Some Thoughts on Rain-Induced Slope Failures

Sur les Glissements de Terrain par les Conditions Météorologiques

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SYNOPSIS The mechanism is discussed by which failures occur in unsaturated soil slopes in which infiltration and pore suction play major roles. It is suggested that the shear properties of the slope material are most appropriately measured in the laboratory by increasing the pore pressure while the total stresses are maintained constant. It is hypothesized that compressive and dilatant soils will behave quite differently under conditions of water infiltration. For soils which fail slowly or for compressive soils which fail rapidly, the controlling pore pressure (suction) is probably entirely governed by the rate of infiltration. The stability of slopes in dilatant material, however, is probably controlled by pore pressures which are both infiltration-dependent and strain-dependent.

INTRODUCTION

It is probably true that the majority of existing cut slopes in residual soils were never designed in the engineering sense and that such slopes defy rational analysis by classical means. This is certainly so for many cut slopes in Hong Kong, where analyses indicate theoretical factors of safety of less than unity even though the slopes have remained stable for many years under conditions of extremely heavy seasonal rainfall. In Hong Kong, efforts are now being made to establish a rational method of design for such slopes in which the main agent of failure is water infiltration. This paper outlines some of the Author's thoughts on the subject.

THE RELEVANT LITERATURE

It seems to the Author that the great majority of the world's slope failures, particularly those large enough to be classified as "landslides", are rain-induced failures which occur in residual soils. A search of the literature readily shows that the analysis of such failures and the design procedures for slopes in residual soils have received the minimum of attention; this has been so even at meetings and conferences devoted entirely to the subjects of slope stability and landslides. Even the few publications which are of direct relevance to the subject tend to be descriptive in nature and do not attempt to provide mechanistic explanations of the failures, nor to present rational design methods.

In the geotechnical research world, there has been a general neglect of residual soils. The main reasons for this are certainly the sampling difficulties that occur with such heterogeneous materials, and the experimental problems which are inherent in working with unsaturated soils in the laboratory. The study of slope stability has hitherto been concentrated almost entirely on slopes in saturated sediments, and very little of this work is applicable to the stability of slopes in unsaturated, residual soils where failure is brought about by water infiltration. For these materials, a different approach to the assessment of slope stability is necessary from the methods commonly used for saturated sediments.

It is worth mentioning the few publications which provide the practitioner with some engineering guidance to the design of slopes in residual soils. De Mello (1972) presented an admirable review of the engineering problems associated with residual soils generally, and a similar review by Deere & Patton (1971) concerned itself specifically with the problem of slope stability, but neither of these publications dealt with the mechanism of rain-induced failure in such slopes. A recent paper by Coates (1977), which was concerned with landslides in general, dealt to some extent with rain-induced failures and provided a good summary of the relevant geological literature.

The mechanism of rain-induced slope failure has received little attention. The first mention of the role of soil suction in slope stability was possibly that made by Terzaghi (1950) in a paper which concerned itself mainly with the geological aspects of slope failures. An early paper by Vargas & Pichler (1957) discussed briefly the pore pressure changes brought about by infiltration into soil slopes, but the earliest attempt to provide a rational link between infiltration and soil suction appears to have been made by Lumb (1962). Later, Lumb (1975) also provided probably the best regional case study that has been published of rain-induced failures in residual soil slopes. Recent papers by Morgenstern & de Matos (1975), Blight (1977) and Morgenstern (1980) have discussed, in very general terms, the mechanism of rain-induced failure, but these writings do not represent an appreciable advance on the state of knowledge set out by Lumb in 1962.

MECHANISM OF FAILURE

When failure of a residual soil slope is brought about by rainfall, the mechanism of failure is that water infiltration causes a reduction in the pore suction (negative pore pressure) in the unsaturated soil; this results in a decrease in the effective stress, which is reflected in a decrease in the soil strength to a point where equilibrium can no longer be sustained in the slope. Most slope failures in areas of heavy rainfall, therefore, take place under conditions of almost constant total stress and increasing pore pressure. The water-table in such areas is often well below the ground surface, and positive pore pressures play very little part in the relatively shallow failures that occur.

It is generally possible to identify the surface on which a failure of a particular residual soil slope has occurred, and this suggests that limit equilibrium methods of analysis for non-circular surfaces might be confidently applied to such failures. For this to be possible, it is necessary to ascertain the appropriate shear properties of the soil and the distribution of pore pressures in the slope, since the stability can only be rationally considered in terms of effective stresses. Our knowledge of the relationships between rainfall, infiltration, pore suction and soil shear properties, however, is very poor, and much work remains to be done.

The shear properties of soils are, of course, intimately related to pore pressure by the effective stress principle. To determine in the laboratory the appropriate shear properties for slope design and slope analysis, it is necessary to model the field mechanism of failure as closely as possible. For many good reasons, the triaxial test is commonly used to study the shear properties of soils, the most usual form of this test being such that the axial stress, σ_1, is increased to failure while the cell pressure, $\bar{\sigma}_3$, is maintained constant; either a drained test is conducted (in which $\Delta u = 0$), or an undrained test (or constant water content test) is carried out during which the pore pressure is measured. The stress path followed in the field during a rain-induced failure, however, is very different from this, since σ_1 and σ_3 are sensibly constant and the pore pressure increases (i.e. suction decreases) as it rains.

Figure 1 illustrates the disparity between the stress paths normally followed in the triaxial test and that which applies to the field conditions; in the figure, $p = (\bar{\sigma}_1 + \bar{\sigma}_3)/2$ and $q = (\sigma_1 - \sigma_3)/2$. Two conclusions can readily be drawn :

(i) The stress paths commonly followed in the triaxial test are quite different from the path which pertains in the field.

(ii) The stress ranges over which triaxial tests are usually conducted are not appropriate to the field conditions.

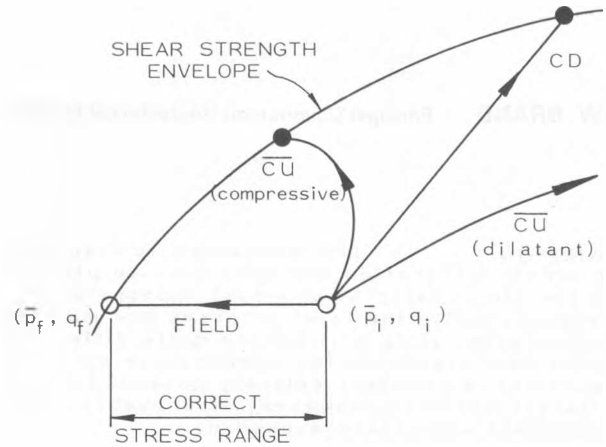

Fig. 1 Comparative Field and Laboratory Stress Paths

The correct mechanism of failure can only be modelled in the laboratory by means of a constant load test (Fig. 2) in which the pore pressure is increased from an initial negative value until failure occurs, but such tests are extremely difficult to conduct satisfactorily. It is also possible to follow the correct stress path simply by decreasing the cell pressure, but this does not simulate the correct mechanism of failure in the field.

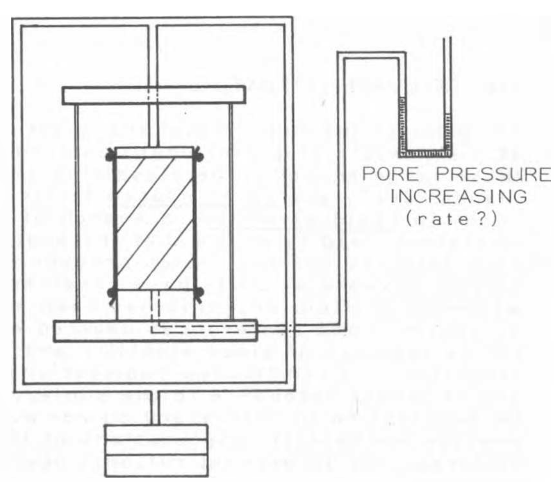

Fig. 2 The Appropriate Triaxial Test

PORE SUCTION AND MODE OF FAILURE

It is obvious that pore suction is the dominant parameter in the analysis and design of slopes where failure is brought about by rainfall. To examine the possible mechanisms of shear failure, it is necessary to consider the conditions in unsaturated soil as the soil suction is reduced by infiltration, and to trace the changes that take place as failure is imminent. Where failure occurs on a relatively shallow surface, as is common, it will be assumed here that the pore air pressure remains atmospheric throughout and that the water infiltration increases only the pore water pressure. What then is the pore water pressure (suction) at failure ?

In the general case, the change in pore water pressure as infiltration occurs will be both infiltration-dependent and strain-dependent. The pore pressure change that is caused directly by infiltration is a function of the rainfall period and intensity, the geometry of the slope, and the diffusivity, porosity and degree of saturation of the soil (Lumb, 1962). The strain-dependent pore pressure is dependent on the properties of the soil and the rate of strain it undergoes.

The two extreme slope failure situations that can occur are :

(i) rapid failure, which takes place under constant water content conditions, and

(ii) slow failure, which takes place under approximately constant suction conditions.

The evidence from Hong Kong (Lumb, 1975) and elsewhere (Deere & Patton, 1971; Morgenstern & de Matos, 1975) is that failures usually occur extremely rapidly, and it will be assumed for the moment that constant water content conditions prevail. Laboratory tests on Hong Kong residual soils have shown that the suction in a specimen sheared at constant water content changes throughout the shearing process in a manner dictated by the mode of shearing behaviour. A dilatant mode causes suction to increase throughout shearing, while a compressive mode results in a suction decrease. This leads to the following hypotheses :

(i) If the soil on a potential failure surface will fail in a compressive mode, the suction will decrease rapidly once the suction loss due to infiltration alone is sufficient to reduce the strength to a level where significant strains will occur. Rapid collapse will result, therefore, because the suction (and hence the strength) will decrease rapidly throughout the shearing process.

(ii) If shear along the potential failure surface will take place in a dilatant mode, the strain-induced suction will increase as the shear occurs, and this will tend to counteract the losses in suction due to infiltration alone.

These two situations are, of course, represented by exactly the same stress path in Fig.1, but the time rate at which compressive soils move along this path is much faster than the rate of the dilatant soils. It is probable that the pore pressure changes and shear strains which occur under the two different modes are as represented in Fig. 3.

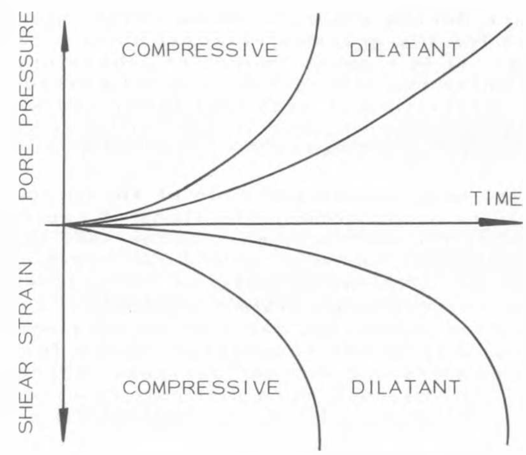

Fig. 3 Effect of Shear Mode

It is possible that the rate of failure of a particular slope will be sufficiently slow (in relation to the soil permeability) for pore pressures to equilibrate in the region of the failure surface throughout the straining process. If this occurs, the strain-induced suction will be zero, and the failure will be brought about purely by infiltration-induced pore pressure changes.

On the basis of the above reasoning, the role of soil suction in slope stability can be summarised as follows :

(i) When failure takes place in a compressive mode under constant water content conditions, a collapse of the slope occurs when the suction pressure is reduced to the critical level by infiltration. In such cases, the shear strength of the soil on the failure surface is governed by the soil suction just prior to failure.

(ii) When failure takes place in a dilatant mode under constant water content conditions, the suction on the failure surface is both infiltration-dependent and strain-dependent. In these circumstances, the shear strength of the soil is governed by both the rate of infiltration and the stress-strain characteristics of the soil.

(iii) If failure takes place under constant suction conditions, the suctions (and hence the strength) are controlled entirely by the infiltration process and are independent of strain. The soil suction just prior to failure is then the controlling pore pressure.

It is suggested therefore, that the mode of failure is critical to the stability assessment of slopes under conditions of water infiltration. The appropriate mode of failure in the field, as in the laboratory, will depend largely upon the stress level during shear. Residual soils at low stress levels often exhibit a quasi-preconsolidation pressure below which dilation occurs during shear; this has been found to be so for the granitic residual soils of Hong Kong. It is clearly important, therefore, to determine the stress-strain-pore pressure characteristics of each soil type, and to establish also whether it will collapse during the shearing process.

Except when a dilatant mode of shear would be likely to occur under conditions of rapid failure, the soil suction appropriate to the analysis of a residual soil slope would seem to be the value which exist in the stable slope under the extreme rainfall conditions. Information about this can only be obtained by means of field instrumentation in the form of tensiometers and similar devices. Appropriate suctions are much more difficult to ascertain where dilation is likely to occur during shear.

POSTSCRIPT

In Hong Kong, the Geotechnical Control Office of the Hong Kong Public Works Department has recently embarked upon an extensive programme of laboratory studies to investigate the fundamental shear behaviour of the predominant residual soils, which are of granitic and volcanic origins. The fully saturated behaviour has first been investigated, and this is being followed by work on the unsaturated material with the pore air pressure vented to atmosphere. In addition, the first tests have been carried out in which the appropriate stress path (Fig. 1) has been followed by decreasing the suction from its initial level until failure occurred. There are considerable experimental difficulties with this kind of test, not the least of which is the equilibration of the pore pressure throughout the specimen as the suction is decreased, but it is thought that these problems will soon be overcome. In conjunction with this work, soil suctions are being monitored on a longterm basis in a number of selected slopes. It is hoped that this experimental work, together with the careful examination and back analyses of existing failures, will result in a more rational design method for Hong Kong conditions and, indeed, for all slopes where failures are rain-induced.

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