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STRESS-STRAIN BEHAVIOUR OF A SATURATED CLAY FOR STATES BELOW THE STATE BOUNDARY SURFACE

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ABSTRACT

The stress paths lying below the state boundary surface of a saturated clay were classified into five groups depending on the increment of stresses and stress ratio. The stress-strain behaviour for all these five groups were studied in detail on saturated specimens of Kaolin, in the conventional triaxial apparatus, under stress controlled conditions. Volumetric and shear strain contours were plotted in the stress space for most of the Groups and wherever possible simple equations have been proposed to describe their behaviour.

Key words: clay, overconsolidation, stress path, stress-strain curve
IGC: D 0/D 6

INTRODUCTION

Satisfactory stress-strain theories have recently been developed for normally consolidated clays. Some of these theories are based on the concepts of plasticity and energy balance equations (see Roscoe, Schofield and Thurairajah, 1963; Schofield and Wroth, 1968; Roscoe and Burland, 1968), while the others include experimental observations and empirical strain equations (Roscoe and Poorooshasb, 1963; and Wroth, 1965). However, very little theoretical work has been carried out on the behaviour of saturated clays when subjected to stress paths which lie below the state boundary surface. The state boundary surface in p, q, e space (where p is the mean normal stress, q is the deviator stress and e the voids ratio) is that surface confining a space between itself and the origin, within which a point can represent a state of an element of soil, but outside of which a point cannot represent such a state (see Roscoe, Schofield and Wroth, 1958; Roscoe and Poorooshasb, 1963; Balasubramaniam, 1974). For normally consolidated clays, the undrained stress paths correspond to constant voids ratio sections of the state boundary surface in the (q, p) plane.

In this paper, experimental observations are provided on remoulded specimens of Kaolin when tested under stress controlled conditions in the conventional triaxial apparatus along stress paths, such that the states of the sample always lie below the state boundary surface. These data would form a useful source of information for the development of stress-strain theories to describe the behaviour of a saturated clay, for stress paths lying below the state boundary surface.

Depending on the increments of the deviator stress, q, the mean normal stress p and the stress ratio q/p $(=\eta)$, the applied stress paths can be divided into five groups. In each

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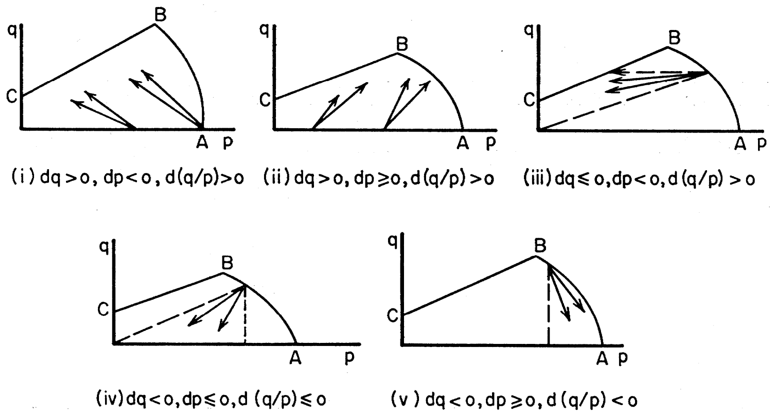

Fig. 1. Division of stress paths into five groups

group, several tests were conducted, and volumetric strain contours and shear strain contours have been drawn. Using these contours it is possible to draw characteristic surfaces in the stress-strain space, and it is the author's opinion that a possible correlation between these surfaces and the yield surfaces used in plasticity theories could be established.

Fig. 1 illustrates all the five different groups of stress paths. Group I stress paths originate from the isotropic stress state, and subsequently q is increased while p is decreased. In this type of stress path, the specimens increase in volume. Group II stress paths also commence from the isotropic stress state, but are of the type where both the deviator stress and the mean normal stress increase. When sheared along this type of stress path, the samples compress in volume. For Group III paths, the initial stress states are on the state boundary surface, with a positive value of the deviator stress q. Subsequently (for these stress paths), the mean normal stress p decreases while the deviator stress q is maintained constant or is decreased. Similar to Group III, the Group IV stress paths also have their initial states on the state boundary surface, with positive values of deviator stress. However, for these latter paths, both q and p are subsequently decreased. Finally, the last Group of stress paths (i. e. Group V) also originate from the state boundary surface, with positive value of deviator stress. Later, however q is decreased, while p is increased or is maintained constant. The dotted lines in Fig. 1 somewhat intutively orrespond to the possible boundaries for each group of stress paths, inside the state boundary surface.

The undrained stress path in the (p, q) space represents constant voids ratio section of the state boundary surface. Roscoe and Thurairajah (1964) and Balasubramaniam (1974) have made a detailed study of the uniqueness of this surface. From a large number of tests conducted with different applied stress paths, Balasubramaniam (1974) has concluded that, provided the effect of initial one-dimensional consolidation stress is not present, then the state boundary surface is unique at least for remoulded specimens of Kaolin prepared from a slurry of constant water content. The volumetric strains experienced by specimens which are subjected to the types of stress paths shown in Fig. 1, will be of an order smaller than the corresponding strains experienced by specimens which are subjected to stress paths which lie on the state boundary surface.

DEFINITION OF STRESS AND STRAIN PARAMETERS

The stress and strain parameters selected are described in detail by Balasubramaniam (1969). Stated briefly here, the stress parameters for the conventional axi-symmetric triaxial apparatus are

$$q=\sigma_1'-\sigma_3'$$

$$\text{and} \quad p=(\sigma_1'+2\sigma_3')/3$$

where σ_1', σ_2' and σ_3' are the principal effective compressive stresses, and $\sigma_2'=\sigma_3'$. Similarly, the volumetric strain v and the shear strain ε are defined as

$$v=(\varepsilon_1+2\varepsilon_3)$$

$$\text{and} \quad \varepsilon=2(\varepsilon_1-\varepsilon_3)/3$$

whre ε_1, ε_2 and ε_3 are the principal natural compressive strains. v and ε are always measured with respect to a datum. Unless otherwise stated, v and ε will be measured from the state of the sample at the end of isotropic consolidation and just prior to shear.

The stress ratio $\eta=q/p$. The parameters q_s, p_s and η_s, with suffix s, refer to the values of q, p and η in the initial state of the sample just before the application of the particular type of applied stress path, as classified under Group IV.

MATERIALS TESTED, SAMPLE PREPARATION AND TESTING PROCEDURE

All specimens were prepared from air-dried Kaolin (liquid limit 74%, plastic limit 42% and specific gravity 2.61) mixed with water to a slurry of 160% moisture content. The slurry was one dimensionlly consolidated in a special mould to a maximum pressure of 22.6 psi. Subsequently, the mould was removed and the sample was isotropically consolidated to the required cell pressure. The sample preparation and testing procedure is described in detail by Balasubramaniam (1969). For "overconsolidated" specimens of Kaolin, the samples were permitted to swell under isotropic stress conditions. Deviatoric stresses are then applied to the samples at the end of their history, under isotropic stress conditions. The effect of miscellaneous test conditions (such as end restraint, initial one dimensional stress, isotropic consolidation stress and load increment duration) were discussed in detail by Balasubramaniam (1973) and by James and Balasubramaniam (1971b). Special precautions were taken to reduce the effects of non-uniformity in deformation by the use of lubricated ends (see Rowe and Barden, 1964). Leakage was virtually eliminated by the use of silicone oil (Ting, 1968).

TEST RESULTS

Specimens Sheared under Group I Stress Paths

As stated before, the Group I stress paths originate from the isotropic stress state, and subsequently the deviator stress q is increased, while the mean normal stress p is reduced. Some specimens were sheared from the maximum pre-consolidation pressure (90 psi), while the others were isotropically swollen from the maximum pre-consolidation pressure and were sheared from the overconsolidated state.

The stress paths followed by these specimens are represented by the dashed lines in Fig. 2, together with contours of constant shear strain, shown by the continuous curves. Test T_3 is an undrained test, and the three specimens BU, T_{15} and BW were sheared from an isotropic stress of 90 psi along the stress paths indicated. Samples DA and DC were isotropically swollen back to stresses of 56 psi and 30 psi respectively and then sheared along the stress paths, as shown in the figure.

Shear strain contours similar to those shown in Fig. 2 were noted by Wroth and Loudon (1967), while shearing overconsolidated specimens of Kaolin, under undrained conditions. The precise shapes of the contours presented by Wroth and Loudon were somewhat different

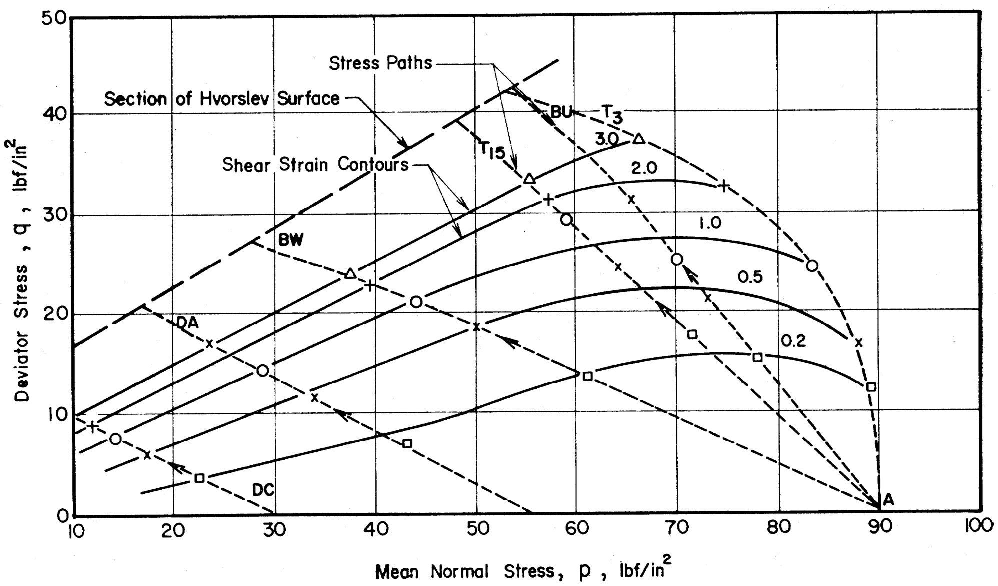

Fig. 2. Shear strain contours of specimens sheared along Group I stress paths ($d\eta>$ and $dv<0$)

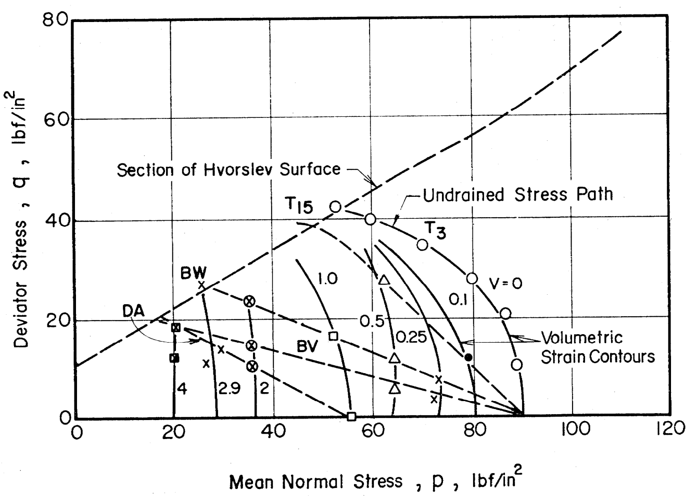

Fig. 3. Volumetric strain contours of specimens sheared along Group I stress paths ($d\eta>0$ and $dv<0$)

from those shown in Fig. 2. In this figure, the shear strain contour corresponding to $\varepsilon=0.5\%$ is approximately half way between the isotropic swelling line (i.e. the p-axis) and the current Hvorslev failure envelope (see James and Balasubramaniam, 1971 a, b). This would imply that the sample is virtually rigid in distortion for stress levels below this contour. Furthermore, the shear strain contours appear to be spaced on a logarithmic scale in the stress plane. If an empirical equation is derived to represent any one contour, then, from the geometrical similarity of the contours, this equation could be generalized to give an expression for the shear strain, ε, in terms of the stresses q and p for all stress levels up to failure.

The corresponding contours of constant volumetric strain for these five tests are indicated in Fig. 3. As stated before, the datum for the volumetric strains recorded for all the tests is taken as zero at the maximum pre-consolidation pressure (90 psi). Since no contours can cross, the upper ends of the contours for small values of v have been sketched in convex to the p-axis. According to the elastic wall concept of the stress strain theories developed at Cambridge (Calladine, 1963; Roscoe, Schofield and Thurairajah, 1963; Schofield and Wroth, 1968; Roscoe and Burland, 1968), the volumetric strain contours should be independent of the mean normal stress and are therefore vertical in the (q, p) space. This seems to be the case at low levels of deviator stress. However, at higher values of the deviator stress, the contours tend to have convex shapes, especially at stress levels close to the state boundary surface.

Stress-Strain Behaviour of Specimens Sheared along Group II Stress Paths

Group II stress paths were imposed on overconsolidated specimens with maximum preconsolidation pressure of 90 psi. During shear, both the deviator stress q and the mean normal stress p were increased, and the specimens decreased in volume. The stress paths followed by these specimens are shown in Fig. 4, where T_3 corresponds to an undrained test on a "normally consolidated" sample, from an isotropic stress of 90 psi. The stress paths CY, BH, T_{24} and CZ refer to undrained tests on specimens overconsolidated from a maximum preconsolidation pressure of 90 psi, to isotropic stresses of 70, 56, 30 and 8 psi respectively. The stress paths BD and BJ correspond respectively to a fully drained test (with constant cell pressure) and to a test with an applied stress path of slope 1.5, on specimens overconsolidated from an isotropic stress of 90 psi to an isotropic stress of 56 psi. The stress path CX corresponds to a test with applied stress path of slope dq/dp, equal to 1, on a specimen previously swollen from an isotropic stress of 90 psi to 30 psi. The shear strain contours of 0.2, 0.5, 1, 2 and 3%, for all the nine tests, which included both lightly and heavily overconsolidated samples, are shown in Fig. 4. It should again be noted that the shear strain contour corresponding to 0.5% is approximately halfway

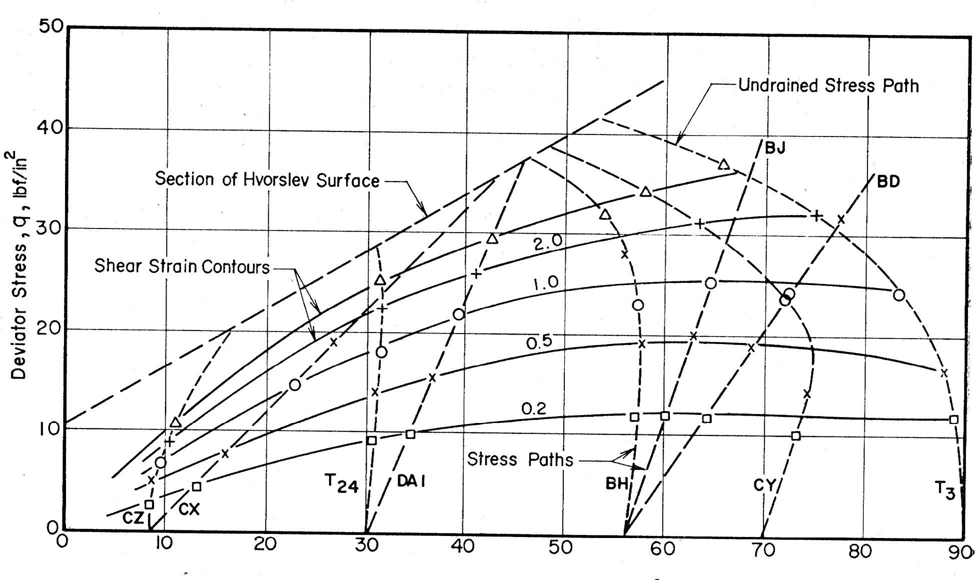

Fig. 4. Shear strain contours for specimens sheared along Group II stress paths ($d\eta > 0$ and $dv > 0$)

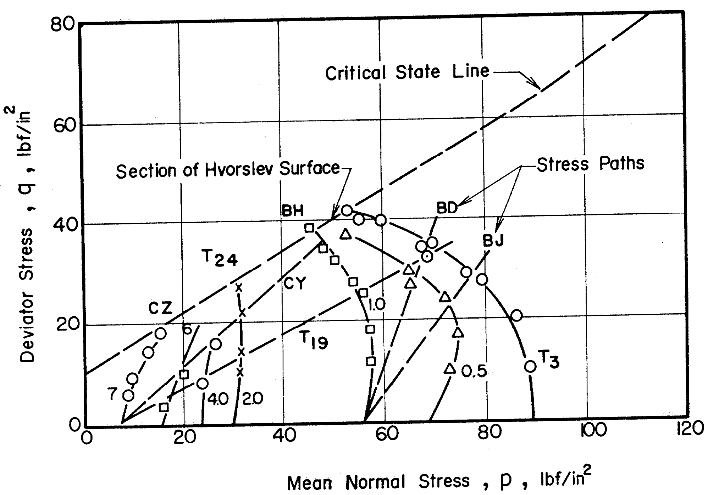

Fig. 5. Volumetric strain contours of specimens sheared along Group II stress paths ($d\eta > 0$ and $dv > 0$)

between the p-axis and the Hvorslev failure envelope.

Fig. 5 presents the volumetric strain contours for all the paths shown in Fig. 4. The constant volumetric strain contours are found to change in shape as the overconsolidation ratio is increased. The constant volumetric strain contours can be used to obtain the state surface relating (q, p and v), for stress paths lying inside the state boundary surface.

Stress-Strain Behaviour of Specimens Sheared Along Group III Stress Paths

Experimental observations provided for the Group I and Group II stress paths are such that the shear strain ε is always associated with stress paths where the deviator stress q was increasing. However, it is possible to impose stress paths with decreasing deviator stress, and thus cause positive shear strain. Typical stress paths of this type are shown in Fig. 6, where the specimen T_{17} was subjected to three stress cycles AB_1A, AB_2A and AB_3A.

Figs. 7 and 8 illustrate the volumetric and shear strains respectively for the stress paths applied on specimen T_{17}. The shear strain was small when the deviator stress q was decreased from 30 to 20 psi during which time there was an increase in (q/p) from 0.33 to

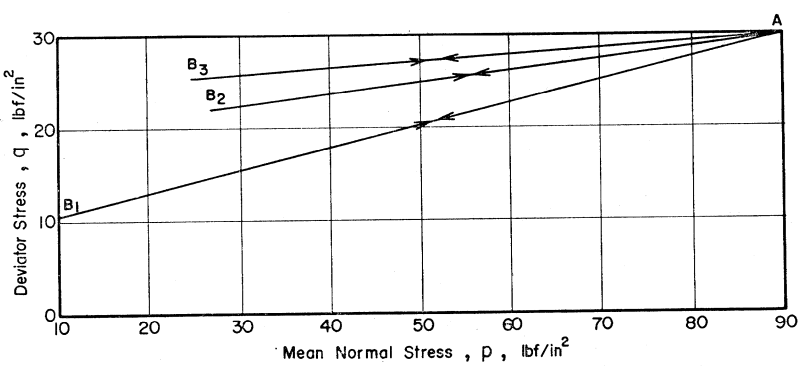

Fig. 6. Group III stress paths

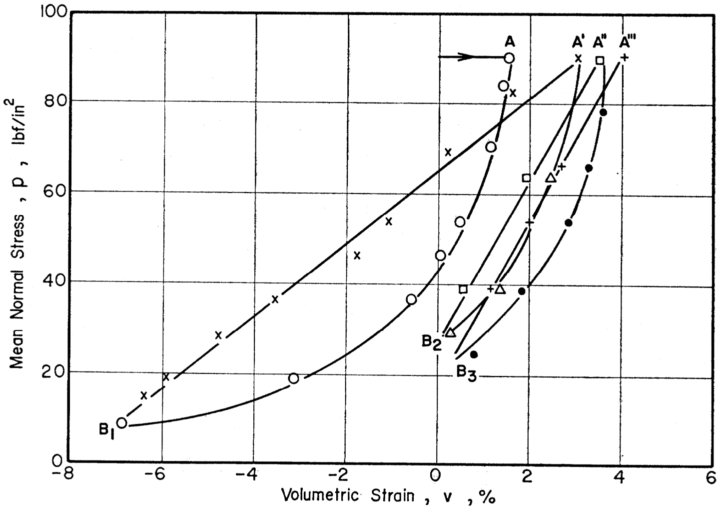

Fig. 7. The (p, v) characteristic of specimen sheared under Group III stress path

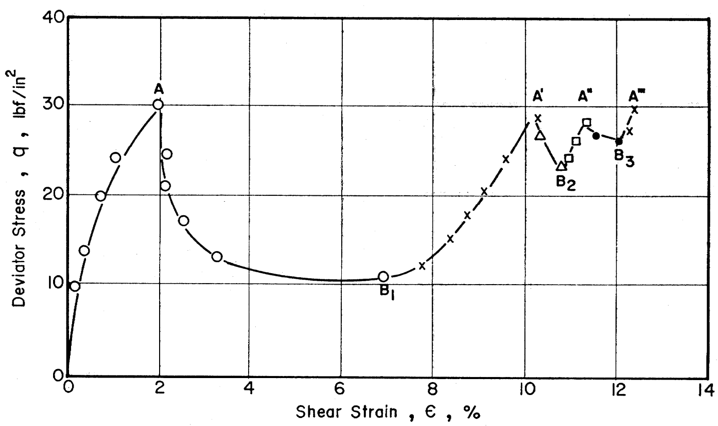

Fig. 8. The (q, ε) characteristic of specimen sheared under Group III stress path

0.4. However, when the deviator stress was further decreased from 20 to 11 psi, with an increase in stress ratio from 0.4 to 1, very large shear strains were experienced by the specimen. During this phase of shear, when the deviator stress q was decreasing and the stress ratio (q/p) was increasing, energy was released from the specimen and was dissipated in plastic shear deformation. This phase of deformation is therefore unstable. The same specimen T_{17} was then sheared along the stress path B_1A, retracing the original path AB_1, with the deviator stress q and the mean normal stress p now increasing, and the stress ratio (q/p) being reduced. During this phase of shear, the specimen was found to undergo positive volumetric and shear strains, as indicated in Figs. 7 and 8. Therefore, in the cycle AB_1A, the specimen experienced shear distortion of the same sign both during the removal and re-application of deviator stress, which corresponded to an increase and a decrease in the stress ratio (q/p). Hence, for stress paths of the form indicated in Fig. 6, it is not possible to define a single yield surface, which is relevant to reversal of stress paths of the type discussed. The specimen T_{17} was subsequently subjected to stress cycles AB_2A, AB_3A and AB_4. The magnitudes of shear strains experienced by the sample

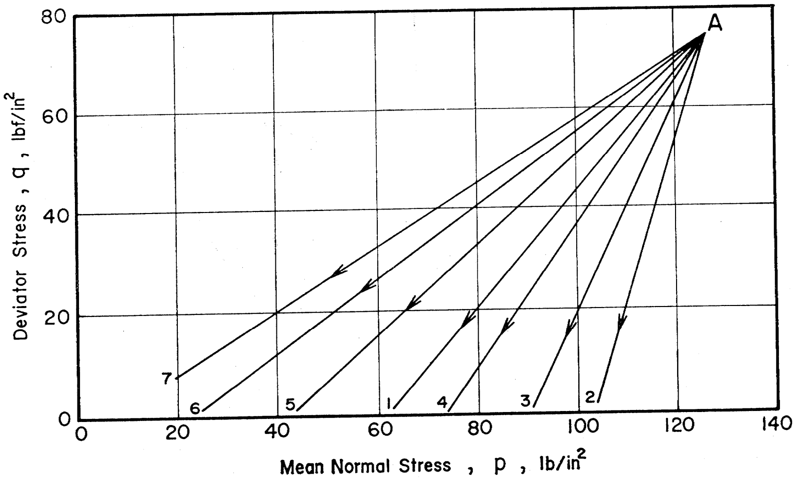

Fig. 9. Group IV stress paths

during these subsequent cycles were small compared to those in the stress cycle AB_1A, even though the specimen was subjected to the same increase in stress ratio for all stress cycles.

Stress-Strain Behaviour of Specimens Sheared along Group IV, Stress Paths

Group IV stress paths are the only paths for which the deviator stress q, the mean normal stress p, and the stress ratio q/p decrease simultaneously. These paths would therefore correspond to the "true unloading" case, with respect to all the stresses and the stress ratio. Altogether five series of tests were carried out corresponding to unloading from stress ratios of 0.34, 0.47, 0.58, 0.64 and 0.75. The stress-strain behaviour corresponding to only one series of tests (where the unloading was from a stress ratio of 0.64) will be presented here. These results however are representative of all the five series.

Fig. 9 illustrates the stress paths of unloading from a stress ratio of 0.64. The (q, ε) characteristics for these paths are found to be unique (see Fig. 10 (a) and arein dependent of (dq/dp). However, there were five different unique curves, corresponding to the five different stress ratios considered on the state boundary surface. The curves in Fig. 10 (a) represent the upper and the lower limits of the scatter in the test data. The results were replotted on a semi-logarithmic scale $(\varepsilon, \log p)$ in Fig. 10 (b). The points in this figure correspond to the lower limit of the (q, ε) characteristics in Fig. 10 (a). This procedure has been adopted since the experimental

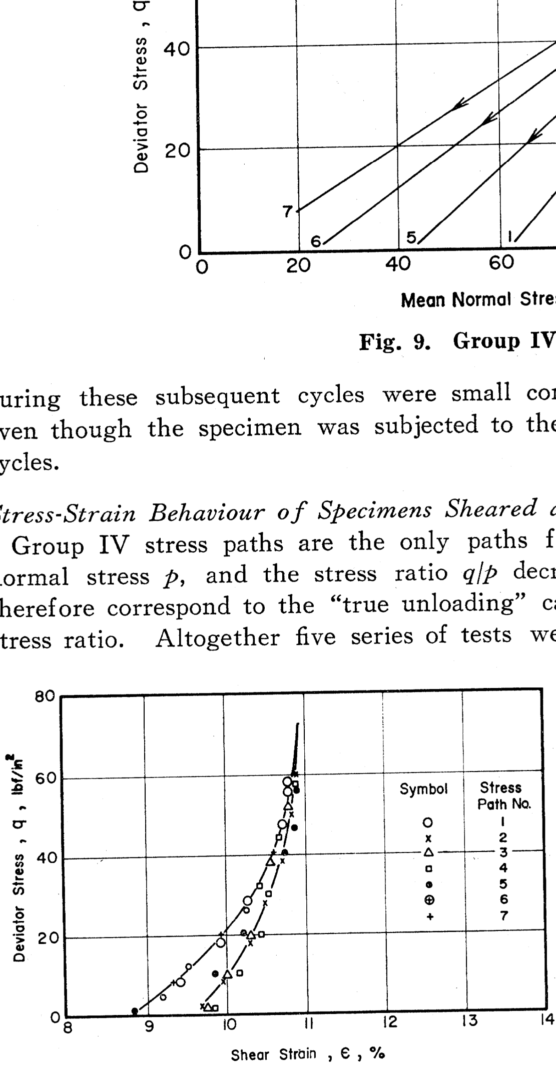

Fig. 10(a) The (q, ε) characteristics of specimens sheared under Group IV stress paths

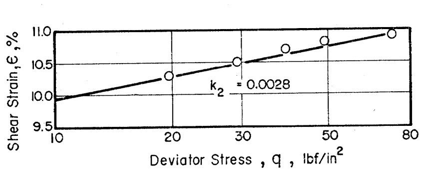

Fig. 10 (b) The $(\varepsilon, \log q)$ characteristic of specimens sheared under Group IV stress paths

observations for most of the series of tests were more closer to the lower limit. Fig. 10 (b) illustrates that the recoverable shear strain varies linearly with log q. Similar linear relationships were noted for all the other four series of tests. The slope $[k\ (\eta_s)]$ of the lines which are a function of the stress ratio η_s (corresponding to the initial stress ratio η on the state boundary surface), are plotted against η_s in Fig. 11. A linear relationship is found to exist between these slopes and η_s. Also, this relationship indicates that the slope is zero when η_s is equal to zero corresponding to swelling under isotropic stress.

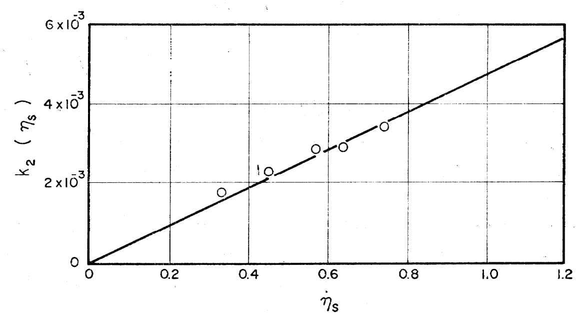

Fig. 11. The variation of $k\ (\eta_s)$ with η_s

For the stress paths considered in Fig. 9, the mean normal stress-volumetric strain relationships (p, v) are given in Fig. 12. A unique relationship exists between the volumetric strain and the mean normal stress, independent of the deviator stress, and of the direction (dq/dp) in which the stresses were reduced. These results are also replotted on a semi-logarithmic scale (v, log p) in Fig. 13, where the variation is found to be linear. A similar linear relationship was noted for each of the other four series of unloading stress paths. However, the slopes of the straight lines were found to be approximately constant and are independent of the direction of the stress path (dq/dp) and the stress ratio η_s.

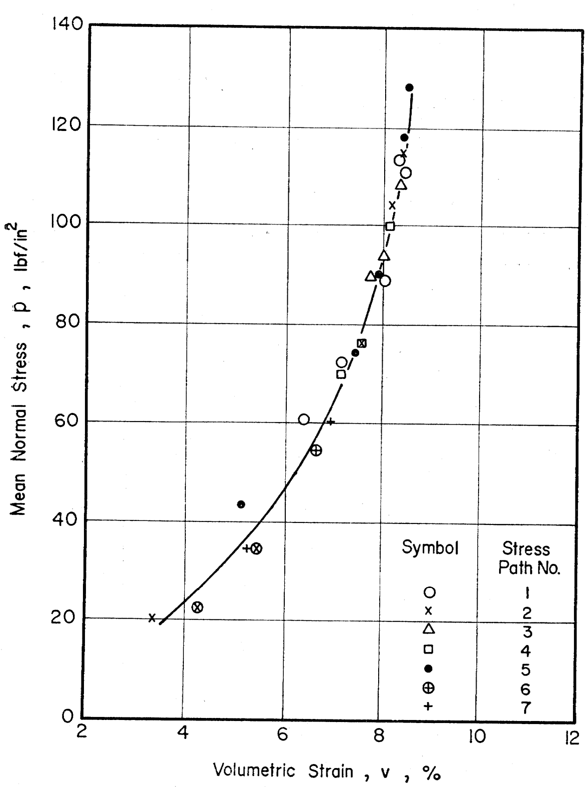

Fig. 12. The (p, v) characteristic of specimens sheared under Group IV stress paths

If the volumetric and shear strains, as measured from the datum corresponding to the maximum stress ratio η_s, are denoted by v_{rs} and ε_{rs} respectively, then

$$v_{rs}=\alpha \log (p/p_s) \quad (1)$$

and $$\varepsilon_{rs}=\beta\ \eta_s \log (q/q_s) \quad (2)$$

both α and β being constants. By differentiating equations (1) and (2) it can be shown that the ratio of the recoverable strain rates is given by

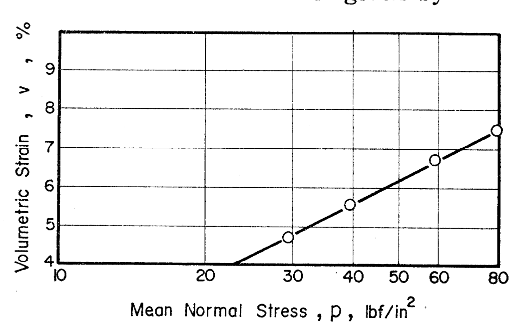

Fig. 13. The (v, log p) characteristic of specimens sheared under Group IV stress paths

$$\left(\frac{dv}{d\varepsilon}\right)_{rs}=\frac{\alpha}{\beta}\cdot\frac{1}{\eta_s}\cdot\eta\ (dp/dq) \tag{3}$$

Equation (3) indicates that the ratio $(dv/d\varepsilon)_{rs}$ of the recoverable strains is a function of the stress ratio η and the stress increment ratio. For the particular case of swelling under constant stress ratio $(\eta=dq/dp)$, equation (3) reduces to

$$\left(\frac{dv}{d\varepsilon}\right)_{rs}=\frac{\alpha}{\beta}\cdot\frac{1}{\eta_s} \tag{4}$$

Thus for unloading under constant stress ratio, the strain rate $(dv/d\varepsilon)$ is a constant. This property has been shown to be true for the deformation characteristics of normally consolidated clays under constant stress ratio (see, Roscoe and Poorooshasb, 1963).

Stress-Strain Behaviour of Specimens Sheared along Group V Stress Paths

The type of stress paths which satisfy the conditions specified above are paths which have been directed inside the current undrained stress path (of the state boundary surface for normally consolidated clay) in the q, p plane, in a direction in which q was decreasing and p was increasing. During the application of these stress paths, the specimens experienced volumetric strains which were very much higher than the corresponding elastic component. In this section, the volumetric and shear strains experienced by samples (*CT*, *CR* and *BU*), are presented when sheared along three stress paths as indicated in Fig. 14. The datum for strains is taken as zero at the initial state *A* on the state boundary surface. The volumetric strain contours are shown by dashed lines in Fig. 15 and are found to be different from those presented in the previous sections for the other groups of stress

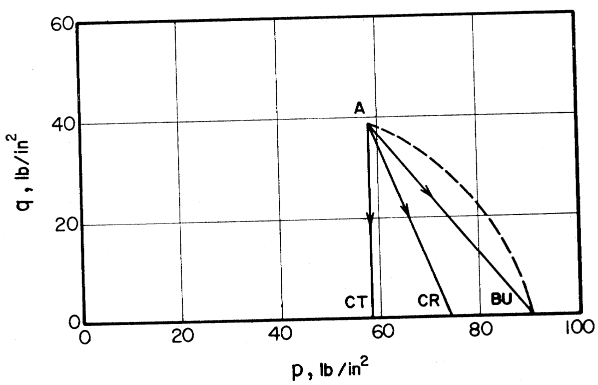

Fig. 14. Group V stress paths

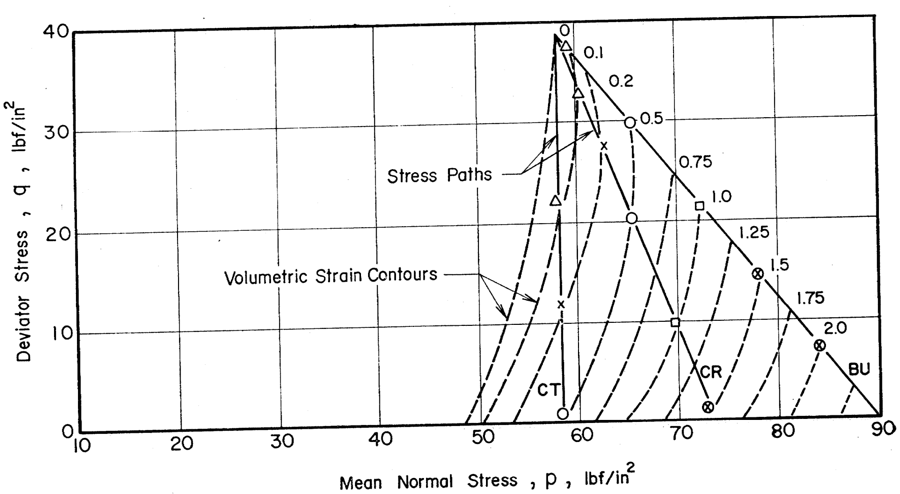

Fig. 15. Volumetric strain contours of specimens sheared along Group V stress paths

paths. Also, they seem to intersect the current undrained stress path through A. The volumetric strain contour in Fig. 15 can be expressed as

$$q = p_o' f(\eta) \quad (5)$$

where p_o' corresponds to the isotropic stress at which the volumetric strain contour meets the p-axis. The variation of the volumetric strain with p_o' is illustrated in Fig. 16, where

$$v = k_1 p_o' + k_2 \quad (6)$$

k_1 and k_2 being constants.

The equations (5) and (6) approximately describe the volumetric strain contours plotted in Fig. 15. The constant k_1 and k_2 may be functions of the stress ratio η_s from which the deviator stress was first unloaded. The shear strain contours for the three specimens are shown in Fig. 17. The contours are found to be approximately horizontal, except for the stress path, which is closer to the undrained stress path corresponding to the state boundary surface.

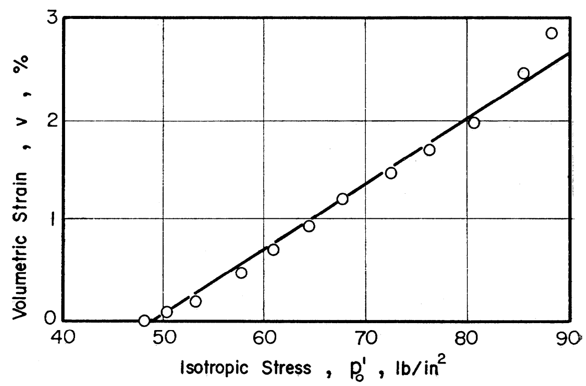

Fig. 16. The (v, p_0') characteristic of specimens sheared along Group V stress paths

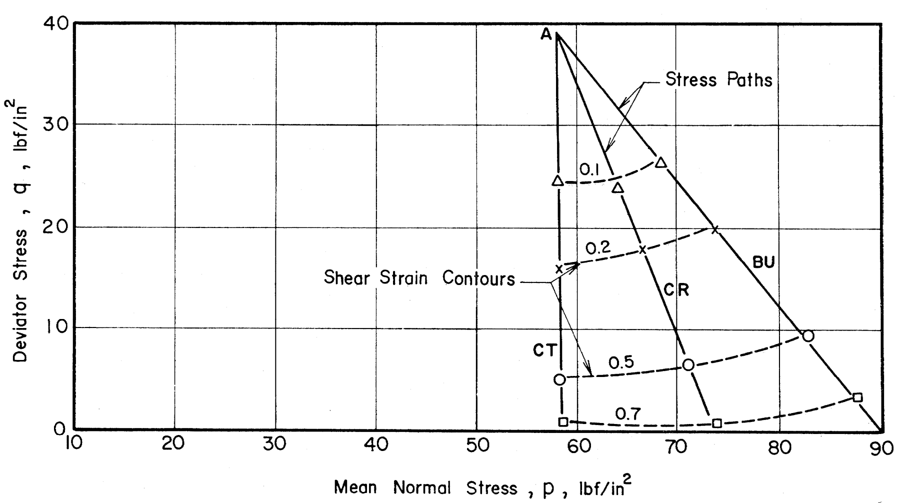

Fig. 17. Shear strain contours of specimens *BU*, *CR* and *CT* sheared along Group V stress paths

CONCLUSIONS

Depending on the increments of the deviator stress, q, the mean normal stress, p, and the stress ratio, q/p, the applied stress paths inside the state boundary surface are divided into five groups (see Fig. 1). Several tests were conducted for each group of stress paths.

Group I stress paths originated from the isotropic stress state and subsequently q was increased while p was decreased. The shear strain contours for these paths were found to be somewhat similar to each other. The volumetric strain contours were only dependent on the mean normal stress p, for all stress levels except for those states which were close to the state boundary surface. Similar volumetric and shear strain contours were observed for the Group II stress paths, where the specimens were sheared from the isotropic stress states under the conditions $dq > 0$, $dp > 0$.

The stress–strain behaviour for the Group III stress paths (where $dq \leq 0$, $dp < 0$ and $d(q/p) > 0$) is shown to be unstable, since the specimens were capable of experiencing positive shear strains for all the stress states in a closed cycle of stress.

For the Group IV stress paths, where the specimens were subjected to the stress conditions $dq < 0$, $dp < 0$ and $d(q/p) < 0$, the volumetric and shear strains (v and ε) were found to vary linearly with log p and log q respectively.

Group V stress paths corresponded to the case where the deviator stress q was decreased while the mean normal stress p was increased. Volumetric and shear strain contours are determined for these paths.

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NOTATION

e = voids ratio
f = function
k, k_1, k_2 = constants
p = mean normal stress
p_s = value of p corresponding to initial state for Group IV stress paths
p_o' = value of p corresponding to zero deviator stress of the volumetric strain contours for Group V stress paths.
q = deviator stress
q_s = value of q corresponding to initial state for Group IV stress paths
v = volumetric strain
v_{rs} = recoverable volumetric strain corresponding to Group IV stress paths
α, β = constants
σ_1', σ_2', σ_3' = principal effective compressive stresses
$\eta = q/p$
$\eta_s = q_s/p_s$
ε_1, ε_2, ε_3 = principal compressive strains
ε = shear strain
ε_{rs} = recoverable shear strain corresponding to Group IV, stress paths

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