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Effective aperture and orientation of fractal fracture network

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HIGHLIGHTS

- New idea of effective fracture explicitly distinguishes laminar and turbulent flows.
- The assumption that Darcy's law applies to the fracture network is not required.
- Effective aperture is mainly related to fractal characteristics of fracture network.

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ABSTRACT

Distribution of fracture length has been shown to exhibit fractal characteristics. In this study, we proposed a new idea of effective fracture in terms of aperture and orientation for a fractal fracture network and developed solutions of effective aperture in relation to fractal characteristics, flow behavior and hydraulic gradient. Another main point is that the use of Darcy's law is not required. The effective fracture approach takes into account the scenario that the entire fractal fracture network may effectively behave similarly to a bundle of fractures where flows may be non-linear. The effective fracture approach explicitly distinguishes laminar and turbulent flows based on the size of effective fracture. To do so, an iterative procedure is developed to determine the effective fracture aperture. Results demonstrate that the effective aperture only slightly varies with hydraulic gradient, which illustrates that the idea of effective aperture can be used in the mixture of laminar and turbulent flows. The effective aperture decreases with the scaling exponent, increases linearly with the maximum fracture length, increases significantly with the minimum over maximum fracture length ratio, and increases with the scaling coefficient. The effective orientation shows expected decrease as the precision parameter of the fracture orientation increases.

1. Introduction

Flow of fluid in fractured rock masses is mainly controlled by connected fractures due to the significantly higher overall permeability of the fractures in comparison to that of the matrix. Determination of permeability is very important for understanding the flow behavior of fractured rock masses, which can be used for large-scale continuum analyses and for more efficient numerical simulations. In rocks with negligible permeability of the rock matrix, the fracture network dominates the permeability and flow in the rock masses. Therefore, the discrete fracture network (DFN) approach is widely used to describe flow behavior in fractured rock masses.

Many discrete fracture network (DFN) modeling techniques have been developed based on the assumption that fluid flows only in the connected conductive fractures with negligible rock matrix permeability [1–4]. Since the fracture network is geometrically complex, a number of parameters are involved in the description of fracture geometries in rock masses

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(e.g., length, aperture, and dip angle). It is challenging to accurately obtain the geometric information of each single fracture under the field conditions [5,6]. Therefore, it is usually assumed that each property of the fractures, such as length, location, orientation and aperture are statistically distributed in DFN modeling. Mathematical expressions have been developed to represent the characteristics of fracture distributions and to describe fluid flow behavior in individual fractures with complex geometries. Previous investigations have shown that the geometric distributions of length of fractures exhibit fractal characteristics, which presented a promising approach to quantitatively estimate the characteristics of fracture distributions [7–15].

Several multidisciplinary studies have also been conducted to investigate transport phenomena and properties and understand the transport mechanisms in fractal-like networks over the recent decades. Some background and research progress made in recent years on the transport phenomenon in fractal-like tree networks have been summarized [16], including scaling laws of the networks, and transport properties for fluid flow and heat conduction in the networks. Analytical models were developed for pressure distribution and hydraulic resistance of the fractal-like network in terms of the geometry and number of network branches, branching levels for laminar fluid flow [17]. Xu et al. [18] analyzed radial flow in the fractal and constructal fractal-like tree networks using a dual-domain model based on the fractal distribution of pore space and tortuosity nature of flow paths. The expressions for permeability of the network, seepage velocity, and pressure drop were derived. It was concluded that the permeability of the network and the volume fraction occupied by the network exhibit linear scaling law with the fractal dimension. Optimal structures of fractal-like branching networks for minimum flow resistance were analyzed for flow in both smooth and rough pipes [19]. It was found that the dimensionless effective flow resistance is sensitive to the geometrical parameters of the structure. Xu and Yu [20] derived scaling exponents of the transport properties in the fractal-like tree networks and showed that the scaling laws are different for different transport processes and the scaling exponents are sensitive to the structures of the networks. The expression for the effective permeability of the fractal-like networks was derived based on the parallel and series models and the relationship between the effective permeability and the geometry structures of the network was analyzed [21]. A comparison of the fractal-like tree network with the traditional parallel net demonstrated that the fractal-like network has much higher permeability than that of the traditional parallel net.

There have been many investigations on the effect of fracture geometry on the permeability and flow behavior in fracture network [22–25]. Most previous studies adopted the concept of effective permeability of fractal fracture network by assuming that flows in individual fractures are all laminar and the fractal fracture network in its entirety behaves similar to a porous medium where Darcy's law applies. Miao et al. [26] applied the fractal scaling law for length distribution of fractures and the relationship between the fractal dimension and other fractal properties to derive a fractal model for the permeability of fractured rocks based on the cubic law for laminar flow in fractures in conjunction with Darcy's law for Newtonian fluid flow. Liu et al. [27] analyzed the relationships between effective permeability and geometric properties, in which fracture length followed a fractal distribution and fracture orientation followed a normal distribution and the fluid flow was assumed to obey the linear Darcy's law. Assumptions were also made that fractures are more permeable than matrix and the fracture networks are consisted of two sets of fractures with different distributions of length, aperture and orientation. Liu et al. [28] proposed a fractal model that represents the geometric characteristics of rock fracture networks to link the fractal characteristics to the equivalent permeability of the fracture networks. The fracture networks were generated using the Monte Carlo method based on a power law size distribution. Although real rock fractures have rough walls and variable apertures, fluid flow through rock fractures has been usually described by the cubic law [29], which assumes that fractures consist of two smooth parallel walls. Miao et al. [30] developed a permeability model using the fractal theory based on the assumption that the length distribution of random fractures obeys the fractal scaling law and flow in each fracture follows the cubic law and the porous matrix of the media consists of a bundle of tortuous capillaries whose sizes also follow the fractal scaling law.

In a single fracture with turbulent flow, the permeability of the equivalent medium decreases as the hydraulic gradient increases when the turbulent flow is represented by the idea of an effective medium since the flowrate of turbulent flow is smaller than that of laminar flow under the same hydraulic gradient due to the fact that frictional loss for turbulent flow is higher. Therefore, occurrence of turbulent flows in any fractures inside the fractal fracture network also reduces the overall effective permeability for the network since the effective permeability concept is built on the use of Darcy's law, which was established for laminar flow conditions only.

Flow in a fracture under a high hydraulic gradient such as that near a pumping well installed in a fractured aquifer [31] or a dam may achieve a very high velocity. Non-Darcian flow behavior was also observed for realistic fractures with rough surfaces [31–33]. The linear Darcy's law describing porous media flow may not be applicable under these conditions and often failed to capture the reality of flow behavior in the fractured systems under relatively fast flow conditions.

Most previous studies of effective permeability of fractal fracture network relied on the assumption that the network behaves similarly to a porous medium where Darcy's law still applies. However, for networks when flows might be turbulent and non-linear, this approach of overall linear flows may not apply. In this study, we seek to explain the effective fluid flow behaviors representing the overall effect of the entire network by studying the statistical properties of the fractal network. There are two new ideas proposed in this study. First we propose the idea of effective fractures instead of effective permeability. The second main novel point is that the assumption that Darcy's law applies to the network is not required because the effective aperture takes into account the flow characteristics in individual fractures in the fractal fracture network. We only need to use flow equations in individual fractures, being either laminar flow equation or turbulent flow