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A stepwise approach for 3D fracture intersection analysis and application to a hydropower station in Southwest China

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ABSTRACT

A stepwise algorithm for determining the intersections between fractures is presented. The stepwise approach is based on the bounding volume technology and separating axis theorem. The length and orientation distribution of the fracture intersections can be obtained by the stepwise approach. The stepwise approach is used to study the connectivity of the rock mass at Songta hydropower station. According to the traces data acquired from a tunnel namely PD231, a DFN model was generated for intersection analysis and connectivity analysis. The results of intersection analysis show that the stepwise approach is effective. Connectivity parameters such as the average number of fracture intersections per fracture, and the length of intersection lines per unit volume, can be calculated. The mean length of intersections is 1.184 m and the variance is 0.622 m. The self-intersection behavior and direction vector of the intersections are studied. The simulations show that the sub-vertical joint set 3 and the shallow joint set 1 constitute the main flow pathways in the fractured rock at dam site. Besides, the results suggest that the sub-vertical joint sets (joint set 2 and 3) are more connected than the shallow joint set (joint set 1).

1. Introduction

Fractured rock is widely distributed in the shallow subsurface of the earth. Fractures endow the rock mass with discontinuous, inhomogeneous, and anisotropic features, which have significant influence on the properties of rock masses, such as deformation, strength, permeability, and failure[1]. It is extremely difficult to investigate the 3D properties of fractures in the field[2]. Besides, fractures are generally randomly distributed in rock masses[3]. Therefore, it is popular to using sampling method to acquire the information of fractures in natural or artificial outcrop[4]. Subsequently, the discrete fracture network (DFN) can be constructed based on the theory of statistics and probability[5, 6].

At present, the actual shape and size of fractures are still not available. For simplicity, some assumptions are adopted for the geometry of the fractures. The most common models to represent fracture shapes in 3D case are disks, ellipses and polygons[7–9]. Due to the simple geometrical configuration of the disk network model, most researchers use the disk network model for seepage computations and practical engineering.

The fracture network, which is composed of fractures, is usually the primary flow path for groundwater flow and solute transport in fractured rocks. So the DFN model is widely used in practical engineering, such as groundwater pollution, nuclear waste storage, geothermal system, and mining water inrush. The pathways for the transportation of fluid are defined as the interactions of fractures (i.e., their intersections)[9]. Because of the complexity of fracture sizes and locations, there are some isolated fractures in the DFN. The isolated fractures don't intersect with other fracture, which have no contribution to the construction of the flow path. Besides, the existence of isolated fractures will increase the amount of computations in the flow path searching. Therefore, it is necessary to remove the isolated fractures in the DFN by intersection analysis in the process of the flow path searching. Intersection analysis is a useful tool to identify all pairs of intersected fractures in the study region[10]. In addition, intersection analysis is a crucial procedure to search the flow paths and the isolated fractures.

In some practical engineering, there are massive fractures in the rock mass. Therefore, a large number of fractures are generated to characterize the actual rock mass in the DFN model. To ensure the accuracy of the model, it is obligatory to build tens or hundreds of DFN models to obtain a reliable DFN model. Thus, the construction of the DFN model and the search of the flow path must be very efficient to meet the actual needs. Researchers have studied the method of intersection analysis for 2D or 3D DFN model, which the exhaustion algorithm is adopted to precisely

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identify whether two fracture intersect each other[9,11–13]. Each possible pair of fractures is checked for the intersection test in the exhaustion algorithm (i.e., a total of $1/2(N^2–N)$ times for N fractures). Besides, the precise identification of pairwise fracture intersections is time-consuming. In order to overcome the above defects, this paper proposes a stepwise approach for intersection analysis.

The connectivity of the fracture network is a crucial parameter to assess the flow behavior and stability of a rock mass[11,14]. Connectivity of a DFN model is a metric of the extent to which the fractures in the network are connected to each other and form flow paths or weak plane[15,16]. The number of intersections between fractures per unit volume C_I, the average number of fracture intersections per fracture λ, and the length of intersection lines per unit volume L_I are always used to describe the fracture connectivity[17–21]. The geometry parameters of the fractures have a significant effect on the connectivity of DFN model[11,21], so it is necessary to do further research.

2. A stepwise approach for fracture intersection analysis

2.1. Precise identification of pairwise fracture intersections

The Baecher disk model developed by Baecher et al.[7] is adopted in this work. The precise identification of pairwise fracture intersections can be determined by the geometrical parameters of the fractures. The geometrical parameters of the ith fracture are represented by six parameters: the coordinates of the disk center (x_i, y_i, z_i), dip angle (α_i), dip direction (β_i), and diameter (d_i). The circle of the ith fracture can be represented mathematically by:

$$\begin{cases} A_i(x-x_i)+B_i(y-y_i)+C_i(z-z_i)=0 & (1)\\ (x-x_i)^2+(y-y_i)^2+(z-z_i)^2=\dfrac{d_i^2}{4} & (2)\end{cases} \tag{1,2}$$

where A_i, B_i, and C_i are equal to $\sin\alpha_i\cos\beta_i$, $\sin\alpha_i\sin\beta_i$, and $\cos\alpha_i$, respectively.

Similarly, the circle of the jth fracture can be expressed by the following equation:

$$\begin{cases} A_j(x-x_j)+B_j(y-y_j)+C_j(z-z_j)=0 & (3)\\ (x-x_j)^2+(y-y_j)^2+(z-z_j)^2=\dfrac{d_j^2}{4} & (4)\end{cases} \tag{3,4}$$

where A_j, B_j, and C_j are equal to $\sin\alpha_j\cos\beta_j$, $\sin\alpha_j\sin\beta_j$, and $\cos\alpha_j$, respectively.

Fracture intersection is only possible to be obtained when both fractures intersect the intersecting line between the two planes. Eq. (1) and Eq. (3) represent the planes on which ith and jth fracture disk belong to, respectively. The angle θ of the two planes can be obtained by:

$$\theta=\cos^{-1}\frac{|A_iA_j+B_iB_j+C_iC_j|}{\sqrt{(A_i^2+B_i^2+C_i^2)\times(A_j^2+B_j^2+C_j^2)}} \tag{5}$$

If θ is equal to zero, it can be known that the two planes are parallel to each other and there is no intersecting line. Otherwise, there is intersecting line between the two planes. If θ is not equal to zero, it is then determined if the two fracture disk intersect the intersecting line. Eq. (1), Eq. (2), and Eq. (3) are combined into a simultaneous equation. If there are two real solutions of the simultaneous equation, the ith fracture disk intersects the intersecting line. Similarly, Eq. (1), Eq. (3), and Eq. (4) are used to determine if the jth fracture disk intersects the intersecting line. Note that if there is one intersection point between the two fracture disks, it would be treated as no intersection in this paper.

Fig. 1 shows that the intersection points can be arranged in three possible ways along the intersecting line[11]. The two fracture disks intersect each other only if the line segment A_1A_2 and B_1B_2 intersect (Fig. 1(a) and (b))[22]. Therefore, it is necessary to sort the four intersection points, and then determine whether the two fracture disks intersect. The detailed flow chart is shown in Fig. 2 and the calculation method of intersecting line length is presented.

If each possible pair of fractures is checked for the precise test (i.e., a total of $N(N-1)/2$ times for N fractures), the amount of computation is very large and it is time-consuming.

2.2. Bounding volume

A closed volume that totally contains a set of objects is called a bounding volume (BV) for this set. The BV concept is widely used in computer graphics, computational geometry and percolation theory (e.g. excluded volume)[23–25]. The objective of a BV is to provide simpler intersection tests and faster responses[26]. Spheres allow the simplest overlap tests[23]. According to the diameter and the center coordinates of a fracture disk, a bounding sphere that contains the fracture disk can be built. To test whether or not two fracture disks intersect, the bounding spheres are built first and further checked whether they overlap. If the bounding spheres are not overlapping, then the fracture disks are guaranteed not to overlap. The judgment conditions of intersection are expressed by:

$$D<(d_1/2+d_2/2) \tag{6}$$

where D denotes the distance between the center of the two spheres; d_1 and d_2 denote the diameter of the fracture disks, respectively.

It is much easier to identify intersection of spheres than to identify intersection of disks in 3D. Besides, a fracture disk usually intersects a very small portion of the fracture disks in the DFN model. Consequently, the massive precise identifications of pairwise fracture intersections can be avoided. In other words, a large number of operations can be reduced by using bounding sphere overlapping test.

2.3. Separating axis theorem

Separating axis theorem (SAT) is a technique to determine if two convex polygons are intersecting and it is widely used in the collision detection for games design and computer graphics[27]. SAT states that: if an axis can be found along which the projections of the two convex objects do not overlap, then the objects don't overlap. For convex polygons A and B in the Fig. 3, Fig. 3(a) shows two nonintersecting polygons and Fig. 3(b) shows two intersecting polygons. As shown in Fig. 3(a), the line where the convex polygons have disjoint projections is called the separating axis, and a separating line is the line that is perpendicular to the separating axis, without touching either polygon (in 3D, it is called the separating plane theorem).

In general, only the normals of each polygon's edges must be tested to determine the relationship of the two polygons in 2D case[28]. For example, for rectangle A and B in Fig. 4, four axes (A1, A2, B1 and B2) is the only potential separating axis. If a separating axis can be found, it is indicated that two polygons are non-intersecting. So the algorithm of SAT can immediately exit when the first separating axis is found. For instance, only one judgment is needful for the rectangle A and B in Fig. 4 (test on the A1 axis). Besides, the implementation of SAT uses the simple basic vector math. The computational efficiency of the program is high.