Electron Microscopic Investigation of Kink-Band Phenomena in Shear Induced Consolidated Kaolinite

by

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Introduction

KINK-BANDS in clay are usually small scale structures which need microscopic investigation, i.e., they are under the discipline of micro-structure of soil. The micro-structure of soil is a characteristic of assemblies of soil particles which has geometrical arrangement, usually referred as fabric and interparticle forces between particles and the cementation between themselves. Thus the investigation of any soil micro-structure primarily means the microscopic investigation of soil fabric at a magnification so as to permit the observation of individual soil particles, preferably with some form of mathematical models to justify the formation of the fabric and the experimental results to explain the behaviour of the fabric in terms of their interparticle forces and cementation.

This paper, as the title suggests, is concerned principally with the electron microscopic investigation of kink-bands of an artificially prepared kaolinite soil. The fabric of kink-bands has been quantified, particularly in terms of the degree of preferred orientation of the kaolinite plate-like particles in a particular direction, and also the preferred orientation of the particles outside the kink-bands and with the hinge zones. A mathematical model of kink-band has been derived from the general characteristics of the kink-bands and both the theoretical and experimental results have been compared.

Kink-bands when referred to by Geologists are usually straight-limbed angular folds (Figure 1) with narrow or multiple hinge zones (Ramsay, 1967) resulting from the operation of a shear couple (Dewey, 1965). This term is given generally, to small scale structures in Geology, where the distance between any two axial surfaces (Figure 1) does not exceed more than 10 cm ; when two limbs form a symmetric fold, the limbs being of equal length, these are generally called a chevron fold.

Kink-bands and chevron folds are usually developed in rocks which have a planer tectonic anisotropy or any materials which possess well-developed thin layering. The fold shape of layers is generally similar and the overall geometrical shape of kink-bands or chevron folds, when examined carefully, is often found to be of parallel form (Ramsay, 1967), i.e., layers keep a fairly constant thickness throughout the fold and the axial surfaces of each fold nearly or generally bisect the angle between sequential fold limbs. Generally the internal deformation that occurs within any one

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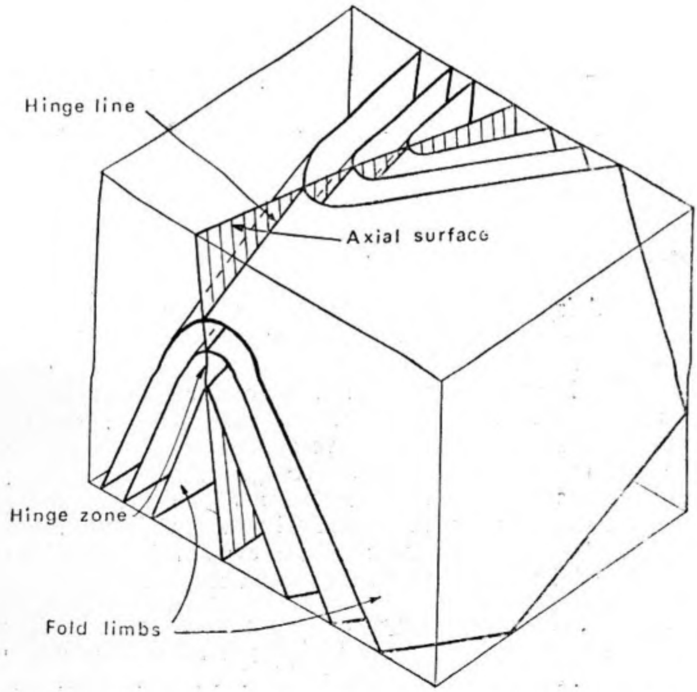


FIGURE 1 : Definition of hinge line, hinge zone, fold limbs and axiai surface in folded layers.

kink-band, shows a constant sense of rotation, designated by normal or reverse and sometimes varying from angular to rounded, as described by Dewey (1965).

In clay, kink-bands assume a similar pattern. These structures, formed as a result of being subjected to a compressive stress and strain acting parallel to the initial direction of layering, were predominant in lightly and medium overconsolidated material (De, 1970); folds of this type also have been produced experimentally in this way by Patterson and (1962) Weiss.

Experimental

SAMPLE PREPARATION

To achieve the control of these influencing factors affecting the initial fabric of a material, the grading of kaolinite was restricted. The kaolinite supplied as a paper clay by English Clays Lovering Pochin & Co. Ltd., St. Austell, was fractionated using gravity sedimentation (De and Foster, 1970 and 1971), and produced a material which had (80 percent by weight) a particle size ranging from 1 to 3 microns (Figure 2). The presence of the finer and coarser particles is attributed to disturbance of the sediment during siphoning off the supernatant suspension (Table I).

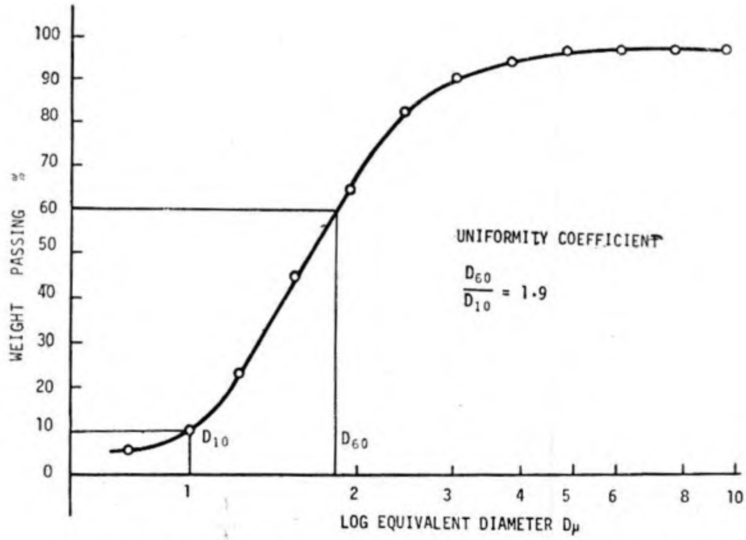


FIGURE 2 : Particle size distribution of fractionated kaolinite.

TABLE I

Properties of fractionated kaolinite.

Liquid limit	69·3
Plastic limit	53·6
Plasticity Index	15·7
Activity	0·23
Uniformity Co-efficient	1·9
Form factors :	
$\frac{\text{Length}}{\text{Width}}$	1·1
$\frac{\text{Length}}{\text{Thickness}}$	12

The fractionated material was allowed to age for one month and a suspension of distilled water of 500 percent moisture content was prepared with pH adjusted to 8 using 0·1 N sodium hydroxide, for effective dispersion of the kaolinite particles. The suspension was stirred in a high speed mechanical stirrer for more than an hour and poured into a oedometer cylinder of 15 cm diameter and subjected to a load of 24 kg/cm². The thickness of material produced was 5 cm. The material was subjected to an unloading and reloading cycle before being removed from the consolidometer; it is being considered that the preferred orientation of the kaolinite flakes will thereby be improved, although no observations have been made to confirm this.

From the consolidated material, a 60 mm × 60 mm × 25 mm direct shear box sample was obtained from the centre of the material, in which the direction of consolidation was normal to the shear loading, i.e., preferred orientation of the kaolinite particles was parallel to the direction of shearing. The remaining consolidated material was stored over water in a dessicator at room temperature, after being wrapped in triple polythene sheets. This was used to investigate the ambient fabric of the consolidated material (Figure 3).

Shear Testing

The 60 mm × 60 mm × 25 mm specimen was further trimmed to fit the modified shear box (Figure 4) which has brass wedges into the ends of

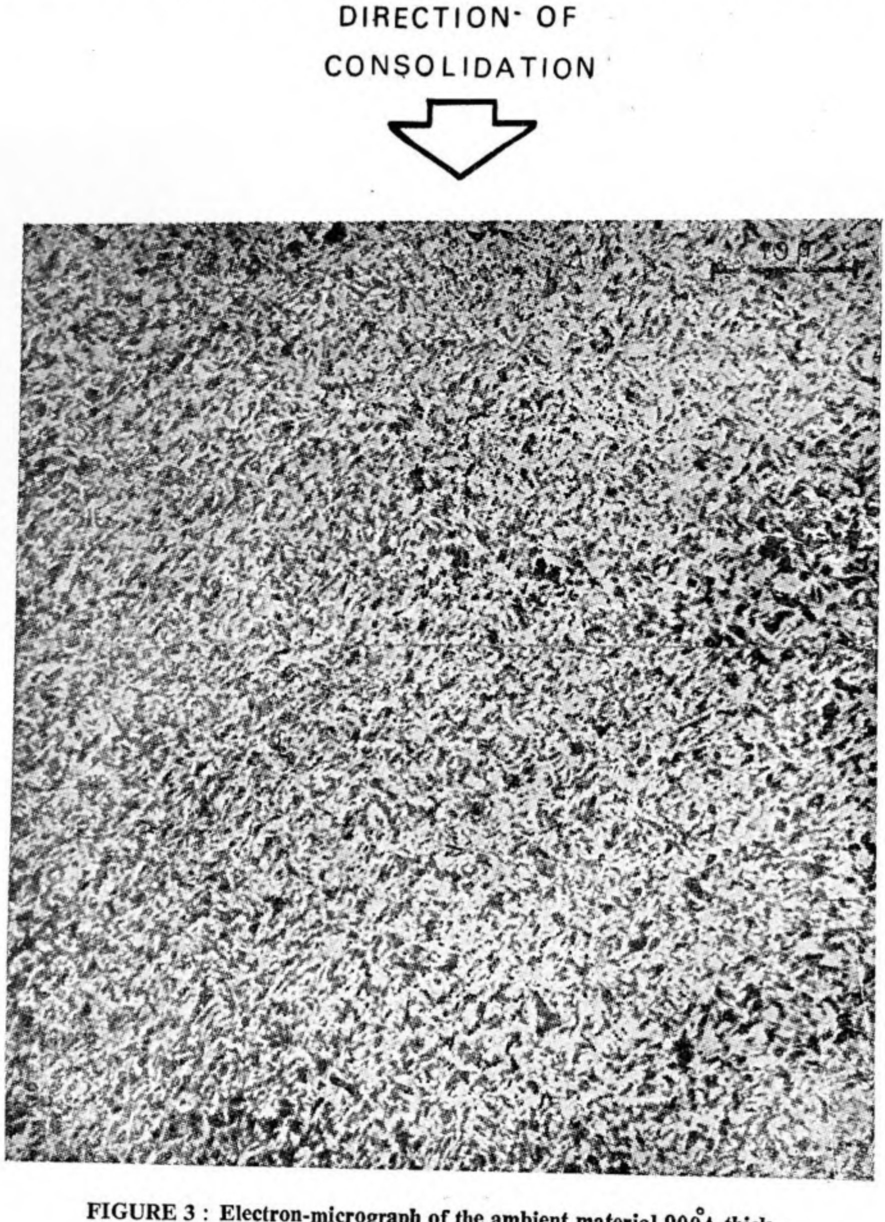


FIGURE 3 : Electron-micrograph of the ambient material 900Å thick. Araldite AY 18 impregnation.

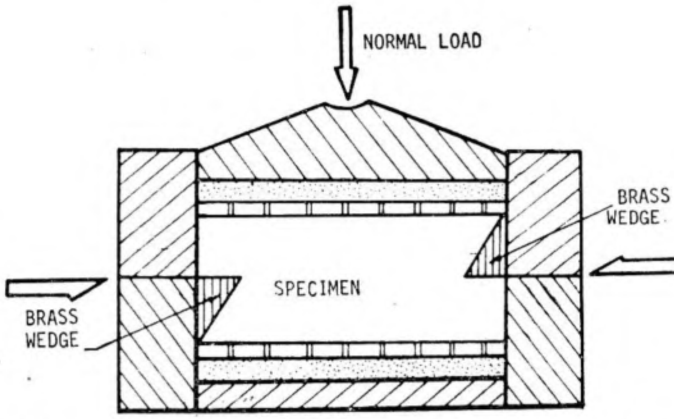


FIGURE 4 : Modification to ends of standard 60 mm × 60 mm direct shear box.

the standard direct shear box (Foster and De, 1971). Shear loading was carried out under normal effective stress (σ_N) of 1·2 kg/cm², thus having an overconsolidation ratio of 20. The rate of shear deformation was 3×10^{-5} mm/sec, and hence can be assumed that stressing occurred under drained condition. The shear deformation continued at this rate until the shear strain was 14·80 percent with an approximate residual shear stress of 0·79 kg/cm² after reaching a peak shear stress of 0·855 kg/cm², at 5 percent strain.

IMPREGNATION

In the end of the shear box test, the specimen was taken out of the box, the brass wedges were removed and the specimen was sliced in the longitudinal vertical plane to yield 2-3 mm thick slices which thus contained the shear induced structures. A razor blade was the best tool for slicing. The 60 mm × 25 mm × 2-3 mm thick slices were impregnated both in Carbowax 6,000 and resins. Out of the four resins, Araldite AY 18, Bakelite, Vestopal W and Araldite AZ 15, the first two were used because of their superiority of impregnation characteristics and ultratomy over the other two (De, 1970). The resin impregnation apparatus and experimental procedures were similar to those described by Smart (1967) with modifications (De and Foster, 1970 and 1971); the successive solutions in which the slices were immersed, followed the sequence : water-methanol, methanol, methanol-acetone, acetone and resin. The Carbowax 6,000 impregnation technique was essentially the same as that of Mitchell (1956) with modifications. One of the modifications was not to use fresh Carbowax after 3-4 days, as it was found unnecessary, and a second one was that the slices were fully immersed in liquid Carbowax.

After the impregnation, the specimen slices were cured. In case of resin impregnation, the curing without cracking involves heating with comparatively small temperature increments up to 105°C. The Carbowax was allowed to cool at room temperature to solidify; the hardness of the Carbowax impregnated slices after solidification was about 2 in geological scale. The resin impregnated slices were very hard but flexible and thus suitable for ultratomy.

Optical and Electron Microscopy

After curing the Carbowax and resin impregnated slices, optical slides of 30-40 μ thick of both, resin and Carbowax impregnated slices, were prepared. The technique of optical slide preparation from Carbowax impregnated slices has been described by Tchelenko (1967) and that of resin by De (1970) and Foster and De (1971), i.e., grinding off one 60 mm $\times$ 25 mm surface carefully, mounting the side on glass slide and, ground off the other side down to 30-40 μ thick. A cover glass was mounted on top of the 30-40 μ thick Carbowax impregnated slice.

For the purposes of investigating soil fabric of the resin impregnated slices by transmission electron microscopy, it is necessary to cut the clay slices to a thickness in terms of Å unit. The optimum thickness of the ultra-thin sections was found to be 700-900 Å; sections of this thickness could cut easily without major tears and holes in the ultra-thin sections and self-supporting on most electron microscopic grids up to 200 mesh (De 1970). The ultra-thin sectioning of the ambient material followed the conventional procedures (Kay, 1965). For the purpose of investigating shear induced structures, such as kink-band, a special technique called selected-area ultra-thin sectioning was employed by this author (De and Foster, 1970 and 1971). The technique is described here briefly: resin impregnated slices which were mounted on geological glass slides using Canada Balsam and without any cover glass, were examined under transmitted polarised light. As an assembly of kaolinite particles exhibits "form birefringence" when observed under polarised light, a change of perferred orientation of the assemblies of kaolinite due to the induced shear strain can easily be detected. As the longitudinal vertical slice contains the shear induced structures in a two-dimensional array, they can be marked and identified. Having identified a kink-band it was isolated within an approximately 2 mm square block to material by incision with a razor blade while under observation under polarised microscope at low magnification (x 24). By melting the Canada Balsam or just lifting the 2 mm square block with razor blade corner, the block was removed and further trimmed to remove the excess material outside the kink-band and to shorten the length of kink-band. The final block should not be more than 1 mm square. It was mounted on top of an Araldite stick having a 2 mm $\times$ 2 mm cross-section. After curing, the stick was ready by conventional ultra-thick sectioning.

Electron microscope used for this research was Siemens Elmiskop II.

Kink-band Model and its Properties

The origin and the geometrical properties of chevron folds and kink-bands have been investigated by Ramsay (1967), by appraising the layering effects in rock (indeed, the layers in the rocks were visible to the naked eye). In clay such layers are not visible to the naked eye but it might be argued that a similar effect could be observed in reasonably preferred oriented clay specimen. (Morgenstern and Tchelenko, 1967). Moreover, the presence of microfissures in the direction of the preferred orientation will favour the condition of 'layering effect'. It has been observed that all lightly and most medium overconsolidated specimens showed a volume decrease before the peak stress (De and Foster, 1970 and 1971) and as the kink-bands form after the peak stress (De, 1970), it is reasonable to suppose that the volume decrease was associated with a collapse of the 'card house' structure of clay resulting a better preferred orientation and kink-bands formed on a preferred orientated clay matrix.

Figure 5 represents a kink-band model in clay and consists of a number of thin layers each of thickness t. The length of any layer measured from one fold hinge to the next hinge retains its original length L, σ_v and σ_h are the principal compressive stresses acting normal and parallel to the original bedding and θ is the inclination of the axial surface (Ransay, Whitten, 1967 and 1966) with respect to the original bedding. The layers within the width of the kink-band are inclined at β degrees to σ_h and those outside the kink-band are at Φ degrees.

The total amount of slip between two adjacent layers may be considered to have two components, for the case of understanding ; $A'F$, produced due to the concertina type folding of the kink-band and FD, due to the inclination of the axes.

$$\text{Thus the total slip between layers} = A'D = t \sec \alpha \, \frac{\sin \beta}{\sin \theta}.$$

Finite simple shear strain, $\gamma_t = \tan \beta$.

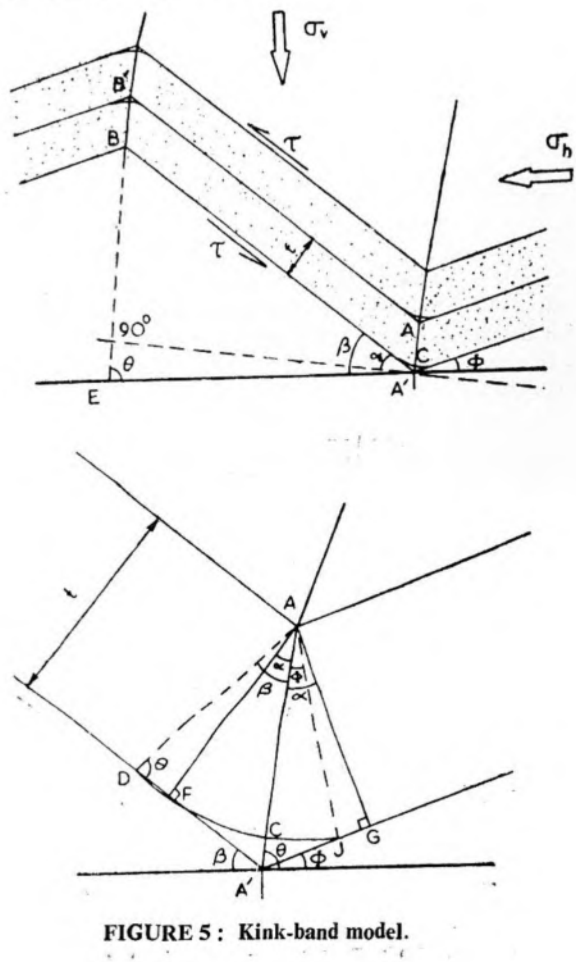


FIGURE 5 : Kink-band model.

From triangle $A'BE$

$$A'B = \left(L - \beta t + t \sec \alpha \ \frac{\sin \beta}{\sin \theta}\right)$$

and $A'E = L\,(1 + \triangle)$

where $\triangle$ is the shortening along the original direction of layering.

$$\text{Hence,} \quad \left(1 - \beta \frac{t}{L}\right) \cos \alpha + \frac{t}{L} \frac{\sin \beta}{\sin \theta} = (1 + \triangle) \sin \theta \qquad \ldots(1)$$

Now $\quad \alpha = (\theta + \beta - 90^\circ) = (90^\circ - \theta + \Phi)$

Substituting the value of α in Equation (1) and differentiating $\triangle$ with respect to β and substituting $\theta = 90^\circ \left(\frac{\beta}{2} - \frac{\Phi}{2}\right)$. We have

$$\frac{d\triangle}{d\beta} = \frac{\left(\beta \frac{t}{L} - 1\right)(\sin \beta + \sin \Phi) + \frac{t}{L}(\cos \beta - \cos \Phi)}{2 \cos^2 \left(\frac{\beta}{2} - \frac{\Phi}{2}\right)} \qquad \ldots(2)$$

Also, because, $\gamma_t = \tan \beta$,

$$\frac{d\gamma_t}{d\beta} \ \sec^2 \beta$$

$$\frac{d\gamma_t}{d\triangle} = \frac{d\gamma_t}{d\beta} \times \frac{d\beta}{d\triangle}$$

$$= \frac{2 \sec^2 \beta \cos^2 \left(\frac{\beta}{2} - \frac{\Phi}{2}\right)}{\left(\beta \frac{t}{L} - 1\right)(\sin \beta + \sin \Phi) + \frac{t}{L}(\cos \beta - \cos \Phi)} \qquad \ldots(3)$$

This relationship is quite general and may be applied to any combination of values of β and Φ. In the case, when $\beta = \Phi = \alpha$ it changes to the form for a standard chevron fold for which α remains constant and $\theta = 90^\circ$, and this special form was derived by Ramsay (1967) on the basis of this specific case :

$$\frac{d\gamma_t}{d\triangle} = \frac{\sec^2 \alpha}{\left(\alpha \frac{t}{L} - 1\right) \sin \alpha}$$

The functions (3) and (1) are correlated in Figures 6 and 7, using $\beta/\Phi = 2$. It may be seen from Equation (3) that the incremental shear strain ratios $\frac{d\gamma_t}{d\triangle}$ are infinite when either $\beta = \Phi = 0$ or $\beta = \Phi = \frac{L}{t}$.

The shear stress τ acting along the fold limbs (Figure 1) of a kink-band is given by

$$\tau = \frac{\sigma_v - \sigma_h}{2} \sin 2\beta \qquad \ldots(4)$$

Let us now discuss the origin and properties of kink-band. At the start of the deformation, when $\beta = \Phi = 0$ and $\triangle = 0$, the incremental shear strain $\frac{d\gamma_t}{d\triangle}$ (Figure 6) on these surfaces must be very high. But as $\beta = 0, \sigma_h$ is acting parallel to the layers, no shear stress can develop on any horizontal plane (Ramsay, 1967). Therefore, the kink-band cannot develop at these conditions of $\beta = \Phi = 0$ and $\triangle = 0$.

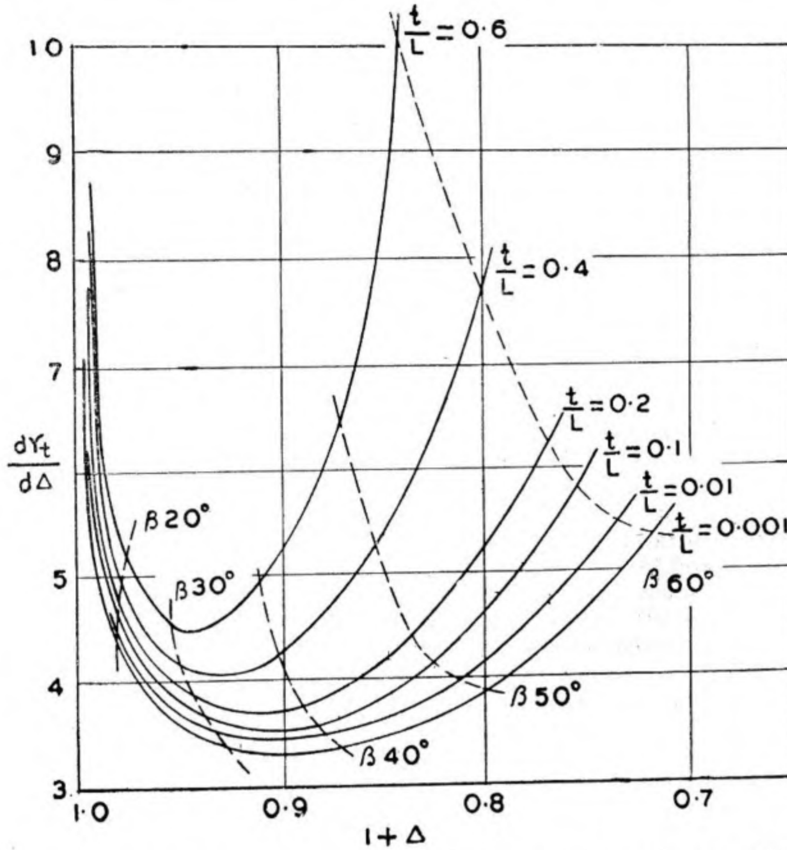


FIGURE 6 : Variation in the shearing strain increments $d\gamma_t/d\triangle$ with variation in total shortening and t/L ratio. The dashed curves show values of inclination, β.

The buckled pattern of kind-band would not be initiated unless either the layers on the applied stress, deviate a slightly from being absolutely horizontal. *For such a deviation to obtain* these are three possibilities. (*a*) the layers are slightly curved, (*b*) they are inclined, leading to a wave instability (Ramsay, 1967), and (*c*) slight variation in the direction of the transmission of σ_h. Thus all the three possibilities, any combination of them or any one of them, may be responsible for the appearance of kink-bands on either side of the shear discontinuities.

Once the initial stage of kinking has passed, the incremental shear strains $\frac{d\gamma_t}{d\triangle}$ in the folded interface layers becomes progressively diminished as the folds develop (Figure 5). The shear stress τ, on the interfaces of the folded layers initially increases as the folds develop, because shear stress is a function of sin β (Equation 4) provided the stresses σ_v and σ_h do not alter appreciably as a result of the development of folds (Ramsay, 1967), and thus the folds develop with increasing ease. The folding will cease due to the relief of σ_h when the shear stress τ, on the folded layer interfaces fall to a value which is too low to overcome the shear resistance of the material (Ramsay, 1967).

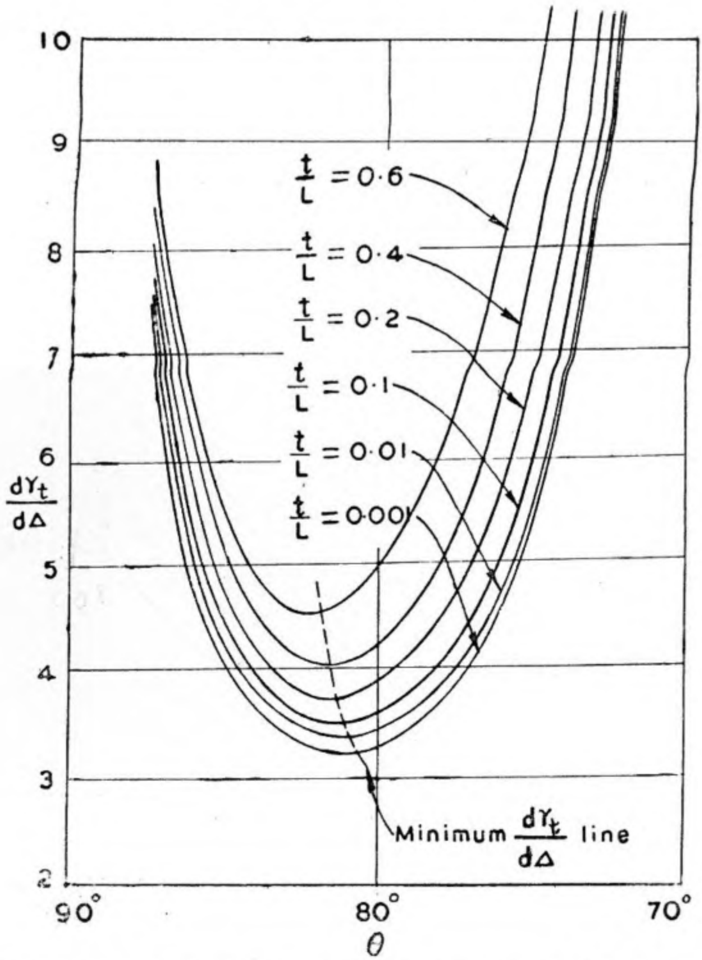


FIGURE 7 : Variation in the shearing strain increments $d\gamma_t/d\triangle$ with the inclination of the axial surface, θ .

Results and Discussions

The failure pattern of the shear box specimen (Figure 8) showed a prominent shear discontinuity across the specimen, together with some closely associated short shear discontinuities and a more prominent set of kink-bands on both sides of the shear discontinuity, with maximum length and thickness at the centre and gradually diminishing in length and thickness as it approaches towards the edges, except in those instances where they were truncated by some other shear discontinuity, thus stopping the propogation of the kink-band. They are usually curved and start from the main shear discontinuity at an angle of 85°–87°. A typical electron micrograph across the full width of a kink-band was obtained (Figure 9) from an Araldite AY18 impregnated slice from the same specimen as was used for Figure 8 (which was Carbowax impregnated) using the technique described before. A simplified diagram of the structural pattern of the particles within the kink-band has been presented (Figure 10) for

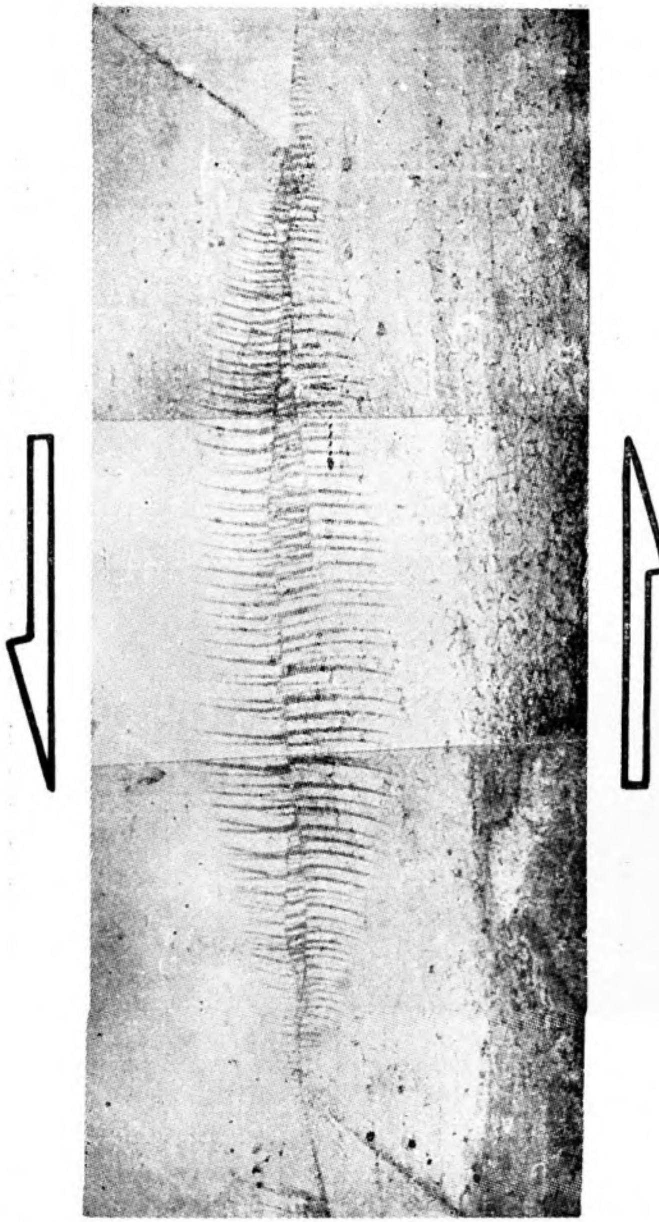
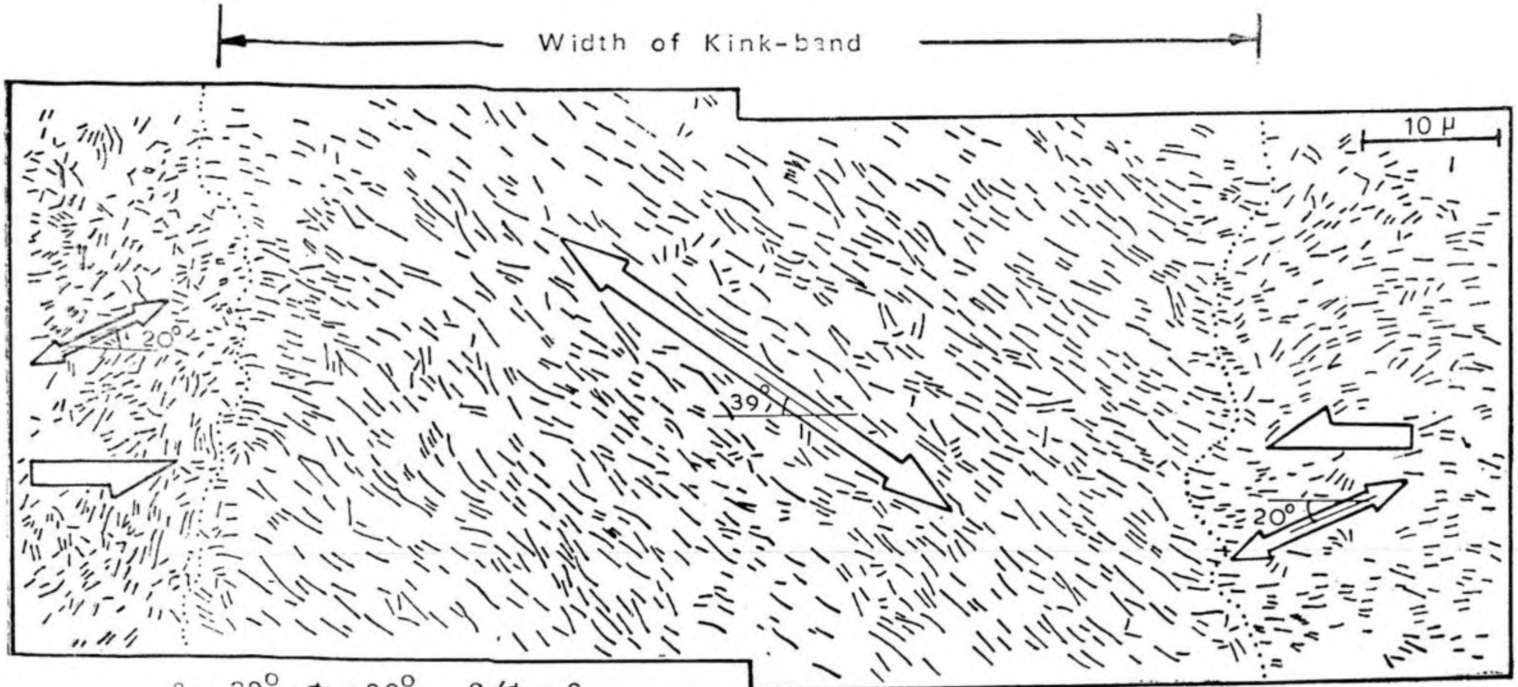


FIGURE 8 : Optical micrograph of medium consolidated material after shearing, showing main displacement discontinuity and kink-band structures (cross nicols).

the ease of understanding and correlation between the kink-band itself and the kink-band model presented before.

The ambient preferred orientation of the particles was along the direction of σ_h (Figure 10). The particles within the kink-band showed an average rotation of 39° from the ambient orientation. It could be observed that the particles within the kink-band were not crushed as occurred in main shear discontinuities (De and Foster, 1970, 1971) but very few 'flocks' remained intact. This again suggests that a simple shear exists in the formation of kink-bands. Assuming the layers made of a

FIGURE 9 : Electron-micrograph of a kink-band. Thin section of Araldite AY 18 impregnated material 700Å thick.



$\beta = 39^\circ \quad \Phi = 20^\circ \quad \beta/\Phi \simeq 2$

FIGURE 10 : Graphical representation of Figure 9.

single kaolinite particle thickness (Figure 10), in which case $t/L \rightarrow 0{\cdot}001$, the kink-band model also suggests the existence of τ in every layer of kink-band.

It has been shown (Ramsay, 1967), that for any particular value of t/L, folding takes place easily until the shearing strain increments $d\gamma_t/d\triangle$ attains the minimum value and after which the fold becomes 'locked', as folding becomes more and more difficult due to the rearrangements of boundaries. From the simplified structural pattern of the kink-band (Figure 10) the value of the ratio β/ϕ is approximately 2 and corresponding to that ratio, the value of β (Figure 6) varies between 30° to 40° depending on the values of t/L. Although the value of t/L for this specimen is not known, the lowest value would be in the order of 0·001 as argued before and a higher value can reasonably be assumed around, say 0·4. It may be seen from Figure 6 that, although the variation of t/L is wide, the variation of β within this range is limited, and it is suggested that $t/L = 0{\cdot}2$ to $0{\cdot}01$ may be regarded as a reasonable first assumption. From the simplified structural pattern of the kink-band (Figure 10), β was 39° and the result is in good argument with that of the proposed kink-band model.

Conclusions

Although this report is based on a very simple analysis of a very simple physical model of kink-band, the results are in reasonable accord with the laboratory test and the model explains that behaviour of kink-band and its formation. The method of selected-area ultra-thin sectioning appears to be an important tool for the investigation of soil micro-structure.

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