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SLIPS IN FISSURED CLAY

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SUMMARY.

The circular slip theory and tests on undisturbed soil samples do not provide means of assessing a factor of safety and preventing slips in fissured clays. The progressive deterioration of such clays originates, according to the observations reported in this paper, in the zone of fluctuating ground water levels. Two types of failure in two distinctly different groups of fissured clays are described, and methods of drainage for them are proposed.

DESCRIPTION OF FISSURED CLAYS AND THEIR PROPERTIES.

The application of the circular slip theory to cuttings in homogeneous clays is very successful, as these clays are a near approach to the isotropic medium assumed in the mathematical treatment. They have a fairly uniform shear strength in depth, and it is possible to determine a factor of safety for given heights and slopes. These homogeneous clays are usually of a recent geological age, and within limits their properties can be easily determined. It is not proposed to deal with them in this paper.

Another group of clays, the fissured clays have proved less tractable. They are of great engineering importance in Great Britain where deposits of older geological periods, such as the Lias, Oxford, Kimmeridge, Weald, Gault and London Clays, are exposed over large areas. These clays have undergone great geological changes involving consolidation under very great surcharges, lifting, denudation, folding by lateral pressures and repetition of these processes over long periods. The clays described under this general name are not distinguished by a common mineralogical composition, origin or method of deposition, identical grading, typical colour or similar index properties. Their common characteristic is the macroscopic structure which is disclosed when a lump of clay with a moisture content below the Plastic Limit is dropped. It then breaks up into small polyhedric fragments with dull or shiny surfaces often differing in colour from the mass. The clay though hard is friable.

The most likely conjecture about the origin of this structure is that it results from the differential variation of vertical and horizontal pressures accompanying the afore mentioned geological movements and of the shear stresses set up in the mass by them.

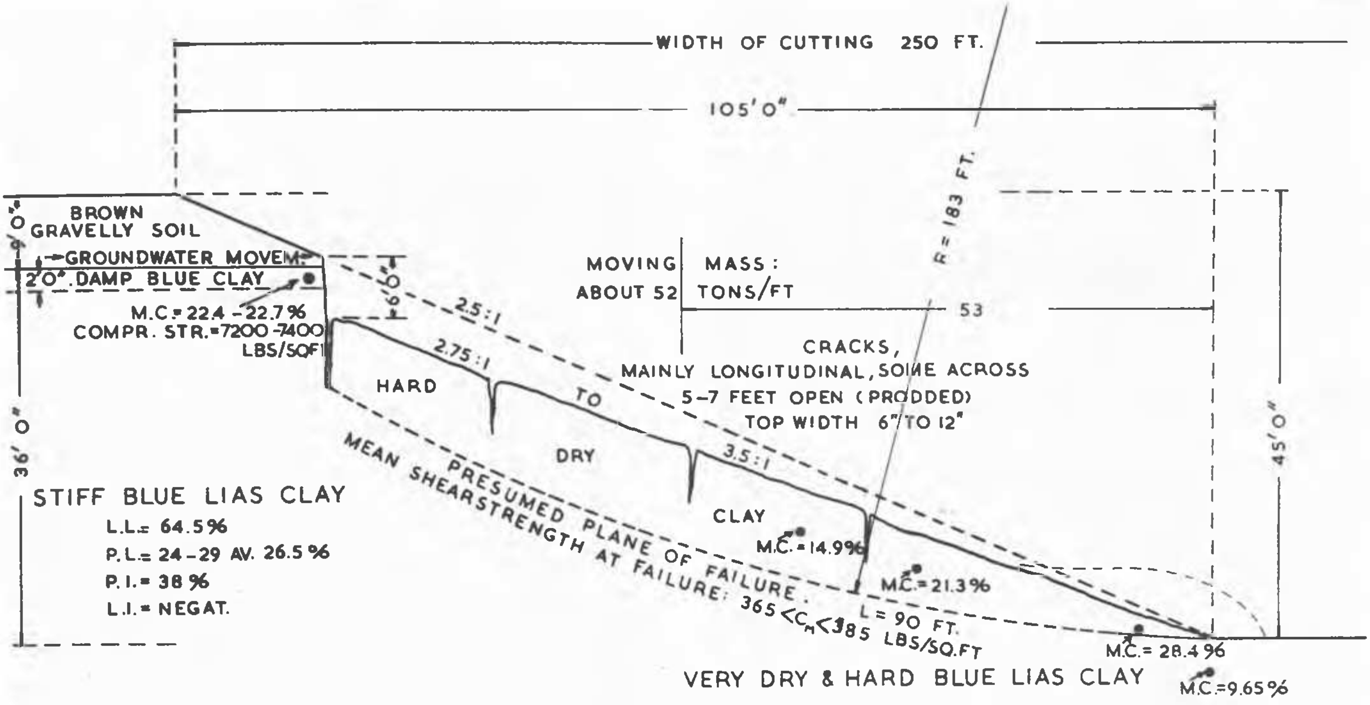
As a consequence of their structure, i.e. of the fissures which run at random through the mass of clay, the physical behaviour of these clays is very different from that of an isotropic medium on which the slip theories are based, and methods applicable to the slip theory fail both to predict slips and to offer explanations of actual slips.

The main consequence of the structure of the fissured clays is a progressive reduction of strength as experienced particularly in cuttings. The construction of deep cuttings involves the removal of surcharge and the reduction of pressures, both vertical and horizontal, the latter one-sided. Overcompacted clays tend to swell, and the fissures open. In the presence of water this starts a process of softening. The water enters the fissures and moves downwards and inwards, or sometimes outwards, continuously increasing the swelling of the clay and the softening of the walls of the fissures. This process goes on until the whole area of pressure relief through the cutting is affected. When the mean strength of the clay is reduced over a large area below that required for the stability of the slope, if only along the fissures, a slip will occur, not necessarily along a theoretical curve, but over a surface depending on the distribution of fissures and the place of water influx. The conditions for a later slip are frequently found where groundwater movement is considerable , even if provision was made for the rapid removal of surface water.

The stiff fissured clays are usually very compact, and apart from fissures relatively impermeable except near the surface and sometimes to a certain depth where they are changed by weathering and swelling to such an extent that a groundwater table can form in the mass. This is the source of the water which causes the deterioration where the table is intercepted by cuttings.

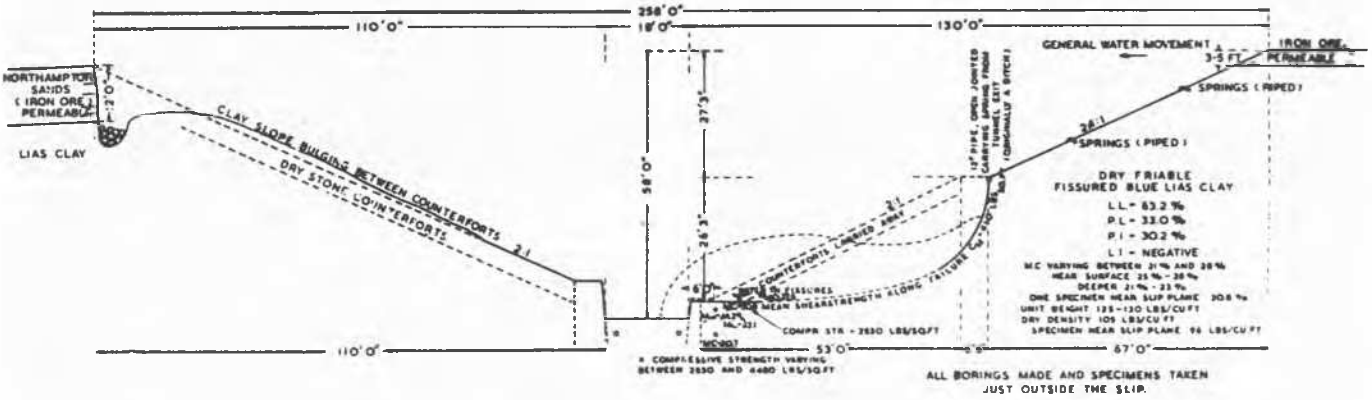
Measured by human scales the time taken by the slow softening and deterioration of the clay is rather considerable. In Great Britain many cases are known where 50,70 or even 90 years had passed since construction before a slip occured. As the oldest railway cuttings are only about 100 years old it is too early to say whether under less favourable ground water conditions the process might not be even slower.

Owing to their geological history the fissured clays which are now near the surface were consolidated under considerably higher pressures than their present surcharge. While the vertical pressures have been reduced by denudation the horizontal pressure corresponding to the previous high vertical stresses are partly still existing and will frequently be higher than the present vertical pressures caused by the clays own weight. This increases the tendency for swelling and opening of fissures to occur as soon as the horizontal resistance is removed by excavation. It also accounts for the peculiar behaviour of these clays in shear tests with varying normal pressures. For a certain range depending on the preconsolidation the shear strength shows little change, but below a certain pressure the shear strength drops and it falls to a minimum at zero pressure. As this is the condition under which the soil exists at the face of a slope after excavation of a cutting the shear strength at zero pressure is a critical value. However as the shear strength of fissured clays is uniform neither through the mass nor in different planes, testing in the laboratory does not easily produce values of the properties required for design. The relation between compressive strength and shear strength is not constant, and it is doubtful whether there is any definite relation, because random planes of incipient weakness exist which may or may



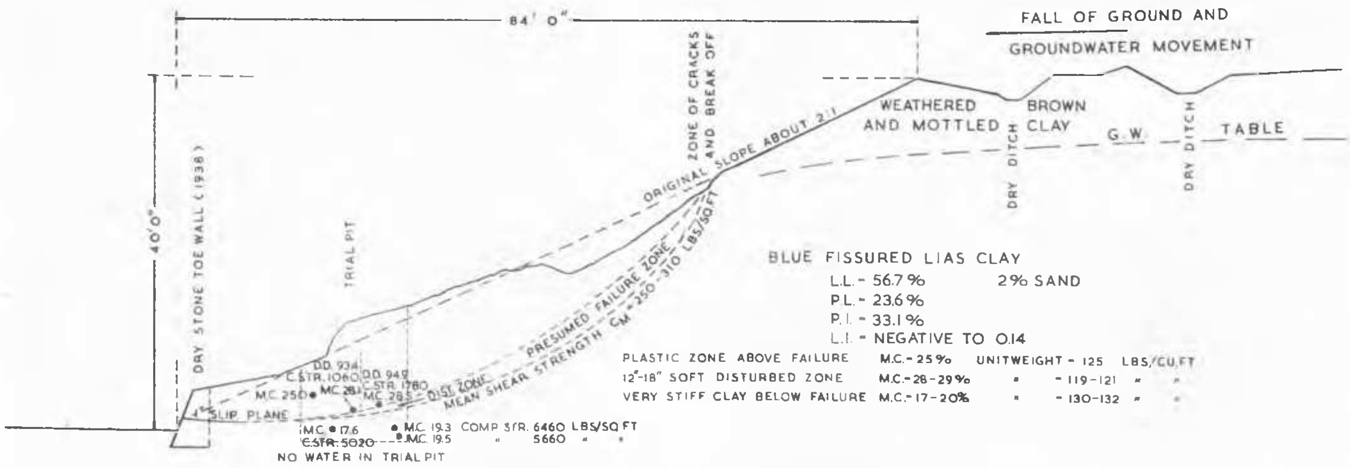
Slip at Toddington (1945)

FIG.1



Slip at Hook Norton (1944)

FIG.2



Slip at Hullavington (1946)

FIG.3

not coincide with the direction of the maximum shear strength of the specimen. The results of unconfined compression tests can therefore only be used with great reserve. While in blue London clay a decrease of the shear strength from one half to less than one third of the compressive strength has been recorded, other cases have been reported where the shear strength measured in shear boxes at zero pressure was only about 1/8 to 1/10 of the compressive strength. This applies to particularly hard and dry clays in virgin state. In such clays the adhesion between the walls of the fissures is apparently very low. In tests carried out on fissured clays it is particularly important that specimens are as little disturbed as possible because, contrary to all other experience, the shear strength of fissured clays increases when remoulded at constant water content. The reason is obviously that through complete remoulding the source of weakness, the fissures, are destroyed, and a practically homogeneous mass is created instead of a conglomerate of hard particles divided by smooth joints.

Numerous investigators have contributed to the knowledge about the constitution and the behaviour of fissured clays. (See Bibliography.) The practical problems posed by this difficult material are however not yet solved. The number and size of slips in old railway cuttings is growing as many now approach the end of the period occupied by the softening process. Remedial measures to stop slips from progressing have to be designed, as well as measures to prevent later deterioration in proposed new cuttings. Intensive studies of actual slips are a necessary preliminary for this task.

DESCRIPTION OF ACTUAL SLIPS.

A selection of the slips in railway cuttings the Author has had to deal with are described, and the results of his observations are presented for discussion.

SLIP AT TODDINGTON (Fig. 1).

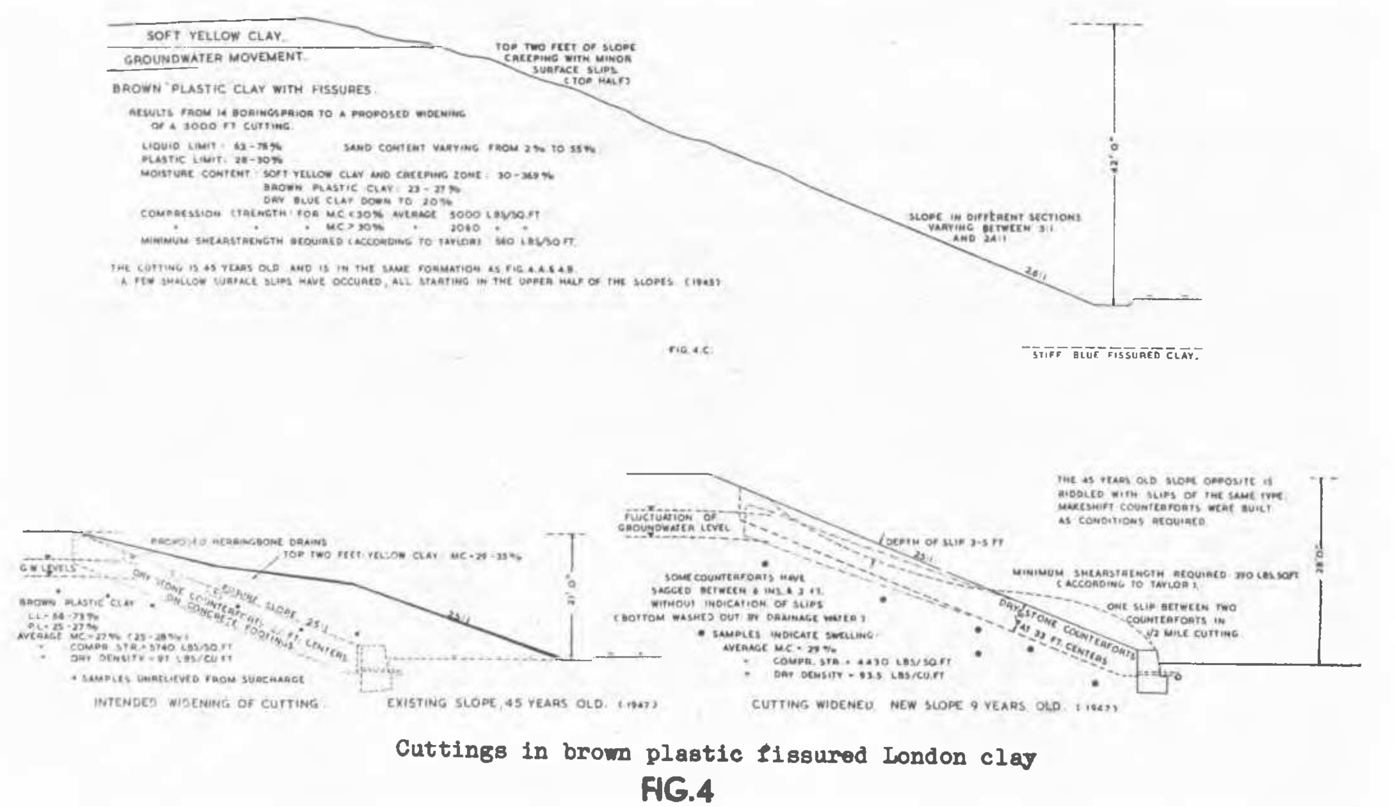
The cutting is 40 years old and is 45 feet deep, in very dry hard fissured clay with slopes of 2.5:1. The slip extended over 250 feet and is the continuation of a slip, immediately adjacent, which occured 27 years ago. The reduction in the calculated shear strength along the fissures and the failure plane was to between 1/19 and 1/20 of the undisturbed compressive strength. Testing was by unconfined compression test. The slope gradient in an homogeneous clay of the same reduced strength would have to be flatter than 7:1, in order to be safe. Very heavy toewalls had stopped further movement completely.

Slip at Hook Norton. (Fig. 2).

The cutting is 70 years old and is up to 58 feet deep, in overconsolidated stiff fissured Lias Clay, with slopes of 2:1. The slip was about 90 feet long. Many slips of similar character occured before in the same cutting,which is 1000 ft long. About half that length is protected now and reinforced by toewalls and counterforts of different types. Reduction of shear strength in the slip plane was to between 1/5 and 1/10 of the compressive strength of the undisturbed material. It is suspected however, that the strength of the clay in situ could be reduced even further by increased swelling and water absorption. In homogeneous clay the slope gradient appropriate to the reduced shear strength would be flatter than 7,5: 1.

Slip at Hullavington. (Fig. 3).

The cutting is 44 years old, is in stiff fissured clay with slopes of 2:1, and is up to 40 feet deep. The slip extended for about 330 feet. The calculated shear strength in the failure plane was reduced to between 1/18 and 1/26 of the undisturbed compressive strength nearby. The slope gradient in homogeneous clay appropriate to the reduced shear strength would



Cuttings in brown plastic fissured London clay

FIG.4

be flatter than 7.5: 1. In an adjacent section where deep counterforts had been constructed when the cutting was first excavated no slips have occured.

A common characteristic of these three slips and others not described, is the position of the tension cracks and the break-off below the top edge of the cutting in the zone of the groundwater tables.

CUTTINGS IN PLASTIC FISSURED CLAYS. (Figs. 4.)

The following conditions are characteristic of a series of cuttings in the London area These were investigated in relation to the intended widening of the line rather than to the seriousness of slip dangers. Major slips were infrequent although the existing slopes were generally weak and distorted at many places. The cuttings are 45 years old, the depth varies up to 42 feet and the slopes are generally 2.5: 1. The cuttings are situated in the weathered top layer of stiff blue London clay. The soil is fissured brown clay, with sandy layers, and shows great variation in for example size distribution, (sand content varies from 2% to 55%), appearance, consistency, density, and accordingly great variations in index properties. However it is always in the plastic state. In one section the widening of the cutting was carried out 9 years ago (Fig. 4.B.), and it is possible to observe changes which have occured within that short period. The results of a large number of tests suggest swelling, increase of moisture content and reduction of density and shear strength in the new section.

The numerous minor slips which occured during the past 45 years were all confined to the surface of the slopes, not extending in depth beyond 3 to 5 feet, and frequently resembling a slow creep. The stiffer clay below that depth remained unaffected suggesting that slow saturation and not opening of fissures caused the weakening of the surface layers. Precautions and remedies have accordingly had to be varied.

These observations suggest the following inference. Slips in fissured clays can conform to two different patterns. In the strongly preconsolidated stiff clays the fissures open to a great depth with an accordingly deep reaching zone of softening. The shape of slips approaches the curved form of the toe slip occuring in uniform clays, while the position of the top crack is determined by the position of the groundwater level. The slip curve however, deviates from a regular curve depending on the development of opened fissures or the existence of irregular impermeable zones. Water movement and softening is determined by those features and the head of water.

In the softer, plactic fissured clays the fissures do not open so deeply. While the line of top cracks is also determined by the position of the groundwater table slips have a greater tendency to be surface slips, extending only to a shallow depth and frequently resembling an slow soil creep. These clays are more disturbed. Their Liquidity Index is positive, and where sand inclusions are absent they assume a rather uniform plastic character. Fissures do not appear to be open in the less disturbed zone say below 5 feet from the surface, and the plastic clay below that depth appears less permeable and less liable to deterioration than the hard and dry clays. On exposure and drying-out however, the fissured structure becomes obvious, and the weathered zone is very unstable.

In both types of clay the deterioration and the final failure start in the zone of groundwater table below the top edge of the cutting as opposed to the conventional conception of tension cracks beyond the top edge. In that zone the fissured clays draw water from behind and swell, a tendency which is facilitated as the moisture content and permeability are higher there than at a greater depth.

REMEDIES.

The design for new cuttings and the remedial measures for slipping slopes must be varied in accordance with the different types of failure.

Measures applied in the examples described were indicated in fig.1-4. Without undue generalisation the following rules are to be recommended.

A) In dry, over-consolidated clays the depth and width of cuttings and the gradients of slopes should be reduced by constructing heavy and wide dry-stone toe walls, about 6 feet high, reinforced by deep-reaching counterforts. Drainage in front of the walls, and by weep-holes through these walls must be provided , and the counterforts must also be utilised as drains.

B) In plastic fissured clays low and relatively thin toewalls are recommended. In new cuttings their use reduces the amount of excavation and the width of the land occupied, and also the slope gradient. The slopes should however, be cut up by numerous stone-filled french drains, 4 to 6 feet deep, at short distances, leading upwards through the groundwater bearing zone and draining to a toe-drain. Toe-walls should have dry-stone backfilling and numerous weep-holes.

In both types of clay considerable care must be devoted to the drainage of the slopes in the zone of groundwater movement. In Great Britain this is usually a zone from about 3 to 5 feet to about 10 to 12 feet below ground level. This zone should be thoroughly drained between the counterforts by systems of shallow stone-filled herringbone drains, doubled or tribled, according to the depth of the saturated zone, and draining into the counterforts.

The down-drains in the weathered clays should have a solid impermeable base, to prevent softening of the clay beneath and sagging of the drain. (See Fig.4.B.)

Another essential is that the clay surface should be covered with soil immediately after the excavation and a mantle of growth created on it as soon as possible. In slips repaired as described, trimming of the surface filling-up of all depressions and cracks, and replanting are equally necessary to prevent renewed deterioration.

CONCLUSIONS.

Tests on undisturbed samples do not provide sufficient information for the estimation of factors of safety in fissured clays. Shear tests on saturated samples at zero pressure might possibly lead to such information though this is not yet proved. Construction based on values obtained from such tests however, would be very expensive and quite uneconomic. As practically all cuttings in stiff fissured clays are potentially liable to deterioration and possibly failure economic considerations demand construction along more customary lines.

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THE RATE OF SOFTENING IN STIFF FISSURED CLAYS, WITH SPECIAL REFERENCE TO LONDON CLAY

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INTRODUCTION.

During the construction of the early railways in the London district, engineers such as Gregory (1844) and geologists such as Sir Henry Delabeche (1844) observed that the London Clay was fissured and that water percolated along these fissures, causing a progressive softening of the clay. In this way Gregory accounted for the fact that several of the slips which he had encountered in cuttings took place several years after the cuttings had been excavated. At the same period Alexandre Collin (1846) in his classic study of the slips in the Canal de Bourgoyne suggested that, in the course of time, clay slopes would progressively flatten until they approached the slopes found in natural hillsides in clay strata.

These valuable observations were not followed up, and in the author's opinion, one of the reasons for the long delay in the development of soil mechanics can be found in the apparently "treacherous" and unpredictable behaviour of stiff-fissured clays: especially since these are very wide-spread in south east England and in France.

No real advance was in fact made until 1936 when Terzaghi presented a clear account of the softening action in stiff-fissured clays and (equally important) pointed to the great differences between fissured and non-fissured on "intact" clays. This account has been substantiated by direct field observations, and it is of great practical importance. Yet before any help of more than a general character can be given to the engineer it is necessary that at least an approximate time scale for the softening process should be obtained. Thus, in the London Clay for example, a cutting 20 ft. deep could be made with vertical sides and remain stable for a few weeks or months, but at a slope of 2:1 this depth would probably remain stable for 10 or 20 years, while at 3:1 or 4:1 it would remain stable for perhaps 50 years or more. In the London Clay an inclination of about 10° is the steepest found in natural slopes, and this is presumably the limiting value for very long periods of time.

In the present paper the author attempts to find a time scale for the rate of softening of London Clay. This attempt is tentative and as more evidence is obtained it will almost certainly have to be modified. But the data, even in its present form, seems to be of some value and for that reason it has been presented to the Conference for discussion.

TERZAGHI'S EXPLANATION OF THE SOFTENING OF STIFF-FISSURED CLAYS.

In its simplest terms Terzaghi's explanation is as follows: In a stiff fissured clay the fissures are normally closed, but when a cutting is made there is an opportunity for lateral expansion towards the slopes. This allows some of the fissures to open and, owing to the high strength of the clay itself, the fissures can remain open at considerable depths. Water will then start percolating through the open fissures and the clay exposed on the faces of the fissures will start softening by absorbing water. This softening will, in its turn, lead to further slight movements and consequently more fissures will be opened. The progressive nature of the process may lead eventually to a slip.

In his paper of 1936 Terzaghi gave four examples of slips in stiff fissured clays and quoted the average shear strength of the clay along the slip surface at the time of failure. These shear strengths are, of course, not necessarily the fully softened strength of the clay since a slip will in general take place before the softening process is complete. Nevertheless, the four examples all showed strengths in the order of 500 to 700 lb/ft^2: an order of strength far less than the original unsoftened strength of the clay.

FIELD EVIDENCE IN LONDON CLAY.

a) Watford By-Pass. Fig. 1(a). This cutting was made in 1927. Several slips occurred between 5 and 10 years later. The average strength at failure, calculated on the $\varphi = 0$ assumption (see Skempton 1948), was about 220 lb/ft^2. Borings were made in the undisturbed ground behind the slip and the unsoftened strength at the average depth of the slip surface was found to be about 1.000 lb/ft^2.