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Simulation of groundwater exchange between an unconfined aquifer and a discrete fracture network with laminar and turbulent flows

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ABSTRACT

In this study, a new approach is developed to simulate groundwater flow through both an overlying unconfined aquifer and an underlying discrete fracture network. The groundwater exchange between the aquifer and the fracture network, including magnitude and direction, is explicitly simulated based on the mass conservation, which depends on a variety of parameters related to flow and network characteristics. In the overlying unconfined aquifer, we approximate the flow using the Dupuit assumptions. In the underlying fracture network, we use the cubic law and Forchheimer's law to iteratively simulate laminar or turbulent flow in individual fractures depending on the Reynolds number. Explicitly separating laminar and turbulent flows in the fractures results in a system of nonlinear equations, which is iteratively solved. While the flow from the overlying unconfined aquifer is a small portion of the overall flow in the underlying fracture network, incorrect use of the laminar or turbulent flow equation in the fractures can lead to significant errors in simulating the flow exchange. As apertures increase, both the portion of the total flowrate in the aquifer and the portion of the flow in the fractures coming from the aquifer decrease. As the overall hydraulic gradient increases, both the portion of the total flow in the aquifer and the portion of the fracture flow that comes from the aquifer increase. The portion of the total flow in the aquifer increases with the aquifer thickness, while the portion of fracture flow coming from the overlying aquifer decreases.

1. Introduction

Groundwater flow and contaminant transport in fractured rocks are mainly controlled by the network of interconnected fractures. Numerous studies related to fractured rocks have been conducted to investigate groundwater flow (Lee and Lee, 2000; Marechal et al., 2004; Roques et al., 2016; Dewandel et al., 2017), transport in aquifers (Dverstorp, 1992; Wealthall et al., 2001; Mota et al., 2004; Tabach et al., 2007) and radioactive waste deposition (Hudson et al., 2001; Tsang et al., 2005; Follin et al., 2014). The discrete fracture network (DFN) approach has been used for modeling hydrologic processes in fractured rock (Klimczak et al., 2010; Elmo and Stead, 2010; Berrone et al., 2014; Xing et al., 2017). Klimczak et al. (2010) determined that total flowrates through fractures were proportional to apertures to the fifth power by considering the square root relationship of displacement to length scaling and the traditional cubic law. They then explored this relationship by examining a suite of flow simulations through DFNs. Meyer and Bazen (2011) presented a mathematical formulation for analyzing multi-stage/multi-cluster transverse DFNs in horizontal wellbores. Leung et al. (2012) simulated flow through a two-dimensional fracture network using a discrete fracture model and computed field-scale permeabilities. de Dreuzy et al. (2012) analyzed the combined effect of the network-scale topology and fracture-scale heterogeneities, based on 2 million DFN simulations. Berrone et al. (2014) developed a numerical method of simulating steady-state fluid flow in DFNs using enrichment functions, optimization procedures and non-conforming meshes. By using a benchmark test problem of a hypothetical repository in fractured crystalline rock, Hadgu et al. (2017) compared the DFN approach with an equivalent continuum model in terms of upscaled observed transport properties through fracture networks. Xing et al. (2017) developed a parallel numerical algorithm to simulate flow and transport in a DFN by discretizing Darcy fluxes based on the vertex-approximate-gradient-finite-volume scheme. Lei et al. (2014) investigated the feasibility of the DFN approach in representing geomechanical response to stresses and hydraulic behaviors and examined the important factors influencing the quality of DFN representations. When flow is laminar, the cubic law can be used to simulate groundwater flows in the fractures (Brush and Thomson, 2003). When the flow is turbulent, Forchheimer's law is often applied to describe groundwater flow behaviors (Chen et al., 2001). One major

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limitation of the previous approaches in simulating groundwater flows in DFNs lies in the assumption that flow within the whole fracture network is either laminar or turbulent.

There have been numerous studies of groundwater flow in unconfined aquifers (Serrano 1995; Liang and Zhang, 2012; Mahdavi and Seyyedian, 2014; Chang et al., 2016), and stream water and groundwater interactions (Workman et al., 1997; Moench and Barlow, 2000; Barlow et al., 2000; Hattermann et al., 2004; Chen and Chen, 2003; Ameli and Craig, 2014; Saeedpanah and Azar, 2017). Serrano (1995) presented an analytical solution of the nonlinear Boussinesq flow equation. For the small regional gradients and the range of recharge values typically encountered in the field, the extensively used linearized equation with the Dupuit assumptions is a reasonable approximation to the exact solution for the hydraulic heads and flow velocities. Liang and Zhang (2012) proposed an analytical method for groundwater recharge and discharge estimates in an unconfined aquifer. The method was based on the analytical solution to the Boussinesq equation and was validated by numerical simulations. Mahdavi and Seyyedian (2014) presented a semi-analytical solution for steady groundwater flow in trapezoidal-shaped aquifers in response to a recharge, which was validated by equipotential contour maps. Chang et al. (2016) developed a three-dimensional flow model for hydraulic-head variation due to localized recharge in an unconfined aquifer using the Laplace and double-integral transforms.

Workman et al. (1997) developed a mathematical model to simulate stream/aquifer interactions in an unconfined aquifer subjected to time-varying river stage. The model took into account several components including the steady-state water level, the steady-state water level due to river stage change, a transient redistribution of water levels from the previous day, and a transient change in water level due to river stage change. Moench and Barlow (2000) presented unified mathematical solutions for confined and unconfined aquifers interacting with streams using Laplace transform step-response functions. The flow could be one-dimensional in the confined and leaky aquifers and two-dimensional in the unconfined aquifers. Barlow et al. (2000) used the analytical step-response functions, developed in Moench and Barlow (2000), in convolution integrals to calculate aquifer heads, streambank seepage rates, and bank storage in response to stream-stage fluctuations and basin-wide evapotranspiration or recharge. Hattermann et al. (2004) developed an integrated catchment model to analyze local water-table variations in subbasins along with river flow at the regional scale, which was able to stimulate daily groundwater levels and discharge. Chen and Chen (2003) investigated the water exchange rate between a stream and aquifer, the storage of the infiltrated stream water in the surrounding aquifer, and the storage zone where groundwater is replaced by the stream water during a flood. Ameli and Craig (2014) developed a semi-analytical series solution for modeling steady-state free boundary groundwater-surface water exchange in complex stratified aquifers. The appropriateness of the Dupuit-Forchheimer approximation for simulating flux distribution was investigated, which illustrated the solution's efficacy for simulating physically realistic domains. Recently, Saeedpanah and Azar (2017) presented an analytical solution to examine interactions between streams with varying water levels and an aquifer using Laplace and Fourier transform methods.

In summary, many previous studies have dealt with groundwater flows in DFNs, in unconfined aquifers, and interactions between aquifers and streams. However, few studies have investigated the exchange between a DFN and an overlying unconfined aquifer. Depending on the behaviors of the fracture network and aquifer, groundwater may flow from the aquifer to the fracture network or vice versa as shown in Fig. 1(a). In this study, we develop a new approach to determine steady-state groundwater flows in a fracture network and an overlying unconfined aquifer and their exchange. The main objectives of this study are three-fold. First, we develop a new approach to simulate groundwater flow through both the overlying unconfined aquifer and the DFN. The groundwater exchange between the aquifer and the fracture network is simulated explicitly. Second, we investigate the factors affecting the groundwater exchange between the overlying unconfined aquifer and the fracture network. Finally, we examine the potential errors of using only the cubic law approach or the Forchheimer's law approach in the whole fracture network in modeling groundwater exchange.

In the overlying unconfined aquifer, we approximate groundwater flow based on the Dupuit assumptions. In the fracture network, we use the cubic law and the Forchheimer's law to respectively simulate laminar flow and turbulent flow in individual fractures depending on the Reynolds number. Explicitly separating laminar and turbulent flows in the fractures results in a system of nonlinear and linear equations, which is then solved by iteration. The exchange between the fracture network and the aquifer is taken into account based on mass conservation. The exchange, including magnitude and direction, depends on a variety of parameters such as aperture, hydraulic gradient, and aquifer hydraulic conductivity.

2. Methodology

To demonstrate the method, a fracture network and unconfined aquifer configuration shown in Fig. 1(b) is used. However, the general approach can be used for any type of fracture network and aquifer configurations. The main flow direction is from left to right through the imposed higher hydraulic head condition on the left. Between the unconfined aquifer and the fracture network, the groundwater may flow down from the aquifer to the fracture network or up from the fracture network to the aquifer. In this study, the rock matrix in the fracture network is assumed to be impermeable. For each fracture and each segment in the unconfined aquifer, we can write one flow equation. For the domain shown in Fig. 1(b), the hydraulic heads at the inlets and at the outlets for both the unconfined aquifer and fracture network are given as the constant head (i.e., Dirichlet) conditions, which represent steady state flows under hydrostatic conditions on both upstream and downstream boundaries. The hydraulic head values at the internal nodes are unknowns. Among them, the hydraulic heads at the nodes in the interface between the aquifer and the fracture network are approximately equal to the saturated aquifer thicknesses as shown in Fig. 1(b). Based on the continuity requirements at each internal node, we can establish mass conservation equations based on the Dupuit assumptions in the unconfined aquifer, the cubic law, or the Forchheimer's law in the fracture network. Because these equations are nonlinear, we solve them iteratively by the Newton-Raphson method.

The continuity equations at node (i, j–1) and node (i, j) are presented as an example to illustrate the method. If the flow directions are as indicated, the continuity equation for node (i, j − 1) is,

$$Q_{(i-1,j-1),(i,j-1)} - Q_{(i,j-1),(i+1,j-1)} - Q_{(i,j-1),(i,j)} = 0 \tag{1}$$

Similarly for node (i, j), the continuity equation can be written as,

$$Q_{(i,j-1),(i,j)} + Q_{(i-1,j),(i,j)} - Q_{(i,j),(i+1,j)} - Q_{(i,j),(i,j+1)} = 0 \tag{2}$$

where the positive sign denotes the groundwater flow toward node (i, j − 1) or node (i, j), while the negative sign denotes that away from node (i, j − 1) or node (i, j). The actual flow direction in each fracture needs to be determined as part of the iterative procedure.

The discrete fracture model, where groundwater flows only occur in the fractures, is used for computing the flow through the fractures and the Dupuit equation is used to describe the steady state flow in the unconfined aquifer. The following equation can be developed based on the continuity requirement at node (i, j − 1),

$$K\left(\frac{T^2_{(i-1,j-1)} - T^2_{(i,j-1)}}{2\Delta L_{(i-1,j-1),(i,j-1)}}\right) - K\left(\frac{T^2_{(i,j-1)} - T^2_{(i+1,j-1)}}{2\Delta L_{(i,j-1),(i+1,j-1)}}\right) - \frac{\rho g b^3_{(i,j-1),(i,j)} H}{12\mu} \cdot \frac{(h_{(i,j-1)} - h_{(i,j)})}{\Delta L_{(i,j-1),(i,j)}} = 0 \tag{3}$$

where K ($L\,T^{-1}$) is the hydraulic conductivity of the unconfined aquifer,