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Effects of Fracture Intersection Characteristics on Transport in Three-Dimensional Fracture Networks

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ABSTRACT

Flow and transport at fracture intersections, and their effects on network scale transport, are investigated in three-dimensional random fracture networks. Fracture intersection mixing rules complete mixing and streamline routing are defined in terms of fluxes normal to the intersection line between two fractures. By analyzing flow statistics and particle transfer probabilities distributed along fracture intersections, it is shown that for various network structures with power law size distributions of fractures, the choice of intersection mixing rule makes comparatively little difference in the overall simulated solute migration patterns. The occurrence and effects of local flows around an intersection (local flow cells) are emphasized. Transport simulations at fracture intersections indicate that local flow circulations can arise from variability within the hydraulic head distribution along intersections, and from the internal no flow condition along fracture boundaries. These local flow cells act as an effective mechanism to enhance the nondiffusive breakthrough tailing often observed in discrete fracture networks. It is shown that such non-Fickian (anomalous) solute transport can be accounted for by considering only advective transport, in the framework of a continuous time random walk model. To clarify the effect of forest environmental changes (forest type difference and clearcut) on water storage capacity in soil and stream flow, watershed had been investigated

key word: fracture intersection, network scale solute transport, local flow cell, anomalous transport

1. Introduction

Solute transport processes in fractured rocks have been the subject of particularly intensive research over the last two decades, spurred largely by programs for radioactive waste disposal in subsurface, hard rock formations [National Research Council, 1996]. However, the geometrical complexity of fracture networks, among other factors, and resulting computational burdens, have made transport simulations in fractured rocks difficult.

In the above context, one of the most important aspects concerns flow interference and mixing characteristics at fracture intersections. Fracture intersection mixing rules have traditionally adopted either complete mixing or streamline routing assumptions. However, in single fracture intersections, these two mixing rules are known to be valid only for a limited range of flow conditions [Park and Lee, 1999]. In parallel, the effects of these intersection mixing rules on network scale transport have been analyzed in regular and random two-dimensional fracture networks [Park et al., 2001a, b]. An intersection in a three-dimensional fracture network is represented by a line segment, and has a dimension of length, in stark contrast to its two-dimensional counterpart, which is represented simply as a point. The objective of this study is to investigate solute transport in three-dimensional fracture intersections, and to determine the effects of local solute transport characteristics on larger-scale transport in three-dimensional fracture networks.

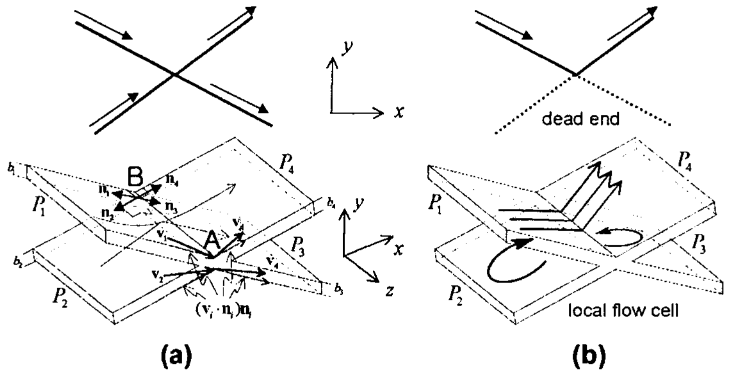

Figure 1. Schematics of flow structure around two intersecting fractures (a) without and (b) with local flow cells.

2. Flow and Transport Through Single Intersections

Flow and transport through two intersecting fractures can be compared in two- and three-dimensional fracture systems, as shown in Figure 1. Figure 1a illustrates the simplest case of a continuous intersection with two adjacent inflow segments. In constrast, Figure 1b demonstrates a very different case, wherein two- and three-dimensional flow structures contain, respectively, 'dead end' segments and 'local flow cells' (Planes P_2 and P_3). The local flow cells that can arise in fracture segments, uniquely in three-dimensional fracture systems, can increase the frequency of low velocities.

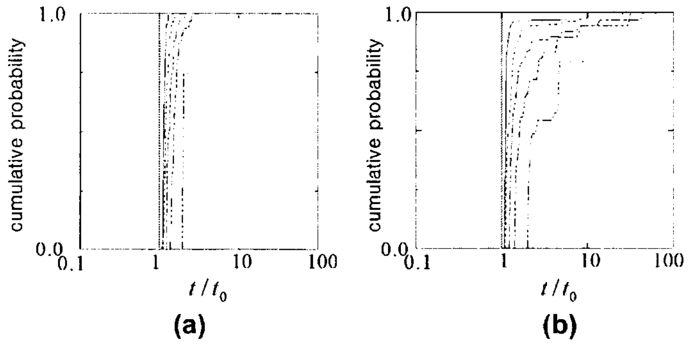

Figure 2. Cumulative particle residence time distributions for the fracture systems shown in Figures 1a and b, with varying direction of the hydraulic gradient.

Cumulative particle residence time distributions are calculated at downstream boundary (Figure 2). On the basis of the above results, it follows that the presence of local flow cells in fracture networks can result in relative time delays of orders of magnitude for some particles. It is intuitively clear that internal no flow boundaries increase, in relative terms, the lower velocity frequencies, and lead to stronger breakthrough tailing. Therefore, non-diffusive advectively-driven breakthrough tailing is influenced by the connectivity or intersection length per fracture, or per unit fracture area, as well as the internal no flow fracture edges in network scale transport.

3. Network Scale Solute Transport

The effects of fracture intersection properties on network scale solute transport are now considered. For this purpose, fracture networks with power law size distributions are considered. Figure 3 shows examples of fracture networks with power law exponents 1.0, 2.5, and 4.5, where longitudinal flow is derived from the upstream to the downstream boundaries.

Spatial and temporal distributions of solute with tails longer than those predicted by Fickian based transport models appear to be a main characteristics of solute transport in three-dimensional fracture networks. It is suggested here that this result may be attributed to, at least in part, the internal no flow boundaries in fracture networks, which lead to local flow cells. In order to illustrate the anomalous feature in solute transport in fracture networks, which can be related to lower velocity frequencies from local flow cells, the particle residence time distributions are averaged over 10 network realizations and compared to fitted solutions of the classical Fickian one-dimensional advection dispersion equation (ADE) and of the continuous time random walk (CTRW) theory.

In order to better evaluate the CTRW and ADE fits, particularly with regard to the long time tails, it is preferable to examine particle residence time distributions plotted on a log-log scale, such as provided in Figure 4. From these results, it is argued that the late time, non-Fickian behavior of solute transport in fractured rocks can be accounted for by consideration of non-diffusive, advective transpot; this behavior can be quantified by CTRW theory.

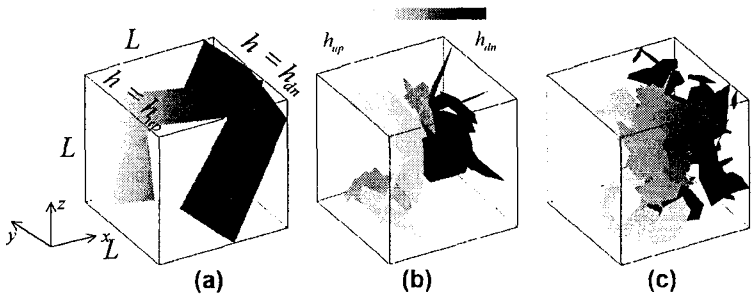

Figure 3. Geometry of and hydraulic heads in fracture networks with power law size distributions: In the case of power law exponent (a) 1.0, (b) 2.5, and (c) 4.5.

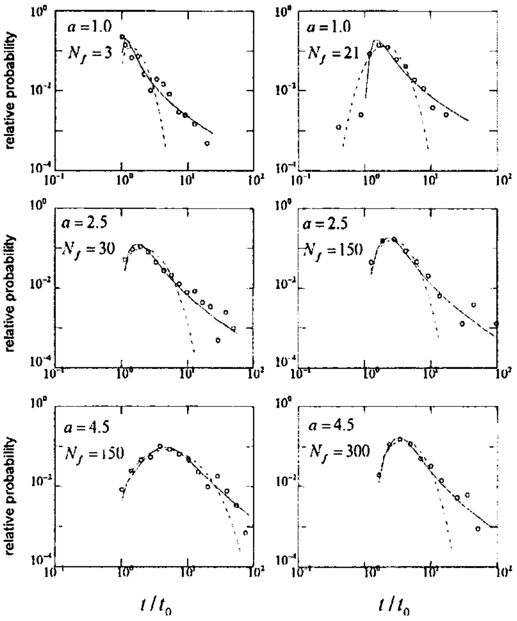

Figure 4. ADE (dashed line) and CTRW (solid line) solutions fit to particle residence time distributions (circles) in fracture networks with power law size distributions.

4. Summary and Conclusions

Transport of solute in two- and three-dimensional fracture networks is analyzed, with respect to the occurrence and influence of dead end fracture segments and local flow cells. Considering local flow cell transport only, it is shown that dead end fracture segments, as internal no-flow boundaries, contribute to a delay of solute by increasing (in relative terms) the lower velocity frequencies. The local flow cell delay mechanism suggested in this study is in accordance with laboratory and field observations of non-Fickian (anomalous) transport in fractured rocks. The CTRW framework is well-suited to explain the nondiffusive, advectively-driven, long-tail breakthough behavior. CTRW solutions are shown to fit effectively, and in contrast to the ADE solutions, simulated breakthrough curves in a wide range of fracture network structures.

A parallel plate idealization for individual fractures, and the validity of the cubic law for flow and transport analyses, are assumed throughout this study. It should be noted that geometrical and hydraulic parameters, such as fracture orientation and shape, the aperture variability among fractures, and flow configurations may introduce other effects within a computational feasibility.

4. References

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