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Statistical analysis of stochastic blocks and its application to rock support

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ABSTRACT

The orientation, trace length, spacing, and location of probabilistic discontinuities in rock masses are randomly developed. Thus, the shape, size, and location of blocks cut off by these probabilistic discontinuities are accordingly stochastic. It is difficult, or even impossible, to determine the volume and location of the blocks using the block theory proposed by Goodman and Shi (1985). Stochastic block analysis (SBA) is capable of identifying three-dimensional (3-D) stochastic blocks from a randomly developed discontinuity network (discrete fracture network). However, in practice, 3-D blocks are not identified well in simulated fracture networks and so the use of SBA is seldom encountered. In this paper, the procedures involved in stochastic block identification are first outlined. The concept and calculation of overlaying area and ratio are then introduced. Then, the stochastic block identification results are used to explore the statistical distribution of the block size and overlaying ratio. Subsequently, the laws governing development of the stochastic blocks were elucidated. The results show that the block size has a negative exponential distribution and the overlaying ratio follows a Γ distribution. The overlaying ratio increases as the trace length to spacing ratio increases. We further outline, for the first time, approaches to determine block support measures by analyzing the characteristics of the statistical distributions of the stochastic blocks. Block support issues relating to a practical underground plant were also studied. The lengths and anchor forces and spacings of the rock bolts were quantitatively determined according to the results of a statistical analysis of the stochastic blocks. Statistical analysis of stochastic blocks is of great significance in understanding the development characteristics of the stochastic blocks and in quantitatively determining block support measures.

1. Introduction

Rock masses are generally composed of rock blocks and discontinuities. Discontinuities (joints, fractures, faults, bedding planes, etc.) divide the rock mass into blocks of various sizes and shapes. Discontinuities may vary greatly in different rock masses. Rock deformation and instability often result from opening, closing, and shearing of discontinuities. In this way, discontinuities control the stability of the rock mass.

In 1985, Goodman and Shi formally proposed the underlying foundations of block theory (Goodman and Shi, 1985). Classical block theory assumes that discontinuities are infinite planes and the blocks cut by discontinuities and excavation surface(s) act as rigid bodies. The motion of the block is assumed to be translational in nature, i.e. rotational motion is not considered. According to this theory, the removability of a block and the block's failure mode can be analyzed using geometry and topological methods. Potentially unstable or key blocks can be determined by incorporating comparatively simple mechanical analysis. Then, the support forces required for the key blocks can be calculated to ensure the stability of the blocks. Block theory has been researched and applied worldwide due to its applicability to the analysis of the local stability of fractured rock masses.

There are two kinds of discontinuity. Probabilistic discontinuities are represented by joints and deterministic discontinuities are represented by faults. In real rock masses, the magnitudes of the probabilistic discontinuities are much larger than those of the deterministic discontinuities, and surveying the former is much more difficult than the latter. The geometrical parameters of probabilistic discontinuities, i.e. orientation, trace length (or persistence), spacing (or density of the joints), and location, are random. Thus, the blocks cut by probabilistic discontinuities are accordingly stochastic, which means that their shapes, sizes, and locations are stochastic.

During the construction of major rock foundations, joint trace maps can be prepared for the exposed faces of the rock masses. From these maps, all the potential key blocks can be located and

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their volumes and shapes can be determined for timely treatment. However, it may not be possible to acquire such specific data before the rock faces are exposed. Monte–Carlo simulations can be used to repeatedly generate a series of 3-D joint network and 2-D trace maps. In this case, it is difficult to determine precisely the locations and volumes of blocks using classical block theory as the locations, spacing, and lengths of the joints are not fixed (Young and Hoerger, 1989; Goodman, 1995). Accordingly, the stability factor considering the cohesion of the sliding face, and the support force considering the volume of the block, cannot be determined (Zhang, 2010). In order to overcome these shortcomings, stochastic block analysis (SBA) has been proposed (Young and Hoerger, 1989; Shi and Goodman, 1989; Shapiro and Delport, 1991; Wu et al., 1998; Shi, 2002; Hatzor and Feintuch, 2005; Zhang, 2010). SBA can directly identify blocks in the simulated discontinuity network (discrete fracture network, DFN). Then, the geometrical characteristics of the blocks can be statistically analyzed and their degree of development realistically evaluated. Block support measures can be analyzed correspondingly. SBA undoubtedly constitutes significant progress in block theory.

The main components of SBA consist of two parts:

(1) *Geometrical analysis of the stochastic blocks*. The stochastic blocks in the 3-D model of the network of discontinuities are identified by employing block theory and geometrical methods.
(2) *Statistical analysis of the stochastic blocks*. Based on the results from part (1), the volume and area of the block and the overlaying area are calculated and analyzed statistically. This aids understanding of the inherent geometrical features of the stochastic block and helps to determine the block support measures required.

Stochastic blocks can be identified in the simulated discontinuities network. Young and Hoerger (1989) proposed a probabilistic approach to key block analysis. This incorporates several probability distributions (for the joint's orientations, trace lengths, spacings, and friction angles in the rock) which are used to predict the size, shape, and frequency of occurrence of the key blocks. Shapiro and Delport (1991) identified closed triangles in the 2-D joint trace map. Then, geometrical analysis was adopted to calculate the probability an intersection point is located within a rock mass so as to form a complete block. Mauldon (1995) identified stochastic blocks in 2-D. Shi and Goodman (1989), Wu et al. (1998), and Shi (2002) identified stochastic blocks in 3-D using procedures involving generating joint trace maps, cutting trees, finding primary loops, and delimiting the maximum probable regions of the blocks. So there is an implicit assumption in this body of work that joints intersecting the excavation surfaces extend far enough to cut the block entirely at their mutual intersections. Since the extents of the joints are always finite, the maximum probable regions of the blocks are not equal to realistic 3-D blocks. Goodman (1995) applied SBA to the Pacoima Dam, Los Angeles County, US.

Hatzor and Feintuch (2005) demonstrated that the probability that a possibly removable joint pyramid consists of more than three mutually exclusive joints in a space is zero. Consequently, only tetrahedral blocks need to be considered in the stability analysis of the analyzed free surface. In addition, they also developed an expression for the probability of joint intersection. This approach is, in fact, highly appropriate if we cannot determine the exact locations of the joints in the stochastic block analysis.

Zhang (2004, 2010) proposed an approach for identifying the true 3-D stochastic blocks in a 3-D simulated discontinuity network. Based on earlier work in the literature (Shi and Goodman, 1989; Wu et al., 1998; Shi, 2002), these authors obtained true 3-D stochastic blocks by generating joint trace maps, cutting trees, finding primary loops, delimiting the maximum probable regions of the blocks, and their novel method of identifying 3-D blocks according to the occurrence of intersection points located within the rock mass. Visualization of 3-D blocks is very convenient for their application and further study. Furthermore, there is another advantage in that all the blocks can be directly identified from the 3-D DFN. The influence of location, spacing, and size of the discontinuities on the block shapes is considered once and for all. In other words, the identified stochastic blocks are the true ones once the 3-D DFN has been determined using simulations, even if the simulated DFN is significantly different from the real rock mass.

Kuszmaul (1999) proposed a method for estimating key block sizes which accounts for joint set spacing. Using this method, the sizes of the key blocks can be determined more realistically. However, the persistence of the discontinuities was assumed to be infinite. By conducting simulations of fracture networks and blocks using the FracMan and RockBlock codes Starzec and Tsang (2002) quantified the relationship between the total volume of the unstable blocks and the density of the intersections between surface fractures. Unlike approaches directly analyzing the statistical characteristics of blocks based on real 3-D stochastic blocks sought from DFNs, some works in the literature (Mauldon, 1995) studied the statistical distribution in the block size by analyzing the probability of intersection of the fractures in the block formations. As most of the published articles have not successfully identified the true 3-D stochastic blocks in the simulated fracture network, the statistical analysis of stochastic blocks is limited and should be studied further. Furthermore, studies on rock support based on the statistical analysis of stochastic blocks are virtually nonexistent.

2. Main procedures for geometrical identification of stochastic blocks

The procedures for the geometrical identification of stochastic blocks are shown in Fig. 1. Below we give brief introductions to the main procedures involved in the analysis.

2.1. Geological statistical analysis and fracture network simulation

There is much in the literature relating to geological statistical methods and probability distributions of the discontinuity's geometrical parameters. Simulation of 3-D fracture networks is also covered extensively.

Polar equal-area projections and strike rose diagrams are usually used in the statistical analysis of fracture orientations and clusters. Research has shown that a hemispherical normal distribution, a log-normal distribution, or Bingham distribution are suitable for representing the probability distributions of the fractures' orientations (Kulatilake et al., 1993, 1996). The scanline method (Priest and Hudson, 1981) is usually used for measuring and statistically analyzing the spacing between the discontinuities. The results show that a negative exponential distribution is most suitable for describing the spacing's statistical distribution (Priest and Hudson, 1981; Dershowitz and Herda, 1992; Kulatilake et al., 1993, 1996). It can be shown mathematically that the discontinuity spacing obeys a negative exponential distribution when the fractures develop uniformly in space. Scanline and sampling windows (Kulatilake and Wu, 1984) are often used in the measurement and statistical analysis of the fractures' trace lengths. The results indicate that a gamma, log-normal, or negative exponential distribution is suitable for describing the distribution in the trace length (Priest and Hudson, 1981; Einstein and Baecher, 1983; Kulatilake et al., 1996).