Undrained and drained cyclic triaxial tests on a marine clay

Essais triaxiaux cycliques non-drainés et drainés sur une argile marine

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SYNOPSIS Cyclic undrained and drained triaxial compression tests were run to define the cyclic undrained strength and to obtain the cyclic strength parameters of a plastic marine clay. In particular, importance of the effect of drainage on cyclic strength was emphasized. The undrained strength calculated by using the methods formerly proposed by authors was proved to fit well with the one observed in monotonic loading triaxial compression tests after cyclic loading. According to the effective stress analysis, a similarity of clay behavior after undrained and drained cyclic loading to behavior of over-consolidated clay without any cyclic loading history was pointed out on the stress path and the stress-strain relationship, respectively.

INTRODUCTION

Cyclic triaxial compression tests on clay have recently been carried out for investigation into the effect of cyclic stress-strain history on strength and deformation (Andersen, et al., 1977 ; Sangrey and France, 1980 ; Hyde and Ward, 1983). The authors (Yasuhara et al., 1982,1983 1984) have also been involved in cyclic loading of clay. In the previous studies, cyclic strength and deformation characteristics of a soft marine clay were examined by the authors from viewpoint of both the effective and the total stresses. Especially, the methods for predicting the change in undrained strength were presented in the present study. However, there still remain many factors to be considered into cyclic loading of clay. Hence, successive to past studies, the present paper deals with the effect of drainage on undrained behavior of clay during and after cyclic loading. Interpretation of test results is discussed in relation to the effects of cyclic loading on the stress path and the strength parameter as the effective stress analysis and on the undrained strength as the total stress analysis.

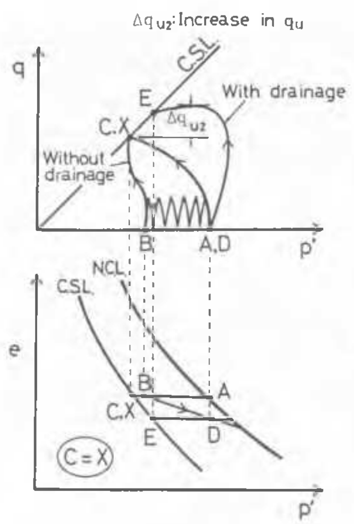

Fig. 1 Stress and State Paths after Cyclic Loading (Model A)

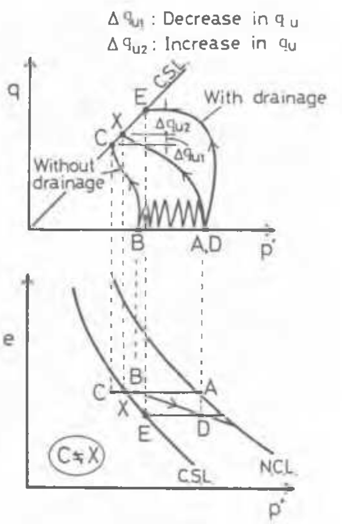

Fig. 2 Stress and State Paths after Cyclic Loading (Model B)

THEORETICAL CONSIDERATION

Fig. 1 and Fig. 2 schematically illustrate the void ratio-mean effective principal stress-undrained strength relationships of a soil sample subjected to cyclic loading. Owing to the critical stress concept (Schofield and Wroth, 1968), undrained strengths at the same void ratio are completely the same as shown in Fig. 1 even if two identical clay specimens are subject to different undrained stress histories. However, if the strength of a clay subjected to cyclic stress-strain history would differ from the one without any loading history, the failure points would fall into the region of the left side of the critical state line (CSL) shown in e-log p' space (Fig. 2).

Fig. 1 and Fig. 2 also illustrate the influences of drainage after or during cyclic loading on the undrained effective stress path. After once a clay sample moves from A to B due to undrained cyclic loading, it accepts the dissipation of cyclic-induced pore-water pressure, $(\Delta u)_{cy}$, by draining. Then, the state path of this sample shifts towards D through B. At this state, the sample is placed in a kind of over-consolidation so called "quasi-overconsolidation" as well as a clay sample under undrained cyclic loading because samples do not lie any longer onto the normally-consolidated line (NCL).

By extending the following empirical relation

$$(s_u/p)_{OC}/(s_u/p)_{NC} = (OCR)^{\Lambda_o} \qquad (1)$$

which was proposed by Mayne (1980) and others for prediction of undrained strength of over-consolidated clay due to stress release, the authors (1983) have proposed the following relations for estimating the undrained strengths, s_{uo}, and, s_{ud}, of clay after cyclic loading with and/or without drainage, respectively

$$s_{uo} = m\, p_i \left[\frac{1}{1 - \frac{(\Delta u)_{cy}}{p_i}} \right]^{\frac{\Lambda_o}{1-\lambda} - 1} \qquad (2)$$

$$s_{ud} = m\, p_i \left[\frac{1}{1 - \frac{(\Delta u)_{cy}}{p_i}} \right]^{\frac{\Lambda_o}{1-\lambda} \cdot \lambda} \qquad (3)$$

where m : undrained strength increment ratio, p_i : initial confining pressure, λ : C_s/C_c (C_s, C_c: swelling and compression indices, Λ_o : experimental constant.

There is an other possibility where a clay is situated under drained cyclic loading. The state path in this case, as a consequence, is similar to the one of clay subjected to secondary compression (refer to Fig. 8). This corresponds with the processes AD in Fig.1 or Fig. 2 and PR in Fig. 8. Undrained behavior of clay after drained cyclic loading was pursued for comparison with that of clay with drainage after undrained cyclic loading.

EXPERIMENTS

A family of undrained and drained cyclic triaxial compression tests were performed on a reconstituted marine clay whose index properties are : $G_s = 2.65$, $w_L = 123\%$; $I_p = 69$, $\phi' = 40^o$, $C_c = 0.700$, $C_s = 0.163$. Undrained cyclic tests have two kinds of the loading sequence as shown

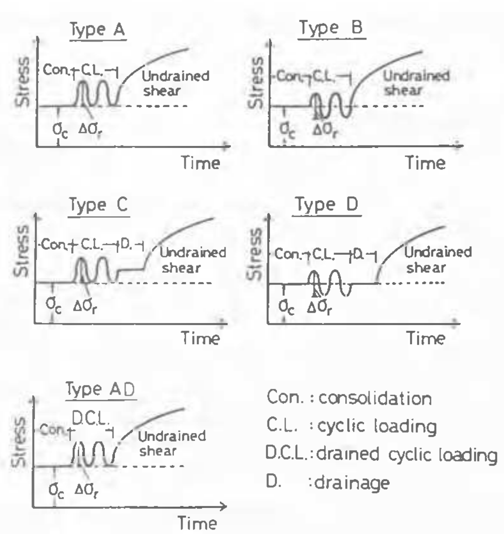

Fig. 3 Loading Sequence of Cyclic Triaxial Compression Tests

in Fig. 3. The one is accompanied by drainage after cyclic loading and the another is not. In this regard, the former is somewhat common with the drained cyclic test. In the series of the type A, one-way load was imposed to each sample while two-way loading was employed in the type B. The frequency of cyclic loading is 1.0 Hz. in every test. We must pay an attention to the fact that two-way loading results in rotation of the direction of principal stresses and this is possible to give rise to a difference of clay behavior from one-way loading.

The test series of types C and D involve the drainage process successive to cyclic loading before undrained shear as shown in Fig. 3. Namely, undrained behavior after cyclic loading is affected by the pre-consolidation pressure, cyclic load intensity and draiange condition.

Drained cyclic triaxial compression tests were carried out in order to compare with undrained cyclic tests with drainage. In both sequences of undrained and drained cyclic tests, monotonic strain controlled triaxial tests with the axial strain rate of 0.1%/min were conducted on the samples after accepting cyclic loading history.

TEST RESULTS AND ANALYSIS

Effective Stress Basis

Fig. 4 shows a comparison of typical effective stress paths during undrained shear after different cyclic loading histories ; undrained cyclic loading without and with drainage, and drained cyclic loading. End points in which failure occurs are plotted in Fig. 5 by the p'-q representation for all the samples with five different cyclic loadings and drainage conditions. It can clearly be seen by the figure that every

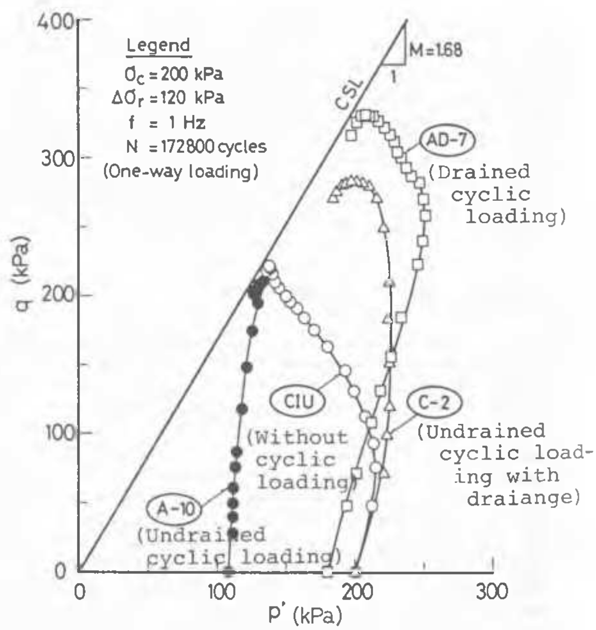

Fig. 4 A Comparison of Effective Stress Path of Clay Samples after Cyclic Loading

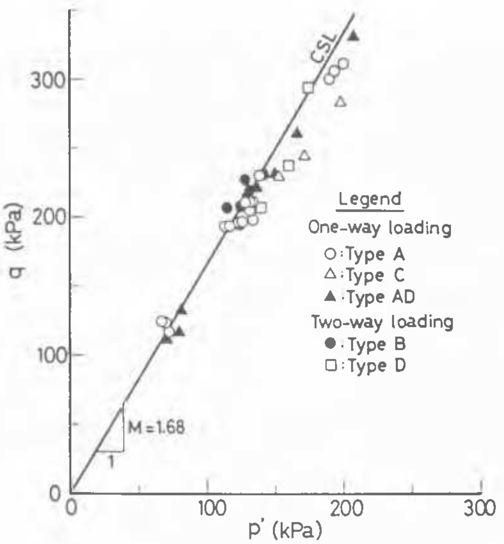

Fig. 5 End points of Effective Stress Paths for Clay Samples Failed under Cyclic Loading

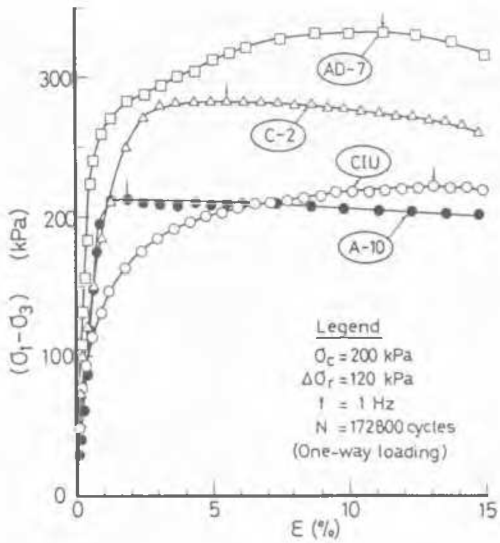

Fig. 6 A Comparison of Stress-Strain Curve for Clay Samples after Cyclic Loading

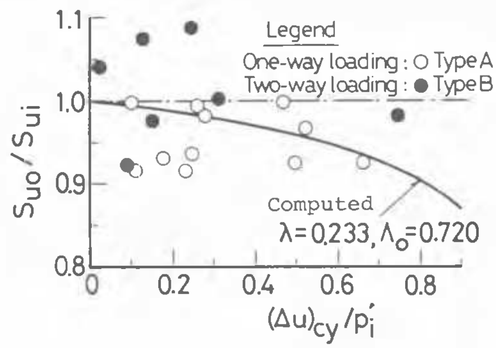

Fig. 7 Computed and Observed Undrain-Strength of Clay Samples after Undrained Cyclic Loading

plot falls along the CSL. This means that the critical state parameter M of a plastic marine clay has nothing to do with the effect of pre-cyclic loading.

Undrained Strength

Changes in undrained strength of clay after cyclic loading were investigated in accordance with different drainage conditions. Cyclic undrained strength was defined by the peak principal stress difference in stress-strain curves in Fig. 6 wich were obtained from monotonic strain controlled triaxial compression tests on each clay sample after cyclic loading. The quasi-overconsolidation ratio was used to compare this undrained strength after a cyclic loading history with the one without any cyclic history. The respective quasi-overconsolidation ratio, n_q, for clays under undrained and drained cyclic loading is designated by

$$n_q = \frac{p'_i}{p'_o} = \frac{p'_i}{p_o - (\Delta u)_{cy}} \qquad (4\text{-a})$$

$$n_q = \frac{p'_e}{p'_i} = \exp\left[\frac{2.303\,(\Delta e)_{eq}}{C_c}\right] \qquad (4\text{-b})$$

where $(\Delta u)_{cy}$: pore-pressure generated during undrained cyclic loading and $(\Delta e)_{eq}$: void ratio change during drained cyclic loading.

Observed undrained strength ratio, s_{uo}/s_{ui}, is plotted in Fig. 7 against the cyclic-induced pore-water pressure normalized by the confining pressure, p'_i. Theoretical curve which was drawn by the solid line using Eq. (2) approximately passes through the observed plots on the average. It is clear in Fig. 7 that undrained cyclic loading makes a plastic clay lose its undrained strength by less about 5 % through 10 %

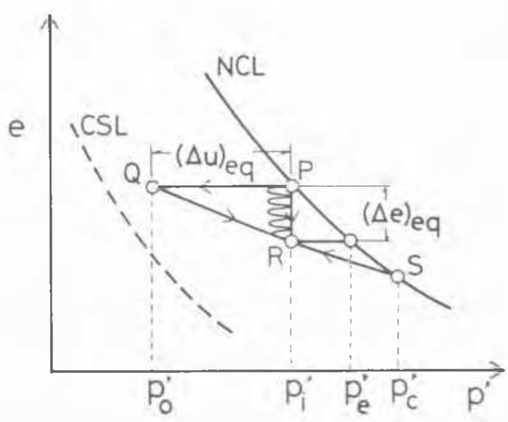

Fig. 8 Definitions of $(\Delta u)_{eq}$ and $(\Delta e)_{eq}$ during Drained Cyclic Loading

than at the normal consolidation.

If Eq. (3) were employed to estimate the undrained strengths after both an undrained cyclic loading with drainage and a drained cyclic loading, the equivalent cyclic pore-water pressure, $(\Delta u)_{eq}$, should be defined as shown in Fig. 8. In this case, Eq. (3) can be rewritten into

$$\frac{s_{ud}}{s_{ui}} = \left[\frac{1}{1 - \frac{(\Delta u)_{eq}}{p_i'}} \right]^{\lambda \frac{\Lambda_o}{1-\lambda}} \qquad (5\text{-a})$$

or

$$\frac{s_{ud}}{s_{ui}} = \left[\exp\left\{ \frac{(\Delta e)_{eq}}{0.434\, C_s} \right\} \right]^{\lambda \frac{\Lambda_o}{1-\lambda}} \qquad (5\text{-b})$$

Fig. 9 compares the observed and calculated undrained strength ratio in undrained cyclic loading with drainage and drained cyclic loading, respectively. Fairly good agreement between theoretical prediction and experimental results can be observed in Fig. 9.

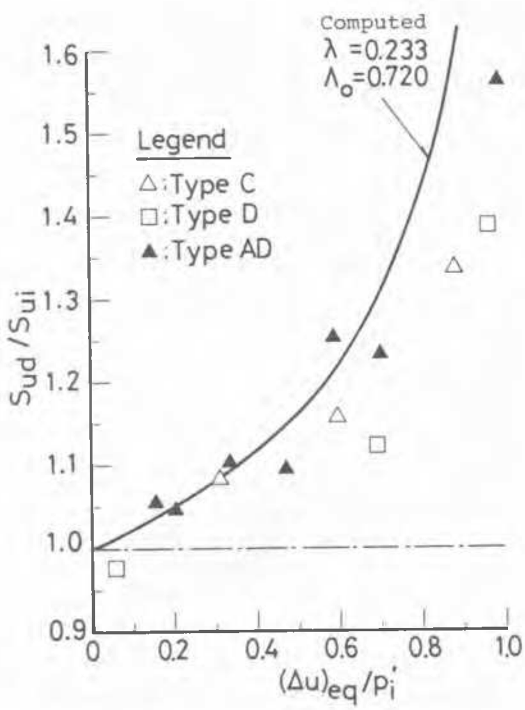

Fig. 9 Computed and Observed Undrained Strength of Clay Samples after Undrained Cyclic Loading with Drainage and Drained Cyclic Loading

CONCLUSION

Undrained and drained cyclic triaxial compression tests on a plastic marine clay were run to study the influences of a cyclic loading history on undrained shear behavior. Results from laboratory tests were analyzed in terms of effective and total stress methods, respectively. The following conclusions were obtained from the present study.

1) Undrained shear behavior of a plastic clay subjected to cyclic loading is not explained by the critical state concept.

2) The effective stress parameter, M, or the effective internal frictional angle, ϕ', is not affected by the undrained and drained cyclic loading histories.

3) Undrained strength of the clay used decreases by undrained cyclic loading but increases by drained cyclic loading.

4) Behavior of clay samples after undrained cyclic loading with drainage is similar to behavior after drained cyclic loading.

5) These decreased and increased undrained strengths can be estimated by authors' modified theories.

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