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Effects of Mixing Characteristics at Fracture Intersections on Network-Scale Solute Transport

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ABSTRCT

We systematically analyze the influence of fracture junction, solute transfer characteristics on transport patterns in discrete, two-dimensional fracture network models. Regular lattices and random fracture networks with power-law length distributions are considered in conjunction with particle tracking methods. Solute transfer probabilities at fracture junctions are determined from analytical considerations and from simple complete mixing and streamline routing models. For regular fracture networks, mixing conditions at fracture junctions are always dominated by either complete mixing or streamline routing end member cases. Moreover bulk transport properties such as the spreading and the dilution of solute are highly sensitive to the mixing rule. However in power-law length networks there is no significant difference in bulk transport properties, as calculated by assuming either of the two extreme mixing rules. This apparent discrepancy between the effects of mixing properties at fracture junctions in regular and random fracture networks is explained by the statistics of the coordination number and of the flow conditions at fracture intersections. We suggest that the influence of mixing rules on bulk solute transport could be important in systematic orthogonal fracture networks but insignificant in random networks.

Key words : transport pattern, fracture junction, regular and random fracture networks, mixing property

I. Introduction

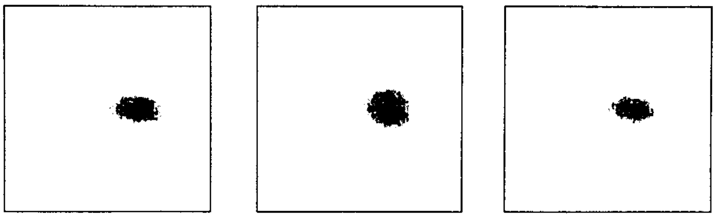
Transport of solute in fractured rocks of low matrix permeability is dominated by advective transport along fractures [*Bear et al.*, 1993; *National Research Council*, 1996]. The solute in a single fracture is redistributed to connected fractures at fracture intersections. Thus, fluid flow and solute transport at fracture intersections might be a key factor for transport in fractured rocks [*Berkowitz et al.*, 1994; *Adler and Thovert*, 1999].

Many field observations of fractured rocks indicate that fracture length distributions in many natural system can be modeled by a power law [*Segall and Pollard*, 1983; *Odling*, 1997]. Power law length distributions account for a broad range of network structures, including networks of infinite and constant length fractures as extreme cases.

This study incorporates an analytical solution for solute transfer probabilities at fracture junctions [*Park and Lee*, 1999] in a simulation study of flow and transport in regular fracture networks. These simulations are used to analyze the distribution of junction transfer characteristics in fracture networks, and to evaluate the effects of mixing characteristics on solute transport behavior at the network scale. In addition, complete mixing and streamline routing rules are applied to transport at fracture intersections, in network structures of different densities and generated with varying power law length exponents, and the transport characteristics of both cases are compared systematically.

II. Regular Lattice Networks

Solute transport in fracture networks with random aperture distributions was simulated using a particle tracking method. For each simulation, 10^4 reference particles were introduced into each network through the midpoint of the upstream boundary. The distribution of particles averaged over 30 realizations, for different aperture distributions. Resulting mass distributions obtained by assuming these two extreme models were compared to those obtained using analytical solutions (Figure 1).



(a) (b) (c)

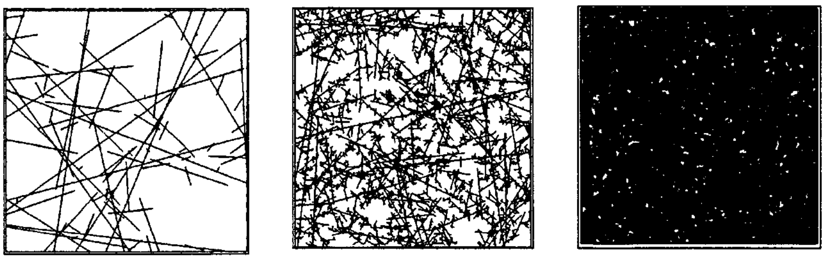
Figure 1. Comparisons of solute distribution in a regular fracture lattice with a lognormal aperture distribution, simulated using (a) forced streamline routing, (b) forced complete mixing, and (c) the analytical solutions of *Park and Lee* [1999]. In (c), the overall solute distribution patterns were found to be relatively insensitive to the overall hydraulic gradient in the range 10^{-7} - 10^{-1}.

II. Random Networks with Power Law Length Distribution

There is increasing field evidence that fracture trace lengths are distributed according to a power law [*Segall and Pollard,* 1983; *Odling,* 1997] defined as

$$n(l) = \alpha l^{-a} \text{ for } l \in [l_{min}, l_{max}]$$

where $n(l)dl$ is the probability of a fracture having a length in the range $[l, l+dl]$, α is a normalization factor, a is the characteristic exponent, and l_{min} and l_{max} are lower and upper cutoffs of the fracture length. Figure 2 shows typical geometry of the fracture networks with power law length distributions. The flow structure and the temporal evolution of spatial moments of the particles are computed (Figure 3).



(a) (b) (c)

Figure 2. Typical geometry of the fracture networks with power law length distributions, with exponent (a) $a=1.5$, (b) $a=2.5$, and (c) $a=3.5$.

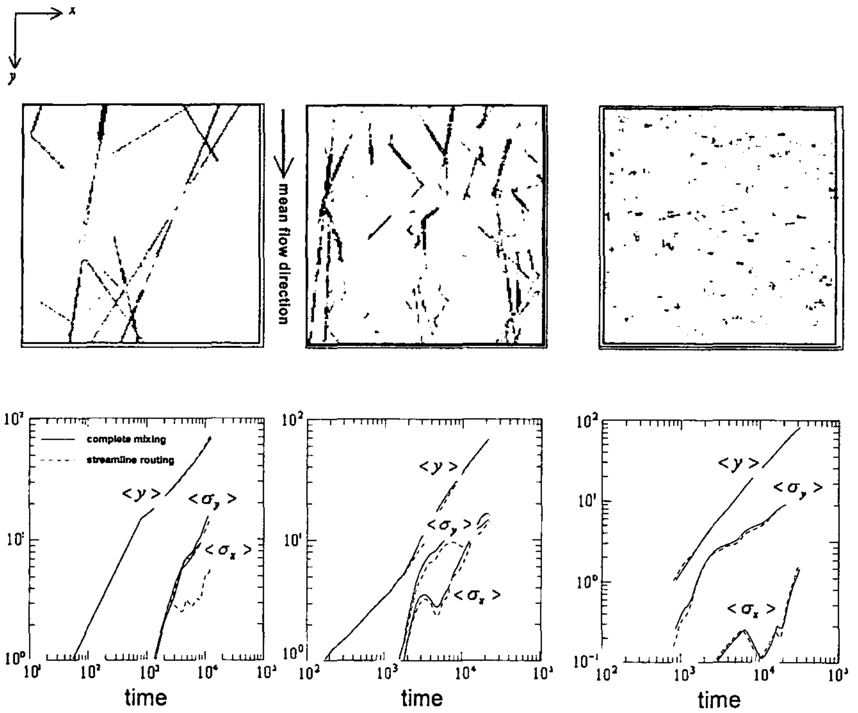


Figure 3. Flow structure and the temporal evolution (in arbitrary units) of spatial moments of solute for the typical power law length fracture networks

IV. Conclusions

Several conclusions can be made on the basis of the investigations on solute transport behavior in regular and random fracture networks:

(1) Mass transfer characteristics at a fracture junction are a function of the local flow condition and of the junction geometry.

(2) The spreading of solute is closely related to the mixing characteristics at fracture junctions. There is a decreasing trend in the dispersivity as the Peclet number, or fluid velocity, increases. Therefore, in fractured rocks or highly heterogeneous porous media, the dispersivisity could be underestimated if, as is often the case, forced hydraulic gradient tests are performed.

(3) Strong channelized transport can be observed when the Peclet number is larger than 0.1~10, according to the models for mixing characteristics at fracture junctions found in the literature.

(4) The choice of mixing rule at fracture intersections could make significant

differences in highly dense homogeneous fracture networks, but may play a less important role in random heterogeneous fracture networks.

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