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THE APPLICATION OF CAM-CLAY MODEL IN INTERPRETING THE RESULTS OF TRIAXIAL KO CONSOLIDATION TESTS

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ABSTRACT

An automated triaxial testing device was used in this study to investigate the K_0 value of Taipei silty clay. It was found that under different initial stress conditions, the resulting effective stress paths would assume different shapes which causes difficulty in interpreting the test results. Numerical analyses based upon the modified Cam-Clay model were subsequently conducted to gain an insight look regarding the characteristics of the K_0 consolidation tests. The numerical results showed that the modified Cam-Clay model is suitable for interpreting the test results. It is also concluded that the accuracy of K_0 value derived from K_0 consolidation test depends very much on the capability of the automated cell in limiting the lateral deformation. A guideline for determining the K_0 values for Taipei silty clay via automated laboratory testing procedures is also provided.

I. INTRODUCTION

The value of K_0 , the coefficient of lateral earth pressure at rest, is an essential parameter in many geotechnical problems. One of the primary uses of K_0 is in estimating lateral pressure against earth retaining structures. Another major application of K_0 is in establishing the initial stress condition for finite element analysis, which is considered a powerful tool for solving complicated boundary value problems often encountered in the field of geotechnical engineering. Experience has shown that the results of numerical analyses using the finite element method can be very sensitive to the initial stress conditions; therefore, the value of K_0 must be accurately ascertained.

Although the importance of K_0 is indisputable, no generally accepted method is currently available for predicting K_0 . At present, four different methods can be used to evaluate K_0 . These methods are : in-situ testing, laboratory testing, empirical correlation and theoretical analysis. Among these methods, empirical correlation is the most widely used. The empirical correlation, generally referred to as Jaky's equation (1944), associated K_0 value with effective friction angle. A study performed by Mayne and Kulhawy (1982) showed that Jaky's equation can at best be regarded as a statistical

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mean value approach with high standard deviation (Fig. 1), which renders this approach unsuitable for advanced numerical analysis. On the other hand, in-situ test is prone to the effect of soil disturbance, often making the interpretation of test results difficult. Though self-boring pressuremeter and Marchetti's flat dilatometer seem to be very promising tools (Jamiolkowski et al, 1985 and 1988), limited experience of these devices suggesting that the reliable determination of K_0 by in-situ tests remains a challenging and not yet completely solved problem.

With the advent of the laboratory testing technique and better understanding of the stress-strain relationship of soils, the most promising approach is to combine laboratory testing and theoretical analysis in determining K_0 . Testing procedures and devices developed in recent years not only offer a viable means to eliminate possible soil disturbance due to sampling, but also provide a well controlled stress environment to simulate the in-situ K_0 condition. Test data, however, need appropriate interpretation to deduce useful results. Theoretical analysis, which is ideal for solving problems with well specified boundary conditions, serves in appropriately interpreting the test data.

In this study, the automated triaxial testing device developed at the University of California at Berkeley (Chan, 1981) was used to conduct K_0 consolidation test. Stress path of each test was plotted to deduce the K_0 value. However, the stress paths were found to assume various shapes and sometimes fail to follow a straight line in contrast to common believe. In order to have a better understanding regarding the nature of K_0 consolidation test, the elasto-plastic modified Cam-Clay model developed by a Cambridge University research group (Roscoe and Burland, 1968) was used in conjunction with finite element method to interpret the test results.

II. LABORATORY TESTING PROGRAM AND RESULTS

The K_0 consolidation tests were conducted via the use of an automated triaxial cell developed by Chan (1981). Computer controlled tests were performed on "undisturbed" Taipei silty clay samples recovered from various locations. The properties of the Taipei silty clay have been extensively investigated in previous studies (Cheng, 1987; Huang et al, 1988), the typical index properties of the soil samples are as follows :

Saturated Unit Weight = 18 KN/m^3
Specific Gravity = 2.70
Liquid Limit, LL = 37%
Plasticity Index, PI = 15%

Soil specimens of 7 cm diameter by 15 cm height were carefully trimmed from "undisturbed" samples obtained by stationary piston sampler and placed inside the triaxial cell with porous stones on top and bottom. A filter paper jacket was applied around the sample to expedite the dissipation of excessive pore pressure. The wrapped sample was then encircled with thin rubber membrane and secured with O-rings. The chamber was placed upon the cell and the cell was filled with de-aired water.

After assembling the triaxial cell, the soil specimen was saturated and isotropically consolidated under the desired back pressure and cell pressure for a period of at least 18 hours to obtain a fully saturated sample. The Skempton's pore pressure parameter, B , was generally found to exceed 0.95 as a result of the saturation process.

To perform the K_0 test, a computer program was subsequently activated to gradually increase the axial stress at a rate slow enough to allow for complete pore pressure dissipation by the end of the loading period. Lateral deformations were monitored indirectly by comparing the magnitude of volumetric and axial strains, and cell pressure was changed accordingly to eliminate any lateral deformation that developed during the loading process. By doing so, a pseudo K_0 condition was maintained and the ratio between effective lateral stress and axial stress is regarded as the K_0 value. It is a common believe that once the effective stress path reaches the normally consolidated state and touches the K_0 line, it will remain on the K_0 line as test progresses.

Three representative K_0 consolidation test results were presented in this study. For the first test, the specimen was recovered from a depth of about 12 m below ground surface and consolidated under an effective isotropic pressure of 8.6 kPa before testing. The ensuing K_0 consolidation process resulted in an effective stress path as shown in Fig. 2. It is observed that the effective stress path surpasses the assumed K_0 line at low stress level, crosses the assumed K_0 line again at high stress level but never stays on the assumed K_0 line as expected. The second set of test was performed on a specimen recovered from a depth of about 7 m. Before subjecting to the K_0 consolidation process, the specimen was isotropically consolidated under an effective stress of 100 kPa. The resulting stress path concaves downward before reaching the assumed K_0 line and remains on the K_0 line thereafter (Fig. 3). The third specimen was recovered from a depth of 18 m and also isotropically consolidated under an effective pressure of 100 kPa before testing. The stress path (Fig. 4) is found to concave upward then downward before reaching and staying on the assumed K_0 line.

The K_0 values obtained from the three series of tests were 0.53, 0.64 and 0.69, respectively. It is observed that laboratory results of the second and third tests eventually fall upon a straight line passing through the origin

as shown in Fig. 3 and 4. These straight lines are regarded as the K_0 lines, resulting in a K_0 value of 0.64 and 0.69 for the second and third tests, respectively. As for the first test, the laboratory curve did not converge to a straight line, slope of the K_0 line was taken as the tangent of the stress path when the applied axial stress just exceeded the estimated preconsolidation pressure. This approach yielded a K_0 value of 0.53 for the first test.

III. NUMERICAL SIMULATIONS

It is of great interest to understand why the stress paths assume various shapes under different initial stress conditions from a theoretical point of view. In the authors' opinion, a modified Cam-Clay model based finite element program is the ideal tool for interpreting the test results. The modified Cam-Clay model (Roscoe and Burland, 1968) is an elasto-plastic isotropic hardening model with elliptical yield surfaces to describe the stress-strain behavior of soft cohesive soils (Fig. 5). Normality principle and associated flow rule constitute the backbone for evaluating the plastic strain increments for soil element subjecting to stress increments in the plastic state. The details regarding the derivation of Cam-Clay constitutive equations were given by Roscoe and Burland (1968).

The constitutive equation alone has only limited capability to solve for complicated boundary value problems, and it has to be implemented through numerical analytical methods to have practical uses. This requirement was achieved by coding the constitutive model into a finite element program CLAY2D as described by Hsieh and Kavazanjian (1987) in a previous report.

Numerical simulation of the triaxial K_0 consolidation tests were conducted by loading a 9-node quadrilateral element in the axial direction as shown in Fig. 6. The single element was laterally confined to simulate the K_0 condition. The initial stress conditions of numerical simulations were the same as their laboratory counterparts, and the preconsolidation pressures were taken as the in-situ overburden pressures, which implied that the first and third simulations were started from an overconsolidated state while the second simulation was initially in a normally consolidated state. The input parameters including the initial stresses and Cam-Clay model parameters were presented in Table 1.

IV. RESULTS OF THE SIMULATIONS

The effective stress paths produced by the numerical simulations were plotted on Fig. 2, 3 and 4 together with the laboratory test curves for comparison. For the first simulation with a low effective confining pressure

of 8.6 kPa, the effective stress path promptly returned to and stayed on the assumed K_0 line without exhibiting the same characteristics as the laboratory test curve (Fig. 2). Failure of the numerical simulation to reproduce the laboratory curve may be attributed to the effect of sample disturbance which is an inevitable consequence of the sampling process. The degree of sample disturbance can not be quantified and is therefore not considered in the analysis. Another possibility is that the soil sample was initially in a heavily overconsolidated state, its behavior simply can not be explained by the use of modified Cam-Clay theory.

Based upon the concept of critical state soil mechanics (Schofield and Wroth, 1968), the heavily overconsolidated soil sample would increase its volume when sheared. Given this information, the automated triaxial cell would respond with a minimal increase in cell pressure, forcing the effective stress path to move across the critical state line until reaching the Hvorslev surface. The effective stress path was expected to return to and stay on the K_0 line at high stress level. However, for this particular test, the effective stress path was found to drop below the assumed K_0 line as shown in Fig. 2. There were no definite explanations for this phenomena at this stage, though it was suspected that sample disturbance, system control algorithm of the automated cell as well as the effect of small lateral deformation might have all played a role in shaping the effective stress path.

For the second numerical simulation, the resulting effective stress path resembled the laboratory test curve as shown in Fig. 3, suggesting that the modified Cam-Clay model is suitable for interpreting the K_0 consolidation test result provided that prior to testing the soil specimen is isotropically consolidated to a normally consolidated state to eliminate most of the sample disturbance.

For the third numerical test, the stress path in general followed the laboratory test curve (Fig. 4). The numerical simulation curve however showed a distinctive "kink" compared with the laboratory curve. From a theoretical point of view, the "kink" was the dividing point between overconsolidated and normally consolidated states, the effective stress path therefore assumed different shapes before and after reaching the modified Cam-Clay yield surface. The laboratory curve did not show the "kink" on the speculation that the sample disturbance might have masked the effect of preconsolidation pressure.

V. DISCUSSIONS

The numerical simulation curves disclose that the effective stress paths will remain on the K_0 line if a "true" K_0 condition can be maintained.

However, laboratory test curves shown on Figs. 3 and 4 were found to only more or less stay on a straight line, the K_0 values had to be determined via a best-fit approach. The deviation of stress path from the K_0 line is attributable to the effect of inevitable small lateral displacement developed during the triaxial K_0 consolidation stage. As the test progressed, the cell pressure had to be constantly increased to eliminate any small lateral deformation detected by the transducers. This process implied that the sample was actually under a pseudo K_0 state with small lateral tolerance.

Laboratory technician reported that the maximum lateral tolerance was controlled under 0.01% in the course of the tests. To what extent the K_0 value may be affected by this amount of lateral tolerance is also investigated. A series of numerical analyses using the same 9-node element were conducted. A small lateral deformation was allowed to develop to simulate the pseudo K_0 condition. The results for soil samples with different material parameters are presented in Fig. 7, indicating that the K_0 value may deviate by about 0.01 if a lateral strain of 0.01% occurs, and by more than 0.04 for a 0.04% lateral deformation.

The selection of Cam-Clay parameters also had profound effects on the outcomes of numerical analysis. The numerical simulations presented in this paper are the so called Type C prediction, in which the input parameters were back calculated from the K_0 consolidation results. In practice, the Cam-Clay parameters are to be derived from one-dimensional consolidation test and triaxial compression test. The parameters presented in Table 1 are markedly different for each test. Considering that soil samples were recovered from different depths and locations, it is only natural to expect that basic soil parameters assume different values.

VI. CONCLUDING REMARKS

It is found in this study that the modified Cam-Clay model is a viable tool in interpreting the triaxial K_0 consolidation test results for normally consolidated or lightly overconsolidated soils. However, the Cam-Clay model can not account for the expanding characteristics of heavily overconsolidated soils as well as the effect of sample disturbance, the prediction is often far from realistic.

The system control algorithm as well as the transducers' sensitivity of the automated cell are both essential for conducting a successful K_0 consolidation test. The automated cell must keep the lateral strain within a reasonable tolerance to ensure that the stress path will fall on a straight line at high stress levels. The K_0 value of the soil sample can then be estimated from the slope of the K_0 line. How sensitive is the K_0 value to the characteristics of the automated cell is not clear at this stage, but

the numerical analysis indicates that the K_0 value may be off by 0.01 or much more depending upon the system characteristics.

Based upon the experience acquired in the course of this study, it is suggested that the soil sample be at least isotropically consolidated to a lightly overconsolidated state to eliminate most of the sample disturbance prior to testing. The K_0 line can be easily identified by inspecting the resulting effective stress path if appropriate testing procedures are followed. If starting the test from a very low effective confining pressure such as the 8.6 kPa used in the first laboratory test, great difficulty is likely to be encountered in interpreting the results.

To the authors' best knowledge, the K_0 value and stress history of the Taipei silt had not been extensively studied in the past. It is difficult to verify if the K_0 values deduced from these three laboratory tests are compatible with the in-situ values. A systematic research incorporating in-situ testing, laboratory testing and numerical analysis is required to establish the K_0 values of Taipei silty clay at various locations for future use.

LIST OF SYMBOLS

- K_0 : The coefficient of lateral earth pressure at rest
 K : The ratio between effective lateral pressure and axial pressure
 B : Skempton's pore pressure parameter
 σ'_1 : Effective axial pressure
 σ'_3 : Effective lateral pressure
 P : Effective stress path parameter, $(\sigma'_1 + \sigma'_3)/2$
 q : Stress path parameter, $(\sigma'_1 - \sigma'_3)/2$
 λ : Virgin compression index
 κ : Recompression index
 M : Slope of the critical state line
 e : Void ratio
 P_c : Preconsolidation pressure

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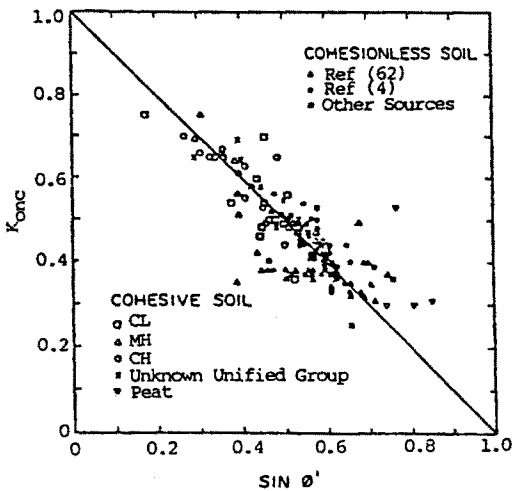


Fig. 1 The Relationship Between K_{0c} and $\sin \theta'$ (Mayne and Kulhawy, 1982).

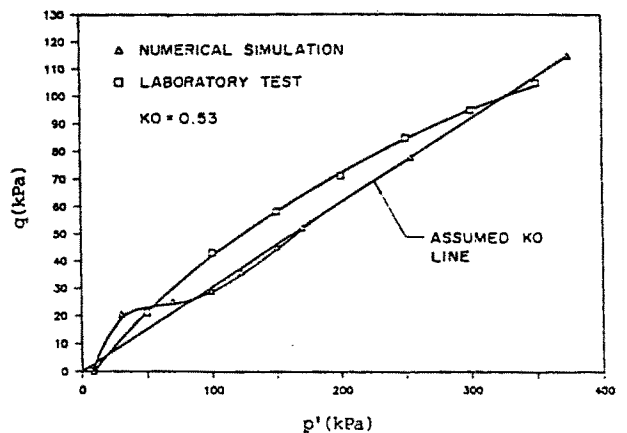


Fig. 2 The Effective Stress Paths of Test #1.

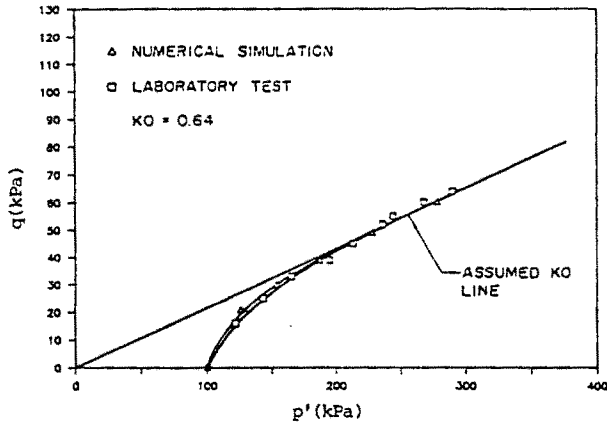


Fig. 3 The Effective Stress Paths of Test #2.

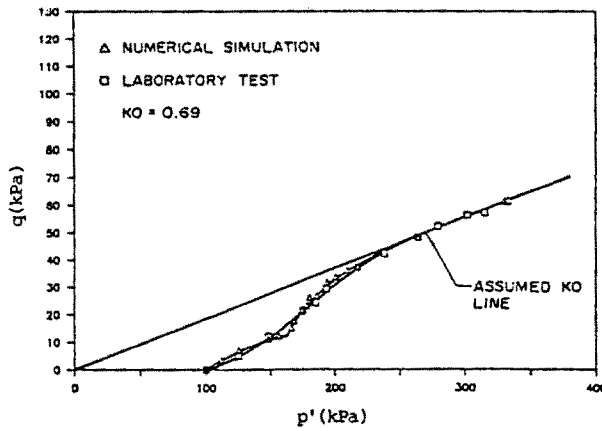


Fig. 4 The Effective Stress Paths of Test #3.

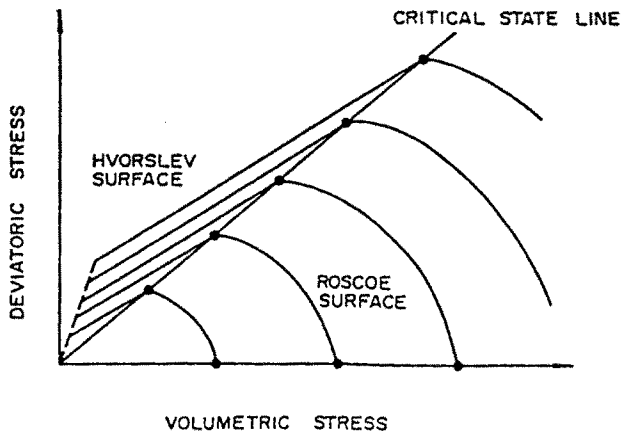


Fig. 5 The Modified Cam-Clay Yield Surfaces

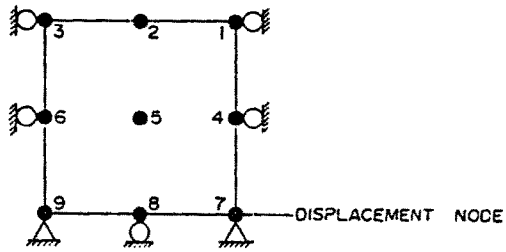


Fig. 6 The 9-Node Quadrilateral Element

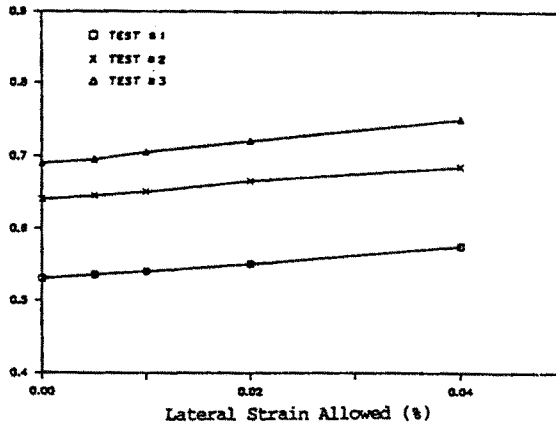


Fig. 7 The Variation of K Values with Lateral Strain.

PARAMETERS	SYMBOLS	Test #1	Test #2	Test #3
Virgin Compression Index	λ	0.16	0.16	0.16
Recompression Index	κ	0.032	0.032	0.016
Slope of Critical State Line	M	1.53	1.22	1.15
Initial Void Ratio	e	1.85	1.78	1.72
Preconsolidation Pressure	Pc	107 kPa	100 kPa	167 kPa

Table 1. Material and State Parameters Adopted for Numerical Simulation