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The Role of Progressive Failure in Clay Slopes

By

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SUMMARY.— Modes of time dependent weakening in clay slopes are discussed and evidence is quoted to show that the dominant pre-slip mechanism of time dependent weakening is a decay in cohesion, c' , alone, while ϕ' remains at, or near to, the peak. That is, progressive failure (which may be defined as a simultaneous decay in both the c' and the ϕ' parameters) will be an untypical occurrence for the majority of clay slopes. Mention is then made of existing hypotheses of progressive failure which are suggested to provide an inadequate explanation of the process when it does occur. It is shown how large deformations, possibly of the order of feet, are necessary in the field in order to produce residual conditions along a potential slip plane and, neglecting landslides, such deformations can generally be satisfied only under a certain set of conditions. The common conditions which meet the requirements are non-homogeneous or localised straining associated with the non-homogeneous swelling of swelling soils present in a cutting or valley slope. Examples are given in support of this hypothesis.

I.— HISTORICAL BACKGROUND

The stability of slopes, especially in over-consolidated clays and clay shales, is a central problem in the Geomechanics field. Since the 1940's, the problem has received increasing attention, with particular attention being focused on the discrepancies between the laboratory strengths of formations and the much lower strengths at which slopes in such formations often failed in practice. Papers by Skempton (1948), Cassell (1948) and Binger (1948) cite quantitative examples of the divergence between laboratory and field, while the first mentioned paper suggests a rate of strength decay for the London Clay formation.

The above analyses, as with all prior to the mid 1950's, were necessarily confined to a $\phi = 0$ approach, using cohesive strengths alone. A more rational approach to stability analysis was made possible with the development of the effective stress method, and work by de Lory (1957) pointed to a more fundamental mechanism of strength decay, confined to the effective cohesion parameter, c' , while the parameter, ϕ' , was taken as sensibly constant. At that stage the possibility of a reduction in ϕ' was not envisaged in Soil Mechanics, and it was not until the early years of the last decade that reliable case histories were published where failure could not be explained even with a cohesion term c' of zero. In other words, some reduction in ϕ' was also needed to obtain a Factor of Safety of unity. Observations in the field by Gould (1960), and in the laboratory by Borowicka (1963) pointed to the fact that the angle of shearing resistance of clays, ϕ' , was decreased permanently due to strain, but the problem was not fully resolved until the phenomenon of residual strength was formerly postulated and defined by Skempton (1964).

The concept of residual strength has possibly effected the most radical change in philosophy in Soil Mechanics during the past decade. Perhaps for this reason there has been a tendency, in most recent years, to over-emphasize the residual approach to the design of slopes; an over-emphasis since knowledge of the actual path from peak to residual in the field, i.e. the progressive failure mechanism, was largely hypothetical. Skempton (ibid) himself introduced an R (Residual) factor to describe the extent to which the strength of a clay had fallen from its peak towards its residual, since the evidence at the time pointed to an inevitable progression of this nature.

It should be pointed out that progressive failure is taken, in this paper, to mean a simultaneous, or quasi-simultaneous, decay in both the c' and ϕ' parameters preceding actual failure.

Several postulations to explain the mechanism of progressive failure have been put forward in recent years:— Skempton and La Rochelle (1965), where the effect of fissuring in over-consolidated clays is discussed; Bjerrum (1966), where the release of strain energy on weathering forms an important aspect of the hypothesis; and Yudbhir (1969) who considers the release of horizontal stresses in over-consolidated clays to be a dominant factor.

In an effort to establish the validity of these or other hypotheses, a large number of case histories were analysed by the author, James (1970). The formations studied were over-consolidated clays and clay shales and from the investigations a pattern was observed which suggested progressive failure was a most uncommon feature. Two dominant

phases were distinguished in the pattern of the development of natural slopes.

(i) A pre-slip stage. Here the loss in strength was found to be almost entirely due to a loss in terms of the parameter c' , as suggested originally by de Lory (loc.cit) and quoted by Skempton (1970). During this phase the value of the parameter ϕ' remains at, or very near to, the peak value since the effect of weathering on this parameter within engineering time scales is generally negligible.

Such a decay in strength is also along the lines of the softening process outlined by Terzaghi (1936). Or, as Terzaghi suggested: on excavation of a cutting, fissures open due to the unequal lateral expansion towards the face; this allows ingress of water into the soil causing softening and swelling along the fissure planes, subsequent rupture of "intact blocks" and thereby production of further fissures. Ad infinitum or slope failure. Slopes failing due to this process are referred to as first time slips.

(ii) A post-slip stage. The necessary condition for this second stage is, obviously, a landslide. The catastrophic failure may have resulted from a general loss of strength outlined in the above paragraph (i); or, alternatively, from some form of progressive failure. In either event the clay is characterised by the presence of slip planes which have undergone considerable strain, and along which the angle of shearing resistance will have dropped some of the way from the peak to the residual value. It is sufficient to note, at this juncture, that the presence of slip planes does not necessarily imply the clay along the plane is at its ultimate residual strength, although it will generally be close to the condition.

Within the general group encompassed by this phase (ii) would be also included sites containing Pleistocene land slip zones, cambered valleys or periglacial shear zones.

For the purpose of design of slopes it is important to distinguish between first time slips in undisturbed material and reactivated slips or slips along some weak pre-existing shear zone as mentioned above.

It is suggested that if a slope in undisturbed material is designed for

$$\begin{cases} (c' \rightarrow 0^*) \\ (\phi' = \phi' \text{ peak}, \end{cases}$$

then the slope will be stable from the long term point of view and, except under special circumstances, will not be subject to progressive failure. This is in contrast to the residual approach where the design could be based on the over-conservative parameters,

$$\begin{cases} (c' = 0 \\ (\phi' = \phi'_r \end{cases}$$

* The value of c' may be increased for cuttings required to be stable over a limited number of years, Skempton and James (in press).

It is the purpose of this paper to outline some of the circumstances which are believed to lead to progressive failure in undisturbed clays, and to suggest means of predicting such occurrences. The criteria for a landslide caused by progressive failure is that (i) the landslide should be a first-time failure and not due to any pre-existing slip planes, and (ii) the slip should fail at a strength at or near to the residual, or at least substantially below the parameters given by $c' = 0$, $\phi' = \phi' \text{ peak}$.

II.- STRAINS REQUIRED FOR RESIDUAL CONDITIONS IN THE FIELD

Most hypotheses on progressive failure appear to contain the implication that residual conditions are developed rapidly on straining. However, before proceeding to discuss the subject, it is important to obtain some quantitative idea of the sorts of deformations needed to produce residual conditions along the slip plane of a landslide.

It has been found, Peck (1967), that residual conditions are reached slightly more rapidly under low stress levels than under high; and this is frequently observed in shear box tests. Since the majority of landslides in engineering works will occur under average effective normal stresses, (σ'), of around 5 lb/sq.in. or less, the tendency will favour a rapid reduction in strength on sliding. Alternatively, in larger landslides it may mean that the slip zone in the toe area will exhibit a lower strength than further back into the slipping mass where the stress level is higher. The orientation of the slip plane in relation to the bedding will also tend to favour an unequal development, James (1970).

However, laboratory work on the microscopic structure of clays under shear, Tchalenko (1967), suggests that for some considerable time after the peak has been passed the shear zone will not consist of a single plane but rather of multiple planes (reidel shears), one set of which is inclined at a small angle to the disturbing stress. Coalescence of these into a single, undulatory, shear plane, usually containing shear lozenges, requires a large degree of deformation; perhaps the equivalent of two or three travels in a repeated shear box test. Hence, reaching residual conditions can be a lengthy process and the effect of multiple shear zones might be expected to be even more marked under the characteristically less specific set of stresses in the field.

In order to compare the various effects of landslides a dimensionless factor, "field strain", may be introduced at this stage. This is taken as the ratio of the amount of slip movement occurring to the length of the slip plane or, more approximately, the ratio of the vertical drop in the head of the slip (height of scarp) to the height of the slip. Profiles of slopes before and after failure may be analysed to determine the strength required under both conditions, and the difference in strength can then be compared with the field strain. First time slips, only, give useful data.

Fig No. 1 shows such a relationship.

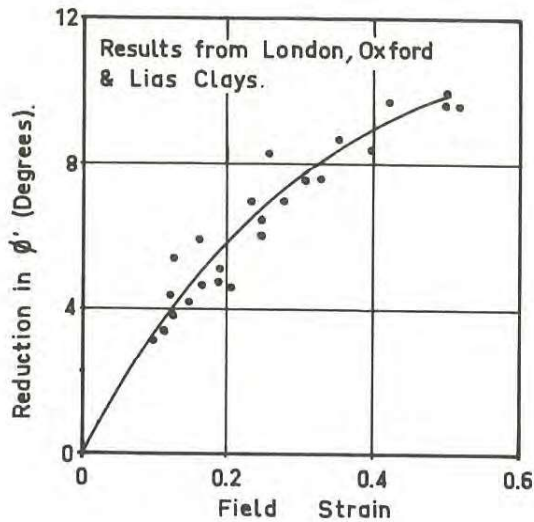


Fig. 1. Loss in strength related to field strain

For convenience, the strength drop is expressed in terms of the drop in ϕ' alone, i.e. the difference in the ϕ' required for stability in each case, assuming c' equals zero. In most of these cases, the value of c' represents less than 10% of the required total strength for stability.

It may be seen from the graph that a definite trend is present and also that considerable deformation is necessary in a first time slip in order to produce conditions which would approximate to the residual over the whole of the slip zone. For example, in a 30 ft high cutting in London Clay, a slip movement of around 7 ft (i.e. a field strain $\doteq 0.25$) would be required to give the necessary drop in ϕ' of 6° between peak and residual. (ϕ' peak = 20° , $\phi'_R = 14^\circ$ for London Clay). In less catastrophic slips it may be inferred that not the whole of the slip plane will exhibit the residual strength, while the average drop in strength will usually be less than occurs in one travel of the conventional shear box test.

In summary, it is seen that the average drop in the angle of shearing resistance of a clay will be approximately proportional to the degree of deformation undergone, with substantial strains being generally necessary to reach residual conditions. Further, residual conditions will, in most cases, tend to occur first near the toe of a slip, both due to bedding and also the lower stress levels usually applicable in this location. Nevertheless, it appears that movements of perhaps feet would be still necessary in the toe region to cause complete reduction in the angle of shearing resistance, particularly where multiple shear zones exist.

III.- MODES OF PROGRESSIVE FAILURE

The need for relatively great deformations to produce residual conditions may now be considered in the light of existing hypotheses on progressive failure, e.g. Bjerrum or Yudbhir. In both cases residual conditions are postulated to be the result of some form of expansion towards a cutting face or, alternatively, into an eroding valley. Little information regarding pre-slip movements is available in the literature, but in London Clay cuttings, de Lory (1957), it appears such movements due to high lateral stresses are small, of the order of inches. Experience in the behaviour of high faces in brick pit excavations confirms this order of magnitude of stable pre-slip movement.

Hence, it is suggested that unless the lateral movements or strains are very much localised, i.e. to one thin seam, such minor pre-slip movements would be insufficient to produce any substantial drop in the angle of shearing resistance of the clay. In other words, progressive failure is therefore unlikely in homogeneous clay slopes. London Clay, for example, would typically fall into the homogeneous category, except perhaps at the brown/blue interface, while compacted fills and many normally consolidated deposits will also be included.

It is also apparent that for a progressive failure mechanism to be effective, it must not only cause this localised straining in the vicinity of the toe of the slope, but also inwards for some distance into the slope. That is, the mechanism should be retrogressive. For most over-consolidated clays a mass lateral movement towards a cutting of several or more inches should be sufficient to release the high in-built horizontal stresses, thus depriving a progressive failure mechanism, due to this alone, of its disturbing influence. In the case of the release-of-strain-energy-due-to-weathering approach, while the rate of release can only be guessed at, there seems to be no reason for such a mechanism to extend with finite strains for any distance into a slope over engineering time scales.

Thus, from the above, it may be inferred that progressive failure, at least as a dominant mechanism of strength decay, requires a certain set of conditions for its implementation. And, in fact, reliable case histories of large seemingly initial movements, i.e. first time slides, at or near the residual strength are rare. Many instances of landslides originally thought to be first time slides at exceptionally low strengths have proved to be reactivation of older landslides, e.g. Walton's Wood, Skempton and Petley (1967); the Seattle Freeway landslides, Wilson and Johnson (1964); Portuguese Bend, Merriam (1960).

The Devon Rd Landslide, (Alberta), Broscoe and Thompson (1967), shown in Fig No. 2 is an initial slide. Slipping has taken place here along a

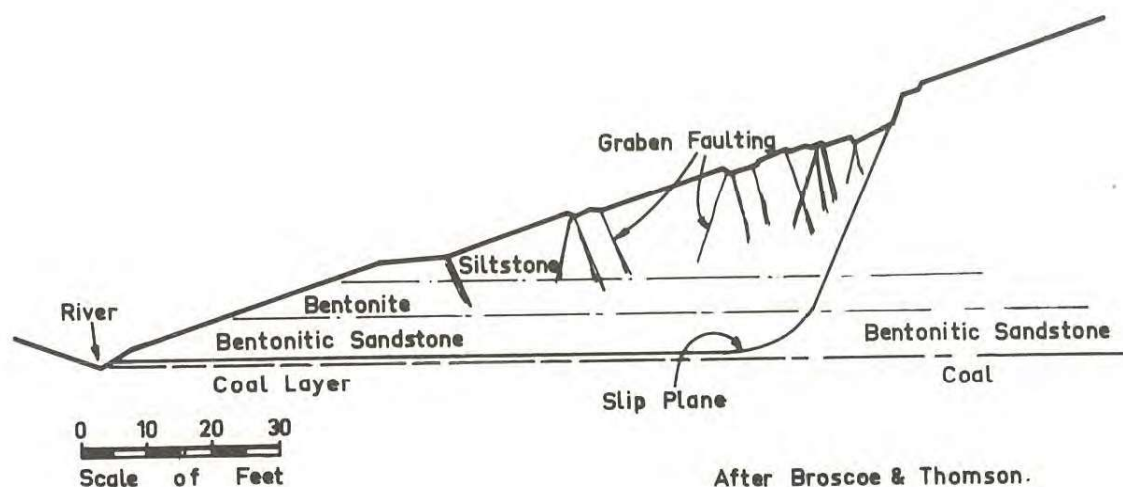


Fig. 2. Devon Rd Landslide, Edmonton

bentonitic layer in a bentonitic sandstone, at or near the junction with the coal layer. The valley in the area shows no signs of instability and the present slide was initiated by a small road cutting near the toe. Analyses indicate that the required angle of shearing resistance here could be as low as 5° , Morgenstern (personal communication). Graben faulting on the surface of the slope also indicates that movement has been retrogressive, i.e. commencing at the toe and working inwards, and drilling behind the slipped area has proved that slickensiding also exists there, in the in-place bentonitic material just above coal. Thus relative deformations have occurred to quite some distance in from the toe. This site has all the attributes of progressive failure.

A mechanism which would here provide the relative deformation and slickensiding in the bentonite, i.e. the progressive failure, would be a non-homogeneous swelling mechanism. By this is meant a differential swelling of the swelling soil layer against the non-swelling layer with strains occurring in a fashion analogous to those at the interface of competent and incompetent beds during folding. Swelling in such a case might be initiated by stress releases during valley formations, and it is possible that swelling pressures up to several tons per square foot could be developed. Expansion would occur out towards the valley sides, thus releasing stresses interiorly, and thereby allowing the process to continue. Hence, non-homogeneous swelling has the attribute of extended retrogressive behaviour, while strains associated with the process will typically be localised to the interface with layers of different composition.

Few sites provide data as dramatic as the Devon Rd site. However, similar tendencies have been observed in other sites with distinct non-homogeneities. For example, the tendency was observed to a lesser degree in several London Clay sites where the failure plane was observed to follow

along the junction of the weathered brown with the unweathered blue clay, James (1970). It is reasonable to assume the reaction of the two forms of the clay to stress release and swelling would be different, thus providing a means whereby differential straining could occur along this brown/blue boundary. In the relevant cases, it was observed that, while the strength required for stability was still well above the residual, it was nevertheless significantly below that typical in a cutting of the same age in this formation. Thus, it is suggested that a small amount of progressive failure could have occurred in such cases. The London Clay contains minor but significant amounts of montmorillonite disseminated in the mass, thus providing a small to moderate swelling potential.

Obviously, there is scope for some detailed analyses and instrumentation of slopes and cuttings to provide further evidence for this non-homogeneous straining hypothesis, but it is the author's opinion that non-homogeneous swelling either after the construction of a cutting or during valley formation, will be the dominant if not the only mechanism for true progressive failure.

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