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A CRITICAL STUDY OF THE UNIQUENESS OF STATE BOUNDARY SURFACE FOR SATURATED SPECIMENS OF KAOLIN

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SYNOPSIS

This paper is concerned with a detailed study of the uniqueness of state boundary surface for saturated specimens of Kaolin. Specimens of Kaolin prepared from a slurry were sheared from several isotropic stress states under a wide variety of imposed stress paths in a conventional axisymmetric triaxial apparatus under stress controlled conditions. The data corresponding to the state paths followed by over 25 test specimens are presented and discussed. The effects of several other factors such as the initial one dimensional consolidation stress used in sample preparation, the load increment size, the load increment duration etc. on the state boundary surface are also considered in detail.

INTRODUCTION

The state boundary surface relating the voids ratio, e, the mean normal stress, p, and the deviator stress, q, is assumed to be a unique surface in almost all the stress-strain theories developed at Cambridge University. However experimental observations provided by ROSCOE & THURAIRAJAH (1964) indicated that the state boundary surfaces obtained in the conventional triaxial apparatus were distinct and different atleast for the two common types of test conditions, namely, the undrained test and the fully drained test. In this paper the author has presented the data associated with the state paths followed by over 25 test specimens subjected to different testing conditions and varying applied stress paths.

STRESS PARAMETERS USED IN TRIAXIAL TESTS

The stress parameters used in the analysis of the triaxial test results are:

$$p = (\bar{\sigma}_1 + 2\bar{\sigma}_3)/3 \quad \text{and} \quad q = (\bar{\sigma}_1 - \bar{\sigma}_3), \quad (\text{since } \bar{\sigma}_2 = \bar{\sigma}_3)$$

$\bar{\sigma}_1$, $\bar{\sigma}_2$ and $\bar{\sigma}_3$ are the principal effective compressive stresses.

PREVIOUS WORK DONE ON STATE BOUNDARY SURFACES

Constant Voids Ratio Contours of RENDULIC *(1936)*

RENDULIC (1936) performed a series of stress controlled compression and

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extension tests on remoulded saturated clay. The results were plotted in a $\bar{\sigma}_1$, $\sqrt{2}\bar{\sigma}_3$ space and Rendulic found that the stress paths followed by specimens sheared at constant voids ratio (undrained test) are in close agreement with the constant voids ratio contours derived from drained tests and isotropic consolidation tests. Further by assuming that these contours are reproducible in the $\bar{\sigma}_1 = \bar{\sigma}_3$ and $\bar{\sigma}_1 = \bar{\sigma}_2$ planes, Rendulic suggested that the constant voids ratio contours form surfaces of revolution about the space diagonal $\bar{\sigma}_1 = \bar{\sigma}_2 = \bar{\sigma}_3$ when plotted in the three-dimensional stress space.

Effective Stress, Water Content Relationships of HENKEL *(1960)*

HENKEL (1960) provided experimental results on Weald Clay and London Clay to illustrate the existence of a unique relationship between the effective stresses and the water content for each clay. The compression test results provided by Henkel are of three types with stress paths of slope, dq/dp, equal to $-3/2$, 3 and ∞ respectively. Similar stress paths are also imposed on the extension side. His results indicated that the constant water content contours obtained from drained tests are similar in form to the stress paths corresponding to the conventional undrained tests.

(p, q, e) Surface of ROSCOE *et al (1958)*

ROSCOE et al (1958) put forward a basic concept of the existence of a unique surface in the three-dimensional space relating the voids ratio e, and the stress parameters q and p. Such a surface for normally and lightly overconsolidated clays is represented by ABCD in Fig. 1 which is based on triaxial test data from Imperial College on Weald Clay. The surface CDEF corresponding to overconsolidated specimens is based on less reliable evidence than that supporting ABCD. Also these authors suggested that it is not possible for the specimen to exist at a state (defined by p, q and e) outside the domain bounded by the two surfaces ABCD and CDEF unless tensile stresses are imposed. These two surfaces are subsequently called the state boundary surface. In describing the surface ABCD in Fig. 1 ROSCOE et al (1958) only used the results of undrained tests.

Similarity of Undrained Stress Path and State Boundary Surface in Two-Dimensional Plot

Assuming that all the e = constant sections of the state boundary surface are geometrically similar ROSCOE & POOROOSHASB (1963) transformed this three-dimensional surface relating *(p, q* and *e)* into a two dimensional curve. The

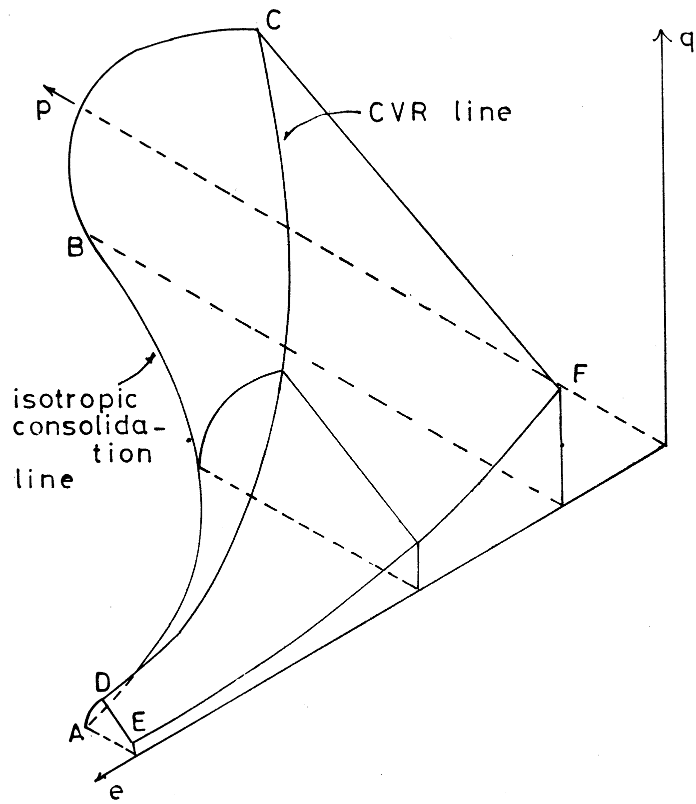

Fig. 1. (p, q, e) surface of ROSCOE et al (1958).

relevant parameters selected were q/p and $\frac{1}{p}$ exp $\left(\frac{e_a - e}{\lambda}\right)$ denoted by η and ξ respectively. The function exp $\left(\frac{e_a - e}{\lambda}\right)$ is equivalent to the parameter p_e defined by HVORSLEV (1937). In this relationship e_a corresponds to the voids ratio at unit pressure on the virgin consolidation line and p_e is the equilibrium pressure corresponding to the instantaneous voids ratio e on this line. Subsequent workers [e.g. BURLAND (1965)] have used the alternative parameters q/p_e and p/p_e for the two-dimensional representation of the state boundary surface. A unique curve can only be expected in this two dimensional plot for that part of the state path followed in any type of triaxial test that lies on the state boundary surface representing the state paths obtained from undrained tests.

Uniqueness of State Boundary Surface, ROSCOE & THURAIRAJAH *(1964)*

A detailed investigation of the state paths followed by specimens in the [η, p exp (e/λ)] space for tests carried out on Kaolin and other clays were reported by ROSCOE & THURAIRAJAH (1964). For Kaolin in the triaxial apparatus these authors found that the drained and undrained test gave different curves in the [η, p exp (e/λ)] space (see Fig. 2). The values of p exp $\left(\frac{e}{\lambda}\right)$ corresponding to a given value of q/p was greater for the drained test path than for the undrained. The state paths followed during anisotropic consolidation (i.e. consolidation) under constant stress ratio $\eta = q/p$ seem to deviate from the drained and undrained surfaces. This deviation was smaller for anisotropic consolidation paths initiated from the drained test path at high stress ratios. These observations will be discussed further in the light of authors' test results.

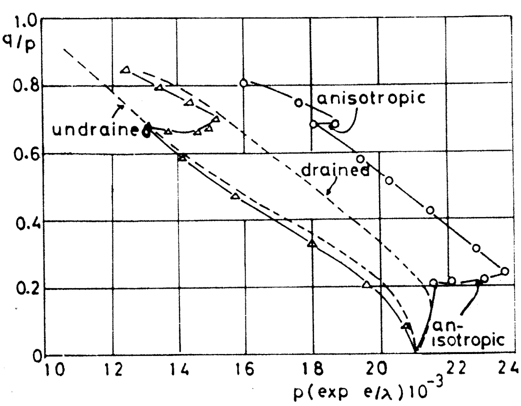

Fig. 2. State paths followed in [q/p, p exp (e/λ)] space of specimens sheared along undrained, fully drained and anisotropic consolidation paths (after ROSCOE & THURAIRAJAH, 1964).

SAMPLE PREPARATION AND TESTING PROCEDURE

Air dried kaolin (liquid limit = 74 %, plastic limit = 42%, plasticity index = 32% and specific gravity = 2.61 %) was mixed with 160% distilled water and was prepared in the form of a slurry. This slurry was one-dimensionally consolidated under an axial stress of 22 lb/in^2 and subsequently isotropically consolidated to the relevant levels of isotropic stress in the triaxial apparatus. The sample former used in the one-dimensional consolidation and other details are given by BALASUBRAMANIAM (1969).

STATE PATHS FOLLOWED BY SPECIMENS PREPARED UNDER DIFFERENT ONE-DIMENSIONAL CONSOLIDATION STRESS

Fully Drained Test Results

Figure 3 illustrates the state path followed by three specimens AU, AB and AR which were prepared under initial one-dimensional consolidation stresses of 11 lb/in^2, 22 lb/in^2 and 55 lb/in^2 respectively. The state paths in the $(q/p_e, p/p_e)$ space are found to be different. Also the specimen with the initial one-dimensional stress close to the isotropic stress of 60 lb/in^2 (i.e. specimen AR) has the highest value of p/p_e for any specific value q/p_e. It can be shown that specimens which have lower volumetric strains (at any particular stress ratio) will have higher values of p/p_e for any specific q/p_e.

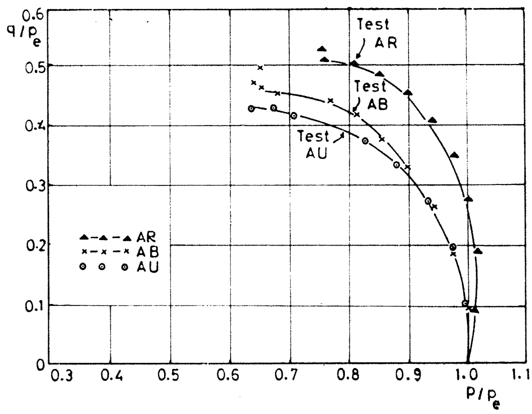

Fig. 3. State paths followed by specimens prepared from different initial one-dimensional stress and subsequently sheared from the same isotropic stress under fully drained conditions.

Undrained Test Results

The observations during undrained tests on two samples T_7 and T_4 will now be presented. Specimen T_7 was prepared from a slurry by initial one dimensional consolidation under a vertical stress of 3 lb/in^2, which corresponds to an applied deviator stress of 1 lb/in^2. This specimen was then isotropically consolidated under a pressure of 60 lb/in^2 and was then sheared in a conventional undrained triaxial compression test. Sample T_4 was subjected to a similar treatment but was given more initial one dimensional consolidation since it was subjected to a vertical stress of 22 lb/in^2 corresponding to an applied deviator stress of 6.6 lb/in^2.

Figure 4 illustrates the state boundary surfaces for the two specimens T_7 and T_4. The undrained state path corresponding to specimen T_7 which had only experienced a previous shear stress of 1 lb/in^2 during one-dimensional consolidation was much higher than that for T_4 (previously subjected to a shear stress of 6.6 lb/in^2). It would, therefore, seem that if no allowance is made for stress or strain history, the undrained state boundary surface is not unique but does depend on the stress history of the sample.

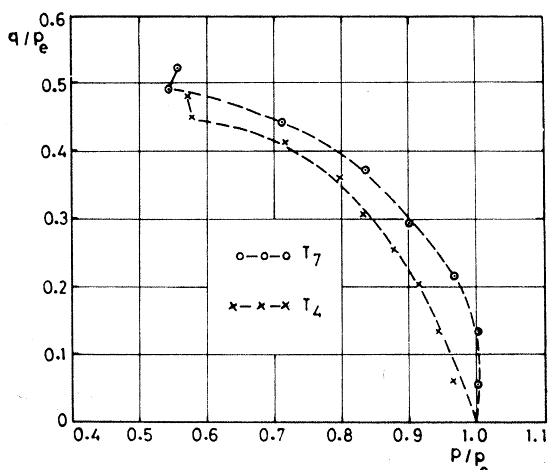

Fig. 4. State paths followed by specimens prepared from different initial one-dimensional stress and subsequently sheared from the same isotropic stress under undrained conditions.

STATE PATHS FOLLOWED BY SPECIMENS SHEARED WITH DIFFERENT LOAD INCREMENT SIZES

Fully drained compression tests at constant cell pressures with large increments can cause high pore pressures to develop and hence the specimen will be virtually subjected to an undrained stress path and a constant q stress path.

Experimental observations on four fully drained tests are presented in this section. The specimen Z was subjected to stress increments of 0.7 lb/in^2 at three hour intervals. Five stress increments were applied during a day and the equilibrium readings were then taken before applying the next increment in the following morning. In test R stress increments of 7 lb/in^2 were applied at two days intervals. Specimen X was subjected to stress increments of 14 lb/in^2 at two days intervals and in test Y a single stress increment of 26 lb/in^2 was used. The $(q/p_e, p/p_e)$ characteristics of these specimens are indicated in Fig. 5. It is seen that the state paths followed by specimens with large increments (namely R, X and Y) always lie between the undrained state path and the path followed by the specimen Z which had a large number of small increments. It is suggested that if there had been no effects of the initial one-dimensional consolidation stress then there would have been a unique $(q/p_e, p/p_e)$ characteristic independent of the load increment size.

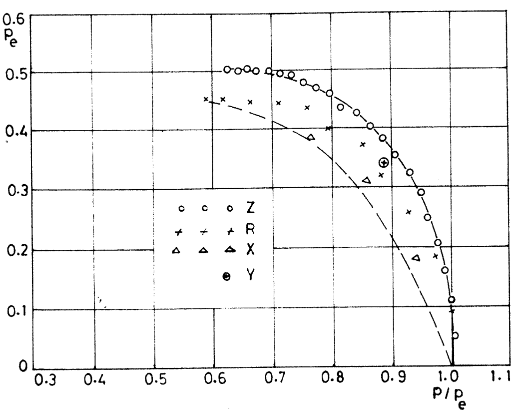

Fig. 5. State paths followed by specimens prepared under identical conditions and sheared from the same isotropic stress state with constant cell pressure but with varying load increment sizes.

STATE PATHS FOLLOWED BY SPECIMENS SHEARED WITH DIFFERENT LOAD INCREMENT DURATIONS

Effects of time on the state boundary surface of fully drained tests are presented in this section. The uniqeness of the state path followed by specimens in a continuous stress controlled test is investigated by carrying out fully drained tests from 60 lb/in^2 cell pressure. Three specimens of Kaolin are tested. These specimens have load increment durations of 1/2 a day (specimen AB), 1 day (specimen W) and two days (specimen R). From ten to twelve increments of load are

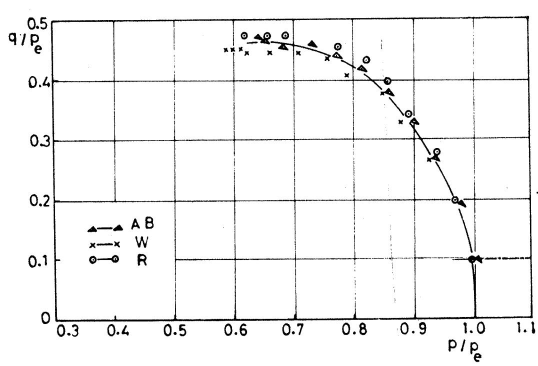

Fig. 6. State paths followed by specimens prepared under identical conditions and sheared from the same isotropic stress state with constant cell pressure and load increments but with varying load increment durations.

applied in each test and, therefore, the duration of the test varied from 5 to 6 days to about 20-24 days. Figure 6 illustrates the state paths followed by these specimens in the $(q/p_e,\ p/p_e)$ coordinates. From these observations it is clear that the state boundary surface corresponding to load increment durations of half a day or greater is approximately unique.

STATE PATHS FOLLOWED BY SPECIMENS SHEARED AT DIFFERNET ISOTROPIC STRESS

In this section the author has studied the state paths followed by specimens sheared from isotropic stress levels of 30, 60 and 90 lb/in^2 when subjected to three different types of imposed stress paths. The stress paths were those of (i) an undrained test, (ii) a constant-p test and (iii) a fully drained test. All specimens were initially prepared under a one-dimensional consolidation stress of 22 lb/in^2 and subsequently isotropically consolidated to the relevant isotropic stress.

First the state paths followed by specimens tested under undrained conditions will be presented. The $(q/p_e,\ p/p_e)$ characteristics of three specimens are shown in Fig. 7. In this figure specimen T_5 corresponds to the sample that was isotropically consolidated to 30 lb/in^2. Specimen T_4 was isotropically consolidated to 60 lb/in^2 and the sample T_3 to 90 lb/in^2. The state paths followed by these three specimens are significantly different. The state paths are found to move outwards away from the origin as the level of isotropic stress is increased.

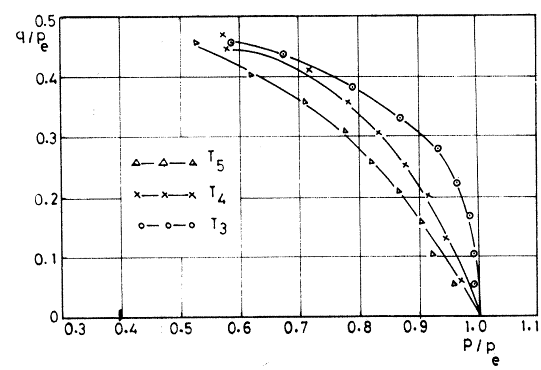

Fig. 7. State paths followed by specimens prepared under the same initial one-dimensional stress, but sheared from different isotropic stress states with constant cell pressure.

Now the state paths of three specimens sheared under constant p condition will be considered. Similar to the undrained tests these specimens were also isotropically consolidated to 30 lb/in^2 (specimen AJ) 60 lb/in^2 (specimen AQ) and 90 lb/in^2 (specimen AO). The state paths of these specimens are illustrated in Fig. 8. Unlike in the case of undrained tests, the state paths corresponding to the constant-p conditions are such that as the level of isotropic stress is increased the state paths move towards the origin. The outermost surface correspond to the lowest isotropic stress and the innermost surface corresponds to the highest isotropic stress. It is interesting to note that the $(q/p_e, p/p_e)$ characteristic of the specimen with isotropic stress of 30 lb/in^2 and one-dimensional consolidation stress of 22, lb/in^2 (i.e. specimen AJ) is approximately the same as that shown in Fig. 3 for the specimen AR which was again subjected to a similar high ratio of one-dimensional to isotropic stress (for specimen AR the initial one-dimensional stress was 55 lb/in^2 and the subsequent isotropic stress was 60 lb/in^2). Thus the ratio of initial one-dimensional stress to the isotropic stress for specimen AR is 55/60 = 0.9; the corresponding ratio for the specimen AJ in Fig. 8 is 22/30 = 0.73

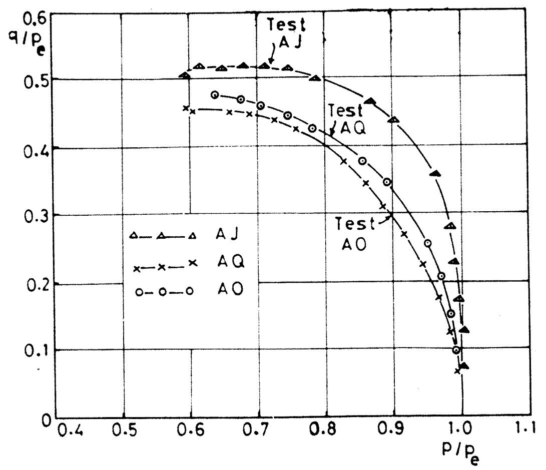

Fig. 8. State paths followed by specimens prepared under the same initial one-dimensional stress, but sheared from different isotropic stress states with constant-*p* stress paths.

Finally the results of three test specimens sheared under fully drained conditions (i.e. with constant cell pressure and $dq/dp = 3$) from isotropic stresses of 30, 60 and 90 lb/in^2 will be presented. The specimen AF was isotropically consolidated to 30 lb/in^2 the specimen Z to 60 lb/in^2 and the specimen AD to 90 lb/in^2. The state paths followed by these samples are shown in Fig. 9. These results too confirmed the finding from the constant-*p* tests in that the specimen subjected to the lowest isotropic stress has a higher state path than the other two specimens. Also, the difference between the specimen AF which was consolidated to 30 lb/in^2, from that of specimen Z consolidated to 60 lb/in^2 is much more pronounced than the corresponding difference in specimens Z and AD. The reason for this observation will be clear once the results presented in Fig. 10 are studied in detail. This figure shows the experimentally

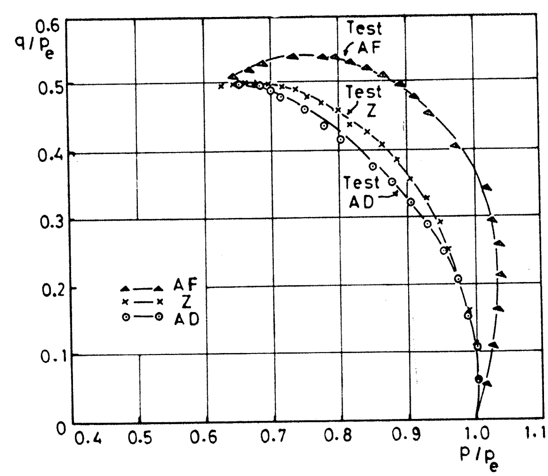

Fig. 9. State paths followed by specimens prepared under the same initial one-dimensional stress, but sheared from different isotropic stress states under fully drained conditions.

observed $(q/p_e, p/p_e)$ curves for all the three types of tests (i.e. undrained, constant-p and fully drained test) at each of the three isotropic stresses of 30 lb/in^2, 60 lb/in^2 and 90 lb/in^2. All the samples had been previously one-dimensionally consolidated under a vertical stress of 22 lb/in^2. The maximum deviation between the three types of stress paths is observed in the case of tests on the samples consolidated at a 30 lb/in^2 isotropic stress; the extent of this type of deviation diminishes as the isotropic stress increases from 30 to 90 lb/in^2. The behaviour at 90 lb/in^2 is approximately unique for all three types of test.

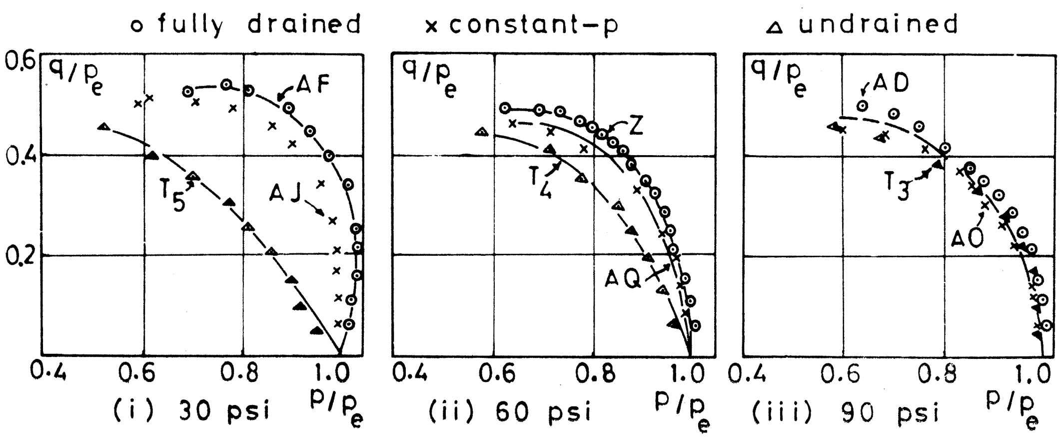

Fig. 10. State paths followed by specimens prepared under the same initial one-dimensional stress but sheared under undrained, constant-p and fully drained conditions from each of the three isotropic stresses of 30, 60 and 90 lb/in^2.

These observations may be compared with those of ROSCOE & THURAIRAJAH (1964). They too noted a difference in the state boundary surface followed by the specimens in the drained and undrained tests on Kaolin when plotted in the alternate plot $[q/p, p \exp (e/\lambda)]$ which is similar to the $(q/p_e, p/p_e)$ plot. The one-dimensional stress used in the preliminary preparation of samples by THURAIRAJAH (1961) was of the order of 33 lb/in^2 which is much higher than the value of 22 lb/in^2 used by the present author. Hence, the difference observed by ROSCOE & THURAIRAJAH (1964) in the $[q/p, p \exp (e/\lambda)]$ plot of the drained and undrained state paths in triaxial specimens of Kaolin can be attributed to the predominant effect of the initial one-dimensional consolidation stress. Measurements of anisotropic strains during isotropic consolidation in Kaolin carried out by BALASUBRAMANIAM (1969) suggests that the effects of the initial one-dimensional stress could only be errased by isotropically consolidating the sample to a value about three times the initial one-dimensional stress used in sample preparation.

From the above results it is apparent that provided the effect of initial one-dimensional consolidation stress has not been there, the state boundary surface is unique at least for the undrained, constant-p and fully drained conditions. This unique state boundary surface is best represented by the results corresponding to the 90 lb/in^2 isotropic stress in Fig. 10. This approximate unique state boundary surface is used as a standard state boundary surface of normally consolidated specimens of Kaolin for comparison with the state paths for all other tests which are carried out to investigate the effects of stress paths. The scatter in the results is allowed for by representing the surface with a double boundary as illustrated in Fig. 11.

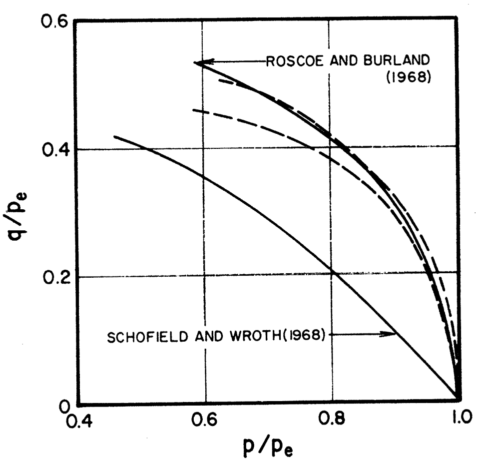

Fig. 11. Approximate unique state boundary surface for specimens sheared under undrained, constant-*p* and fully drained conditions from 90 lb/in^2 isotropic stress.

The state boundary surfaces as predicted by the stress-strain theories of ROSCOE & BURLAND (1968) and SCHOFIELD & WORTH (1968) are also shown in Fig. 11. The theoretical model of ROSCOE & BURLAND is found to predict the state boundary surface remarkably well.

STATE PATHS FOLLOWED BY SPECIMENS SHEARED UNDER WIDE VARIETY OF STRESS PATHS

The state paths considered so far always corresponded to the conditions that during an applied stress path the deviator stress q and the stress ratio q/p have always been increasing from the maximum preconsolidation pressure. For these cases, a unique state boundary surface was found as that presented in Fig. 11. Now it will be interesting to consider other types of stress paths such as:

(i) anisotropic consolidation, where the stress ratio q/p is maintained constant;

(ii) constant-q, where the deviator stress is maintained constant;

(iii) decreasing q, with a consequent decrease in stress ratio q/p;

(iv) those corresponding to extension condition, where the principal axes of stresses are rotated from those corresponding to the compression condition; and

(v) isotropic swelling (corresponding to overconsolidated samples) followed by stress paths with increasing q and q/p.

In all these cases, the stress paths followed by the specimens will be presented together with the state paths for clarity of the presentation of results.

State Paths Followed during Anisotropic Consolidation

The stress-strain theory of ROSCOE & POOROOSHASB (1963) assumes that the state paths during anisotropic consolidation lie on the state boundary surface. The subsequent theories due to ROSCOE et al (1963) and ROSCOE & BURLAND (1968) also imply that the state paths during anisotropic consolidation lie on the state boundary surface. However, the experimental observations provided by ROSCOE & THURAIRAJAH (1964) indicated that the state path corresponding to anisotropic consolidation does not lie on the same state boundary surface as that corresponding to the undrained or drained test. Therefore, the present investigation carried out by the author would help to resolve whether the state path corresponding to anisotropic consolidation does or does not lie on the unique state boundary surface obtained in Fig. 11 from undrained, constant-p and fully drained tests.

Several anisotropic consolidation tests were carried out but experimental observations will only be provided on two samples designated BC and BL which are representative of all the tests. Sample BC was sheared from 90 lb/in^2 isotropic stress along an undrained stress path until the stresses q and p were 32 lb/in^2 and 77 lb/in^2 respectively. Thereafter, the specimen was sheared along an anisotropic consolidation path with the stress ratio q/p being maintained at a constant value of 0.42. The stress path and the state path followed by this sample is shown in Fig. 12. The state path corresponding to anisotropic consolidation is found to lie on the state boundary surface derived for normally consolidated clays (see Fig. 11). The stress condition of

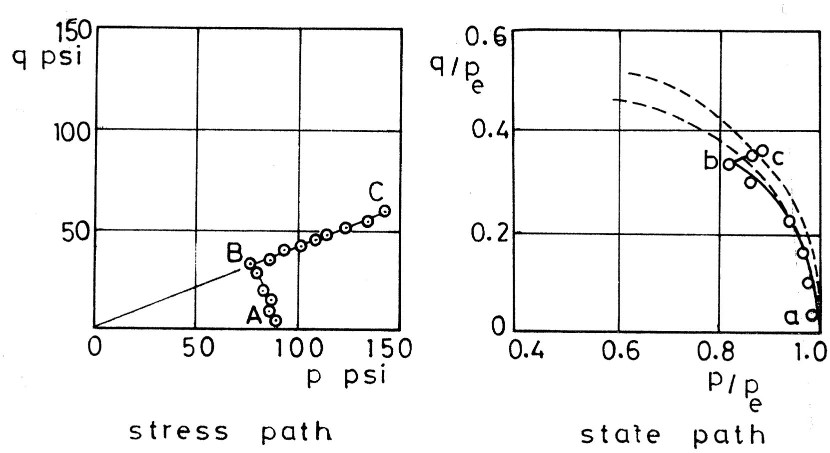

Fig. 12. Stress path and state path followed by specimen BC during anisotropic consolidation.

specimen BC at the end of anisotropic consolidation was $q = 57$, lb/in² and $p = 145$ lb/in².

Figure 13 illustrates the stress path and the state path followed by specimen BL. This sample was subjected initially to a convex stress path from its isotropic consolidation pressure of 90 lb/in² until the stresses q and p were 65 lb/in² and 110 lb/in² respectively. From this stress level it was subjected to an isotropic consolidation with $q/p = 0.58$ till $q = 105$ lb/in² and $p = 180$ lb/in². The state path followed by this sample was also found to lie on the state boundary surface for normally consolidated clay specimens. The results presented here would, therefore, indicate that irrespective of the shape of the initial stress path followed, all specimens have their state path on the state boundary surface during anisotropic consolidation. These results are in contradiction to those of ROSCOE & THURAIRAJAH (1964) and are in agreement with the stress strain theory of ROSCOE & POOROOSHASB (1963), ROSCOE et al (1963) and ROSCOE & BURLAND (1968).

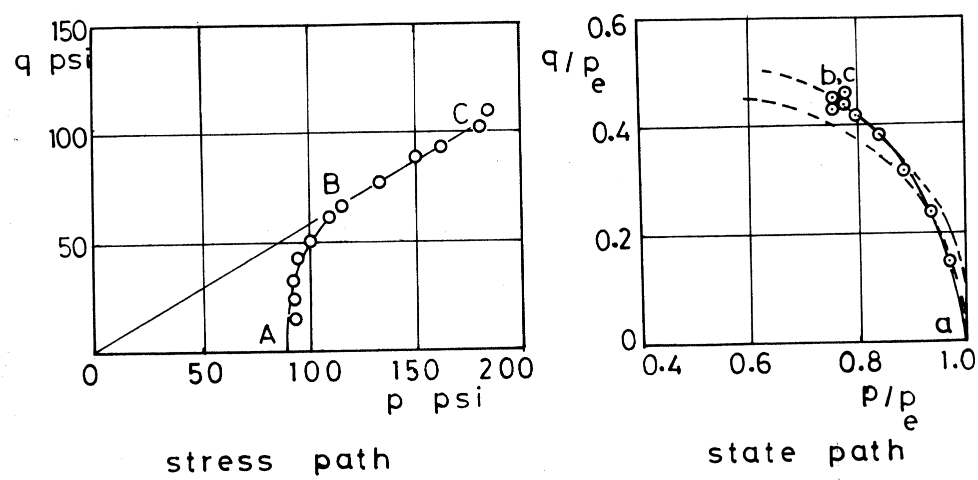

Fig. 13. Stress path and state path followed by specimen BL during anisotropic consolidation.

State Paths Followed by Specimens Sheared along Constant-q Stress Paths

Constant-q stress paths have important applications in the field in the sense that when a large increment of load is applied to a layer of clay, initially the layer would be subjected to undrained stress conditions and there would be an increase in the pore pressure. The subsequent dissipation of pore pressure will be under constant deviator stress and, therefore, will be the same as that of a constant-q stress path. Several constant-q tests were performed, but only the observation on one sample T_{13} will be presented here. The observation provided for sample T_{13} is representative of all the samples tested under constant-q condition.

Specimen T_{13} was initially subjected to a constant-p stress path from an isotropic stress of 90 lb/in^2 until the stresses were $q = 30$ lb/in^2 and $p = 90$ lb/in^2. This constant-p stress path was followed by a constant-q stress path until the mean normal stress reached a value of 117 lb/in^2. Finally, this specimen was sheared to failure by an applied stress path of slope 3 (i.e. fully drained condition with constant cell pressure). The stress and state path followed by this specimen is shown in Fig. 14 and the state path is found to lie on the state boundary surface derived from undrained, constant-p and fully drained tests.

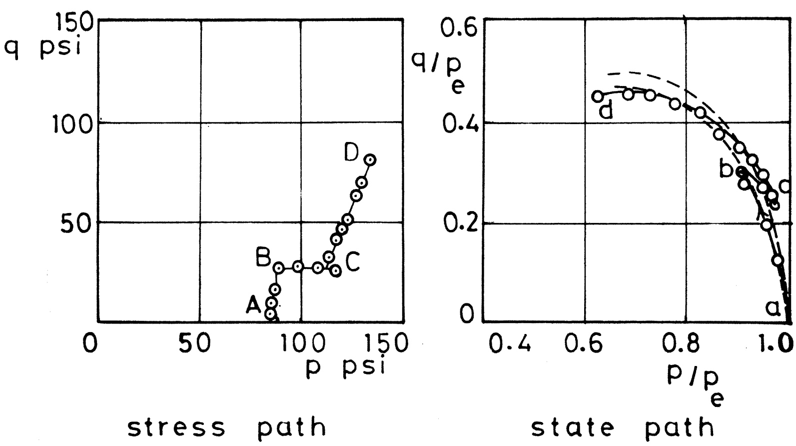

Fig. 14. Stress path and state path followed by specimen T_{13} during constant-q path.

State Path Followed by Specimens Sheared under Decreasing Deviator Stress Condition

Experimental observation will only be presented on one sample, CO, where the behaviour exhibited is typical of several other samples tested under similar conditions. Sample CO was sheared under constant-p condition from 90 lb/in^2 isotropic stress up to a stress level of $q = 17$ lb/in^2 and $p = 90$ lb/in^2. Thereafter, the specimen was subjected to a stress path with decreasing deviator stress and increasing mean normal stress until the stresses are $q = 2$ lb/in^2 and $p = 145$ lb/in^2. Finally the specimen was sheared along a fully drained stress path with slope $dq/dp = 3$. The stress path followed by this specimen and the state path are indicated in Fig. 15. It is noted that the state path corresponding to the stress path followed by specimen CO fully lies on the state boundary surface derived from the undrained, constant-p and fully drained tests.

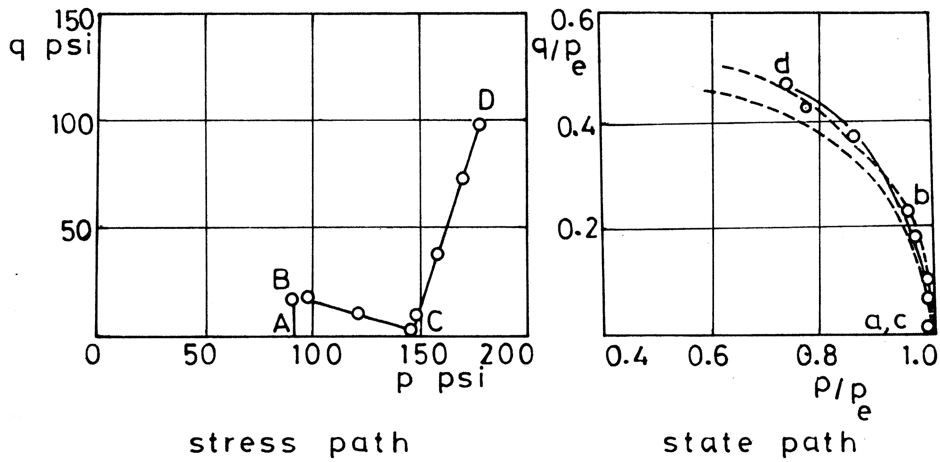

Fig. 15. Stress path and state path followed by specimen CO during the phase when the deviator stress *q* was decreased.

State Paths Followed by Specimens of Kaolin in Extension Tests

The experimental observations provided so far have been from compression tests performed on normally consolidated specimens of Kaolin. During compression test the major principal stress is along the axis of the sample. It will now be interesting to observe the state paths followed by specimens in extension tests. During extension the lateral stresses are the major principal stress and, therefore, any effect due to initial anisotropy in the sample developed as a result of the initial one-dimensional consolidation will be shown pronouncedly in specimens of Kaolin sheared under extension.

Experimental observation will only be presented on one sample, BG, which was sheared from an isotropic stress of 60 lb/in^2 along an applied stress path of slope 3. In presenting the data for extension test, the deviator stress q would be considered as $\sigma_3 - \sigma_1$ instead of being $\sigma_1 - \sigma_3$. This procedure is only adopted to avoid a negative sign in the values of q during extension tests. The stress path and the state path followed by this sample are shown in Fig. 16. The state path of this specimen is also found to lie on the state boundary surface derived from undrained, constant-p and fully drained tests. The result presented for specimen BG is representative of the behaviour of several other samples tested under similar conditions.

From the experimental observations of PARRY (1956, 1960) ROSCOE & POOROOSHASB (1963) suggested that the state boundary surface of specimens sheared under extension conditions with $\bar{\sigma}_1$ = constant and $\bar{\sigma}_3$ decreasing could be different from those of the specimens sheared under conditions of p increasing. The author's results of extension tests, though not carried out

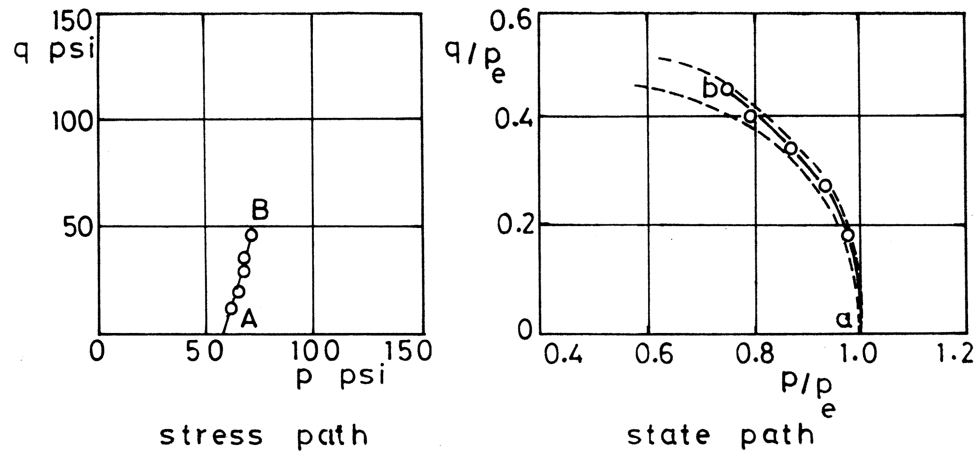

Fig. 16. Stress and state path followed by specimen BG during extension test.

under the above conditions, indicate that the state boundary surface is unique for specimens sheared under both compression and extension conditions.

LELIEVRE & WANG (1971) presented the results of compression extension tests indicating the effect of strain-hardening with respect to distortional strains. It would be interesting for future research workers to study such secondary effects on the state boundary surface.

State Paths Followed by Lightly Overconsolidated Samples

Experimental observations will now be presented on two lightly overconsolidated samples, BD and BJ, which have been isotropically consolidated to 90 lb/in^2 and then swollen back to 56 lb/in^2 under isotropic conditions. Specimen BD was subjected to a fully drained stress path of slope 3. The stress and state path followed by this sample are shown in Fig. 17. It is noted that

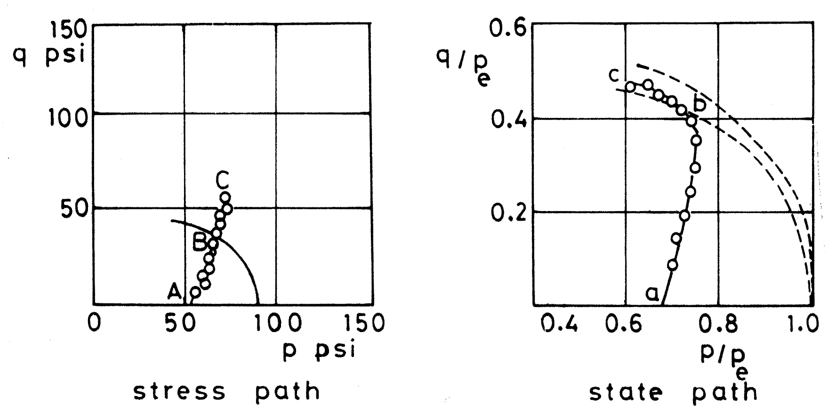

Fig. 17. Stress and state path followed by lightly overconsolidated sample BD under constant cell pressure condition.

the state path rises from the p/p_e axis and lies inside the state boundary surface for all values of stresses corresponding to points which lie inside the undrained stress path passing through the point $q = 0$ and $p = 90$ lb/in^2. For states of stress lieing outside this undrained stress path the state path is found to lie on the state boundary surface. This observation is further confirmed by the behaviour of specimen **BJ** which has been subjected to an applied stress path of slope 1.5. These results are presented in Fig. 18.

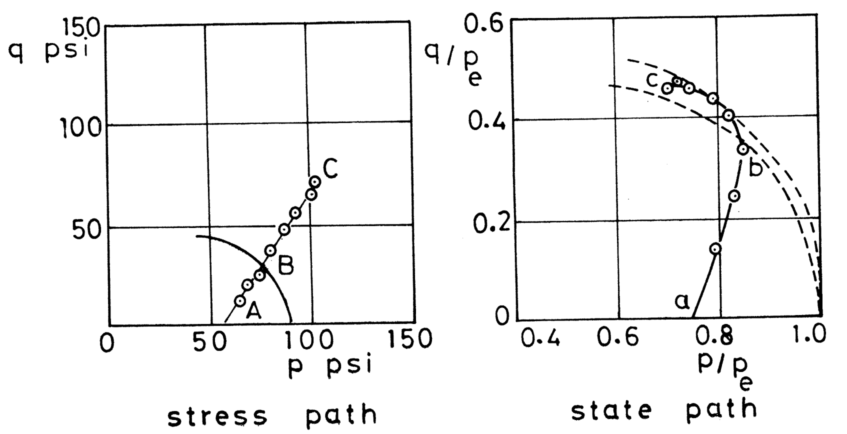

Fig. 18. Stress path and state path followed by specimen BJ sheared from a lightly overconsolidated state along an applied stress path of slope 1.5.

The above results would indicate that, for the states of stress which lie inside the undrained stress path through the maximum preconsolidation pressure, the state paths lie inside the state boundary surface. For the states of stress which lie outside or on the undrained stress path the state paths lie on the state boundary surface.

CONCLUSIONS

Fully drained compression tests (with constant cell pressure) on specimens prepared under different initial one-dimensional consolidation stress and subsequently consolidated to the same isotropic stress showed that the state paths followed in $(q/p_e, p/p_e)$ space are dependent on the magnitude of the initial one-dimensional consolidation stress. A set of undrained tests performed in a similar manner revealed the same finding.

Factors such as the load increment size and the load increment duration do not seem to have appreciable effect on the state boundary surface provided there is no effect of initial one-dimensional consolidation stress.

Three types of test (undrained test, constant-p test, and fully drained test) carried out on specimens prepared under the same initial one-dimensional stress condition and subsequently sheared from three different levels of isotropic stress indicated that the state paths followed in the $(q/p_e, p/p_e)$ space are dependent on the magnitude of the isotropic consolidation stress. At any one particular isotropic stress the largest deviation is observed for tests conducted at the lowest consolidation pressure and those conducted at the highest consolidation pressures were virtually identical.

For the following types of applied stress paths imposed on normally consolidated specimens of Kaolin, the state paths were found to lie on the unique state boundary surface derived from undrained, constant-p and fully drained tests conducted on specimens isotropically consolidated to 90 lb/in^2.

(i) anisotropic consolidation paths;

(ii) constant-q path;

(iii) stress path with decreasing q; and

(iv) extension paths.

A series of tests performed on lightly overconsolidated samples indicated that the state path lies inside the state boundary surface for all states of the stress that lie inside the undrained stress path through the maximum preconsolidation pressure. For the states of stress which lie outside the undrained stress path the state paths lie on the state boundary surface.

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