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Refined modeling and identification of complex rock blocks and block-groups based on an enhanced DFN model

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ABSTRACT

Valid modeling and identification of rock blocks are the keys to analyzing rock-mass stability. Based on the Monte Carlo method and 2D Poisson point process, an enhanced polygonal discrete fracture network (DFN) model is proposed firstly. The equal area conversion algorithm and subarea simulation method are used to control fracture size and to determine fracture shape, respectively. Then, coupling the polygonal DFN model with the large-scale geological model, a refined rock mass structure model for identifying rock blocks is established. Subsequently, the spatial representations of polygonal fracture planes, complex geological surfaces and free surfaces are presented. And the major characteristics and the refined modeling method of complex rock blocks and block-groups are analyzed. Finally, a modified and precise topology-based identification method of rock blocks and block-groups is put forward. The application in the underground powerhouse of a hydropower station indicates that the proposed approach and scheme are very efficient and can identify arbitrary-shaped rock blocks. The identified rock blocks and block-groups contain geometric information, geological information as well as physical and mechanical information. This research contributes to further study on the stability analysis of rock blocks and block-groups and rock mass seepage.

1. Introduction

There are a large number of blocks in rock masses. Many engineering practices have revealed that the failures of rock masses are caused by the instable rock blocks. Researchers have proposed some methods to analyze fractured rocks, such as block theory, finite difference method (FDM), finite element method (FEM), boundary element method (BEM), discrete element method (DEM), discrete fracture network method (DFN) and hybrid models (Jing, 2003). A fundamental and important step in the analysis of rock blocks is the refined modeling and identification of complex rock blocks. Some researchers have carried out a lot of useful studies over the decades. For example, Heliot (1988) developed a block generator to reconstruct the three-dimensional block structure. Shi and Goodman (1989) identified rock blocks based on searching the closed loops on fracture trace maps. Mao et al. (2005) used the stereographic projection method to study the rock blocks. Nevertheless, the identified rock blocks by these methods were convex blocks. Vector identification method was employed (Ikegawa and Hudson, 1992; Lu, 2002), and they identified three-dimensional multi-block system through edge detection, loop (face) tracing and body identification. González-Palacio et al., 2005 proposed geometrical method to identify both pyramidal and non-pyramidal key blocks in rock masses. Yu et al. (2009) introduced the element-block-assembling approach where the fractures have finite size and the excavation can be an arbitrary complex shape, and similar methods have also been discussed (Zhang et al., 2012; Zhang and Lei, 2013). So far, these identification methods for rock blocks had been able to identify both convex and concave rock blocks.

With the development of the computer technology, researchers attempted to find out new methods that can identify more complex rock blocks. Xu (2009) proposed an algorithm for identifying deterministic and stochastic blocks based on hierarchical rock-mass structure model. Zhang et al. (2010) employed finite element modeling technique to identify rock blocks considering complex profile and layout of underground caverns. Elmouttie et al. (2010) and Zheng et al. (2015) presented new methods for identifying rock blocks formed by both curved and planar fractures. Li et al. (2013) put forward four principles of closure, completeness, uniqueness, and validity to search, identify, and analyze surface

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blocks on the basis of an integrated 3D rock mass model of engineering-scale major geological structures and small-scale minor structural planes. Fu and Ma (2014) and Fu et al. (2016) proposed a force transfer algorithm to consider the force interactions of the adjacent batches of key blocks and presented stability analysis with stochastic representation of rock mass. Xia et al. (2015) presented a new concept of blockiness to measure a rock's level of being an assemblage of isolated blocks. Zhu et al. (2016) demonstrated and evaluated an integrated system coupling three-dimensional binocular photogrammetry and discontinuous deformation analysis (DDA) for identification and stability analysis of rock blocks in tunnels. Ma et al. (2016) applied the Continuous-Discontinuous Element Method (CDEM) to simulate micro-cracks of rock masses under excavation-induced unloading conditions.

In conclusion, currently it still lacks effective technical approaches to measure the exact or actual spatial extension for large amounts of finite fractures, and block identification methods have been developed from 2D to 3D and from identification of simple rock blocks to identification of complex rock blocks. However, the rock mass structure models for block identification are mostly geometric models. Wang et al. (2013) adopted Monte-Carlo method to reproduce the location and shape of joints around a tunnel in the joint modeling process. Based on the quantified relationship between total unstable block volume and fracture spacing (Starzec and Tsang, 2002) and the bootstrapping technique (Rogers et al., 2006), Elmo et al. (2014) developed a full-scale DFN model including fracture orientation, size and intensity from all available geotechnical data. Zhang et al. (2014) studied the statistical distribution laws of the block size and overlaying ratio according to the results of geometrical identification of stochastic blocks. Some geological surfaces such as the complex slope surfaces are often simplified as planes or curved surfaces, though they are poly-surfaces in practice. In this case, the identified blocks may be very different from their actual shapes. Moreover, the rock block-groups that contain many geometrically connected blocks have not been identified availably. Although some methods can identify both convex and concave rock blocks, the complicated rock blocks and block-groups with surfaces and poly-surfaces are still difficult to be identified. Meanwhile, some methods lack efficiency when the fractures are dense due to a great deal of computation.

Our identification method is improved based on our previous work (Li et al., 2013, 2016), and an enhanced DFN model is employed rather than Baecher disk model and the identification process are improved to identify both the complex blocks and block-groups efficiently. It is useful to stability analysis and support design of rock blocks in small volumes of fractured rock masses. In order to identify complex blocks, five steps are conducted as follows: (1) An enhanced method for simulating random polygonal discrete fracture network is presented. (2) Coupling with the geological model, a refined rock mass structure model is established. (3) The geometrical characteristics of the complex rock blocks and block-groups are analyzed. (4) A valid identification scheme based on computer graphics and mathematical geology is described in detail. (5) The proposed approach is applied in a case study.

2. Enhanced polygonal DFN model

The refined rock mass structure model is the basis of the accurate identification of complex rock blocks. It can be divided into large-scale geological structures and small-scale geological structures to model respectively, which will be integrated as a refined rock mass structure model according to their actual position in the engineering area.

At present, the modeling of large-scale 3D geological structures such as strata, faults and weak layers is relatively mature and has been applied widely in engineering. Here an integrated 3D geological modeling methodology based on the non-uniform rational B-spline (NURBS) technique, the triangulated irregular network (TIN) algorithm and boundary representation is adopted (Zhong et al., 2006). It has been proved to be a precise and effective modeling approach for complicated geological conditions in lots of large engineering.

For small-scale geological structures mainly refer to discrete fracture network (DFN), the simulation is implemented with hypothetical probability models. Both polygonal and disk fracture models are proposed based on certain hypothesis and mathematical generalizations and are so far recognized feasible for fracture modeling. Currently, there are mainly five kinds of DFN models as follows: Orthogonal model (Weiss, 1972), Baecher disk model (Baecher et al., 1977), Veneziano model (Veneziano, 1978), Dershowitz model (Dershowitz and Einstein, 1988), Mosaic block tessellation models and the modified tessellation models (Ivanova et al., 2014).

The application of orthogonal model is limited due to the excessive assumptions. The complex modeling process, incomplete expression of fracture geometric characteristics and necessarily discarded fracture-unlike polygons make above three conventional polygonal models rarely apply to engineering practices. Nowadays, Beacher disk model is the most commonly used model for small volumes of fractured rock mass in engineering, because the modeling process is simple and can basically meet the needs of the project. However, as we all know rock masses are inhomogeneous, discontinuous and anisotropic medium. Fracture shape has to do with fracture mechanics and energy at the crack tip. They usually extend to be polygons rather than discs in practice. Besides, investigations from the filed also indicate that polygon is more appropriate to express fracture shape.

Considering fracture shape is important to the sizes, shapes and volumes of rock blocks in small volumes of rock mass, an enhanced polygonal DNF is proposed based on Monte Carlo method and 2D Poisson point process. The study mainly focuses on the simulations of fracture shape and size, while the simulations of its position, orientation, density (spacing) and trace length are similar to Baecher disk model (Barthélémy et al., 2009).

2.1. Simulation of polygonal fracture size

It can be proved that on a two-dimensional finite plane that takes (0, 0) as the center point, if the incidence of per unit area of Poisson points λ is a constant value, then the two-dimensional Poisson process is a stationary random process. In such case, the length of the line segment d that between any Poisson point and the center point obeys to Rayleigh distribution. The angle θ between the line segment and the X axis obeys to uniform distribution (Guo et al., 2013). Therefore, as long as the occurrence probability and occurrence area of Poisson points are determined, d and θ can be simulated. Then the 2D coordinates of the Poisson points are obtained and regarded as polygonal vertexes.

Observations from the field suggest that polygonal fracture shape is often not more than 6-sided. The number of a fracture's sides in polygonal models that currently proposed by researchers is also generally between 4 and 6 (Mao et al., 2005; Ivanova et al., 2014). In fact, fracture shape is governed by mechanics and geology. The fractures in diverse types of rock masses may have different sides. For instance, a 4-sided shape is appropriate for simulating fractures in mechanically layered rock while a 6-sided equidimensional shape is more suitable for simulating fractures in massive granites. After the number of a fracture's sides n is determined, the occurrence probability of Poisson points is always