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Solution of two key issues in arbitrary three-dimensional discrete fracture network flow models

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SUMMARY

It is necessary to consider a great number of arbitrarily developed fractures in applications involving realistic 3-d fracture network flow models of rock masses. In order to model the fluid flow in a complicated arrangement of discrete fracture networks (DFNs), two core issues have to be solved. Firstly, how does one identify the connection relationships between fractures in the 3-d arbitrary fracture network? Secondly, how can one calculate numerically the fluid flow in arbitrarily-shaped 2-d domains? This paper first proposes that the boundaries of all enclosed blocks form flow pathways. All enclosed blocks can be identified using a 3-d block cutting method. The boundaries of the blocks are composed of loops which are formed by intersecting lines between all faces (fractures and other surfaces). Therefore, the connection relationships between fractures can be determined according to the linkages of the loops. Accordingly, the linkages of the finite element nodes between different faces can also be determined. On the other hand, the fluid flow occurring in the fractures can be treated as a 2-d continuous flow within the arbitrarily shaped loops in the fracture's local coordinates. We propose that these loops can be meshed into triangles using a method of simplex triangulation of the arbitrarily shaped domain. Then, according to the linkages between nodes, the global conductivity matrix can be assembled and the solution of the equations governing flow can be derived. Three cases are used to validate the model. Finally, an analysis is made of a practical engineering example (with 8914 lines of intersection and 4188 loops) which shows that the proposed flow model is practicable and can deal with complicated DFNs.

1. Introduction

Fluid flow in discontinuous rock masses is predominantly controlled by the characteristics of fractures that develop (aperture, orientation, extension, spacing, etc.), and shows great anisotropy. There are many related subjects which are not well understood and need to be studied further. These include *in situ* investigations of the geometrical and physical attributes, testing and characterization of hydraulic properties, theoretical study of fluid flow models and their numerical simulations, as well as verification, application, and interpretation of the modeling results. For example, the inherent complexity of fracture network formations severely limits the certainty of the data obtained from field measurements. Furthermore, the uniqueness and reliability of model calculations will be similarly doubtful. For a summary of some of the critical unsolved problems concerning fluid flow analysis in fractured rock masses, the reader is referred to the work of Berkowitz (2002).

This paper focuses on a three-dimensional (3-d), numerical flow model for arbitrary fracture networks. There are three major kinds of approach used for modeling fluid flow in fractured rocks. These are based on the so-called equivalent porous medium (EPM), discrete fracture network (DFN), and fractured porous medium (FPM) flow models.

The EPM flow model assumes the rock mass consists of continuous porous media. This kind of model is based on the notion and existence of a representative elementary volume (REV) and an associated REV-averaged permeability tensor (see, for example, Long et al., 1982; Wang et al., 2002; Hitchmough et al., 2007; Coli et al., 2008). Although this kind of model is the one that has been most widely used, they are inappropriate under conditions in which the REV can only be defined on a scale that is similar to the problem of interest or, if a network consists of fractures, there is no characteristic size limit.

The DFN model assumes that the rock matrix is impermeable and groundwater can only flow through the fracture system (Tsang and Tsang, 1987; Cacas et al., 1990; Kolditz, 1995; Maryška et al., 2004; Kalbacher et al., 2007; Erhel et al., 2009; Blöcher et al., 2010; Pichot et al., 2010; Blessent et al., 2011;

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Mustapha, 2011). The DFN approach can effectively reflect the anisotropy of the fractured rock mass and is more suitable when the rock matrix is less permeable. A 2-d DFN model can deal with planar anisotropy. However, the anisotropy in real fractured rocks is mostly 3-d as the orientation of most fractures develop randomly. Thus, the advantage of a fully 3-d DFN model is that it is able to match the non-planar anisotropy of real fractured rocks. In a 2-d model, fluid flows through intersections from one 1-d fracture segment (with a certain aperture) to another. The connections between segments are easy to analyze and 2-d modeling is comparatively well developed. However, the development of 3-d DFN models has been slow due to the complexity of the configurations involved and the seepage properties of the 3-d fractures in real fractured rocks.

The FPM flow model (also called discrete fracture continuum flow model or dual-medium flow model) considers that fluid simultaneously flows within fractures and through block matrices embedded in fractures (Huyakorn et al., 1983; Castaing et al., 2002; Peratta and Popov, 2006; Hoteit and Firoozabadi, 2008; Hattingh and Reddy, 2009; Blessent et al., 2011; Mourzenko et al., 2011). Discrete fractures are used to describe the fluid movement in major structural planes, e.g. faults, which are usually of high hydraulic permeability. Porous media are used to describe the fluid movement in rock matrices and minor fractures. This kind of model can benefit from the advantages of both the continuum model (representing the block matrix flow) and the DFN model (simulating the high conductivity of the fractures). This kind of model is the best choice when the effects of storage or conductivity of the rock matrix cannot be neglected (especially if the study involves energy or solute transport, e.g. petroleum and geothermal applications). In addition, when the quantity of fractures is excessively large such that simulation using DFNs is unwieldy, the permeability effects of small fractures may be averaged into the matrix so that only the bigger fractures need to be simulated explicitly. Thus, an FPM model may require only a low calculation capacity but still be used to solve problems involving large-scale fractured rock masses. In short, FPM models have a broader perspective in practical applications. As the theory used to simulate flow in fractures is similar to that required in a DFN flow model, advances in FPM flow modeling depends to a large degree on the breakthroughs made in DFN flow modeling.

Flow models have been studied and widely applied in industries related to nuclear waste disposal, reservoir exploration, and water resource utilization. Selroos et al. (2002) and Tsang et al. (2005) have summarized the characteristics and differences between different models using realistic simulations in relation to the DECOVALEX III project.

This paper focuses on a 3-d DFN flow model. It is popular to assume a parallel plate model may be used to simulate flow transport in fractures. In this model, the fractures are assumed to be smooth and parallel, which is obviously different to real fractures, as pointed out by Mourzenko et al. (1996). The fractures in real rocks are rough and not parallel and they have gouges or fillings between their two faces. So, the internal heterogeneity of the fractures is obvious. However, precise measurements of the roughness, aperture, orientation, and size of the fractures in real rocks are very difficult to achieve. Hence, simplifying fractures as two parallel faces with deterministic apertures is widely accepted.

In the parallel plate model, there are two approaches used to numerically simulate the planar flow. One is to convert the DFN into a network of pipes which have approximately equivalent connectivities, flow rates, and hydraulic properties as the planar fractures (Tsang and Tsang, 1987; Cacas et al., 1990; Nordqvist et al., 1992). The pipe elements are 1-d and this approach is called 'the pipe network model'. The other approach is to explicitly discretize the fracture planes into finite elements and use the finite element method (FEM) (Kolditz, 1995; Maryška et al., 2004; Kalbacher et al., 2007; Erhel et al., 2009; Blöcher et al., 2010; Pichot et al., 2010; Mustapha, 2011). The FracMan/MAFIC software developed by Golden Co. adopted both kinds of approach (Fox et al., 2005). In addition, Andersson and Dverstorp (1987) used a boundary element method to solve the fluid movement in fractured discs.

In the pipe network model, flow simulations are carried out in the pipe network to determine the head field within the model. A pathway search algorithm has been developed by employing graph theory to identify and characterize the flow pathways between designated sources and sinks (Dershowitz and Fidelibus, 1999; Outters and Shuttle, 2000). As the pathways identified are not unique, a preferential pathway is chosen by optimizing a user-specified priority ranking such as the flow rate. This aspect makes a pipe network model difficult to use when the connection relationships between the discrete fractures are complex. However, some scholars believe a pipe network approach can simplify an otherwise computationally intensive task (this computational intensity does not necessarily arise from the complexity of the connection relationships between fractures). When the connection relationships between the fractures are complex, those between pipes are difficult to determine and the resulting flow pathways may be inconsistent with the actual physical phenomena. In fact, the real pathways, which should be unique for a specified fracture network and set of boundary conditions, can be determined automatically by the flow balance in the calculations. In addition, as Erhel et al. (2009) pointed out, it is difficult to choose the hydraulic parameter of a pipe (this should be approximately equivalent to that of the portion of the fractures represented by the pipe). The assumption that the fluid flows from center to center is also unrealistic, especially in the case of complicated DFNs.

In FEM-based numerical modeling, all fractures are used to construct the flow paths except for those which are isolated or partially connected with others or inflow and outflow boundaries. Fluid flow in a 3-d DFN is actually assembled from many facial flows within the various fractures. The fluid exchange between different fractures occurs through their common intersection lines according to the law of conservation of mass. So, the relationships between intersections in the fractures control the flow paths and, consequently, the connection relationships between FEM nodes. Using the connection relationships between nodes, the elements meshed in each individual fracture can be assembled together to form a global conductivity matrix. In terms of FEM principles, the consistency of the discretization of the intersecting line belonging to two neighboring fractures ensures the correct connection between the finite elements so as to ensure local and global mass conservation. Therefore, it is crucial to determine the intersection relationships between fractures which control the linkages between FEM nodes.

When the configuration of the DFN is simple, discretizing fractures into elements may be easy and it may not be necessary to give special consideration to the linkages between fracture intersections. Most meshing software can deal with this scenario properly (Kolditz, 1995; Blöcher et al., 2010; Pichot et al., 2010; Mourzenko et al., 2011). However, when the DFN configuration is complex, it is not easy to properly determine the linkages between fractures and to correctly discretize the 2-d domains of each fracture. Several solutions have been proposed for solving the problem of fracture connections. Discretization of the DFN has been manually implemented via local modification of the grids (Kalbacher et al., 2007), by making small modifications of the fracture network structure (Maryška et al., 2004), by slightly modifying the structure using a 'projection method' (PM) (Mustapha, 2011), and other similar methods (Erhel et al., 2009). Based on the hypothesis that water pressure can be considered to be constant along short intersections (or represented using a piecewise constant function),