Assessment of the stability of jointed rock slopes

Evaluation de la stabilité des pentes rocheuses jointées

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SYNOPSIS Geological structure plays a dominant role in determining the stability of most rock and certain soil slopes. The analysis of geological structure by means of stereographic projection is an established technique, but one which tends to be confusing except to routine users.

The paper describes simple methods of stereographic projection for analysis of geological structure. The techniques presented can assist in determining likely modes of failure and worst stability conditions (i.e. lowest Factor of Safety) for jointed rock slopes.

INTRODUCTION

Rock slopes, except those which exhibit low intact strength or intense fracturing, tend to fail along discrete dicontinuities such as bedding planes, joints and faults. Some slopes composed of stiff or residual soil display similar behaviour and it is therefore appropriate to review techniques for design of jointed rock slopes in these proceedings.

Most rock masses contain a number of sets of discontinuities, each set being composed of planes of varying orientation, frequency, extent and surface properties. The orientation and characteristics of these surfaces are usually studied by means of stereographic projection.

Analysis of rock slope stability is further complicated by the range of possible failure mechanisms which include sliding along discontinuities, rotation of blocks (e.g. toppling) and failure through intact material. Failure will often involve more than one of these mechanisms. Common failure modes are illustrated in Fig. 1.

STEREOGRAPHIC PROJECTION

When studying the orientation of a large number of planar discontinuities, stereographic projection is still the most effective method. The planes are considered to lie at the centre of a hemisphere and their projection from the surface of that hemisphere are displayed on a circular plot or net. Projection from the lower hemisphere to the equatorial plane is used throughout this paper. The techniques have been described in more detail by many authors (Phillips, 1971; Hoek & Bray, 1977). Unfortunately, the techniques of stereographic projection are rather confusing even to many seasoned practitioners.

Two types of stereographic projection are commonly used: the equal angle net is formed by direct projection from the hemisphere, whereas the equal area net is generated such that area relationships on the hemisphere are maintained on the projection.

The equal area net is used for plotting poles (or normals) to planes. Each plane with a given dip and dip azimuth, is represented by a point (as shown in Fig. 2).

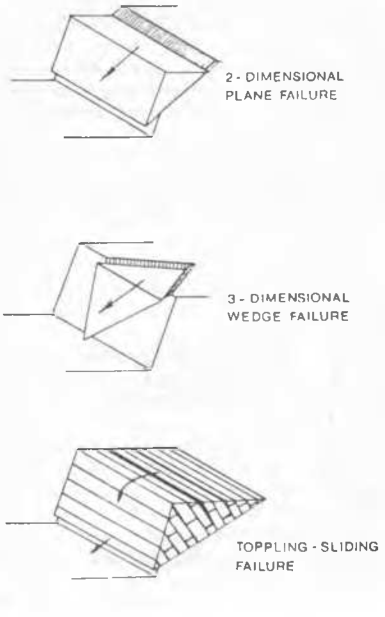

Fig. 1: Common Modes of Failure

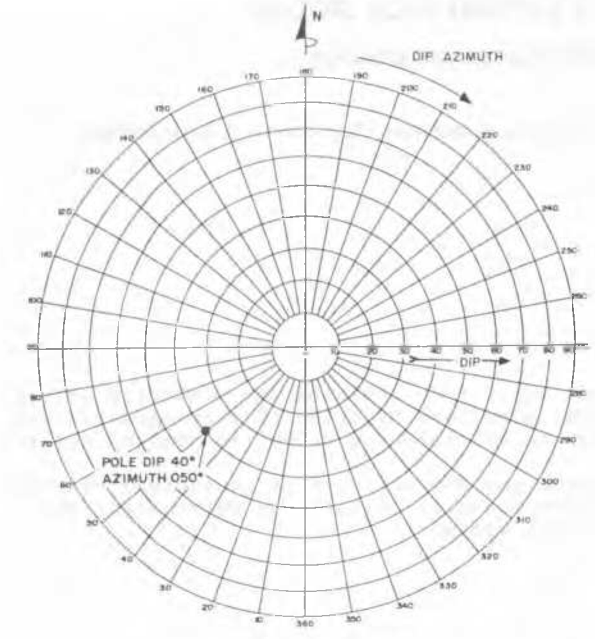

Fig. 2 Stereographic Pole Plotting Form (Polar, equal area, lower hemisphere)

The traditional method of plotting stereograms involved a confusing and cumbersome process of rotating a piece of tracing paper overlayed on a stereonet. A faster method involves direct plotting on a blank form as illustrated in Fig. 2. The dip direction (or azimuth) is read off a scale around the circumference of the net and the dip, from a radial scale about the centre.

Statistical study of the orientation of discontinuities is best carried out on an equal area net. The distribution of poles is contoured to define sets or populations of discontinuities. Computer plotting and contouring routines are readily available but manual contouring using a counting circle as illustrated in Fig. 3 is fast and simple.

The counting circle has an area which is one percent of the total area of the projection. The one percent contour is drawn by moving the circle around the plot to include one percent of the total poles represented. Higher value contours are then added. By this means a typical contour plot can be completed in a few minutes.

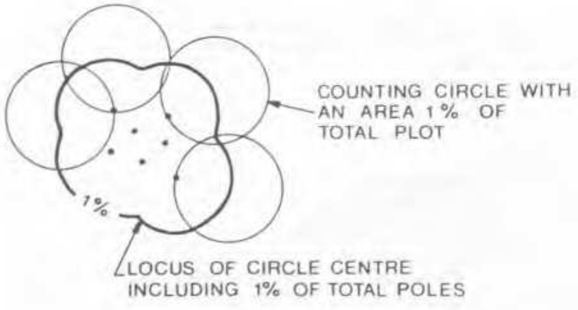

Fig. 3 Use of a Counting Circle for Contouring of a Stereonet (100 poles)

Planes can also be represented by their great circle traces on an equal angle projection. This enables angular relationships between planes to be measured fairly accurately. Unfortunately, great circle construction tends to be confusing especially when more than a few planes are represented. For this reason, equal area pole plots are used in the technique presented in this paper.

GREAT CIRCLE STABILITY ANALYSIS

Great circle construction has been used almost exclusively for analysis of the stability of jointed rock slopes (John, 1969; Hoek & Bray, 1977). By this method, the angular relationships between the slope face and major discontinuities are determined, enabling likely (kinematically possible) failure combination to be ascertained. Simple tests are applied to determine whether the discontinuities will undercut or "daylight" the slope. Lines of intersection of planes combining to produce 3-dimensional wedges can be measured and compared to the friction angle. As a first approximation, when the planes daylight and the dip of the line of intersection exceeds the friction angle of the planes, failure will occur.

In a simple situation with few planes, the great circle method is adequate. For the analysis of more complex structures where a number of failure modes are expected, the method tends to be cumbersome and confusing.

SEARCH NET TECHNIQUE

The "search net" technique has been used over a number of years by the author. The method avoids depicting discontinuities by great circles, in favour of equal area pole plotting and use of an overlay or "search net" for the analysis. An example of a search net is shown in Fig. 6 and its construction is illustrated in Figs 4 & 5.

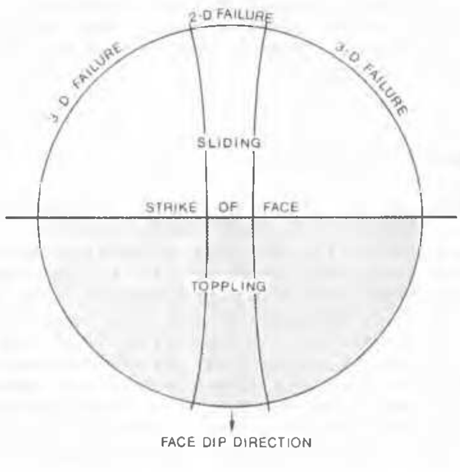

Fig. 4 Search Net, Basic Construction

In many design situations the trend or strike of the slope varies. For this reason, the search net is usually drawn on an overlay so that it can be oriented to the slope trend (or strike). In Figs. 4, 5 & 6 the slope trend is drawn from left to right.

The search net is divided into two main semicircular zones oriented about the slope trend. Any discontinuity with a pole falling within the unshaded portion of Fig. 4 dips out of the slope and may cause failure by sliding. The shaded area includes discontinuities that form blocks that could topple if undercut or released by displacement at the toe of the slope.

The search net is further subdivided into 2-dimensional and 3-dimensional zones as illustrated in Fig. 4. The 2-D zone is approximated by a band (formed by two small circles) lying arbitrarily within 10 degrees to the normal to the face strike. Any discontinuities with poles lying within the 2-D field tend to dominate the stability of the slope. This is because 2-D planes strike approximately parallel to the slope trend and create a weakness relatively unrestrained by end-effects.

An important division is made on the search net by plotting the pole of the slope face. With an equal area equatorial net, a great circle is drawn through the face pole to intersect the slope trend (as shown in Fig. 5.) Planes with poles lying in the unshaded segment not only dip out of the slope but also undercut of "daylight" the slope. Planes in zone "A" will fail by 2-dimensional plane failure when the disturbing forces exceed the strength of the planes. Planes in zones B,B' can combine to form approximately symmetrical 3-dimensional wedges with lines of intersection daylighting the slope.

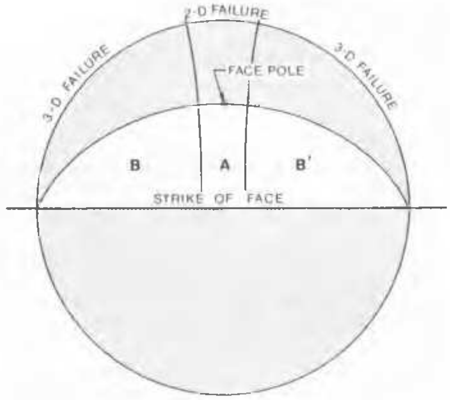

Fig. 5: Search Net, Symmetrical "Daylighting" Planes

Asymmetrical wedge failure is even more difficult to visualise, but may occur when planes in zones E / B & C', or B' / E & C combine (refer to the complete search net, Fig. 6). These asymmetrical combinations will only "daylight" leading to possible failure of the slope when certain geometrical conditions are met. A simple test for these conditions involves the rotation of the great circle and the unshaded zone in Fig. 5 about the face pole (see Fig. 7).

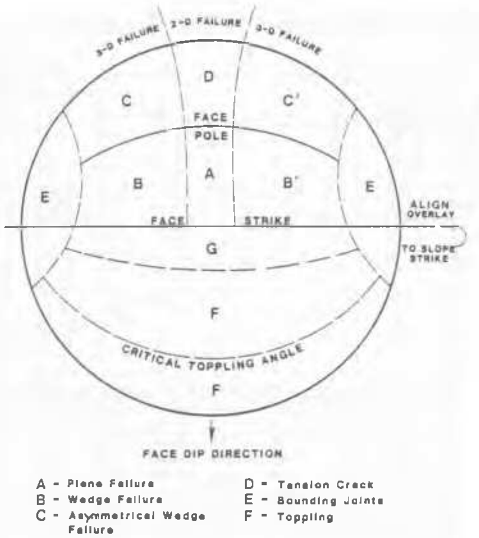

Fig. 6 Complete Search Net (Slope Angle 45°)

Toppling as a sole mechanism can obviously only occur when steeply dipping discontinuities in zone F are undercut. However, a far more common and significant type of failure may take place when steeply dipping discontinuities in zone F occur in combination with shallow daylighting planes in zone A, leading to toppling-sliding (Ashby, 1971; de Freitas & Watters, 1973).

A practical trial using the search net will clearly illustrate the ease of use and power of the technique.

FLOATING PLANE STABILITY ANALYSIS

Having determined the modes of failure that are kinematically possible, final design requires comprehensive analysis. Various methods are available for stability analysis using either graphical or computer solutions (Hoek & Bray, 1977). Limiting equilibrium analysis is generally used and the 2-dimensional analysis of a slope mass sliding on a daylighting discontinuity is straightforward. Geometrically more complex analyses of 3-dimensional wedges can be handled, but are best run on a programmable calculator or computer. Unfortunately, toppling - sliding is still difficult to handle rigorously (Goodman & Bray, 1976).

Even with rapid computational methods, design of jointed rock slopes can still be complicated by the number of variables entering into the analysis. Variables include the failure mode, the orientation, extent and strength of discontinuities, the strength of the intact material, water pressure and external loads. The effect of varying individual design parameters can be presented by sensitivity analysis. However, the effect of varying the orientation of discontinuities is more difficult to display (See Fig. 7).

FLOATING-PLANE:

AZ	DIP								
	10	20	30	40	50	60	70	80	90
110.0	26.64	15.59	12.01	10.30	9.41	12.12	-9.99	-9.99	-9.99
120.0	13.46	7.84	6.00	5.17	5.37	-9.99	-9.99	-9.99	-9.99
130.0	9.11	5.25	3.99	3.56	8.25	-9.99	-9.99	-9.99	-9.99
140.0	6.97	3.96	3.00	2.90	-9.99	-9.99	-9.99	-9.99	-9.99
150.0	5.73	3.19	2.41	2.65	-9.99	-9.99	-9.99	-9.99	-9.99
160.0	4.95	2.69	2.02	2.52	-9.99	-9.99	-9.99	-9.99	-9.99
170.0	4.43	2.35	1.74	2.28	-9.99	-9.99	-9.99	-9.99	-9.99
180.0	2-D FAILURE				-9.99	-9.99	-9.99	-9.99	-9.99
190.0	4.03	2.16	1.66	1.97	-9.99	-9.99	-9.99	-9.99	-9.99
200.0	4.22	2.32	1.79	1.92	-9.99	-9.99	-9.99	-9.99	-9.99
210.0	4.55	2.54	1.97	1.94	4.78	-9.99	-9.99	-9.99	-9.99
220.0	5.05	2.87	2.22	2.05	2.66	-9.99	-9.99	-9.99	-9.99
230.0	5.83	3.35	2.58	2.30	2.41	4.73	-9.99	-9.99	-9.99
240.0	7.06	4.09	3.15	2.75	2.64	2.97	10.63	-9.99	-9.99
250.0	9.18	5.36	4.13	3.56	3.29	3.25	3.70	20.16	-9.99
260.0	13.51	7.91	6.10	5.25	4.78	4.54	4.49	4.90	20.55
270.0	26.68	15.63	12.05	10.33	9.38	8.82	8.51	8.40	8.65
280.0	*******	*******	*******	*******	*******	*******	*******	*******	*******
290.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
300.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
310.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
320.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
330.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
340.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
350.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
360.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
10.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
20.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
30.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
40.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
50.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
60.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
70.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99
80.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	20.55
90.0	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	-9.99	23.47	8.65

-9.99 - FAILURE OF COMBINATION NOT KINEMATICALLY POSSIBLE
******* - FACTOR OF SAFETY OVER 1000.00
0.00 - LARGE BUOYANT FORCE CAUSES WEDGE TO "FLOAT"

Fig. 7 Factors of Safety for the Combination of a Floating Plane and a Fixed Plane (Fixed plane dip 70/100, Slope dip 45/180)

The 3-dimensional wedge analysis used in preparing Fig. 7 was based upon the "Comprehensive Wedge" solution (Hoek & Bray, 1977). A Fortran programme was written in which one plane can be fixed while the other is allowed to "float" in ten degree increments of dip and dip azimuth (Carney, 1983). To simplify presentation and to determine the most likely mode of failure (ie. the minimum Factor of Safety), Factor of Safety for combinations of joints can be contoured on a stereoplot (Fig. 8)

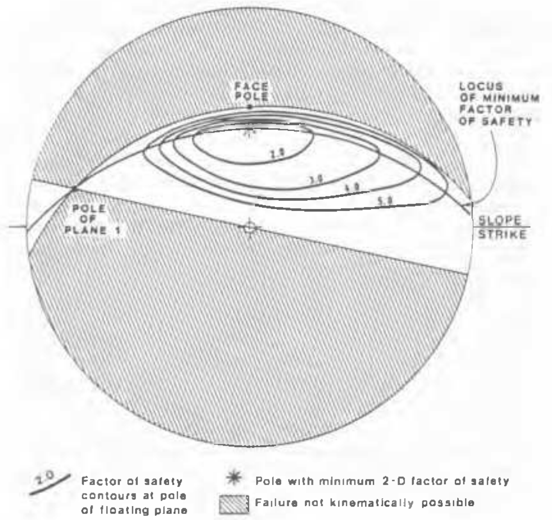

Fig. 8 Stereogram Showing Factor of Safety Contours for 3-D Wedge Combinations

In Fig. 8 the Factor of Safety contour values refer to the 3-D combination of the floating and the fixed planes. The geometry of the slope and other variables including shear strengths were fixed. The Factor of Safety contours (Fig. 8) are displayed at the location of the floating pole. The contours are somewhat elliptical in shape and lie within the unshaded segment in which failure is kinematically possible. the minimum Factor of Safety occurs as the floating plane approaches the 2-D configuration, with a dip which yields the minimum Factor of Safety in a 2-D analysis. The locus of minimum Factor of Safety for the various combination of the fixed and floating planes is the great circle passing through the poles of the fixed plane and the plane with the minimum Factor of Safety for 2-D analysis. The segment, containing poles of planes for which failure is kinematically possible, is bounded by: (a) the great circle through the fixed pole and the face pole, and (b) a straight line through the fixed pole and the centre of the stereoplot.

CONCLUSIONS

Plotting of poles of discontinuities on a equal area stereographic projection is the most versatile method of presenting geological structural information for design of jointed rock slopes.

The search net described in this paper, can be used with pole plots not only to determine which modes of failure are kinematically possible, but which discontinuities can combine to yield the minimum Factor of Safety for the slope.

By contouring of Factor of Safety of joint combinations on a stereoplot of poles, basic construction techniques emerge that can further simplify the design process.

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