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Fractured porous medium flow analysis using numerical manifold method with independent covers

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ABSTRACT

Due to the complexity of geometry and the difficulty of mesh discretization of 3D (three-dimensional) blocks cut by complexly distributed fractures, explicitly considering arbitrary fracture network in fractured porous medium (FPM) flow analysis is very challenging for various numerical methods. In this study, we developed a FPM flow model by taking full advantage of numerical manifold method (NMM) with independent covers. With the independent covers, arbitrarily-shaped 3D blocks identified by block-cutting analysis can be directly used as basic computational elements. Along the boundaries of the divided blocks, fractures elements are generated according to the fractures' apertures. Therefore, it is able to handle very complicated fracture network in 3D flow analysis without need to subdivide 3D blocks into computational meshes. In order to refine the meshes, we introduced artificial fractures with same material properties as surrounding rock into a fracture network, without need to coordinate with the shapes of the blocks. We demonstrated our new model on different 2D examples. At last, we applied our model to 2D and 3D examples with complexly distributed fractures, and achieved reasonable results. The results show that our model is very powerful to analyze fluid flow in arbitrarily and complexly fractured rock mass in 3D.

1. Introduction

There are three major kinds of approach used for modeling fluid flow in fractured rocks. These are based on the so-called: (i) equivalent continuum medium or equivalent porous medium (EPM), (ii) discrete fracture network (DFN), and (iii) fractured porous medium (FPM) or dual-medium 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 (Long et al., 1982; Hitchmough et al., 2007; Coli et al., 2008; Rong et al., 2013). The DFN model assumes that the rock matrix is impermeable and that the groundwater can only flow through fracture system (Tsang and Tsang, 1987; Cacas et al., 1990; Maryška et al., 2004; Kalbacher et al., 2007; Erhel et al., 2009; Pichot et al., 2010; Mustapha, 2011; Jiang et al., 2014; Zhang and Yin, 2014; Zhang, 2015a,b). This kind of model can reflect the essential characteristic when the groundwater is mainly controlled by the fracture system and is more suitable for the rock matrix with much less permeability than the fractures. The FPM flow model considers that the fluid simultaneously flows within fractures and through block matrices in which the fractures are embedded (Huyakorn et al., 1983; Bogdanov et al., 2003; Peratta and Popov, 2006; Hoteit and Firoozabadi, 2008; Hattingh and Reddy, 2009; Grillo et al., 2010; 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 filled with a porous medium having different flow properties (e.g. porosity and permeability) from those of the porous medium of block matrices, and usually of high hydraulic permeability. Block matrices are used to describe the fluid movement in rock matrices and minor fractures. The fluid exchanges between rock matrices and fractures. Thus, this kind of model can benefit from the advantages of both the EPM models (representing the flow in the block matrices) and the DFN models (simulating the high conductivity of the fractures). In short, the FPM models have a broader perspective in modeling groundwater flow in strongly heterogeneous geological media. Besides, from the basic assumptions and characteristics of these three categories of flow models we can find that they are problem-dependent (in the sense that the use of one in lieu of the others depends on the physical problem to solve) and are, thus, not equivalent.

In the earlier time, the fractures and the rock matrices were equivalent to two different porous media in the FPM flow models. These two kinds of media were overlapped each other and

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possessed different water pressures in a same position. Hence, the fractures had not special positions and shapes. Lately, most models consider explicitly the existence of the fractures which have special positions, shapes and permeabilities. The fractures subdivide the rock mass to form block matrices, and cut each other to form fracture facets as well. The block matrices may be very complexly shaped when the fractures are complexly distributed. Water exchanges happen at the interfaces between fractures and rock matrices. The permeability of the fractures is usually high, whereas the aperture (width) of fractures is much smaller than both the extensions of fractures and the dimensions of rock blocks. These characteristics may cause discontinuity of some calculated physical quantities and difficulty in numerical calculations due to the great difference of the conductivity between fractures and rock matrices.

The finite element method (FEM) was usually used to study the FPM models. The fractures and the rock blocks need to be discretized into FEM meshes. Besides, the finite volume method (FVM) (Grillo et al., 2010; Reiter et al., 2012) and the boundary element method (Peratta and Popov, 2006) are also used in this study. Almost all the numerical methods, including the FEM, the finite difference method (FDM) and the FVM, have strict requirements in the computational meshes: the meshes are usually generated within the solving domains (A solving domain is corresponding to an arbitrarily-shaped block or a fracture facet generated by fracture network cutting in FPM flow model) with the constraints of geometrical features of the domains' boundaries. The meshes should be compatible with each other, i.e. the connection relationships between the meshes associated with fractures and blocks should be identical both in their common intersection lines and at their common interfaces. The meshes should not be too distorted in order to guarantee the computational precision. Actually, the meshless methods also have computational meshes and the solving domains' boundaries affect the arrangement of meshes.

When the amount of fractures is small and the configuration of fracture networks is simple, it is easy to generate the computational meshes within the solving domains and to ensure consistency of meshes in both the common intersection lines and interfaces. However, the configuration of fracture networks may be very complicated in natural rock masses. The shape of rock blocks may be arbitrary and very complex. According to the results of three-dimensional (3D) block-cutting analysis (Zhang, 2015a, 2015b), a great number of blocks may be identified from a fracture network, a block may be of dozes of or hundreds of surfaces, and the intersection distances and intersection angles may be very small when the fractures are dense, finite and arbitrarily oriented. Under such conditions, it is very difficult and even impossible to discretize 3D blocks into FEM meshes.

The Delaunay triangulation/tetrahedralization methods were employed in most researches to discretize the fractures and/or blocks (see, for example, Taniguchi and Fillion, 1996; Bogdanov et al., 2003; Blöcher et al., 2010; Mustapha, 2011). Other methods, such as the advancing-front techniques, have also been applied (Koudina et al., 1998; Maryška et al., 2004; Mourzenko et al., 2011). These meshing methods can produce fine meshes, but they are not flexible enough when dealing with complicated intersections between fractures. An extremely large number of meshes or low-quality meshes may be generated when small intersection distances or tiny angles between fractures exist. Besides these, it is not easy to ensure the consistency of the meshes within the common intersection lines and interfaces. According to the figures and algorithms given in these literatures, the intersection relationships between fractures were usually somewhat simplified.

HydroGeoSphere, a famous software in groundwater simulation, did not discuss the issue associated with complicated configuration of fractures (Therrien et al., 2009; Blessent et al., 2011) in their FPM flow models.

The extended finite element method (XFEM) allow the fractures to be non matching with the edges of the grids of block matrices (Fumagalli and Scotti, 2014; Formaggia et al., 2014). So, this approach is an commendable tool for modeling flow in porous media with arbitrary distribution of fractures. However, the configuration of fractures is very simple and the 3D problems have not been studied in these literatures.

In general, it is very difficult or even impossible to generate computational meshes when the 3D blocks are complex enough in their geometries. However, the mesh discretization is unnecessary in FPM analysis by using numerical manifold method (NMM) with independent covers. Therefore, both the difficulties in mesh discretization and the disadvantages caused by the triangu lation/tetrahedralization methods, such as low-quality or large number of meshes due to the existence of small intersection distances or tiny angles between fractures, can be avoided.

The NMM proposed by Shi (1991, 1995) has two independent cover systems, i.e. mathematical cover system and physical cover system. The mathematical covers, which are used to construct an approximation physical field, are not required to coincide with physical domains, i.e. the construction of mathematical covers is independent of the boundaries of physical domains and can be of arbitrary shape. The simplest shape for the mathematical covers are triangular, rectangular and tetrahedral. The physical covers, divided mathematical covers by physical boundaries define the integration area of physical domains. The computational elements (called manifold elements) are the overlapped parts of physical covers. As for flow analysis using NMM, the present studies mainly focused on the solution of Navier-Stokes equations (Zhang et al., 2010), analysis of free surface flow (Jiang et al., 2010; Wang et al., in press) and flow in heterogeneous media (Hu et al., 2015), and so on. These studies mainly focus on two-dimensional (2D) problems with simple physical boundaries.

This paper first briefly introduces the conception of NMM. Then, the origin and conception of the independent cover (Su et al., 2013a, 2013b; Su and Qi, 2013; Lin and Su, 2014) are introduced. By using the NMM with independent covers, any arbitrarily-shaped blocks cut by fractures can be used individually as computational elements. Block cutting analysis are used to identify all the arbitrarily-shaped blocks from complicated DFN and the approach of generation of manifold elements is proposed. Then, the formulae of FPM model are presented. Finally, demonstration examples are presented and 2D and 3D cases are studied. By this approach, the FPM flow model can be extended into the flow analysis of realistic fractured rock mass of arbitrary fracture networks, which is no doubt a great advance in the development of flow model. In the other hand, one will be free from arduous tasks of mesh subdivision. The NMM with independent covers provides a powerful approach for numerical analyses concerning fractured rock masses and other arbitrarily-shaped solving domains.

2. Arbitrarily-shaped cover and independent cover in NMM

2.1. Brief introduction of NMM

For numerical modeling of various problems such as groundwater flow, most of the numerical methods (e.g. the FEM, the FDM and the FVM) have strict requirements of the computational meshes. The meshes, generated with some special techniques, should be "compatible", "consistent" and "not too distorted", as pointed out above. Hence, the geometric feature of the solving domains dramatically affects the meshing difficulty and quality. However, the fractures in natural rock mass may be very