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ON THE LABORATORY MEASUREMENT OF TIME-DEPENDENT K_o BEHAVIOR

A PROPOS DE MESURES EN LABORTOIRE DE K_o EN FONCTION DU TEMPS

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SYNOPSIS: Lateral stress changes during drained creep of saturated, cohesive soil is reviewed and evaluated based on laboratory investigations and finite element simulations. Laboratory tests were conducted on medium plastic, glacial Chicago clays. The numerical simulations utilized a constitutive model which separated the time-independent and time-dependent parts. The time-independent behavior is simulated using an elasto-plastic isotropic-hardening model whose yield surface is the ellipsoid of the Modified Cam clay model. Time-dependency is incorporated by allowing creep strains and quasi-preconsolidation to develop. The K_o triaxial test is shown not to be an elemental test, i.e., global measurements do not represent an elemental behavior of the specimen. System leakage is shown to be an important testing detail which is often overlooked. Finally, the variation of K_o with time is shown to be minor for the medium plastic Chicago clay.

INTRODUCTION

Drained creep of saturated, cohesive soil is generally assumed to take place under conditions of constant effective stress. For conditions of zero lateral strain, equilibrium considerations require that the vertical effective stress remains constant during long term sustained loading. However, the horizontal effective stress is not dictated by such equilibrium constraints. How these lateral stresses change during creep involves correctly predicting a fundamental aspect of soil behavior.

Oedometers and triaxial cells are typically used to measure lateral stresses during one-dimensional drained creep, or secondary compression. Oedometers have either semi-rigid confining rings to which strain gauges are attached or flexible walls wherein the strain is measured and horizontal stress is increased to maintain the zero lateral strain condition. In the semi-rigid oedometer, small but measurable lateral strain occurs. While the flexible wall oedometer allows lateral strain, the strains can be controlled within some minimum tolerance and the lateral stress is easily measured.

Three types of modified triaxial cells have been developed to measure lateral stresses: rigid, null, and control volume. The rigid cell and null triaxial are comparable to the semi-rigid oedometer and the flexible wall oedometer, respectively. The control volume triaxial cell measures global radial strains by detecting the changes in volumetric and axial strain. Volumetric strain is determined by measuring the quantity of water that exits the specimen during the test. Axial strain is determined by means of a global axial displacement. To maintain K_o conditions, the lateral pressure is measured and altered to approximately maintain a condition of zero radial strain.

The elemental nature of the tests from which K_o is measured is questionable. When clays are consolidated, the rate must be slow enough to preclude excessive pore pressure accumulation in the specimen. For strain controlled tests, uniform stresses are difficult to maintain as a result of pore pressure accumulation during straining, especially for large diameter specimens.

One way to evaluate the elemental nature of the test is to conduct finite element simulations, which necessitates specifying a constitutive model. If stress changes during creep are required, then a time-dependent model is needed. Various theoretical approaches have been developed to study the general effects of rate-dependent material response. However, they are generally based on either axisymmetric or one-dimensional constrained response. Material time-dependence has been incorporated into general constitutive models for plane strain and three dimensional loadings (e.g., Hsieh and Kavazanjian,1987). Of course, specifying the constitutive response sets the nature of the time-dependent behavior. However, a coupled pore pressure and displacement finite element analysis can allow hydrodynamic time-dependence and uniformity of internal stresses to be evaluated.

The purpose of this paper is to review existing long-term lateral stress data and to evaluate the responses with respect to testing details. Finite element simulations based on existing rate-dependent formulations are presented to further illustrate some of the limitations of these published results as well as to evaluate the elemental nature of the tests.

EXPERIMENTAL DATA BASE

The question of time-dependent K_o behavior has not been completely resolved, as illustrated by the wide variation of experimental results on the subject shown in Table 1.

In Table 1, the method of lateral restraint is indicated. Direct restraint refers to a semi-rigid oedometer. Indirect control refers to apparati in which lateral strains are measured and compensated. As indicated in Table 1, much of the variation in existing K_o laboratory results is apparently device related. With the exception of the early work of Thompson (1963), only the tests performed in triaxial cells show an increase of K_o. The triaxial cell utilizes an indirect method of controlling the zero lateral strain condition. In the K_o triaxial test, cell pressure is automatically adjusted such that the volumetric strain is maintained equal to the axial strain. However, if the volumetric contribution does not correctly reflect the change in the specimen volume then the correction will be inaccurate. Tavenas et al. (1983), Mesri and Castro (1987), and Gausseres (1988) all found that leakage occurs in the most careful experimental techniques. If this is unaccounted for, an automated system will sense less volumetric strain than is actually occurring in the specimen, therefore, spuriously increasing the cell pressure, resulting in a higher apparent K_o value. The only triaxial cell test which shows a decrease in K_o is that of Gausseres (1988). Details of Gausseres' tests will be presented to show the effects of leakage on reported results.

Leakage Effects

Gausseres (1988) conducted long-term K_o tests on natural Chicago clay specimens using an automated triaxial cell. The axial strain rate during consolidation was 0.0066 %/hr. At this rate, 330 hours were needed to consolidate the Chicago clay to a vertical effective stress of 200 kPa. The sustained vertical load was maintained for 400 hours. Mid-plane pore pressures were monitored throughout the test. Figure 1 shows a typical response wherein K_o decreased with time during creep.

Table 1. Reported K_o Behavior During Creep

Apparatus	K_o Result	Method of Lateral Strain Control	Reference
Oedometer	Increased	Direct Restraint	Thompson (1963)
Flexible Oedometer	Constant	Indirect; Lateral Strain Control	Newlin (1965)
Oedometer	Decreased	Indirect; Volume Control	Davidson and Schmertmann (1985)
Square Oedometer	Constant	Direct Restraint	Jamiolkowski et al. (1985)
Triaxial Cell	Increased	Indirect; Volume Control	Lacerda (1977)
Automated Triaxial Cell	Increased	Indirect; Volume Control	Hsieh and Kavazanjian (1985)
Triaxial Cell	Increased	Indirect; Volume Control	Mesri and Castro (1987)
Automated Triaxial Cell	Decreased	Indirect; Volume Control w/Leakage Adjustment	Gausseres (1988)

Gausseres (1988) found that water leaked from the system at a rate of 1.8 x 10^{-3} cc/hr (1 drop of water every 28 hours). The effect of this water loss was incorporated into the testing sequence by adding this water loss to the measured volume of water expelled from the system. The following equation, based on linear elasticity, was used to evaluate the lateral stress changes caused by leakage:

$$\Delta\sigma_3 = \frac{(e_a - e_{vol})\,(2\sigma_3 + \sigma_1)(1 + e)}{3\kappa} \qquad (1)$$

For the observed leakage rate, Equation 1 indicates that the value of K_o for a Chicago clay specimen would be overestimated by an amount equal to 0.0002/hr if the water loss was not considered. For the test shown on Figure 1, after 400 hours of creep the final K_o value would be 0.50 rather than 0.42 if leakage was not taken into account. This change is relatively small but would imply different conclusions about rate-dependent behavior. The value of K_o measured during creep is a sensitive number whose true value can easily be masked by laboratory testing procedures. Leakage and temperature control constitute the two main problems associated with testing procedures. Effects can be minimized by conducting the experiments in a temperature controlled environment using large specimens and including the leakage effects in the control loop.

NUMERICAL SIMULATIONS

The general creep-inclusive constitutive equation developed by Hsieh and Kavazanjian (1987) was used herein to evaluate the elemental nature of the K_o triaxial test.

Model Description

As suggested by Bjerrum (1967), the deformation behavior of normally to slightly overconsolidated clays may be separated into a time-independent part and a time-dependent part. The time-independent behavior is simulated using an elasto-plastic isotropic-hardening model whose yield surface is the ellipsoid of the Modified Cam clay model. (Time-independent volumetric strains consist of an elastic component whose magnitude is governed by the recompression index, and a plastic volumetric component obtained from the associative flow rule with a consistency requirement on the yield surface.) Time-independent deviatoric strains contain an elastic component governed by the elastic shear modulus, and a plastic deviatoric component scaled from the normal to the yield surface. This differs slightly from the Modified Cam clay model which assumes that deviatoric strains are purely plastic.

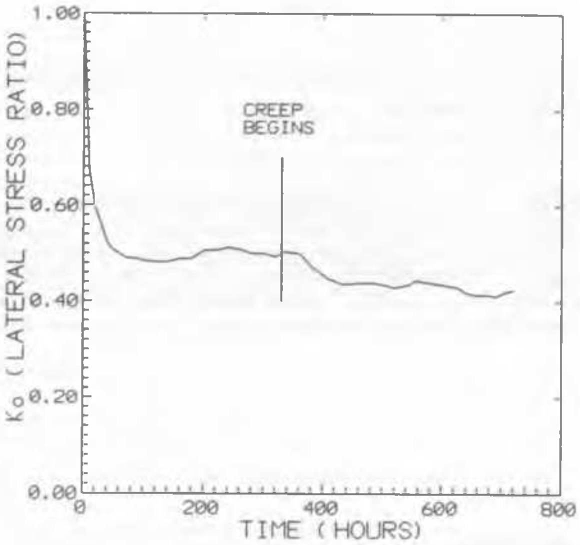

Figure 1. K_o versus Time for Chicago Clay

Time dependency is incorporated by allowing creep strains and quasi-preconsolidation to develop. The effect of quasi-preconsolidation is to make the size of the yield surface grow with time. The creep strain is determined either by prescribing the creep strain component along the volumetric axis according to the coefficient of secondary compression (volumetric scaling) or along the deviatoric axis according to the Singh-Mitchell creep function (deviatoric scaling).

Simulation of Tests

The purpose of the finite element simulations was to evaluate the internal stress-strain-pore pressure changes so that globally measured quantities can be interpreted. Vertical drainage with one pervious boundary (i.e. single drainage) was modeled in the simulations.

The finite element simulations employed an element with nine displacement nodes and four pore pressure nodes, one at each corner of the element (Q9P4). The Q9P4 element is a continuous pressure element for which a proof of convergence has been established (Hsieh and Kavazanjian, 1987).

The laboratory tests were performed by first, K_o consolidating a specimen by displacing the specimen at a constant rate and adjusting the cell pressure to indirectly maintain zero lateral strain (strain-control), and second, maintaining a constant stress at the top of the specimen and allowing it to deform freely (stress-control).

In the finite element simulation, load was applied at top of the specimen beginning with the initial confining stress and increased over the time of consolidation until the sustained vertical stress was reached. The vertical load was maintained through the creep stage.

The model parameters used in the finite element program are summarized by Harris (1991). The compression index, λ, is 0.180; the recompression index, κ, is 0.025; and the secondary compression index is 0.01. The hyperbolic stress-strain parameters a,b, and R_f are 0.0053, 1.45, and 0.90 respectively. The permeability of the Chicago clay is 2x10^{-7} m/min. The failure slope, M, is 1.13 and the critical state void ratio is 1.62.

OBSERVED AND COMPUTED RESULTS

Figure 2 shows a comparison plot of the e-log p' curve determined in the laboratory to that computed in the finite element simulation. This plot serves to confirm the validity of the parameters selected. The plot shows, however, that the slope of the virgin compression curve, C_c, was slightly overestimated in the finite element simulation. The reason for this was that the parameters chosen were not determined from the specific test performed by Gausseres (1988), but instead were average Chicago clay parameters developed from results of an extensive laboratory testing program (Chung,1991).

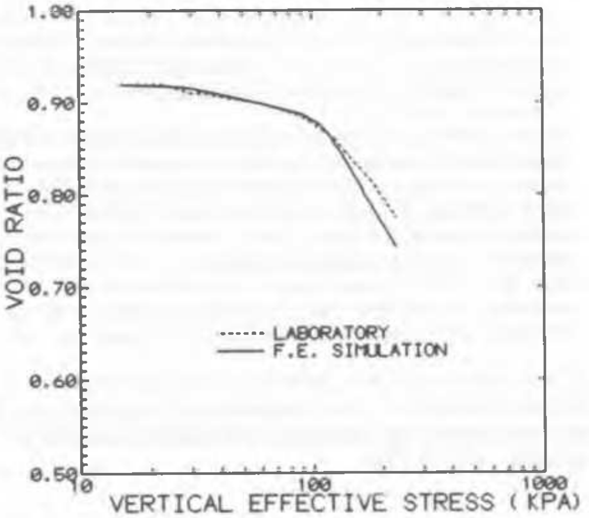

Figure 2. Comparison of e-log p'

Figure 3 shows a comparison plot of K_o versus vertical effective stress. Laboratory data is presented for the stresses based on both the pore pressures measured at the top (drained boundary) and bottom (mid-plane) of the specimen. Gausseres (1988) observed that, for Chicago clay, the value of K_o decreased until the effective vertical stress reached the in-situ effective vertical stress (σ_{vo}') of 92 kPa for the specimen shown in Figure 3, then increased until the loading equaled the maximum past vertical pressure (σ_p') and decreased during the "creep" stage of the test. The correct trend of behavior was predicted by the simulation. However, the simulation computes that a minimum K_o value is attained prior to σ_{vo}' and, K_o in the virgin compression range is overpredicted. This latter response is a commonly observed behavior of the modified Cam clay model (Wroth and Houlsby,1981).

Figure 3 also shows the influence of drainage boundary position on the computed K_o response. The simulated K_o values vary due to the relative proximity of each individual element to the drainage boundary. The laboratory K_o values vary over a range which overlaps that of the computed responses.

Figure 4 shows a comparison of K_o versus time for the Chicago clay. The laboratory results, which account for leakage, show K_o decreasing with time at a rate of 0.0002/hr. The finite element simulation results, however, indicate that the magnitude of K_o reaches a constant to slightly decreasing value. However, the results were found to be sensitive to the rate of leakage as shown previously.

Figure 5 compares the laboratory pore pressures observed at the mid-plane with those computed in the finite element simulation. In the laboratory test, the pore pressures increase until the sustained load is reached; thereafter the pressure begins to dissipate until a constant value is reached. Note that the pore pressures never fully dissipate at the mid-plane in the creep stage. This would indicate that a pore pressure gradient exists well into the "creep" stage and that tests conducted with displacement-controlled loading cannot be elemental. This pore pressure variation affects the K_o value found in the results of triaxial tests.

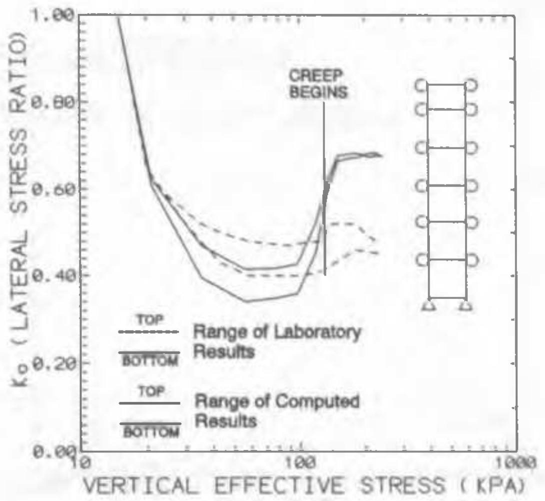

Figure 3. K_o versus Vertical Effective Stress

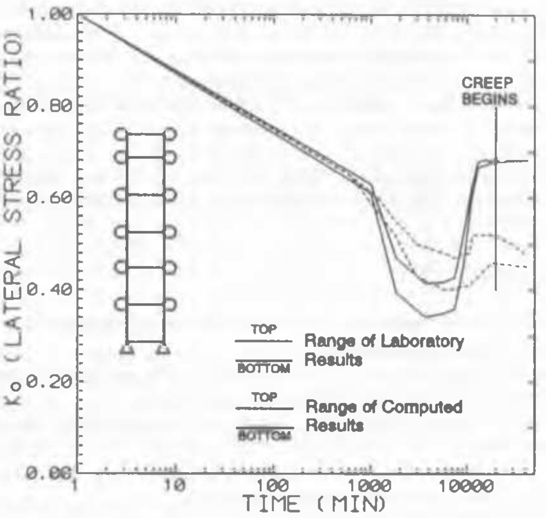

Figure 4. Comparison of K_o versus Time

DISCUSSION

The experimental and computed results suggest that the K_o triaxial compression test is not an elemental test. Figure 4 shows that the globally measured conditions are not an accurate representation of the specimen response. In fact, the response varies throughout the specimen due, primarily, to drainage boundary proximity. It would imply that the stress conditions in the specimen during K_o consolidation may not be what they seem (i.e., a lower effective stress than expected).

The experimental results of researchers on this topic have shown that the system control is influential in determining the K_o value obtained. The measurement of K_o during a long term test is extremely sensitive to fluctuations in the system such as unavoidable system leakage.

The importance of system leakage is that the commonly used triaxial devices

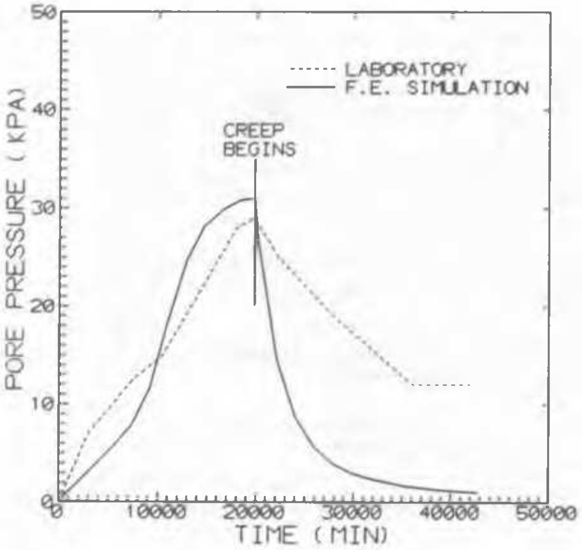

Figure 5. Comparison of Pore Pressure versus Time

mask the actual behavior of K_o with time because the devices are so sensitive to leakage as illustrated by Gausseres' experiments. When leakage was accounted for K_o apparently decreased with time. However, this result depends on the assumed rate of leakage employed in the control of the test. The net result is that K_o does not vary significantly with time, at least for medium plastic Chicago clays. This result would indicate that the values of K_o measured in the laboratory and in the field will not show significant differences due to aging effects. Also, the lateral stresses that exist in a soil deposit will show little, if any, variation over time due to mechanical effects alone.

CONCLUSIONS

Based on the experimental and numerical evaluations presented herein, the following conclusions can be drawn:

1. The K_o triaxial test is not an elemental test. The global measurements do not represent an elemental behavior of the specimen.
2. System leakage affects the value of K_o determined in automated laboratory testing. For triaxial tests which utilize an indirect method of control, leakage may result in the volumetric strain being underestimated which would lead to an overestimated value of K_o.
3. The variation of K_o with time of medium plastic, glacial Chicago clays is minor.

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