J. King Saud Univ., Vol. 1, *Eng. Sci.* (1,2), pp. 67-82, Riyadh (1409/1989)

Effect of Stress Rotation on the Strength and Deformation of Laboratory Prepared Clay Samples

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Abstract. The behaviour of laboratory prepared kaolin clay samples has been studied using triaxial series on normally and overconsolidated soil samples with various degrees of anisotropy. The influence of anisotropic stress history and stress rotation was investigated. It was noted that the degree of initial anisotropy has a large influence on the observed undrained shearing strength. The stress-strain relationships for anisotropically consolidated clay samples were found to be influenced by the induced anisotropic stress history. The failure condition of anisotropically consolidated clay samples in compression mode seems to be represented by the unique (straight line) envelope, while in extension mode, no such envelope was clearly defined.

1. Introduction

In nature most clay deposits are anisotropic. Soil anisotropy is mainly due to the mode of soil deposition and subsequent K_0 consolidation. The process of consolidation in nature may occur under a variety of different stress conditions other than the one-dimensional condition which is normally assumed. Stress conditions depend upon natural phenomenon and other factors such as soil type and the soil's stress history. K_0-consolidation is one form of such natural processes. Many studies have shown that K_0 has a range of values from less than one in normally consolidated soil with a rapid increase to a value up to 3 in highly over-consolidated clays [1-5].

The problem of undrained shear strength anisotropy in clays was first reported by Hansen and Gibson [6]. Since then, a number of studies on directional properties of natural deposits of normally or overconsolidated clays were made by many workers notably [7-13].

Mayne [14], summarized data for 42 different clays which had been tested under both isotropic and anisotropic conditions and confirmed the findings of Mitachi and Kitago [12] that the anisotropic undrained shear strength could be conservatively estimated as 80% of the isotropic shear strength for "typical" conditions.

This conclusion was drawn based on comparisons of various test data on natural clay deposits. The purpose of the present study is to interpret the behavior of natural deposits in relation to degree of anisotropy and to quantitatively show the influence of induced anisotropy on the behavior of laboratory prepared clay samples.

Sampling natural deposits, no matter how perfect the sampling technique used, cause disturbances to take place. Consequently, truly undisturbed naturally deposited clay samples are almost impossible to obtain. Besides, the anisotropic stress history in natural deposits is not easily and accurately available in most cases. It may also be pointed out that laboratory prepared soil samples are different from natural deposits particularly in effect of aging.

Therefore, a systematic testing program was designed to test laboratory prepared anisotropic clay samples consolidated under conditions similar to those experienced in nature (*i.e.* samples were consolidated one dimensionally under controlled different stress ratios from a slurry state condition).

Clay samples prepared under anisotropic stress history were tested under both uniaxial compression and extension modes. The test program was planned to help understand the influence of anisotropic stress history and to permit the development of a conceptual model for anisotropic clays. Keeping the critical state concept in mind, the observed test results were normalized and interpreted in forms suitable for comparison with the critical state theory outlined in reference [15].

2. Test Program

Kaolin clay specimens prepared in the laboratory from a slurry condition were tested. An oven dried kaolin (LL = 52, PL = 26) was mixed with distilled water in a de-airing chamber in ratio of 1:1 by weight. The slurry was then spooned into a consolidometer mold similar to that described by Stipho [16]. Test specimens in a state possible to be handled were produced under K_0-consolidation conditions. The level of maximum pressure was selected within available testing facilities so as not to have future influence on the observed behavior. The influence of molding stress and disturbances on observed soil behavior is fully discussed by Skempton and Sowa [17], Broms [18] and Stipho [16]. The molded specimens were then trimmed to form fully saturated samples 75 cm × 15 cm and made ready for mounting in the triaxial cell.

Subsequent consolidation and swelling of the samples were carried out in the triaxial cell. Consolidation and swelling cycles were conducted under constant predetermined stress ratio $K_c = 1.0, 1.25, 1.5, 1.75$ ($K_c = \frac{\sigma'_{1c}}{\sigma'_{3c}}$); while overconsolidation ratios between 1 to 12 were considered.

Overconsolidated samples were produced by allowing the samples to swell back along the same stress paths used during the consolidation phase, somehow different of what actually occured in the field.

The stress paths followed during consolidation and swelling are shown in Fig. 1. The samples were tested under stress controlled compression and extension (loading and unloading) under undrained conditions, in two different triaxial cells. Compression tests were carried out in triaxial cell having a 2.5 cm diameter ram while extension tests were carried out in a cell having 7.5 cm diameter ram clamped to the top plate on the sample. The test set up in extension test could subject the sample to the unnecessary weight of the ram before the application of cell pressure. However, this was prevented by the use of a supporting frame designed specifically to carry the weight of the ram during the mounting process of the sample in the triaxial cell. The cell was then placed on the testing machine, where predetermined increments of load were applied. Stress controlled tests are useful and attract many researchers, their drawback is noticed only in extension tests and that is due to the sticking of the ram at the start of decrements as also noticed by Parry and Nadarajah [19]. Herein, free movement of the ram was achieved by honing of the ram at contacts, but this increased the cell fluid leakage. However, by filling the top one centimeter of the cell with thick oil, the cell fluid leakage as well as the ram friction was minimized. It should be mentioned that appropriate measures and corrections to minimize machine interference, sample disturbances and ram friction were applied at all stages. A small side program to determine the best rate of loading that allow pore water pressure stabilization was also conducted. The test program followed in this work is outlined in Table 1.

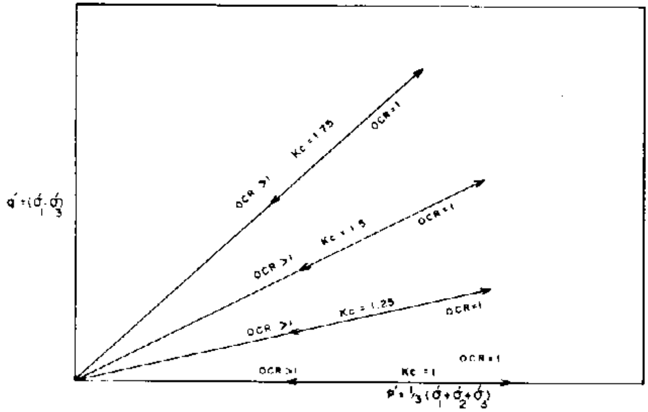

Fig. 1 . Stress paths adopted in the consolidation phase

3. Test Results

Consolidation and swelling behavior of the isotropically and anisotropically consolidated samples are shown in Fig. 2, in terms of water content versus log P′

Table 1. Test program

Test designation	P'_c KN/m^2	P'_e KN/m^2	OCR	w%	$K_c = \frac{\sigma'_{1c}}{\sigma'_{3c}}$
IC-1	412.5	412.5	1.0	35.2	1
IC-2	365.0	365.0	1.0	35.4	1
IC-3	365.0	304.2	1.2	35.9	1
IC-4	385.0	192.5	2.0	36.8	1
IC-5	378.0	75.6	5.0	35.3	1
IC-6	385.0	48.0	8.0	38.5	1
IC-7	412.5	34.4	12.0	38.8	1
IE-1	385.0	385.0	1.0	35.3	1
IE-2	412.5	412.5	1.0	35.2	Failed
IE-3	412.5	206.3	2.0	36.3	1
IE-4	412.5	343.7	1.2	35.3	1
IE-5	550.0	91.7	6.0	38.0	1
IE-6	412.5	41.2	10.0	39.0	1
AC-1	206.0	206.0	1.0	38.2	1.25
AC-2	206.0	103.0	2.0	39.8	1.25
AC-3	206.0	51.5	4.0	40.5	1.25
AC-4	550.0	68.7	8.0	38.0	Failed
AC-5	550.0	68.7	8.0	37.4	1.25
AC-6	206.0	206.0	1.0	37.9	1.5
AC-7	206.0	103.0	2.0	39.9	1.5
AC-8	206.0	51.5	4.0	40.3	1.5
AC-9	550.0	68.7	8.0	37.2	1.5
AC-10	206.0	206.0	1.0	37.6	1.75
AC-11	206.0	103.0	2.0	39.3	1.75
AC-12	206.0	51.5	4.0	40.1	1.75
AC-13	550.0	68.7	8.0	40.1	Failed
AC-14	550.0	68.7	8.0	39.7	1.75
AE-18	550.0	68.7	8.0	38.2	1.25
AE-19	206.0	206.0	1.0	37.8	1.50
AE-20	206.0	103.0	2.0	39.5	1.50
AE-21	344.0	86.0	4.0	40.2	1.50
AE-22	550.0	68.7	8.0	38.0	1.50
AE-23	206.0	206.0	1.0	37.6	1.75
AE-24	206.0	103.0	2.0	39.4	1.75
AE-25	344.0	86.0	4.0	40.0	1.75
AE-26	550.0	68.7	8.0	38.1	1.75

Almost parallel sets of lines during the compression and rebound phases are observed. This straight line relation on the w - log P′ plot supports the critical state concept put forward by Roscoe, Schofield and Wroth [20]. The slope of the compression phase is designated by λ and the slope of the rebound lines is designated by K. For the clay used λ and K were found to have values equal to 0.14 and 0.05 respectively. The existence of the multiple parallel consolidation lines for a soil consolidated anisotropically under various stress ratios ($K_c = \sigma_{1c}/\sigma_{3c}$) supports the concept of existence of multiple inclined planes within a state boundary surface with various angles of inclination (θ). The angle is diversified from the isotropic condition (θ = 0) as the consolidation stress ratio moves towards anisotropy *i.e.* $K_c \geqslant 1$ as proposed by Ohta and Hata [21]; Ohta and Wroth [22]; Banerjee, Stipho and Yousif [23] and Stipho [24, 25].

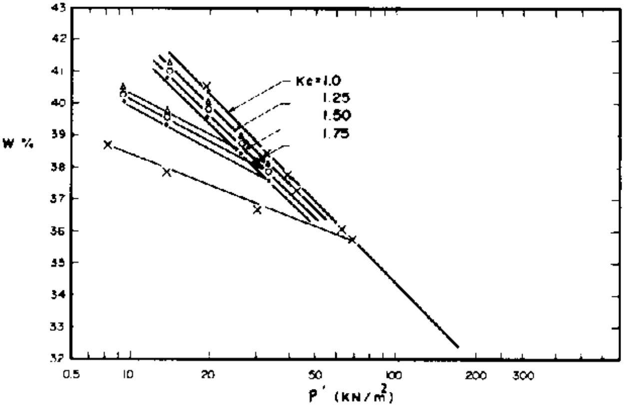

Fig. 2 . Consolidation behavior W-log P' relation

This concept allowed for useful mathematical developments towards modeling the behavior of anisotropically consolidated clays. These inclined planes are well within the proposed unique state boundary surface introduced within the critical state concept. Graham and Li [26], observed a similar trend of findings on testing naturally deposited K_0-consolidated clay and laboratory prepared anisotropically consolidated Winnipeg clay.

4. Effective Stress Path

Typical effective stress paths for isotropically and anisotropically consolidated samples tested under compression and extension loading are shown in Figs 3 and 4. The effective deviator stress q′ and the mean effective stress P′ are normalized by dividing by the effective mean consolidation pressure P_0' at beginning of shear failure. The parameters q′ and P′ are defined as:

$$q' = \sqrt{\frac{1}{2}\left[(\sigma_1' - \sigma_2')^2 + (\sigma_2' - \sigma_3')^2 + (\sigma_1' - \sigma_3')^2\right]}$$

while

$$P' = \frac{1}{3}(\sigma_1' + \sigma_2' + \sigma_3')$$

The overconsolidation ratio OCR is defined as OCR = P_c' / P_0' when P_c' is the effective mean preconsolidation pressure the material ever subjected to, and P_0' is the mean effective all round pressure at the start of the shearing.

Under conventional axisymmetric loading in triaxial compression (in extension $\sigma_1' = \sigma_2'$) the condition is $\sigma_2' = \sigma_3'$. Accordingly the above parameters are reduced to:

$$q' = (\sigma'_1 - \sigma_3')$$

$$P' = \frac{1}{3}(\sigma_1' + 2\sigma_3')$$

It was observed that the undrained effective stress path of anisotropically consolidated clay (Normally and Overconsolidated) followed a distinctly different path in compression than that followed during extension mode. The material tends to follow a very long path in extension testing compared with the relatively short path followed during compression loading. These differences become more pronounced with increasing K_c values. Under compression loading the material seems to fail on a unique failure envelope similar to that defined in the critical state line (CSL) by $M = (q'/P')_f$.

In extension tests, such well-defined straight line failure envelope cannot be evaluated. More data, particularly for highly overconsolidated anisotropic clays, are needed to eliminate possible doubt and to define soil behavior in this area.

The data presented in Fig. 4 may also indicate the presence of a curved failure envelop rather than straight line (showed dotted). Some test results on kaolin clay reported by Nadarjah [4], and that of natural Bangkok clay deposits reported by Balasubramaniam and Waheed Uddin [27] showed similar trends of curved failure envelopes in extension tests, though no comments were made in either case.

The influence of stress rotation on the normalized undrained effective shearing strength presented in terms of variation of η_f' (where $\eta_f' = \frac{q'_f - q_0'}{P'}$ in both compression and extension at failure) for various degrees of anisotropy is shown in Fig. 5.

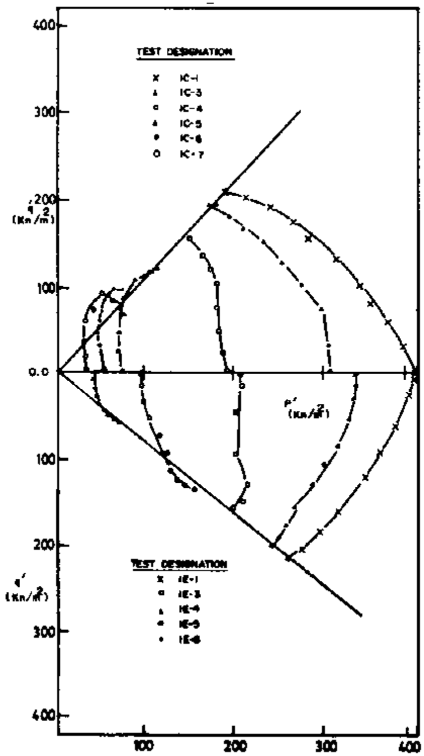

Fig. 3 . **Effective stress paths for isotropically consolidated and compression samples in both extension mode**

The normalized undrained effective shearing strength of isotropically consolidated samples in both compression and extension modes seem to lie on an envelope sloping at almost 45°, a 1:1 relation. The slope of this envelope starts to deviate from the 1:1 relation as the degree of anisotropy of soil is progressively increased to K_c = 1.75. The influence of stress rotation on anisotropically consolidated clay samples could well be explained by distinct patterns of particle arrangement which took place during anisotropic stress history.

5. Stress Strain Relations

Normalized stress strain curves for normally consolidated clay samples under both compression and extension modes are presented in Figs. 6, 7 and 8. To incorpo-

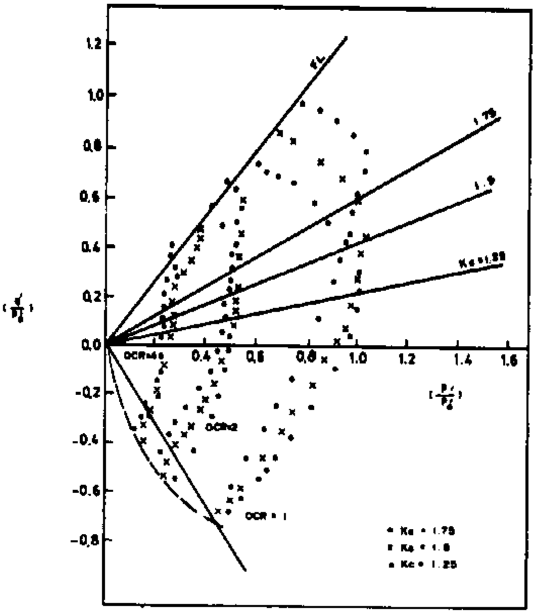

Fig. 4 . Effective undrained stress paths for anisotropically consolidated clay samples in both extension and compression

rate the influence of pore water pressure developed during undrained tests, the net post consolidation current effective deviator stress to the current mean effective all round pressure (P') represented by $\eta' = (\frac{q' - q'_0}{P'})$ is plotted against axial strain. At a particular strain level, η' is found decreasing with increasing degree of anisotropy. In extension mode this ratio was found increased negatively with increasing degree of anisotropy.

The influence of degree of anisotropy on the stress-strain relations is observed to be considerable. The shearing resistance of the anisotropically consolidated clay samples quickly reaches its maximum at small strain levels. This behavior is equally true in compression and extension modes and it differs from that observed in isotropically overconsolidated clays Figs. 7 and 8. Figure 9 shows the variation of the net effective deviator stress $(q' - q'_0)$ normalised by the mean effective consolidation pressure at the start of loading (P'_0), at various axial strain levels (ε_1 % and ε_f % at failure), with respect to the anisotropic stress history in both extension and compression modes of testing.

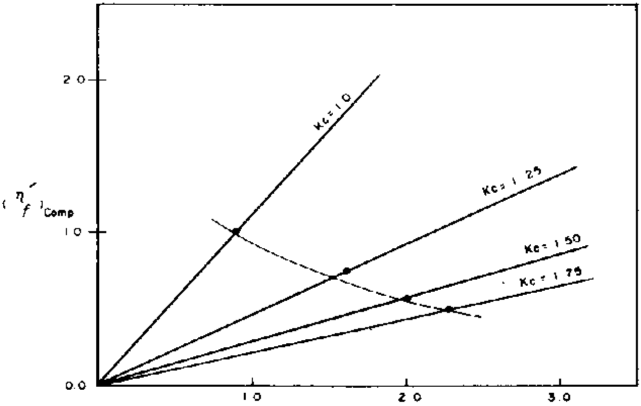

Fig. 5 . Normalized undrained effective strength of anisotropically consolidated clay with relation to mode of deformation

Anisotropically overconsolidated clay samples showed smaller axial strain at failure than that for normally consolidated specimens. However, the highly overconsolidated clay samples tested demonstrated little tendency for strain softening and dilatancy after failure. This behavior is normally controlled by the microfabric patterns that developed in the sample during its stress history. Unloading processes which produce overconsolidated samples, seem to introduce little alteration to already developed particle orientation in the clay tested.

During the process of anisotropic consolidation some of the work is dissipated by irreversible changes in particle arrangement, while only a small part of the energy is recovered on unloading (elasto-plastic behavior). Within the context of critical state theory, anisotropically consolidated clays may be considered in a state of stress that lies on the state boundary surface of the material which encloses the elastic domain.

6. Pore Pressure Coefficient

The excess pore water pressure that developed during undrained triaxial test of a saturated clay sample (*i.e.* B = 1) and during compression loading can be obtained from;

$$\Delta U = A\Delta\,(\sigma_1 - \sigma_3)$$

where A the pore pressure parameter, and is known to change during loading. Its variation during loading until failure is of particular interest. This soil parameter is found to vary with intial state of stress, stress history and consolidation condition.

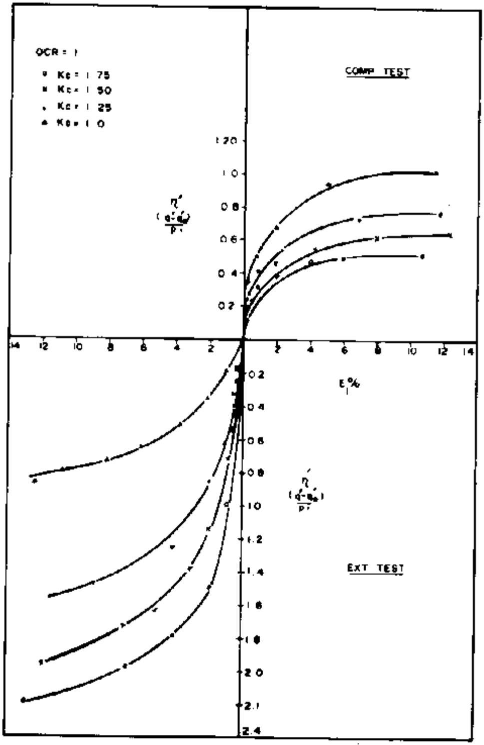

Fig. 6 . Normalized stress strain relation for normally consolidated isotropic and anisotropic clay samples

Figure 10 shows the variation of the parameter A during triaxial compression in isotropically and anisotropically normally consolidated clays. The terminal dotted line in the figure represents the value of A at failure (A_f), *i.e.* at $(\sigma_1' / \sigma_3')_{max}$.

7. Conclusions

The appreciable influence of the anisotropic stress history on the observed soil behavior during consolidation and triaxial loading which is well established is supported herein. Stress history is found to affect the shearing strength of the clay tested; the level is dependent upon the intial degree of stress anisotropy. Consequently isotropic triaxial test results over-predict the anisotropic undrained shear strength of normally consolidated clays in most cases.

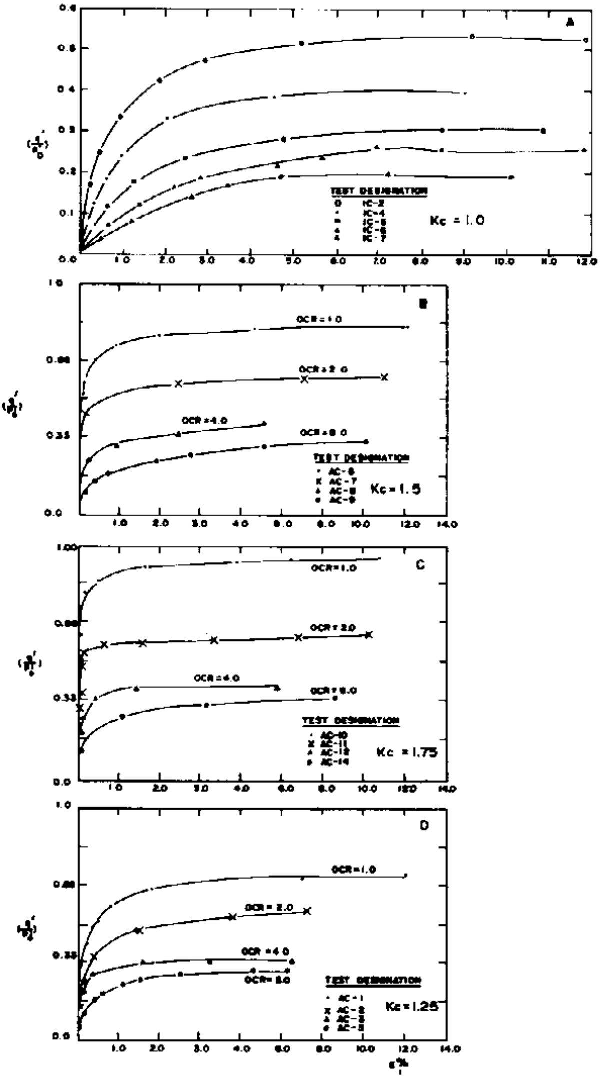

Fig. 7 . The influence of degree of anisotropy and over consolidation ratio on the stress strain relation in compression test

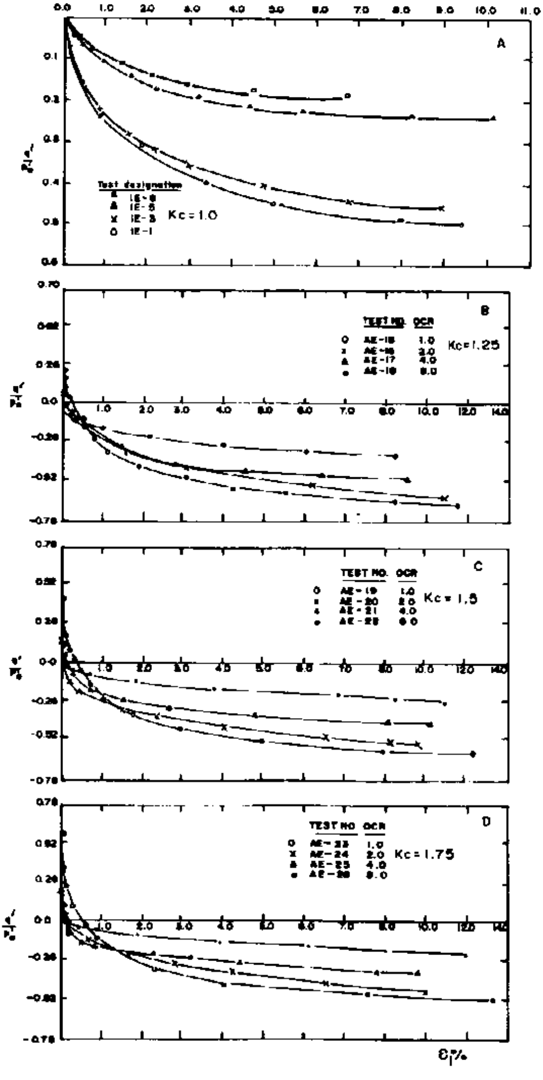

Fig. 8 . The influence of degree of anisotropy and over consolidation ratio on the stress strain relation in extension test

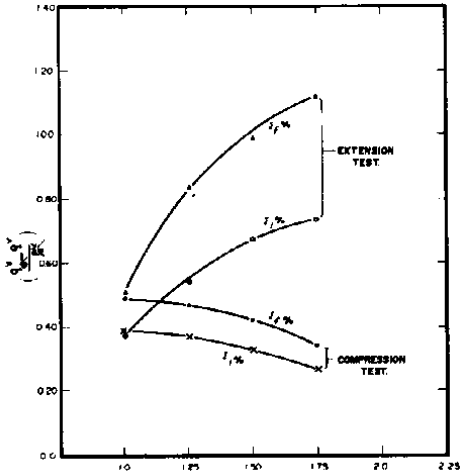

Fig. 9 . Influence of initial consolidation and loading condition on net effective deviator stress on normally consolidated clay

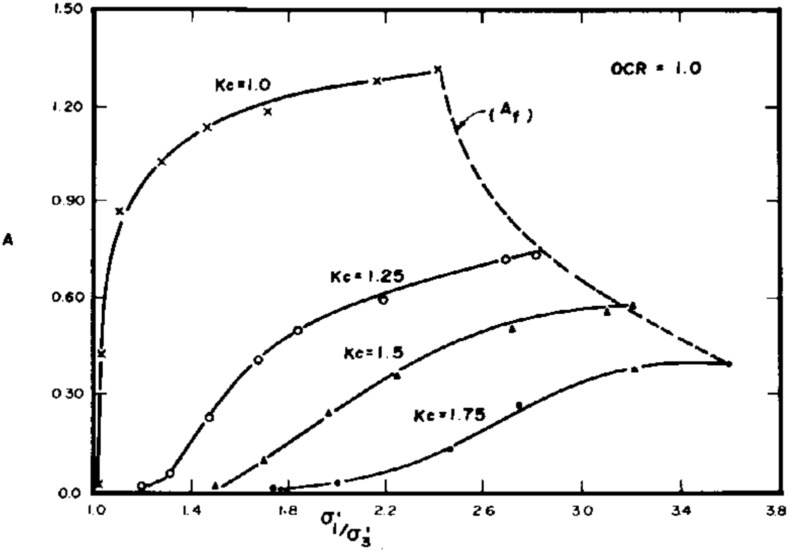

Fig. 10 . Changes of water pressure parameter a during compression loading of samples with various unisotropy

The behavior of anisotropically consolidated samples was also found to be influenced by stress rotation. Isotropically consolidated clay gave almost identical measures of undrained shearing strength in both the extension and compression modes of deformation. The change in shear strength as represented by the parameter η' during the extension and compression deformation modes seems to range between 1 to 4.5 times depending upon the induced anisotropic stress history.

The examination of the shape of the undrained stress path of isotropically consolidated clay supports the concept of the cam-clay model proposed within the critical state models introduced by Schofield and Wroth [15]. The undrained stress paths for the anisotropically consolidated clay samples are seen rotated in unsymmetrical form along the P axis or the consolidation (q'/p') axis. This rotation is found increasing with degree of anisotropy. More data are needed to establish the shape and condition of failure of anisotropically overconsolidated clay in extension mode.

The main experimental program was conducted at the soil's laboratory of the University College Cardiff, U.K. The author's thanks and appreciations are due to Professor K. Majeed for stimulating discussions.

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(*Manuscript Received:* 8-11-1987; *Accepted:* 8-3-1988)

تأثير تغير الإحداثيات على خواص مقاومة القص والتشويه في عينات تربة محضرة بالمختبر

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ملخص البحث: يدرس هذا البحث تأثير تغير إحداثيات الفحص على خواص تربة طينية من نوع الكاؤولين محضرة في المختبر. عينات سليمة مشددة تم فحصها تحت إجهادات غير متجانسة. لقد تم التركيز على دراسة تأثير إجهادات الفحص والتشديد غير المتجانس مع طريقة ومقدار التشديد على خواص التربة وتصرفات هذه العينات. لقد لوحظ تأثير درجة التحميل غير المتجانس على مقاومة القص غير المصرف والعلاقات الجزئية للإجهاد والتشوه في تصرفات التربة. إن حالة الإخفاق في التربة المشددة تحت إجهادات غير متجانسة تختلف في حالة التحميل بالضغط عن ذلك في حالة التحميل بالشد، كذلك مغلف الإخفاق في حالة الضغط أمكن تقريبه إلى خط مستقيم لجميع العينات المشددة وغير المشددة، ولم يمكن التوصل إلى مثل هذا التقريب في العينات التي فحصت تحت أحمال الشد.