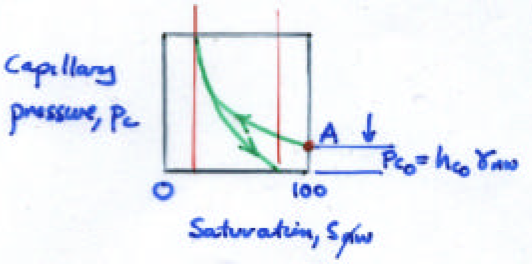
2.5 Non-Aqueous Fluid Penetration (Static groundwater field)

Question: How deep will a DNAPL penetrate?; Will it arrest?
Experience/evidence shows insidious penetration.

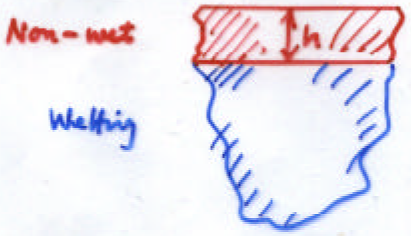


P_{c_0} = entry pressure

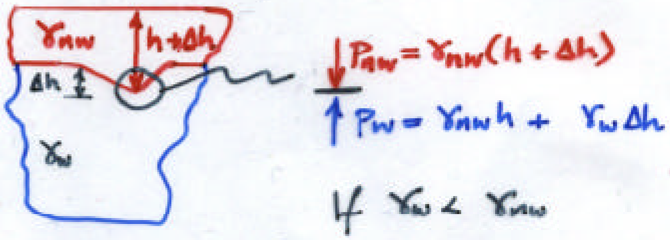
Note – wish to penetrate at minimum saturation, not to saturate.

i.e.: Penetrate @ low saturation

Consider without porous medium



No penetration unless instability develops



$P_{nw} = \gamma_{nw}(h + \Delta h)$

$P_w = \gamma_{nw} h + \gamma_w \Delta h$

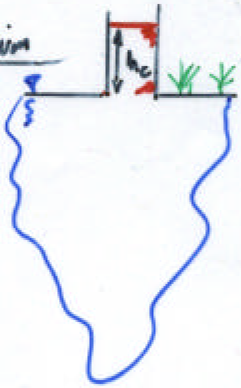
If $\gamma_w < \gamma_{nw}$

then $P_w < P_{nw}$

∴ Instability develops and pressure difference builds as Δh increases

i.e. Accelerating instability

In porous medium



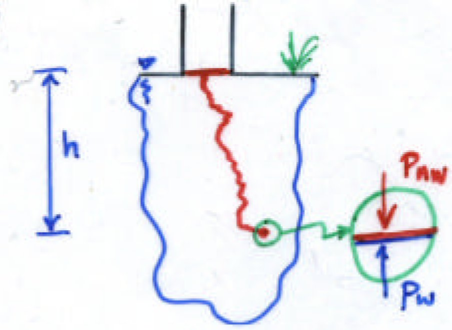
$P_{c_0} = h_c \gamma_{nw}$

Fluid will penetrate into porous medium. Two possibilities.

1) Flows until all large void space is filled, and stops?

2) Flows, but large void space is sufficiently connected to drain reservoir? ✓

Can flow stop?



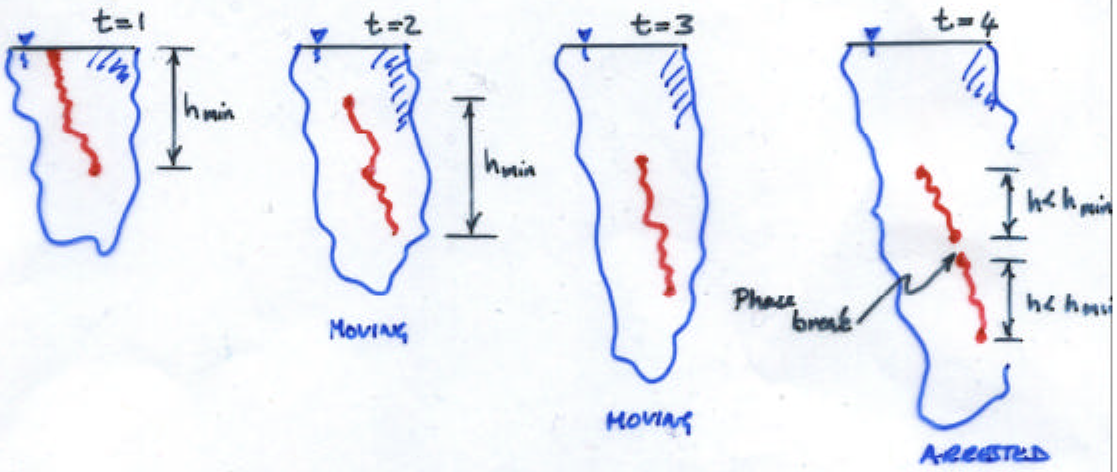
Will stop if $p_{nw} \le p_w + p_{co}$ (1)

$$h\gamma_{nw} \le h\gamma_w + h_c\gamma_{nw} \quad (2)$$

$$h\frac{\gamma_{nw}}{\gamma_w} - h = h_c\frac{\gamma_{nw}}{\gamma_w} \quad (3)$$

$$\boxed{h_{min} = \frac{h_c}{(1-\gamma_w/\gamma_{nw})}} = \frac{P_{co}/\gamma_{nw}}{(1-\gamma_w/\gamma_{nw})} \quad (4)$$

Only limitation is that "phase must be "continuous"."



Equation (4) shows: • h_{min} largest if densities of fluids are close —
as γ_{nw} becomes denser, then less high column
of non-wetting fluid needed to generate P_{co}.

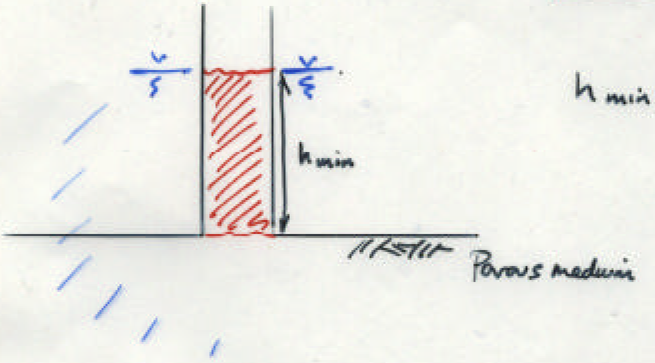
Practical Implications

1. Will only stop if (a) Fills "large voids" space and no connected "large void" space remains.
   (b) Flow "necks-down" and h_{min} is split
   (c) Fluid system is not "static". What is flow direction.

Important parameter is the connected pore space!!
This is difficult to evaluate with conventional test methods.

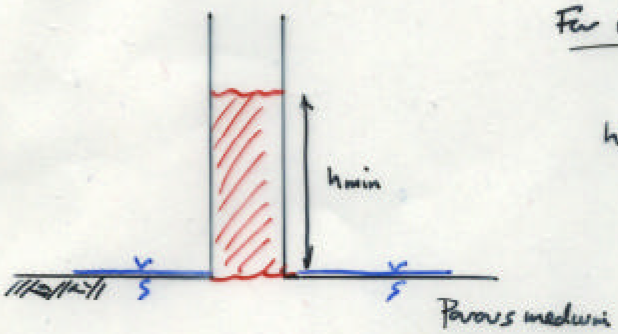
MAKE SURE YOU UNDERSTAND THE UNDERLYING ASSUMPTIONS

BEFORE YOU APPLY THESE



For invasion:

$$h_{min} = \frac{P_{co}/\gamma_{nw}}{(1-\gamma_w/\gamma_{nw})} = \frac{h_c}{(1-\gamma_w/\gamma_{nw})}$$



For invasion:

$$h_{min} = P_{co}/\gamma_{nw} = h_c$$

Table 4-2. Relationships between capillary pressure, gravity, and hydraulic forces useful for estimating conditions of DNAPL movement (from Kueper and McWhorter, 1991; WCGR, 1991; and Mercer and Cohen, 1990).

Condition	Equation
(a) Capillary pressure exerted on the surface of a nonwetting NAPL sphere	$P_c = P_{NAPL} - P_w = (2\sigma\cos\phi) / r$
(b) Capillary pressure exerted on the surface of NAPL in a fracture plane where b is the fracture aperture	$P_c = P_{NAPL} - P_w = (2\sigma\cos\phi) / b$
Hydrostatic Conditions	
(c) Critical height of DNAPL required for downward entry of DNAPL through the capillary fringe (the top of the saturated zone)	$z_n = (2\sigma\cos\phi) / (r\, g\, \rho_n)$
(d) Critical height of DNAPL required for downward entry of DNAPL into the water-saturated base of a lagoon where DNAPL is pooled beneath water; or, below the water table, for entry of DNAPL into a layer with smaller pore openings (assuming top of DNAPL body last existed under imbibition conditions)	$z_n = (2\sigma\cos\phi) / [rg(\rho_n - \rho_w)]$
(e) Critical height of DNAPL required for entry of DNAPL into a water-saturated fracture at the base of a lagoon where DNAPL is pooled beneath water; or, below the water table, for entry of DNAPL into a water-saturated fracture having an aperture, b, smaller than the host medium pore radii; or, below the water table, for entry of DNAPL into a water-saturated fracture segment having an aperture smaller than that of the overlying host fracture segment (assuming top of DNAPL body last existed under imbibition conditions)	$z_n = (2\sigma\cos\phi) / [bg(\rho_n - \rho_w)]$
(f) Critical height of DNAPL required below the water table, for entry of DNAPL into a layer with smaller pore openings where the top of the DNAPL body is under drainage conditions	$z_n = [P_{d(fine)} - P_{d(coarse)}] / [g(\rho_n - \rho_w)]$
(g) The stable DNAPL pool length, L_p, that can exist [illegible] the water table following initial DNAPL migration where θ is the di[illegible] of the base of the host medium and L_p is measured parallel to the host mediu[illegible]se slope	$L_p = (2\sigma\cos\phi) / [rg(\rho_n - \rho_w)\sin\theta]$
(h) T[illegible] stable DNAPL pool length, L_p, within a fracture that can exist below the water table following initial DNAPL migration where θ is the dip angle of the fracture, b is the maximum fracture aperture at the leading edge of the DNAPL pool, and L_p is measured parallel to the fracture slope	$L_p = (2\sigma\cos\phi) / [bg(\rho_n - \rho_w)\sin\theta]$
Hydrodynamic Conditions	
(i) Neglecting capillary pressure effects, the critical upward hydraulic gradient, i_c, required across a DNAPL body of height z_n to prevent downward DNAPL migration in a uniform porous medium	$i_c = \Delta h / \Delta z_n = (\rho_n - \rho_w) / \rho_w$
(j) Neglecting capillary pressure effects, the minimum hydraulic head difference between the bottom and top of a DNAPL body of height z_n to prevent downward DNAPL migration in a uniform porous medium	$\Delta h = i_c\, \Delta z_n = z_n(\rho_n - \rho_w) / \rho_w$
(k) Neglecting capillary pressure effects, the critical hydraulic gradient, i_c, required to prevent the downward movement of DNAPL along the top of a dipping (angle = θ) capillary barrier (i.e., in sloping fractures, bedding planes, or within a sloping coarse layer above a fine grained layer) with i_c measured parallel to the slope	$i_c = [(\rho_n - \rho_w)\sin\theta] / \rho_w$
(l) [illegible]e critical horizontal hydraulic gradient, i_c, which must exist across a DNAPL pool of length L beneath the water table to overcome capillary resistance and mobilize DNAPL in the pool (to calculate i_c for a pool of DNAPL in a horizontal fracture, replace r with the fracture aperture, b)	$i_c = (2\sigma\cos\phi) / (r\rho_w g L)$
(m) The critical upward hydraulic gradient, i_c, required to arrest the downward migration of DNAPL through an aquitard of thickness, Δz, where ΔP_c is the capillary pressure of DNAPL pooled at the top of the aquitard minus the threshold entry (displacement) pressure of the aquitard	$i_c = \Delta h / \Delta z = [(\rho_n - \rho_w)/\rho_w] + [\Delta P_c / (\rho_w g \Delta z)]$