THE NATURE OF FAILURE THROUGH THE INTACT MATERIALS IN THE STEP JOINT MECHANISM FOR ROCK SLOPES

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by

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DECLARATION

I, the undersigned, declare that this thesis

1. is entirely my own work

2. has not been submitted to another university for any degree.

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SYNOPSIS

Frequently the failure of slopes cut in rock combine failure through intact rock and failure along joint planes. The failure mechanisms for different joint configurations are investigated in plaster of paris in uniaxial compression. The modes of failure for different joint configurations are established. Calculations of failure loads are shown and their validity is discussed.

A description of the model preparation and material properties is included.

CONTENTS

CHAPTER 1

ROCK AND ROCK FAILURE

Chapter 1

1.1 Statement of the Problem

All rock masses contain joints, or at least some structural discontinuities. When failure occurs in a rock mass, it follows surfaces along which the strength is exceeded. Such a failure surface will consist, in part, of actual joint surfaces (or other structural discontinuities). Between these pre-existing planes of weakness, the actual intact rock has to fracture. Various combinations of shear and tension fractures are possible through this intact part of the rock. The problem in this thesis was to investigate modes of failure through, in particular, the intact rock between the planes of weakness.

1.2 Background Remarks

1.2.1 Introduction

It has been recognised that the stability of a rock mass is a problem in engineering geology, combining the arts of estimation and judgement which are features of both disciplines. The mechanisms of failure are similar to those found with soil, with this basic difference - in soils the surface of failure will follow a path of exceeded strength, whereas in rock, where the strength of the material is relatively high, the surface of failure will follow preferred planes of weakness which are determined by geological features such as faults, contacts, bedding planes, cross joints and random joints. Water pressures in the joints, and to a lesser extent in the pores of the intact rock, will play the same important role as do porewater pressures in soils.

The condition of stability will depend on the margin by which the maximum possible value of the forces which tend to resist failure exceed the forces which tend to cause failure. The application of applied mechanics in the analysis of the discontinuous media becomes viable only with a thorough understanding of the defective planes. This involves a determination of the attitude, geometry and spatial distribution of the discontinuities, paying particular attention to:-

1. the geometric arrangement of the discontinuities,
2. their relationship to possible failure surfaces,
3. the strength parameters of the joints which includes an investigation of properties of both the joint planes and any infilling material(s) that occur in these; and
4. an assessment of the water pressures acting in the joints.

1.2.2 The Rock Mass

Before proceeding further, it is worthwhile examining some of the fundamental aspects relating to properties and characteristics of the rock mass. The rock mass is a discontinuous medium consisting of tightly fitting partitioned and partly partitioned solid bodies which may be small or large in comparison to the mass as a whole.

In hard rocks of high compressive strength the surface of failure is fundamentally affected by the discontinuities and, depending upon their orientation and positions, the shear surface may follow entirely on discontinuities. Shear strength in the rock mass will be determined largely by the shear strength on the discontinuities resulting in anisotropic behaviour. Also water flow in rock masses is, in general, controlled by the flow along discontinuities and the permeability of the intact rock is usually very different from that along joints. The flow through the mass is largely controlled by these discontinuities and the resulting anisotropy of permeability for a rock mass may be large.

From the foregoing discussion the fundamental properties of the rock mass, because of the very nature of the medium, can be summarized as follows:

1. failure within the rock mass will preferentially occur along structural discontinuities,
2. the rock mass is anisotropic in that the strength, permeability and deformational properties are directional,
3. the rock mass is heterogeneous in that the physical and lithological properties of the rock material are variable, and
4. it is discontinuous since it is made up of aggregates of blocks separated by planes of weakness.

Two approaches to the determination of the strength properties and failure criteria for rock masses appear to be in current use. In considering the basic characteristics of a rock mass, it is reasonable to accept that the most logical approach to analysing the mass must include foremost the discontinuities. A method is to measure the strengths of large representative rock samples by a series of in situ uniaxial, biaxial or triaxial compression or direct shear tests. This is a logical procedure, however, the tests are both difficult and expensive to carry out. Consequently the number of in situ tests undertaken at any site is usually very limited. A second and less expensive approach involves the separate assessment in the field, supported by tests in the laboratory, of the shear strengths of the intact rock material and the discontinuities. Using a measured or assumed stress distribution, the stability of any point in the mass can be investigated by assuming that failure will be by fracture of the rock material, or by slip on a joint plane or some other plane of weakness, according to the predetermined failure criteria which are usually taken to be of the linear Mohr-Coulomb type.

1.2.3 Geological Propositions

Before going into the mechanisms of failure which occur in rock masses, it is necessary to acknowledge certain premises which represent a particular concept and allow for rational analysis of a rock mass, using measurements on the structural discontinuities. The validity of any theory which incorporates structural discontinuities in the analysis depends on the degree to which these geological propositions may be considered to apply reliably. Four propositions, based on concepts relating to the characteristic features of the discontinuities in a rock mass, which can be utilized to analyse for the stability condition are described by Piteau (1970) as follows:-

1. Structural discontinuities will exist in the rock mass as detectable features and it will be possible to describe their properties in a quantitative way, particularly as these relate to shear strength in the plane of the joint concerned.
2. In the rock mass definable boundaries exist, enclosing volumes which will be called structural regions, within which the joints occur in a systematic fashion forming one or more joint sets each of which is designated a design set.
3. Sampling and analysis can be carried out on elements with reasonable expectation that similar conditions will apply to the particular portion of the rock mass under consideration, i.e. a reliable model can be constructed to represent the jointing in the rock mass. The determination of the composition of any potential failure plane requires an assumption of a definite model or picture of jointing.
4. Failure surfaces will be essentially pla[illegible] or combinations of planes.

It has already been pointed out that, since structural discontinuities in the mass are planes of weakness relative to the strength of the intact rock, failure in rock will preferentially follow these planes. Such a condition implies that the surface of failure will consist of planes of discontinuities or a combination of planes of discontinuities wherever possible.

1.2.4. Modes of Rock Failure

Any analysis of the stability of a rock mass requires that surfaces of failure which will more probably involve one or more joint sets be considered in various kinematically possible failure forms. That is, the various modes of failure which are kinematically possible for either one joint set or a combination of joint sets, of different orientation and position in space, must be investigated. Jennings and Robertson (1969) have investigated this subject and it will be covered only briefly herein. First a two-dimensional and then a three-dimensional mode will be considered.

Consider a slope cut in jointed rock in which the joints all lie in the same direction (Figure 1.2.4.1). A depth of cracking, Z_o, at the top of

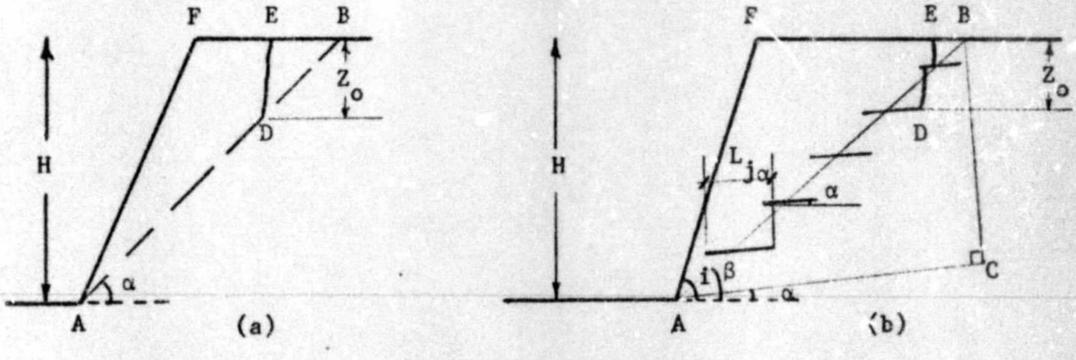


FIGURE 1.2.4.1 A SLOPE CUT IN JOINTED ROCK IN WHICH THE JOINTS ALL LIE IN THE SAME DIRECTION

the slope is accepted. These tension cracks need not be vertical and can foll- planes of weakness.

Figure 1.2.4.1 (a) shows the special case of (b) where a number of joints are on the same plane. The block ADEF will slide out, movement taking place in the α-direction, and the following will happen:

1. Sliding along the joint surfaces in the α-direction.
2. Shearing in the α-direction where joints do not occur.

In the alternative case shown in Figure 1.2.4.1 (b), the mass will again move in the α-direction and the following will happen:

1. Sliding along the joint surfaces in direction α
2. Shearing in the α-direction where joints do not occur.
3. Tension separation along surfaces between joints, usually perpendicular to α-joints.

Sliding on joints and shearing parallel to the joints will take place along a length AC = H cosec β cos $(\beta-\alpha)$.
Tension separation will occur on a length BC = H cosec β sin $(\beta-\alpha)$.

If the joints lie on a plane such that $\beta=\alpha$ (Figure 1.2.4.1 (a)), then the mass will slide only, down the β (or α) plane and no tension separation need take place.

In can be seen that shearing takes place through both joint material and intact rock material. Considering the length of the joints and total length of shear failure the joint contribution to shear strength is equal to the sum of the joint strengths. Thus a factor called the continuity factor is defined as

$$k_\alpha = \frac{\Sigma L_{j\alpha}}{AC} \qquad (\leq 1)$$

and the discontinuity factor is defined as

$$1-k_\alpha = (AC - \Sigma L_{j\alpha})/AC$$

It has been assumed that when the slope fails the coefficient of continuity is the ratio of the joint lengths to the total length of failure, i.e. $k_\alpha = \Sigma L_{j\alpha}/AC$. This is true only in the two-dimensional case; but failure takes place on a surface, thus the true continuity should be defined as the ratio of the area of the joints to the total area on which failure will take place.

If $\beta = \alpha$, the smallest value of k_α on a potential failure surface will occur when the failure line intercepts only one α-joint and the continuity,

$$k_\alpha = L_{j\alpha}/H \text{ cosec } \beta$$

If $\beta > \alpha$, the failure line will intercept n α-joints of average length $L_{j\alpha}$, then the continuity will be

$$k_\alpha = n.L_{j\alpha}/H \text{ cosec } \beta \cos(\beta - \alpha) \quad (\leq 1)$$

If β is increased, more α-joints are intersected until $\beta = \beta_K$ when $K_\alpha = 1{,}0$. If $\beta > \beta_K$ there are some joint sections which are not fully utilized in slippage and the value of k_α remains at 1,0.

The above assumes that stepping down will occur from the bottom end of an upper joint and will always encounter the higher end of a lower joint (Figure 1.2.4.2 (a)). This is unlikely and in most cases the step down will fall outside or inside a joint (Figures 1.2.4.2 (c) and (b)). Thus, in the calculation of continuity, a value less than $n.L_{j\alpha}$ must be used as the

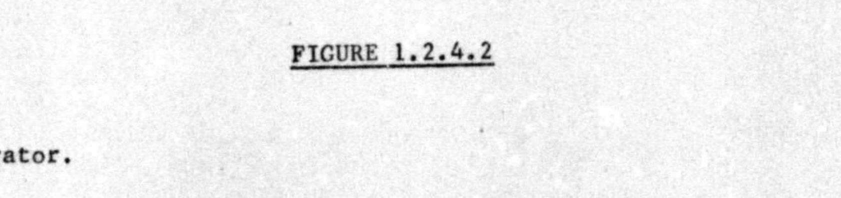
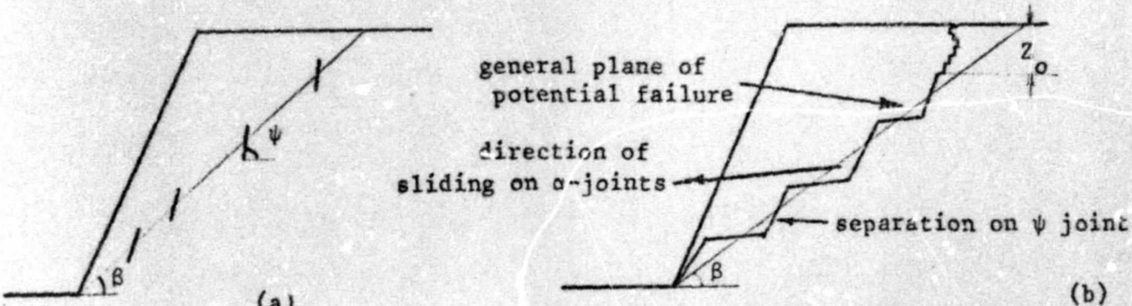


FIGURE 1.2.4.2

numerator.

Now consider a second set of joints at a steeper angle, ψ to the horizontal, to be added to the above case. The vector of movement is still in the



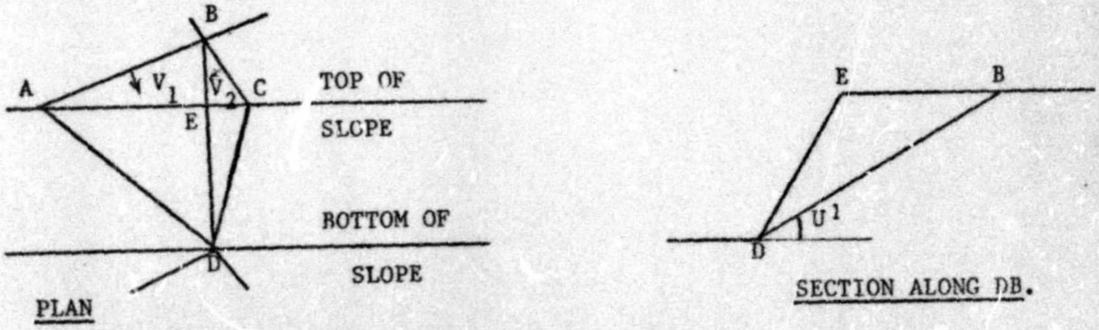
JOINTS AT A STEEPER ANGLE, ψ

FIGURE 1.2.4.3

STEP JOINT FAILURE

α-direction (Figure 1.2.4.3 (b)). Sliding and shearing still take place in the α-direction and separtion occurs on the ψ-joints. This Step Joint failure occurs along the β-plane until the depth of cracking is reached and from there tension cracks occur.

Let us now consider a 3-dimensional failure mode. If two intersecting planes of weakness are such that the line of intersection between them has a component of dip down a slope, the wedge thus formed may rotate or slide out either as a rigid body or as a broken mass, if failure also takes place within the wedge. ABD (Figure 1.2.4.4) represents the plan of a joint with strike AB and dip V1; BCD that of a joint with strike BC and dip V2; the intersection



PLAN

SECTION ALONG DB.

FIGURE 1.2.4.4

of the two planes is given in plan by the line DB having an apparent dip U^1. If the block remains intact then sliding may occur in the direction BD or on either of the intersecting planes of weakness, depending on the activating forces. Rotational failure modes are also possible and analysis can be carried out by three dimensional resolution of forces.

Jennings and Robertson have developed two other modes of failure (the conjugate joint zone failure and the conjugate joint block failure) both involving failure on mean planes, but in these cases multiple planes are involved.

If the factor of safety, F, is taken on the shear strength, in the way commonly used in slope stability analysis, the necessary equations for the four modes of failure may be set up. They become somewhat involved if considerations of water pressures and combinations of surcharge and Z_o are included. The solution requires the use of a highspeed computer.