단순 열극매질내 확산에 관한 연구

Investigation of Complex Dispersion in Simple Fractured Media

김정곤[1] · Franklin W. Schwartz[2] · 이광만[3] · 고익환[4]

1. Introduction

A solute moving in a fracture network by advection undergoes spreading on several scales: microscopic scale, scale of individual fracture planes, and macroscopic scale [*Smith and Schwartz*, 1980]. The cumulative effect of these processes is to cause a solute plume to expand as it moves through the fracture network under the influence of the mean hydraulic gradient. By analogy to transport in porous media, the macroscale description of this spreading is termed dispersion.

Our understanding of dispersion within a fracture network is incomplete while mass transport occurring at this scale is important for many field-scale applications. In this study, we present a numerical investigation of solute dispersion in two-dimensional discrete fracture networks with variable apertures and interconnectivities. Solute transport through networks of discrete fractures is modeled using a particle tracking technique. The main objective of this study is to investigate how features of fractured-rock systems affect transport, particularly dispersion.

2. Method

The flow and mass transport simulations involved a two-dimensional discrete fracture network. For simplicity, we assumed that flow and transport only occur in the fractures. Figure 1 shows the geometry of a fracture network consisting of two sets of essentially infinite fractures. The attitude of each fracture (θ_1 and θ_2) in relation to the x-axis and the fracture length, s_f, defined the network geometry. The two fracture sets were oriented at 90° with respect to one another and generated in a rectangular domain of 1.0 m x 0.5 m. Fractures in each set were of equal length except for those truncated at the boundaries.

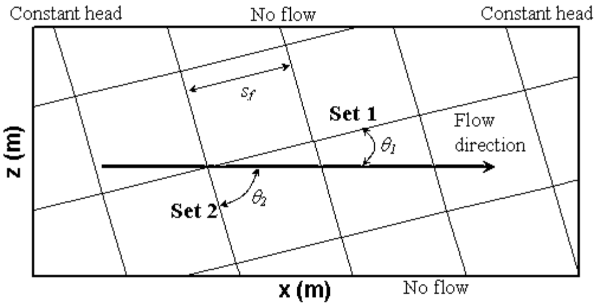

Figure 1. A schematic of fracture network geometry.

---

[1] 정회원, 한국수자원공사 수자원연구원 책임연구원 (E-mail: jkkim@kowaco.or.kr)

[2] 비회원, Ohio state University, Dept. of Geological Science, Professor

[3] 정회원, 한국수자원공사 수자원연구원 수석연구원

[4] 정회원, 한국수자원공사 수자원연구원 수자원시스템연구소장

The aperture was uniform in all fractures at 200 μm. The hydraulic gradient was 0.1.Boundary conditions for the flow problem are depicted in Figure 1. The meanhydraulic gradient was aligned with the horizontal axis, and the upper and lower boundaries of the domain were assumed to be impermeable. The left and right sides of the domain were assigned constant values of hydraulic head. The steady - state saturated water flow through the fracture network under the imposed boundary conditions was solved to obtain hydraulic head at each node in the network. Once the flow equation is solved and the flow field is defined, mass transport within the discrete fracture network was simulated with a particle tracking technique [*Smith and Schwartz*, 1980; *Schwartz et al.,* 1983].

3. Simulation Results

3.1 Simple Networks

First, simple networks without variability in flow due to aperture variability (σ_a) or local modifications in fracture connectivity were considered. Figures 2a - 2c show the regularities of the networks and how the trials differed from one another due to a rotation in the orientation of the fracture network relative to the mean hydraulic gradient (Θ_1 = 0°, 15°, and 45°, respectively). Shown in Figures 2a - 2c are particle distributions at 1.44, 3.6, and 7.2 minutes following the start of each simulation trial. Clearly, particle transport in these simple fracture networks was complex. Different spreading patterns were associated with differing fracture orientations.

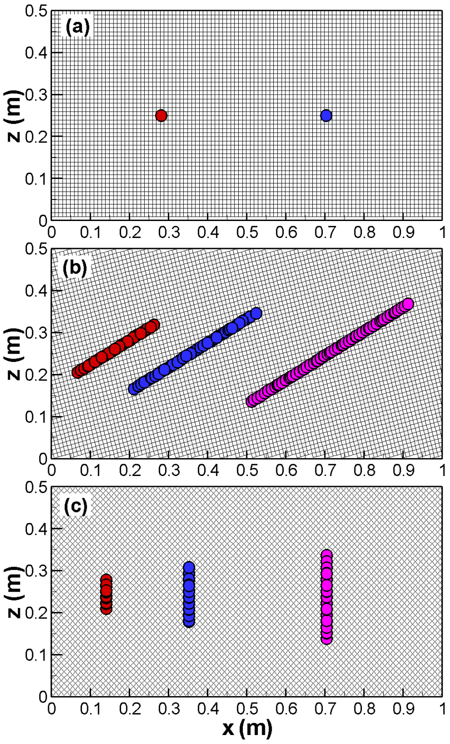

Figure 2. Particle distributions with σ_a = 0 for the networks with Θ_1 = (a) 0°, (b) 15°, and (c) 45°: Red, blue and pink symbols represent particle locations at 1.44, 3.6, and 7.2 minutes, respectively, after the injection of the particles.

3.2 Effect of Variability in Fracture Aperture

The complexity of the network was added by providing variability in aperture thickness. We worked with the same basic fracture geometries as before, oriented in different ways with respect to the mean hydraulic gradient with Θ_1 = 0°, 15°, and 45°. Because fracture apertures in the networks are randomly generated, spreading patterns and transit times for particles can differ significantly for different realizations of the fracture network.

Due to space limit, simulation results in the fracture network with only Θ_1 = 15° are presented. Detailed analysis can be found in Kim et al. (2004), Figure 2 shows particle distributions at 7.2 minutes. Four results obtained with differing σ_a are presented. Adding even tiny variation in fracture aperture produced a dramatic change in particle spreading. Overall, increasing network heterogeneity through an increased σ_a, changed the patterns of particle spreading from those observed with the simple fracture networks (Figure 2). Increasing σ_a promoted significant particle spreading, and as heterogeneity increased, the particle swarm tended to be more elliptical.

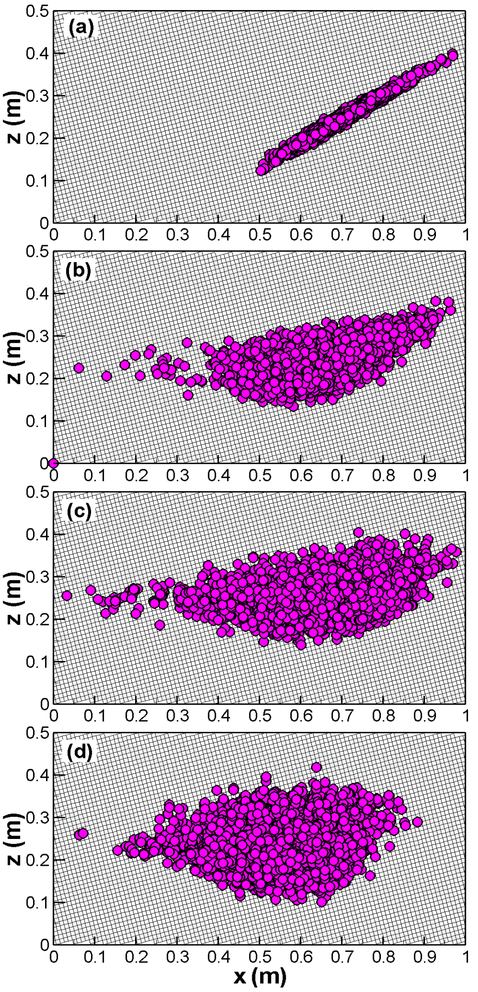

Figure 3. Particle distributions at 7 minutes with σ_a = (a) 0.01, (b) 0.05, (c) 0.1, and (d) 0.2.

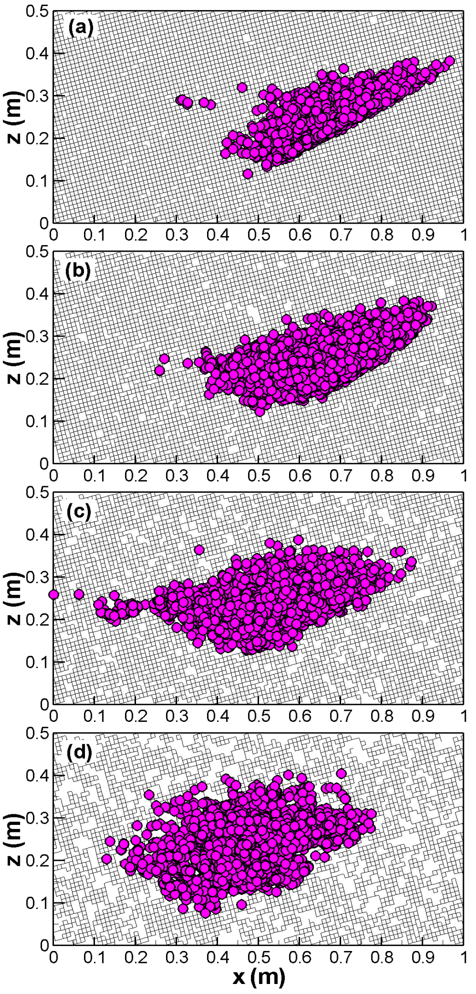

Figure 4. Particle distributions at 7 minutes with scanline density = (a) 98 fractures/m, (b) 93 fractures/m, (c) 87 fractures/m, and (d) 78 fractures/m.

3.3 Effect of Reduced Network Connectivity

As was the case with variable fracture aperture, successively reducing the connectivity of the network added increased heterogeneity. The collection of model trials encompassed three network orientations $\Theta_1 = 0^{\circ}$, 15° and 45°, and four cases of varying connectivity (98, 93, 87, and 78 fractures/m). Again, due to space limit, simulation results in the fracture network with only Θ_1 = 15^o are presented here. The networks in Figure 3 show how trials gradually increased in complexity from a nearly perfect network, to one that was filled with holes. Figure 3 shows particle distributions at 7.2 minutes. Decreasing network connectivity promoted the spreading of the particle swarm vertically, as was the case before with increasing variability in fracture aperture.

4. Summary and Conclusions

The grid-orientation effect explained the complex spreading of particles in idealized, fractured media. Such spreading has some similarities with the well-known isotropic model of dispersion, but the axes of spreading are not generally oriented parallel and perpendicular to the mean hydraulic gradient. The addition of heterogeneity produces a different pattern of particle spreading that provides for more conventional longitudinal and transverse spreading. When both spreading mechanisms are operative, particle swarms take on a curious hybrid shape reflecting the outcome of two different spreading mechanisms. With sufficient heterogeneity, the grid-orientation effect is swamped and disappears. It remains to be seen whether this concept can be extrapolated to real fractured media.

5. References

Kim, J., F. W. Schwartz, L. Smith, and M. Ibaraki, Complex dispersion in fractured media, *Water Resour. Res.,* 2004, in print.

Schwartz, F. W., and L. Smith, A continuum approach for modeling mass transport in fractured media, *Water Resour. Res.,* 24(8), 1360 - 1372, 1988.

Schwartz, F. W., L. Smith, and A. S. Crowe, A stochastic analysis of macroscopic dispersion in fractured media, *Water Resour. Res.*, 19(5), 1253 - 1265, 1983.

Smith, L., and F. W. Schwartz, Mass Transport. 1. An analysis of the influence of fracture geometry on mass transport in fractured media, *Water Resour. Res.,* 20(9), 303 - 313, 1980.