암반절리대에서의 DNAPL의 이동특성 및 정화

DNAPL Migration and Removal in Rock Fractures

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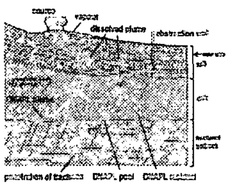
What and Why DNAPL?

- <u>D</u>ense <u>N</u>on<u>a</u>queous <u>P</u>hase <u>L</u>iquid
- Chlorinated solvents (e.g., PCE, TCE, DCE, VC)
- Health information of TCE
  - liver and kidney damage; carcinogenic; reproductive effects
- Physical properties
  - denser than water; less viscous than water; low solubility for water
- Dense non-aqueous phase liquids (DNAPLs) are a common groundwater contamination source, because of extensive use in industrial processes.

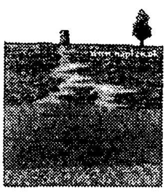
DNAPL Contamination in Rock Fractures



- It is very difficult to determine migration path of DNAPL in fractures.
- DNAPL trapped in rock fractures produces a serious long term dissolved contamination plume exceeding drinking water standard.
- The U.S. National Research Council rated DNAPL in fractured rock as "extremely difficult" to deal with, and advised that new technologies are needed to deal with this problem.

DNAPL Migration in Fractured Rocks

Factors controlling DNAPL Migration



Major factors controlling DNAPL migration in rock fractures are

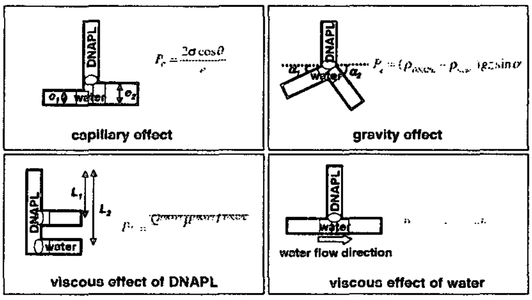
- Viscous force of DNAPL
- Viscous force of groundwater
- Capillary force
- Gravity force

MIP (Modified Invasion Percolation) Model

$$I = \frac{2\sigma\cos\theta}{\ldots} - \ldots + \frac{Q\,\mu\,L}{\ldots} + (\rho_{\ldots} - \rho_{\ldots})g\sin\alpha$$

capillary term — viscous terms — gravity term

Factors controlling DNAPL Migration in Fracture Network

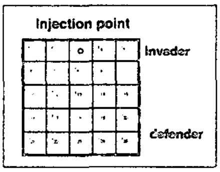


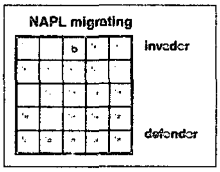
Invasion Percolation (IP) model

- new form of percolation (Chandler et al., 1982)
- the flow of two immiscible fluid in porous media
- Algorithm

  random number generation (invadability)

  cluster grows into the biggest random number





Equations governing Fluid Flow

Navier-Stokes Equations $\rho\frac{\partial u}{\partial t}+\rho(u\cdot\nabla)u=\mu\nabla^2 u-\nabla p-\rho g$

$\frac{\rho U b}{\mu}\left(\frac{b}{\lambda}\right)<<1$

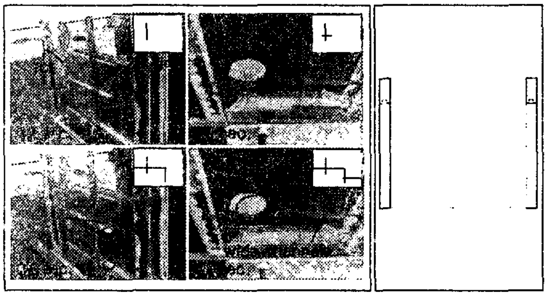
Stokes Equation $\mu\nabla^2 u=\nabla P$

$(b/\lambda)^2<<1$

Reynolds Equation $\frac{\partial}{\partial x}\left(b^3(x,y)\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial y}\left(b^3(x,y)\frac{\partial P}{\partial y}\right)=0$

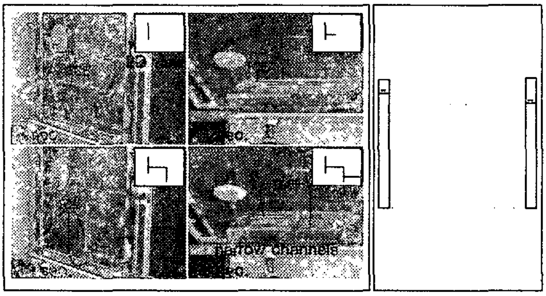
Cubic Law $Q=\frac{\rho g b^3}{12\mu}w\frac{dh}{dx}$

DNAPL Migration Path : static case



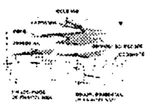
OBSERVED PREDICTED

DNAPL Migration Path : ∇h_w=0.2



OBSERVED PREDICTED

DNAPL Remediation in Fractured Rocks



Remediation Techniques of DNAPL

- Technologies to remediate DNAPL contamination usually involve the delivery of remedial fluids to the contamination source.

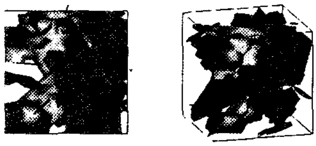
  for example,

  water for pump-and-treat,
  surfactant for mobilization and solubilization,
  vapor for vapor extraction,
  air for air sparging.

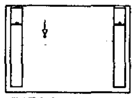
- Remediation technologies have been used to remediate DNAPL sites in soil porous media, but have not proved for fractured rocks.

DNAPL Remediation in Rock Fractures

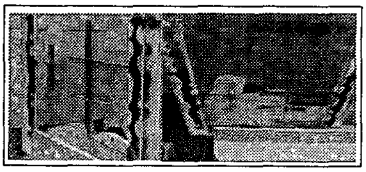
- The fractured rock environment makes effective delivery of remedial fluids very difficult to achieve.
- In particular, remedial fluids is rarely delivered to dead-end fractures.

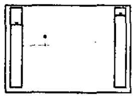


Water Flushing

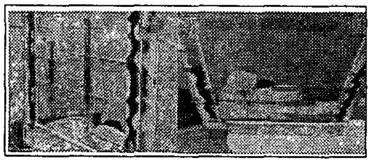


TCE Injection

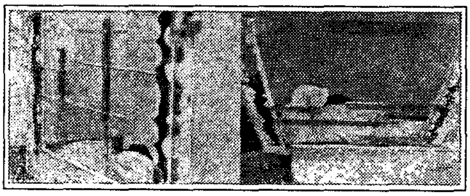




Water Flushing with Vh_w=0.4



Water Flushing Test



- The remedial fluid removes DNAPL in a horizontal fracture acting as a main flow path.
- This test indicates that conventional remedial fluids are rarely delivered to dead-end fractures.

Density-Enhanced Controlled Method

The main idea of this method is that denser fluid, then DNAPL, injected into fracture network turns DNAPL into LNAPL relative to the density of surrounding aqueous fluid, which results in the floating of DNAPL from dead-end fractures to fluid-flowing channels of fractures (Miller et al., 2000).

Physical Property of Dense Fluid

Calcium Bromide 100g + Water 100g = Dense Fluid (Density 1.52 g/cc)

tension with TCE : 0.01603 N/m

Safety Information of $CaBr_2$

Effects of overexposure: dust may irritate skin

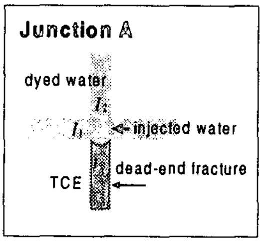
Target organs: none identified

Medical conditions by exposure: none identified

Test Results of Density-Enhanced Method

- Dense fluid flows through the fluid-flow channels, but does not invade dead-end fractures.
- Dense fluid fails to displace TCE trapped in dead-end fractures.

Analysis I for Water Flushing



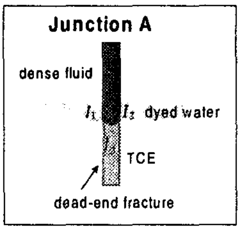
	capillary	gravity	
I_1 =	0	+ 0	= 0.000
I_2 =	0	+ 0	= 0.000
I_3 =	-238.0	- 228.3	= - 466.3

$$I = \frac{2\sigma\cos\theta}{e} - (\rho_{invader} - \rho_{defender})g\sin\alpha$$

Remedial fluid takes the path with higher "I" value.

θ ranges from 0° to 90° for wetting invasion and 90° and 180° for nonwetting invasion (Glass et al., 2001)

Analysis II for Dense Fluid



	capillary	gravity	
I_1 =	0	+ 0	= 0.000
I_2 =	0	+ 0	= 0.000
I_3 =	-160.6	+ 26.4	= -134.2

"More Effective"

Interfacial Tension ↓ Density ↑	or	Density ↑

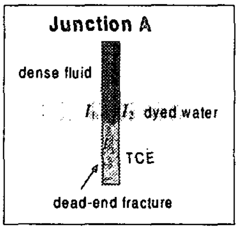
Design for Remedial Fluid

Physical Property of Dense Fluid

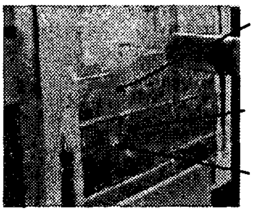
Calcium Bromide 150g +
Water 100g +
SDS (2g) =
Dense Fluid (Density 1.67 g/cc)

tension with TCE : 0.00732 N/m

	capillary	gravity	
I_1 =	0	+ 0	= 0.000
I_2 =	0	+ 0	= 0.000
I_3 =	-73.2	+ 102.9	= 29.7



Result



Dense fluid with surfactant

Dead-end fractures

TCE

▪ Surfactant-added dense fluid removes DNAPL from dead-end fractures successfully.

Conclusions

▫ Factors such as gravity, capillary force, viscous forces of water and DNAPL proved to play a major role in controlling DNAPL migration in a fracture network, and the predicted DNAPL path by MIP model agreed with the observed one.

▫ Surfactant-added dense fluid removed DNAPL from dead-end fractures more efficiently than conventional remediation methods.

▫ Further researches on the effective DNAPL migration model and remediation design is now being conducted.