Geological contributions to engineering investigation of rock mass

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SUMMARY

Rock masses comprise densely packed blocks bounded by joints and other discontinuous geological structures. The strength of a rock mass is controlled by the geometry of the blocks and by the frictional properties of the block surfaces. Empirical engineering methods combine structural geology features into design parameters. There are numerous aspects where geological information and methodology can contribute to advancing engineering investigations of rock mass. Three of these aspects are 1) explicit analysis of the anisotropy of fracture systems, 2) structural analysis of anastomose fracture patterns and 3) application of hydrothermal alteration studies to engineering assessment of joint coatings. Investigations of rock mass anisotropy can be enhanced by recording the orientation of fractures relative to a system of reference axes. Anastomose patterns of fractures can be detected in borehole data by recording the relationship between spacing and dihedral angle of adjacent fractures. The systematic definition of mineral assemblages in hydrothermal alteration studies forms a useful framework for characterising the mechanical properties of joint surfaces.

Key words: rock mass, joints, fractures, shear strength

INTRODUCTION

Engineering solutions to geotechnical problems often apply a one-parameter solution and consequently also require data to be reduced to a single parameter. For example, reinforcement of rock during excavation may be quantified as the density of the rock bolting pattern, hence the aim is to characterize rock masses in terms of their required rock bolt pattern density. Vast engineering experience is synthesized in an array of empirical methods which have converged on two main approaches, the RMR (Bieniawski, 1989) and Q (Barton and Grimstad, 1994) methods.

Geology can provide avenues for further improvement and generalization of these methods. However, geologists must understand that the engineer does not necessarily seek to 'understand' the rock mass and all its complexity. Rather, the aim is to reduce the complexity to provide simple, reliable design rules. In this paper I identify three aspects of rock mass geology which have not been thoroughly developed in previous work. Each of these aspects will be introduced and the potential for improvement to engineering assessment of rock mass is discussed.

The empirical methodology employed by engineers quickly converges on approaches which consistently provide results which are generally correct but err on the conservative side. Empiricism does not always promote innovation except where spectacular failures occur. Since the aim is to establish accepted standard practices, change is implemented cautiously. I content that good engineering practice will benefit from a concerted scientific enquiry into rock mass. However, there is no expectation that engineering practice will change immediately in response to innovation. When empirical methods fail, as they do periodically, engineers need to turn to scientific principles to seek improvements.

Three aspects of rock mass geology which are relatively weakly applied in current engineering approaches to rock mass characterization follow.

- Reducing the orientation of discontinuities, in particular the anisotropy of fracture patterns and the implications for rock mass strength, to systematic parameters.
- Recognition of the anastomose nature of many fracture systems.
- Directly utilizing the available knowledge of hydrothermal alteration assemblages and related mineral coatings in the interpretation of frictional properties of discontinuities.

ANISOTROPY OF FRACTURE SYSTEMS

Engineering approaches to rock mass typically attempt to identify the 'critical' structural orientation for a given situation during a specific analysis. In the RMR system (Bieniawski, 1989), points are awarded on whether the critical structures are favourably or unfavourably oriented according to a detailed scoring scheme. Alternatively (e.g. Hoek and Brown, 1980), the fracture pattern is assumed to be isotropic on the basis that at large scale and for large numbers of fracture sets isotropic behaviour is approached.

However, the importance of deterministic analyses, such as analysis of sliding surfaces, in rock engineering makes it clear that, even at larger scales of investigation, the distribution of fracture orientations will be significant. Most analysis of orientations are conducted on an *ad hoc* basis by assessing the kinematic feasibility of sliding along the defined mean orientations of discontinuity sets.

A brief consideration of the potential 3D influence of simple fracture patterns on the mechanical properties of a rock mass soon demonstrates why this aspect has received limited attention. Even for a fracture pattern which is symmetrical, it does not follow that the strength anisotropy is simple. Take, for example, the relatively simple case of three evenly spaced orthogonal joint sets. Existing engineering models focus on the three axes of symmetry perpendicular to each set and conclude that the properties (strength & deformation modulus) will be isotropic or, at worst, orthotropic (Kulhawy and Goodman, 1987). However, following basic crystallography of the cubic system, there are also four axes (of 3-fold rotation) which are oblique to all joint sets. Since sliding on joints due to high shear stress, is one of the most common deformation mechanisms for a rock mass, these four axes will be the locus of low strength values. The resulting anisotropy involves a complex pattern of four low strength directions and three high strength directions.

Smith (2004a) introduced a method ('Stereoscan') intended to provide a systematic analysis of structural orientations. In this system the orientation of discontinuities is defined relative to 33 reference axes. The 33 reference axes were selected to have an average angular difference between axes of approximately 30°. This angle is considered significant as planes at approximately 30 ° to an applied force are most likely to shear. Therefore, the method can rapidly summarize the relative abundance of structures with orientations most susceptible to sliding under any applied loading. The axes also conform to a simple symmetrical geographical coordinate system.

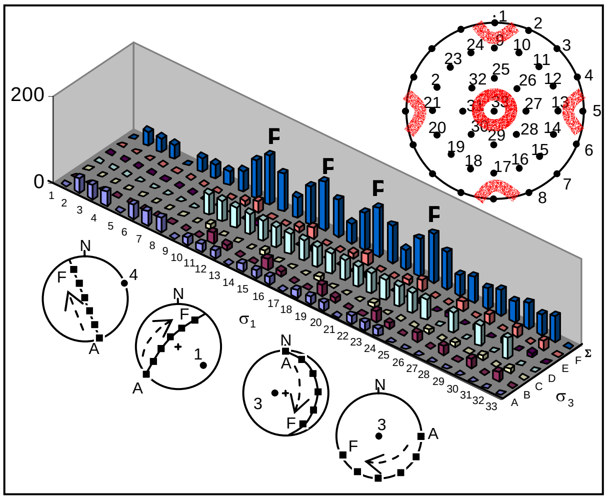

Figure 1. An oblique 3-D column graph showing approximate abundance of discontinuities oriented at 30° (±15°) to the maximum compressive principal stress (σ_1) and 30° (±15°) to the minimum compressive principal stress (σ_3). Columns show values for pairs of $\sigma_1 - \sigma_3$ axes with the sum (Σ) for all σ_3 axes shown at the rear (peaks marked P). The data is representative of three orthogonal discontinuity orientations as shown in the stereogram (red). The stereogram also shows the 33 primary reference axes (σ_1). Stereograms at lower left show examples of orientations of six secondary reference axes (squares labelled A-F) (σ_3) for each primary reference axis.

The example of three orthogonal joint sets, discussed above, can be investigated using the 'Stereoscan' method (Smith, 2004a). Figure 1 shows the 33 reference axes on a stereogram with concentrations of poles of three orthogonal discontinuity sets shown in red. The tall columns at the rear of the 3D graph show the abundance of discontinuities oriented 30° (±15°) to each of the 33 reference axes. The four peaks (P) are the directions of the four directions which trisect the three discontinuity sets. The remainder of the graph and the stereograms in the lower left of Figure 1 record the orientation of discontinuities relative to pairs of axes. This more detailed information can be used where properties in the $\sigma_1 - \sigma_3$ plane are being investigated.

As Figure 1 shows, even simple symmetrical fracture patterns can result in highly complex distributions of strength anisotropy. Orthotropic models of anisotropy can only be expected to provide the most general correlation with observation.

ANASTOMOSE FRACTURE SYSTEMS

It is generally accepted that many brittle geological structures, especially those formed by faulting. have an anastomose or braided pattern (e.g. Smith, 1993). Surprisingly, a systematic description of the anastomose geometry has not yet been presented in the structural geology literature. The shape of blocks within an anastomose pattern (e.g. Fig. 2) is distinctive, with 'pinched' ends where the surrounding surfaces meet. A thorough geometric analysis of these blocks or 'horses' would define the asymmetry of their shape and determine the range of lengths and widths. There is potential for an isogonal classification of block shape analogous to the fold class system of Ramsay and Huber (1987) or sigmoidal en echelon veins (Smith, 1999).

Figure 2. Rock fragment from an anastomose fracture system controlled by foliation overprinting (scale marks are cm) (Chariot gold mine, NT, sample courtesy of Joel Anders).

It is not intended to present a systematic treatment of block shape here, but rather to introduce some features of fracture data which may reveal the presence of anastomose structures. Smith (1994b) proposed that by measuring the distance and dihedral angle between adjacent fractures in core, information about the block sizes and shapes can be inferred. It was shown to be hypothetically possible to differentiate between anastomose and planar fracture systems. The difference being evident in changes of dihedral angle relative to fracture spacing. For planar systems, dihedral angles will be constant with some random noise. In contrast, an anastomose system should show small dihedral angles at small intervals and the highest dihedral angles should correspond with intermediate intervals. Dihedral angles should decrease as spacing reaches a maximum.

Data on the distance and dihedral angle between adjacent fractures (n=135) was collected from a core in metamorphosed turbidite rocks from central NSW, Australia

(Fig. 3). The smoothed data indicates the general pattern expected for anastomose fractures. The dihedral angle reaches a peak of 34^{o} at a spacing of approximately 50cm. If the surfaces approximate a sine wave, the maximum dihedral angle is located at the inflection at one-quarter wavelength. For sine wave geometry, the average width of blocks would be twice the fracture spacing, i.e.1m. Sine wave geometry would also indicate a length-width aspect ratio of 5, i.e. a block length of 5m (Fig. 4). A detailed investigation of anastomose structures may find that models other than the sine wave provide a better description of the block shape

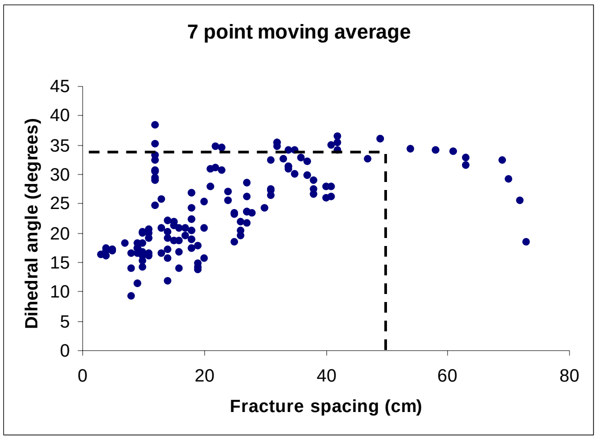

Figure 3. Graph showing smoothed data of dihedral angle versus interval length of fractures in core (Tritton mine, NSW) revealing an anastomose pattern in the fracture system.

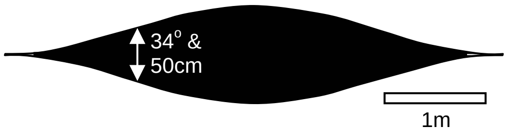

Figure 4. Dimensions of the average block inferred from Figure 3 based on a symmetric sine wave model.

If the wavelength and amplitude (i.e. block length and width) of an anastomose fault system can be accurately assessed from drill core there are many benefits to geological and geotechnical interpretation. First, the location of structures can be better modelled, for example, the validity of correlations of individual structures between borehole intersections can be assessed. If the borehole spacing exceeds the inferred block lengths then correlation should not be attempted. Second, the range of orientations of structures can be better modelled. For example, waviness of discontinuities is a major control on stability against sliding.

HYDROTHERMAL ALTERATION OF FRACTURE SYSTEMS

Engineering descriptions typically classify joint surfaces and coatings into simple groups with associated rankings. Clays and talc typically form the most problematic group and phyllosilicates such as chlorite and mica the next. Surface hardness is accepted as a general indicator of strength. For example, field estimates of strength (Hoek and Brown, 1997) include 'extremely weak' (indented by thumbnail) and 'very weak' (…can be peeled by a pocket knife.) to 'medium strong' (cannot be scraped or peeled with a pocket knife…). Surface characteristics of rocks are incorporated into rock mass studies in a number of ways. Firstly, most rock mass assessment systems directly record the nature of surface coatings and provide a numerical rating. Secondly, the JCS (joint compressive strength) is used as an input for the Barton and Bandis (1990) joint friction model.

As Hoek et al. (2000) point out, mining geotechnics is almost always confronted by rock which has undergone hydrothermal alteration. Hydrothermal alteration has been studied extensively for metallogenic purposes and systematic assemblages have been established (e.g. Corbett and Leach, 1998). Such studies normally emphasize the hydrothermal alteration effects that can be seen to permeate the rock. The fracture surfaces will host alteration effects which may differ from the local whole rock alteration state. Nevertheless, hydrothermal alteration tends to follow a common sequence of mineral reactions even for a wide range of original rock types (Reed, 1997).

One of the few geotechnical investigations which includes reference to specific hydrothermal alteration assemblages is Hoek et al. (2000). That work included a very brief discussion of a small data set (n=16) from Chuquicamata mine in Chile, indicating that alteration type systematically affected intact rock strength.

Ersoy and Waller (1995) found that an overall Moh's hardness, derived from weighted averages of component mineral hardness, correlated well with absolute hardness measures. Clearly, this is only a crude indication of the mechanical properties of the alteration assemblage. The proportions of minerals will vary and the influence of grainsize is unknown. Corbett and Leach (1998) define 59 specific mineral assemblages within seven common alteration assemblages. In their scheme the assemblages are organized according to the temperature and pH of the fluid. Figure 5 shows the overall hardness estimated for the alteration mineral assemblages.

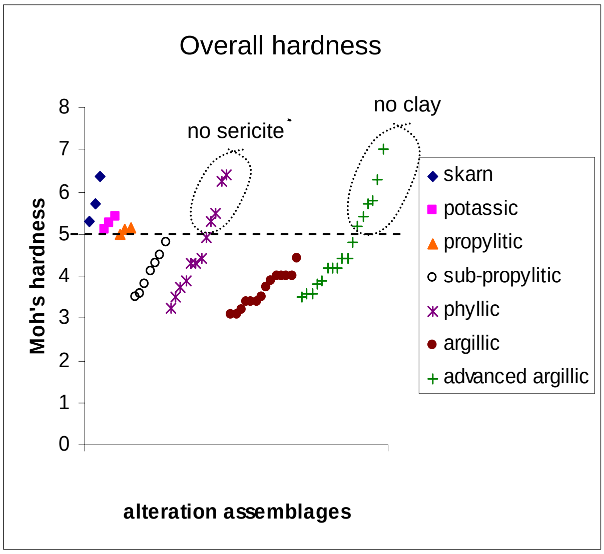

Figure 5. Overall Moh's hardness values for 59 mineral assemblages within seven alteration assemblages as defined by Corbett and Leach (1998).

The assemblages appear to form two main groups above and below a hardness of 5 (Fig. 5). Above hardness 5 are the skarn, potassic and propylitic assemblages. High temperature phyllic assemblages which lack sericite and low pH advanced argillic assemblages which are leached of clay also have overall hardness above 5. Below hardness 5 are the sub-propylitic, phyllic (where sericite is present), argillic and advanced argillic (where clays are present) assemblages.

Currently, there are no models to define the relationship between mineral alteration, hardness and frictional properties of fracture surfaces. Oguchi (2001) conducted a detailed study of the hardness of weathering rinds that may provide a suitable model. The advantage of developing a better understanding of the mechanical behaviour of alteration mineral assemblages in rock and as surface coatings, is that the raw data is routinely collected by geologists and could potentially provide a wealth of geotechnical information. Potentially, the distribution of inter-block friction could be interpreted from a small number of measurements combined with a detailed hydrothermal alteration model.

CONCLUSIONS

Rock mass properties should be an important focus of structural geology research. Advances in understanding rock mass can be readily applied to a wide range of engineering problems. Empirical methods have evolved from experience but without much regard to underlying fundamental structural geological principles. The three aspects highlighted in this paper, anisotropy, anastomose patterns and hydrothermal alteration, represent areas in which further improvements to rock mass analysis can be made.

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