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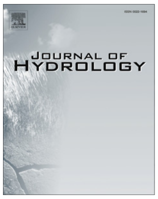

Research papers

Unified pipe network method for simulation of water flow in fractured porous rock

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ABSTRACT

Rock masses are often conceptualized as dual-permeability media containing fractures or fracture networks with high permeability and porous matrix that is less permeable. In order to overcome the difficulties in simulating fluid flow in a highly discontinuous dual-permeability medium, an effective unified pipe network method is developed, which discretizes the dual-permeability rock mass into a virtual pipe network system. It includes fracture pipe networks and matrix pipe networks. They are constructed separately based on equivalent flow models in a representative area or volume by taking the advantage of the orthogonality of the mesh partition. Numerical examples of fluid flow in 2-D and 3-D domain including porous media and fractured porous media are presented to demonstrate the accuracy, robustness, and effectiveness of the proposed unified pipe network method. Results show that the developed method has good performance even with highly distorted mesh. Water recharge into the fractured rock mass with complex fracture network is studied. It has been found in this case that the effect of aperture change on the water recharge rate is more significant in the early stage compared to the fracture density change.

1. Introduction

Fractures are important geological structures that affect both mechanical and hydraulic behavior of rock mass. A number of numerical methods have been proposed to reflect the influences of fractures on fluid flow in natural rock mass, among which dual continuum models and their variations (Barenblatt et al., 1960; Blaskovich et al., 1983; Warren and Root, 1963; Wu and Pruess, 1988) have been widely used due to the simplicity of treating fractured rock as a homogeneous continuum. Recently reported continuum model (Gan and Elsworth, 2016) is able to simulate large-scale reservoir including the long-term coupled thermal–hydraulic–mechanical response. However, the traditional continuum models, without explicit representation of fractures, inherently suffer the drawbacks such as over homogenization of characteristics of individual fractures (Reeves et al., 2014), neglect of complex patterns of fracture connectivity (Liu et al., 1998), and some non-physical adjustable parameters caused by the homogenization, and the introduction of the fluid interchange term between fractures and the matrix (Singhal and Gupta, 2010).

For accurately catching the complex geometry of fractures and their spatial connectivity, discrete models are more suitable. Because of the relative low permeability of the matrix block of hard rock, only the permeability of the intricate fracture network is considered in many cases. For rocks with significant porosity and permeability, consideration of the interaction between the fractures and the rock matrix is necessary. The difficulties of implementation of discrete models mainly lie in the complexity of the geometry of fracture networks and the interaction between the two media, the fractures, and the rock matrix, which have drastically different material properties. Furthermore, the computational cost is another important issue when the number of the fractures increases.

Most discrete models implement relatively sophisticated mathematical models to achieve accurate results. The FEM (Baca et al., 1984; Karimi-Fard and Firoozabadi, 2003; Kim and Deo, 2000; Kolditz, 1995; Noorishad and Mehran, 1982) is one of the representative methods to solve the governing equation describing the flow in both fractures and matrix. Commercial software is also available such as ConnectFlow (AMEC, 2012) and Fracman (Dershowitz et al., 1998). To guarantee mass conservation for multi-phase flow, a mixed finite element and discontinuous Galerkin method (Hoteit and Firoozabadi, 2006; Hoteit and Firoozabadi, 2008; Rivière et al., 2000) is required. Another numerical method to conduct

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simulation of fractured porous media is using the control volume method (Bogdanov et al., 2003a,b; Castaing et al., 2002; Hyman et al., 2015; Karimi-Fard and Durlofsky, 2016; Reichenberger et al., 2006) or the mixed mimetic finite difference method and finite volume method (Huang et al., 2014; Yan et al., 2016). However, these methods involve complicated mathematical calculation. It is also arduous for computer programming.

One of the main aims of this paper is to develop a relatively simple yet accurate and robust numerical method to simulate fluid flow in discrete dual-permeability media. In order to overcome the difficulties encountered in the discrete models, researchers have proposed some simplified models to conduct simulations. One of the simplified methods is to treat disk-like 2-D fractures as mono-dimensional pipes connecting fracture centers with connected fractures (Bodin et al., 2007; Cacas et al., 1990; Dershowitz and Fidelibus, 1999; Dverstorp et al., 1992; Moreno and Neretnieks, 1993; Nordqvist et al., 1992). This method simplifies the mesh generation of each fracture and reduces the size of the problem. However, the flow pattern in the fracture is unrealistic and the choice of the pipe transmissivity is difficult. It is also impossible to evaluate the uncertainties (Erhel et al., 2009b). Besides, a pipe flow model was developed to simulate the karst development (Bodin et al., 2007; Clemens et al., 1996), in which the fissured system (continuum model) and the pipe network are coupled interactively through a linear exchange term similar to that in dual continuum model. A similar model was also reported in a Conduit Flow Process for MODFLOW-2005 (Shoemaker et al., 2008), which also included turbulent flow in cylindrical pipes. Ubertosi et al. (2007) proposed a pipe network method to simulate preferential flow in highly channelled fracture planes and fracture networks. It is quite simple in terms of network topology, which is at the cost of losing local geometry. In contrast, Jourde et al. assumed that the preferential flow channels are located at the intersections between fractures or between fracture and bedding plane thus to build the pipe network models (Jourde et al., 2002). Vitel and Souche (2007) used a pipe network to represent both matrix and fracture and it is upscaled by applying electric simplifications and pipe decimation to perserve the same pressure response in coarse-scale model. Ren et al. (2016) developed 2-D pipe network model to study unconfined flow in fractured porous rock.

The fracture continuum method (Botros et al., 2008; Reeves et al., 2008; Svensson, 2001) or heterogeneous continuum porous medium model (Jackson et al., 2000) is another simplification, which maps fractures onto a finite difference mesh or finite element mesh. It locally homogenizes the fracture property as continuum elements. In this way, the discontinuous problem is converted to the continuous problem, which preserves certain geometrical characteristics of the fracture network. However, the accuracy of the method is highly dependent on the resolution of the mesh. A coarse grid will overestimate the connectivity of the fracture network, which results in unrealistic prediction.

Li et al. (2014) and Xu et al. (2014) have proposed the graph-theoretic pipe network method for water flow simulation in discrete fracture network and porous medium, respectively. The features of the method have been demonstrated in some 2-D static single-phase saturated flow problems. Their method treats the line fractures as oriented and weighted pipes. Porous media can also be equivalent to oriented and weighted pipes (Xu et al., 2014). It is convenient to treat porous media in a similar way as the fracture network, especially when these two materials are coupled. However, their method has some drawbacks. First, the pipes in their method should be oriented, and this becomes time-consuming when labelling all the directions of pipes in a large complex fracture network. Second, each boundary node should be connected to a reference node to form boundary pipes for establishing the unified governing equation, and this is not so flexible to apply boundary conditions. Third, the governing equation incorporates the unknowns of the pipe flow rate, which greatly increases the problem size. Actually, when the pressures of the two ends of the pipe are known, the flow rate of the pipe can be readily calculated. More importantly, the incorporation of pipe flow rate into the governing equation makes the coefficient matrix nonsymmetrical and ill-conditioned.

In this paper, a unified pipe network model (UPM) is proposed to simulate fluid flow in discrete fracture network and porous medium. The UPM is conceptually simple, which treats fractures and porous medium as virtual connected pipes in domain space. The flow properties of pipes are not stochastically assigned but are derived based on geometrical and hydraulic properties of the corresponding fractures and rock matrices, which are the conceptualizations of the fractures and the porous media. Thus, the selection of the preferential channels on a fracture plane is not required. The fractured porous medium can be reconstructed by the systematic assembly of the fracture pipes and the matrix pipes. The interaction between rock matrix and fractures is achieved by applying the continuity condition at the interface. No interchange terms are introduced. The straightforward model building process well balances the accuracy and the simplicity in flow simulation. Numerical cases are presented to demonstrate the feasibility, robustness, and effectiveness of the UPM. The effects of fracture density and fracture aperture size on the water recharge into fractured rock formation are studied.

2. Derivation of unified pipe network model

2.1. Conceptualization of fractured porous rock

Natural fractured rock mass contains a large number of fractures in different sizes. The fractures containing relatively large voids compared to pores in the matrix rock, link each other to form main flow conduits in the rock mass. The rock block is treated as a kind of porous medium, which contains interconnected small pores for fluid flow. These spatial interconnected pores and voids are conceptualized as interconnected pipes with different equivalent hydraulic parameters. Thus the fractured rock mass is treated as a pipe lattice system or a pipe network system, which is shown in Fig. 1. This conceptualization can significantly simplify the treatment of the fractured rock mass, which becomes the assembly of the weighted flow pipes. Multi-scale fractures and rock matrix can be uniformly handled. Both 2-D and 3-D problems can be constructed by the discrete 1-D pipe segments. There are two types of pipes, namely, fracture pipes corresponding to fractures and matrix pipes corresponding to rock matrix. The equivalent hydraulic parameters of the pipes can be derived by reconstruction of the locally homogenized macroscopic media, which will be discussed in the following sections.

This conceptualization is based on the exact information of fracture network as well as the permeability of the rock matrix rather than the simplified flow channels. Dead-end fractures, which can be important in fluid flow and mass transfer are not trimmed in the model, because they are integral parts of the detailed geometry of the fracture networks. They increase contact areas between fracture networks and matrix thus affecting fluid flow. Admittedly, it is not always possible to obtain the exact information of the fractures in rock under current survey technology. However, some detailed statistical information of the fractures such as the distributions of the dip, dip direction, size and aperture, can be collected by current technology, based on which the statistical equivalent UPM models can be built to conduct Monte Carlo simulations if necessary.