CYCLIC STRENGTH OF UNDERCONSOLIDATED CLAY

KAZUTOSHI HIRAO¹⁾ and KAZUYA YASUHARA¹⁾

ABSTRACT

The effect of preconsolidation period on cyclic strength of a reconstituted clay was investigated using cyclic triaxial tests. It was indicated from the test results that cyclic strength of underconsolidated clay was more uniquely defined by the degree of consolidation in terms of effective stress than volumetric strain. Further, by using undrained static strength instead of effective stress in normalizing cyclic shear stress, we obtained a very unique relation between the cyclic shear stress and the number of load cycles which is not influenced by the consolidation time. This is because the undrained strength is directly proportional to the magnitude of effective stress developed during consolidation. Thus, a new cyclic stress ratio using undrained static strength instead of effective confining pressure was proposed to define the cyclic strength of clay.

Key words : cyclic strength, cyclic triaxial test, underconsolidated clay (IGC : D 7/D 6)

INTRODUCTION

Generally speaking, fine grained soils exhibit larger resistance to cyclic loading than sands. However, there have recently been many opportunities for us to encounter underconsolidated clays observed in reclamation areas at water front facilities or in the ground where land subsidence or consolidation settlement has been taking place (Yasuda, et al., 1990). The strength of these underconsolidated clays may sometimes not be enough to resist against cyclic loads.

Though many serious geotechnical problems involved in underconsolidated fine grained soils are induced by earthquakes whose recent example was observed in Loma Prieta Earthquake in 1989, others may occur in such situations subjected to wave-induced cyclic loading as

nearshore or offshore structures on seabed deposits of clay. Regarding the problem of this kind, there was a famous case history in the Mississippi delta where landslides due to wave loading occurred in submarine deposits of underconsolidated clay (Henkel, 1970).

To discuss the cyclic strength of clay at various stages over its history from underconsolidation to long-term consolidation, we should investigate from a fundamental point of view the effect of consolidation period on cyclic behaviour of clay. The present paper provides some preliminary data on this subject.

TESTING PROGRAMME

Reconstituted Ariake clay ($G_s=2.58$, $w_L=115\%$, $I_p=72$) was used to run a family of cyclic triaxial tests listed in Table 1. The

¹⁾ Research Associate, Department of Civil Engineering, Nishinippon Institute of Technology Kanda, Fukuoka-ken 800-03.

¹⁾ Professor, Department of Urban & Civil Engineering, Ibaraki University, Hitachi, Ibaraki 316.
Manuscript was received for review on August 6, 1990.

Written discussions on this paper should be submitted before July 1, 1992, to the Japanese Society of Soil Mechanics and Foundation Engineering, Sugayama Bldg. 4F, Kanda Awaji-cho 2-23, Chiyoda-ku, Tokyo 101, Japan. Upon request the closing date may be extended one month.

Table 1. Programme of cyclic triaxial test
(1 kgf/cm²=98 kPa)

$\sigma_c=2.0$ kgf/cm², $BP=2.0$ kgf/cm², $f=0.1$ Hz

Test No.	w_i (%)	t_c (hr)	$\frac{\sigma_r}{2 \cdot \sigma_c}$	N_f (cycles)
T-01	89.70	0	0.070	1
T-02	89.80	0	0.041	4
T-03	89.53	0	0.035	41
T-1	89.81	0.5	0.175	1
T-11	89.45	0.5	0.150	11
T-12	89.46	0.5	0.125	38
T-13	90.49	0.5	0.100	18551
T-23	90.46	1	0.225	2.5
T-2	89.80	1	0.200	12
T-21	91.37	1	0.175	24
T-22	89.07	1	0.150	2765
T-6	89.26	4	0.300	6
T-5	89.51	4	0.250	24
T-3	90.18	4	0.200	173
T-31	89.46	4	0.175	18854
T-4	89.64	8	0.200	1518
F-1	92.10	24	0.375	2
F-2	90.53	24	0.350	3
F-3	89.04	24	0.300	14
F-4	90.94	24	0.275	24
F-5	89.15	24	0.250	58
F-6	91.58	24	0.225	213
F-7	91.49	24	0.200	3435
T-7	89.53	24	0.200	9256

(t_c : Preconsolidation time)

Legend

$u(t)$: Isocrone of excess pore pressure during consolidation
 $\bar{u}(t)$: Isocrone after equalization of excess pore pressure

Fig. 1. Distribution of excess pore water pressure in underconsolidated clay specimen

height and the diameter of each specimen are 10 cm and 5 cm, respectively. A cyclic load was pneumatically applied to each specimen. A back pressure of 2.0 kgf/cm² (196 kPa) equal to the confining pressure was applied to a specimen for 2 hours before isotropic consolidation. To investigate the cyclic behaviour of underconsolidated clay, five kinds of consolidation period were selected.

After the preconsolidation under a confining pressure of $\sigma_c=2.0$ kgf/cm² (196 kPa) for a given period was complete, a drainage line was closed to achieve homogeneity of a specimen due to redistribution of excess pore pressure, as is schematically illustrated in Fig. 1. A two-way cyclic stress with a loading frequency of 0.1 Hz was then applied to each specimen. The cyclic stress level is designated by $\sigma_r/2 \cdot \sigma'_c$ (σ_r : cyclic stress, σ'_c : mean effective principal stress during consolidation). The stress-controlled cyclic loading was employed in each test until the double amplitude of cyclic strain reaches 5% at which a specimen is considered to have failed. The loading sequence through a test is shown in Fig. 2. Testing conditions used in the present study are summarized in Table 1.

Legend

u_r : Residual excess pore pressure at arrested drainage
 u_o : Excess pore pressure after being left for one hour under undrained conditions
 $u_{t, f}$: Excess pore pressure after the completion of undrained cyclic loading
 u : Excess pore pressure before allowing reconsolidation
 $u_{cy, f}$: Amount of cyclic-induced excess pore pressure

Fig. 2. Variations of excess pore pressure with elapsed time

STATIC UNDRAINED SHEAR BEHAVIOUR OF UNDERCONSOLIDATED CLAY

Prior to investigating the cyclic behaviour of underconsolidated clay, we examined static undrained behaviour by monotonic strain-controlled triaxial tests on the same clay. The strain rate in these undrained tests was 0.1%/min. The effective stress paths and the principal stress difference-axial strain curves obtained from a family of undrained monotonic triaxial tests are presented in Fig. 3a and Fig. 3b, respectively. Fig. 3a indicates that every stress path comes onto the critical state line

Fig. 3a. Stress path of underconsolidated clay in static triaxial shear tests (1 kgf/cm²=98 kPa)

Fig. 3b. Stress-strain curves of underconsolidated clay (1 kgf/cm²=98 kPa)

(CSL) of normally consolidated clay. Half the peak value of principal stress difference is taken as undrained strength, s_u , and is plotted against the effective confining stress, σ'_c , in Fig. 4. The results from undrained monotonic triaxial tests are listed in Table 2. Each point falls almost onto the line given as:

$$s_u = m \cdot \sigma'_c \quad (1)$$

where m : undrained strength ratio of normally consolidated clay and σ'_c : effective mean principal stress which is equal to the confining pressure used in the present study.

Fig. 4. Undrained shear strength versus effective confining stress relation in underconsolidated clay (1 kgf/cm²=98 kPa)

Table 2. Results from undrained monotonic triaxial tests (1 kgf/cm²=98 kPa)

$\sigma_c = 2.0$ kgf/cm², $BP = 2.0$ kgf/cm²

Test No.	w_i (%)	t_c (hr)	U_σ (%)	σ'_c (kgf/cm ²)	s_u (kgf/cm ²)
CUC 0	89.72	0	0	0	0.098
CUC30	90.38	0.5	42	0.84	0.416
CUC 1	89.54	1	61	1.23	0.559
CUC 4	89.36	4	89	1.78	0.799
CUC 8	89.28	8	100	2.00	0.796
CUC24	89.05	24	100	2.00	0.811

(t_c : Preconsolidation time)

EXCESS PORE PRESSURE AND SHEAR PERFORMANCE OF UNDERCONSOLIDATED CLAY

The typical results from cyclic triaxial tests on underconsolidated specimens with a stress level, $\sigma_r/2\sigma_c=0.175$ was presented in Fig. 5a and Fig. 5b. Figs. 5a and 5b illustrate the variations of excess pore pressures and shear strains with the number of load cycles (N) for specimens under three kinds of the consolidation period, 30 min, 1 hour and 4 hours, respectively. These correspond to 49%, 66% and 91% of the degree of consolidation in

Fig. 5. Effect of preconsolidation period on development of cyclic-induced excess pore pressures and shear strains

terms of effective stress which were calculated by:

$$U_o = 1 - \frac{1}{\sigma_c} \int_{-r}^r u(r, t) dr = 1 - \frac{\bar{u}(t)}{\sigma_c} \quad (2)$$

where $\bar{u}(t)$: equalized excess pore pressure after closing the drainage line as was illustrated in Fig. 1. These values of the degree of consolidation were determined by Fig. 6, which demonstrates, by the shaded bands of the average value from the results of several tests, the variations of excess pore pressure and volumetric strain with time during isotropic consolidation under $\sigma_c = 2.0 \text{ kgf/cm}^2$ (196 kPa).

Fig. 5a clearly illustrates the effect of consolidation period on the development of excess pore pressures in clay specimens. It is also clear in Fig. 5b that the 5% double amplitude of axial strain is attained at the smaller number of load cycles with the shorter period of preconsolidation.

It is well known that saturated sands are liquefy when excess pore pressures during cyclic loading are developed until increasing up to the equal magnitude of confining pressure, that is, $u_t/\sigma_c = 1.0$ where u_t is the peak value of excess pore pressure at each cycle. For clays, on the contrary, cyclic failure is attained even though excess pore pressure does not

Fig. 6. Variations of excess pore pressure and volumetric strain with elapsed time during isotropic consolidation ($1 \text{ kgf/cm}^2 = 98 \text{ kPa}$)

Fig. 7. Normalized excess pore pressure versus cyclic stress ratio

become completely equal to the confining pressure, namely $u_t/\sigma_c < 1.0$ (Hirao, et al.: 1998). To ensure this, Fig. 7 summarizes the normalized excess pore pressure $u_{t, DA=5\%}/\sigma_c$ versus cyclic stress ratio, $\sigma_r/2\sigma_c$, relation at the 5% double amplitude of axial strains, indicating that at a certain value of cyclic stress the shorter the preconsolidation period is, the larger excess pore pressure is generated. It is also pointed out from Fig. 7 that the cyclic-induced excess pore pressure increases with decreasing cyclic stress ratio, regardless of the preconsolidation period. Besides, these tendencies in Fig. 7 show that the double amplitude shear strain reaches 5% before the excess pore pressure rises up to the confining pressure. From these tendencies appeared in Fig. 7 we conclude that cyclic strength must be different from the cyclic failure determined in terms of cyclic-induced excess pore pressure.

CYCLIC FAILURE AND STRENGTH OF UNDERCONSOLIDATED CLAY

Fig. 8 shows the relation between $\sigma_r/2\sigma_c$ ($=R$) and N for each value of double amplitude of cyclic shear strain, ϵ_{DA} , obtained from cyclic triaxial tests on the same Ariake clay. When we assume the cyclic stress ratio, R_f , at $N=20$, as the cyclic strength of underconsolidated clay corresponding to a given consolidation period, Fig. 8 indicates that the

Fig. 8. Cyclic stress ratio versus number of load cycles relation in underconsolidated clay

Fig. 9. Unified $R-N_f$ relation using the consolidation degree in terms of volumetric strain

cyclic strength tends to become larger with increasing preconsolidation period.

There are two ways to determine the degree of consolidation of underconsolidated clay. These are in terms of volumetric strain (U_ϵ) and effective stress (U_σ) developed during consolidation. It can be said that for the convenience of measurement in laboratory, it is rather easier to use for this purpose the degree of consolidation in terms of volumetric strain than to use that in terms of effective stress.

The cyclic stress ratio versus number of load cycles relations are plotted in Fig. 9 in which the degree of consolidation, U_ϵ , in terms of the volumetric strain is adopted for the definition of the cyclic stress ratio. Fig. 9

Fig. 10. Unified $R-N_f$ curve of underconsolidated clay using the degree of consolidation in terms of effective stress

shows that some plots pertaining to the specimens with the shorter consolidation period than the primary consolidation period are deviated from the average line.

In order to define unified cyclic strength of underconsolidated clay, which will be independent of the preconsolidation period, we use effective confining stress ($\sigma'_c \cdot U\sigma$) instead of total confining stress (σ_c) for normalizing cyclic stress (σ_r). Then, we obtain Fig. 10 which gives the relation between cyclic shear stress ratio $\sigma_r / 2 \cdot \sigma'_c \cdot U\sigma$ ($U\sigma$: the degree of consolidation in terms of effective stress) defined by the effective stress and the number of load cycles, N_f , corresponding to $\epsilon_{DA} = 5\%$. In Fig. 10, we can recognize that there is a very unique relation between R_i and N_f , which is not influenced by the preconsolidation period.

Although the effective stress basis is very reasonable in many situations of soil mechanics, for example, as was pointed out in the discussion on cyclic strength of underconsolidated clay as well as static strength (Towhata and Kim, 1990), it is always difficult to measure the precise value of effective stresses even in a clay specimen in the laboratory cyclic test. Thus, we attempt to adopt the undrained strength of each specimen instead of effective confining pressure, σ'_c , as shown in Fig. 11 because undrained strength is directly proportional to the magnitude of effective stress as is given by :

$$s_u = m \cdot \sigma'_c = m \cdot \sigma_c \cdot U\sigma \quad (3)$$

Fig. 11. Unified $R-N_f$ relation of underconsolidated clay with consideration of undrained static strength

Fig. 12. Unified $R-N_f$ relation of underconsolidated clay with consideration of undrained static strength

By following the same manner as used in Fig. 10, the cyclic shear stress normalized by the undrained strength is plotted to the number of load cycles at $\epsilon_{DA} = 5\%$ and is illustrated in Fig. 11. As is suggested by Eq. (3), the tendency appeared in Fig. 11 is the same as in Fig. 10. Judging from the fact that it is much easier at fields to measure undrained strength than effective stress, it is more practical for defining the cyclic strength of clay to use static undrained strength than effective stress.

By replotting the results in Fig. 11 into Fig. 12 using logarithmic scales for both cyclic stress ratio, $\sigma_r / 2 \cdot s_u$, and the number of load cycles at failure, N_f , we obtain :

$$\frac{\sigma_r}{2 \cdot s_u} = a \cdot N_f^b \quad (4)$$

where a, b : experimental constants ($a = 0.85$,

$b = -0.069$ for the reconstituted Ariake clay used in the present study). Eq. (4) is a very unique and practical relation for us to obtain the cyclic strength of underconsolidated clay. Eq. (4) seems to be valid as well for predicting the cyclic strength of normally consolidated and long-term consolidated clay when we measure the static undrained strength of each clay. Fig. 12 and Eq. (4) also indicate that the strength ratio, $\sigma_r/2 \cdot s_u$, for determining the cyclic strength of clay is more useful than the stress ratio, $\sigma_r/2 \cdot \sigma'_c$ which is normally used for definition of dynamic strength or liquefaction of sands.

CONCLUSIONS

1) Cyclic strength of underconsolidated clay is governed by an increase in effective stresses developed during the progress of consolidation.

2) For general definition of the cyclic strength of underconsolidated clay it is more reasonable to adopt the degree of consolidation in terms of effective stress than in terms of consolidation strain.

3) Judging from the difficulty in precise determination of effective stresses at fields, however, it is more practical for defining the cyclic strength of underconsolidated clay to normalize the cyclic shear stress by static undrained strength than by effective confining stress.

ACKNOWLEDGEMENTS

This research was partly supported by a grant-in-aid (the research representative is Professor Susumu Yasuda, Kyushu Institute of Technology) from the Ministry of Education, Science and Culture of Japan. We would like to express sincere thanks to the support.

REFERENCES

- 1) Henkel, D. J. (1970): "The role of waves in causing submarine landslides," *Géotechnique*, Vol. 20, No. 1, pp. 75-80.
- 2) Hirao, K., K. Yasuhara and A. F. L. Hyde (1988): Undrained cyclic triaxial tests on highly plastic clay," *Proc. Symp. on Undrained Cyclic Tests*, pp. 113-118 (in Japanese).
- 3) Hirao, K. and K. Yasuhara (1990): "Cyclic behaviour of underconsolidated clay," *Proc. 25th Japanese Conf. on SMFE* Vol. 1, pp. 813-814 (in Japanese).
- 4) Towhata, I. and S. R. Kim (1990): "Undrained strength of underconsolidated clays and its application to stability analysis of submarine slopes under rapid sedimentation," *Soils and Foundations*, Vol. 30, No. 1, pp. 100-114.
- 5) Yasuda, S., I. Tohno, K. Yasuhara, F. Kuwahara, K. Itahashi and K. Shimizu (1990): "Earthquake-proof system of facilities founded on grounds under subsidence," *Report for Grant-in-aid* (No. 62601030 and No. 63601029) from the Ministry of Education, Science and Culture (in Japanese).