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State boundary surface for weathered and soft Bangkok Clay

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This paper is concerned with a detailed study of the state boundary surface for undisturbed samples of weathered and soft Bangkok Clay which were taken from a site about 20 km from Bangkok. Both triaxial compression and extension tests were carried out with a wide variety of applied stress paths. The stress paths and the state paths followed by these test specimens are presented and discussed. At low levels of deviator stresses the stress paths followed by weathered clay at pressures less than the maximum past pressure are nearly sub-parallel to the deviator stress axis in a deviator stress-mean normal stress plot. For each type of applied stress path, the state paths followed by weathered and soft clay in the normally consolidated range are found to be virtually the same. At higher deviator stress levels, the state paths are found to be different for weathered clay tested under drained and undrained conditions. For soft clay tested under a wide variety of applied stress paths, the state boundary surface is found to be unique, within experimental limitations. However, differences are noted between the state paths observed in compression and in extension tests especially at deviator stress levels close to failure. At low levels of deviator stresses, where settlement calculations are often carried out, the state boundary surface for normally consolidated Bangkok Clay can be assumed to be unique for a first degree of approximation. This unique surface can be successfully used in the prediction of volumetric and shear strains. Thus, it is possible to estimate the settlement of layers of soils subjected to different applied stress paths.

SYMBOLS

e_0	initial voids ratio
e	current voids ratio
K_0	coefficient of earth pressure at rest
k	slope of isotropic swelling line in $(e, \log p)$ plot
M	slope of critical state line in (q, p) plot
p	mean normal stress
q	deviator stress
p_0	pre-shear consolidation pressure
p_e	mean equivalent pressure $= p_0 \exp \frac{e_0 - e}{\lambda}$
λ	slope of isotropic consolidation line in $(e, \log p)$ plot
η	stress ratio $= q/p$
$\bar{\sigma}_i$	principal effective compressive stresses. $i = 1, 2, 3$

INTRODUCTION

The work presented in this paper is an extension of that carried out by Balasubramaniam (1969, 1974) on the uniqueness of state boundary surface for saturated specimens of kaolin. In these publications, specimens of kaolin which were resedimented in the laboratory from a slurry were used. From a wide variety of tests carried out under different applied stress paths on normally consolidated specimens of kaolin, a unique state boundary surface was established. As a logical extension of this work, the present paper presents the investigation carried out on undisturbed samples of weathered and soft Bangkok Clay.

STRESS PARAMETERS USED IN TRIAXIAL TESTS

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

$$p = (\bar{\sigma}_1 + 2\bar{\sigma}_3)/3$$

and $q = (\bar{\sigma}_1 - \bar{\sigma}_3)$,

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 SURFACE

Balasubramaniam (1974) has presented a detailed description of work carried out in relation to the state boundary surface for saturated clays.

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The pioneer investigation in this field started with Rendulic (1936), who performed a series of stress controlled compression and 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) were in close agreement with the constant voids ratio contours derived from drained tests and isotropic consolidation tests. By assuming that these contours are reproducible in the $\bar{\sigma}_1 = \bar{\sigma}_2$ and $\bar{\sigma}_1 = \bar{\sigma}_3$ planes, Rendulic suggested that the constant voids ratio contours form surfaces of revolution about the space diagonal $\bar{\sigma}_1 = \bar{\sigma}_2 = \bar{\sigma}_3$.

Following Rendulic's work, Henkel (1960) was the first to provide 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. Henkel's results indicated that the constant water content contours obtained from drained tests were similar in form to the stress paths corresponding to the conventional undrained test.

In parallel with Henkel's contribution, Roscoe, Schofield and Wroth (1958) proposed a classic concept of the existence of a unique surface in three-dimensional space, relating the voids ratio e , and the stress parameters q and p . Assuming that all e equals constant sections of the state boundary surface are geometrically similar, Roscoe and Poorooshasb (1963) transformed this three dimensional surface which relates, p , q and e into a two dimensional curve. Burland (1965) used the alternative parameters q/p_e and p/p_e for the two dimensional representation of the state boundary surface and defined $p_e = p_0 \exp \frac{e_0 - e}{\lambda}$ where (p_0, e_0) corresponds to the pressure and voids ratio on the isotropic consolidation line and λ is the slope of the isotropic consolidation line in the $(e, \log p)$ plot.

A unique curve can only be expected in the 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. Experimental observations provided by Roscoe and Thurairajah (1964) indicated that the state paths followed in the $(q/p_e, p/p_e)$ plot were distinct and different at least for the two common types of test conditions, namely, the undrained test and the fully drained test. A critical reappraisal of the work of Roscoe and Thurairajah (1964) was subsequently made by Balasubramaniam (1974). From a large number of triaxial tests conducted on saturated specimens of kaolin, Balasubramaniam demonstrated that the state boundary surface was unique for a normally consolidated clay for all types of applied stress paths with varying degrees of volumetric strain and the unique state boundary surface could be successfully used for the prediction of strains. Thus it appeared settlement calculations could be made from the strains predicted from the state boundary surface. The present work therefore was aimed in investigating the state boundary surface for undisturbed samples of weathered and soft Bangkok Clay as a first phase of the application of recent theories in the prediction of settlements.

GENERAL DESCRIPTION OF BANGKOK CLAY

The subsoil deposit at Nong Ngoo Hao site is a part of the soil deposited in the Chao Phraya Plain under a marine environment. Generally, clay deposits known as Bangkok Clay rest over sand and gravel beds with some sandy clay which occurs alternately to a depth of at least 300 m. Muktabhant (1967) reported that bedrock has never been seen on the plains even though borings have been made to depths in excess of 300 m.

Bangkok Clay can be divided into three different zoners according to the strength and stress-strain characteristics, and have been described by Moh, Nelson and Brand (1969) as follows

- (i) an upper zone of weathered Bangkok Clay to a depth of about 4.5 m below ground surface, behaving as an apparently overconsolidated clay
- (ii) a highly compressible soft clay underlying weathered clay to a depth of 10 m. This clay layer behaves as a normally consolidated clay of low shear strength.
- (iii) the third zone is stiff clay occurring to an approximate depth of 15 m over sand and gravel beds. This layer shows all the behaviour of overconsolidated clays. Moh et al (1969) concluded that the reason behind the geological history of these clays is complex as there is no evidence yet available to indicate surface erosion subsequent to the deposition of soft clay.

The subsoil profile at Nong Ngoo Hao was essentially the same as that presented for Bangkok Clay. The weathered zone was found to be about 4 m thick. Observations during sampling process indicated a marked effect of weathering process in this zone. In the upper part, the soil was found to be dark grey in colour and light brown horizontal silt seams were observed at different depths in the upper 2 m thickness. Small holes were also found in this portion, probably created by earth-worms or decayed roots. Between 2.0 m and 2.5 m depth, a layer of light grey clay having traces of dark coloured decayed organic matter was observed. Below a depth of 2.5 m, the soil became more uniform in colour and the holes were no longer apparent.

The general properties of weathered and soft clays are shown in Table 1.

Table 1. Properties of weathered and soft clays

Property	Weathered clay	Soft clay
Natural water content, %	133 ± 5	112 — 130
Natural voids ratio	3.86 ± 0.15	3.11 — 3.64
Degree of saturation, %	95 ± 2	97.8 — 100.0
Specific gravity	2.73	2.75 ± 0.1
Liquid limit, %	123 ± 2	118.5 ± 1.0
Plastic limit, %	41 ± 2	43.1 ± 0.3
Plasticity index	82 ± 4	75.4 ± 1.3
Dry density t/m ³	0.58 ± 0.03	0.65
Soluble salt content, gm/litre	7.0	13.1
Organic matter, %	4.0	3.55
pH	8.5	
Grain Size Distribution		
Sand, %	7.5	4.0
Silt, %	23.5	31.7
Clay, %	69.0	64.3
Colour	dark grey	greenish grey

The maximum past pressure for weathered clay is 69 kNm⁻².

SAMPLING PROGRAMME

Undisturbed samples were taken with 25.4 mm in diameter and 56 mm long thin-walled sample tubes. Samples of weathered clay were taken at a depth of 2.5 to 3.0 m. The soft clay samples were taken at a depth of 5.5 to 6 m. The extruded sample from each tube was divided into three portions, properly sealed with wax paper and paraffin and stored in the humidity controlled room of the Soil Mechanics Laboratory at the Asian Institute of Technology. Afterwards each portion was further sub-divided into smaller pieces similarly sealed. During the testing phase, each piece of sample was taken out, and the paraffin and wax were carefully removed. A trimming frame and a wire saw were used to trim the clay sample to the desired dimension (3.6 mm in diameter and 7.2 mm height). A split-former was used to hold the specimen after vertical trimming. Two porous stones were placed one at each end of the sample. Also, Whatman No. 40 filter paper side drains were placed along the circumference of the sample. The sample was then enclosed within two rubber membranes which were separated by a thin coating of silicone grease. The upper and lower ends of the rubber membrane were sealed against the top cap and the pedestal respectively, by hard Gaco "O" ring seals. The chamber surrounding the sample was then filled with silicone oil.

For all test series, the samples were consolidated isotropically at various consolidation pressures. The consolidation was carried out against an elevated back pressure to ensure complete saturation of the sample. A back pressure of 207 kNm⁻², which has been found sufficient to dissolve all the air, was applied. The volume change of the sample was measured at various intervals of time until all the excess pore pressure was dissipated. Depending on the consolidation pressure, the duration for full dissipation of pore pressure varied from 2 to 5 days. The cell pressure was maintained constant by a Bishop type constant pressure mercury column. For the stress controlled tests, the deviator load was applied through a dead load hanger.

TRIAXIAL TEST SERIES

Triaxial compression and extension tests were carried out on both the weathered clay and the soft clay. Therefore, the triaxial tests could be broadly divided into four groups: compression tests on weathered clay; extension tests on weathered clay; compression tests on soft clay and extension tests on soft clay.

The compression tests on weathered clay could again be sub-divided into two types, depending on the pre-shear consolidation pressure. One type corresponded to the case when the pre-shear consolidation pressure was less than the maximum past pressure, thus the behaviour of these samples would correspond to an overconsolidated clay. The other type corresponded to pre-shear consolidation pressures higher than the maximum past pressure, i.e. the behaviour corresponding to normally consolidated state. A similar distinction could be also made on the extension tests carried out on weathered clay. Furthermore, some drained tests were also carried out on both clays. However, most of the tests conducted under extension condition on weathered clay were undrained tests.

With soft clay, the compression tests were carried out under different applied stress paths. The compression tests included undrained, fully drained, constant mean normal stress and anisotropic consolidation tests.

The extension tests carried out on weathered clay were of three types. The first type was an undrained test, wherein the axial stress was reduced while the lateral stress was maintained constant. A similar test where the axial stress was maintained constant while the lateral stress was increased was the second type of test conducted. The third type of test was similar to the first type, except that these tests were fully drained tests. In addition to these three types of tests, the extension tests on soft clay included a fourth type, which was similar to the second type, but it was fully drained.

RESULTS OF TESTS ON WEATHERED CLAY

Compression tests at low pre-shear consolidation pressure

In this series of tests, specimens of weathered clay were sheared under undrained conditions from pre-shear consolidation pressures of 14, 21, 34.5 and 41.5 kNm⁻² respectively. These stresses were below the maximum past pressure and hence the behaviour of the specimens corresponded to overconsolidated specimens. All samples were sheared under stress controlled conditions with constant cell pressure.

Fig 1 shows the stress paths followed by the specimens in a (*q*, *p*) plot. The stress paths are found to be approximately vertical, indicating that the mean normal stress *p* does not vary during shear. These results are in good agreement with the elastic wall concept of the stress-strain

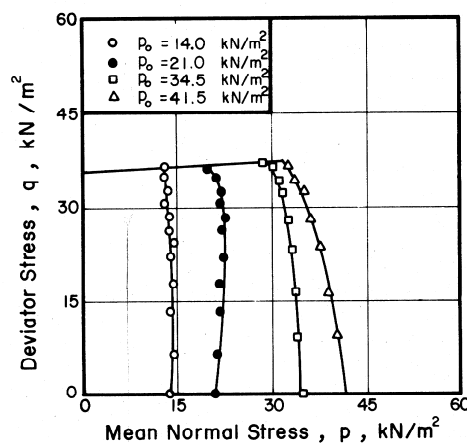


Fig 1. Effective stress paths followed during compression tests on weathered clay at low pre-shear consolidation pressure.

theories developed by Calladine (1963); Roscoe and Burland (1968); Schofield and Wroth (1968). According to these theories only elastic volumetric strains would take place inside the state boundary surface and these volumetric strains are only dependent on the mean normal stress. Since the volumetric strains are zero in undrained test, there would not be any change in the mean normal stress; thus the stress paths rise vertically in the (q, p) plot till failure is reached.

Extension tests at low pre-shear consolidation pressure

In this section the stress paths followed by specimens of weathered clay when sheared under low pre-shear consolidation pressure, will be presented and discussed. The specimens were sheared under strain controlled condition and the strain rate used was 0.0046 mm/minute.

Fig 2(a) illustrates the applied stress paths of the specimens sheared under undrained unloading condition (i.e. the axial stress reduced and the lateral stress maintained constant). Fig 2(b) illustrates the effective stress paths during shear of the samples consolidated to pre-shear consolidation pressures less than 69 kN/m². The shapes and positions of the effective stress paths in this plot are found to be dependent on the magnitude of the pre-shear consolidation pressure. It is noted that the initial portion of the effective stress paths for all the samples are nearly vertical. This may be due to the fact that in all the samples initially negative pore pressures developed and therefore p is higher than those corresponding to the applied stress path. The effective stress paths of the samples sheared from isotropic stresses of 10.5 and 16 kN/m² started off initially in a vertical direction and then deviated to the right towards failure. This trend indicates that the negative pore pressure was being increased with continued shear. These two stress paths would therefore correspond to the stress paths followed by heavily over-consolidated samples. The effective stress path of the specimen sheared at 21 kN/m² pre-shear consolidation pressure extended almost vertically in the (p, q) plot until failure. For all the tests at higher consolidation pressures (41.5 or 48.5 kN/m²), initially the stress paths are nearly vertical and thereafter they gradually deviate with decreasing p . These paths are therefore similar to those followed by lightly overconsolidated specimens.

An extension of these studies would be to investigate the type of stress paths followed by the specimens during loading tests (i.e. the axial stress maintained constant and the lateral stress increased). Hence, five specimens were sheared from pre-shear consolidation pressures of

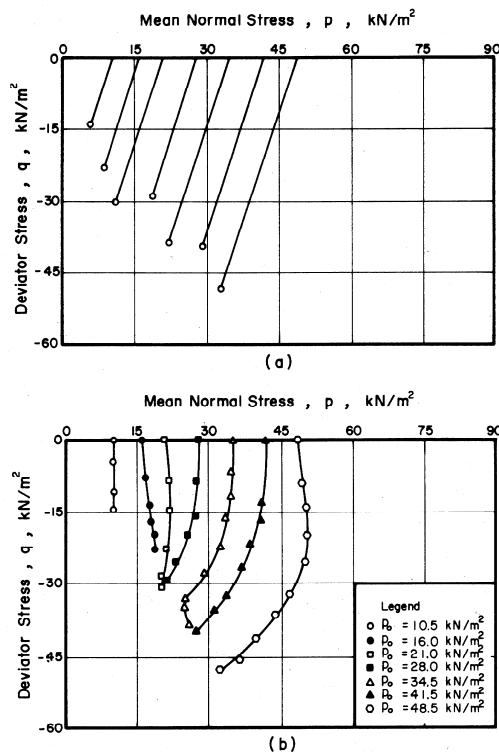


Fig 2. (a) Applied stress paths of specimens of weathered clay sheared in extension under undrained unloading conditions. (b) Effective stress paths.

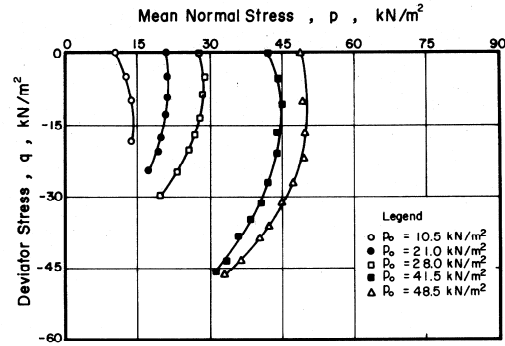


Fig 3. Effective stress paths of specimens sheared in extension under undrained unloading conditions.

10.5, 21.0, 28, 41.5 and 48.5 kN/m² respectively. The effective stress paths followed by the specimens are shown in Fig 3. The effective stress paths are found to be convex towards the origin and are similar to the effective stress paths exhibited by lightly overconsolidated clay. In all specimens, positive pore pressures developed during shear and the positive pore water pressures decreased the mean normal stress. The stress paths followed by the specimens sheared under loading conditions are very nearly the same as those sheared under unloading conditions. At low deviator stress levels, both types of stress paths are sub-parallel to the q -axis in the (p, q) plot.

Compression tests at higher pre-shear consolidation pressures

In this series of tests, four samples were sheared from pre-shear consolidation pressures of 103.5, 207, 276 and 414 kN/m² under undrained conditions. Also, three specimens were sheared under drained conditions with constant cell pressure from pre-shear consolidation pressures of 103.5, 207 and 276 kN/m². The specimens would be in a normally consolidated state prior to shear. These specimens were sheared under stress controlled conditions.

The effective stress paths followed by the specimens sheared under undrained conditions are shown in Fig 4(a). The end points of the specimens are also shown in this plot. They are found to lie on a straight line and will correspond to the projection of the critical state line (see Roscoe, Schofield and Wroth, 1958; and James and Balasubramaniam, 1971a and 1971b), in the (q, p) plot. The slope M of the critical state line is found to be 0.9.

The effective stress paths are found to be similar for all the four specimens sheared under different pre-shear consolidation pressure. The

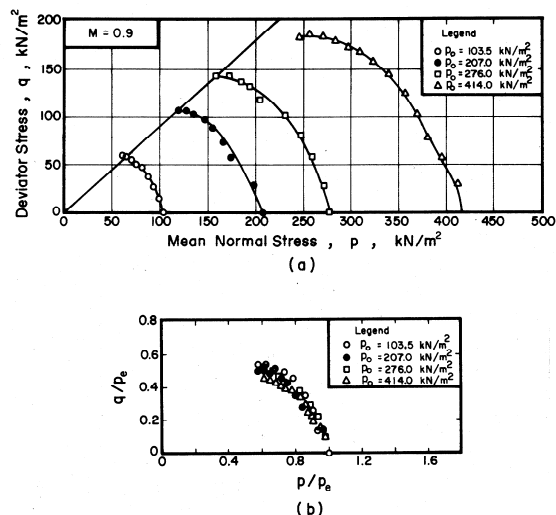


Fig 4. (a) Effective stress paths of specimens of weathered clay during undrained compression tests from higher pre-shear consolidation pressure. (b) State paths followed by specimens of weathered clay during undrained compression test.

effective stress paths are therefore normalised by using the stress parameters (q/p_e , p/p_e). These parameters transformed the state boundary surface for normally consolidated clays in (e , p , q) space to a two-dimensional curve. The state paths followed by these specimens are shown in Fig 4(b) and are found to be unique in the plot, thus confirming the similarity of undrained stress paths and the uniqueness of the state boundary surface. A similar conclusion was reached by Balasubramaniam (1974), when normally consolidated specimens of kaolin were sheared under undrained conditions in the conventional triaxial apparatus.

The stress paths followed by the specimens in the fully drained tests are shown in Fig 5(a). The state paths followed by these specimens are shown in Fig 5(b) in the (q/p_e , p/p_e) plot. The state paths followed by the drained test specimens are very nearly the same. However, when comparison was made with the corresponding state paths followed by the undrained test specimens, only the specimen sheared under drained conditions from a pre-shear consolidation pressure of 103.5 kNm⁻² was found to have the same state path as the undrained test specimen. The specimens sheared under drained conditions from pre-shear consolidation pressures of 207 and 276 kNm⁻² were found to show deviations from the undrained stress paths, especially at higher deviator stress levels. Since only three drained tests have been carried out it is difficult to make any definite conclusion. It must be remembered that the parameter p_e is defined as $p_0 \exp \frac{e_0 - e}{\lambda}$, and therefore small errors in the measurement of volumetric strains could show large deviation in the (q/p_e , p/p_e) plot.

Extension tests at higher pre-shear consolidation pressures

Fig 6(a) illustrates the effective stress paths for the samples sheared under undrained conditions from the higher pre-shear consolidation pressures. The pre-shear consolidation pressures of the specimens were 69, 103.5, 172.5, 207, 276, 348 and 414 kNm⁻² respectively. These specimens were sheared under strain-controlled conditions. The strain rate used was 0.0046 mm/minute. Even for these specimens, the initial portion of the stress paths are found to be nearly vertical. This effect may be due to the development of negative pore pressure in the sample. At higher values of the deviator stress, positive pore pressure was developed and the mean normal stress decreased. The effective stress paths, therefore, tend to become convex towards the origin. Another

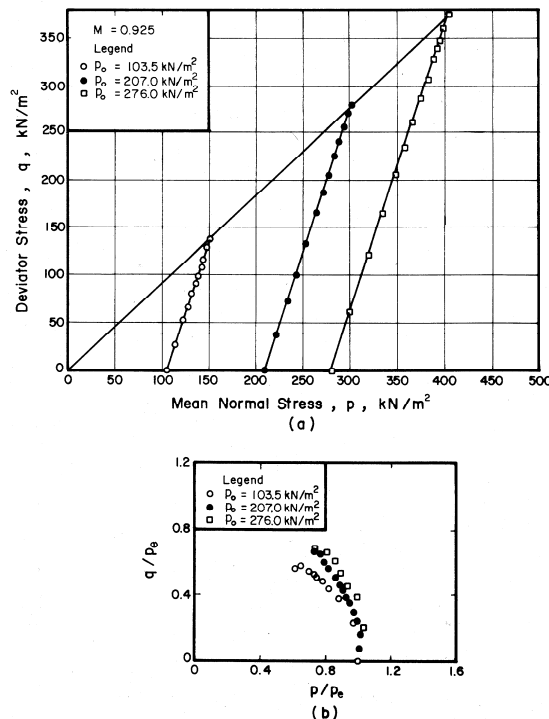


Fig 5. (a) Effective stress paths of specimens of weathered clay during fully drained compression tests from higher pre-shear consolidation pressure. (b) State paths followed by specimens of weathered clay during drained compression test.

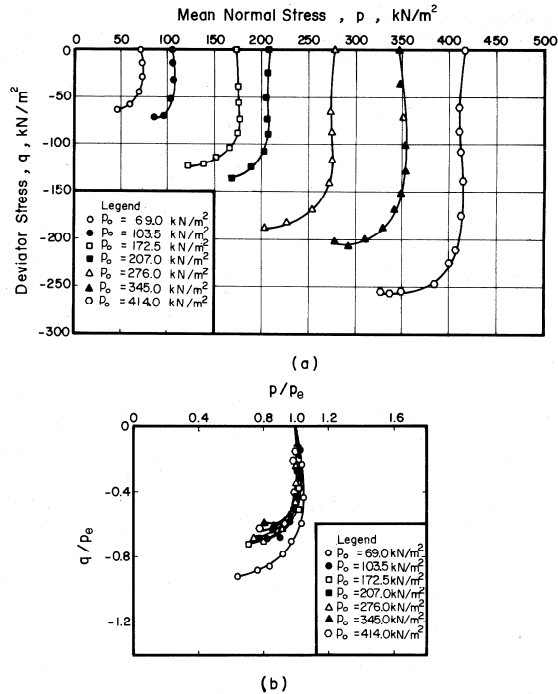


Fig 6. (a) Effective stress paths of specimens of weathered clay during undrained extension tests from higher pre-shear consolidation pressures. (b) State paths followed by specimens of weathered clay sheared in undrained extension from higher pre-shear consolidation pressures.

characteristic of these stress paths was that all of them were geometrically similar. Fig 6(b) shows the state paths followed by the samples at higher consolidation pressures. Except for the specimen which was sheared from the pre-shear consolidation pressure of 69 kNm⁻², for all other specimens, the state paths are virtually the same. The pre-shear consolidation pressure of 69 kNm⁻² was very close to the in-situ overburden pressure. In the field the specimen would have been existing under K_0 (coefficient of earth pressure at rest) conditions.

Thus in effect it would have been sheared to a certain deviator stress level. However, when this specimen was subsequently sheared from an isotropic stress level close to the previous in-situ stress, some effect due to the initial shear stress (experienced by the specimen in the field) could be expected. Similar effects were noted by Balasubramaniam (1973), when remoulded specimens of kaolin were prepared under an initially one-dimensional consolidation process and subsequently sheared from isotropic stress states. Also, the soft clay could have developed a certain degree of apparent overconsolidation due to ageing and prolonged secondary consolidation. These effects could only be erased if the specimens are subsequently consolidated to a higher pre-shear consolidation pressure. The state paths followed by the specimens in the extension tests are found to be different from the state paths followed by similar specimens when tested in compression under loading condition. Thus the weathered clay seems to indicate some effects of anisotropy, when tested under compression and extension stress conditions.

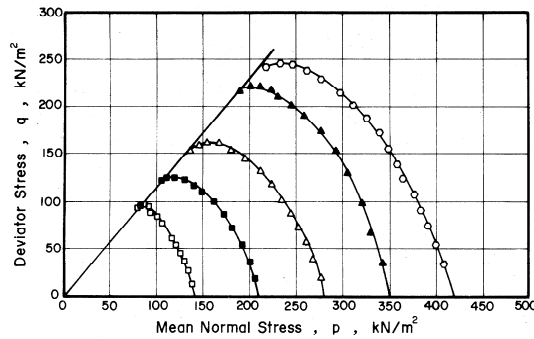
RESULTS OF TEST ON SOFT CLAY

Compression tests

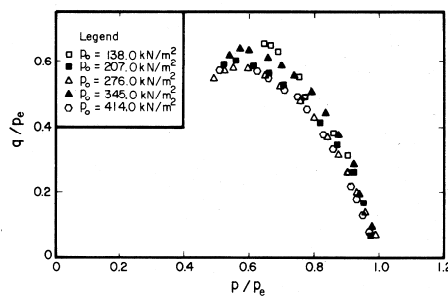
Four types of compression tests were carried out and these included (i) undrained (ii) fully drained with constant cell pressure (iii) constant mean normal stress and (iv) anisotropic consolidation tests. The data from these tests will be presented separately and discussed. All specimens were sheared under stress controlled conditions.

Undrained Tests

In this series altogether five undrained tests were carried out on samples isotropically consolidated to stresses of 138, 207, 276, 345 and 414 kNm⁻² respectively. These samples were subsequently sheared with increasing axial stress and under constant cell pressure.



(a)



(b)

Fig 7. (a) Effective stress paths followed by specimens of soft clay during undrained compression tests.
(b) State paths followed by specimens of soft clay during undrained compression tests.

Fig 7(a) illustrates the effective stress paths followed by the specimens in a (q, p) plot. The effective stress paths are found to be virtually similar. Fig 7(b) illustrates the state paths followed by all the test specimens in the $(q/p_0, p/p_0)$ plot. This would be the two-dimensional representation of the state boundary surface for soft Bangkok Clay when sheared under undrained conditions in the conventional triaxial apparatus. Similar, two-dimensional representation of the state boundary surface for normally consolidated specimens of Weald Clay was first presented by Roscoe and Poorooshasb (1963). A critical study of the uniqueness of the state boundary surface has recently been made by Balasubramaniam (1974), for remoulded specimens of kaolin when tested in triaxial apparatus under a wide variety of applied stress paths. A unique curve, such as that shown in Fig 7(b) would imply that a unique relationship exists between the water content, w , and the stresses q and p for soft Bangkok Clay. The above finding is in agreement with the constant voids ratio/water content contours of Rendulic (1936), Henkel (1960) and the (p, e, q) surface of Roscoe, Schofield and Wroth (1958).

Fully drained tests

In this series, five fully drained tests were carried out on soft clay, isotropically consolidated to pre-shear consolidation pressures of 138, 207, 276, 345 and 414 kN/m^2 respectively. All specimens were sheared under stress controlled conditions. The cell pressure was maintained constant and the deviator stress was increased.

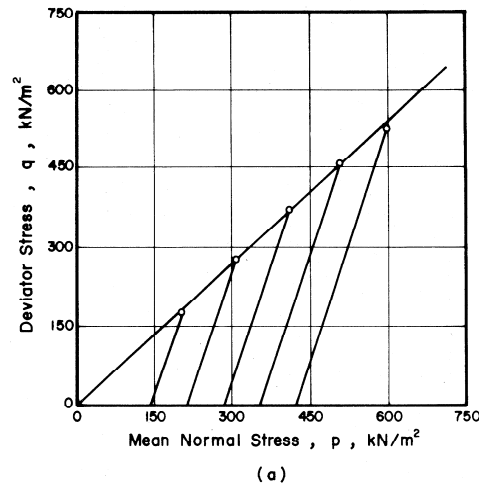
Since these tests were fully drained tests, the effective stress paths would be linear in the (q, p) plot with dq/dp equal to 3 (see Fig 8(a)). The state paths followed by all the drained test specimens in a $(q/p_0, p/p_0)$ plot are shown in Fig 8(b). The state paths followed by all the specimens are virtually the same at low deviator stress levels. However, significant differences are noted in the state paths at stress states closer to failure. The specimen which was consolidated to the lowest pressure seems to show the largest deviation from the rest of the sample. This effect has already been discussed for the weathered clay. The state paths corresponding to isotropic stresses of 207, 276 and 414 kN/m^2 show unique behaviour during drained tests.

Constant mean normal stress tests

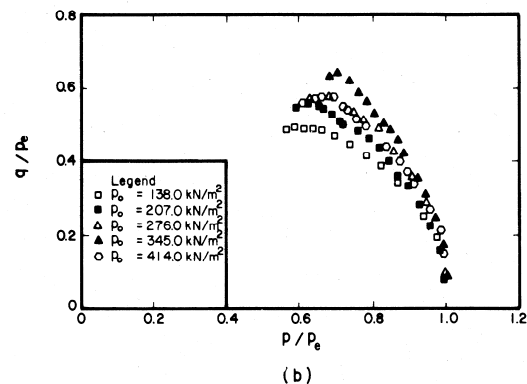
The stress paths corresponding to four specimens sheared under constant p conditions are shown in Fig 9(a). During these tests, the axial stress was increased and the lateral stress was decreased, so that the mean normal stress p remained constant. The state paths followed by the specimens sheared from pre-shear consolidation pressures of 207, 276 and 414 kN/m^2 were found to be virtually the same (Fig 9(b)). As for the fully drained test, the specimen sheared under constant p conditions from a pre-shear consolidation pressure of 138 kN/m^2 shows the greatest deviation from the paths followed by the rest of the samples. As stated before, this difference in behaviour could be expected to some extent as this sample was consolidated to the lowest isotropic stress and perhaps there would be some effect caused by the initial shear stress due to K_0 consolidation in the field. The unique state boundary surface noted for constant p test specimens is similar to that observed for fully drained test specimens.

Anisotropic consolidation tests

The stress-strain theory of Roscoe and Poorooshasb (1963) assumed the state paths followed during anisotropic consolidation lie on the state boundary surface. The subsequent theories due to Roscoe et al (1963) and Roscoe and Burland (1968) also implied that the state paths during anisotropic consolidation was on the state boundary surface. However, the experimental observations provided by Roscoe and 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. Several anisotropic consolidation tests carried out by Balasubramaniam (1969, 1974) indicated that the state paths corresponding to anisotropic consolidation did lie on the same state boundary surface as that corresponding to the undrained tests on normally consolidated specimens of kaolin. Fig 10 illustrates the state paths followed by two



(a)



(b)

Fig 8. (a) Effective stress paths followed by specimens of soft clay during fully drained tests.
(b) State paths followed by specimens of soft clay during fully drained tests.

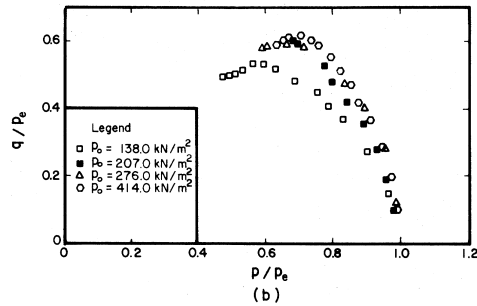
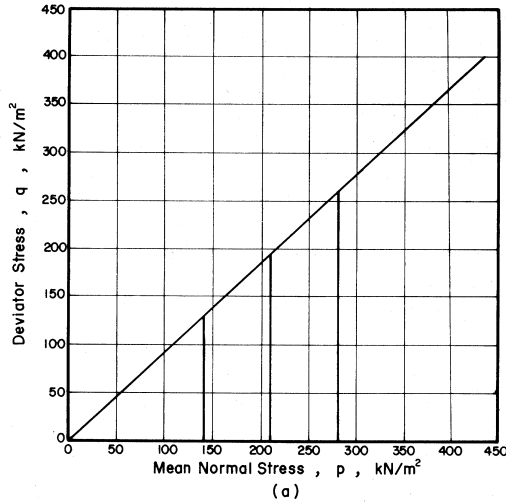


Fig 9. (a) Effective stress paths followed by specimens of soft clay during constant p tests. (b) State paths followed by specimens of soft clay during constant p tests.

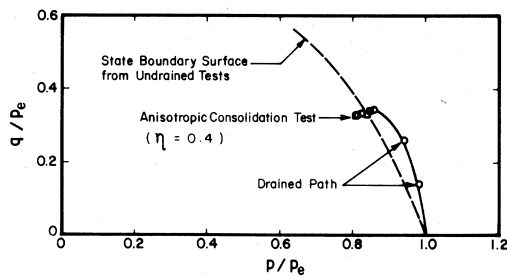
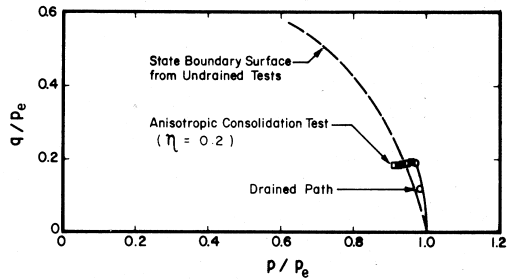


Fig 10. State paths followed during anisotropic consolidation.

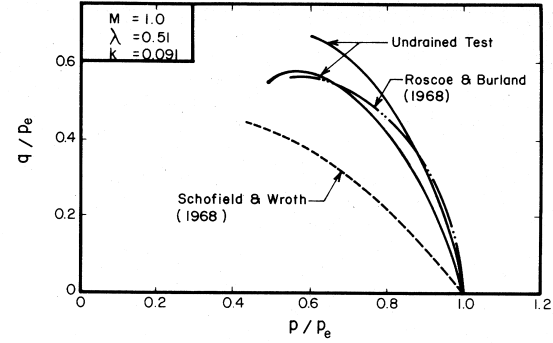


Fig 11. Observed and predicted state boundary surface for soft Bangkok Clay.

specimens of soft Bangkok Clay sheared along anisotropic consolidation paths with η values of 0.2 and 0.4. In this figure the state paths corresponding to undrained tests on soft Bangkok Clay are also shown. It is interesting to note that the state path corresponding to anisotropic consolidation lies on the same state boundary surface as that corresponding to the undrained tests.

The slope λ of the isotropic and anisotropic consolidation lines in the $(e, \log p)$ plot for soft Bangkok Clay is 0.51. Also, the slope k of the isotropic swelling line in the $(e, \log p)$ plot is 0.091. Knowing the values of M , λ and k , the state boundary surface for normally consolidated clays could be predicted using the Critical State Theories (see Roscoe and Burland, 1968; Schofield and Wroth, 1968). The equations for the state boundary surface are as follows

$$\log_e \frac{p_e}{p} = \left(1 - \frac{k}{\lambda}\right) \frac{\eta}{M} \quad \text{Schofield and Wroth (1968)}$$

$$\log_e \frac{p_e}{p} = \left(1 - \frac{k}{\lambda}\right) \log_e \left(\frac{M^2 + \eta^2}{M^2}\right) \quad \text{Roscoe and Burland (1968)}$$

The observed and predicted state paths for soft Bangkok Clay tested under compression conditions are shown in Fig 11. Good agreement is noted between the experimentally observed state boundary surface and that predicted by Roscoe and Burland theory.

Extension tests on soft clay

As already stated, three series of extension tests were carried out. Two of them were undrained tests with loading and unloading conditions respectively. The third series corresponded to drained loading conditions. All specimens were sheared under strain controlled conditions.

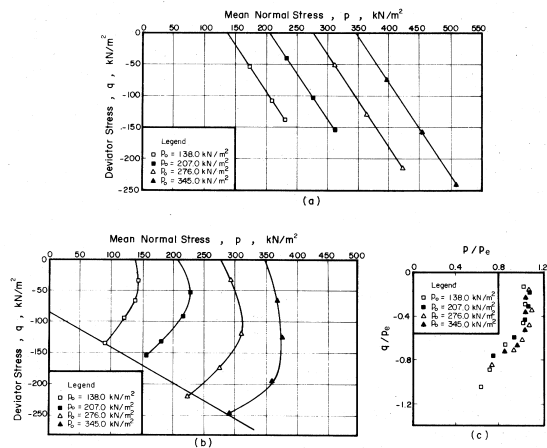


Fig 12. (a) Applied stress paths on soft clay specimens during extension tests under undrained loading conditions. (b) Effective stress paths during extension under undrained loading conditions. (c) State paths during extension under undrained loading conditions.

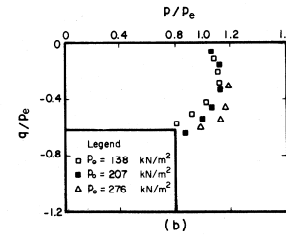
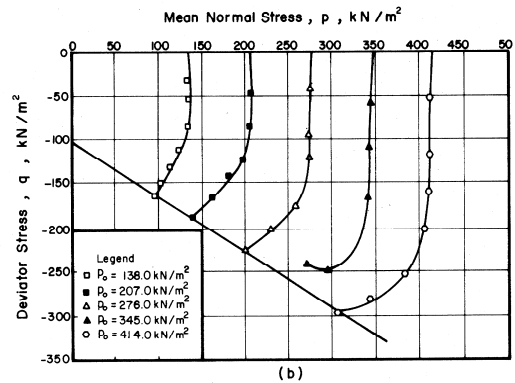
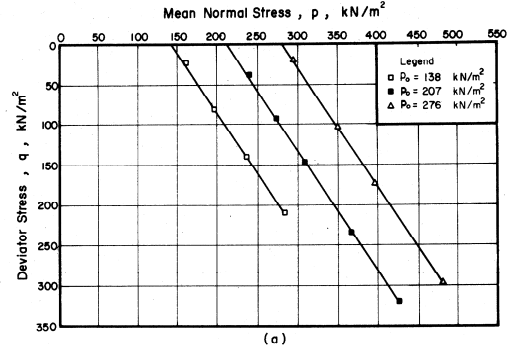
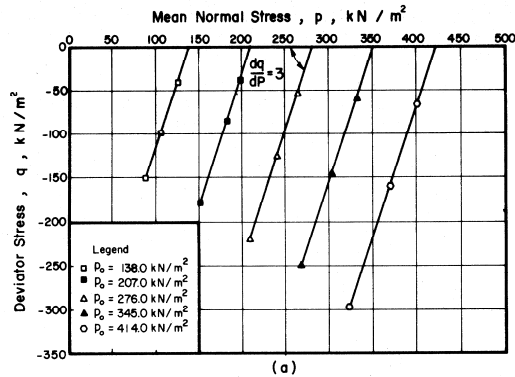


Fig 14.(a) Effective stress paths followed by specimens of soft clay during extension under drained loading conditions.
(b) State paths during extension under drained loading conditions.

Undrained loading tests

In this series four specimens of soft clay were sheared from pre-shear consolidation pressures of 138, 207, 276, 345 kN/m² respectively. The strain rate used was 0.0046 mm/minute. The applied stress paths and the effective stress paths followed by the specimens are shown in Figs 12(a) and (b). The effective stresses are then normalised and the results are presented in the $(q/p_e, p/p_e)$ plot in Fig 12(c). Here again, the state path followed by the specimen sheared from the lowest pre-shear consolidation pressure (138 kN/m²), is found to be different from the rest of the specimens which do follow a unique state boundary surface.

Undrained unloading tests

In this series five specimens of soft clay were sheared from pre-shear consolidation pressures of 138, 207, 276, 345, 414 kN/m² respectively. The strain rate used was 0.0046 mm/minute. The applied stress paths and the effective stress paths followed by the specimens are shown in Figs 13(a) and (b). The effective stresses are normalised and the state paths followed by the specimens are shown in Fig 13(c). The state paths followed by the specimens are found to be approximately unique and are similar to those followed by the specimens sheared under loading conditions.

Drained loading tests

In this series three specimens were sheared from pre-shear consolidation pressures of 138, 207 and 276 kN/m² respectively. The strain rate used was 0.000122 mm/minute. The applied stress paths and the effective stress paths would be coincident and these paths are shown in Fig 14(a). The state paths followed by the specimens are shown in Fig 14(b). For a first approximation, the state paths followed by these specimens could be considered to be the same.

The state paths followed by the specimens sheared in extension under undrained loading and unloading conditions are virtually the same. However, differences are noted between the state paths followed during undrained and drained extension tests.

CONCLUSIONS

The stress paths and the state paths followed by specimens of weathered and soft Bangkok Clay are presented and discussed. Both compression and extension tests were carried out under a wide variety of stress paths.

Fig 13.(a) Applied stress paths on soft clay specimens during extension tests under undrained loading conditions.
(b) Effective stress paths during extension under undrained unloading conditions.
(c) State paths during extension under undrained unloading conditions.

For specimens of weathered clay sheared in compression under stresses less than the maximum past pressure the undrained stress paths are found to be approximately sub-parallel to the q axis in the (p, q) plot.

For specimens of weathered clay sheared in extension under stresses less than the maximum past pressure, the undrained stress paths are only sub-parallel to the q axis at low levels of deviator stress. At higher levels, the stress paths tend to become convex towards the origin in the (q, p) plot.

For specimens of weathered clay sheared in compression under stresses higher than the maximum past pressure, the state paths followed during undrained and drained tests are found to be each unique. However, significant differences are noted between the undrained and drained state paths at higher pre-shear consolidation pressures.

For specimens of weathered clay sheared in extension under stresses higher than the maximum past pressure, the state paths followed under undrained unloading conditions, are unique. This unique state surface is different from that observed under compression conditions especially at higher levels of deviator stress.

For soft clay tested in compression under a wide variety of stress paths (undrained, constant p , fully drained and anisotropic consolidation) the state boundary surface is unique and could be successfully predicted from the Roscoe and Burland theory.

For soft clay tested in extension under undrained and drained conditions, the state paths are found to be unique for each type of test, but are different from each other.

The differences noted in the state boundary surface are found to be predominant only at higher deviator stress levels close to failure. Settlement computations are generally carried out at deviator stress levels much lower than the peak values. For these purposes it appears that the state boundary surface can be assumed to be unique. Using this unique surface, volumetric strains and shear strains can be computed. Hence the settlements can be evaluated from these strains.

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REFERENCES

- BALASUBRAMANIAM, A. S. (1969). *Some factors influencing stress-strain behaviour of saturated clay*. Thesis (Ph.D.) Cambridge.
- BALASUBRAMANIAM, A. S. (1973). Stress history effects on stress-strain behaviour of a saturated clay. *Geotechnical Engg., Jour. of Southeast Asian Soc. of Soil Engg.*, Vol. 4, No. 2, pp. 91-111.
- BALASUBRAMANIAM, A. S. (1974). A critical study of the uniqueness of state boundary surface for saturated specimens of kaolin. *Geotechnical Engg., Jour. of Southeast Asian Soc. of Soil Engg.*, Vol. 5, No. 1, pp. 21-38.
- BURLAND, J. B. (1965). The yielding and dilation of clay. Correspondence. *Geotechnique*, Vol. 15, No. 2, pp. 211-4.
- CALLADINE, C. R. (1963). Correspondence on: A theoretical and experimental study of strains in triaxial tests on normally consolidated clays by Roscoe and Poorooshasb. *Geotechnique*, Vol. 13, No. 3, p. 250.
- HENKEL, D. J. (1960). The relationship between the effective stresses and water content in saturated clays. *Geotechnique*, Vol. 10, No. 2, pp. 41-5.
- JAMES, R. G. and BALASUBRAMANIAM, A. S. (1971a). The peak stress envelopes and their relation to the critical state line for a saturated clay. *Proc. 4th Asian Regional Conf. on Soil Mech. & Foundn. Engg., Bangkok*, Vol. 1, pp. 115-20.
- JAMES, R. G. and BALASUBRAMANIAM, A. S. (1971b). A comprehensive experimental study of the strength characteristics of remoulded specimens of kaolin. *Geotechnical Engg., Jour. of Southeast Asian Soc. of Soil Engg.*, Vol. 2, No. 1, pp. 21-33.
- MOH, Z.-C., NELSON, J. D. and BRAND, E. W. (1969). Strength and deformation behaviour of Bangkok clay. *Proc. 7th Int. Conf. on Soil Mech. & Foundn. Engg., Mexico*, pp. 287-95.
- MUKTABHANT, C. (1967). Engineering properties of Bangkok sub-soils. *Rept. Chulalongkorn Univ., Bangkok*, 37 pp.
- RENDULIC, L. (1936). Relation between voids ratio and effective principal stresses for a remoulded silty clay. *Proc. 1st Int. Conf. on Soil Mech. & Foundn. Engg., Cambridge, Mass.*, Vol. 3, pp. 48-51.
- ROSCOE, K. H. and BURLAND, J. B. (1968). *On the generalised stress-strain behaviour of wet clays. Engineering plasticity*. Cambridge, Cambridge Univ. Press, pp. 535-609.
- ROSCOE, K. H. and POOROOSHASB, H. B. (1963). A theoretical and experimental study of strains in triaxial tests on normally consolidated clays. *Geotechnique*, Vol. 13, No. 1, pp. 12-38.
- ROSCOE, K. H., SCHOFIELD, A. N. and THURAIRAJAH, A. (1963). Yielding of clays in states wetter than critical. *Geotechnique*, Vol. 13, No. 3, pp. 211-40.
- ROSCOE, K. H. and THURAIRAJAH, A. (1964). On the uniqueness of yield surfaces for wet clay. *Proc. Int. Symp. Rheology & Soil Mech., IUTAM, Grenoble*, pp. 364-81.
- ROSCOE, K. H., SCHOFIELD, A. N. and WROTH, C. P. (1958). On the yielding of soils. *Geotechnique*, Vol. 8, No. 1, pp. 22-53.
- SCHOFIELD, A. N. and WROTH, C. P. (1968). *Critical state soil mechanics*. London, McGraw-Hill.