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Analysis of fluid flow and solute transport through a single fracture with variable apertures intersecting a canister: Comparison between fractal and Gaussian fractures

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Abstract

Canisters with spent nuclear fuel will be deposited in fractured crystalline rock in the Swedish concept for a final repository. The fractures intersect the canister holes at different angles and they have variable apertures and therefore locally varying flowrates. Our previous model with fractures with a constant aperture and a 90° intersection angle is now extended to arbitrary intersection angles and stochastically variable apertures. It is shown that the previous basic model can be simply amended to account for these effects. More importantly, it has been found that the distributions of the volumetric and the equivalent flow rates are all close to the Normal for both fractal and Gaussian fractures, with the mean of the distribution of the volumetric flow rate being determined solely by the hydraulic aperture, and that of the equivalent flow rate being determined by the mechanical aperture. Moreover, the standard deviation of the volumetric flow rates of the many realizations increases with increasing roughness and spatial correlation length of the aperture field, and so does that of the equivalent flow rates. Thus, two simple statistical relations can be developed to describe the stochastic properties of fluid flow and solute transport through a single fracture with spatially variable apertures. This obviates, then, the need to simulate each fracture that intersects a canister in great detail, and allows the use of complex fractures also in very large fracture network models used in performance assessment.

Keywords: Groundwater; Fluid flow; Solute transport; Fractures; Modelling

1. Introduction

Quantifications of fluid flow and solute transport through fractured rock are essential for the performance assessment of a geologic repository for high-level radioactive wastes. For this reason, the concepts of the volumetric flow rate Q and the equivalent flow rate Q_{eq}, which have been well defined in a previous paper (Liu and Neretnieks, 2005), are commonly used; they provide a simple means to describe, respectively, the ability of the fracture to transmit fluid and solute through its connected space. In addition, in nearly all applications, fluid flow through a single fracture is assumed analogous to laminar flow between two perfectly smooth parallel plates. By this simplification, Liu and Neretnieks (2003) have formulated both the volumetric and the equivalent flow rates for general cases, where a single fracture is allowed to intersect the canister or the deposition hole at any angle. The formulations proposed have been verified by numerical examinations; they are not only simple in the forms but also general in the applications, where fluid flow may be taken normal, inclined or parallel to the axis of the canister.

The parallel plate model can, however, only be considered a qualitative description of fluid flow and solute transport through real fractures, which have not smooth but rough surfaces and variable apertures as well as asperity

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regions (Brown and Scholz, 1985). Thus, fluid and solute it contains are expected to take tortuous paths when moving through a real fracture, and only small fractions of the fracture are responsible for most of the flow and transport.

To explore the magnitude and nature of the disagreement between the predictions of the parallel plate model and the actual flow and transport through rough-walled fractures, it becomes necessary to generate natural fractures numerically and to make a multitude of simulations for both flow and transport.

In this paper, we present and discuss mainly the simulation results obtained for the fractal fractures, with respect to the distributions of the volumetric and the equivalent flow rates. The objective is to highlight the effects of the flow direction, the fracture type, the roughness and matedness of the aperture field on fluid flow and solute transport through a single fracture.

This paper is actually a companion to a previously published work (Liu and Neretnieks, 2005), where the Gaussian fractures were mainly dealt with. We thus recommend the reader refer to it for a detailed discussion of the scenario studied, the equations to be solved as well as the method used for the simulations.

2. Description of real fractures

Numerous observations (Hakami and Larsson, 1996; Keller, 1997) suggest that the aperture field of real fractures follows, mostly, a lognormal distribution without regard to horizontal spatial positions. Thus, we can write the probability density function of the aperture distribution as:

$$p(\ln b) = N(m, s) \tag{1}$$

where b denotes the fracture aperture, and N stands for a normal distribution with the mean m specified by the first element and the standard deviation s by the second element.

The mean μ and the variance σ^2 of the apertures are then related to m and s in the following way,

$$\mu = \exp(m + s^2/2) \tag{2}$$

$$\sigma^2 = \exp(2m + s^2)[\exp(s^2) - 1] \tag{3}$$

On the other hand, the spatial variations of the aperture field can best be described by either a Gaussian autocovariance function or a power law power spectrum (Brown, 1995). This suggests that we may classify the real fractures into two categories; one is the Gaussian fractures and the other is the fractal fractures.

In the type of Gaussian fractures, the aperture distribution varies spatially according to an isotropic Gaussian autocovariance function, or a similar one (Moreno et al., 1988), with a specified correlation length l; i.e. we can write the autocovariance function as (Liu and Neretnieks, 2005),

$$A(\mathbf{h}) = \sigma^2 \exp\left(-\frac{4|\mathbf{h}|^2}{l^2}\right) \tag{4}$$

where $\mathbf{h}$ is a vector-valued distance between two locations of the fracture plane.

In the fractal fractures, however, the spatial variations of the aperture field is described more appropriately by an isotropic decaying power law power spectrum, with a specified crossover dimension λ_0 (Liu and Neretnieks, 2005; Brown, 1995), i.e.,

$$P(\mathbf{f}) = \frac{C}{(f_0^2 + |\mathbf{f}|^2)^{\frac{\alpha+1}{2}}} \tag{5}$$

where C is a proportionality constant; $\mathbf{f}$ is a vector-valued spatial frequency; f_0 is the cutoff frequency, the inverse of which is the crossover dimension λ_0; and α is the spectral exponent of the aperture distribution (typically between 2 and 3), which is approximately the same as that of fracture surfaces (Brown, 1995).

Thus, the crossover dimension is essentially the largest wavelength present in the aperture distribution with any significant amplitude. The fracture then appears flat at scales far larger than the crossover dimension, while at scales far smaller than the crossover dimension the fracture looks quite rough and steep (Brown, 1995).

With mathematical descriptions (1) and (5) at hand, one can generate two-dimensional natural fractures numerically with great efficiency by using the Fourier filtering method or other algorithms (Liu and Neretnieks, 2005). An example of realizations of the fractal fractures with a preselected mean μ, a standard deviation σ and a crossover dimension λ_0 is shown in Fig. 1, together with its power spectrum examination.

To distinguish further the essential difference between the two types of fractures, one needs to compare their autocovariance functions directly. For fractal fractures, however, it is difficult to obtain an explicit autocovariance function $A(\mathbf{h})$ by inverting the Fourier transform of the power spectrum, if $P(\mathbf{f})$ is given by Eq. (5). Nevertheless, one can perform semivariogram examinations for fractal fractures to give an approximation to the autocovariance function. An example of realizations of statistically generated fractal fractures is shown in Fig. 2, together with its semivariogram analyses.

These examinations indicate clearly that the spatial variations of the fractal fractures decay exponentially in real space, and for fractal fractures with a spectral exponent $\alpha = 2.7$ it has been found that the autocovariance function can best be described by,

$$A(\mathbf{h}) = \sigma^2 \exp\left(-\frac{4|\mathbf{h}|}{l}\right) \tag{6}$$

with the spatial correlation length l roughly given by,

$$l = 0.9\lambda_0 \tag{7}$$

Notably, Eq. (6) has exactly the same form as that used by Moreno et al. (1988), which differs from Eq. (4) only in the power. This, together with the difference exhibited in the steepness of the Gaussian and exponential curves