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THREE TECHNIQUES FOR FABRIC VIEWING AS APPLIED TO SHEAR DISTORTION OF A CLAY

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Abstract—A knowledge of the microscopic physical behavior of soils is important and necessary for the correct interpretation of observed macroscopic deformations in soil bodies. This study was designed to determine the particular pattern and distribution of extensive fabric alteration accompanying shear strains in a clay specimen subjected to triaxial stress combinations. The techniques used for observing these microscopic features were polarized light microscopy of thin sections from Carbowax-fixed clay samples, scanning electron microscopy of thinly coated cleavage surfaces in vacuum desiccated specimens, and transmission electron microscopy of metal-shadowed carbon replicas made of similar cleavage surfaces. All three methods showed that the zone of extensive fabric alteration in the triaxially sheared bodies was planar and had an average thickness of about 30 μ.

Most clay particles in the zone were aligned parallel to the zone direction. The results of the study also demonstrated the particular merits of each of the three techniques for fabric viewing.

INTRODUCTION

A GENERAL problem which exists in soil mechanics is that of determining correct physical models to allow for appropriate soil behavior analyses. In particular, the nature and extent of large shear distortions during yielding of a triaxially loaded clay body are not exactly known. In the observations which have been made of millimeter-wide shear disturbances in remoulded clays, it is noted that these were constrained to occur in direct shear devices. For example, in the study by Sloane and Nowatski (1967), replicas of sections taken through carbowax-fixed direct shear specimens were observed by transmission electron microscopy. In other studies using polarized light microscopy, Morgenstern and Tchalenko (1967), viewed vertical thin sections from direct shear box clay samples, while Yong and Leitch (1965) reported the observation of vertical and horizontal thin sections through a double shear box deformation zone.

In the present study, fabric distortion of a right prismatic specimen of a saturated clay, subjected to three independently variable principal stresses in an undrained condition, is examined. This ideal configuration is shown schematically in Fig. 1. The diagram also includes a representation of the observed deformation mode when such a clay specimen is loaded to the state of instability. While the direction of relative motion undergone by two parts of the body may be seen with the naked eye, the amount of material involved in the accompanying shear process cannot be determined by macroscopic observations. Therefore, the pattern of extensive material shear and fabric distortion in the clay during yield is unknown.

EXPERIMENTATION

A device which provides the stress state of Fig. 1 has been described by Yong and McKyes (1971). The basis of this apparatus is a standard 4-in. sample diameter triaxial cell, with modified end loading platens for a rectangular sample. Brass pressure boxes with flexible polyethylene membranes are installed to provide an intermediate principal stress σ_2 to prismatic soil specimens. In addition, dial gauges are attached to one of the boxes in order to measure lateral specimen deformations in the σ_3 direction through simple levers.

The clay used for this experimental study was a kaolin with the name, English Clay S-187. An X-ray powder diffraction study of this clay showed that it was composed primarily of kaolinite with a trace of mica, and a sedimentary grain size determination indicated that most of the particles were in the 0·5–2 μ size range. The clay was found to have plastic and liquid limits of 37·5 per cent and 54·5 per cent respectively. In Fig. 2 a transmission electron micrograph of a Pt–Pd shadowed carbon replica, taken over sedimented clay particles*,

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*The details of this technique, described by Brown (1964), were communicated to the McGill Soil Mechanics Laboratory by Professor R. L. Sloane, University of Arizona.

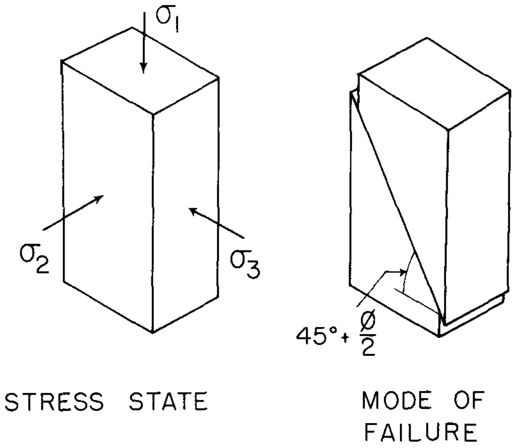

Fig. 1. The ideal stress state and observed mode of failure of kaolin clay samples subjected to three variable principal stresses.

reveals the discrete micron-sized kaolinite particles to be fairly well crystallized, in spite of a certain chewed appearance on some particle edges.

Saturated samples of this clay were prepared by slurrying at 120% water content, by weight, and vacuum drawing into a three inch diameter lucite tube filled with deaired water. Reduction of the water content to the final test density was achieved by one dimensional compression in the tube to an average pressure of 0·5 kg/cm^2, followed by isotropic consolidation in a triaxial cell to 2·0 kg/cm^2 pressure. Specimens were subsequently trimmed to their prismatic testing shape and loaded by the true triaxial device with various combinations of the three principal stresses.

TECHNIQUES FOR FABRIC VIEWING

Microscopic techniques must be employed to detect the detailed patterns of shear distortions as reflected by clay particle movements. Therefore, the problem becomes the particular one of selecting methods for fabric viewing which will render faithful pictures of the clay fabric after shear loading. These techniques must involve not only the fixing of the wet clay particle arrangement for observation, but at the same time should preferably not be too lengthy in procedure or costly for extensive programs of fabric study.

The three techniques for fabric viewing used in this study were thin sections in polarized light, scanning electron and transmission electron microscopy. The first of these involved the exchange of pore water in the clay for liquid Carbowax 1500 in a manner similar to that used by Martin (1966). Thin sections of the clay and solidified carbowax were made by a microtome knife and were viewed in a polarized light microscope. The two other techniques were scanning electron microscopy of cleavage surfaces in vacuum desiccated clay specimens, coated with 150 Å of gold–palladium alloy, as well as transmission electron microscopy of metal shadowed carbon replicas taken of similar surfaces. The vacuum drying of wet clay samples for the latter two methods involved a lineal shrinkage of about 3 per cent from their original dimensions. While such a procedure would involve the diminishing of some pore space sizes, (Diamond 1970), from an average of 0·45 cm^3/g to approximately 0·38 cm^3/g, it was one of the objectives of this study to determine whether the simple vacuum desiccation technique could preserve fabric patterns in this clay which would be indistinguishable from those observed by polarized light microscopy of carbowaxed thin sections. If this were true, the more complex methods for removing water and fixing clay fabric, such as freeze-drying, freeze-fracture-etching, or critical region drying (Diamond, 1970), could be avoided. In view of the clay used, the problems of expansive clay curling under vacuum (Sloane and Diamond, 1970), were not encountered in this study.

Figure 2 showed that the kaolin clay under study consisted of discrete, micron-sized, and reasonably well-formed kaolinite platelets. Therefore it is a suitable material for the fabric viewing techniques employed because particle shapes and arrangements can be identified in electron micrographs, and the optical properties of the mineral particles were sufficiently pronounced for polarized transmitted light microscopy. In this latter method, advantage is taken of the birefringence of the kaolinite mineral, which causes the incoming polarized light to be split into components parallel to the mineral optical axes. The component ray nearly parallel to the *c* axis of a particle is retarded behind the other component by a distance Δ, which corresponds to a specific phase difference according to the wavelength of the rays. Thus, when plane polarized light passes through a clay particle, the retardation of rays in one component direction causes a variation in the intensity of light which is allowed to pass through the analyzer polarizing screen (Kerr, 1959), depending upon the orientation of a clay particle. The resultant light intensity observed in the polarizing microscope is a maximum when the *c* axes of kaolinite particles are oriented at an angle of about 45° to the direction of incoming polarized light. The intensity is a minimum when the *c* axes are nearly coincident with the polarizer or analyzer directions, or parallel to the direction of light travel. This phenomenon allows for the partial determination of fabric in

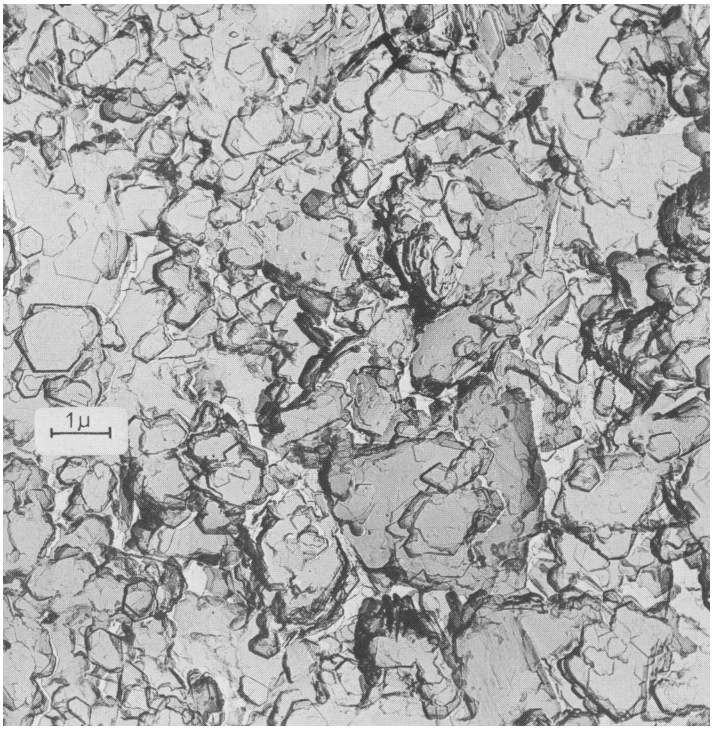

Fig. 2. Replica transmission electron micrograph of oriented kaolin particles (English clay S-187).

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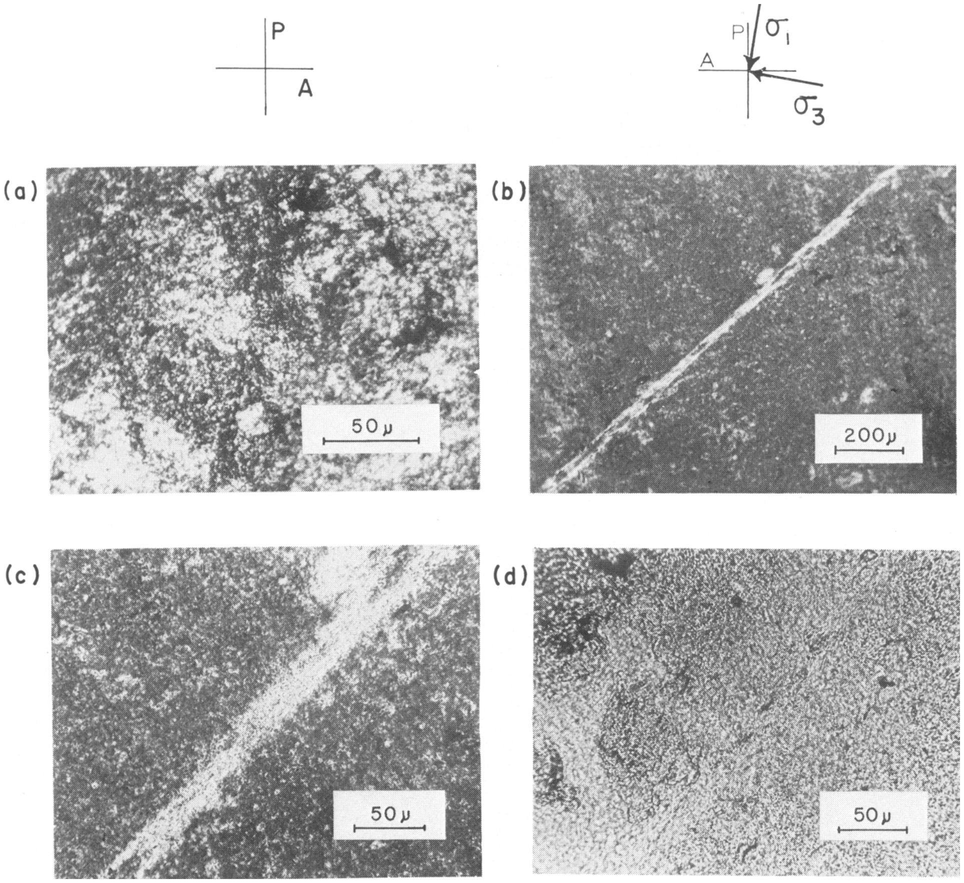


Fig. 3. Light micrographs of kaolin thin section: (a) Unsheared, crossed polarizers; (b) Failed sample, crossed polarizers; (c) Failed sample, crossed polarizers; (d) Failed sample (*c*), plane light.

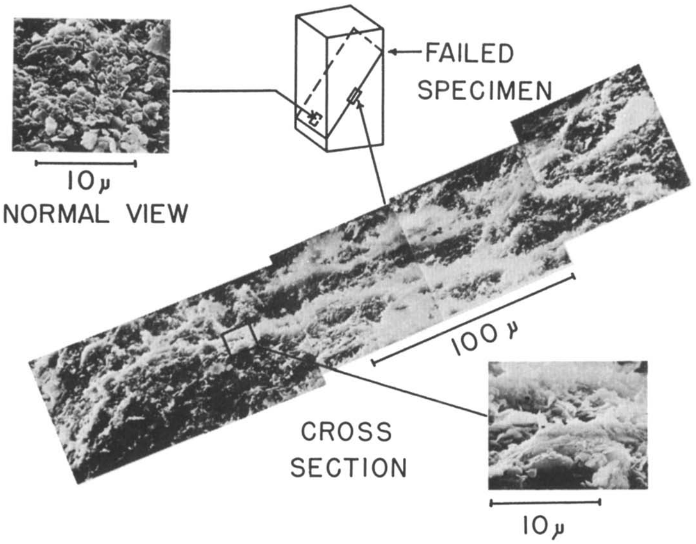
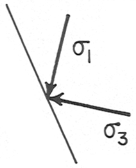


Fig. 4. Montage of scanning electron micrographs of cleavage surfaces in a sheared clay sample.



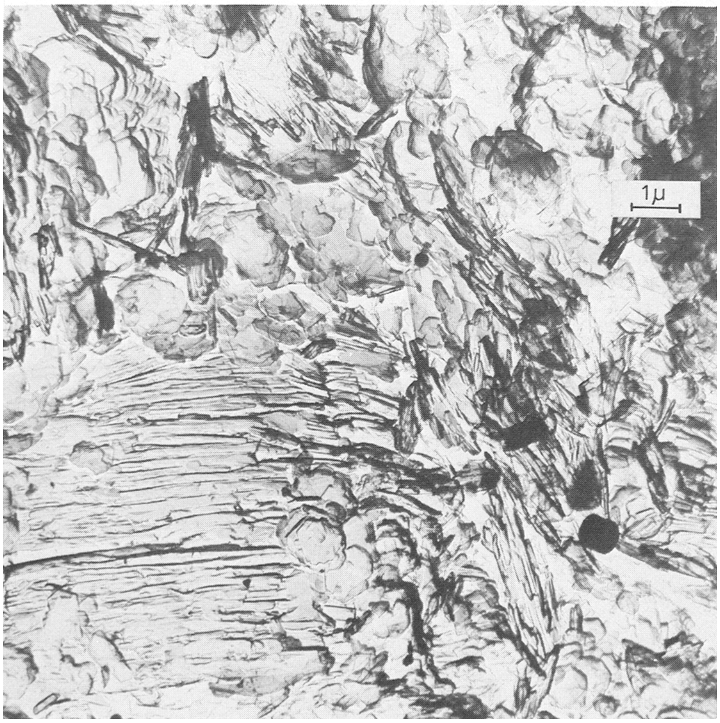


Fig. 5. Replica transmission electron micrograph of a cleavage surface in a sheared clay sample.

thin sections of clay by the identification of groups of oriented clay particles, according to the intensity of light resulting from each group or area of the section.

RESULTS

The resultant interference pattern produced by kaolin clay in the polarized light microscope is shown in Fig. 3a, together with the polarizer and analyzer directions *P* and *A* respectively. This is a sample which was consolidated to the test dentisy, but not shear loaded. The distribution of light intensity in the typical area shown in Fig. 3a is quite random, although groups of oriented particles are seen to exist in areas of diameters from 10 to 30 μ. A 24 μ thin section taken from one of the clay specimens failed by stresses σ_1 and σ_3 as indicated, is shown in Figs. 3b and c. A bright zone, (15–40 μ in width), runs straight diagonally through the micrographs making angles of approximately 45° and 35° to the polarizer and σ_1 directions, respectively. The zone is mostly white, although it contains some darker areas, indicating that a large proportion of the clay particles lie parallel to the zone direction. In all observations of failure zones, the areas of material fabric outside the zones could not be distinguished in character from views of unsheared clay specimens, such as that in Fig. 3a. This thin zone therefore constitutes the only apparent area of extensive fabric alteration produced by the shear yielding process. Figure 3d is a view of the same sample area shown in Fig. 3c, but with plane light, and is presented as evidence that the area is uniform in clay content with no holes or cracks filled with carbowax.

A closer examination of the details of clay particle arrangement in the shear zone is provided in the scanning micrographs of Fig. 4. The figure is a montage of scanning electron microscope views at an angle of 45° to surfaces which were cleaved vertically through the interior of a sheared clay specimen (*Cross-section*), and parallel to the failure zone (*Normal view*). The same fabric pattern is evident here as that deduced from the polarized light micrographs. Lines of particles oriented parallel to the zone direction are separated by groups of more random platelets. As in the light microscopic views, the zone is seen to vary from about 20–40 μ in width, and is surrounded by a clay fabric which is essentially similar to that of unsheared samples. Similar zones were located and seen to extend along the entire length of all failed samples which were scanned in the microscope.

Better resolution and identification of individual clay platelets in the disturbed area can be provided by a transmission electron micrograph, such as that shown in Fig. 5. This is a view of a Pt–Pd shadowed carbon replica of a vertical cleavage surface through a sheared kaolin specimen. The magnification of this micrograph, as indicated by the micron marker, is such that the width of the shear zone is not fully encompassed therein. However, the resolution of particles and their arrangements allows the observation of lines of parallel platelets circumnavigating a sizable kaolinite crystallite, situated at the lower left in Fig. 5. The small percentage (by weight) of these crystallites in the English Clay are the probable cause for some of the variations in the observed shear zone width. The average width of shear zones was determined by scanning over larger areas of cleavage surface replicas than that shown in Fig. 5, and in all cases was found to be nearly equal to that seen in polarized light and scanning electron microscopic views.

SUMMARY AND CONCLUSION

The results of this study indicate that the three methods for fabric viewing employed showed essentially similar fabric changes in this regime of stress combinations and clay density. That is, in each undrained prismatic sample of saturated kaolin clay, brought to yield by three variable principal stresses, a thin shear zone is constrained to form. This zone, consisting largely of lines of highly oriented clay particles, is approximately 20–40μ thick and passes through a relatively undisturbed fabric in the remainder of the clay samples. The shear zone makes an angle of approximately $(45° - \phi'/2)$ with the major principal stress direction, where the effective internal angle of friction for this clay, $\phi' = 19°$ (Yong and McKyes, 1971).

Replica transmission electron microscopy provides the best resolution of clay particles and their detailed arrangement, while scanning electron microscopy allows for a good three dimensional view of a cleavage surface through the shear zone. Polarized light microscopy yields the best integral view of the zone and its surroundings, and may be the best method to use for determining the direction of the shear movement or other large scale features of the phenomenon.

The overall objective of the study was achieved in that the extent and pattern of major fabric alterations resulting from shear distortion were determined for the stress states imposed. The analytical model of the yield phenomenon in these triaxial clay specimens could then be formulated compatible with the physical behavior. The observed results provide a better insight of the clay behavior and impetus for investigating the reasons for the observed mechanisms from a micromechanics point of view. Eventually a better understanding of some of the elemental physics governing clay behavior should result from such studies.

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Résumé—La connaissance du comportement physique des sols à l'échelle microscopique est importante et nécessaire pour interpréter correctement les déformations observées à l'échelle macroscopique dans les masses de sol. Cette étude a été conçue en vue de déterminer l'allure particulière et la distribution des modifications d'une structure étendue qui accompagnent les tensions de cisaillement dans un échantillon d'argile soumis à des combinaisons de contraintes triaxiales. Les techniques utilisées pour observer ces caractéristiques microscopiques sont la microscopie en lumière polarisée de lames minces d'argile fixées au carbowax, la microscopie électronique à balayage de surfaces de clivage finement métallisées d'échantillons desséchés sous vide, et la microscopie électronique par transmission de répliques de carbone ombrées obtenues à partir de surfaces de clivage similaires. Les trois méthodes ont montré que la zone d'altération de la structure étendue, dans les masses soumises au cisaillement triaxial sont planes et ont une épaisseur moyenne de 30μ environ.

Dans la zone d'altération, la plupart des particules d'argile sont alignées parallèlement à la direction générale de la zone. Les résultats de cette étude démontrent également les avantages particuliers de chacune des trois techniques pour l'examen de la structure.

Kurzreferat—Eine Kenntnis des mikroskopischen physikalischen Verhaltens von Böden ist wichtig und notwendig für die richtige Auswertung beobachteter makroskopischer Deformierungen in Bodenkörpern. Diese Untersuchung wurde unternommen zur Bestimmung des jeweiligen Bildes und der Verteilung umfassender Strukturveränderung im Gefolge von Schubspannungen in einer Tonprobe, die triachsillen Spannungskombinationen ausgesetzt ist. Die zur Beobachtung dieser mikroskopischen Erscheinungen verwendeten Methoden umfassten die Mikroskopie von Dünnschnitten von mit Carbowax fixierten Tonproben im polarisierten Licht, Abtastelektronenmikroskopie dünn bestrichener Spaltoberflächen in vakuumgetrockneten Proben, und die Durchstrahlungs elektronenmikroskopie metallbeschatteter Kohlenstoffrepliken aus ähnlichen Spaltoberflächen. Alle drei Methoden zeigten, dass das Gebiet ausgedehnter Strukturveränderung in den triachsial schubbeanspruchten Körpern planar war und eine durchschnittliche Dicke von etwa 30 μ aufwies.

Die meisten Tonteilchen in der Zone waren parallel zu der Zonenrichtung ausgerichtet. Die Ergebnisse der Untersuchung zeigten ferner die jeweiligen Vorteile der drei Methoden bei der Strukturbetrachtung.

Резюме — Знание микроскопически наблюдаемых физических свойств почв важно и необходимо для правильной интерпретации макроскопически наблюдаемых деформаций почв. Исследование имело целью определить специфическую картину и распределение широко проявляющегося изменения, сопровождающего сдвиговые напряжения в образце глины, подвергнутом действию комбинаций трехосного стресса. Для наблюдения этих микроскопических особенностей были использованы: микроскопическое изучение в поляризованном свете шлифов глинистых образцов (в карбоваксе); сканирующая электронная микроскопия плоскостей спайности (с тонкими пленками) образцов, разрезанных в вакууме; электронная микроскопия на просвет оттененных металлом угольных реплик с аналогичных плоскостей спайности. Все три метода показали, что зона широкого изменения строения в образцах, испытавших действие трехосного стресса, является плоской и имеет среднюю толщину около 30 мк. Большинство глинистых частиц в этой зоне располагается параллельно ее направлению. Результаты исследования демонстрируют также специфическое значение каждого из трех методов оптического изучения для выяснения особенностей строения образцов.