TECHNICAL NOTE

INFLUENCE OF THE NUMBER OF LOAD STEPS IN
 K_0 CONSOLIDATION ON THE UNDRAINED
SHEAR STRENGTH

AKIO NAKASE*, TAKESHI KAMEI** and FUMIAKI TANAKA**

ABSTRACT

In order to investigate the influence of the number of load steps on the strength characteristics of normally consolidated cohesive soils in K_0 -consolidated undrained ($\overline{CK_0U}$) triaxial test, K_0 -consolidated undrained triaxial compression and extension tests are performed on two different samples.

It was found that the c_u/p values obtained by $\overline{CK_0U}$ triaxial tests tend to decrease with an increase in the number of load steps in K_0 consolidation and the c_u/p value of soil with low plasticity index is subjected more easily to the influence of multi-step loading. This is particularly significant for extension test.

Kew words : anisotropy, consolidated undrained shear, cohesive soil, plasticity, secondary compression, shear strength, stress-strain curve, test procedure, triaxial compression test (IGC : D 6/D 5)

INTRODUCTION

In the process of consolidation in triaxial tests, it has been recommended to perform the K_0 consolidation, in which the condition of no lateral strain is maintained throughout the consolidation process, so as to simulate the consolidation condition in the ground (Bishop and Henkel, 1962). In order to maintain the no lateral strain condition, it has been found easier to perform the consolidation, under a specified pressure increment, in several steps (Henkel and Sowa, 1963). This type of multi-step consolidation

has also been recommended for obtaining more uniform one-dimensional deformation of the sample (Karube, 1975).

It has been pointed out, however, that the difference in the number of load steps in consolidation process might give rise to the different soil structure (Henkel and Sowa, 1963). The same sort of question has been also raised in the case of oedometer tests (Rowe, 1959; Crawford, 1964; Leonards and Altschaeffl, 1964). Investigation was then made on the influence of the number of load steps in the K_0 consolidation on the strength characteristics of

* Professor, Department of Civil Engineering, Tokyo Institute of Technology, O-okayama, Meguro-ku, Tokyo.

** Postgraduate student, ditto.

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cohesive soils.

EXPERIMENTS AND SOIL SAMPLES

K_0 -consolidated undrained triaxial compression and extension tests were performed. These triaxial tests are denoted as $\overline{CK}_0UC$ and $\overline{CK}_0UE$ tests respectively. Two different kinds of samples were used, one was Kawasaki clay, and the other was reconstituted by mixing Kawasaki clay, Toyoura sand and partly crushed Toyoura sand. The two samples were named M-30 and M-10 respectively after their values of the plasticity index I_p . The preparation method of soil samples has been previously reported in detail elsewhere (Nakase and Kamei, 1983).

Two different values of vertical effective consolidation pressures were used in the consolidation process; 196 kPa and 392 kPa in the case of compression tests, and 392 kPa and 588 kPa for extension tests respectively. A back pressure of 196 kPa was applied to all the test specimens throughout the consolidation and shear processes. Pore pressure coefficient B in the present series of Kawasaki clay and mixture was found to practically equal to unity, because of high degree of saturation. The smallest value of B measured in the present experiment was 0.99. Compression and extension tests were carried out with a constant rate of axial strain of 0.07%/min. In the present test, strips of filter-paper drains were placed around the specimens in the longitudinal direction and drainage is possible only in the radial direction because both ends of the test specimen are carefully lubricated by using double rubber membranes with silicone grease between them. Degree of dissipation of excess pore pressure at each steps was measured at the bottom end of the test specimen by a pore pressure transducer. In the consolidation process of each test, the specified consolidation pressure was applied in either one step or several steps as shown in Table 1.

Two common methods are used for K_0 consolidation of triaxial test; one is by increasing axial pressure, lateral pressure

Table 1. Consolidation pressure at each step

	number of load steps	1	2	3
$\sigma'_{vc} = 196 \text{ kPa}$	1 st step	196	74	74
	2 nd step		147	98
	3 rd step		196	123
	4 th step			147
	5 th step			172
	6 th step			196
	number of load steps	1	3	6
$\sigma'_{vc} = 392 \text{ kPa}$	1 st step	392	147	98
	2 nd step		294	123
	3 rd step		392	245
	4 th step			294
	5 th step			343
	6 th step			392
	number of load steps	1	4	8
$\sigma'_{vc} = 588 \text{ kPa}$	1 st step	588	147	98
	2 nd step		294	172
	3 rd step		441	245
	4 th step		588	319
	5 th step			392
	6 th step			466
	7 th step			539
	8 th step			588

being kept constant and the other is by decreasing lateral pressure, axial pressure being kept constant. The K_0 condition, however, can not be easily maintained in the former method by using the lateral strain indicator designed by Bishop and Henkel (1962), because of large lateral strain when the specified consolidation pressure is high. In the present test, the latter method has been used and the K_0 condition was maintained using a servo mechanism. In order to check the difference of two methods, the results obtained from both tests with three-step loading were compared. No significant difference is observed. The reason behind is as the servo mechanism in controlling lateral pressure has speedy response, effective stress paths in K_0 consolidation tends to approach the K_0 -line in a relatively short time. Key sketch of total stress paths of one-step loading and multi-step loading in K_0 consolidation process

Fig. 1. Key sketch of total stress paths of one-step loading and multi-step loading in K_0 consolidation process

are shown in Fig. 1. In the total stress diagram, the portions of q constant indicates the process of increasing the confining pressure under undrained condition. The portions of creeping up to K_0 -line represents the process of adjusting the lateral pressure under drained condition so as to maintain the K_0 condition, no lateral strain condition, while axial pressure being kept constant. Effective stress paths of one-step and six-step loadings in K_0 consolidation process are shown in Figs. 2 and 3. Effective stress paths in K_0 consolidation have progressed along the K_0 -line although an initial portion

Fig. 2. Effective stress paths of one-step and six-step loadings of M-30 in K_0 consolidation process

Fig. 3. Effective stress paths of one-step and six-step loadings of M-10 in K_0 consolidation process

of consolidation paths are out of position. It is natural that the number of load steps in K_0 consolidation should be increased, in order to maintain the ideal K_0 condition. Change in the diameter of a test specimen was continuously monitored with two lateral displacement transducers having a sensitivity 1/250 mm, which is equivalent to a radial strain of about 0.016%. This sensitivity is slightly more superior to that of the lateral strain indicator designed by Bishop and Henkel (1962). In practice, it is recommended to carry out the CK_0U tests of cohesive soils for 24 hours (Triaxial Compression Tests Standardization Committee, 1975). In the present investigation, this 24 hour test was employed. The total time including the processes of trimming, consolidation and shearing was 24 hours, hence the consolidation time was about 1000 minutes.

TEST RESULTS AND DISCUSSIONS

Process of Consolidation

Fig. 4 shows the relationship between the ratio of excess pore pressure to applied pressure and axial displacement in the case of the one-step loading. As reported by Crawford (1964), a linear relationship between this pressure ratio and axial displacement is seen in Fig. 4, and it is possible to establish

Fig. 4. Relationship between the ratio of pore pressure to applied pressure and axial displacement in the case of the one-step loading

a well defined end of the primary compression by extrapolating this straight line to the zero excess pore pressure condition. Crawford also reported that thus determined end of the primary compression occurs somewhat earlier than that determined by conventional graphic procedures.

As seen in Fig. 4, the axial displacement corresponding to secondary compression in M-30 is considerably larger than that in M-10. It is also found that there is not much difference in the rate of the pore pressure dissipation with axial displacement in both samples; since the two lines are roughly parallel to each other.

Fig. 5 shows the change in void ratio with time. In this figure, the end of primary compression is defined as the time of full dissipation of excess pore pressure, judged from the reading of pore pressure transducer. As seen in the figure, the time period of secondary compression in the one-step con-

Fig. 5. Change in void ratio with time

solidation is considerably longer than that in the multi-step consolidation for both of the samples. Reflecting the difference in soil permeability, the time period of the secondary compression of M-10 is longer than that of M-30. The void ratio at the end of consolidation does not seem to depend much on the number of load steps, though the void ratio for the one-step consolidation is a little smaller than that for the six- and eight-step consolidation. The K_0 value seemed to be independent of the number of load steps, and they were in the range between 0.37 and 0.46.

Shear Characteristics

Figs. 6 and 7 show typical stress-strain curves of the $\overline{CK}_0UC$ and $\overline{CK}_0UE$ tests, where the principal stress difference $q = \sigma_a - \sigma_r$ is normalized by dividing by the vertical effective consolidation pressure σ_{vc}' . Although it is common to use positive strains in compression test and negative strains in extension test, both axial strains are plotted in terms of absolute value in the present paper. The advantage of this approach is that the difference of the stress at the same strain level can be easily compared. As shown in the figures, the strength of the one-step consolidated samples is larger than that of the multi-step consolidated samples,

Fig. 6. Typical stress-strain curves of M-30 in $\overline{CK}_0U$ tests

Fig. 7. Typical stress-strain curves of M-10 in $\overline{CK}_0U$ tests

in particular in the case of M-10 and the extension tests, though there is no marked difference in the shape of stress-strain curves.

In the case of compression tests, the stress decreases after it has reached the yield stress and this trend is particularly significant for the compression tests of M-10. It has been reported that some clays rapidly reach their maximum cohesion value and this value then decreases with continued strain while the mobilized angle of friction continues to increase. This behaviour has been termed as "peaking effect" and the maximum value of cohesion is termed the "peak cohesion". It seems that the peaking effect is increased as the amount of coarse particles in the clay is increased (Schmertmann and Osterberg, 1960). In the present experiment, the above behaviour was also observed. In addition, in the case of M-10, the once reduced stress increases again after the strain reaches about 4%. The magnitude of increase was larger in the case of one-step consolidation than that of multi-step consolidation. The number of loading steps in K_0 consolidation seems to have no influence on the pore pressure set up during shear. The values of axial strain at failure, ϵ_f , pore pressure coefficient at

Fig. 8. Change in c_u/p value with the number of load steps

failure, A_f , in the case where $(\sigma_1 - \sigma_3)_{\max}$ is taken as the failure condition, and angle of shear resistance, ϕ' , which determined at $(\sigma_1'/\sigma_3')_{\max}$ condition, appear to be independent of the number of load steps. Fig. 8 shows the change in c_u/p value with the number of load steps. As seen in the figure, c_u/p values obtained by the $\overline{CK}_0UC$ and $\overline{CK}_0UE$ tests decrease with increase in the number of load steps. In order to clarify this trend, ratios of the c_u/p value of n -step consolidation to that of one-step consolidation, $(c_u/p)_n/(c_u/p)_1$, in the case of $\sigma'_{vc}=392$ kPa are plotted against the number of load steps in Fig. 9. As seen in the figure, $(c_u/p)_n/(c_u/p)_1$ values decrease with the increase in the number of load steps. For each tests, the $(c_u/p)_n/(c_u/p)_1$ values of M-10 are smaller than that of M-30. In addition,

Fig. 9. Ratios of the c_u/p value of n -step consolidation to that of one-step consolidation in the case of $\sigma'_{vc}=392$ kPa are plotted against the number of load steps

in the case of six-step consolidation test, there is a significant reduction in the $(c_u/p)_n/(c_u/p)_1$ value, and particularly significant for $\overline{CK}_0\overline{UE}$ tests of M-10.

The strength reduction due to the increase in the number of load steps may be explained by the smaller amount of secondary compression and the slightly larger value of void ratio. As for the soil type, the influence of multi-step loading seems more marked for soils with low plasticity index. It has been reported that the influence of sampling disturbance is larger in soils with a low plasticity index (Nakase et al, 1978). Then the frequently changing stress condition in the multi-step loading may have similar influence on the soil structure as the sampling disturbance. In view of both the easiness of maintaining the K_0 condition and practical preference of safer side designing, the K_0 tests performed in the more loading steps is recommended.

CONCLUSIONS

The influence of the number of load steps on K_0 -consolidated undrained triaxial compression and extension test results of normally consolidated cohesive soil is investigated.

The conclusions from this study are:

- 1) The c_u/p values obtained by the $\overline{CK}_0\overline{UC}$ and $\overline{CK}_0\overline{UE}$ tests tend to decrease with the increase in the number of load steps in K_0 consolidation.
- 2) The influence of multi-step loading is larger in the soil with low plasticity index, especially in extension tests.

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NOTATION

- A =pore pressure coefficient at failure
 B =pore pressure coefficient
 c_u/p =ratio of the undrained shear strength to the vertical effective consolidation pressure

$\overline{CK}_0\overline{UC}$ = K_0 -consolidated undrained compression tests

$\overline{CK}_0\overline{UE}$ = K_0 -consolidated undrained extension tests

K_0 =coefficient of earth pressure at rest

M =letter M is named after their plasticity index

ϵ_f =axial strain at failure

σ_{vc}' =vertical effective consolidation pressure

ϕ' =angle of shear resistance when $(\sigma_1'/\sigma_3')_{\max}$ is taken as the failure conditions

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