure, τ_f, secant deformation modulus, E_{50}, and failure strain, ϵ_f, with increasing of the cyclic straining level. On the other hand, the consolidation after cyclic loading offers such better resistance to the subsequent static loading as can be clearly noticed in Fig.2.

Figure 3 shows the effective stress paths for the same tests as in Fig.2. It can be seen that the effective stress paths both for specimens of Groups 1 and 2 seem to pass the failure envelope for the static test on a specimen of Group 3 and reach a higher failure level. This observation means that the cyclic loading gains a strain softening to the NC specimens which leads them to fail on a line similar to the overconsolidation line. On the other hand, the subsequent consolidation after cyclic loading causes a state of strain hardening to the specimens of Group 2, resulting the aforementioned observation. Also, as for the obtained stress paths for the specimens of Group 2, it is remarkable that the specimens failure mechanism is changed by increasing the cyclic straining level. This means that the cyclic loading still plays an important role on the subsequent static failure mechanism.

3.2 Prediction of subsequent shear characteristics

As can be sighted from Fig.3 the NC clay subjected to cyclic loading behaves in a similar way to that of the ordinary OC clay. This observed similarity established the equivalent overconsolidation hypothesis suggested in Matsui et al. (1991, 1992). Based on this hypothesis the changes in the aforementioned shear characteristics can be predicted in terms of the equivalent overconsolidation ratio, OCR_{eq}, calculated from the measured residual pore water pressure after cyclic loading as written by Eq.(1).

$$OCR_{eq} = \frac{\sigma_e'}{[\sigma_e' - u_r]} \qquad (1)$$

in which σ_e' is the pre-cyclic equivalent consolidation pressure and u_r is the residual pore water pressure after cyclic loading.

In Figs.4, 5 and 6 the test results for the aforementioned shear characteristics normalized by those of Group 3 are plotted against the obtained OCR_{eq} values. Figure 4 shows the undrained strength degradation, τ_f/τ_{fo}, versus inverse of OCR_{eq}. Figures 5 and 6 show the test results for the secant deformation modulus degradation, $E_{50}/(E_{50})_o$ and failure strain degradation, ϵ_f/ϵ_{fo}, versus OCR_{eq}, respectively.

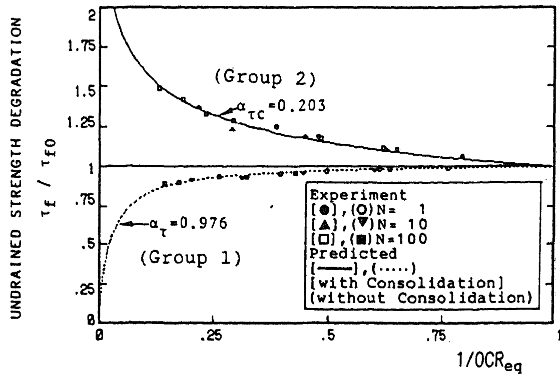

Fig. 4 Undrained strength degradation versus inverse OCR_{eq} for NC undisturbed clays

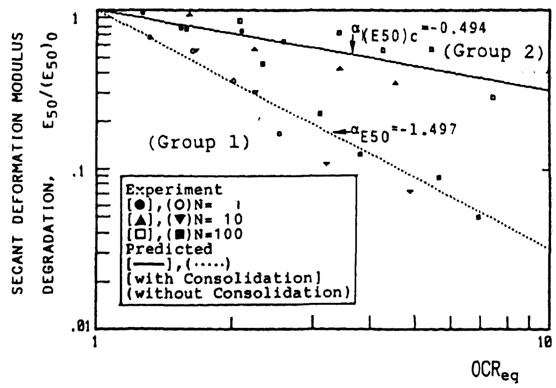

Fig. 5 Secant deformation modulus degradation versus OCR_{eq} for NC undisturbed clays

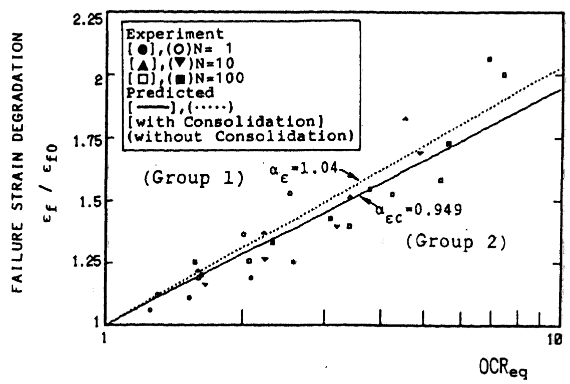

Fig. 6 Failure strain degradation versus OCR_{eq} for Nc undisturbed clays

From the inspection of the results it can be observed that the data points at different number of cycles for both specimens subjected only to cyclic loading and those subjected to cyclic loading and consolidation can be represented well by the solid and dotted lines in these figures, respectively. Therefore, τ_f/τ_{fo}, after both cyclic loading and cyclic loading followed by consolidation are expressed by Eqs. (2) and (3), respectively. Also, both $E_{50}/(E_{50})_o$ and ϵ_f/ϵ_{fo} are expressed by Eqs. (4) and (5), respectively.

- after cyclic loading

$$\frac{\tau_f}{\tau_{fo}} = \frac{1}{\{\alpha_t + [1-\alpha_t]\ OCR_{eq}\}} \qquad (2)$$

- after cyclic loading followed by consolidation

$$\frac{\tau_f}{\tau_{fo}} = \left[\frac{1}{OCR_{eq}}\right]^{-\alpha_{\tau c}} \qquad (3)$$

- after both cyclic loading and cyclic loading followed by consolidation

$$\frac{E_{50}}{(E_{50})_o} = [\ OCR_{eq}\ ]^{(\alpha_E \text{ or } \alpha_{Ec})} \qquad (4)$$

- after both cyclic loading and cyclic loading followed by consolidation

$$\frac{\epsilon_f}{\epsilon_{fo}} = 1 + (\alpha_\epsilon \text{ or } \alpha_{\epsilon c})\ \mathrm{Log}\ OCR_{eq} \qquad (5)$$

The parameters α and α_c are the corresponding degradation parameters after cyclic loading and cyclic loading followed by consolidation, respectively. The obtained parameters are shown on Figs. 4, 5 and 6.

As can be seen in Figs. 4, 5 and 6 well agreement between the data points and the suggested relations are confirmed. As a result of this evaluation, the stress-strain relation after both cyclic loading and cyclic loading followed by consolidation can be predicted as a function of OCR_{eq} when the excess pore water pressure generated by cyclic loading is given (Matsui et al. 1992).

4 CONCLUSIONS

From this study the main conclusions can be summarized as follows:

1. The cyclic loading further degrades the post cyclic static shear characteristics of NC clays, while the consolidation after cyclic loading offers better resistance for NC clays to the subsequent static loading.
2. Although the consolidation makes the rearrangement of clay particles, the cyclic loading plays an important role on the subsequent static failure mechanism of NC clays.
3. It is possible to predict the relations for the subsequent static shear characteristics degradation after both cyclic loading and cycling loading followed by consolidation based on the rise in pore water pressure associated with cyclic loading effect.

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