

## Rock mass characterization using photoanalysis\*

JOHN A. FRANKLIN, NORBERT H. MAERZ and CARALYN P. BENNETT

*Photoanalysis Research Group, Department of Earth Sciences, University of Waterloo, Ontario, Canada*

Received 27 July 1987

### Summary

Rock formations are distinguished from each other by measuring first the properties of the intact rock, and second those of the jointing. Whereas simple methods are available for measuring intact rock properties, those available for measuring jointing remain slow, expensive, and sometimes dangerous. Digitized photographs ('photoanalysis') may provide a solution. In this paper, the new techniques of photoanalysis are reviewed together with applications, promising areas for research, and also some obstacles that remain to be overcome. Aspects of the rock mass that lend themselves to photoanalytical measurement include those of individual joints, such as persistence, orientation and roughness, and those relating to the mass as a whole, such as block size and the spacing or intensity of jointing. Photoanalysis can also be applied to measurement of blasting. It allows characterization of the rock about to be blasted, helping the engineer to predict fragmentation and to design an appropriate blasting pattern. Afterwards, the same methods can be used to measure fragmentation, overbreak and backbreak, for quality control and for diagnosis of problems.

*Keywords:* Rock mass characterization; blast fragmentation; rock photoanalysis; joint measurement; joint spacing.

### Introduction

#### *Role of jointing data*

Most schemes for classifying the rock mass have two components, the first serving to characterize the jointing, and the second to characterize the rock material. For example, the 'size-strength' system (Franklin, 1976) classifies rock according to the size of blocks and their strength. Rocks that are massive and strong are difficult to excavate (requiring explosives) yet easy to support. Those that are broken and weak are easy to excavate yet difficult and expensive to support.

Early research (1965–70) by the principal author and colleagues was aimed at developing simplified index testing methods for the characterization of intact rock, and resulted in the point load and slake-durability tests for this purpose. More recently at the University of

\* Presented at the 28th US Rock Mechanics Symposium, Tucson, Arizona, 29 June–1 July 1987.

Waterloo, we have been addressing the second aspect, namely that of developing simplified methods for characterization of jointing systems.

Reliable information on rock jointing is needed in addressing nearly every kind of problem. Jointing very largely controls the strength and deformability of a foundation; the flow of groundwater; the ease with which rock can be blasted, and the size of the fragmented product, to name just a few examples.

Information on jointing has traditionally been difficult, slow, and often dangerous to obtain by direct measurement using a tape and geological compass (Barton *et al.*, 1974; Herget, 1977; ISRM, 1981). The rocks exposed in underground stopes and chambers and high in the walls of open pit mines and natural cliffs are often inaccessible. Time is often short, and because of all these factors, data obtained on jointing are often fewer than needed for a satisfactory statistical sampling of jointing patterns. Numerical models of jointed media such as using distinct element methods (Cundall, 1971) and key block methods (Goodman and Shi, 1985) are now more sophisticated than the data on which they are based.

#### *Outline of the photoanalysis method*

Photographs offer a very convenient solution to this problem. Using digital photoanalysis (Franklin and Maerz, 1986, 1987; Maerz *et al.*, 1987a,b,c) and with the help of a microcomputer, the image of the rock is converted into an array of pixels that can be stored, enhanced, displayed, and processed. The method uses either 35 mm black and white still photography or 8 mm video tape. Parameters can be measured that characterize individual fissures (such as roughness and orientation), or the fissure network as a whole (such as block size and intensity of jointing). The direct measurements can be converted into estimates of rock properties such as shear strength and hydraulic conductivity, making use of analytical or empirical relationships, many of which already exist, or new and improved predictive models.

A 'joint photoanalysis study group' ('rock video group') has been formed at the University of Waterloo, to focus research on this very challenging, interdisciplinary topic. The group includes rock engineers and also specialists in structural geology, cartography, statistical geometry, and image analysis.

### **Applications**

#### *Rock mass characterization*

The commonly used rock mass classifications, including RQD, RSR, RMR, and Q systems, focus on the intensity of jointing expressed as a 'block size' or a linear or volumetric joint count. By consensus, this property of 'brokenness' is probably the most significant one affecting the quality of the rock mass, although other properties are also important, such as the strengths of intact material and joint faces.

Photographs can greatly assist in rock mass classification, first by allowing zones with different patterns and intensities of jointing to be identified and the boundaries between them defined, second by allowing the distributions of block sizes and shapes within each zone to be measured. Rock can be classified conventionally with the help of photographic data. Also, photographs can assist in the search for improved classification systems: ones that better

describe real features of rock jointing, that differentiate one rock formation or zone from the next.

Current approaches to geometric characterization of jointing patterns are in their infancy. The concepts of spacing, persistence, etc. (e.g. ISRM, 1981) rely heavily on being able to separate joints into sets, which is not always easy, possible, or even desirable, and imply the greatly over-simplified concept of rock as a 'brick wall'. The concept of 'blocks' is too simple. Real rock masses are cut by discontinuous joints, and a cross-section reveals a network of terminating lines rather than a polygonal honeycomb pattern. Photographs show this true pattern, unaffected by any preconceived notions of block formation.

#### *Derivation of mechanical properties*

Mechanical characteristics can be predicted from photographic data. Properties can be estimated that pertain either to a continuum or a discontinuum type of model.

Most geomechanics models (e.g. finite element) are of the equivalent continuum type in which joints are represented not individually, but by their influence on a large element of the rock mass. Elastic modulus, for example, is obtained either by large-scale testing of rock containing many joints, or, at less expense, by applying a reduction factor to the modulus obtained from small scale tests on intact rock. The reduction factor depends on joint spacing and compliance in the direction of loading. Spacing can be obtained from a photographic line scan, as a function of direction of loading. Compliance depends on aperture and filling, and requires a separate estimate and some degree of error. However, the overall error is reduced if at least the spacing parameter can be estimated reliably.

Other models (e.g. those based on the key block concept) are capable of taking into account the position and mechanical characteristics of individual joints, which also can be obtained photographically. Positions, for example, can be defined within a model either by individual mapping in the case of a large feature such as a fault, or by Monte Carlo random generation knowing the statistical distributions of spacing and orientation.

The shear strength of a joint can be estimated from its roughness together with the strength and thickness of filling materials, using a variety of empirical or semi-empirical methods. Shear strength on the small scale can be extrapolated to the scale of the rock mass by taking into account large scale roughness, usually expressed as Patton's rise angle ' $i$ '. Roughness must be measured, but the well-known methods using comparators, geodetic surveying, compasses or profilographs are slow and often unreliable.

The authors, in cooperation with Noranda Mines Ltd, are investigating joint roughness and shear strength photographically. The digitized waveforms of individual joints are being expressed in various ways such as using the classical root mean square roughness, Fourier spectra, Barton's JRC Roughness Coefficient, fractal number, and Patton's ' $i$ ' angle. Various empirical correlations are being compared to predict shear strength as outlined below.

#### *Modelling of groundwater flow*

The same measures of roughness are relevant in the analysis of groundwater flow. Hydraulic conductivity of the rock mass depends on spacing and connectivity of the network of joints, and on the roughnesses and apertures of each individual joint. Three of these four properties (spacing, connectivity, and roughness) can be measured using photographs. The fourth, aperture, is very difficult to measure in the field, by any technique including photoanalysis.

Aperture is stress-dependent, and under most conditions flow rate is proportional to its third power (Witherspoon, 1986). Small changes in stress have a substantial effect. Many researchers are investigating stress–aperture–conductivity relationships to provide data for the several ongoing radioactive waste disposal projects. At Waterloo, we have recently completed water and air flow testing on single fissures, measuring aperture by a Boyle's law gas expansion method at each increment of applied normal loading, and relating this to the measured permeability (McKee, 1986). The study of single fissures is being extended and linked to photographic measurements of spacing, roughness and connectivity, in an attempt to model the hydraulic conductivity of the rock mass.

#### *Evaluation of blast fragmentation*

Fragmentation is an important measure of the efficiency of a blast. Smaller fragment sizes give reduced costs for loading, hauling, and crushing, but require more drilling and explosives. Larger fragment sizes are essential in some applications, such as when quarrying for armorstone, and a well-graded product is needed if rock fill is to be used for construction of a dense and stable embankment. If fragmentation can be measured quickly and easily, quality of each of these quarried products can be controlled much more readily, and the blast design adjusted for optimum efficiency.

Traditional methods for estimating block size distributions are inaccurate and tedious, with the result that often no measurements are made at all. Boulder counting (Grant and Dutton, 1983) is time consuming and inaccurate. Sieving (Dick *et al.*, 1973) is prohibitively expensive for full scale blasts. Predictions of block sizes from blasting parameters and rock structure (Just and Henderson, 1971) do not actually measure the fragmentation. Measurements from photographs have relied on counting only the wholly visible fragments, ignoring the ones overlapped by other particles (e.g. Carter, 1977; Aimone and Dowding, 1983; Gama, 1984). This has given a serious sampling bias.

A new method for measuring fragmentation by digital photoanalysis determines the sizes of overlapping as well as non-overlapping fragments, and reconstructs a true size distribution. It has been tested during the summer of 1986, by full scale blasting trials (Maerz *et al.*, 1987a,b,c).

Photographs are taken of the fragmented rock (Fig. 1a), then the block outlines are digitized (Fig. 1b). The areas of whole and partially obscured blocks are measured by counting pixels. From this, a true 3D distribution of fragment volumes or weights is obtained by a process known in the science of stereology as 'unfolding' (Underwood, 1970; Weibel, 1979-80). Finally, the distribution is converted from a frequency histogram which expresses the number of particles in each volume class, into a cumulative weight distribution as used more commonly for the characterization of soils and rock aggregates. The following 'unfolding equation' was derived from geometric probabilities (Maerz *et al.*, 1987a,b,c):

$$N_v(d) = \frac{1}{df(d)} N_a(d)$$

where  $N_v$  is the number of blocks per unit volume,  $N_a$  is the number of profiles per unit volume,  $d$  is the diameter class, and  $f$  is an empirical coefficient of proportionality derived from experiments on crushed rock in the gravel size range. In the laboratory-scale calibrations, the logarithmic size distribution of the 'model blast', measured by sieving and

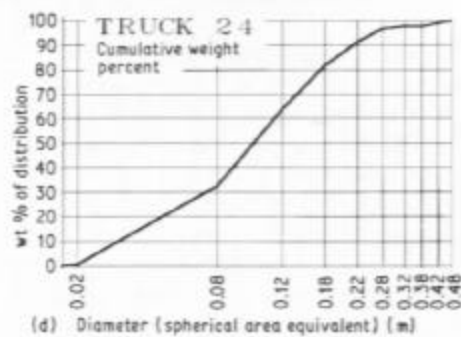
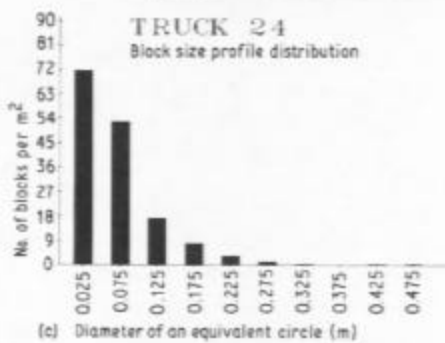
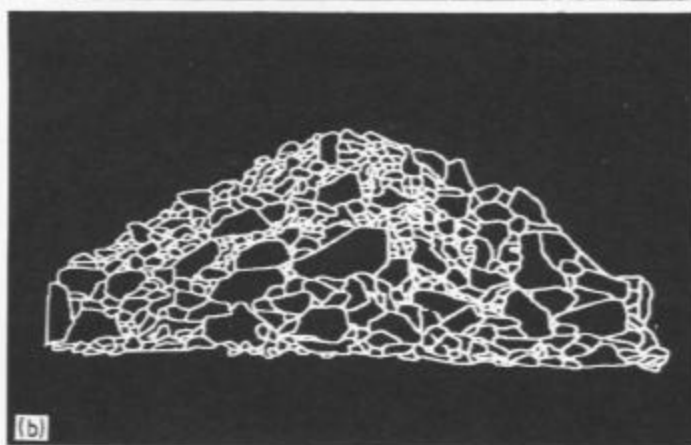


Fig. 1. Measurement of blast fragmentation, (a) broken rock in haulage truck, (b) digital image of muckpile, (c) histogram of block size distribution for truck 24,  $\min=0.000$ ,  $\max=0.450$ ,  $n=678$ ,  $\bar{x}=0.070$ ,  $s=0.054$ , (d) gradation curve for the broken rock (truck 24).  $D_{10}=0.039$ ,  $D_{25}=0.063$ ,  $D_{50}=0.103$ ,  $D_{75}=0.156$ ,  $D_{90}=0.218$ ,  $C_u=3.019$ ,  $CS=2.474$ .

by caliper, was compared with the apparent distribution obtained by photoanalysis. The value of  $f$  has been found to approach unity for all but the smallest size classes.

Fragment size distributions are presented either as histograms (Fig. 1c) or as cumulative curves (Fig. 1d), in much the same way as for a sieve analysis. Statistics are computed for uniformity and sorting. In recent blasting trials, we were able to demonstrate a correlation between the intensity of pre-blast jointing in a rock bench, and the size distribution of fragments produced by blasting, both measured by photoanalysis.

#### *Evaluation of blast overbreak and shatter*

Whereas in production blasting the miner's or contractor's objectives are to achieve the maximum yield and required distribution of sizes, in controlled perimeter blasting the objective is to avoid shatter and overbreak, and to preserve the walls of the rock excavation intact using as little support and replacement concrete as possible.

Photoanalysis promises to offer a very quick and convenient method firstly to measure and record the results of blasting, and secondly to diagnose and help cure any blasting problems. Overbreak can be measured either by stereoscopy or more quickly and directly using photoanalysis with the same straightedge shadow method described below in the context of roughness determination. Fractures induced by blasting can often be differentiated from natural rock jointing. Wall failures can be back-analysed using data on joint orientations and roughnesses measured by photoanalysis, to decide the extent to which rock slides might have been triggered by blast vibrations, or by gravitational forces alone.

These techniques were tried out at a hydropower site in Manitoba, to investigate the extent and causes of overbreak in the powerhouse excavation walls. Photographs were digitized to measure joint orientations, block sizes, and volumes of overbreak. Because the procedures were then early in their development, all results were cross-checked by direct measurements on the rock faces.

#### **Details of the method**

In an earlier publication (Franklin and Maerz, 1986) we reviewed photoanalysis applications in various disciplines. The Quantimet image analysing computer, for example, is very effective in measuring the mineralogical composition of ores. Image processing systems like the Dipix are used routinely in geographic and military applications such as for Landsat image analysis (DeHoff *et al.*, 1968, 1972; Hord, 1982).

These large and expensive image analysing computers are 'dedicated' to other tasks, and are not well suited to rock engineering applications. For rock work, a much more flexible alternative is to build an image analysing system from a microcomputer, a videocamera, a digitization board, and various other hardware such as an enhanced graphics monitor. Software also is needed to obtain, store, process, and display the image. Some of this is multi-purpose and available off-the-shelf, whereas other programs have to be designed specifically for rock applications.

In the remaining part of this paper, we review some aspects of digital photoanalysis techniques under the headings 'input', 'data processing', and 'output'. In other words, how can we obtain the image, and compute and display the jointing or fragmentation pattern?

## Input

The objective is to obtain a digitized network of thin lines representing the traces of joints on a rock face, or the boundaries of fragments of blasted or crushed rock. The start-point is assumed to be a photograph or video tape, although this must eventually be integrated with the linear data obtained by logging drill core and from optical and acoustic images of the borehole walls.

*Face enhancement.* Most photographs are taken of an untreated rock face, which sometimes needs to be washed to remove accumulated dust. Fine microfissures and blast-induced cracks, when difficult to observe directly, can be made to stand out by spraying the face with water, or by spraying with fluorescent dye and photographing in ultraviolet light. These methods are particularly useful to accentuate fine microjoints and fissures induced by blasting.

*Photography.* A standard analogue television signal (RS-170) is digitized using a video digitizing circuit board plugged into an IBM AT microcomputer. The RS-170 signal can be taken from a video camera trained on the rock, from a video camera trained on a photograph of the rock, or from a video tape recording. The analogue frame is split into 480 lines of 512 pixels (picture elements) per line. The intensity (brightness) of the image at each pixel is recorded as one of 256 grey tones.

*In situ* rock needs to be viewed from several directions to adequately sample the 3D pattern of jointing and variations of structure. A more pressing difficulty of sampling occurs when photographing blasted rock. The muck is sorted by ejection from the rock face. Large blocks are often thrown to the outer edges of the pile, and the upper surface becomes coated by finer particles. Pictures are more representative if they are taken of truckloads of excavated broken rock rather than of the *in situ* muckpile itself.

Various photographic questions remain to be answered, such as how to obtain powerful uniform lighting, and to remove photo distortions in the confined spaces of an underground excavation so as to produce an undistorted map of the crown and walls. Panoramic cameras could be used. A more attractive alternative might be to photograph small areas with a scanning video camera coupled to a rangefinder, correct the photographs digitally for scale differences and tilt, and store the data in appropriate positions in a coordinate system. This is tantamount to constructing a photo-mosaic, but using digital manipulation in place of scissors and glue.

*Edge detection.* The photograph, in 256 grey tones, must be converted into a network of thin white-on-black lines (a binary joint trace map) by a process known as 'edge detection'. A glacially polished rock face needs little enhancement and edge detection because it already shows a joint pattern close to an ideal network. More often, however, the face is rough and appears 'faceted' like a diamond, with each facet a different shade of grey. Overhangs produce further shadows, and colour differences are associated with different rock and mineral beds and veins. The face may be further marked by vegetation or lined by blastholes.

Edge detection can be performed in various ways. The quickest and easiest, but one over which the rock specialist has only limited control, is to enhance the grey-tone 'raster' image automatically using transforms and filters, line shrinkage and dilation, to accentuate or eliminate dark areas, light areas, lineations etc. Many techniques can be easily and very quickly applied (Castleman, 1979; Serra, 1982; Fabbri, 1984).

If the joint traces are extremely well defined, such as light lines on a dark background, or vice versa, a binary image can be created by thresholding: the process of mapping pixels below a given intensity to black, and those above to white. A second method is to use a convolution filter such as a gradient operator. This gives a binary image of lines coincident with the greatest rate of change of grey tone intensity.

A much more promising method of joint detection is to identify 'peaks' or 'valleys' in intensity (Karpala and Jernigan, 1981). This is done by convolving the image with a low pass filter (e.g. a Gaussian filter), taking the first difference of the image, and identifying the points of inflection (bottoms of the valleys) by detecting zero crossings. An example is shown in Fig. 2.

Post-processing to further enhance the binary joint trace image is usually needed to filter out spurious lines and other noise. The image may need to be skeletonized or converted to a vector database using a raster to vector conversion algorithm.

A much slower method but one that can more readily be tempered by subjective

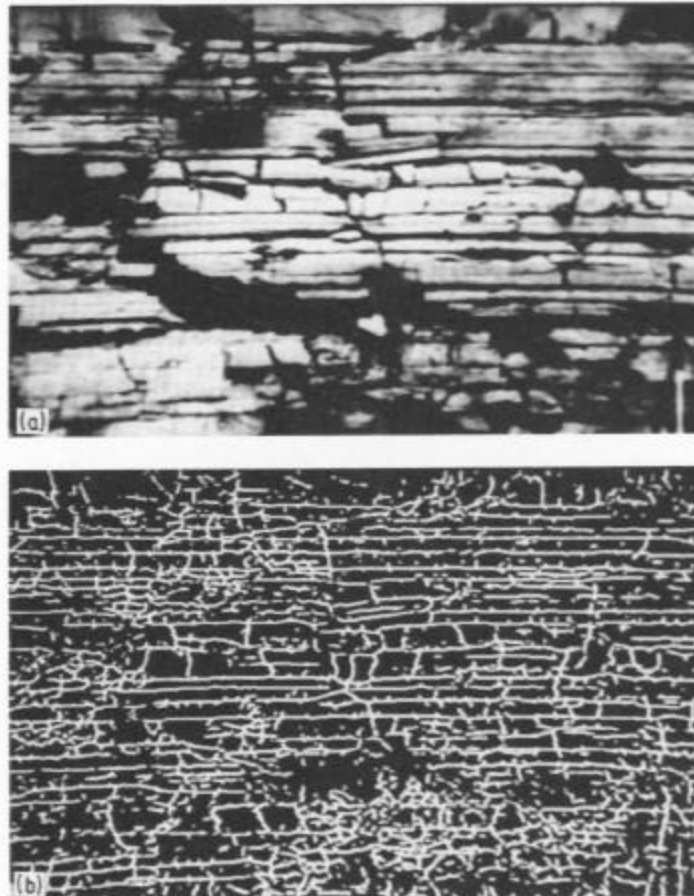


Fig. 2. Enhancement of rock jointing image, (a) photograph of rock (thinly bedded limestone), (b) binary joint trace map produced by photoenhancement.



judgement, is the 'vector' technique of entering data point-by-point using a 'puck' and digitizing board. It takes 3 h to digitize a truckload of broken rock using this method, but the results are reliable because the boundaries of blocks are 'detected' by a geologist who is better than a computer at defining block edges and joint lineations.

While fully automatic methods remain a medium to long term goal, a compromise solution is being used in our work on broken rock, in which the required edges are first traced by pencil, and the pencil network scanned and digitized automatically by video camera. This reduces the time required for digitization, from 3 h to about 1.5 h in the truckload example.

Whichever method is used for digitizing the joint trace map, completing the job requires human input. An editing program has been developed that permits a geological engineer to add joint features where these have been missed, and delete superfluous textures and 'noise'.

### Data processing

*Correcting for the faceting effect.* The network captured from the photograph is still unlikely to be a true 2D cross-section through the rock mass. Further image processing is needed to correct for 'faceting' of the face. The faceting problem, complex and not yet solved, may be summarized as follows.

Facets in the rock face are created by the plucking of blocks, as a result of either blasting or natural weathering. They are absent only in a glacially polished rock outcrop or when the face has been perfectly smooth-wall blasted.

A faceted face exhibits many more joint lineations than a smooth face cut through the same rock. For example, consider a smooth face cut through rock with a cubic jointing system. Visible are the triangular bases of pyramid-shaped corner-cubes. If one of these pyramids is 'plucked', three further joint traces are revealed. The more plucking, the denser the apparent jointing.

To obtain a true 2D cross-section from a faceted image requires an 'unfolding function' along the same lines as the one described earlier, used to convert the image of a muckpile into a true volumetric distribution of particle sizes. The methods of stereology are again applicable (DeHoff and Rhines, 1968; Underwood, 1970; Weibel, 1979–80). However, the rock face problem is more difficult than the muckpile one, because the extent of plucking can vary from none to extensive. Plucking could result in substantial errors in estimating jointing intensities and block sizes. Data on joint orientations could be affected to a lesser extent, although plucking may introduce a sampling bias in this measurement also.

*Derivation of persistences and orientations.* Once the data network has been captured and stored digitally, the engineer can quite easily measure the parameters that have traditionally been used to describe individual joints and jointing systems, and can search for better ways of characterization. The aim is to simplify or 'model' the pattern and to represent its key features by statistics, so that a similar pattern can be generated whenever needed as input to a geomechanics model.

From the binary joint trace image, trace lengths and orientations can be found using 'line walking' methods, in which an algorithm follows the trace pixel by pixel to record lengths and average orientations.

The image can be further processed, for example by fitting straight line segments to elements of the network, retaining information on the roughness, length, and direction of

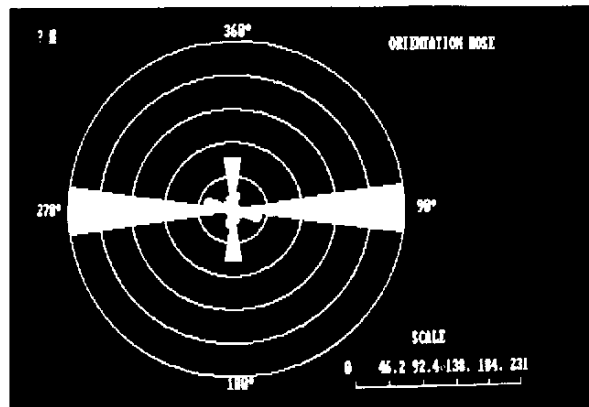


Fig. 3. Rose diagram showing 2D orientations of joints in an photograph of sedimentary rock.

each. 2D orientation rosettes can be constructed for each image (e.g. Fig. 3), and fused to form a 3D orientation database as outlined below.

*Joint sets identified in multi-dimensions.* Traditionally and, we believe, erroneously, joint sets have been defined just in terms of direction, by the clustering of poles on a stereoplot. Joint sets defined in this manner often are difficult to identify, because stereoplots can show great scatter even when joint sets are obvious to the naked eye. Such sets are in nature characterized not by one, but by several attributes, such as by joints being longer or rougher in one direction than another. These multivariate patterns of jointing remain to be explored.

Joint sets, if they exist, can be identified by examining the clustering of trace characteristics in multi-parameter space. Each segment is then tagged with a joint set designation. Statistical values and dispersions can be calculated for each set and each attribute, e.g. orientation and spacing. Note the important differences between this approach and the classical one in which joints are grouped into sets according to orientation only, before measuring any other property.

3D orientations can be obtained for each joint set using 2D photographs, without using stereoscopy which is slow and expensive. Oriented photographs are obtained of two non-parallel faces in the same rock mass. A joint rosette is constructed for each photograph using photoanalysis (Fig. 3). Corresponding elements of the two rosettes are then paired up to give dip magnitudes and directions for each set, using the classical geological three-point method (Franklin and Maerz, 1986). A further, alternative method might make use of grey tones on the joint facets, which are shaded according to orientation with respect to the angle of illumination. This method has yet to be tried out.

*Derivation of joint spacing and block size parameters.* Spacing of joint traces can be found using a scan line at any required angle, in which an algorithm counts the number of intersections.

In the absence of complete polygonal blocks, a linear joint count can be obtained as the number of joints intersecting any line in the plane of the photograph, per metre length of line.

This is equivalent to joint intensity measured in a rock core (also a linear sample). The inverse of linear joint intensity can be considered as a measure of block size. Note that the linear joint intensity is a directional property that can be used to measure anisotropy of jointing whether or not the joints form sets. It can be defined and measured whether or not the joints are persistent so as to form blocks.

ISRM (1981) and Beyer and Rolofs (1981) present methods of determining block size from linear measurements on a rock face. A photoanalytical method can be used to automatically measure the number of blocks per unit length of line, or per unit area, from which can be derived either the previously defined or new measures of block size or intensity of jointing.

The mechanical quality (e.g. shear strength, hydraulic conductivity) of rock is affected by whether the joints form blocks with continuous boundaries. One way of measuring this property in 2D is to extrapolate the linear joint segments until they meet adjacent joints. The persistence of jointing can then be measured in terms of the percentage of a polygon's circumference that is formed by real as opposed to extrapolated joints, or in 3D, as the equivalent percentage of surface area.

*Measurement of joint roughnesses.* Rough joint surfaces tend to be stronger and also less permeable than smooth ones. Knowing the roughness, predictions can be made of both shear strength (e.g. Barton and Choubey, 1977) and hydraulic conductivity (e.g. Barton *et al.*, 1985).

Traditional methods for measuring joint roughness include profilometry (Weissbach, 1978), compass and disc-clinometry (Feckers and Rengers, 1971), and photogrammetry (Ross-Brown, 1973). They are inconvenient and slow. Two photoanalytical alternatives have been investigated by the authors, the 'low incidence shadow' and the 'straightedge shadow' methods. The latter, because of its simplicity, has been more fully explored and developed, although the former shows much promise also.

The low incidence shadow method relies on shadows being cast only by those steeper-sided roughness asperities whose rise angle  $i$  exceeds  $[90 - I]$ , where  $I$  is the angle of incidence of the lighting. In principle at least, distribution of asperity  $i$  angles can be measured by counting the number of shadows that appear as the lighting is varied from normally incident ( $I = 0$ ) to increasingly oblique angles, say in steps of  $10^\circ$ . Measurements can also be made of the width of shadows, equal to one half the roughness wavelength. However, quantitative measurements of this sort are not easy. All that the authors have so far achieved is to measure shadow as a proportion of total surface area, which gives some indication of relative roughnesses.

The straightedge shadow method is based on the intersection of a plane of light and a joint being a straight line if the joint is perfectly flat, but an undulating line if the joint is rough. The 'plane of light' is made visible by casting a shadow onto the joint facet by a straightedge held near or against it. The same can be done remotely using a focused beam (e.g. searchlight). The undulation of the edge of the shadow is proportional to roughness of the joint, according to the following relationship:

$$x/y = \tan I$$

where  $x$  is the amplitude of the undulating shadow,  $y$  is the corresponding true amplitude of roughness, and  $I$  is again the angle of incidence of the lighting. When  $I = 45^\circ$ , the true and apparent roughnesses are evidently equal.

In Fig. 4, the straightedge shadow method is demonstrated using corrugated cardboard:

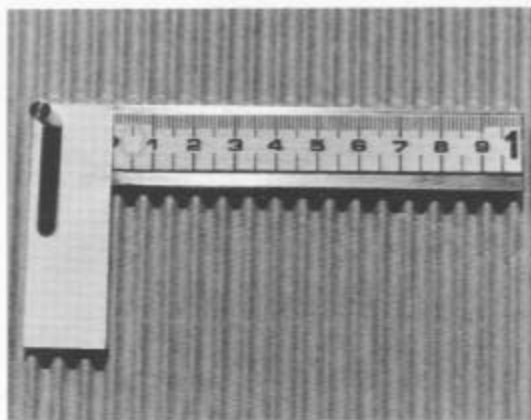


Fig. 4. Demonstration of straightedge shadow method, using corrugated cardboard.

the edge of the shadow mimics the profile of the cardboard. The incident angle of light can be conveniently measured from the length of a shadow cast by a post of known height onto a disc of white cardboard or plastic resting on the joint. This device, termed a 'sundial', is routinely placed in the field of view (Fig. 5).

Image processing techniques are applied to the digital image to enhance the edge of the shadow. A threshold operator is applied to produce a binary image, then the edge of the shadow is isolated using a line-thinning algorithm. The resulting roughness trace is converted into a string of cartesian coordinates using a raster to vector conversion algorithm, and into a true amplitude profile using the above equation based on the angle of incidence of the lighting (Fig. 6).

Roughness can then be characterized by any of several conventional or unconventional parameters. Three of these are routinely computed by the authors: the root mean square of the first derivative ( $Z2$ ); the roughness profile index ( $R_p$ ), defined as the ratio of the length of the trace to its length projected on the mean plane; and the micro-average  $i$  angle, defined as the average inclination angle of the trace at the smallest scale of resolution (i.e. from one pixel

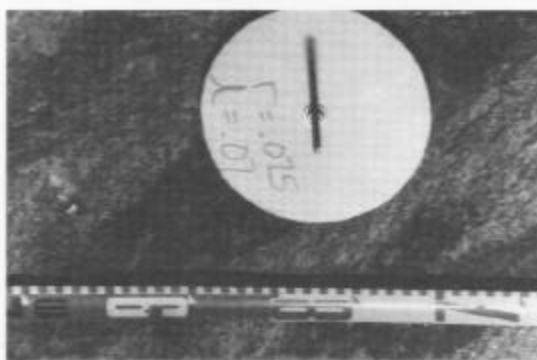


Fig. 5. Straightedge shadow method during field trials at Noranda's Hemlo gold mine in Ontario. Note use of 'sundial' to give angle of incidence of light.

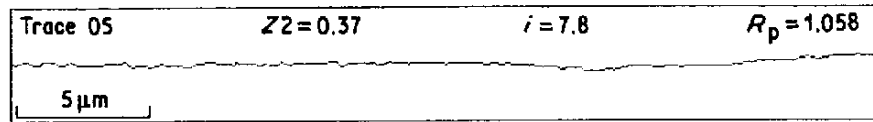


Fig. 6. Typical computer-generated roughness profile obtained by straightedge shadow method.

to the next). Each of these is correlated with JRC (joint roughness coefficient) by comparison with a digitized version of Barton's ten roughness profiles (Barton and Choubey, 1977). The correlation has been demonstrated by Tse and Cruden (1979). The resulting regression equations give an estimate of JRC, from which can be predicted shear strength using the empirical model of Barton and Choubey (1977). Values for JCS (joint wall compressive strength) must be assumed or measured. Other parameters such as the fractal number of the joint, and  $i$  angle as a function of base length, have more recently been studied.

In summary, joint surface roughnesses can be determined quickly and accurately using the new straightedge shadow method. The method can be applied on any scale, from micromerements using a razor blade as a straightedge beneath a microscope, to measurements over many metres such as to quantify overbreak in the wall of an excavation, or caving in the hangingwall of a stope. From the measurements, the joint roughness can be quantified and related to shear strength.

### Output

Jointing data, being 3D, are difficult to visualize in relation to the 3D geometry of rock excavations. Therefore no photoanalysis program is complete without a graphical display capability.

As with the input facility, we considered using off-the-shelf graphic display software such as the CAD (computer aided design) system, which has attractive features such as the ability to expand and contract scales, rotate the image, and use colour for added effect. Again, however, purpose-designed systems proved too expensive and too inflexible for the geomechanics application. A graphics system is therefore being developed for use with the AT computer, to display jointing patterns and the outlines of excavations.

This is linked with a computer simulation that generates a rock mass of known jointing parameters, and outputs a 3D cubic display, and a planar cross-section (a joint trace map) cut at any required direction (Fig. 7). Monte Carlo methods are employed to generate three or more sets of joints intersecting the cube, and dividing it into several thousand blocks. The volume of each can be calculated to determine the true block size distribution of the assemblage, for comparison with areal distributions measured in cross-section. Various unfolding functions and other theoretically derived geometric relationships can thus be tested.

We plan to develop the display facility to simulate excavation into the rock mass, and to permit the engineer to 'drive around' within the excavation using joystick control. The purpose is to help visualize the jointing and key blocks in relation to the excavation walls and support systems.

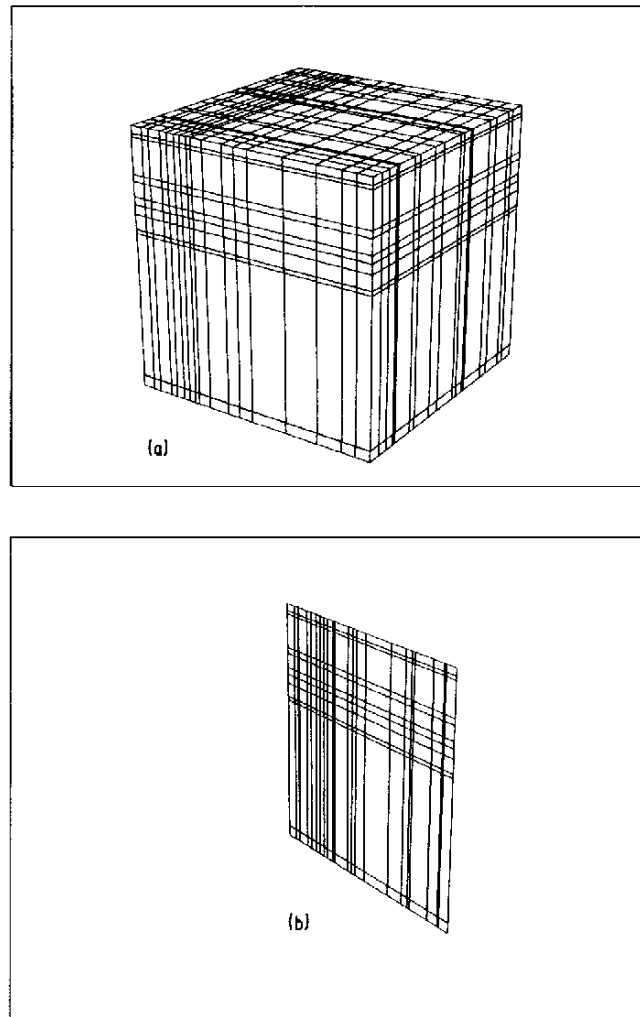


Fig. 7. Graphic display of jointing systems, (a) cubic display with three sets of joints generated at log-normal spacing, using a Monte Carlo random number generator, (b) cross-section through the cube, giving a joint trace map in any required direction.

### Acknowledgements

Funding for this research has been provided by the NSERC (Canadian Natural Sciences and Engineering Research Council); CANMET (Energy Mines and Resources, Canada); EI du Pont de Nemours & Company Inc. (blasting aspects), and Noranda Mines Ltd (roughness and shear strength aspects). The authors are grateful for their continued sponsorship.

## References

- Aimone, C.T. and Dowding, C.H. (1983) Fragmentation measurement results for fourteen full-scale production blasts: a comparison with a three dimensional wave code. *Proceedings of the Ninth Conference on Explosives and Blasting Technique*, pp. 310-33.
- Barton, N. and Choubey, V. (1977) The shear strength of rock joints in theory and in practice, *Rock Mechanics* **10**, 1-54.
- Barton, N., Lien, R. and Lunde, J. (1974) Engineering classification of rock masses for the design of tunnel support, *Rock Mechanics* **6**, 189-236.
- Barton, N., Bandis, S. and Bakhtar, K. (1985) Strength, deformation and conductivity coupling of rock joints, *International Journal of Rock Mechanics and Mining Sciences Geomechanics Abstracts* **22** (3), 121-40.
- Beyer, F. and Rolofs, F. (1981) Kluftrpergrssenverteilungen aus Messungen auf Anschnitten, *Rock Mechanics* **14**, 105-13.
- Carter, J.W. (1977) Analysis of a simple photographic method proposed for determining size distribution of ore fragments, *USBM Laboratory Report RBM 77-03*, 19 pp.
- Castleman, K.R. (1979) *Digital Image Processing*, Prentice-Hall Inc., Englewood Cliffs, New Jersey, p. 429.
- Cundall, P. (1971) A computer model for simulating progressive large scale movements in blocky rock systems, *Proceedings of the International Symposium on Rock Fracture*, Nancy, France, paper II-8, pp. 00-00.
- DeHoff, R.T. and Rhines, F.N. (1968) *Quantitative Microscopy*. McGraw Hill, New York, 422 pp.
- DeHoff, R.T., Aigeltinger, E.H. and Craig, K.R. (1972) Experimental determination of the topological properties of three-dimensional microstructures. *Journal of Microscopy*, **95** (1), 69-71.
- Dick, R.A., Fletcher, L.A. and D'Andrea, D.V. (1973) A study of fragmentation from bench blasting at reduced scale, USBM Report 7704, Washington DC, pp. 1-22.
- Fabrizi, A.G. (1984) *Image Processing of Geological Data*. Van Nostrand Reinhold Company, 244 pp.
- Feckers, E. and Rengers, N. (1971) Measurement of large scale roughness of rock planes by means of profilograph and geological compass, *Proceedings of the International Symposium on Rock Mechanics*, Nancy, France, pp. 1-18.
- Franklin, J.A. (1976) An observation approach to the selection and control of rock tunnel linings, *Proceedings of the Conference on Shotcrete for Ground Support*, Easton, Maryland, ASCE, pp. 556-96.
- Franklin, J.A. and Maerz, N.H. (1986) Digital photoanalysis of rock jointing, *Proceedings of the Thirty-ninth Canadian Geotechnical Conference*, pp. 11-20.
- Franklin, J.A. and Maerz, N.H. (1987) Photographic measurements of jointing and fragmentation, *Proceedings of the Second International Symposium on Field Measurements in Geomechanics*, Kobe, Japan, pp. 1-12.
- Gama, C.D. (1984) Microcomputer simulation of rock blasting to predict fragmentation, *Proceedings of the Twenty-fifth U.S. Symposium on Rock Mechanics*, pp. 1018-30.
- Goodman, R.E. and Shi, G. (1985) *Block Theory and its Application to Rock Engineering*, Prentice-Hall, Englewood Cliffs, New Jersey, 338 pp.
- Grant, J.R. and Dutton, A.J. (1983) Development of a fragmentation monitoring system for evaluating open slope blast performance at Mount Isa Mines, *Proceedings of the First International Symposium on Rock Fragmentation by Blasting*, Lulca, Sweden, pp. 637-52.
- Hergert, G. (1977) *Pit Slope 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, 123 p.
- Hord, R.M. (1982) *Digital Image Processing of Remotely Sensed Data*. Academic Press, New York, 256 pp.

- ISRM Commission on Testing Methods (1981) Suggested methods for the quantitative description of discontinuities in rock masses, in *Rock Characterization, Testing and Monitoring, ISRM Suggested Methods*, (edited by E.T. Brown), Pergamon Press, pp. 3–52.
- Just, G.D. and Henderson, D.S. (1971) Model studies of fragmentation of explosives, *Proceedings of the First Australia–New Zealand Conference on Geomechanics*, 1, pp. 238–45.
- Karpala, F. and Jernigan, M.E. (1981) An optimal frequency domain filter for peak detection, *Proceedings of the International Conference on Cybernetics and Society*, pp. 1–5.
- Maerz, N.H., Franklin, J.A. and Coursen, D.L. (1987a) Fragmentation measurement for experimental blasting in Virginia, *Proceedings of the Third Society of Explosives Engineers, Mini-Symposium on Explosives and Blasting Research*, Miami, pp. 56–70.
- Maerz, N.H., Franklin, J.A., Rothenburg, L. and Coursen, D.L. (1987b) Measurement of rock fragmentation by digital photoanalysis, *Proceedings of the Sixth International Congress on Rock Mechanics, Montreal*, A.A. Balkema, Rotterdam, Volume 1, pp. 687–92.
- Maerz, N.H., Bennett, C.P. and Dony, R.D. (1987c) Microcomputer image analysis of rock fabric, *Proceedings of the First Canadian Symposium on Microcomputer Applications to Geotechnique*, Regina, Saskatchewan (in press).
- McKee, J.A. (1986) Laboratory Investigation of Fluid Flow Through Intact and Fractured Core Specimens, MSc Thesis, University of Waterloo, Ontario, 198 pp.
- Ross-Brown, D.M. (1973) Suggested method for the determination of joint orientations by photogrammetry, Imperial College Rock Mechanics Research Report 24, 25 pp.
- Serra, J. (1982) *Image Analysis and Mathematical Morphology*, Academic Press, London, 610 pp.
- Tse, R. and Cruden, D.M. (1979) Estimating joint roughness coefficients, *International Journal of Rock Mechanics Mining Science and Geomechanics Abstract* 16, pp. 303–7.
- Underwood, E.E. (1970) *Quantitative Stereology*. Addison Wesley, Reading, Massachusetts, 274 pp.
- Weibel, E.R. (1979) Stereological Methods, in *Theoretical Foundations*, Volume 1, Academic Press, London, 415 pp.
- Weibel, E.R. (1980) Practical Methods for Biological Morphometry, in *Theoretical Foundations*, Volume 2, Academic Press, London, 415 pp.
- Weissbach, G. (1978) A new method for the determination of the roughness of rock joints in the laboratory, *International Journal of Rock Mechanics Mining Science and Geomechanical Abstracts* 15, 131–33.
- Witherspoon, P.A. (1986) Flow of groundwater in fractured rocks. *Bulletin of the International Association of Engineering Geology*, 34, 103–15.