HKIE Geotechnical Group paper
Publication only

Limitations of stereographic projections for rock slope stability analysis

S.R. Hencher, BSc, PhD, DIC, CEng, MIMM, MHKIE, FGS
Lecturer in Engineering Geology,
Department of Earth Sciences, Leeds University.

Introduction

The stereographic projection is a powerful tool for representing the orientation of discontinuities through rock in a simple, visual way and for allowing potential failure mechanisms to be recognised.

It is clear, however, that many geotechnical engineers, whilst understanding the mechanics of plotting, contouring and interpreting data, do not realise the limitations of the method and it is the purpose of this paper to highlight some of the most common misuses.

It should be noted that the terms 'joint' and 'discontinuity' have been used here essentially synonymously and interchangeably.

Background

Hoek & Bray's excellent textbook on Rock Slope Engineering has done much to encourage the use of stereographic projections in rock slope stability studies. It is very noticeable, however, that their recommendations regarding the use of stereographic projections became markedly more cautious from the first edition (1974) to the second edition (1977), particularly regarding the statistical collection and interpretation of data, and their reservations are highlighted by the following paragraphs (Hoek & Bray, 1977, pages 54, 55):

> "..... it will be clear that the collection and interpretation of structural geology data for the purposes of slope stability analysis cannot be treated as a routine statistical exercise. The rock mass knows nothing about statistics and there are many factors, in addition to the density of pole concentrations, which have to be taken into account in assessing the most likely failure mechanism in any given slope. An appreciation of the role of these other factors, which include the strength of the rock mass and the groundwater conditions in the slope, will assist the geologist in deciding on how much structural geology data is required in order that he may make a realistic decision on the slope failure mechanism." and

> "The authors feel that it is necessary to add their own words of caution in emphasising that a contoured pole diagram is a necessary but not a sufficient aid in slope stability studies. It must always be used in conjunction with intelligent field observations and a final decision on the method of analysis to be used on a particular slope must be based upon a balanced assessment of all the available facts."

Analysis of rock slopes using stereographic projection comprises two main, interrelated stages. Firstly, sufficient data must be collected to allow potential failure mechanisms within the rock mass to be identified, and secondly, the data must be analysed and interpreted in a sensible way.

Regarding the optimum number of joints to measure, Hoek & Bray (1977) emphasise the importance of experience but suggest that inexperienced persons might use Stauffer's methods (1966), although these methods are perhaps more suited to proving the validity of preferred orientations (statistical sets) than to assessing the overall nature of a rock mass. The distinction is important and illustrates one of the subtle misconceptions that can lead to misinterpretation of data as plotted stereographically. Stauffer's methods are directly applicable to problems in structural geology involving rock joints where only systematic joints are of interest (Price, 1966), but for rock slope stability, it is adverse joints that are important whether or not they are systematic. The blind use of Stauffer's methods for assessing the adequacy of data for rock slope stability analysis can lead to too great an emphasis on sets for the inexperienced person who might, as a result, disregard data that, whilst falling outside set concentrations, may be the most critical for stability.

The neglect of rare but critical points by the application of statistical contouring techniques is one of the most common errors in the use of stereographic projections for rock slope engineering and will be illustrated below together with some discussion of other limitations.

Typical procedures

Data collection

Data are often collected by measuring the dip and dip direction of all discontinuities intersecting a line drawn across an exposed rock face. Data may also be obtained from orientated rock core or by using downhole instruments such as the borehole periscope. A more subjective approach is for the orientation of selected discontinuities to be measured over a wide area of an exposed face. Methods for collecting data are discussed by Herget (1977) and Harris (1982).

Plotting data

Poles to the discontinuities are plotted as in Figure 1. This and following stages are clearly explained in many references including Richards *et al.* (1978), Hoek & Bray (1977) and Attewell & Farmer (1976).

Contouring data

In order to make the data more manageable, particularly

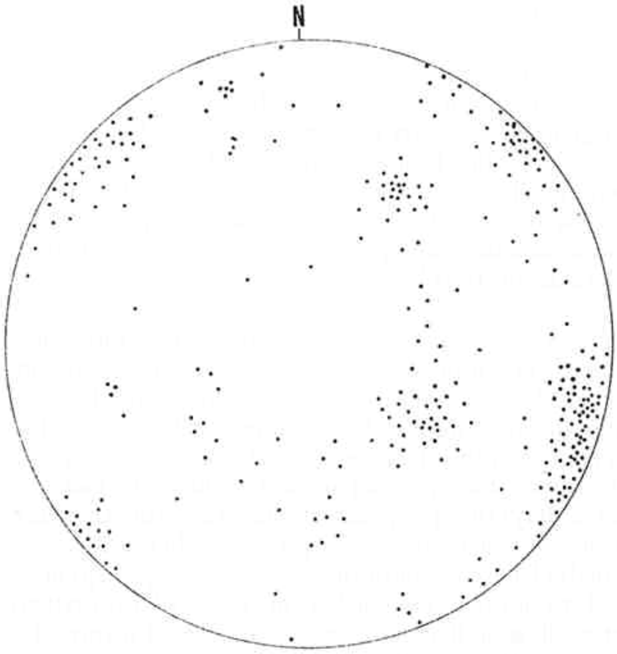

Fig. 1 Discontinuity data

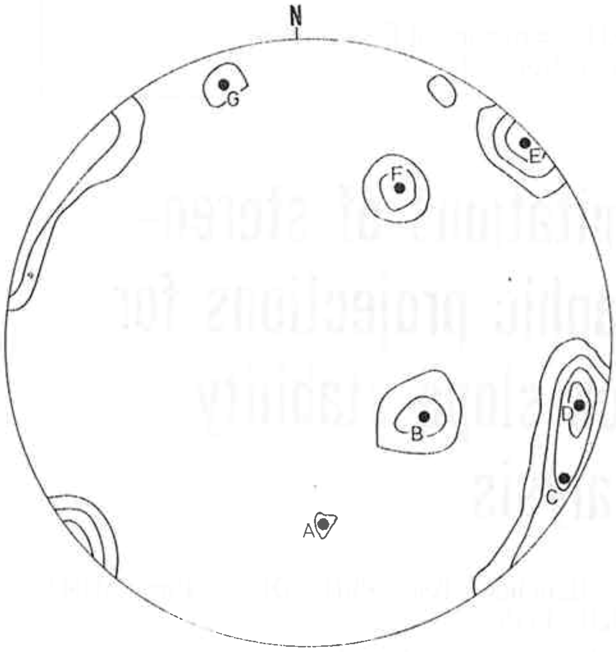

Fig. 2 Contoured data

for the construction of possible wedges formed by the intersection of joint sets, the data are contoured to reveal major pole concentrations as shown in Figure 2.

Stability check

Centres of pole concentration are transferred to a new diagram together with poles of lines of intersection (wedges) as in Figure 3. Then the 'day-light envelope' and 'friction circles' are drawn and the 'unstable zone for sliding' delineated. Finally a 'toppling zone' is constructed.

Interpretation

Figure 3 might be interpreted as indicating that, whilst instability along planes is unlikely (no pole concentrations fall inside the unstable zone), there may be a risk of sliding along intersections AC and AD, which daylight at angles steeper than the assumed friction angle of 30°.

It would be considered necessary to check for those unstable wedges in the field. Such unstable wedges could be designed against by cutting the slope at a shallower angle (making the daylight envelope smaller). Alternatively, preventive measures could be designed perhaps using buttresses or anchoring systems.

This interpretation, however, relies upon several unjustified simplifications and these will be discussed in the next section.

Discussion

Representativeness of data

The first thing that should be questioned is how well do the original, raw data represent jointing within the rock mass. If only poorly, then the results from the analysis must be treated with due caution.

Optimum sample size is, and should be, a subjective matter, the decision being made by an experienced person. Harris (1982) gives a useful discussion on this point. Statistical methods such as those of Stauffer (1966) can help but with the pitfalls outlined earlier.

Directionally biased sampling can be corrected for statistically (Terzhagi, 1965; Hudson & Priest, 1983) although the implicit assumption of systematic pattern is perhaps more applicable to probabilistic study of economic risk in a mine (Piteau, 1973; Priest & Brown, 1983) than to the safe design of a specific slope.

An important factor that is seldom considered adequately is the variation in orientation along a single discontinuity (see Piteau, 1973; Piteau & Martin, 1977). Each discontinuity is commonly measured at only one location and therefore represented by a single pole on a stereoplot. That pole will probably not represent the average orientation of the discontinuity if data have been collected from a line survey or drill hole. To illustrate this point, Figure 4 is a plot of poles, not of a well-defined joint set, but for a single, continuous discontinuity measured over an exposure of approximately 100 m^2 on a ½ metre grid system using a 110 mm diameter plate. It can be seen that the measured dip angle and orientation varied by ± 40 degrees over a ten metre length in any direction. When assessing data such as those given in Figure 1, it should be borne in mind that each pole might be subject to similar scatter to that in Figure 4 over a similar length, depending upon the type of discontinuity.

Generally, variation along a single discontinuity can only be guessed on the basis of limited exposure and should be recorded as recommended by the International Society for Rock Mechanics (1981). It is important, however, always to bear in mind that data, as plotted in Figure 1, are only poorly representative of the real situation in terms of orientation of joints.

Other factors not represented in Figure 1 include infill, persistence and ultimately, individual joint strengths. Such data should be available from the original investigation, and the assumptions made for interpretation earlier should have been justified. Some workers might attempt to distinguish between different types of discontinuity on a single plot using different symbols but this will inevitably be very

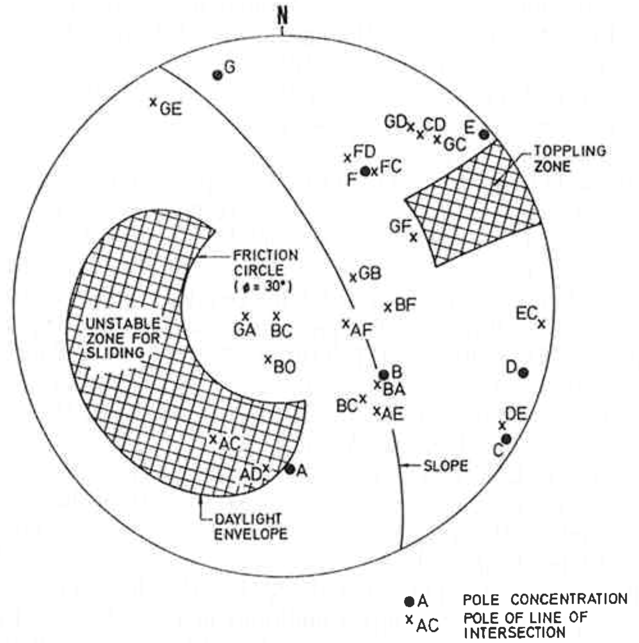

Fig. 3 Stability check

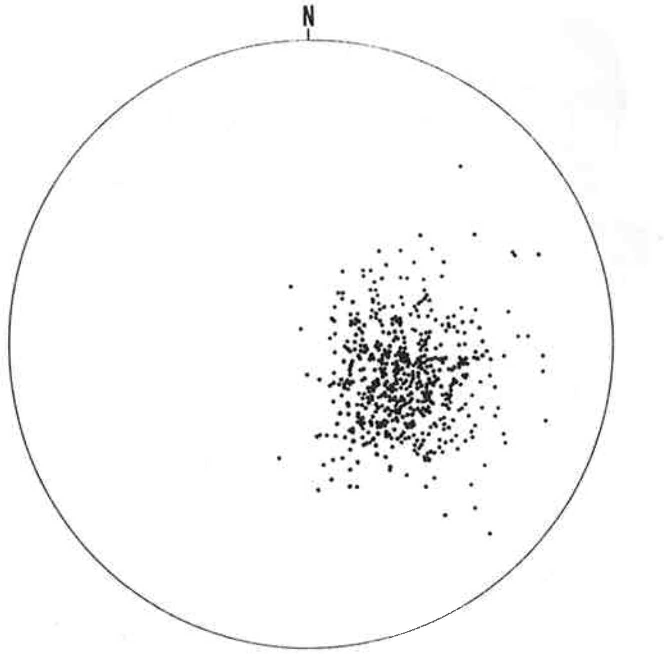

Fig. 4 Poles for a single joint using a 110 mm plate at 0.5 m centres

simplistic. The main role of stereographic projection in rock slope stability analysis should be recognised as one of making data more manageable and for the identification and clarification of possible problems. Each problem once identified should be considered individually using more rigorous techniques and taking account of all the relevant joint properties.

Interpretation of contoured data

The contouring shown in Figure 2 was carried out carefully using one of the techniques given in Hoek & Bray (1977), and the necessity of trying to simplify data in this manner for further analysis is clear. Problems arise however if statistically derived pole concentrations are used exclusively for all subsequent interpretations as in the example given earlier.

The interpretation of Figure 3 showed there to be an apparently minor problem with daylighting wedges associated with the concentrations A, D and C. Most pole concentrations, however, were interpreted as not adverse. Those conclusions were, however, based on several major and possibly unconservative assumptions as listed below:

- that the pole concentrations were representative of the scatter of discontinuities through the slope,
- that the friction angle of 30° was valid for all points,
- that groundwater would not effect stability.

Considering the latter two first, the validity of these assumptions should be questioned by reference to investigation data as discussed, in part, in the previous section.

The most serious oversimplification however concerns the representativeness of pole concentrations.

In Figure 5, the unstable zones for sliding and toppling from Figure 3 have been superimposed upon the plot of original discontinuity data. It is clear that, whereas none of the pole concentrations fall inside either zone in Figure 3, a significant number of the original poles do so. Similarly, many paired combinations might form wedges.

It is essential to remember that for rock slope stability analysis concerning sliding along joints, those data that fall within the unstable zones are much more important that even major sets that fall outside. Were one of those data points to represent a major, water-carrying fault, the orientation of which bears little relationship to the main groupings of discontinuities, it might prove very serious despite its unimportance statistically.

The rule must be: do not contour data unless absolutely necessary and when assessing the stability of the slope, reconsider the original data.

Conclusions

Stereographic projection is a powerful tool for the rock slope engineer. Use without consideration of the limitations can, however, lead to inaccurate conclusions. Where simplistic assumptions are made, the designer must remain aware of the limitations of his data. When using the technique, the following points should be remembered:

- Do not contour sparse data.
- Contouring may oversimplify a complex situation and result in critical data being overlooked.
- When analysing a slope using the centres of sets determined by contouring, always re-examine the original, uncontoured data.
- Consider carefully the implications and significance of each individual adverse data point and possible wedge intersection.
- Always critically appraise the results from the stereographic analysis by returning to the field.
- Only rarely, and with difficulty, can water pressures be taken into account in stereographic analysis.
- Generally only an approximated frictional component of shear strength can be allowed for and cohesion tends to be ignored.
- Remember that each joint is usually only represented on the plot by a single data point which will not fully characterise the waviness and general variation in attitude

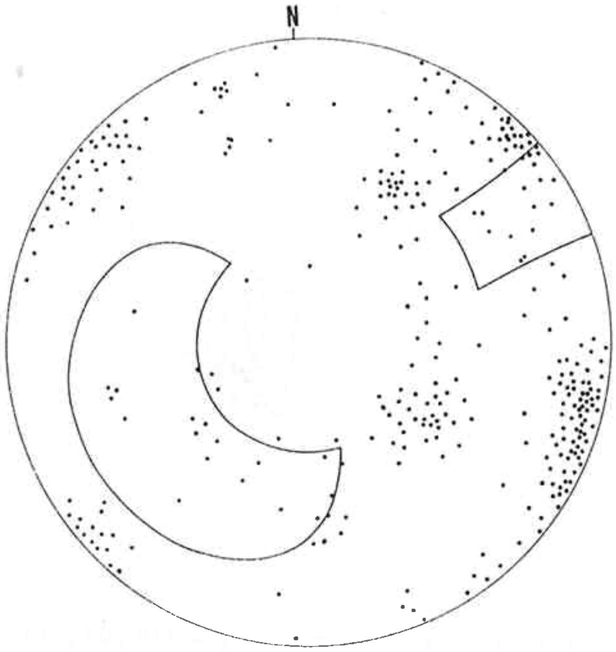

Fig. 5 Unstable zone and original data

of that joint.

- When assessing stability always reconsider the degree to which the data can be taken as representative.
- Once discontinuities with the potential for causing instability have been identified then full account should be taken of such properties as roughness, infill, persistence and water pressures in carrying out a detailed analysis.

Appendix I summarises many of the major uses, limitations and misuses of the technique together with some hints for good practice.

Acknowledgements

This technical note is based on an internal report prepared within the Geotechnical Control Office and is published with permission of the Director of Engineering Development, Hong Kong Government.

References

Attewell, P.B. & Farmer, I.W. (1976). 'Principles of Engineering Geology.' Chapman and Hall, London, 1045p.

Harris, R. (1982). 'Stereographic projections for the engineering of rock.' *Hong Kong Engineer*, vol. 10 and no. 8, pp. 37-48.

Herget, G. (1977). 'Pitslope Manual Chapter 2 – Structural Geology.' CANMET (Canada Centre for Mineral and Energy Technology, formerly Mines Branch, Energy, Mines and Resources Canada), CANMET REPORT 77-41; 123p.

Hoek, E. & Bray, J.W. (1974). 'Rock Slope Engineering.' First Edition. Institute of Mining and Metallurgy, London, 309p.

Hoek, E. & Bray, J.W. (1977). 'Rock Slope Engineering.' Revised Second Edition, Institute of Mining and Metallurgy, London, 402p.

Hudson, J.A. & Priest, S.D. (1983). 'Discontinuity frequency in rock masses.' International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts, vol. 20, pp. 73-89.

International Society for Rock Mechanics. (1978). 'Suggested methods for the quantitative description of discontinuities in rock masses.' International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts, Vol. 15, pp. 319-368.

Piteau, D.R. (1973). 'Characterizing and extrapolating rock joint properties in engineering practice.' Rock Mechanics, Supplement 2, pp. 5-31.

Piteau, D.R. & Martin, D.C. (1977). 'Slope stability analysis and design based on probability techniques at Cassiar Mine.' The Canadian Mining and Metallurgical Journal, March, pp. 1-12.

Price, N.J. (1966). 'Fault and Joint Development in Brittle and Semi-Brittle Rock.' Pergamon Press, London 176p.

Priest, S.D. & Brown, E.T. (1983). 'Probabilistic stability analysis of variable rock slopes.' Transactions of the Institution of Mining and Metallurgy (Section A : Mining industry), Vol. 92, pp. A1-A12.

Richards, L.R. & Cowland, J.W. (1982). 'The effect of surface roughness on the field shear strength of sheeting joints in Hong Kong granite.' *Hong Kong Engineer*, Vol. 10, no. 10, pp. 39-43.

Richards, L.R., Leg, G.M.M. & Whittle, R.A. (1978). 'Appraisal of Stability Conditions in Rock Slopes.' In Foundation Engineering in Difficult Ground, ed. Bell, F.G., Newnes – Butterworths, London, 589p.

Sekula, J. (1982). 'Stereographic projections for the engineering of rock.' Letter to Editor, *Hong Kong Engineer*, Vol. 10, No. 11, p. 59.

Stauffer, N.R. (1966). 'An empirical-statistical study of three-dimensional fabric diagrams as used in structure analysis.' Canadian Journal of Earth Sciences, Vol. 3, pp. 473-498.

Terzhagi, R.D. (1965). 'Sources of error in joint surveys.' Geotechnique, Vol. 15, pp. 287-304.

Appendix I Use and misuse of stereographic projections

Uses for rock slope stability

- representing the orientations of discontinuities visually
- recognition of patterns in discontinuity orientation
- simplification of complex situations by contouring
- measuring angular relationships between discontinuities
- demonstrating relationships between discontinuities and slope face geometry thereby showing which individual discontinuities or wedges daylight and therefore might cause failure
- comparing inclinations of potential failure planes and wedge intersections with trial friction angles
- to demonstrate the degree of roughness of a single discontinuity (see Richards & Cowland, 1982)
- can be used directly for analysis providing shear strength parameters c & $\emptyset$ and water forces U & V are known (see Attewell & Farmer, 1976)

Limitations

- spatial relationships not shown (e.g. two joints apparently forming wedge on the stereoplot may be separated in the slope)
- nature of individual joints not represented
- discontinuities plotted as single poles
- cohesional component of strength not readily taken into account

- effects of water not readily taken into account (see discussion by Sekula, 1982)

Common misuses

- used directly for analysis in an oversimplistic manner rather than as tool to aid understanding
- contouring to show centres of joint sets can overshadow more important, adverse joints
- contouring of too few joints

Hints

- identify joints in the field individually by painted number so that findings of the analysis can be checked
- only contour data where absolutely necessary or to get a better understanding of the problem; do not contour a limited amount of data
- always check the nature of any 'adverse' joints removed by contouring
- once adverse joints have been identified, then analyse potential failures individually, using limit equilibrium methods to take full account of strength, water pressures, and other characteristics of specific joints of interest
- critically assess the representativeness of your data

Author

Steve Hencher joined the Geotechnical Control Office in Hong Kong in January, 1980 following several years' experience working for consulting engineers W.S. Atkins and Partners whom he joined after completing his research at Imperial College, London. In Hong Kong he was mainly concerned with landslide studies and with the description and characterisation of weathered rocks as well as continuing his interests in the shear strength of rock joints.

He left Hong Kong in September, 1984 to take up the post of Lecturer in Engineering Geology at Leeds University where most of his time is spent lecturing to MSc students. He is hoping to take on several research students shortly to study the development of discontinuities due to weathering and the shear strength of heterogeneous mixtures of soil and rock.