DNAPL migration in fracture networks and its remediation

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Abstract

We applied the modified invasion percolation (MIP) model to the migration of DNAPL within a two-dimensional random fracture network. The MIP model was verified against laboratory experiments, which was conducted using a two-dimensional random fracture network model. The results showed that the MIP needs modification. To remove TCE trapped in a random fracture network, the density-surfactant-motivated removal method was applied and found very effective to remove TCE from dead-end fractures.

key word : DNAPL migration, fracture network, MIP model, density-surfactant -motivated removal method

1. Introduction

Dense non-aqueous phase liquids (DNAPLs) are a common source of groundwater contamination. Because DNAPLs are denser than water, they may rapidly migrate through surficial sediments and enter fractures within the underlying bedrock. In order to locate, assess, and remediate DNAPLs within fractured bedrock, we must first understand the distribution, or structure, of the fluid phases (water and DNAPL) within the fracture network. Phase structure will be ultimately dependent on the mechanisms through which a DNAPL invades the water-saturated fracture network. *Glass et al.* [2001] suggested the MIP model to characterize the gravity-destabilized DNAPL migration problem in a heterogeneous porous medium. The MIP model was formulated including the effects of capillary, gravity, and viscous forces of DNAPL. *Ji et al.* [2003] modified the MIP model adding the effect of viscous force of groundwater and applied it to DNAPL migration problem in two-dimensional orthogonal fracture network. Then, they analyzed the effect of ambient groundwater flow on DNAPL migration through numerical and experimental approaches. In a random fracture network that is more realistic than an orthogonal fracture network, because abovementioned forces affect DNAPL migration intricately, it is difficult to estimate DNAPL phase structure thus needed to verify the applicability of the MIP model in a random fracture network.

To remediate DNAPL in subsurface, various remediation techniques were suggested. They almost involve the delivery of remedial fluids to the contaminant sources but it is very difficult in fractured rocks that have no fluid flow zone (e.g. dead-end fractures). *Yeo et al.* [2003] suggested the density-surfactant-motivated removal method to remove DNAPL trapped in vertical downward dead-end fractures. They observed that dense fluid (a mixture of water, calcium bromide and sodium doceyl sulfate that is denser than TCE and has low interfacial tension with TCE) displaced TCE from vertical downward dead-end fractures successfully.

In this study, we applied the MIP model to DNAPL migration in a two-dimensional random fracture network with variable aperture. To test MIP, we conduct DNAPL migration experiment with an artificial two-dimensional random fracture network. In addition, we applied the density-surfactant-motivated removal method to TCE trapped in a random fracture network and evaluated its applicability.

2. DNAPL migration in fracture networks

Ji et al. [2003] suggested the MIP model that has a mechanistic growth algorithm: the invader fluid invades the region that has the highest invadability. Then, the invadability is defined as:

$$I = \frac{2\sigma\cos\theta}{e} + (\rho_{invader} - \rho_{defender})gz\sin\alpha + \frac{Q_{invader}\mu_{invader}L}{kA} - \rho_{defender}gh_{defender} \quad (1)$$

The first term on the right in equation (1) represents the capillary force, the second term the gravity term, and the third and fourth terms the viscous forces of invader and defender fluids respectively.

Figures 1a and 1b show the experimental setup and used fracture network model respectively. TCE was injected into one of the fractures as seen in Figure 1b at a rate of 2.9ml/min.

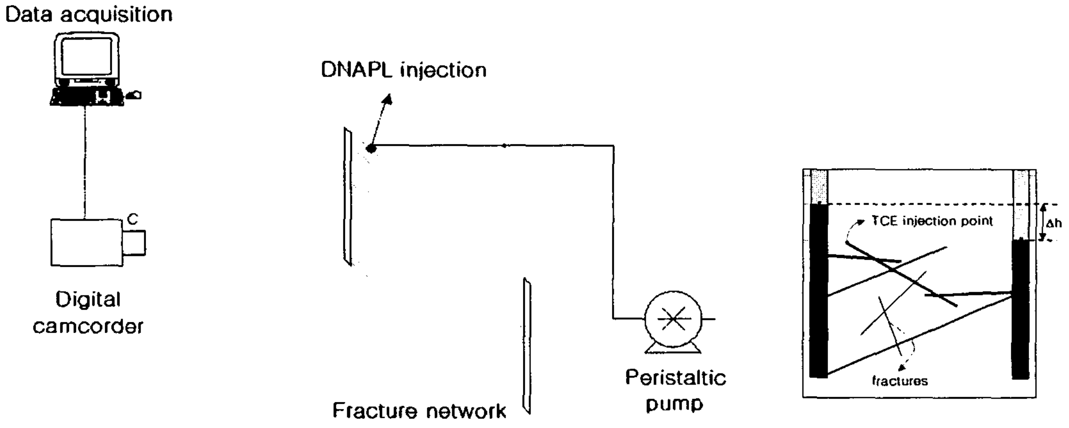
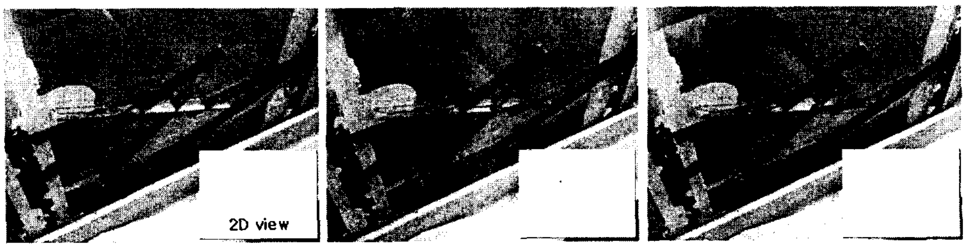


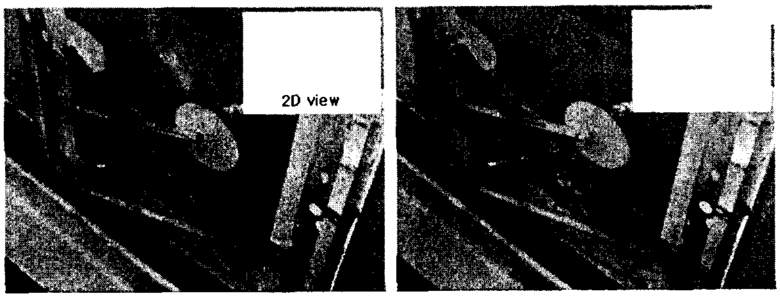
Figure 1. (a) Schematic diagram of experimental setup. (b) A fracture network model used for experiments. Fractures have various apertures ranged 0.05mm～ 0.096mm



(a)

(b)

Figure 2. (a) Experimental results. (b) Simulated results.



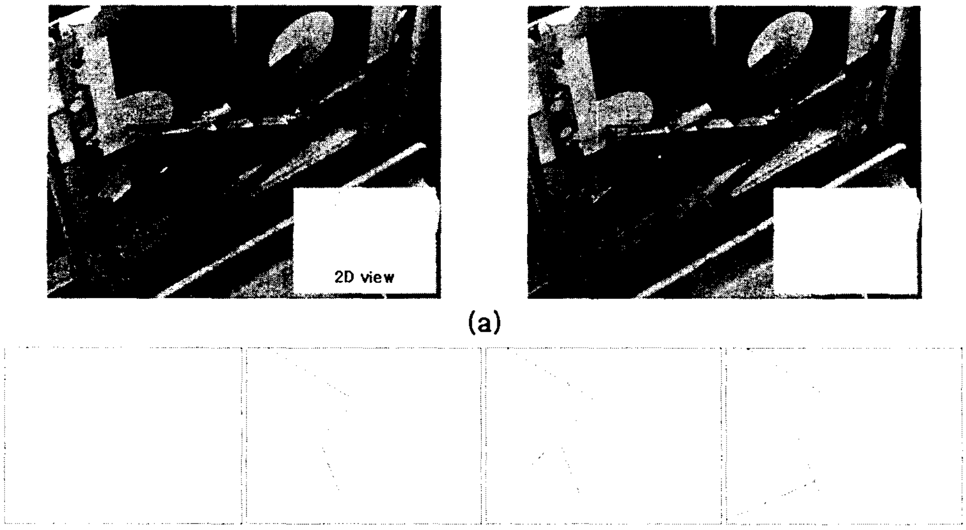
(a)

(b)

Figure 3. The case in which TCE was injected into another fracture. (a) Experimental results. (b) Simulated results

Figure 2 shows experimental and simulated results. It was simulated that TCE migrated through the injected fracture, then invaded more dipping fracture although it had small aperture of 0.070mm. However, in the experiment, TCE migrated through the fracture, which had large aperture of 0.091mm but extended toward anti-gravity direction, after invading the injected fracture. The difference between experimental and simulated results was observed in different cases: (i) TCE was injected at a different rate of 1.03ml/min; (ii) TCE was injected into another fracture (Figure 3).

Figure 4 shows the results of the case in which TCE was injected into a fracture network whose apertures are constant of 0.05mm. Although experimental and simulated results are different with each other, it is acceptable considering errors from experimental set up. From the results, it estimated that there are weight factors in each term of equation (1) and apertures of each fracture, thus the capillary force affects DNAPL migration in fracture networks more than others. For the further study, above assumptions will be evaluated through experiments using another form of random fracture network model.



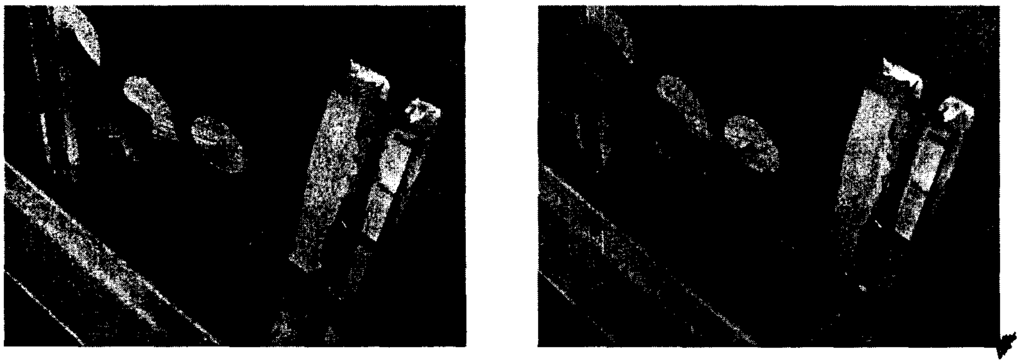
(a)

(b)

Figure 4. The case in which TCE was injected into a fracture network whose apertures are constant of 0.05mm. (a) Experimental results. (b) Simulated results

3. Application of Density-surfactant-motivated removal method to TCE trapped in a random fracture network

To evaluate the applicability of density-surfactant-motivated removal method in a random fracture network, TCE was injected into various fractures and TCE injection was ceased when TCE was placed in a fracture network. Figure 5a shows the initial distribution of TCE after injection of TCE. To remove TCE located in dead-end fractures, dense fluid (a mixture of 38% water, 57% calcium bromide and 5% SDS by weight whose density is 1.67g/cc and tension with TCE is 0.0073N/m) was injected with syringe and spread out into the whole fracture network because of its high injection rate. Injected dense fluid displaced TCE trapped in dead-end fractures, and then displaced TCE was moved into the fractures where water could flow (Figure 5b). From the results of the remediation test, it is proved that density-surfactant-motivated removal method is effective to remove TCE trapped in dead-end fractures in random fracture networks.



(a) (b)

Figure 5. (a) Initial distribution of TCE. (b) Distribution of TCE after injection of dense fluid

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