Multi-Phase Fluid Flow in Porous Media

Duke Engineering & Services

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SEAR Workshop

Objective

- Provide a brief review of fundamental concepts of multi-phase fluid flow through porous media

- Multi-phase fluids include a combination of two or more of the following: gas, aqueous, and immiscible (or nonaqueous) phases

Outline

- Basic definitions
- Relative permeability
- Capillary pressure
- Capillary trapping
- Capillary desaturation curves
- Wettability

Basic Definitions

- Residual NAPL
  - Trapped NAPL that is immobile typically ~ 15% to 25%
- NAPL pools
  - NAPL saturations greater than residual saturations
  - NAPL is mobile when it exists in the form of pools

Darcy's Law

General Form

$$u = -\frac{kk_{ri}}{\mu_i}\nabla\phi$$

One-Dimensional Representation

$$k = \frac{q_i \mu L}{A}\left(\frac{\partial p_i}{\partial z} \pm \rho_i g\right)$$

Relative Permeability: Concept

- Defined as apparent permeability divided by intrinsic permeability
- Measure of the resistance to flow due to an additional fluid
- Always less than 1

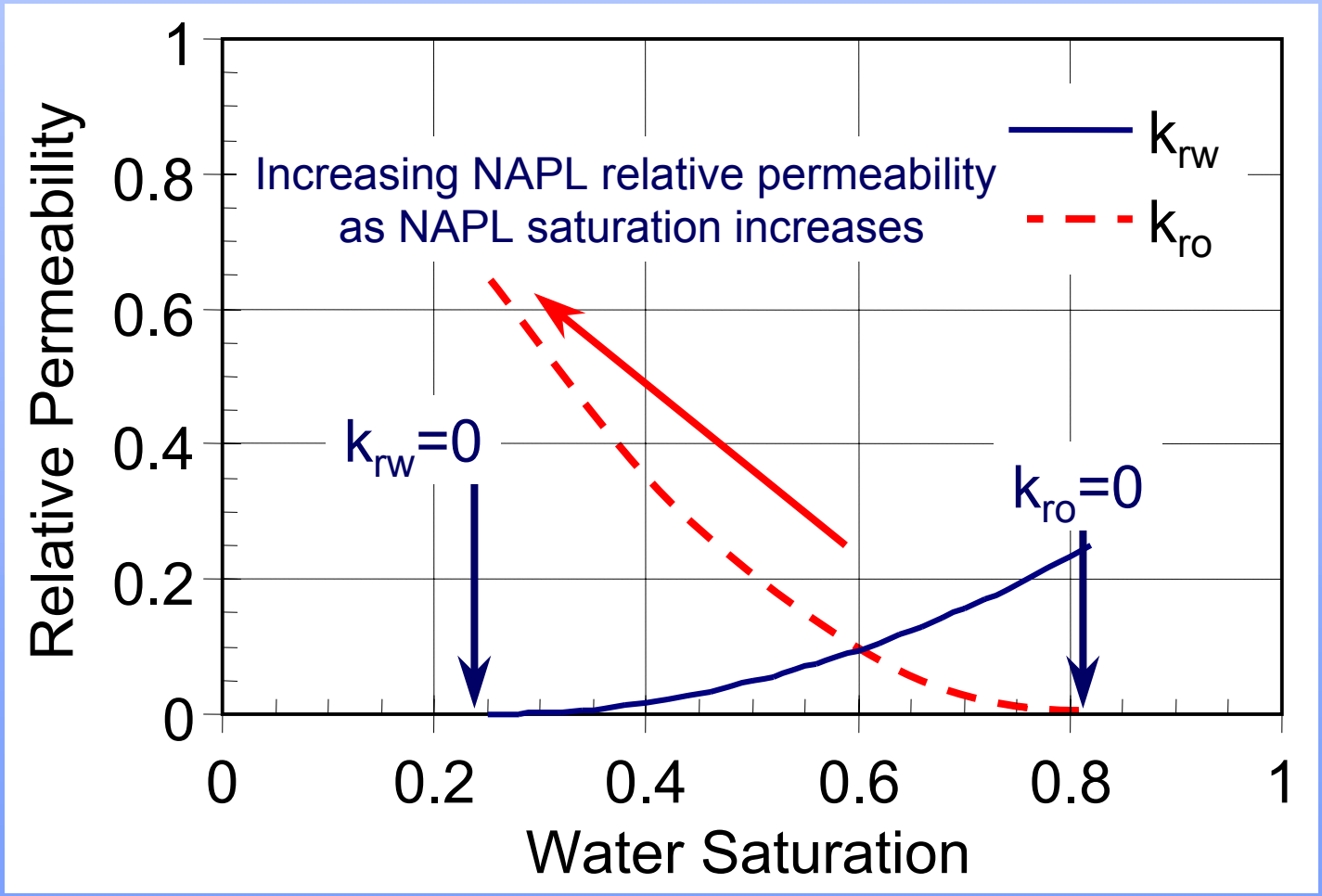
$$k_{rw} = \frac{k_{apparent}}{k_{intrinsic}} = 1$$

$$S_w = 1$$

$$k_{rw} = \frac{k_{apparent}}{k_{intrinsic}} < 1$$

$$S_w = 0.8$$

Example Curve



Significance

Observation

- Relative permeability of water is zero only at residual water saturation

Inference

- Therefore water can flow through a NAPL pool as long as the water saturation is greater than residual water saturation

Significance

- Partitioning tracers will detect NAPL even it exists in the form of pools

Capillary Pressure: Concept

- Capillarity describes the combined effects of interfacial tension and wettability
- Capillary pressure is the difference between the non-wetting-phase and wetting-phase pressures

$$P_c = P_{nw} - P_w = P_o - P_w$$

General Form (Laplace's Eqn)

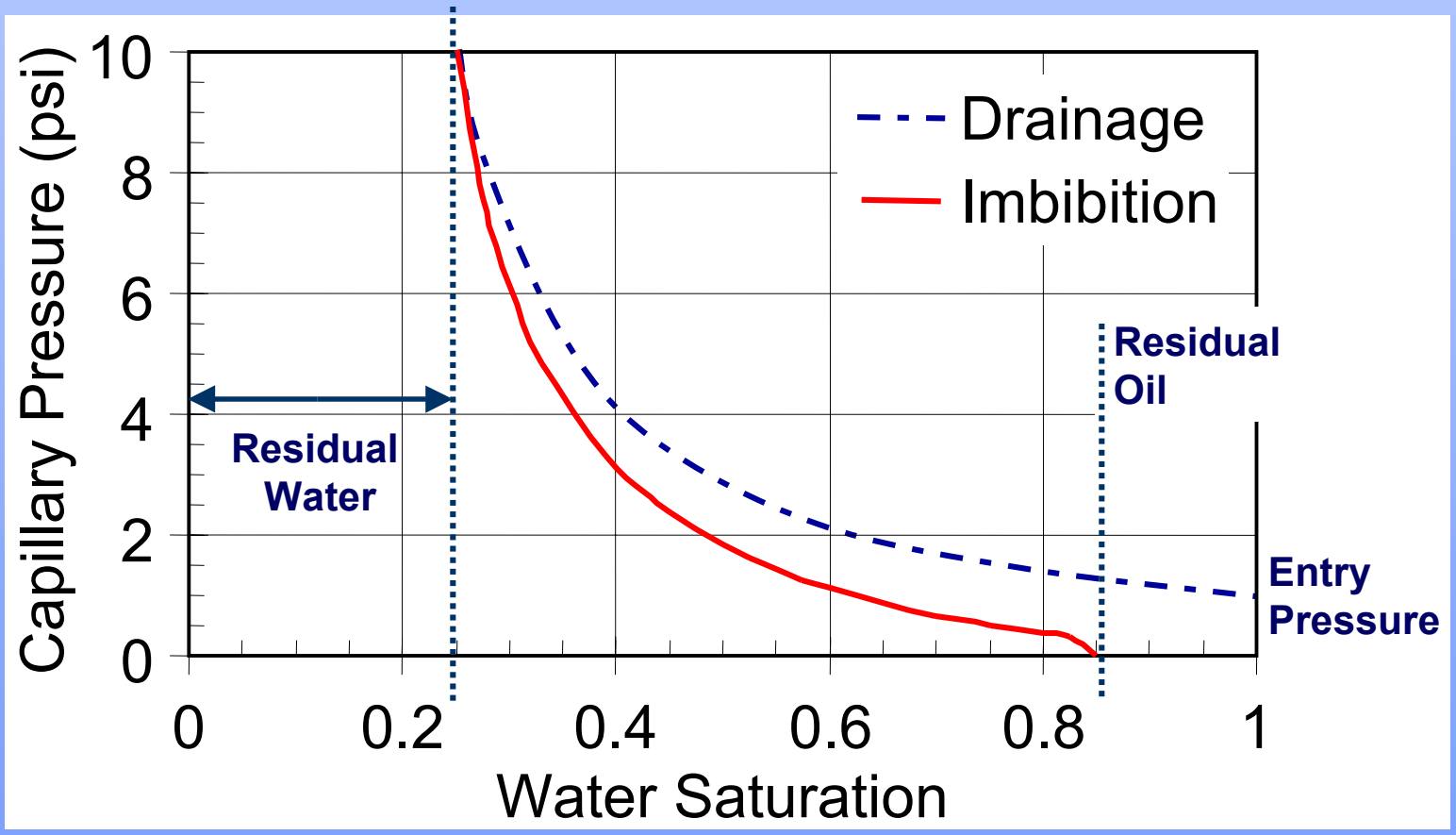
$$P_c = P_o - P_w = 2\sigma H$$

H = curvature

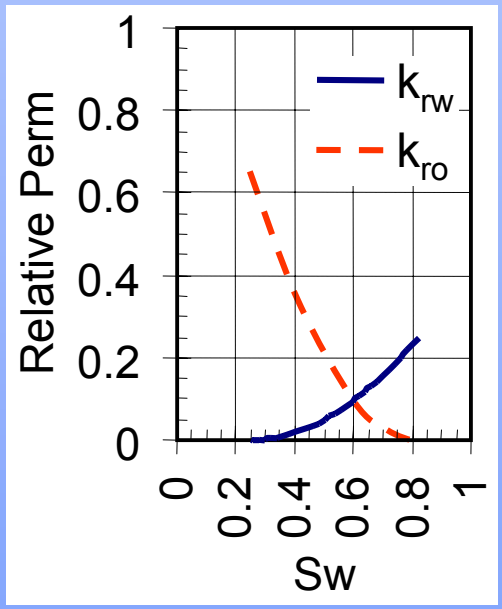
In a capillary tube

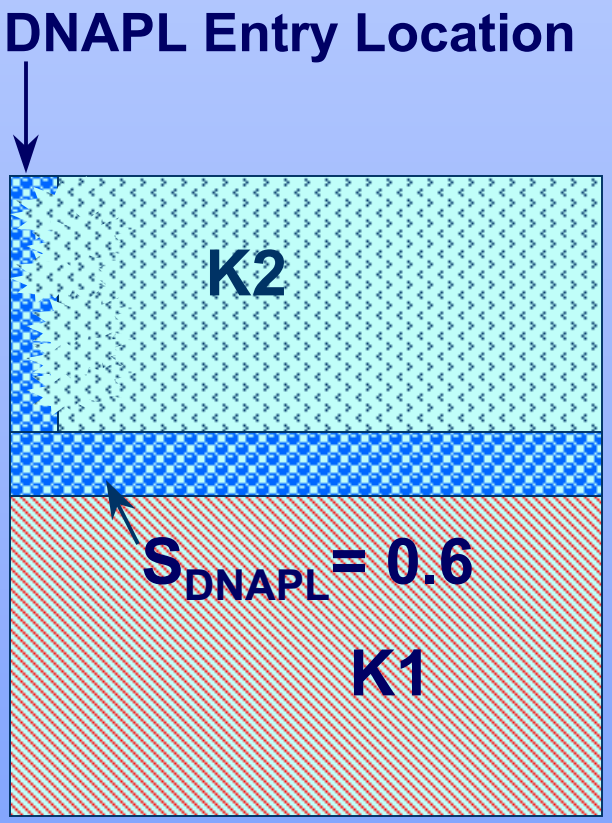
$$P_c = \frac{2\sigma \, Cos\,\theta}{r}$$

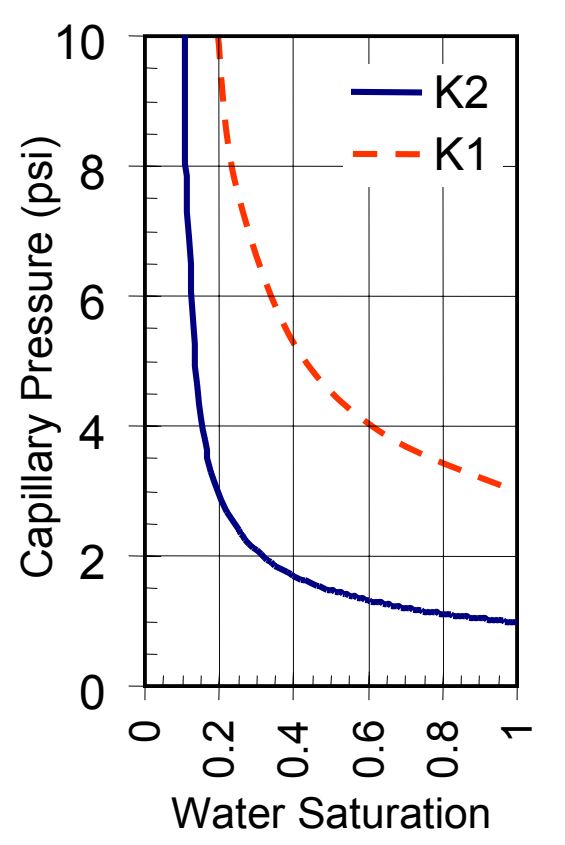
Drainage and Imbibition



Practical Significance







DNAPL zone effective permeability = 0.1K2

Inferences

- NAPL trapping will occur over less permeable zones
- Water can flow through NAPL pools
- Reduced flow of water through NAPL pools translates into reduced viscous forces and therefore a less efficient NAPL displacement

Capillary Trapping

- Due to capillary forces that hold NAPL
- NAPL movement can be induced by
  - Viscous forces
  - Gravitational forces
- NAPL will be mobilized when the vector sum of the viscous and gravitational forces exceed capillary forces

Dimensionless Parameters

Capillary Number

$$N_{ca} = \frac{kk_{ri}}{\sigma}\frac{\Delta\Phi}{L}$$

Bond Number

$$N_B = \frac{kk_{ri}}{\sigma}\Delta\rho\, g$$

$$N_t = \sqrt{N_{ca}^2 + N_B^2 - 2N_{ca}N_B\, Sin\alpha}$$

For horizontal flow

$$N_t = \sqrt{N_{ca}^2 + N_B^2}$$

Capillary Desaturation Curves

- Plot the reduction in saturation against the trapping number
- Practically determine whether NAPL can be easily mobilized
- Provide insights into wettability
- In water-wet sediments NAPL is usually mobilized for $N_t \sim 10^{-4}$
- Pumping/waterflooding $N_t \sim 10^{-7}$ to 10^{-5}
- Surfactant flooding $N_t \sim 10^{-4}$ to 10^{-2}

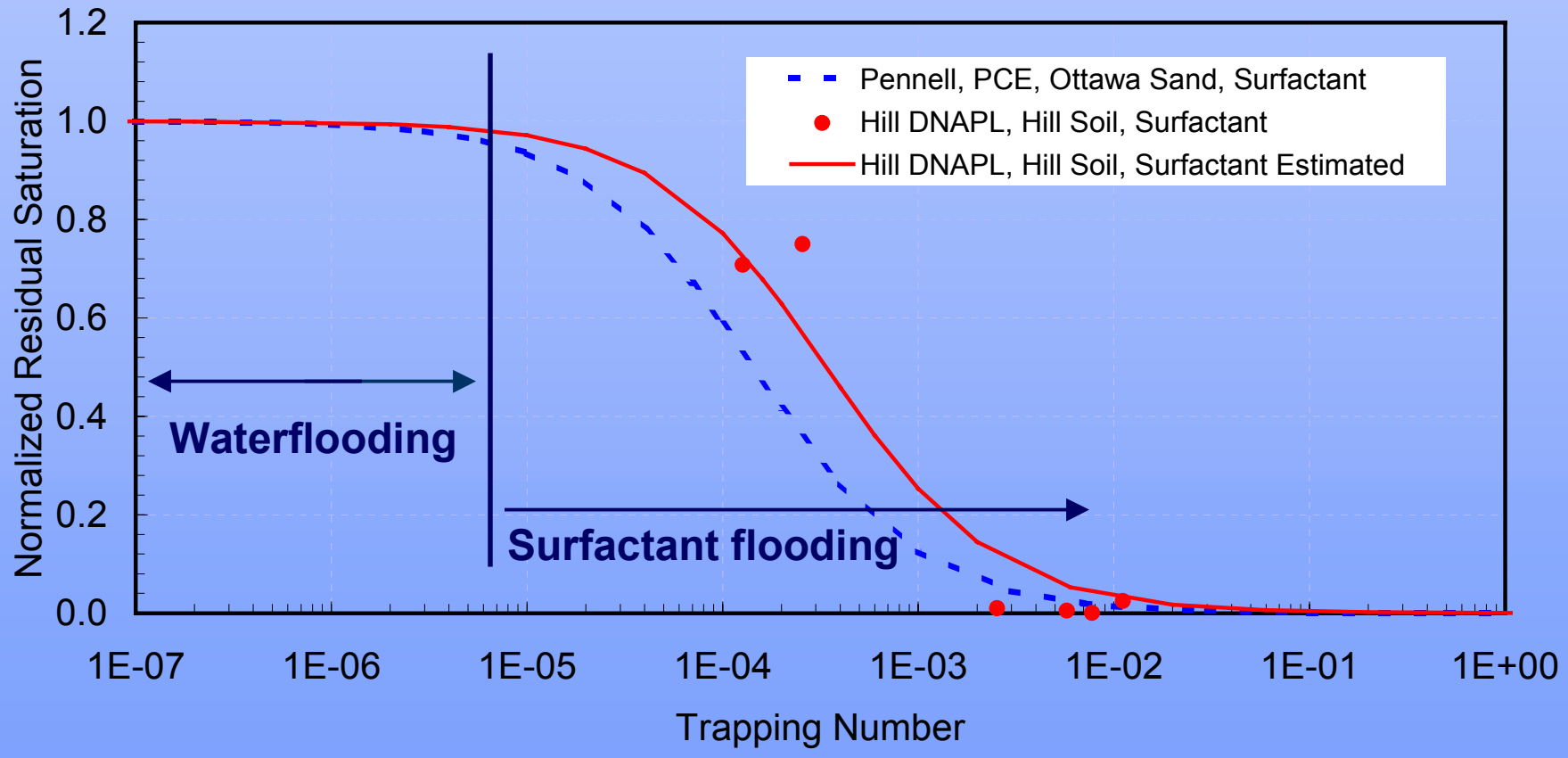
How to Mobilize NAPL

- Viscous forces can be increased by increasing gradient
  - Increasing the gradient increases the viscous force
  - Practical limits to increasing gradient
- Interfacial tensions can be decreased
  - Reduces the capillary forces and raises the proportion of the viscous and gravity forces with respect to capillary forces

How to Prevent NAPL Mobilization

- Select a surfactant with a sufficiently high IFT such that the critical trapping number is not exceeded ($<10^{-4}$)

Example of CDC in Water-Wet Material



Wettability

- Classic assumption: Aquifers are water-wet
  - NAPL resides in large pores, is easily accessible
- Aquifer material is mixed wet to oil-wet
  - NAPL resides in small pores
- The application of a well-behaved anionic surfactant will make the aquifer material more water-wet

Amott Wettability Results

Site	NAPL	Amott	USBM
OU 2, Hill AFB	TCE	0	-0.1
OU 1, Hill AFB	Weathered JP-4	0	-0.1 to 0.28
Refinery Site	Weathered Gasoline	0	--

	Amott	USBM
Oil-Wet	-0.3 to -1	Negative
Water-Wet	+0.3 to +1	Positive
Mixed Wet	-0.3 to +0.3	Zero

Summary

- Water can flow through a NAPL pool due to relative permeability effects
- NAPL flow is controlled by capillary pressure and relative permeability concepts
- NAPL can be mobilized by reducing IFTs and predicting mobilization using CDCs
- Aquifer material generally is mixed wet and should be accounted for during design

Any Questions?

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