STABILITY OF NATURAL SLOPES AND EMBANKMENT FOUNDATIONS

STABILITE DES TALUS NATURELS ET DES FONDATIONS DE REMBLAIS

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The 26 papers in this Session divide fairly naturally into the following 5 groups:

1. Regional studies
2. Slope movements
3. Case records
   3.1 Slopes
   3.2 Banks
4. Theoretical considerations
5. Experimental techniques

1. REGIONAL STUDIES

An excellent example of the value of a comprehensive regional approach to landslide problems is provided in the paper by Bjerrum, Løken, Heiberg & Foster. This defines and evaluates the factors responsible for quick clay slides in an area north-east of Oslo where the front of Post-glacial dissection fingers into an uneroded plain of marine clays which originally formed the sea bed. It is found that the incidence of the quick clay slides is controlled chiefly by the relative rates of weathering and erosion and is thus highest in the vicinity of the front of dissection. As established previously in the Namdalen investigations (Hutchinson, 1960; 1961), the quick clay bodies occur generally in localities where the depth of the clay is moderate or small and leaching is dominated by a strong upward seepage of ground-water from the bedrock. The important finding is made that continuation of the leaching leads eventually to a reduction of sensitivity and an increase of shear strength by chemical weathering. It is concluded that if stream erosion can be prevented, by the construction of check dams for example, the danger of quick clay slides will be much reduced in the short-term and in the long-term virtually eliminated.

The very different landslide problems in the vicinity of Rio de Janeiro are described in a regional study by Barata. The paper deals largely with the disastrous effects of the exceptional rains of 1966 and 1967 upon the local residual and colluvial slopes. Classifications are presented of the various types of slope in the region and of the landslides affecting them: the importance of weathering, climatic and human factors in causing the landslides is particularly emphasized. By a combination of regional investigations and the instrumentation and observation of critical slopes, it is hoped to anticipate future failures.

A further study of the same catastrophic events and the subsequent remedial works is given in a paper by Da Costa Nunes. He concludes that most of the damage caused by the rainstorms was due to the effects of intense erosion on the steeper slopes, and mentions that the structure of the local colluvial soils is commonly loose enough for them to be prone to flow slides. Both in this and in the preceding paper attention is drawn to the danger of falling, or rolling, of residual boulders exposed by erosion.

2. SLOPE MOVEMENTS

The papers submitted to this Session reveal an increased interest in the study of slope movements. While partly the result of improved instrumentation, this seems chiefly to reflect the realisation that such studies, in addition to being of considerable diagnostic value, are essential for progress in the difficult problems of progressive failure and prediction of failure.

A well-documented study of progressive movements in freshly cut slopes of the stiff fissured Boom Clay* at Antwerp is given by De Beer. The slopes vary between 11 and 15 metres in height and range in slope from vertical to about 25°. The vertical slope

* The geotechnical properties of this clay have been described elsewhere (De Beer, 1967).

failed some weeks after completion of excavation after a forward movement of its crest of about 10 cms; the other slopes remained stable for periods up to a year.

Measurements of surface movements and of deformations within the slope (made by inclinometer) indicated that, in all cases, the deformations began in the vicinity of the slope foot and progressed gradually inwards and upwards. Tension cracks appeared at a fairly late stage in this process. A similar pattern of deformation was also observed in a canal cut in stiff-fissured clay at La Fléchère, where a renewal of movement on pre-existing slip surfaces was commencing.

A large landslide which took place on the River Danube, south of Budapest, in 1964, is described by Kézdi. This appears to have been a first-time slide, involving chiefly loess: the failure was seated, however, in underlying Pannonian sediments consisting chiefly of clayey silts and fine sands. Pre-failure movements were measured on a house situated at the crest of the 50 metre high slope. These took place at an average rate of about 36 cm/year over the last 6 months before failure. The rate of movement increased towards the time of the slide: the total movement before failure was more than 47 cm. The reported post-failure movements average about 45 cm/year. They fluctuate in rate with the level of the Danube and reach a maximum when the river is high.

An old landslide near Istanbul, involving stiff to very stiff fissured clays and marls, is described by Peynircioğlu. The sliding, involving a slope inclined at about 10°, results from a renewal of movement on a pre-existing slip surface. Measurements extending over a period of 4 years indicate that the average rates of movement in the slide ranged between 110 and 570 cm/year. Movements of related type, in an old slide in the stiff-fissured Beaumont Clay of Texas, are reported by Focht & Sullivan to have taken place at rates of between 10 and 30 cm/year.

Saito presents the results of his further work on the problem of forecasting the time at which a slope failure will take place from measurements of the preceding surface movements. Records are given of several cases in Japan in which the time of failure was predicted fairly closely from movements measured generally during the preceding week or ten days. Although the proposed method appears to be too empirical to have general application, the author should be congratulated on the progress he has made in this important field.

A convenient method of representing the displacement rate of vectors of ground movements is put forward by Ter-Stepanian. It is shown how the resulting plots can be diagnostic of various types of movement.* Particular emphasis is laid on the occurrence of "multi-storied" landslides, in which movements of unlike speeds and directions may take place simultaneously at different depths. It may be preferable to describe such phenomena as mass movements of various types superimposed: for instance, a mudflow taking place on a slow-moving, deep-seated rotational slip.

The data on slope movements provided by the foregoing papers usefully complement, but do not extend, that given in Tables 1 and 2 of our State-of-the-Art Report.

3. CASE RECORDS

As we have emphasised in the State-of-the-Art Report, case records, especially well analysed and documented ones of slope failures, lie at the heart of studies of slope stability. Probably because of the more generous space allowance at this Conference, more papers of this type have been submitted than has recently been the case.

3.1 Slopes

Further studies of short-term, first-time failures in the slopes of the stiff-fissured Valderno Clay in the Santa Barbara opencast mine near Florence are reported by Esu & Calabresi. These are of particular interest as the stability of slopes in this well-jointed lacustrine Pliocene clay is controlled almost entirely by the strengths on extensive planar discontinuities, generally joints and bedding planes and occasionally faults: block slides are thus the characteristic type of failure in the pit. After a thorough investigation of the engineering geology of the site and of the geotechnical properties of the clay, approximate analyses are made of two such slides. These indicate that the maximum shear strength mobilised in these short-term failures on pre-existing discontinuities (as distinct from shears) is approximated to by the peak angle of shearing resistance, ϕ', and a c' value close to zero. The value of this work would be greatly enhanced by the measurement of pore and cleft water pressures within the slopes at the various stages of their development.

Two slope failures in the stiff-fissured Pleistocene Beaumont Clay of the Texas Gulf coast are described by Focht & Sullivan. The 1966 slide into the Houston Ship Channel appears to have been a long-term, first-time slide. The unknown resistance provided by the wharf piling renders the stability analysis rather approximate. The 1964 slide into Neches River Ship Channel was clearly a renewal of movement on a pre-existing slip surface. The post-failure movements of this slide, already referred

* In this connection an approximate method of estimating the depth of a slide from its surface displacements may be mentioned (Jakobsen, 1952).

to, had been in progress for several decades. A stability analysis by the Bishop Simplified Method, based on approximately defined ground-water conditions, yields shear strength parameters of $\emptyset = 15^{\circ}$ for c' = 0.

These are close to the residual values indicated for the Beaumont Clay by limited laboratory tests.

A valuable analytical case record of a first-time failure in the slope of a canal cut in slightly over-consolidated, intact Late-glacial clay in southern Finland is provided by Kankare. The clay is fairly similar to that at Lodalen (Sevaldson, 1956), though rather softer and more sensitive. In 1965 a major slide took place, about 3 years after commencement of the canal excavation and 9 months after its completion. Exceptionally good pore pressure measurements are available from piezometers installed 16 months before the slide. By chance, these were sited almost on the centreline of the eventual slide, and were swept away by it. Thorough field and laboratory investigations to determine the drained and undrained shear strengths of the clay were also made.

As the slide was retrogressive, the actual shape of the first failure is unknown. An effective stress analysis of the canal slope by the Bishop Simplified Method yields a safety factor very close to 1.0 for the most critical slip circle, using the peak drained shear parameters $c' = 0.49\ t/m^2$ and $\emptyset' = 27.7^{\circ}$. This result reinforces the evidence that peak strength controls the long-term stability of stiff, intact clay slopes.

As might be expected, a $\emptyset = 0$ analysis of the Kimola failure over-estimated the long-term stability. The General Reporters can see no rational basis for the suggestion that a more correct result may be obtained from such an analysis by using the undrained residual strength of the clay as indicated by vane tests.

The failures described by St.John, Sowers & Weaver occurred in cut slopes of residual soils in Puerto Rico, North Carolina and Georgia. Attention is drawn to the controlling influence on stability of thin black seams within the residual soil profile. These are thought to result from the infilling of cracks and joints by iron and manganese compounds. Similar observations have been made in residual soils in North Carolina by Deere (1957).

The several slides described, although not analysed, are of considerable qualitative interest. In each case the failure surface followed, either completely or in part, discontinuities of the above description. The times which elapsed between completion of the cuttings and the occurrence of the slides are not stated, but most of the failures appear to be short-term. Ground-water pressure measurements, more detailed shear strength testing and stability analyses are needed to complete this promising study.

3.2 Banks

The paper by Hamon & Post describes the problems posed by the foundation of the Djatiluhur dam in Java. Here the initial design of the dam cross-section was based on in situ shear tests at foundation level which indicated minimum shear parameters of $c' = 0$, $\emptyset' = 25^{\circ}$. During excavation, however, bands of tectonically sheared clay a few centimetres thick were discovered to extend beneath the whole dam site, generally at low angles of dip. Laboratory shear tests on these revealed their strength to be at its residual value of about $c' = 0$, $\emptyset' = 14^{\circ}$. As a result a major modification of the dam cross-section was necessary. This situation has many similarities with that which arose in the course of the Mangla project (Binnie, Clark & Skempton, 1967; Skempton & Petley, 1967) and provides a further example of pre-existing shear surfaces formed tectonically, to which attention is drawn in our State-of-the-Art Report.

The remaining three papers in this sub-section are concerned mainly with the instrumentation and performance of trial embankments built on soft clays. All reflect recent improvements in field instrumentation.

The paper by Justo describes a section of trial embankment and associated channel built over soft organic clays approaching 20 feet in depth near Valencia. The most important finding was that the mass permeability of the deposit was much higher than expected, with the result that the greater part of both vertical and lateral deformations took place during the construction period. Brief reference is made to a failure in the clay induced by a spoil heap which, on analysis by the $\emptyset = 0$ method, yielded a factor of safety close to unity. Details of this failure, and of the method used to measure the undrained shear strength of the clay, would be of interest.

An embankment on a soft organic clay deposit also forms the subject of a well-documented paper by Ladd, Aldrich & Johnson. The deposit, in a tidal area of Portland, Maine, is 25 to 30 feet thick and fairly heterogeneous. It is overconsolidated in its upper parts and normally consolidated at its base. The embankment failed during construction by deep-seated rotational shear failure. Analysis by the $\emptyset = 0$ method shows that the factor of safety based on field vane undrained strengths is over-estimated by a factor of two, while the average shear strength indicated by unconfined compression tests was 15 to 20% too low. Surface settlement and lateral displacement measurements, in combination with sub-surface inclinometer observations, gave effective warning of increasing distress.

Parallels may be drawn between this failure and those which occurred during construction of trial embankments for the Bangkok-Siracha Highway (Eide, 1968). The Bangkok Clay which formed the foundation is soft and organic and is also over-consolidated in its higher parts. The factor of safety of the embankment failures was over-estimated by a factor of 1.5 or more by vane shear strengths: shear strengths from unconfined compression tests gave values closer to unity.

Neither of these important cases of wide discrepancy between the strength mobilised during undrained failure and that measured in field vane tests has been fully explained. In the case of the Bangkok Clay, however, Eide points out that, although soft, it is fairly strongly fissured and slickensided. He suggests that this factor, together with a high dependency of strength on loading rate, is likely to be relevant to this problem.* As pointed out in the Portland paper, the vane tests there were carried out unusually fast. In the light of the Bangkok experience, it seems worthwhile to study further the effect of speed of vane rotation on the response of the Portland clays and to ascertain whether they are in fact free from fissures.

Finally, Rico, Moreno & Garcia present the results of preliminary investigations on two, well-instrumented test embankments on the deep, soft organic clay deposits of Texcoco Lake. Vane shear tests associated with one of the banks indicate that significant increase of undrained strength has taken place in the underlying clays as a result of 30 months consolidation. Maximum settlements and lateral deformations measured during this period are of the order of 100 cms and 10 cms respectively. No slips are reported.

4. THEORETICAL CONSIDERATIONS

Eight papers fall into this category, of which two are concerned with seismic effects.

Biernatowski discusses the application of probability theory to the relation between an appropriate design factor of safety and the degree of numerical certainty in the soil properties.

Christian & Whitman set up a one-dimensional mathematical model to investigate the initiation and propagation of progressive failure along the contact between a clay layer of uniform thickness and a sloping rigid base. Failure is due to the removal of K_o compressive stresses. This model simulates the mechanism of progressive failure suggested by Bjerrum (1967). Further work on this problem would be of interest, but the possibility should be checked as to whether failure might not occur within the clay mass rather than by progressing along the contact plane.

Jennings & Robertson consider the stability of block slides moving on pre-existing discontinuities such as faults and joints. They recognise that, in general, the failure surface has to pass through a certain amount of intact rock and detailed consideration is given to such factors as the attitude, length and spacing of the joint sets, the nature of the joint surfaces, strength of the rock, and water pressures. It would be of great value to see the application of such analyses to actual slope failures.

Lorente de Nó explores the effect of curvature in plan on the stability of vertical slopes in purely cohesive materials. He derives finite element solutions and adopts the von Mises criteria of failure. If, for example, the radius of curvature of the vertical face is twice its height, the stability number is 4.3 for a concave slope and 3.7 for a convex slope, as compared with 4.0 for the classical two-dimensional case. The paper is brief and it is to be hoped that a more complete publication will appear elsewhere.

Nascimento presents an approximate method for calculating the state of stress within a slope produced by the erosion of a valley. A numerical example is presented in which the stresses on a horizontal plane towards the base of a 100 m high slope, as derived by this method, are compared with those calculated by Mr. E.R. Oliveira (in an unpublished report) using finite element and integral methods.

Ranganatham, Sani & Screenivasulu give results of tests to determine the influence of anisotropy on strength of a remoulded black cotton soil (LL = 224, PL = 70). When normally consolidated at pressures less than about 20 lb/in^2, the undrained strength on planes parallel to bedding is less than the strength on planes normal to bedding, but at higher consolidation pressures the effect is reversed. This is found to be the case whether the soil is untreated or dispersed in sodium oxalate. In contrast, when the soil is flocculated by lime, no anisotropy could be detected. Consolidated undrained triaxial tests with pore pressure measurements (presumably on untreated soil) show a minimum strength, in terms of effective stress, on planes sub-parallel to bedding; but the difference from the strength as measured on samples with their axis vertical to bedding is only about 8 per cent.

The authors then proceed to develop expressions for simple cases of bearing capacity and slope stability modified to take account of strength anisotropy (see also Lo, 1965).

* Further studies of the mechanical properties of the Bangkok Clay are presented in the paper by Moh, Nelson & Brand to this Conference (Session 1).

Finn & Byrne extend the bi-linear hysteritic shear-slice model, currently used in structural dynamics, to study the earthquake response of a sloping layer of soil. They demonstrate the usefulness of this model by utilising a simplified example. They show that the post-yield displacements that can be induced on a slope by an actual earthquake depend not only on the intensity of the ground motion itself, but also on its duration and on the distribution with depth of the undrained strength of the layer. One difficulty that arises with this class of non-linear problems is the choice of the optimum number of slices that should be used; this will depend not only on the elastic properties of the layer but also on the frequency content of the ground input motion. Another point that needs further study is the validity of the use of viscous damping during the fully plastic movement of two contiguous slices. The absence of a provision in the computer programme to remove viscous damping during plastic excursions will result in underestimating actual displacements and overestimating forces or absolute accelerations. Perhaps the most interesting point raised in this paper is the inappropriateness of the use of the "elastic" seismic coefficient. The authors demonstrate once more that a given layer of soil can neither experience, nor transmit to a structure founded on it, forces greater than those that the layer can withstand without failing. This will be particularly true for sensitive deposits as well as for layers liable to liquefaction.

The problem treated by Prakash, Saran & Purushothamaraj suggests that we need more research in understanding and formulating the basic mechanism that controls the earthquake stability of slopes.

5. EXPERIMENTAL TECHNIQUES

Apparatus for the centrifugal testing of model slopes up to 18 cms in height and 15 cms thick is described by Avgherinos & Schofield. Tests are described in which slopes of saturated kaolin*, consolidated from a slurry, were brought to failure by rapid draw-down. Surface deformations and internal strains were observed throughout the tests, and the strengths mobilized at failure calculated by use of the $\emptyset = 0$ analysis. Some pore pressure measurements have also been made. Centrifuge testing of model slopes is a promising technique in the study of deformations and failure mechanisms in slopes of non-fissured soils, and the results of further work will be awaited with interest.

Tcheng & Absi describe the construction of a testing station in the vicinity of Paris in which full-scale earth pressure experiments will be carried out. It is to be hoped that the research planned will eventually provide much needed clarification of the relationships between wall movement and earth pressure, particularly for cohesive soils.

* Related tests on slopes of frictional material are reported in the paper by Mikasa, Takada & Yamada to this Conference (Session 3).

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