

SOME OBSERVATIONS ON THE BEHAVIOR OF SOFT CLAY UNDER UNDRAINED CYCLIC LOADING

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ABSTRACT

This note presents the results of a series of cyclic loading triaxial tests under undrained conditions that examines the effectiveness of consolidation history on reconstituted soft clay. For any particular consolidation history, the experimental results confirm the concept of the critical stress level of repeated deviator stress below which a state of non-failure stress equilibrium exists and above which effective stress failure occurs. However, an interesting finding of this study is that for heavily over-consolidated clay, both the state of stress equilibrium (below the critical stress level) and state of effective stress failure (above the critical stress level) develop at the very first few cycles of loading.

Key words: cyclic loading, triaxial testing, undrained condition, over-consolidation, soft clay.

1. INTRODUCTION

The study of cyclic loading behavior of saturated clay under undrained conditions is of utmost importance to stability of geotechnical engineering structures constructed on low-lying estuarine soils and subjected to cyclic loading such rail track foundations and road pavements. A better understanding of the undrained response of clay subgrade to repeated loading enables a safe design of such structures, with less frequent maintenance and repairs. The undrained behavior of clay under repeated loading has been investigated by many researchers (*e.g.* Heath *et al.* 1972; Larew and Leonards 1962; Lefebvre *et al.* 1989; Mitchell and King 1977; Procter and Khaffef 1984; Sangrey *et al.* 1969; Shahu *et al.* 2008), and the existence of critical stress level (or threshold stress) has been long recognized. The critical stress level is the stress below which the soil does not suffer failure regardless of the number of applied cyclic loading and above which effective stress failure occurs. The present study investigates experimentally the effect of consolidation history on the behavior of soft clay at stress levels below and above the critical stress. Reconstituted soft clay soils of different consolidation history (*i.e.* normally consolidated as well as lightly and heavily over-consolidated) are examined and the results are presented and discussed.

2. EXPERIMENTAL PROGRAM

2.1 Soil Tested

The soil used in this study is kaolinite clay that was reconstituted by one-dimensional consolidation of slurry that is pre-

pared by mixing dried commercial grade kaolinite powder with distilled water. Tube samples of diameter of 35 mm were extracted from the consolidated clay, and the final prepared specimen size was 35 mm in diameter and 70 mm in height. The following properties were found from laboratory tests carried out on the clay samples: Specific gravity $G_s = 2.65$; plastic limit $w_p = 26\%$; liquid limit $w_L = 53\%$; compression index $C_c = 0.42$; swelling index $C_s = 0.06$; and coefficient of consolidation $c_v = 1.27 \text{ m}^2/\text{year}$.

2.2 Testing Apparatus and Procedures

The testing apparatus used in the current study is capable of conducting static as well as cyclic loadings. The triaxial system used is shown in Fig. 1, which consists of the following components: Triaxial cell, loading frame with computer-control platen that applies cyclic axial load on top of soil specimen, two computer-control flow pumps to control the chamber pressure and back pressure, high performance linear servo control electro actuator for cyclic loading with update rates of 500 times per



Fig. 1 Static/cyclic loading triaxial system used

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second, micro-processor for controlling cyclic loading, PC with a Pentium processor to control the test and a data logger. Various transducers are mounted in the system for measuring the axial load, confining pressure, pore-water pressure and axial strain.

Four series of cyclic loading tests were conducted on soft clay soil specimens over a range of consolidation history, including normally consolidated and over-consolidated soils with over-consolidation ratio of 1.5 and 20. All soil specimens were consolidated using a back pressure of 200 kPa, which is considered to be sufficiently enough to achieve full degree of saturation. Over-consolidation was prepared by applying a prior consolidation to the soil specimens and subsequently allowing them to swell under a lower isotropic consolidation pressure. In each consolidation (or swelling) stage, all-round pressure was maintained for a period equal to three times that of T_{100} (*i.e.* time factor corresponding to 100% consolidation).

Before conducting the cyclic loading tests, static undrained compression tests were first performed to determine the maximum static deviator stress, $q_{\max\text{-static}}$, at which the cyclic deviator stress, q_{cyclic} , needs to be applied so that a certain cyclic stress ratio, $CSR = q_{\text{cyclic}} / q_{\max\text{-static}}$, is achieved. The static axial compression tests were conducted at a control rate of deformation between 0.0035 ~ 0.015%/min. The range of axial strain rate was deemed to be slow enough to ensure adequate equalization of excess pore water pressure within the specimen before reaching its peak strength.

In each cyclic test, the clay specimen was subjected to cyclic undrained compression by continuous application of cyclic deviator stress, q_{cyclic} , of a sinusoidal shape. The cyclic loading was continued until the specimen either failed (with large deformation) or reached a state of stress equilibrium at which the stress path in the p' - q plane followed closed hysteresis loops. In each series of the cyclic loading conducted, various CSR were carried out so as to reach the failure state at CSR higher than that of the critical stress. All tests were conducted at a cyclic loading frequency of 1Hz, and the excess pore water pressures were measured at the top and bottom of each specimen. With cyclic loading frequency at this rate, the equalization of pore water pressure within the specimen did not take place in each loading cycle; however, the pore water pressure has been equalized after the arrival of the state of stress equilibrium.

2.3 Testing Results and Analysis

Normally Consolidated Samples

In this series, all test specimens were subjected to an isotropic consolidation pressure of 300 kPa. As mentioned previously, static undrained compression test was first performed to determine the maximum static deviator stress, which was found to be equal to 140 kPa and was reached at 15% total axial strain (*i.e.* recoverable elastic + unrecoverable plastic). The cyclic undrained compression tests were thus conducted at various proportion of 140 kPa, representing various CSR and the results of the excess pore pressure and total axial strain versus number of load cycles are shown in Figs. 2 and 3, respectively. It can be seen that, within the range of the CSR values considered, the tests conducted up to $CSR = 0.63$ showed no sign of failure. Within this range, Fig. 2 shows that the excess pore water pressure

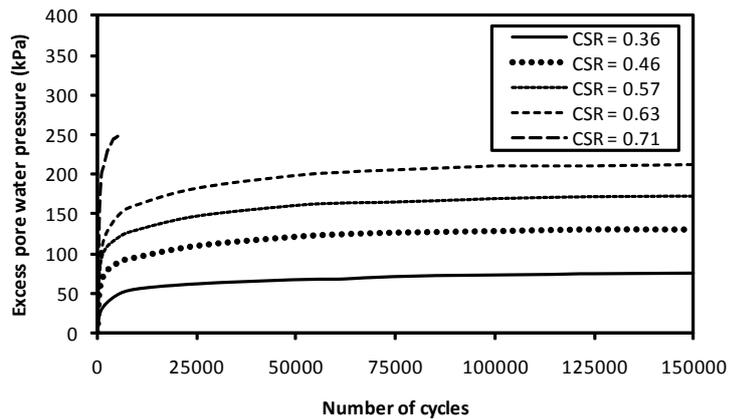


Fig. 2 Development of excess pore water pressures during cyclic loading for the normally consolidated soil specimens ($\sigma_3' = 300$ kPa)

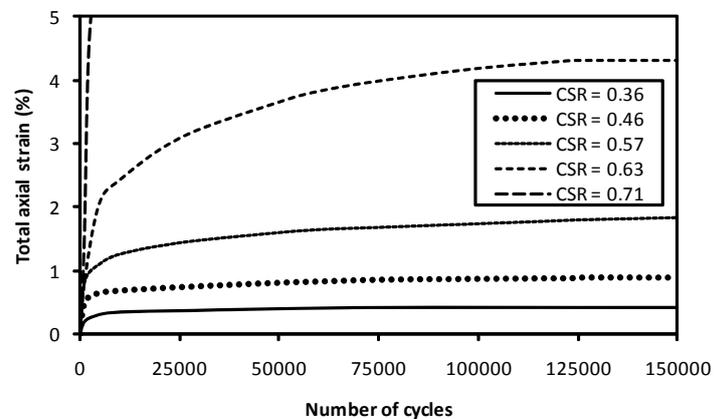


Fig. 3 Total axial strain during cyclic loading for the normally consolidated soil specimens ($\sigma_3' = 300$ kPa)

builds up at a reducing rate until it reaches a plateau at about 100,000 cycles. Figure 3 shows that the total axial strain was also increasing at a decreasing rate with the loading cycles and starts to show stabilization at 100,000 cycles. It can also be seen that at $CSR = 0.71$, very sharp increase in excess pore water pressure (Fig. 2) and total axial strain (Fig. 3) occurred after the first few thousands of cycles, leading to a marked increase in non-recoverable deformation and eventually failure.

In order to appreciate the significance of the above results, the data obtained are represented in the stress path of p' - q plane. An example of the stress path obtained for a cyclic deviator stress of 50 kPa (*i.e.* $CSR = 0.36$) is shown in Fig. 4. It can be seen that due to the increase in pore water pressure, the stress path of each load cycle gradually migrates to the origin of the p' - q plane and begins to form closed hysteresis loops at about 100,000 cycle. At this stage, the total axial strain of soil specimen has also achieved strain stabilization, as shown previously in Fig. 3. Consequently, a state of elastic resiliency has arrived in which both the state of stress equilibrium and strain stabilization exist. The term "peak stress path" is introduced here which represents the state of stress in each cycle when the deviator stress is at its maximum value, as shown in Fig. 4. In Fig. 5, an overall view of the stress paths represented by the peak stress path curves is shown for all normally consolidated soil specimens. The peak stress paths indicate that

all tests have reached the state of stress equilibrium, except that for the peak stress path of $CSR = 0.71$, which shows that each load cycle leads to further plastic deformations and ultimately effective stress failure. It can also be seen from Fig. 5 that under an isotropic normally-consolidation pressure of 300 kPa, the threshold stress can be achieved at CSR between 0.63 and 0.71; however, more tests between these CSR values are needed for exact estimation of the threshold stress.

Over-Consolidated Samples

Cyclic loading tests were also conducted on lightly over-consolidated soil specimens of $OCR = 1.5$ and heavily over-consolidated soil specimens of $OCR = 20$. For lightly over-consolidated soil, the specimens were first consolidated to 300 kPa and subsequently swelled to a consolidation pressure of 200 kPa. For heavily over-consolidated soil, the specimens were first consolidated at much higher pressure of 600 kPa and were then left to swell at a consolidation pressure of 30 kPa. As previously made with the normally consolidated soil specimens, static loading triaxial tests were conducted before the cyclic loading tests so as to obtain the maximum deviator static loading at which various CSR are applied in the cyclic loading tests. The maximum static deviator stress for soil of $OCR = 1.5$ was found to be equal to 115 kPa and was reached at 10% total axial strain. On the other hand, the maximum static deviator stress for soil of

$OCR = 20$ was found to be equal to 70 kPa and was reached at 12% total axial strain. The peak stress paths of the cyclic loading tests at various CSR are shown in Figs. 6 and 7 for tests conducted at $OCR = 1.5$ and 20, respectively.

It can be seen that for both lightly and heavily over-consolidated soil specimens, the state of stress equilibrium has been reached for all cyclic deviator stresses lower than the critical stress level. However, an interesting finding demonstrated in Fig. 7 for heavily over-consolidated clay of $OCR = 20$ is that there was no sign of progressive excess pore water pressure build-up below or above the critical stress level, and both the state of equilibrium (below the critical stress level) and the state of effective stress failure with large strain (above the critical stress level) have been reached after the very first few cycles of loading.

3. CONCLUSIONS

A series of undrained triaxial compression tests under cyclic loading conditions was conducted on reconstituted soft kaolinite clay. The effect of stress history (*i.e.* over-consolidation ratio) on the behavior of clay under successive repeated loads was investigated. The findings of the study suggest that the level of critical stress is dependent on the current state of stress and stress history.

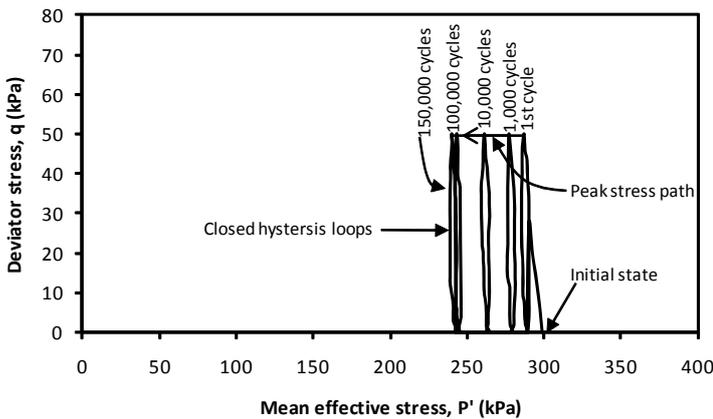


Fig. 4 Typical example of stress path for the normally consolidated soil specimen tested at $CSR = 0.36$ ($\sigma'_3 = 300$ kPa)

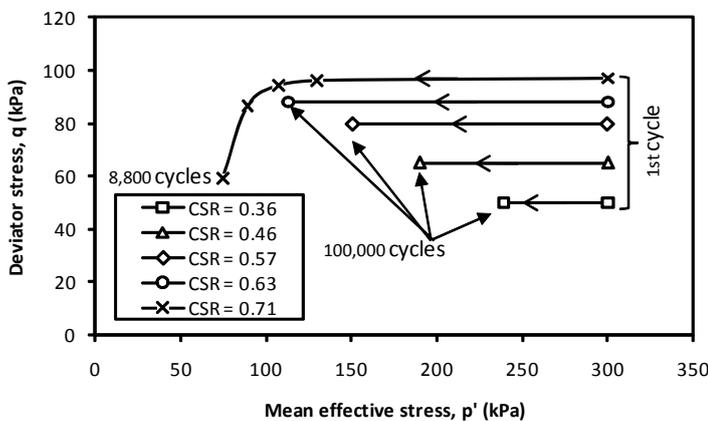


Fig. 5 Peak stress paths for the normally consolidated soil specimens tested at various CSR values ($\sigma'_3 = 200$ kPa)

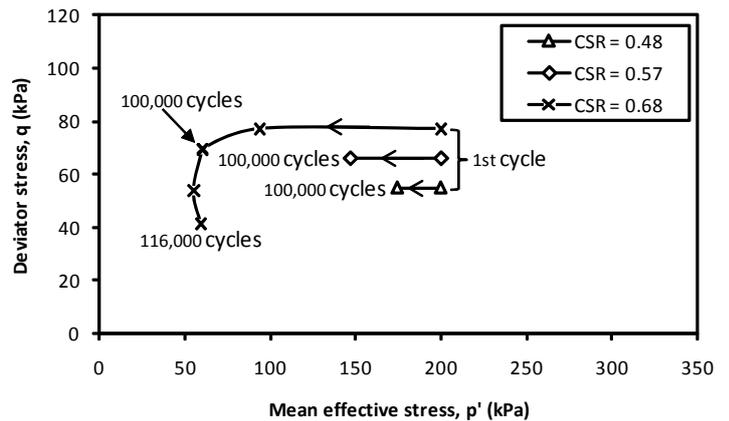


Fig. 6 Peak stress paths for the lightly over-consolidated soil specimens of $OCR = 1.5$ tested at various CSR values ($\sigma'_3 = 300$ kPa swelled to 200 kPa)

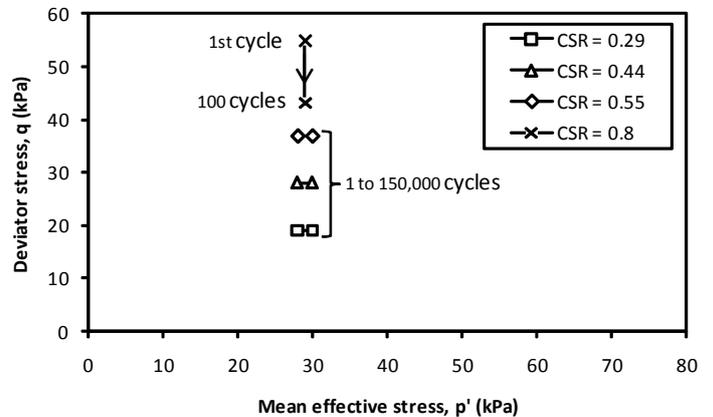


Fig. 7 Peak stress paths for the heavily over-consolidated soil specimens of $OCR = 20$ tested at various CSR values ($\sigma'_3 = 600$ kPa swelled to 30 kPa)

The results of the tests conducted indicate that, if the clay soil is tested at a deviator stress below the critical stress level, a state of non-failure stress equilibrium is reached and the soil eventually behave elastically. However, for heavily over-consolidated soil of $OCR = 20$, the elastic behavior commences at the very first few load cycles. On the other hand, if the soil is tested at a deviator stress higher than that of the critical stress level, progressive pore water pressures build up and each load cycle leads to further plastic deformations and soil ultimately reaches a state of effective stress failure. However, for heavily over-consolidated soil of $OCR = 20$, soil does not show sign of progressive pore water pressures build-up and the soil ultimately fail at large strain after the very first few load cycles. It should be noted that the results obtained are subject to the levels of confining pressures used and more tests are needed with different confining pressures and more consolidation ratios so that the above findings can be confirmed. However, based on the limited data from the current study, the findings obtained provide an important insight, though preliminary, into the effect of stress history on the behavior of soft soils subjected to repeated loading. These findings have a direct relevance that benefits the stability studies of geotechnical structures constructed on low-lying estuarine soils and subjected to cyclic loading such rail track foundations and road pavements.

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