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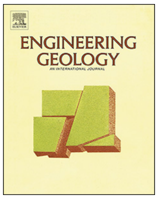

An iterative procedure for the simulation of the steady-state fluid flow in rock fracture networks

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ABSTRACT

Equivalent pipe network (EPN) modelling is widely accepted as an effective technique for modelling fluid flow through fracture networks in rock masses. The major advantages of this approach are its simplicity and computational efficiency, which make it capable of dealing with complex, reservoir-scale problems. The major disadvantage, however, is that the derived flow model depends primarily on the pipe network used and the construction of a representative pipe network model is still very challenging, particularly for large and complicated fracture networks. Existing approaches for constructing EPN are primarily geometrical and do not take account of flow kinematics within fracture networks. Consequently, the flow model obtained is less realistic due to the unavoidable subjective assumptions involved in pipe connections. This paper describes a recently proposed iterative process for deriving a more realistic flow model by taking into account the flow kinematics within the fracture network while constructing the EPN model. To do so, the connection pipes are based on the flow sources and sinks of fracture intersection traces on each individual fracture. However, the input in this case is also part of the solution output and therefore the process must be iterated until the model converges to a stable solution. A simple 3D fracture network is used to cross-validate the proposed approach against a COMSOL finite element model. Finally, as a case study, the method is applied to the reservoir-scale flow analysis of the Habanero geothermal field in the Cooper Basin of South Australia.

List of symbols

T_i	Transmissivity of Fracture i
$w_m(j\text{-}k)$	Mean channel width between fracture intersection Trace j and Trace k on a fracture
$l(j\text{-}k)$	Pipe length between fracture intersection Trace j and Trace k on a fracture
C_{jk}	Equivalent pipe conductance between fracture intersection Trace j and Trace k on a fracture
$h(\mathbf{x})$	Hydraulic head at location $\mathbf{x}$ on a fracture where $\mathbf{x} = \{x_1, x_2\}$ is the coordinate system on the fracture
$\mathbf{n}$	Boundary normal
$\mathbf{h_e}$	Vector of the nodal hydraulic heads at the fracture external boundary
$\mathbf{h_t}$	Vector of the nodal hydraulic heads at fracture intersection traces
$\mathbf{q}$	Vector of the nodal fluxes at fracture intersection traces
$\mathbf{A_{ee}}$. $\mathbf{A_{te}}$, $\mathbf{A_{et}}$, $\mathbf{A_{tt}}$	**A**-type matrices (to be multiplied by the hydraulic head vectors $\mathbf{h}_t$ and $\mathbf{h}_e$) of the BEM equation where the first subscript refers to the portion of the boundary of the collocation node, the second subscript refers to the portion of the integration node; note: "*e*" refers to the fracture external boundary, "*t*" to the traces
$\mathbf{B_{et}}$, $\mathbf{B_{tt}}$	**B**-type matrices (to be multiplied by the vector of nodal fluxes at the traces $\mathbf{q}_t$) of the BEM equation (for the subscripts see what reported for **A**-type matrices)
Q_{jk}	Discharge of a source-sink path between fracture intersection Trace j and Trace k on a fracture

1. Introduction

Discrete Fracture Networks (DFN) are widely used to model or simulate fluid flow in a rock mass, especially when hydraulic stimulation is used to create artificial networks of connected fractures to form pathways and facilitate large flows (Huang et al., 2017; Ren et al., 2017; Pan et al., 2010). Examples include Enhanced Geothermal Systems (EGS), unconventional gas production (shale gas or tight gas) and in-situ mineral recovery through stimulated reservoirs. In these

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applications, natural fractures are generally closed or sealed, exhibiting very low hydraulic conductivity due to micron-scale hydraulic apertures, and hydraulic stimulation is used to generate a connected, industrial-scale reservoir (Nguyen et al., 2017). Under high hydraulic pressures the existing fracture planes can slip and become misaligned, thus increasing the apertures due to dilation (Khang et al., 2004). New fractures can also be created due to hydraulic fracturing. The extension, fracture intensity and structure of the resulting fracture network can be inferred by monitoring the induced seismic events (Bruel, 2007; Xu et al., 2013; Xu and Dowd, 2014; Mohais et al., 2016). Direct borehole observations, if available, can also be incorporated as additional conditioning data while considering potential systematic biases (Benedek and Molnár, 2013). In the DFN approach, each fracture is modelled explicitly as an elliptical disk or a polygonal plane, resulting in an assembly of connected objects that resembles the fracture network of a rock mass. As such, a DFN preserves heterogeneity and directionality, which are usually distinctive features of a fracture network.

Numerical methods used to simulate the flow regime in a DFN include the Finite Element Method (FEM; e.g. Berrone et al., 2014; Hyman et al., 2015; Pichot et al., 2012) and the Boundary Element Method (BEM; e.g. Lenti and Fidelibus, 2003). For large-scale problems the derived system of algebraic equations may become numerically intractable, especially when the fracture network is complex (Bodin et al., 2007). Various techniques to improve computational efficiency have been explored, including parallel computing (Berrone et al., 2015) or transformation of the DFN to reduce the computational demand. Two transformation approaches are available: the Equivalent Porous Medium (EPM) approach (Berkowitz, 2002; Singhal and Gupta, 2010) and the Equivalent Pipe Network (EPN) approach (Cacas et al., 1990; Dershowitz and Fidelibus, 1999; Xu et al., 2014).

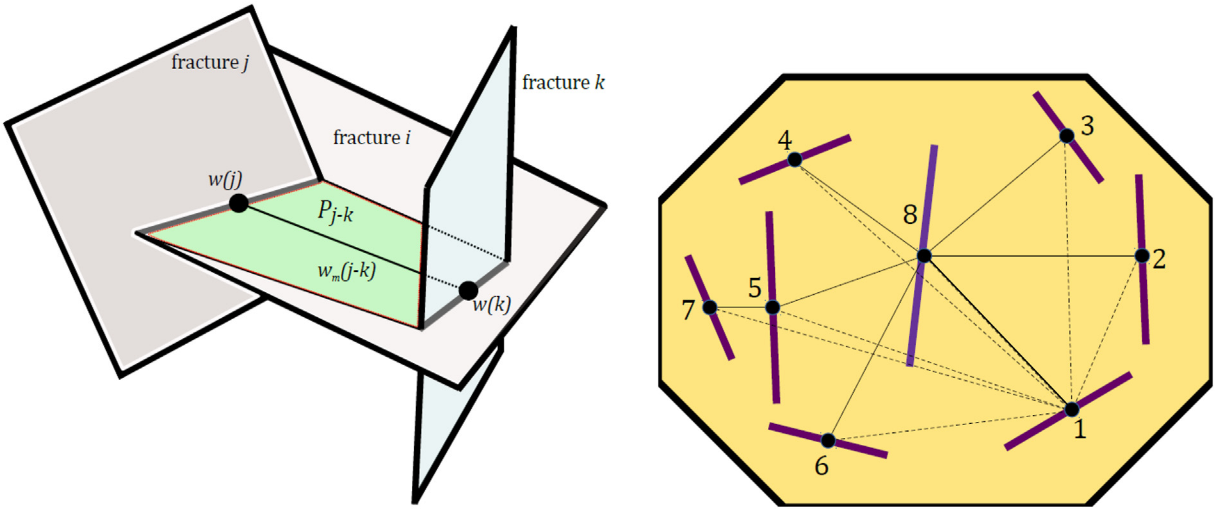
In the EPM approach, the fractured medium is converted into a porous continuum with an equivalent hydraulic conductivity tensor $\mathbf{K}_e$, provided that a Representative Elementary Volume (REV) exists, which may not always be the case for practical applications. The REV can be found by using recursive analyses of the directional fluid flow inside cubic elements of increasing size D extracted from the DFN. A tensor $\mathbf{K}(D)$ of the hydraulic conductivity can be defined for each size. The size D_{REV} for which such a tensor stabilizes is the REV and the associated tensor $\mathbf{K}(D_{\text{REV}})$ is the tensor $\mathbf{K}_e$ (Cravero and Fidelibus, 1999). Standard numerical codes can then be used to simulate the flow regime. In the stochastic continuum (SC) or fractured continuum (FC) approach (e.g., Tsang et al., 1996) a DFN is subdivided into equivalent porous blocks for which associated hydraulic conductivity tensors are defined by means of geostatistical simulation, global statistical indicators of the state of fracturing (such as the crack tensor, Oda, 1985) or numerical estimates of directional fluid flows.

As EPM does not necessarily preserve heterogeneity and directionality, the EPN approach may be preferred. The DFN is transformed into a network of one-dimensional conductors (*pipes*) with given conductances. These conductors originate and end at the mid-points of fracture intersections (*traces*), thus the connections among fractures are maintained and the only approximation is the fluid flow inside each fracture. While this simplification significantly increases computational efficiency, several serious issues remain; in particular, the rules for defining the connections, especially for complex fracture intersections with multiple sources/sinks on a fracture, and the calculation of the equivalent pipe conductance (Dershowitz et al., 1999). Unfortunately, the constructed EPN dictates how the solution matrix is set up and, consequently, the final solutions. Thus, a pipe network adequately representing the flow pattern within the fracture network is of primary importance in deriving a realistic flow model. The direct solution is difficult as, to a large extent, the solution is also part of the input needed to derive the solution. This paper describes an iterative procedure for deriving an EPN that is close to the primitive DFN for the purpose of flow modelling. Once an EPN model is created to represent a fracture network, it can then be used in various analyses related to the fracture system such as modelling solute/contaminant transport, transient flow, multiphase flow and heat transfer.

In the following, the criteria currently used for the equivalence between DFN and EPN are reported first, then the proposed procedure for the derivation of an EPN is described, followed by an application example. Finally, conclusions are drawn on the merit of the procedure.

2. Criteria for the DFN-EPN equivalence

In flow analysis using the DFN approach, a fracture i intersects $n(i)$ other fractures of the network, with $n(i) \geq 2$, otherwise i is a dead-end fracture and can be removed from the network. On the fracture plane, a pipe is defined as a one-dimensional conductor connecting the mid-points of two fracture intersections, thus $n(i)(n(i) - 1)/2$ pipes may be generated on fracture i. However, it is not necessary to include in the final EPN all possible connections; in fact, some of them are 'weak' (not practically conductive), or the flow kinematics is such that the pressure gradient between the related traces is too low to produce any effective flow, or may be meaningless in the physical sense (see examples below). For a more realistic representation of the flow pattern on the fracture, it



(a)

(b)

Fig. 1. Equivalent pipe network (EPN) construction within a discrete fracture network.