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Assessment of the Stability of Jointed Rock Slopes.

By

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Assessment of the stability of jointed rock slopes

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ABSTRACT: Geological structure plays a dominant role in determining the stability of most rock slopes. The analysis of geological structure by means of stereographic projection is an established technique. Even with the advent of powerful computer graphics, stereographic projection still ranks among the most effective means of presenting and visualising complex combinations of geological structures. The paper reviews simple methods of stereographic projection for analysis of geological structure. The Search Net technique is presented. The Search Net is superimposed on stereographic projections of poles and used to determine likely modes of failure and worst stability conditions (i.e. the lowest Factor of Safety) for jointed rock slopes.

1 INTRODUCTION

Rock slopes, except those which exhibit low intact strength or particularly intense fracturing, tend to fail along discrete discontinuities such as bedding planes, joints and faults.

Most rock masses contain a number of sets of discontinuities. Each set can be 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. Stereographic projection is a powerful aid in the visualisation of complicated 3-D structure.

Analysis of rock slope stability is further complicated by the range of possible failure mechanisms that include sliding along discontinuities, rotation of blocks (e.g. toppling) and failure through intact material. Failure will often involve a combination of these mechanisms. The orientation of major joints plays a major part in determining the probable mode of failure. Basic modes of joint controlled failure are illustrated in Figure 1.

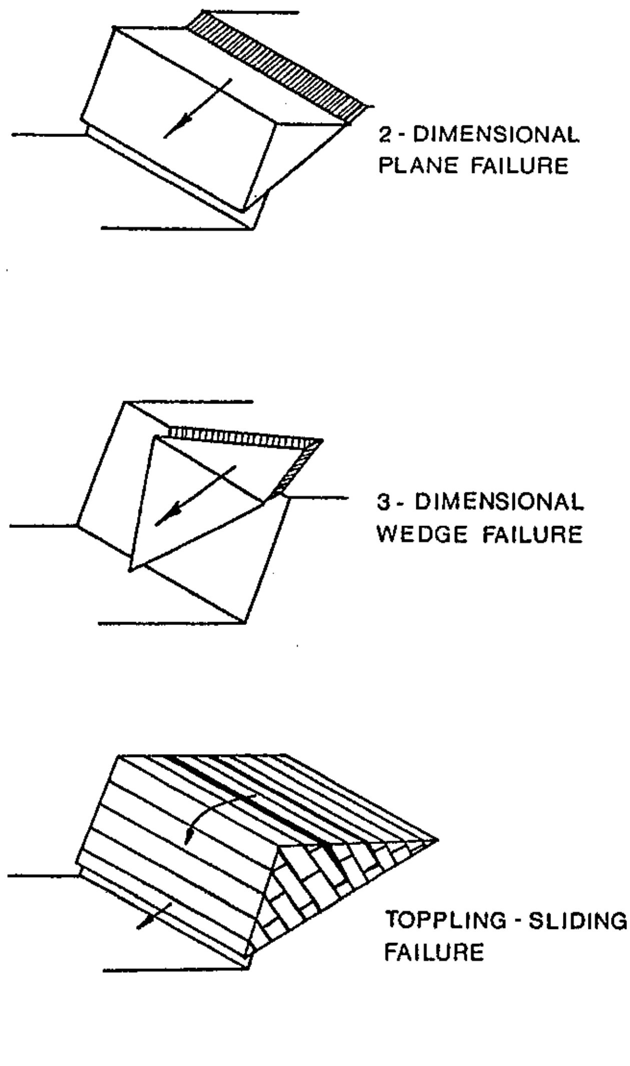

Fig. 1 Common modes of failure

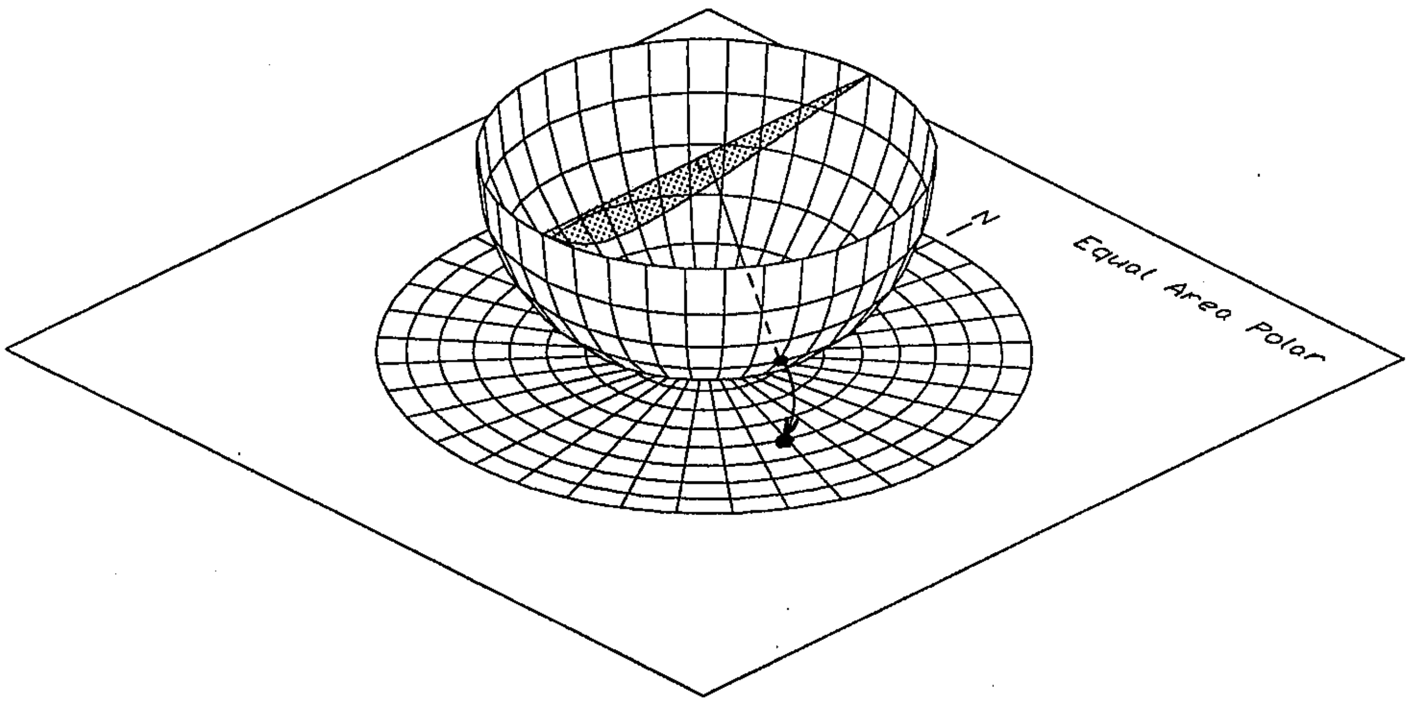

Fig. 2 Lower hemisphere equal area projection of plane dipping 50° azimuth 290°

2 STEREOGRAPHIC PROJECTION

Stereographic projection is a powerful aid in the visualisation of complicated 3-D structure. When studying the orientation of a large number of planar discontinuities, stereographic projection is still the most effective method.

When generating a stereogram, the planes are considered to lie at the centre of a hemisphere and their projections from the surface of that hemisphere are displayed on a circular plot or net (Figure 2). Projection from the lower hemisphere to the polar 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 can be rather confusing even to many seasoned practitioners.

Two types of stereographic projection are in common use:

1) The equal angle net is formed by direct projection from the hemisphere such that angular relationships are honoured.

2) The Schmidt or equal area net is generated such that area relationships on the hemisphere are approximated 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 Figure 3).

The traditional method of plotting stereograms manually involved a confusing and cumbersome process of rotating a piece of tracing paper overlaid on a stereonet. A faster method involves direct plotting on a blank form as illustrated in Figure 3. The dip direction (or azimuth) is read off a scale around the circumference of the net and the dip, from a radical scale about the centre. With the advent of PC and readily available and relatively inexpensive software, stereograms can be plotted even more rapidly and to a camera ready quality (Figure 4).

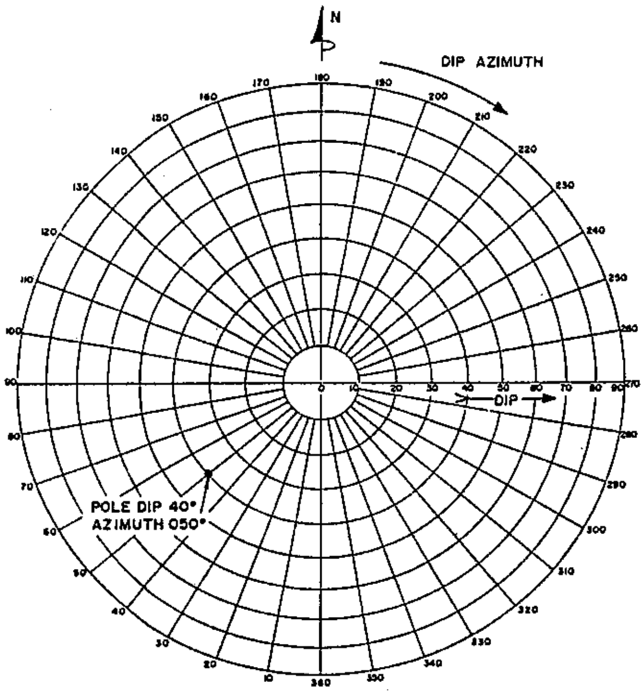

Fig. 3 Stereographic pole plotting form (polar, equal area, lower hemisphere)

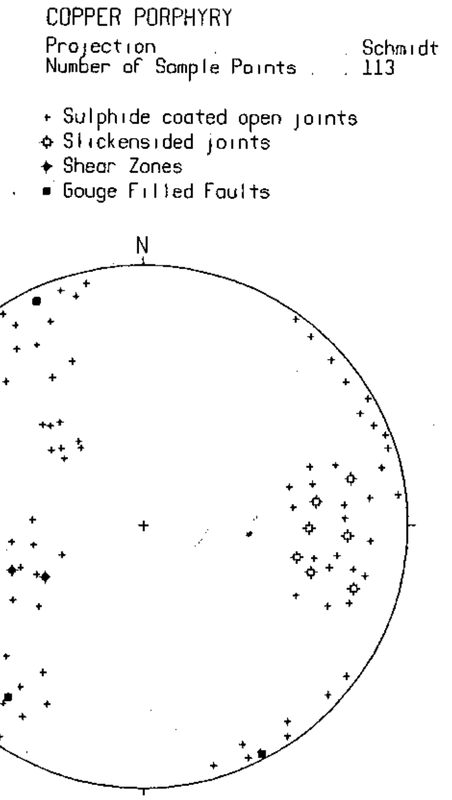

Fig. 4 Computer plotted stereogram of poles

Statistical study of the orientation of discontinuities is best carried out on an equal area net. The density distribution of poles is contoured to define sets or populations of discontinuities. Computer routines are readily available that smooth the contours. A Gaussian normal smoothing routine was used in preparing the contours in Figure 5.

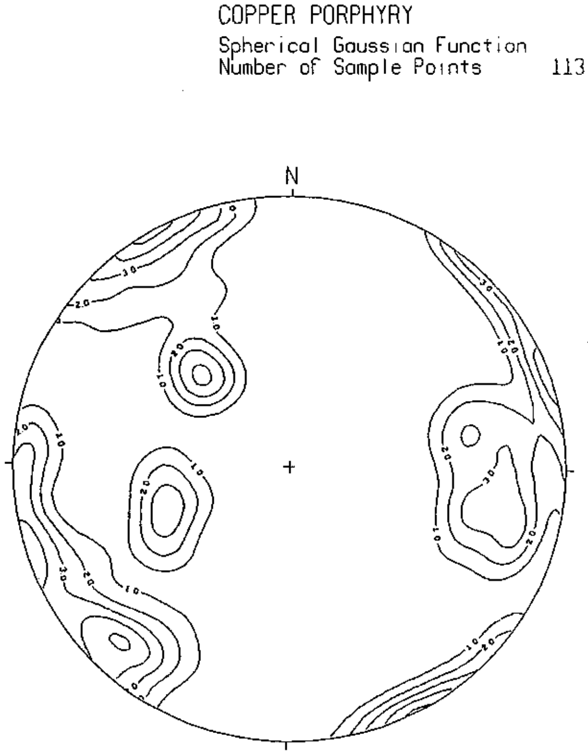

Fig. 5 Computer generated contours (Schmidt plot 113 poles)

In absence of a computer, manual contouring using a counting circle illustrated in Figure 6 is fast, simple and informative.

The counting circle has an area that is one percent of the total area of the projection. The one percent density contour (i.e. one percent of total poles lying in one percent of the area of the net) 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.

Planes can also be represented by their great circle traces. This is best carried out on an equal angle projection although the error in using an equal area net is not significant, for most practical purposes. Use of great circles 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.

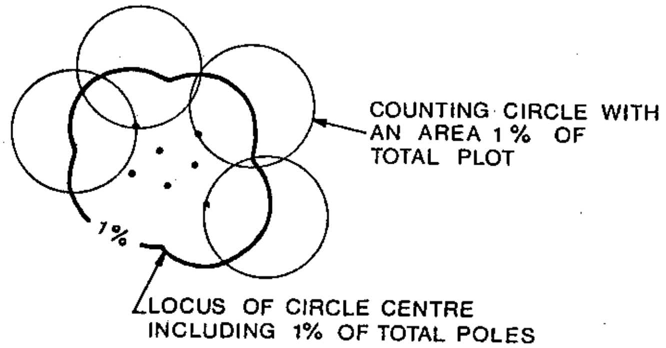

Fig. 6 Use of a counting circle for contouring of a stereonet (100 poles)

Figure 7 shows the great circles of the 113 poles in Figure 4 and is included to illustrate just how confusing great circle plots can be.

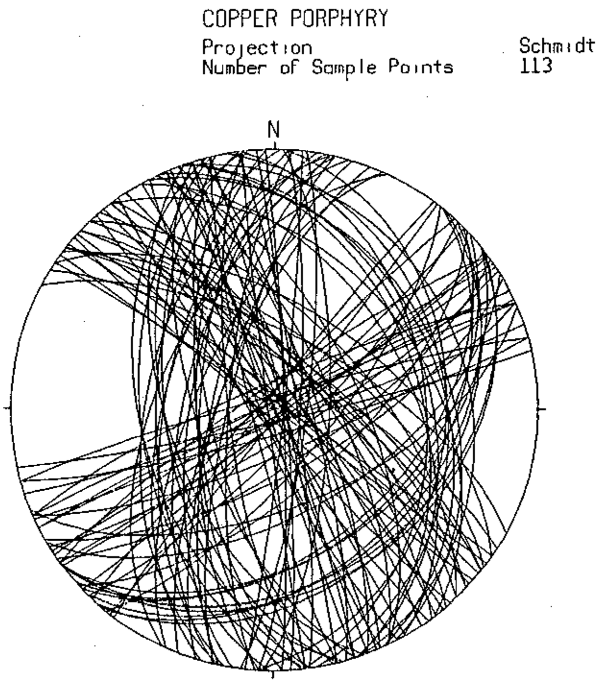

Fig. 7 Great circles of poles from Figure 4. (Schmidt plot 113 poles)

Because of the confusion that can result from use of great circles, equal area pole plots are used in the technique presented in this paper.

3 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 combinations 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 using the concept of the friction cone. As a first approximation, failure will occur when the planes daylight and the dip of the line of intersection exceeds the friction angle of the planes.

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.

The "Search Net" is an alternative technique for determining whether failure is kinematically possible.

4 THE SEARCH NET TECHNIQUE

The "Search Net" technique has been developed over a number of years by the author. The method enables the user to determine the likely mechanism(s) of failure and discontinuities most likely to lead to instability. The method involves use of an overlay, oriented with respect to the strike of the face, that is superimposed on a plot of joint poles. The analysis avoids the use of great circles. An example of a Search Net is shown in Figure 11 and its construction is illustrated in Figures 8 & 9.

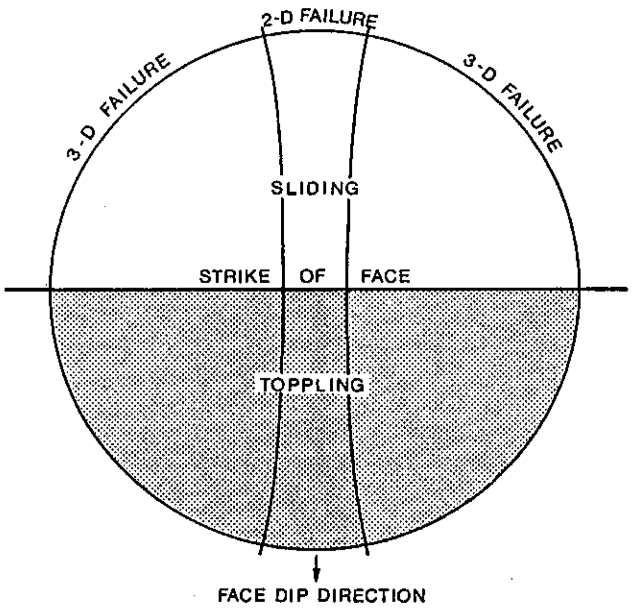

Fig. 8 Search Net, basic construction

In many design situations the trend or strike of the slope varies. For this reason, the search net is best drawn on an overlay so that it can be rotated to parallel the trend (or strike) of the slope. In Figs. 8, 9 & 11 the slope trend is drawn from left to right. The Search Net is divided into a number of zones which are labelled in Figure 11. Joints that have poles lying within a particular Zone are susceptible to failure in a particular way as follows:

4.1 *Discontinuities dipping into or out of the slope*

The Search Net is divided into two main semi-circular zones oriented about the slope trend. Any discontinuity with a pole falling within the unshaded portion of Figure 8 dips out of the slope and may cause failure by sliding. The shaded area includes discontinuities that form blocks that may topple if undercut or released by displacement at the toe of the slope.

4.2 *2-D and 3-D failure*

The search net is divided into 2-dimensional and 3-dimensional zones as illustrated in Figure 8. The 2-D zone is approximated by a band (formed by two small circles) lying arbitrarily within 10 degrees to the normal to the strike of the face. Any discontinuities with poles lying within the 2-D Zone tend to dominate the stability of the slope. This is because 2-D planes strike approximately parallel to the slope trend and are relatively unrestrained by end-effects.

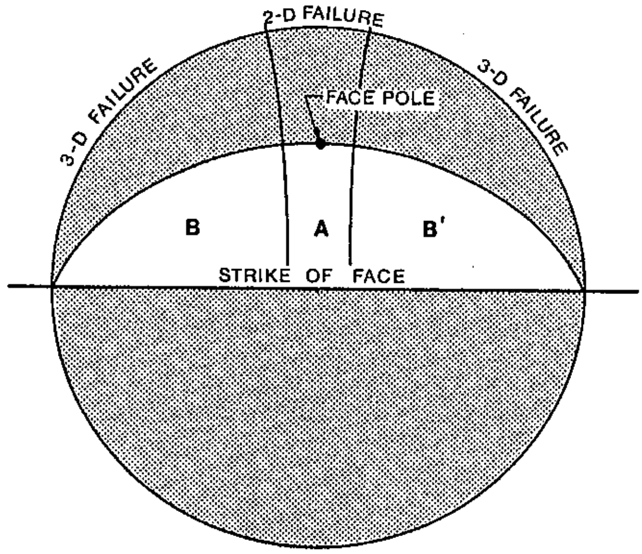

Fig. 9 Search Net, symmetrical "daylighting" planes

4.3 *Daylighting discontinuities*

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 Figure 9)

4.4 *2-D plane failure*

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. 2-dimensional failure is facilitated by the presence of bounding joints in Zone E and tension cracks formed from joints in Zones D, C or C'.

4.5 *3-D wedge failure*

Planes in Zones B and B' can combine to form approximately symmetrical 3-dimensional wedges with lines of intersection daylighting the slope. Tension cracks controlled by joints in Zones D, C or C' are often a feature of large scale 3-D wedge failures.

4.5 *Asymmetrical wedge failure*

Asymmetrical wedge failure is even more difficult to visualise than the symmetrical counterpart. Asymmetrical wedge failure may occur when planes in Zones B, E or C, and Zones B', E or C' combine (refer to the complete search net, Figure 11). 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 Figure 9 about the face pole as shown in Figure 10.

4.6 *Toppling failure*

It is self evident that toppling as a sole mechanism can 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).

Modelling work (Ashby 1971) suggested that the most critical dip angle for toppling failure probably occurs when the poles of discontinuities in Zone F fall on the great circle through the pole dipping at $(90°-\frac{\phi}{2})$, where ϕ is some function of the friction angles of the sliding and toppling discontinuities. Because of the complexities of toppling-sliding failure, the critical angle should be checked in each situation.

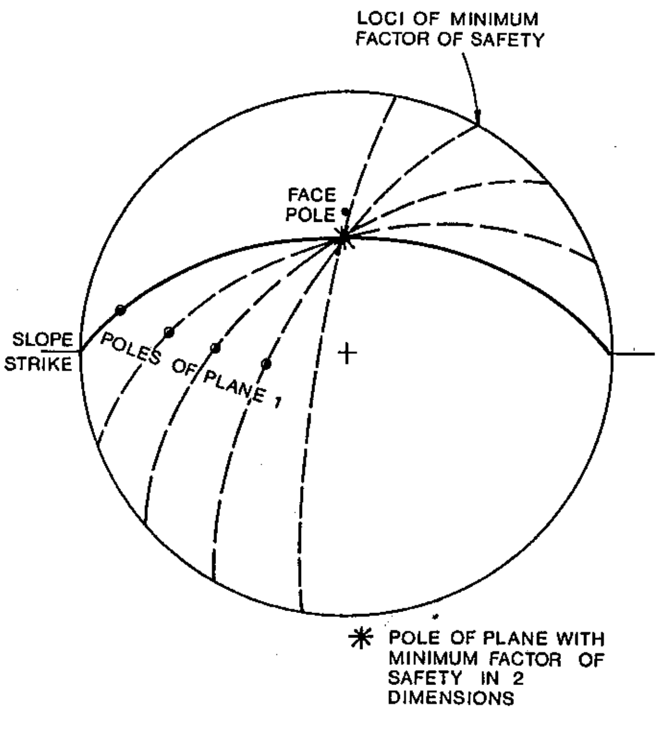

Fig. 10 Minimum Factor of Safety for asymmetrical wedge combinations

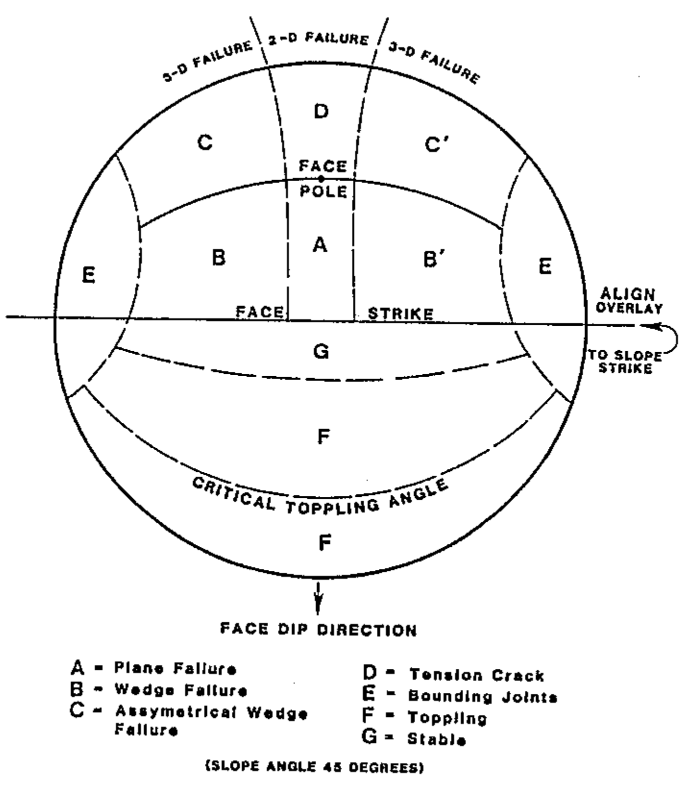

Fig. 11 The complete Search Net showing mode of failure "Zones" (slope angle 45°)

4.7 *Other joint orientations*

Joints lying in Zone G are sometimes involved at the toe of large scale sliding and toppling-sliding failures. These situations, in which movement occurs up-dip near the toe failure, are surprisingly common.

Bounding joints in Zones E and tension cracks in Zones D, C and C' are important planes of weakness that facilitate failure. In strong rock, where the probable failure mechanism is 2-dimensional, the presence or absence of these weaknesses may determine whether failure will occur or not.

A practical trial using the Search Net will clearly illustrate the ease of use and power of the technique in determining combinations of joints that may fail by a number of failure mechanisms.

5 FLOATING PLANE STABILITY ANALYSIS

Having determined the modes of failure that are kinematically possible, slope design requires comprehensive analysis of the various joint combinations. Various methods are available for stability analysis using either graphical or computer solutions (Hoek & Bray 1977). Traditionally, limiting equilibrium analysis has been used. 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 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. For each mechanism, the variables include the failure mode, the orientation, frequency, 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 and visualise. The crudest method of representing the results is a printout in the form of a two dimensional array of Factor of Safety for varying combinations of dip and dip azimuth (See Figure 12). The 3-dimensional wedge analysis used in preparing the Figure was based upon the "Comprehensive Wedge" solution (Hoek & Bray 1977). A Fortran program 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).

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	-9.99	-9.99	-9.99	-9.99	-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. 12 Factors of Safety for the combination of a floating plane and a fixed plane (fixed plane dip 70°/100°, Slope dip 45°/180°)

Presentation of the results using stereographic projection is recommended as an alternative to the rectangular plot of Figure 12. To simplify presentation and to determine the most likely mode of failure (i.e. the minimum Factor of Safety), Factor of Safety for combinations of joints can be contoured on a stereoplot (Figure 13).

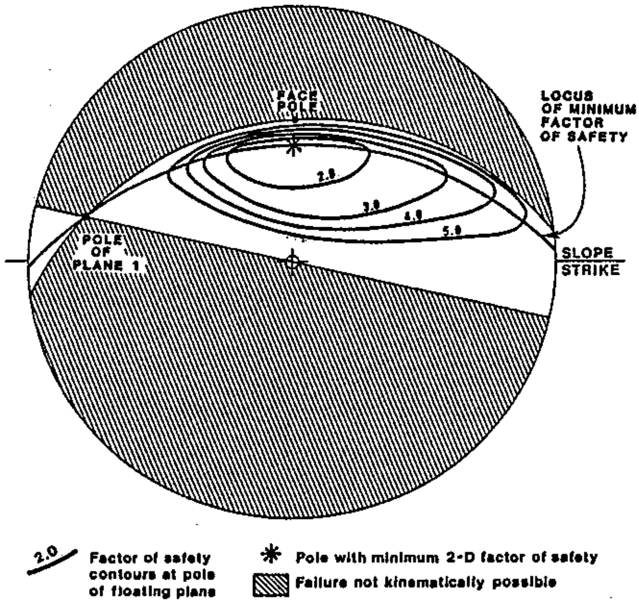

Fig. 13 Stereogram showing Factor of Safety contours for 3-D wedge combinations

The Factor of Safety contour values in Figure 13 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 (Figure 13) 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 that yields the minimum Factor of Safety in a 2-D analysis.

The locus of minimum Factor of Safety for the various combinations 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 (Figure 10). The segment, containing poles of planes for which failure is kinematically possible, is bounded by:

1) the great circle through the fixed pole and the face pole, and

2) a straight line through the fixed pole and the centre of the stereoplot.

7 CONCLUSIONS

Plotting of poles of discontinuities on an equal area stereographic projection is the most versatile method of presenting geological structural information for design of jointed rock slopes. Even with powerful computer graphics, the stereographic projection is still an invaluable tool for presenting and visualising complex structural combinations.

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 also 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, intuitive patterns and construction techniques emerge that can further simplify the design process.

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