An Expert System to perform:
Discontinuity Analysis and Prediction in Singularly Deformed Areas

Colin N Winsor
Mineral Resources, School of Engineering,
University of South Australia
The Levels, SA, 5109

Rock discontinuities, including bedding surfaces, cleavage, joints and faults, are low tensile strength defects across which displacement can occur. They are described without genetic connotation and impart rock mass anisotropy, which controls strength. Systematic discontinuity analysis is ideally undertaken during rock excavation design, to quantitatively determine their characteristics. Rock mechanics engineers have developed sampling and data processing techniques and classification schemes that yield quantitative assessment, although these techniques provide unbiased results they are often spatially restricted and commonly do not assess the macro (large) scale. A methodology is developed here involving regional structural geology analysis and interpretation to enable rock discontinuity characteristics predictions and link determination of regional structure to tools to scan rock masses and determine discontinuity properties, providing benefits of improved efficiency, safety and lowering cost. Predictions are verified from field examples and the design of a knowledge based system incorporating crisp and fuzzy logic is proposed enabling geologists and engineers to determine discontinuity characteristics ahead of geotechnical operations.

Key Words
Structural geology, rock engineering, knowledge system, predictions

Introduction

Discontinuity analysis should be undertaken during rock excavations manually (using a method such as that described by Priest 1993a,b) or semiautomatically, to determine in a quantitative manner the defect characteristics. However, this is often not always possible due to budget constraints or poor exposure. Rock mechanics engineers have developed sampling, data processing techniques and classification schemes that can yield quantitative data, which although providing unbiased data, can be of little value unless linked to a larger scale assessment. Current systems enable the macrostructure to be determined and can perform geological data analysis, but lack the capacity to make rock mass predictions by incorporating regional and local geology assessment.

Rock mass analysis is performed by professionals with different objectives:

i) Rock mechanics engineers conduct site surveys, using a rational sampling system determine properties, the present state and stability, develop mass behaviour models and apply engineering principles to analysis and design. A scanline (or area) method operates in an objective sampling regime, without requiring highly trained professionals to produce quantitative results (as outlined by Priest 1993a,b), however it is time consuming, unable to predict beyond the sampled zone, ignores the large scale and individual defect contribution. To implement a survey a tape is extended along a rock exposure and data collected including: distance, discontinuity orientation and length etc (Figure 1), for input into computer programs (eg. Meyers et. al 1993a,b), which perform cluster analysis combining and distinguishing sets, determine mean set size and ideal distribution. Recent automated, terrestrial photogrammetric systems (as revealed by Speight et. al 1997), can quickly survey rock faces, but currently lack a capacity to look into the rock mass, determine the control on discontinuities and make forward predictions.

ii Structural geologists are primarily concerned with the intermediate to large scale rock structure, time and development nature. Rock structure data is collected along with information indicating type, timing and modification processes. Through such investigations

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the spatial and sequential relationships between elements are defined, discontinuities classified, origins inferred and fabrics extrapolated (Mashak & Mitra 1988).

Extrapolation and interpolation of discontinuity data

Discontinuity extrapolation is of fundamental concern to mining engineers, but as Figure 1 illustrates the geology at an exposed rock face may be quite different from that within the rock mass. The affect of large scale folding or faulting is clear as the properties measured at the rock face may not reflect those in the mass. Generally the discontinuous and variable rock mass nature inhibit realistic predictions (Brady & Brown 1985) and despite predictions being attempted by geologists, the benefits of regional structural geological assessment is not generally recognised by engineers, whose approach is to apply geostatistics, this is despite the method generally assuming a random distribution. Although there has been debate concerning the merits and problems in using statistics to analyse discontinuities, distributions are not commonly random (Barton & Stephenson 1990 & Villaescusa & Brown 1982), however can appear so in highly foliated rocks (Rives et. al 1982). Statistical methods of analysing geotechnical data are not favoured in providing a realistic model to enable extrapolation, as they generally assume homogeneity or stationarity, implying that local anomalies cannot be realistically predicted.

Geologists have developed interpretative tools to extrapolate and determine the relationship between structural fabrics/elements. Generally limitations exist on the availability of rock mass data (Hocke, Kaiser, Bawden 1995) and the length of time required to collect data. As pointed out by Vaughan (1995) "Better analysis offers better prediction and better understanding. Both are only possible when reality is modelled". However, there are often natural situations involving multiple folding and/or faulting which may be too complex to model, and the available knowledge is of qualitative rather than quantitative character. In this case fuzzy logic (Terano et. al, 1994, Zimmermann 1991) which is defined by a membership function and uses the principle that everything is a matter of degree, applying rather than a yes/no approach, a multivariate methodology. Although fuzziness is identified to be widespread throughout all areas of human thought and interpretation, there has been a resistance to use this approach widely in science (Kosko 1993). In the area of mining and geology the articles by Kacewicz (1989, 1987) are significant. Kacewicz (1987) has incorporated the subjective view of a geologist into calculations, with significant benefits in terms of predicting slope stability. The approach outlined below is more directed towards using geological data to make predictions on discontinuity characteristics.

Using either established rules or expert knowledge a fuzzy system uses this information to reason a relationship or pattern, just as a geologist would do when confronted with local and regional geological information, a geometrical pattern can be established, relationship identified and controls recognised.

Whereas traditional logics examines values as either "true" or "false", fuzzy logic expresses lack of precision in a quantitative fashion by introducing a set membership function that can take on real values between 0-1. The theory is not concerned with how these possibility distributions are created, but rather with the rules for computing the combined possibilities, over expressions that each contain fuzzy variables. Fuzzy logic has been successful in enabling the problem solving system to deal with vague rules, like joint spacing generally increases with rock unit thickness. There are not many situations where such an approach cannot be justified, particularly in the realm of human judgement and interpretation all decisions made are approximately fuzzy by nature and the linguistic terms used by humans are fuzzy.

In geology where information about the third dimension is often not known with certainty and where little meaningful data can be gathered in terms of the probability, a theory based on possibility would appear a more realistic approach. This model must be fuzzy although based on the available data. If more data becomes available the macroscopic three dimensional model may change either drastically or only to a minor extent. Another aspect of geological investigation which by its very nature is fuzzy, is the interpretation of the geological history of

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an area. Again this is based on the available data, but because geologists tend to use descriptive adjunctives rather than definitive numbers, the interpretation is fuzzy. Terms like steeply dipping, coarse grained, strongly jointed, shallowly plunging are fuzzy. These are the terms that geologists often use to describe local situations. The common situation is the development of an interpretation of the third dimension based on the available evidence, such as drill hole or seismic information. Even with this information the interpretation developed is just that, an interpretation. Through fuzzy logic an approach is available to transfer vague linguistic terms such as those used by geologists or areas of human judgement, evaluation and decision making, into a strict mathematical framework that can be used by engineers by applying expert judgement or mathematical relationships. Fuzzy numbers are initially defined based on mathematical relations, expert knowledge or common sense intuition.

A geological example of the use of fuzzy logic using local and regional structural relationships is expressed below. Consider two rock units A, a competent (brittle) unit and unit B an incompetent (ductile) unit. Unit A which has not been folded, exhibits discontinuities controlled by bedding orientation, being normal to bedding and normal and parallel to an existing stress field or primary anisotropy in the rock mass (RULE 1: If A non deformed then discontinuities will be normal and parallel any primary anisotropy and/or insitu stress orientation, therefore measure local discontinuities and determine is related to anisotropy). Unit B which has been folded by one folding event is older and underlies unit A which has not been folded. For unit B discontinuities should be parallel and normal to layering and the fold axis (RULE 2: If B folded discontinuities, parallel and normal to layering, normal and parallel to the fold axis). Spacing of discontinuities in unit B is likely to be greater in the hinges of folds (RULE 3: If A folded discontinuity spacing greater in the hinges of folds). Depending on local conditions discontinuities may be more intense in either rock unit (eg. RULE 4: if B is moderately to intensely folded discontinuity spacing will be greater than unit A and orientation will be subparallel to the axial plane). Other rules can be constructed depending on the local and regional conditions-relationships. Following identification of relationships (or rules) between the macro and mesostructure the controls exerted on discontinuity characteristics can be established and these controls can be used to make prediction of discontinuity properties throughout the rock mass. Once using local and regional relationships, the rules have been constructed, then numerical numbers can be assigned related to the degree that a relationship is established, either based on expert opinion/local knowledge and field observations.

The concept of incorporation of fuzzy logic into aspects of rock mechanics investigations and theory has been considered by Hudson (1993) to be enormous. However the idea of a knowledge based system as an aid to determine ground conditions is not entirely new, as such a system has been applied to geological and mining investigations (e.g. Aminzadeh 1994). Studies have been initiated by others to incorporate structural geology into rock engineering practise (Winsor & Priest 1996), however to date a knowledge based system has not been developed to access regional and local structural geology and make forward predictions.

**Geological discontinuities**

Rock discontinuities can be distinguished as either penetrative and nonpenetrative (Hobbs 1993). **Penetrative** fabrics persist continuously throughout the rock mass as finely spaced microfractures or defects (anisotropy) include bedding, schistosity and mineral lineations. **Non penetrative** fabrics include cleavage, lineations, joints, veins, faults, shear zones, dykes, sills, unconformities and intrusive contacts, often exhibiting a larger spacing than penetrative defects. The nature of discontinuities is mainly controlled by rock type, fabric and processes which have affected the rock mass. For **Igneous rocks** - Discontinuities are geometrically related to contact geometry, the magma flow direction and/or topography. In **Sedimentary rocks** - Discontinuities are controlled by stress conditions during deposition. Solutional effects are common. In **Metamorphic rocks** - A prominent anisotropy is present as a foliation and/or lineation. Other structures include folds, faults, shears, veins and fractures. For geological terrains, a distinct set of discontinuities develops reflecting the rock mass history.
To illustrate the concept of identifying controls exerted on discontinuities a couple of simple geological environments are illustrated below, representing a small spectrum of terrains that may be experienced. Commonly in a given area for a given rock type, a specific geological history/modification history can be established. Although the orientations of the stress field will vary for individual locations and geometry of discontinuities may be different in variable rock types, a general relationship should be identified between discontinuities and the macrostructure, as revealed below.

1. Igneous intrusion - fabrics in a granitic mass include foliation parallel to flow surfaces, lineation - parallel or at right angles to the flow direction. For steeply sided igneous bodies a foliation and lineation is strongly developed on the sides of the bodies and flattens in the central portion (Price & Cosgrove 1990). Veins, faults and fractures are related to the body shape and size.

2. Subhorizontal flat lying sediments (platform rocks) - discontinuity types include: bedding surfaces, normal and/or subvertical joints (Figure 2). Joints have geometries related to prevailing or reactivated stress fields and/or sedimentary anisotropy. Through going systematic joints preserve trends over a large area, commonly normal to bedding and related to folding and/or faulting. In competent rock types, joints maintain a consistent pattern, but this relation is not maintained for incompetent lithologies. In platform terrains there is often basement structure - folds and faults reactivation, resulting in cover sediments with discontinuities that reflect the characteristics of the underlying basement.

3. Fold - compressive fault blocks and basement thrust belt, can vary considerably in width, with antitaxic lines present on the hanging walls of thrust faults, with axes parallel to thrusts. Folds are commonly angular or kink like. Many faults are closely related to folds. Mesodiscontinuities are bedding and cleavage. Normal, reverse or strike-slip faults have predictable geometries, but their location usually must be confirmed by geological mapping. Structures associated with thrusts can include: ramps, footwall synclines, fault bend, fault propagation and drag folds, and horse-slices. Normal faults are commonly listric and may be a result of: a) basement, b) soft sediment deformation, c) stretching and shearing within an orogenic system. Fractures often have systematic geometries related to a large scale (Fig. 3) and can be geometrically predicted (e.g. Winsor 1985).

4. Simple folded regions - the fold axis is horizontal to gently dipping. Folds are often associated with steeply dipping reactivated faults. Fold limbs, across adjacent anticlines and synclines dip from a few degrees up to 90° (after Uemura & Mizutani 1979). Fold style is influenced by: a) the rate of increase of the stress field and b) temperature. For cylindrical folding a common fold axis can be determined normal to a great circle to bedding normals (poles). If non cylindrical, bedding surfaces plot about a small circle. Chevron folding is restricted to thin well bedded sedimentary sequences. Fold size is often related to the layer thickness. Joints related to folding exhibit distinct orientations.

Figure 1 Illustrating the problem of of rock properties within a variable rock mass

Fig. 2 Ideal discontinuities extrapolation subhorizontal sediments after Price & Cosgrove (1990).

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5 Wrench faulted (strike-slip) areas - are regions affected by vertical lateral faults, that develop as a conjugate set. Associated structures tend to exhibit more diverse forms than in other regimes. In shear zones extension fractures, en echelon riedal, splay faults, low angle shears are geometrically related to the shear (as shown in fig. 4). Fault geometry depends on shearing direction, whether sinistral (left lateral) or dextral. Secondary shears may include riedal shears, P shears, first splays and first lenses. Shear development is dependent on displacement amount.

Fig. 3a, b  Ideal discontinuities across a fold after Price & Cosgrove (1990)

Fig. 4  Ideal discontinuities related to a fold with axial planar foliation.

Fig. 5  Stereonet plot of ideal discontinuities in a wrench system (after Hancock 1985).

6 Non systematic and/or man made joints (eg. due to blasting) - the common situation is of random orientation and spacing, however rock type and pre-existing history may exert a control.

Examination of crisp and fuzzy relationships that can be transformed into rules as a basis for discontinuity predictions

The following are crisp and fuzzy rules which are incorporated into the proposed rule knowledge based system. Where local conditions indicates a particular relationship that can be denoted by a local rule this will be used, however if local relationships are not available a general rule will be assigned, with respectively a lower degree of certainty can be designated.

QUANTITATIVE (CRISP and SEMICRISP) RULES:

a Discontinuity orientations are variably controlled : by structural history, lithology (rock type) and topography. Orientation may not be self similar (non fractal). For fault zones microfracturing orientation is a function of distance from a fault zone.

b Discontinuity spacing : there is a transition with increasing joints from 1) random, 2) log normal to 3) normal distributions (Rives et. al 1982). The most common law is negative
exponential. Spacing may exhibits a fractal distribution, but often there exists a regional control. Microfracturing decreases exponentially with distance from macrofaults (Castagna et al. 1996). For sedimentary units spacing may be inversely proportional to rock unit thickness and vary by a hyperbolic law. Spacing related to Young's modulus.

c  Discontinuity roughness: no current way to accurately quantify roughness.

d  Discontinuity length: Strike slip faults follows a log normal distribution (Ranalli 1980). Hudson & Priest (1983) recognised a log normal distribution for meso discontinuities. In some cases the length can exhibit a fractal relationship (e.g. Fuller & Sharp 1992). Distributions under estimate lengths. Length possibly proportional to layer thickness.

e  Discontinuity density: Is not self similar (not fractal) (Castagna et al. 1996).

f  Discontinuity length / displacement: Fault displacement is proportional to length, depending on the local rock properties and displacement may exhibit a power law relationship to length (Cowie et al. 1996 & Dawers & Anders 1995). Fracture strength decreases with porosity (Dunn et al. 1973) but no general rule exist.

QUALITATIVE (FUZZY) RULES:

   a  AREAS NOT AFFECTED BY FOLDING OR FAULTING ORIENTATION: random at a distance from deformed regions.

   SPACING: differences are associated with rock type variability, pore fluid and stress conditions. For topography related joints, spacing increases with distance from an escarpment.

   i  Sedimentary rocks: bed thickness controls joint spacing (locally) and may exhibit a linear relationship, however spacing and frequency are independent and may be nonlinear. Spacing is influenced by lithology, mechanics and strength (Hobbs et al. 1996).

   ii  Igneous rocks: columnar joint spacing is proportional to the cooling rate. Spacing depends on grain size: smaller in finer grained material and dependent on intrusion depth. Joint types: orientation a) cross joints are perpendicular to flow directions, b) longitudinal joints are parallel to flow direction, c) diagonal fractures 45° to flow, d) primary flat lying joints are parallel to topography, e) dykes transect the structural grain.

   iv  Metamorphic rocks: discontinuities include: bedding, penetrative or non penetrative cleavage. Spacing influenced by ambient stress perturbations. In strongly foliated rocks discontinuities generally exhibit a power law distribution (Barton & Zoback 1990).

   v  Weathered rock - spacing increases with degree of weathering.

DEFORMED REGIONS

   a  AREAS OF SIMPLE FOLDING - Orientation: hinge lines bearing and plunge, hinge surface dip and direction, Boulter (1989). Style: angularity, dihedral angle, symmetry. JOINT/FOLD RELATIONS: joint orientations depend on the fold size and type, rock unit thickness and competency. Joints are commonly related to the fold axes and bedding orientations (a, b, c - b is parallel to the fold axis, ab plane is the bedding plane, c is normal to bedding), i.e. Hancock (1985) distinguished six fracture sets related to folds including: 1) longitudinal joints (subparallel to the fold axis) - bc joints, cross joints perpendicular to the fold axis (ac joints), strike and dip joints, and bedding joints. More fractures can be expected in areas under tension. If deformation produces a penetrative foliation, significant parallel discontinuities could be expected on fold limbs and fractures develop normal and parallel to the mineral elongation direction. The discontinuities develop across folds depends on the degree that the rock mass is dominated by either bedding or cleavage anisotropy's. In cases where both bedding and cleavage are of equal significance, discontinuities will reflect this relation.

   b  AREAS OF SIMPLE FAULTING: Fault description: 1) amplitude - dip and strike or dip direction, 2) separation geometry, 3) slip data, 4) patterns. Fractures developed close to faults often exhibit simple patterns. END RELATIONSHIPS - There is an exponential fall-off of meso and macrofractures away from a fault zone. Fault related fractures: orientations are a function of distance (Chinnery 1966). Fractures are more abundant closer to a fault where the main set is subparallel to the fault, a weaker set is subnormal. Microfracturing orientations are dependent on displacement. Fractures developed close to faults exhibit similar patterns. Conjugate faults usually have a dihedral angle near 60°. Thrust faults are the dominant structures in orogenic belts (Boulter 1989). Fault related SPACING 'rules' -
i) Spacing decreases with increased applied stress.
ii) Microfracturing density dependent on fault displacement. Fracture density decreases in an exponential fashion away from a fault.
iii) Spacing is independent of fault type.

**c** AREAS OF JOINTS/FRAC TURES - Shear fracture characteristics depend on lithology. A regional joint pattern can often cut the tectonic grain. Two orthogonal joint systems are common. Joint height often exhibits a Gaussian form.

**d** ROCK PROPERTIES - Stiffness: for stiff beds (>Youngs modulus), spacing reduced. Spacing related to grain size, i.e. closer in finer grained rocks. Shear strength: is affected by past jointing. Joint zones: may result in spurious effects.

**e** FOLD/FAULT RELATIONS - see Boulter (1989, p. 264) basic rules for establishing a deformation history. Before discontinuity spacing is affected by unit thickness, it is affected by degree of strain.

Rules: i) folds younger than folded rocks ii) faults are younger than rocks they cut.

iii) an unconformity is younger than underlying and older than overlying rocks.

iv) metamorphism is younger than rocks it affects.

v) intrusive rocks are younger than the host.

**f** TOPOGRAPHICAL RELATIONS

Joints often exhibit geometries controlled by topography, parallel and perpendicular to an escarpment (Babcock 1974). Spacing may increase with distance from the escarpment.

**Design of a knowledge based system**

Below is an outline of a proposed knowledge based system comprising five modules that can undertake various tasks: A) Macroscopic interpretation/collection of macrodata, B) local geological data gathering, C) identification of ideal survey position, D) discontinuity survey, E) establishing the controls influencing discontinuities and F) making rock mass predictions. This program will assist non technical staff, Mining Engineers and geotechnical engineers/geologists perform these tasks.

Prior to running this program a thorough review should be undertaken of the past work, published and unpublished. A reconnaissance visit to the site should be made and common discontinuities identified. The nomenclature used will be consistent, with the program allowing the changes to the interpretation and modification to the data base.

**Module A  Macroscopic interpretation**

- **Input** Location/spatial data
- **Input previous data/interpretation** (drill holes, geophysics (fuzzy))
- **Known/interpreted geological setting** (fuzzy)

**Establish relations meso and macro structure and reinterpret.**

- **Link local geology rock type, geometry, Module C**

**Use if/then rules to determine the macrostructure.**

- **Undertake analysis rock deformed or not (fuzzy)**

**Separate on the basis of rock type sed. igneous.**

**Determination of discontinuity characteristics**

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Module B  Local geological - structural data - material properties

- Input Location/Spatial data
- Input previous data/interpretation (drill holes, geophysics (fuzzy))
- Known/ or interpreted rock type, identify fabric elements (fuzzy)

Determination of characteristics
- Identify any structural timing criteria
- Determine whether deformed or undeformed

Module C  Identification of survey position

1. Location of scanning position:
   a) Check if rock mass is homogeneous
   b) Check if meso and macrostructure is consistent identify three or two and subvertical and subhorizontal scanlines
   d) Check if the orientation of the survey tape is maintained.
2. Undertake a scan line survey:
   a) Determine general site location/orientation of the tape
   b) Macrostructure c) Rock type and condition
   d) Scanline (area) details c) Specific length of tape
   f) Data logged by g) Discontinuity type
   b) Measurement of each discontinuity characteristic
3. Data input into scan master or a comparable program which performs computer analysis.

Module D  Local and regional controls influencing discontinuity characteristics

- Location/Spatial data (crisp)
- Undertake / input modules A, B & C
- Determine rock type, regional and local discontinuities and distribution (fuzzy)

Controls
- Identify the controls exerted on discontinuities
- Determine the geometrical relationships

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Module E Predictions of discontinuity characteristics

Greater input of geological information, automation and the development of tools to predict discontinuities, will have a significant impact on geotechnical discontinuity investigations through reducing costs and improving safety. The evaluation of discontinuity characteristics when linked to other geotechnical testing, will improve the degree of accuracy of these parameters. Benefits of an automatic approach to discontinuity analysis and prediction could extend to allied areas of the mineral resource industry i.e. minerals, water and petroleum exploration through the identification of structural controls. The fuzzy approach suggested here will allow for the integration in the system interpreted linguistic terms commonly used by geologists.

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REFERENCES


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