Zonal Concept for Spatial Distribution of Fractures in Rock

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SUMMARY Evaluation of the spatial distribution of fractures within the dolomitic shales at the Mount Isa Mine suggests that fractures tend to occur in zones. Computer modelling of fracture distributions indicates that the field mapping technique of single line sampling fails to provide sufficient data to fully characterize the rock mass. A simple data collection and model formulation concept is described that will enable the local variability within any rock mass to be assessed. The method permits the statistical evaluation of masses in terms of fracture intensities of each set that is likely to be associated with underground openings of any given shape and size. This information can then be extended to evaluate the variability in the mechanical properties of the rock surrounding underground openings.

1 INTRODUCTION

To a large extent, the physical and mechanical properties of rock masses are functions of the attitude, geometry and spatial distribution of faults, joints and other geological discontinuities within the mass.

Spatial distribution refers to the position of fracture plane centres within a given volume of rock. A literature survey indicates that very little information appears to have been published on this topic.

A number of writers have recognized the tendency for sets of fractures to occur in zones. However, most geotechnical analyses continue to be based on assumptions that the spatial distribution is random. It appears to be commonly presumed that the observed fracture clusters are purely a result of a random process.

Data collected at the Mount Isa Mine suggests that the observed spatial distribution of fractures at the mine cannot be explained in terms of the random model. The study indicates that it may be necessary to invoke a zonal model to satisfactorily account for the observed relationships within some rock masses.

2 GEOLOGICAL CONSIDERATIONS

2.1 Data Collection

Structural data requirements for engineering purposes and the necessary sampling procedures have been described in detail by a number of authors and will not be reiterated here. The most recent review of recommended techniques was released by the International Society for Rock Mechanics during 1978.

A commonly recommended field mapping procedure is the line sampling method, where all fractures crossing a continuous straight sample line are included in the data. The principal advantage of this technique is that it tends to yield unbiased results. Furthermore, it enables a direct comparison to be made between in situ mapping and orientated drill core data.

Between 1970 and 1974 most detailed structural data at Mount Isa Mine were collected by means of extensive line sampling of underground openings and logging of orientated drill cores, i.e. Baczynski (1974), Bridges (1975).

2.2 Orientation and Continuity of Fractures

Although orientation and continuity describe two very important properties of fracture planes, a detailed knowledge of these parameters is not required for purposes of the present discussion. It is sufficient to mention that field work at the mine suggests that the distribution of fracture trace lengths (as encountered along line samples) may be represented by a lognormal probability density function. However, evidence for this model is outside the scope of this paper.

2.3 Fracture Spacing

Investigations suggest that the spacing between adjacent fractures of each set (along line samples) may also be best described by means of a lognormal probability density function. A typical cumulative frequency plot on logarithmic probability paper is illustrated in Figure 1. The plot summarizes the spacing model for two of the fracture sets defined at the mine. The illustrated results are based on diamond drill core data and therefore the sample includes all fractures with continuities down to a lower limit of about 0.02m.

In general terms, the distributions highlight the observation that spacing between adjacent fractures is markedly skewed towards the smaller spacings in a manner such that the logarithm of the spacing variable is normally distributed. This suggests that fractures of a particular set are not evenly distributed within the rock mass, but tend to occur in clusters.

3 "RANDOM" SPATIAL MODEL

3.1 Assumptions Underlying Model Testing

The validity of the random model can be most readily tested with the aid of a simple computer prog-

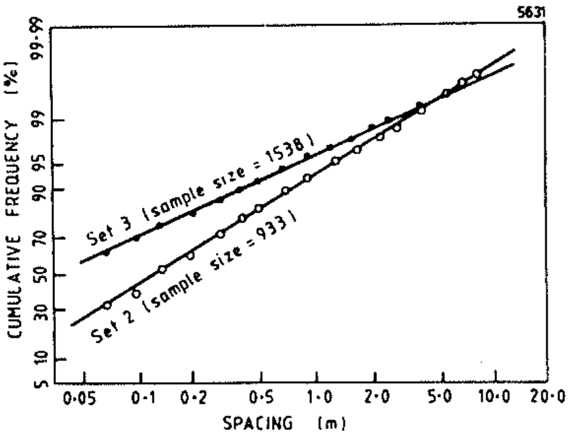

Figure 1. Cumulative Frequency Distribution for In Situ Spacing of Fractures.

ram based on the "Monte Carlo" method (Hammersley and Handscomb, 1964). The necessary input data for a fracture set to be simulated consists of:

(i) Average orientation of the fracture traces which is assigned to each member of the set,
(ii) Model for fracture trace continuity,
(iii) Mean spacing between fractures along line samples, and
(iv) A suitable model for the number of fractures or the total fracture trace length to be generated within the defined area.

The first three parameters may be determined from field data, whereas the fourth requires some consideration.

Assuming that the dimensions of the area selected for fracture trace generation are very large in comparison to the mean spacing between fractures, then on the average it would be expected that the spacing between fractures encountered along each and every hypothetical sample line transecting this area in a direction normal to the trace of the planes would approach the mean spacing for the set. On this premise, the total trace length of all fractures within the generation area may be simply derived by the formula:

$$\text{Total Trace Length} = \frac{D_n}{S_m} \times D_p$$

where,
D_n = Average dimension of the area in direction normal to fracture traces (parallel to line samples),
D_p = Average dimension of the area parallel to fracture traces, and
S_m = Mean spacing between fractures along line samples.

This estimate of the anticipated total trace length may be used to furnish the necessary fourth parameter.

The basic computer procedure adopted for generation of fracture traces within a defined area consisted of the following three iterative steps:

(i) Random generation of mid-point coordinates for fracture trace,
(ii) Statistical generation of trace length in accordance with a fracture continuity model, and
(iii) Determination of x- and y-coordinates for extremities of the fracture trace through the designated mid-point.

The iterative procedure is concluded when the cumulative trace length of the generated fractures equals or just exceeds the permissible total length. The coordinate data may then be output to a plotter. Furthermore, the fracture traces can be computer tested for intersection with selected sample lines and the spacing model may be derived.

3.2 Results of Model Testing

Figure 2 presents a typical fracture trace pattern generated on the basis of the random model. The most striking feature of this plot is the relatively homogeneous density of fractures over the entire area.

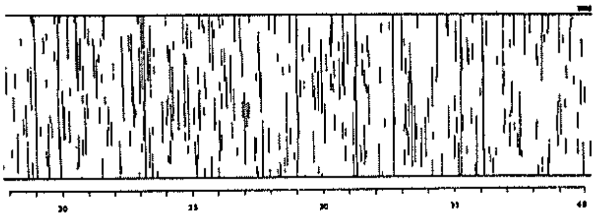

Figure 2. Typical Fracture Pattern Generated on Basis of a "Random" Spatial Distribution Model for Fracture Plane Centres.

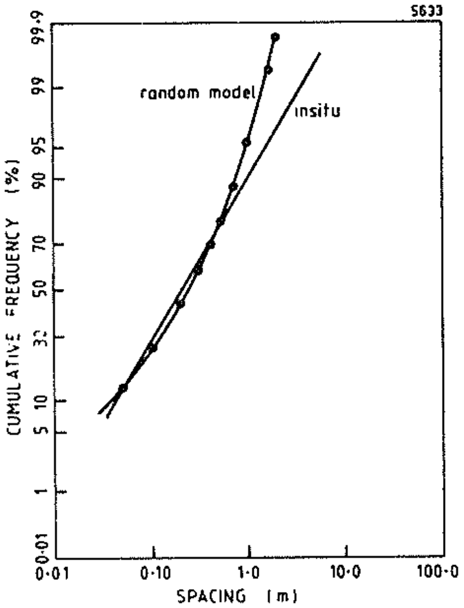

Figure 3. Cumulative Frequency Distribution for Spacing of Fractures Generated on Basis of "Random" Spatial Model.

The resulting cumulative frequency plot for the spacing between adjacent fractures is presented on logarithmic probability paper in Figure 3. It is apparent from this plot that the random spatial model fails to reproduce the lognormal spacing model observed at the mine.

4 "ZONAL" SPATIAL MODEL

4.1 Data Collection

In order to test the validity of this model, a mapping programme of continuous area traverses was undertaken at several locations in the mine. A simple and rapid procedure was adopted for mapping of underground openings.

After selected areas were photographed, a set of suitably enlarged, overlapping photographs were used as base maps to mark on the traces of all visible fractures in the walls of the openings. On completion of underground mapping, the data were transferred to non-distorted maps and fracture traces were assigned to sets on basis of their orientation. A separate transparent overlay was compiled for each set.

4.2 Data Analysis and Model Development

Each transparent overlay was sub-divided into unit areas, in the manner illustrated in Figure 4. For purposes of the analysis, "unit areas" were defined as an area equivalent to $1.0m^2$ in the direction normal to the average strike of the fracture set. This permitted the dimensions of unit areas to be adjusted according to the angular relationship between the strike of the set and the strike of underground openings, such that the "normalized" unit area remained the same or constant.

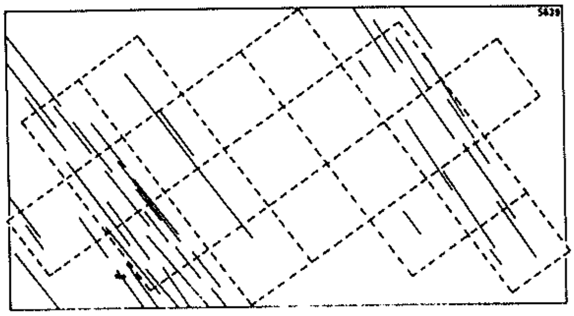

Figure 4. "Unit Area" Concept.

The total trace length of each set of fractures was determined within each unit area. The prime purpose of these analyses was to derive a model for the variability in the intensity of fracturing between unit areas (Figure 5), including determination of conditional probability density functions for the extent of fracture intensity "zones" in directions parallel (Figure 6) and normal to the average trace of a set.

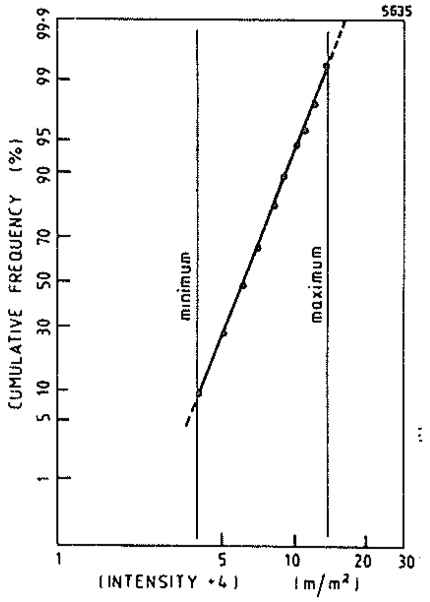

Figure 5. Cumulative Frequency Distribution for Intensity of a Fracture Set per Unit Area.

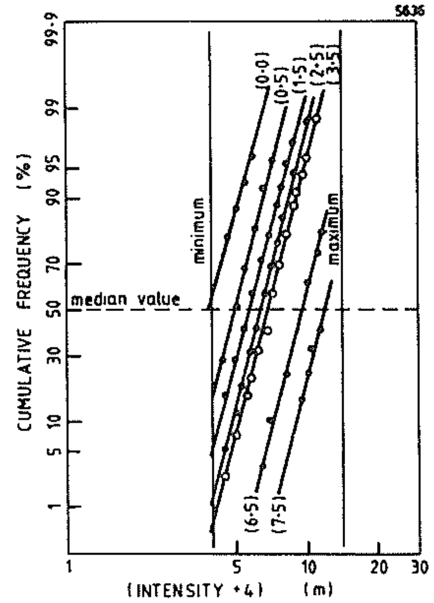

Figure 6. Cumulative Frequency Distribution for Intensity of a Fracture Set in a Unit Area Adjacent to a Unit Area with an Intensity Indicated by the Median Value, in the Direction Parallel to the Average Trace of fractures. (Conditional Probability Density Functions).

To enable the 2-d model to be extrapolated into the third dimension, it was necessary to assume that each fracture plane continued for a unit distance into the third dimension, e.g., a 2-d unit area with an intensity of 8.0 linear metres of fracture traces was converted in the 3-d model to $8.0m^2$ per cubic metre unit domain. In short, this model assumes that for each fracture set, each unit volume of the rock mass is homogeneous for a metre in the direction parallel to the average strike of the set.

It is apparent that such assumptions would be very difficult to justify in situations where a relatively large dimension had been selected for unit areas or volumes. The smaller the dimensions, the more likely it is that the assumptions are valid. The dimensions of unit areas selected for the Mount Isa Mine study are approximately 2.5 times the mean spacing between fracture planes of the most common set and about 0.7 times their mean trace length.

4.3 Model Testing

4.3.1 Objectives of Tests

The prime purpose of the tests was to verify that the "zonal" model would yield the same mean fracture intensities per unit volume, as well as the lognormal spacing along line samples.

4.3.2 Testing Technique

The validity of the model was tested by comparing the above two parameters as generated by the computer modelling process with the prototype. A computer program developed by the author was used in the analysis. The basic principles underlying the program are indicated below.

(i) Selection of the desired dimensions for the test block and sub-division into unit volumes,

(ii) Assignment of fracture intensities to unit volumes in accordance with the statistical model determined for the set,

(iii) Generation and location of fracture planes within the test block until all designated local intensities within the test block are satisfied, and

(iv) Calculation of mean fracture set intensity per unit volume of the test block and generation of fracture plane patterns on selected planes "cut" through the block. Determination of spacing model for adjacent fracture traces along line traverses.

4.3.3 Results

On the basis of several hundred test blocks, each comprised of approximately 3500 unit volumes, that were generated for each fracture set, a reasonable correlation was achieved between the generated and in situ fracture intensity, as well as the spacing model for adjacent fractures along line samples.

The results for the fracture sets delineated in the dolomitic shales at the mine are summarized in Table I, which indicates the in situ and generated mean intensities per unit volume of the average test block.

Table I

Mean Intensity of Fractures per Unit Volume of Block

Fracture Set	In situ	Simulated
1	2.17	2.15
2	2.17	2.15
3	1.12	1.12
4	0.24	0.27
5	0.12	0.14
6	0.28	0.31
7	0.05	0.06
8	0.23	0.27
9	0.15	0.18
10	0.12	0.14

The typical fracture pattern generated with one set is illustrated in Figure 7 and the corresponding line sample spacing results are presented in Figure 8.

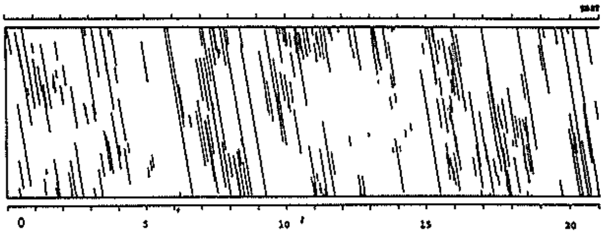

Figure 7. Typical Fracture Pattern Generated on Basis of a "Zonal" Spatial Distribution Model for Fracture Plane Centres.

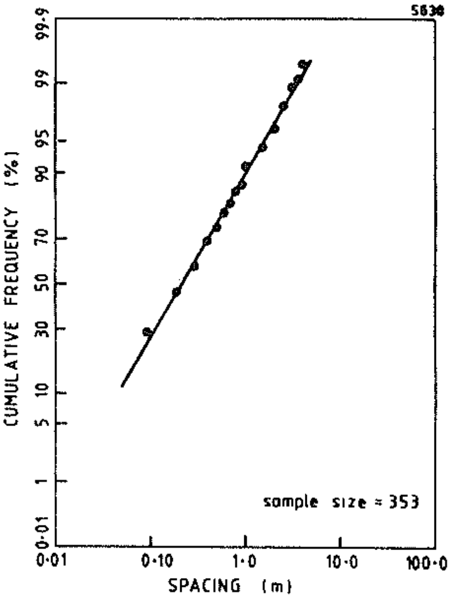

Figure 8. Cumulative Frequency Distribution for Spacing of Fractures Generated on Basis of a "Zonal" Spatial Model.

Figure 9 illustrates a typical pattern generated with the first six sets listed in Table I above. Rock mass variability and the contrast between low and high fracture intensity sub-domains are highlighted by this figure.

5 PRACTICAL APPLICATION OF ZONAL CONCEPT

The results indicate that fracture distributions generated on basis of the "zonal" concept are not only in accord with field evidence, but also they highlight to a greater extent the true variability within rock masses.

Provided that suitable sample areas exist, then the described principles of data collection can be applied to any rock mass, irrespective of the spatial distribution of fractures within them. Moreover, the additional data necessary for the development of a "zonal" model is not excessive, and the

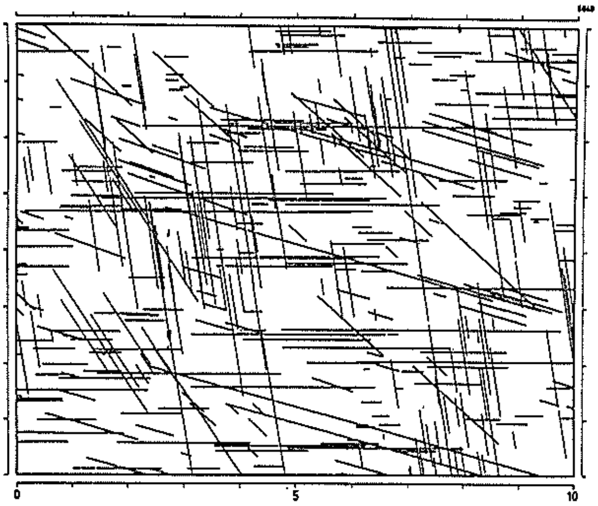

Figure 9. Typical Fracture Pattern Generated on Basis of a "Zonal" Spatial Distribution Model for Six Sets of Fracture Plane Centres.

investigation programme can be completed within a relatively short period of time. It should also be possible to derive similar models on the basis of orientated drill core data from two or more boreholes drilled parallel and within very close proximity to each other.

Once the field data have been analysed, the derived model may be utilized in its "rough" form, or alternatively it may be approximated by means of some standard statistical distribution such as the Gaussian or Poisson probability functions. However, care should be exercised to ensure that standard distributions are not always assumed even where these exhibit a poor degree of correlation with the "rough" distribution. An adequate sample size is necessary in all cases.

After formulation of the statistical model, it is then a routine matter to evaluate the variability in the average fracture intensity between rock mass blocks with any specified dimensions.

This information then yields a better understanding of the ground conditions that are likely to be encountered in the mass. For example, given the block dimensions, an iterative "Monte Carlo" method can be used to sample the population in order to evaluate the variability in modulus (provided that the normal and shear stiffness of fractures and intact rock are known), or to assess the likely range of various rock mass classification ratings (from which such parameters as stand-up time, support requirements, modulus, and others may be deduced).

6 CONCLUSIONS

The evidence presented suggests that the observed spatial distribution of fractures in at least one rock mass is not random. However, a zonal distribution appears to account for the lognormal model derived for spacing between adjacent fractures of the same set which transect straight line samples.

The spatial distribution of high intensity zones is assumed to be random for a defined volume of rock mass. On the other hand, the 2-d extent of zones in directions parallel and normal to the average orientation of fractures within them may be predicted statistically.

The zonal model approach offers a rapid and simple field method for the statistical evaluation of the rock mass in terms of fracture intensities of each set which is likely to be associated with underground openings of a defined shape and size. The model also provides a basis for the assessment of a number of rock mass parameters, including strength, modulus, stand-up time and others in terms of published rock mass classification systems.

In view of the fact that data collected purely on the basis of single line samples did not furnish all the necessary information for the 2-d or 3-d understanding of the spatial distribution of fractures in rock, the explicit use of this sampling technique should be reassessed. Consideration should be given to use of continuous area samples to supplement line sample data.

7 ACKNOWLEDGEMENTS

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