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Influence of ambient groundwater flow on DNAPL migration in a fracture network

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Abstract

We consider influences of the aperture variation and the ambient groundwater flow on the migration of DNAPL within a fracture network. In context of a modified invasion percolation (MIP) growth algorithm, we formulate a mechanistic model that includes capillary and gravity forces as well as viscous forces within the DNAPL and the ambient groundwater. The MIP model is verified against laboratory experiments, which is conducted using a two-dimensional random fracture network model. The results show that the aperture variation and ambient groundwater flow can be significant factors controlling DNAPL migration path witin fracture networks.

key word : DNAPL migration, fracture network, capillary force, gravity force, viscous force, MIP model

1. Introduction

While the study of DNAPL contamination in sediments has received significant attention, far less research has considered the underlying fractured rock. The problem is one of first, understanding DNAPL migration within fractured rock and second, understanding its subsequent dissolution and thus contaminant loading of the groundwater system. Within the topology of the fracture network where individual rough walled fractures intersect, migration of the liquid phase DNAPL is governed by the interplay of capillary, gravity, and viscous forces [e.g., *Kueper and McWhorter*, 1991]. Dissolution can take place into the water flowing in individual fractures [e.g., *Detwiler et al.*, 2001] or into the surrounding matrix if porous [e.g., *Parker et al.*, 1994, 1997; *VanderKwaak and Sudicky*, 1996].

To understand the processes that govern DNAPL migration, mechanical models formulated below the usual scale of porous-continuum averaging, are of great use. Such models often begin with modifications of invasion percolation (IP). IP has been modified (MIP) in many ways such as to include capillary forces, gravity/buoyancy forces and viscous forces [e.g., *Wilkinson and Willemsen*, 1983; *Glass et al.*, 2001].

In this study, we apply MIP to DNAPL migration within fracture networks. In particular, we are interested in influences of the aperture variation and the ambient groundwater flow within the fracture network on DNAPL migration. We first modify MIP to include this influence through the hydraulic gradient within the groundwater. To test our model, we then design a random fracture network with variable apertures and conduct three experiments that vary the influence of ambient groundwater flow.

2. Conceptualization of MIP model

To model the influence of ambient groundwater flow on DNAPL migration within a fracture network, we develop and apply a mechanistic growth algorithm that is a modification of IP. In IP, random numbers ("invadability") are assigned to each site on a lattice representing a random medium. Initially, all sites are occupied by the "defender fluid" and then one site is occupied by the "invader fluid" at its point of injection. The IP algorithm works by repeating the following two steps: 1) Identify the defender fluid site adjacent to the invaded region; and 2) Invade the identified site that has the highest invadability.

We modify IP to identify the invadability at each site with an invasion pressure due to local capillary, gravity, and viscous forces. Neglecting curvature in the plane of the fracture, the capillary pressure P_c is given by the LaPlace-Young equation as:

$$P_c = -\frac{2\sigma\cos\theta}{e} \tag{1}$$

where, σ is the interfacial tension, θ is the contact angle with respect to the fracture plane (0 degrees for wetting and 180 degrees for nonwetting fluid invasion), and e is the fracture aperture. The gravity pressure P_g is represented by the density difference between wetting fluid and nonwetting fluid as:

$$P_g = (\rho_{invader} - \rho_{defender}) gz\sin\alpha \tag{2}$$

where $\rho_{invader}$ and $\rho_{defender}$ are densities of invader and defender fluid, g is the acceleration due to gravity, z is the vertical thickness of invader fluid, and α is the dip angle of a fracture. The viscous pressure within the invader fluid P_{vi} increases back to the point of injection as:

$$P_{vi} = \frac{Q_{invader}\mu_{invader}L}{kA} \tag{3}$$

where $Q_{invader}$ is the local flow rate, $\mu_{invader}$ is the viscosity of the invader fluid, L is the distance back along the flow path from the interface between the two fluids to the injection point, k is the permeability of the fracture, and A is the local cross-sectional area of the flow path. The viscous pressure within defender fluid P_{vd} is given as:

$$P_{vd} = \rho_{defender} g h_{defender} \tag{4}$$

where $h_{defender}$ is the viscous component of the local hydraulic head within the defender fluid due to ambient groundwater flow.

Combining equations (1), (2), (3), and (4), the invadability for a site is defined as:

$$I = \frac{2\sigma\cos\theta}{e} + (\rho_{invader} - \rho_{defender}) gz\sin\alpha + \frac{Q_{invader}\mu_{invader}L}{kA} - \rho_{defender} g h_{defender} \tag{5}$$

For nonwetting fluid such as DNAPL, the capillary term in (5) is negative and thus invadability increases with aperture e. Likewise, the gravity term increases invadability for locations lower in the network as invasion proceeds. Finally, the viscous terms cause invadability to increase both back toward the point of injection, as well as downstream within the ambient groundwater flow field.

3. Results and discussion

For numerical test, a random fracture network model is designed (Figure 1). Fractures in the model have variable apertures of 0.2 *mm,* 0.4 *mm* and 0.6 *mm* (Figure 1). TCE is injected into one of fractures with constant injection rate.

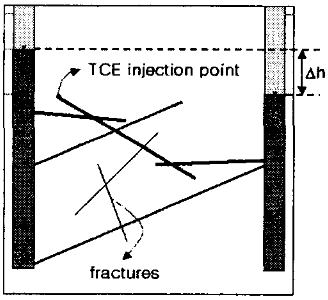

Figure 1. Designed fracture network. Thickest lines, medium-thick lines, and thinner lines show fractures of 0.6 *mm*, 0.4 *mm*, 0.2 *mm*, respectively.

To characterize the DNAPL migration process in fracture networks, three hydraulic conditions are assumed: (i) case 1 - static hydraulic condition (Figure 2a); (ii) case 2 dynamic hydraulic condition with global hydraulic gradient h_{global}=0.2 (Figure 3a); (iii) case 3 - dynamic hydraulic condition with global hydraulic gradient h_{global}=-0.2 (Figure 4a). The DNAPL migration patterns of each case are simulated with the MIP model and simulations are terminated when DNAPL invades light or left reservoir.

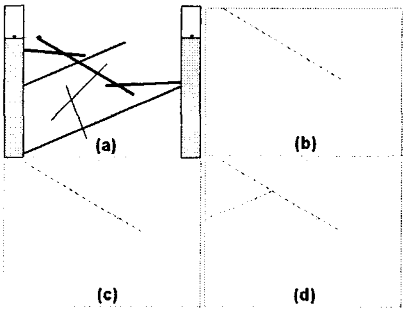

Figure 2. (a) Hydraulic condition of case 1; (b-d) results of case 1.

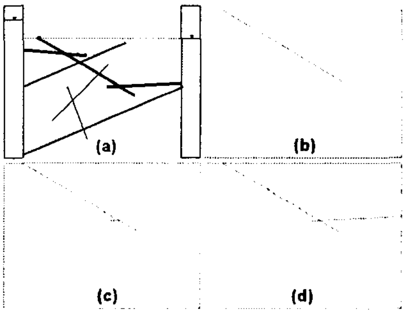

Figure 3. (a) Hydraulic condition of case 2; (b-d) results of case 2.

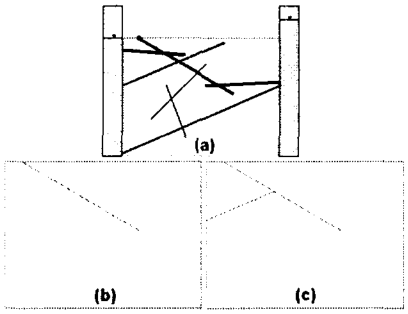

Figure 4. (a) Hydraulic condition of case 3; (b-c) results of case 3.

Figures 2-4 show results of case 1-3, respectively. The results suggest that DNAPL migration path is determined as a result of mutual cooperation of capillary, gravity, viscous forces, and fracture geometry, thus ambient groundwater flow can significantly influence the migration of DNAPL in fracture networks.

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