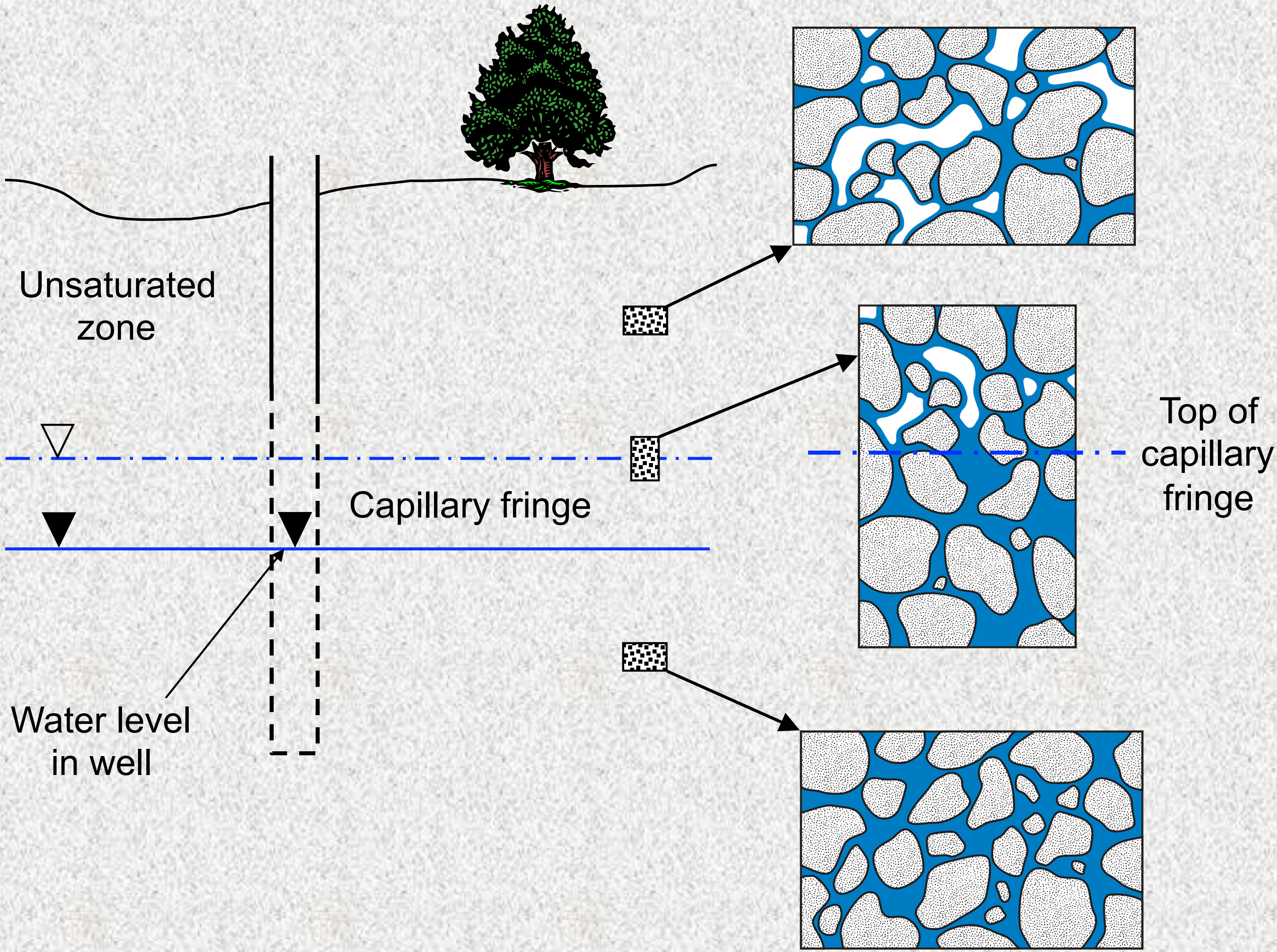
Vadose Zone (Unsaturated Zone)

Suggested reading: Schwartz and Zhang Ch. 6

The region situated between the land surface and the water table is referred to as the vadose zone and/or the unsaturated zone although there are some distinctions.

It represents the critical link between the ground surface and underlying groundwater resources. It is the most active region of the subsurface in terms of chemical, biological and hydrologic activity.

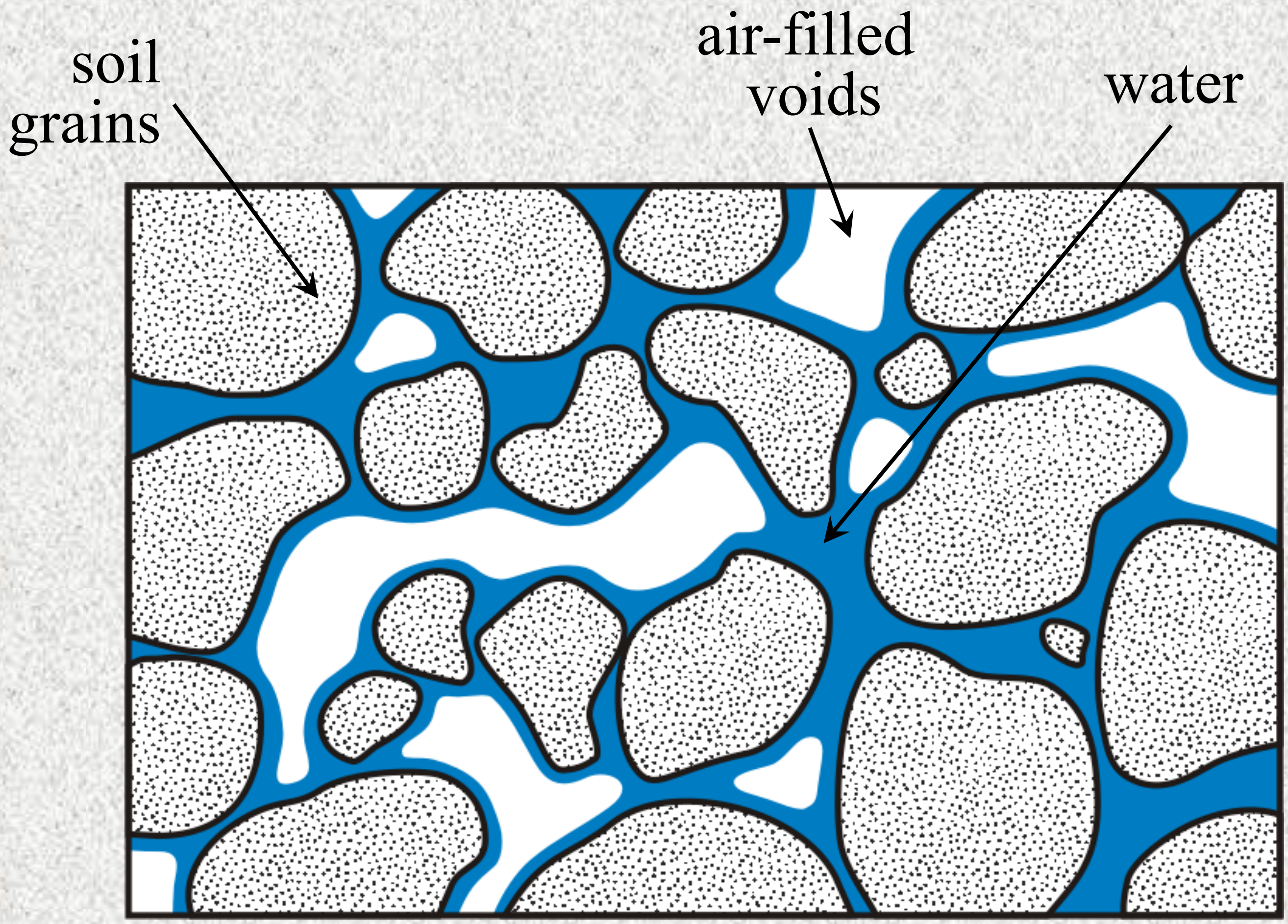
Flow processes are considerably more complex in the vadose zone than in the saturated zone below the water table.



Unsaturated zone
Capillary fringe
Water level in well
Top of capillary fringe

Partially Saturated Soil Model

We now have multiple phases that can flow – air and water.



Vadose Zone vs. Groundwater

The physics of flow is different in the vadose zone.

Component	Groundwater	Vadose Zone
Phases	Soil and water	Soil, water and air
Water Pressure	Positive	Negative
Darcy's Law	Applies	Applies?
Flow	K is constant	K is dependent on θ
Storage	Elastic expansion & contraction (α and β)	Controlled by changes in θ

Vadose Zone Flow and Storage

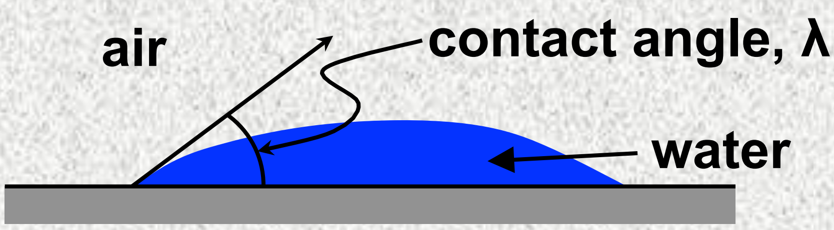
Our goal is to understand how water moves in the vadose zone and continue developing tools we can use to quantify these processes.

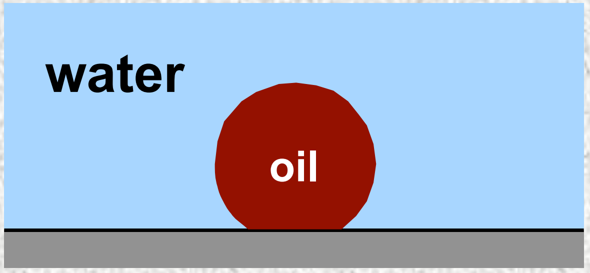
In order to understand the flow of multiple fluid phases (termed multiphase flow), it is important to understand the concepts of wettability, interfacial tension, and capillary forces. These concepts can be applied to a variety of systems.

- air and water - vadose zone
- oil and water - petroleum migration
- oil, gas, and water - oil spills in vadose zone, petroleum/natural gas migration

Wettability

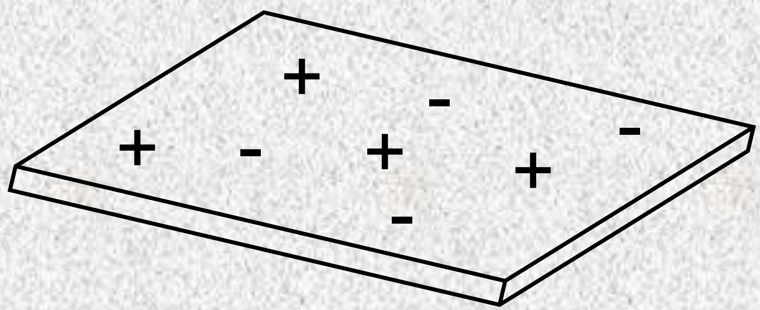
When two immiscible fluids contact a solid surface, one will adhere more readily to the surface. This is referred to as the <u>wetting phase</u> because it wets the solid surfaces. The other phase is call the <u>non-wetting phase</u>.

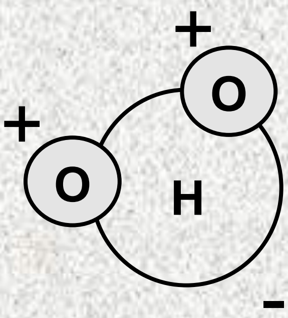




The type of surface and fluids under consideration will control the wettability. We will deal exclusively with water-air-soil systems.

The relative attraction of fluids to a surface depends on electrostatic and other forces. Remember that water is a polar molecule.





Mineral surfaces have an uneven distribution of + and – charges. Mineral surfaces usually love to hold water and are termed <u>hydrophilic</u>.

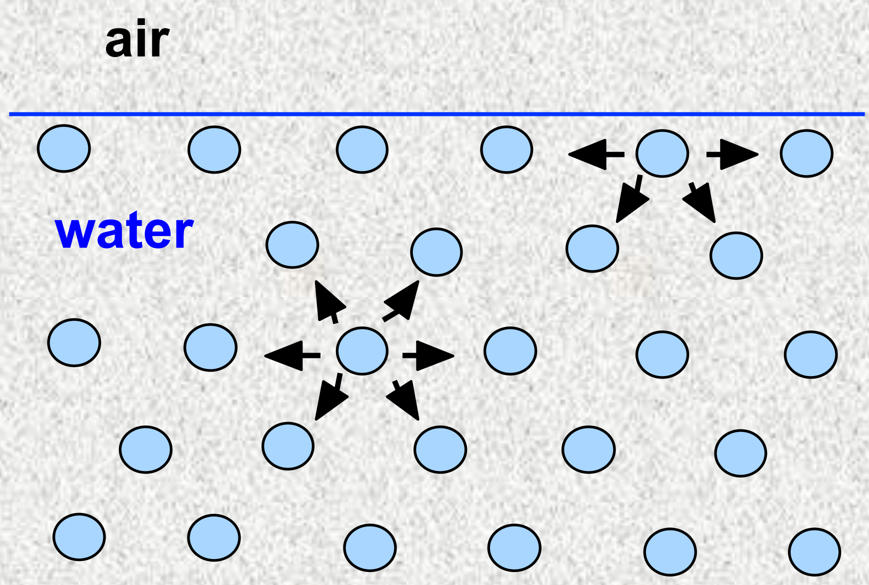
As such, water is the wetting fluid with respect to air and will generally coat soil grains, while air occupies the central region of pores.

Interfacial Tension, σ

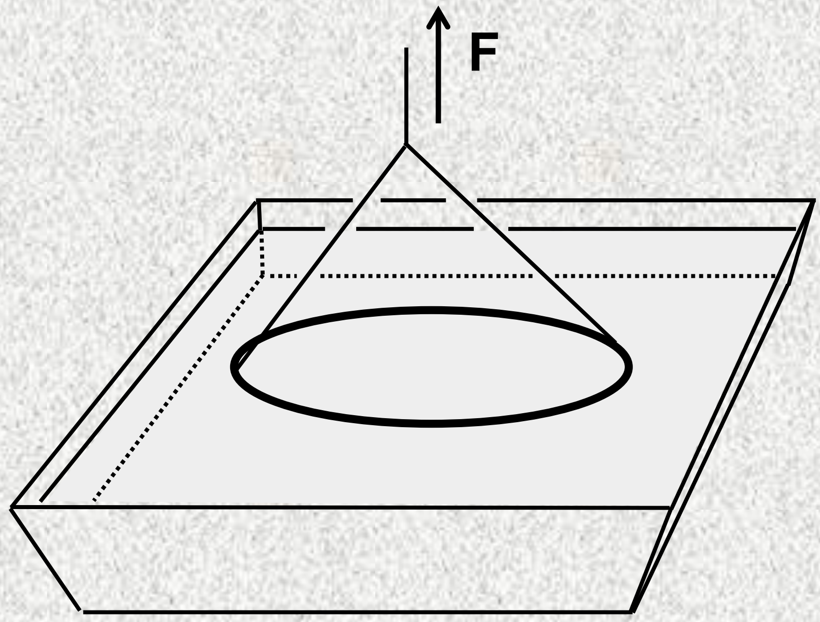
Refers to the phenomenon at the interface between two immiscible fluids. The molecules in one fluid will have a greater attraction for each other than they do for the opposing fluid. Also called surface tension in an air-water system.

Molecules near the air-water interface feel a stronger force inward than outward.

A body of water tends to have the minimum surface area for a given volume.



We need to apply some force to increase the surface area of an air-water interface. This force is equal to the surface tension.



Interfacial tension has units of energy/area or force/length. It is dependent on the two fluids that form the interface as well as the temperature.

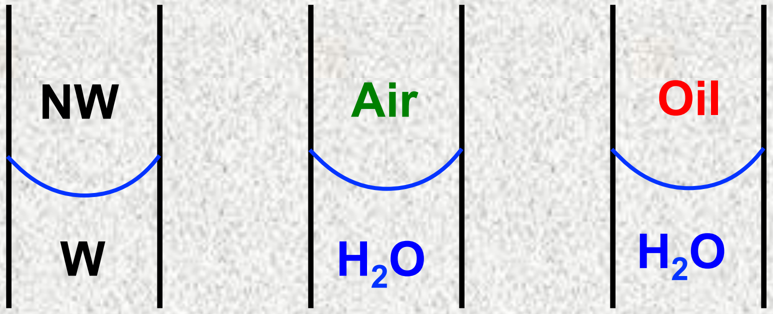
- $\sigma_{air\text{-}water} \approx 0.072$ N/m (@ 25°C)

Capillary Pressure

These cohesive interfacial forces cause the fluid interface to curve and result in a pressure difference across the interface. This pressure difference is called the **capillary pressure, P_c** and is given by:

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

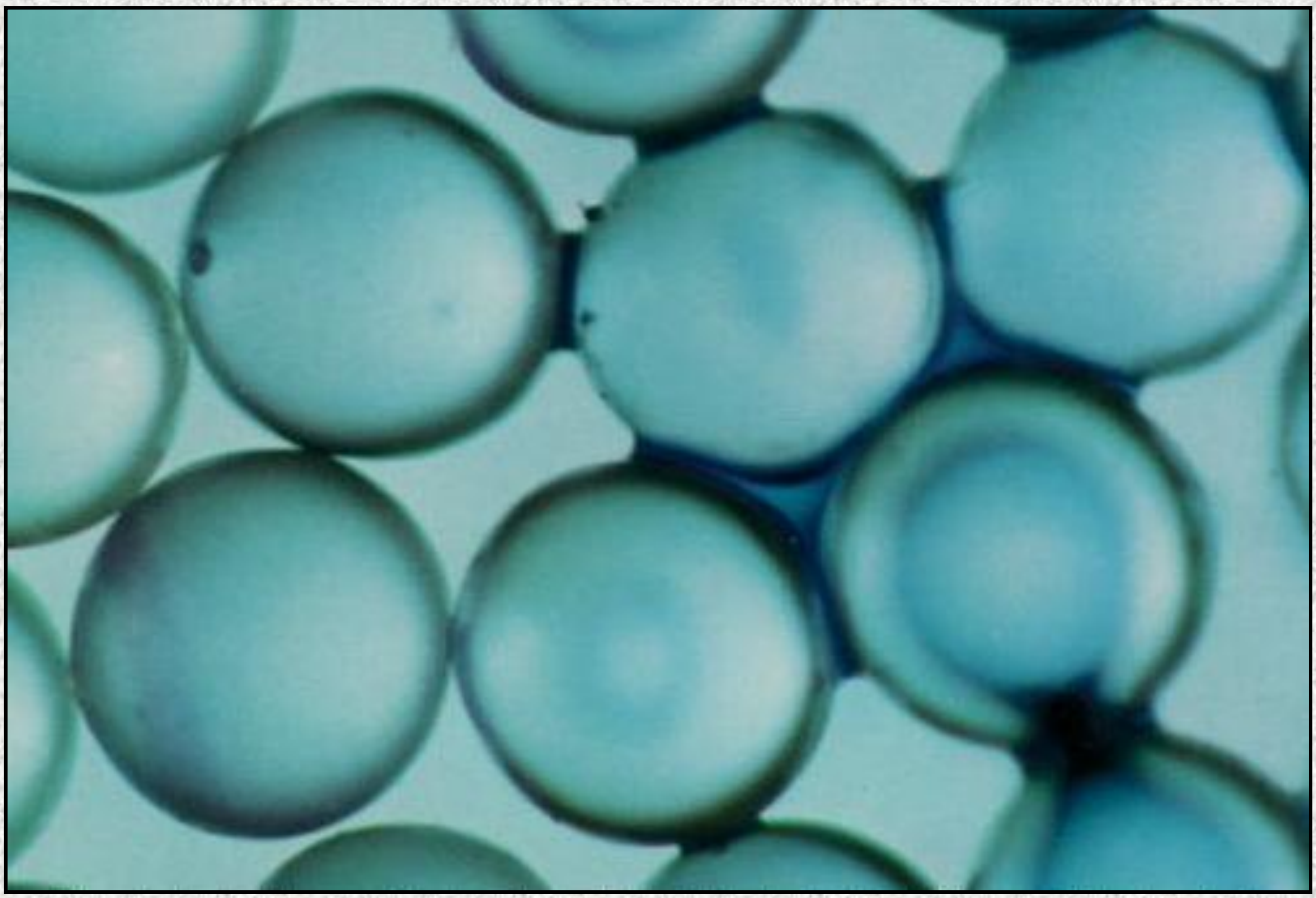
where P_{nw} and P_w are the fluid pressures in the non-wetting and wetting phases, respectively.



P_{nw} is always greater than P_w.

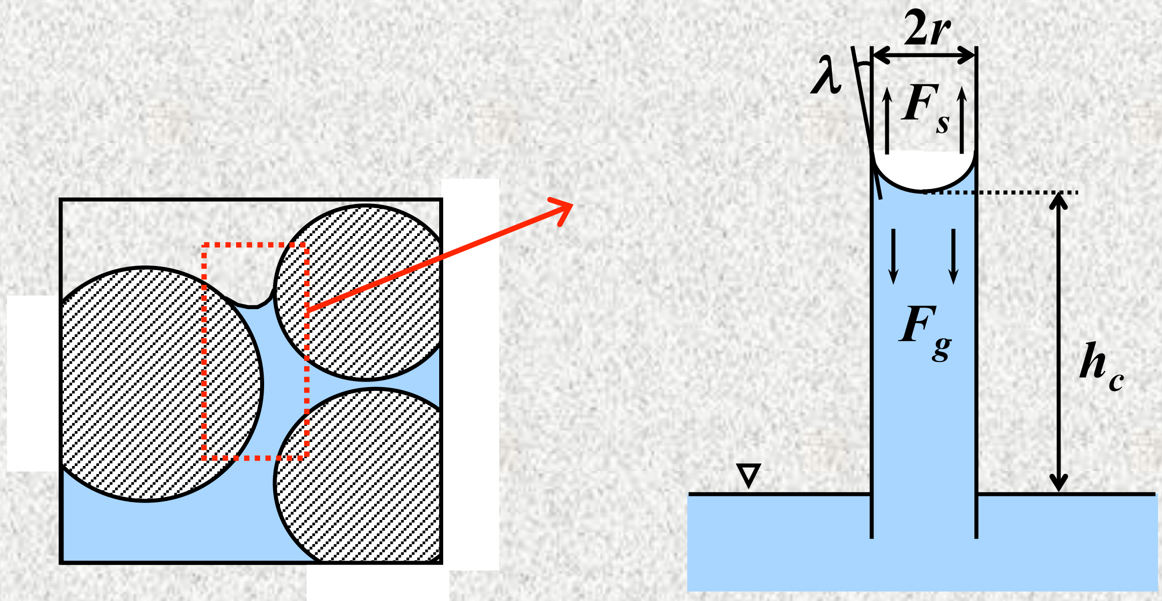
If P_{nw} is zero (say for air) then P_w must be negative.

Photo of **water** (dyed blue) and **air** in a glass bead pack. The diameter of the glass beads ranged from 0.85 to 1.23 mm. Notice the curvature of the air-water interfaces. Water is the wetting fluid and is bound in the smallest pores.



(Source: Friedrich Schwille, Dense Chlorinated Solvents [Translated by James F. Pankow] 1988)

Capillary Tube Model



Soil particles hold water in the same way as a capillary tube.

Upward force
(Surface tension)
$F_s = 2\pi r\sigma \times \cos\lambda$

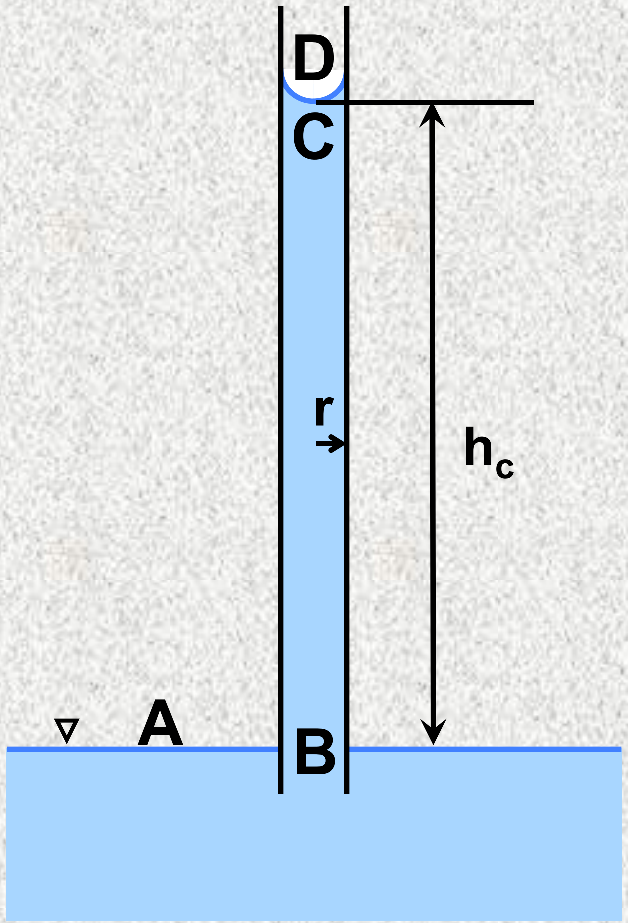
Downward force
(Gravitational)
$F_g = \pi r^2 \rho_w g h_c$

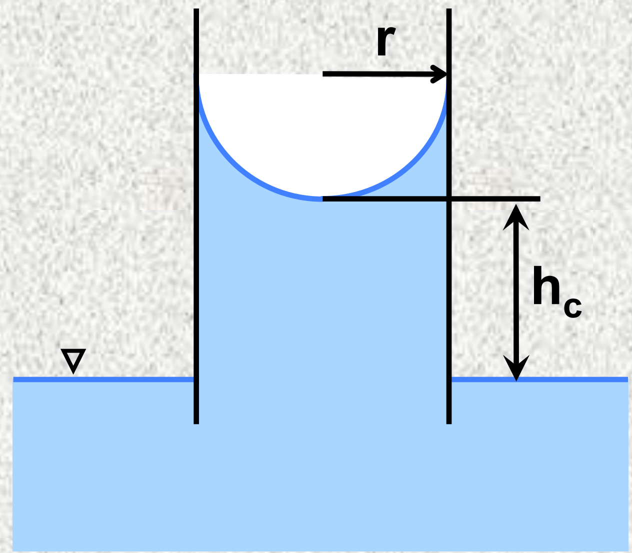
λ : contact angle (usually small, i.e. $\cos\lambda \cong 1$)

Forces are balanced when F_g equals F_s. Capillary pressure is thus related to the radius of curvature of the interface, which is related to pore radius.

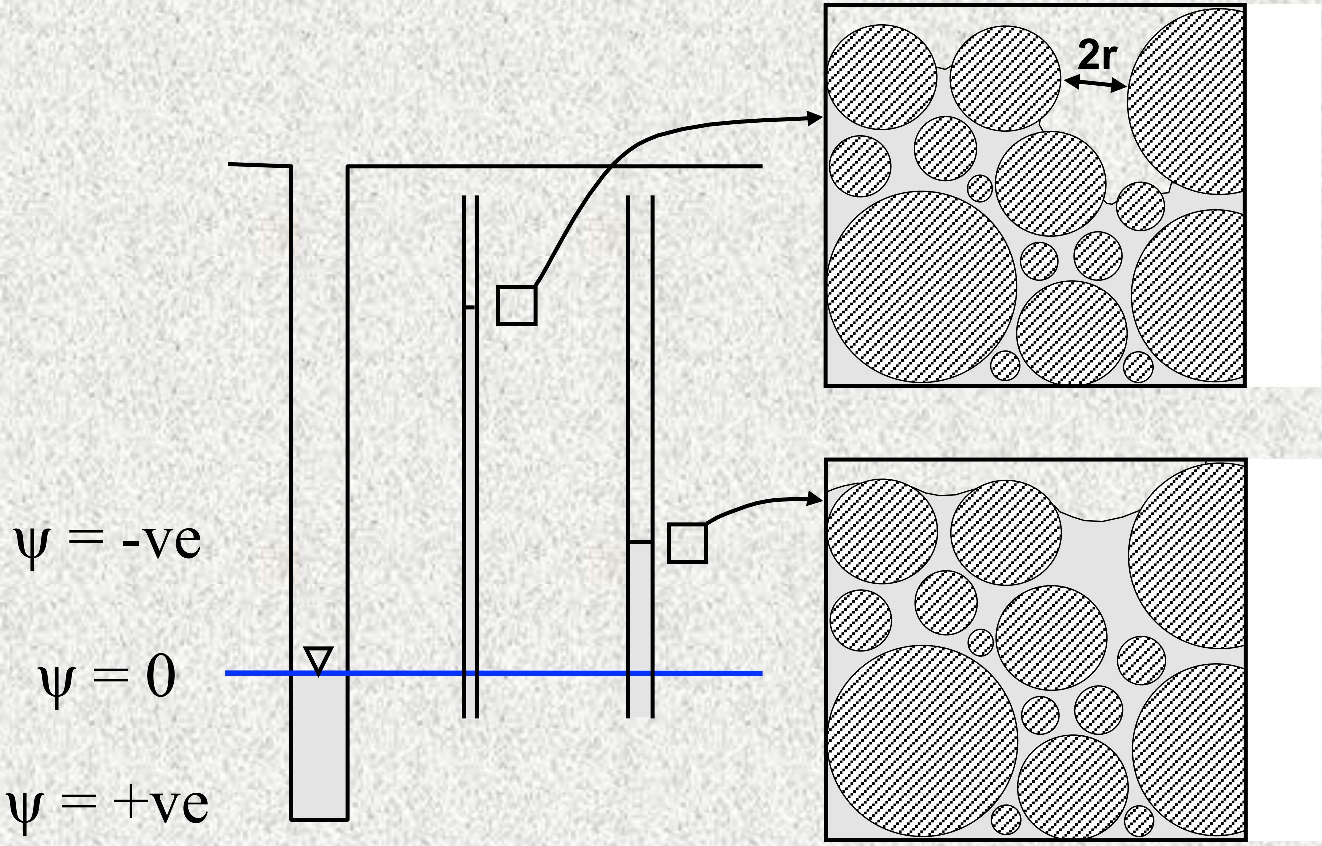
$$\boxed{P_c = \frac{2\sigma \cdot \cos\lambda}{r}}$$

$$\boxed{h_c = \frac{2\sigma \cdot \cos\lambda}{\rho g r}}$$





Water pressure is zero at the water table. Above the water table, water is held under tension (negative pressure) by capillary forces.

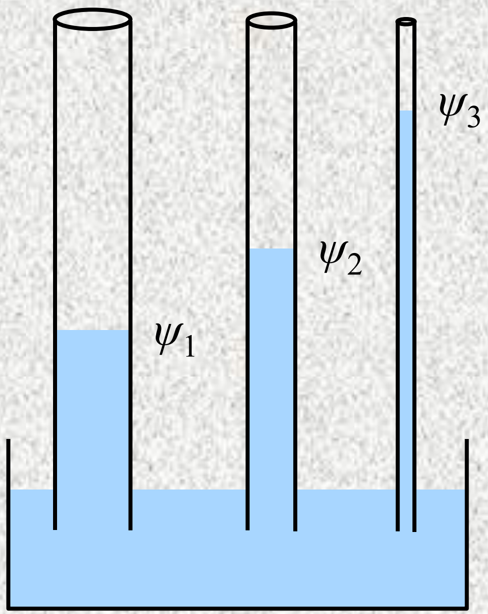


Water Content-Pressure Relationship

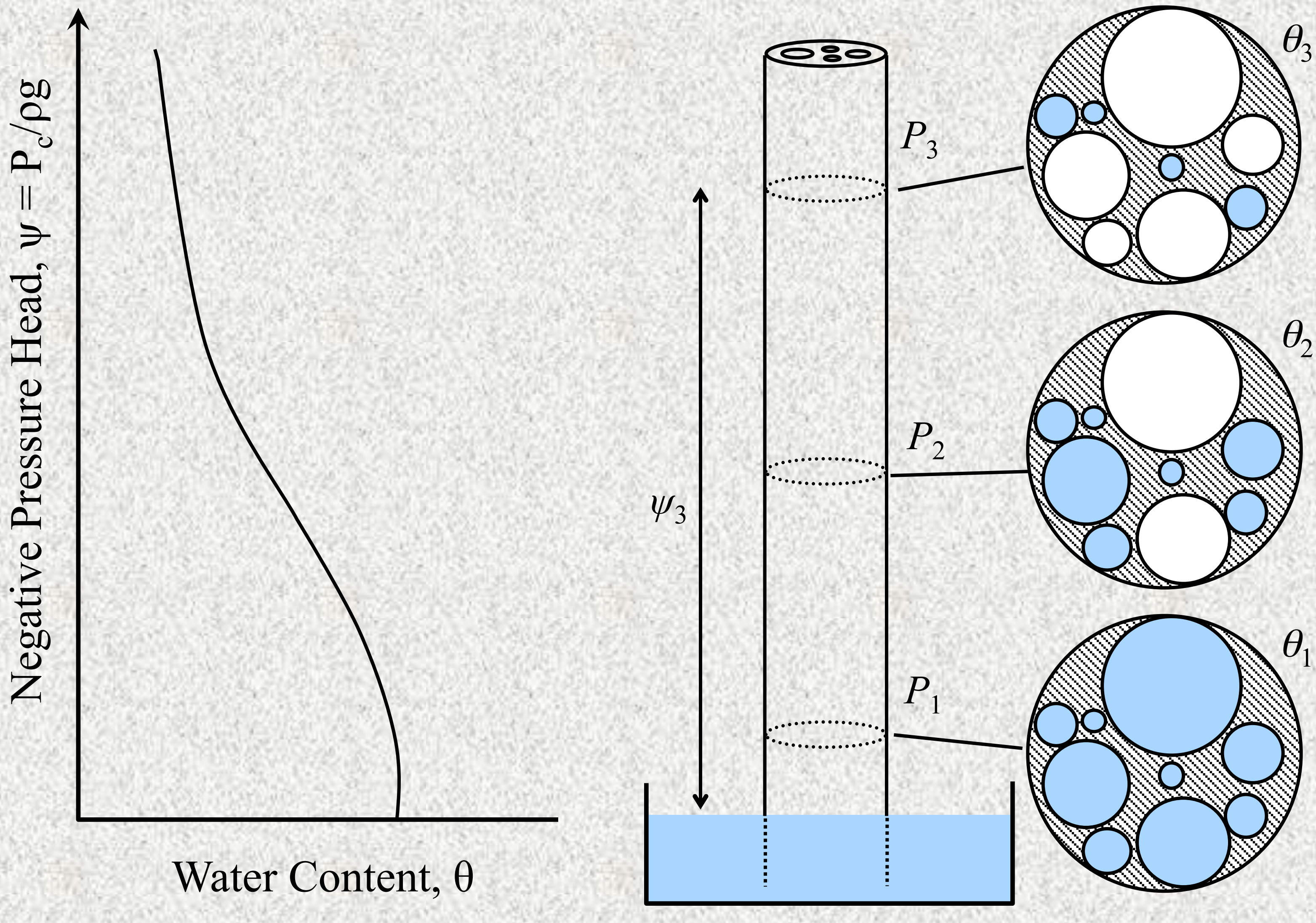
Let's revisit our capillary tube-bundle model for soil pores. There are a variety of different sized tubes representing the range in pore sizes.

If connected to the water table, the water level rise in each tube is a function of the tube radius.

$$\psi = -\frac{2\sigma \cdot \cos\lambda}{\rho g r}$$



Soil Water Retention Curve

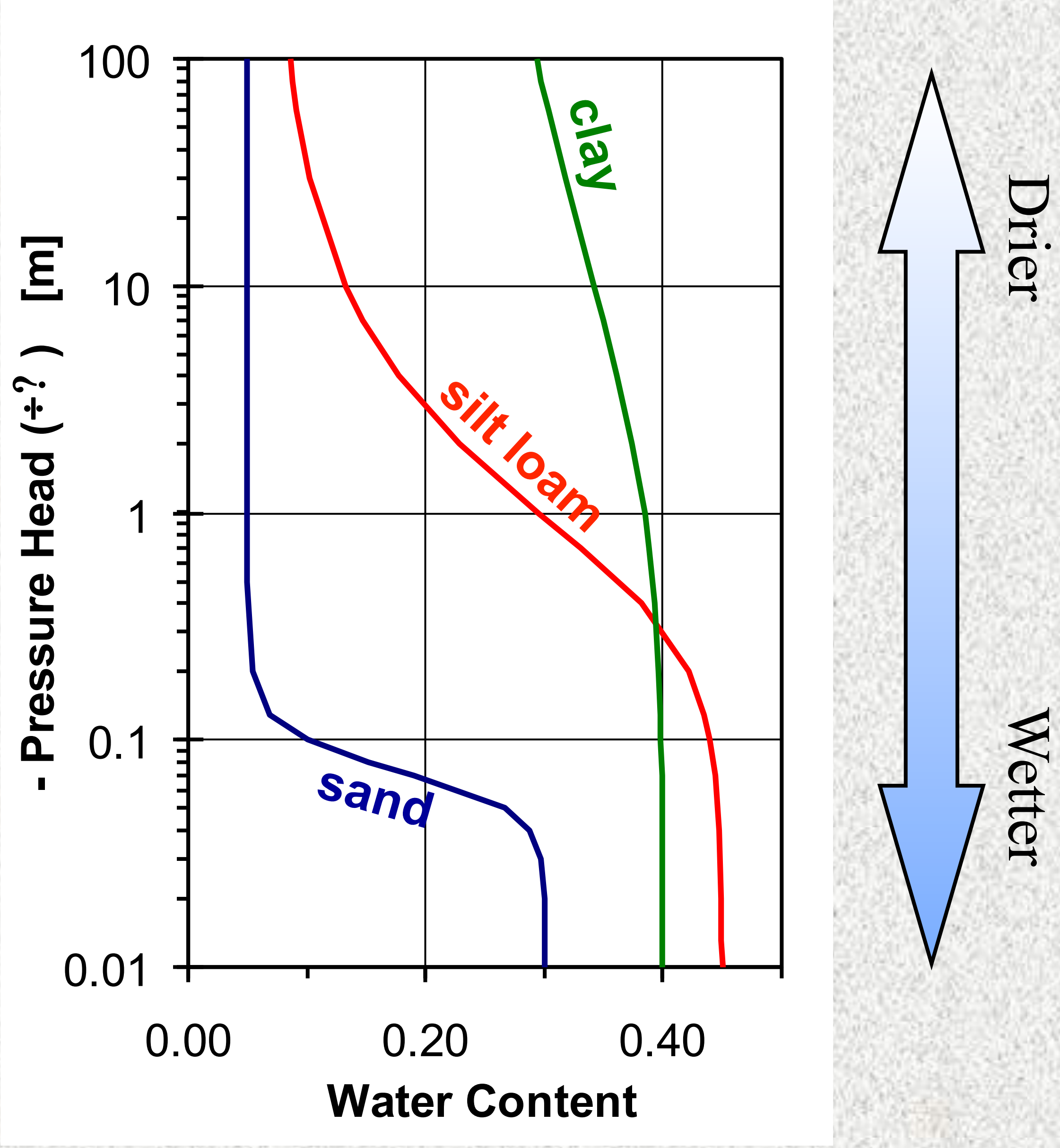


The soil water retention curve (also called a characteristic curve) is dependent on the range of pore sizes in the soil.

- The smaller the pores, the greater there ability to retain water at negative pressures (or tensions).

Conversely, the degree of dryness of a soil is a function of its pressure condition.

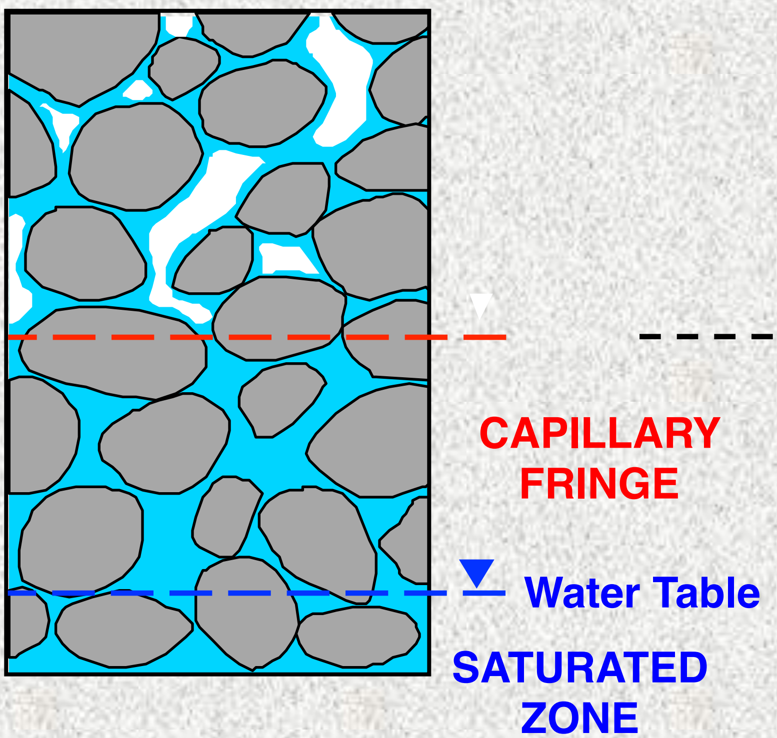
- At more negative pressures (or tensions), water will tend to reside only in the smaller pores and air fills the larger pores
  - i.e., soil becomes drier

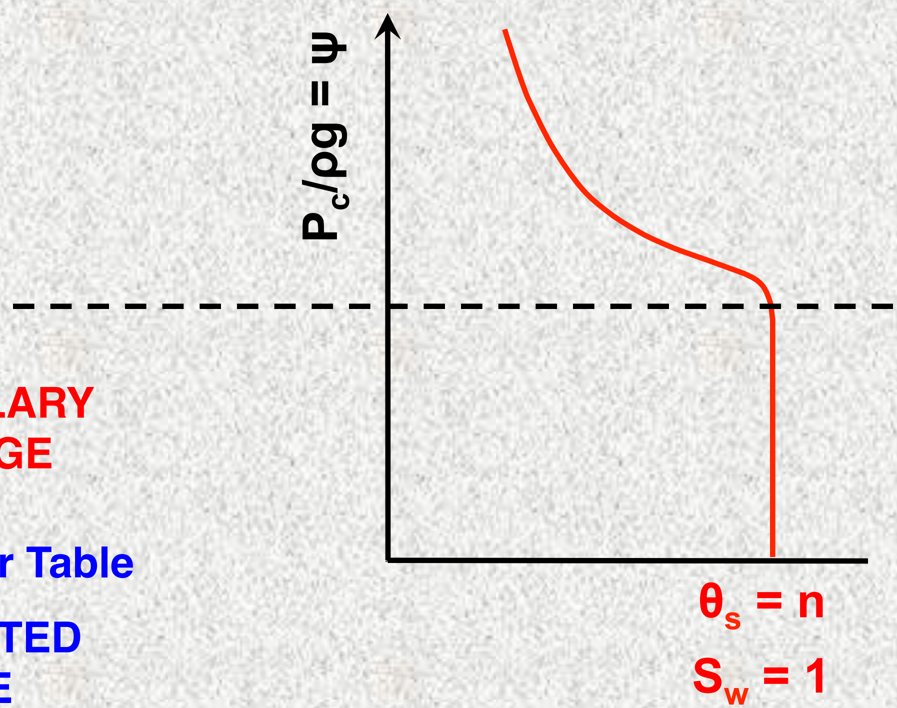


100
10
1
0.1
0.01
- Pressure Head (÷?) [m]
0.00
0.20
0.40
Water Content
clay
silt loam
sand
Drier
Wetter

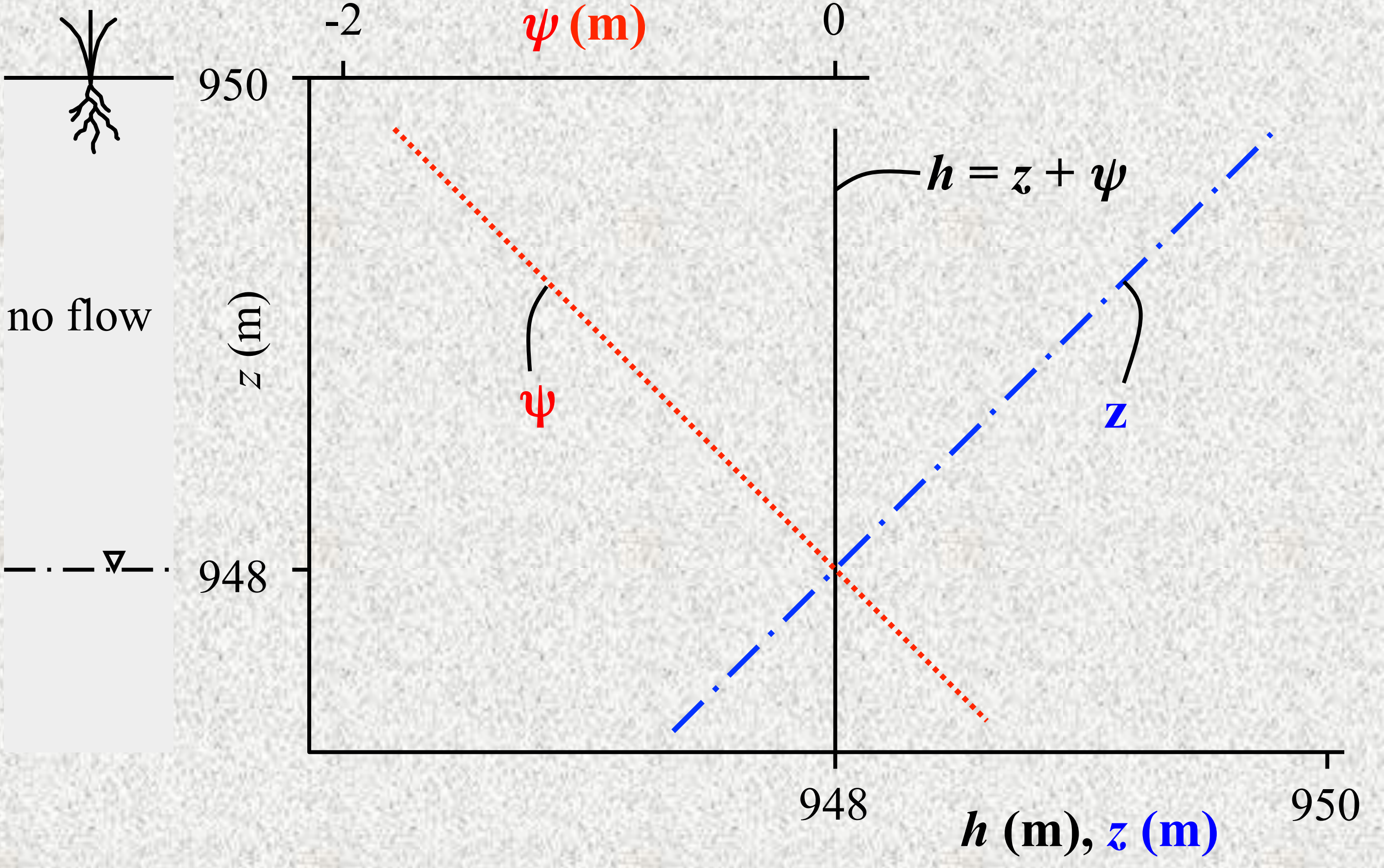
Capillary Fringe

Refers to the tension saturated zone immediately above the water table. Water is held under slight tensions, yet the porous media remains saturated.





What is the ψ distribution under hydrostatic (no flow) conditions? What condition is required for no flow?



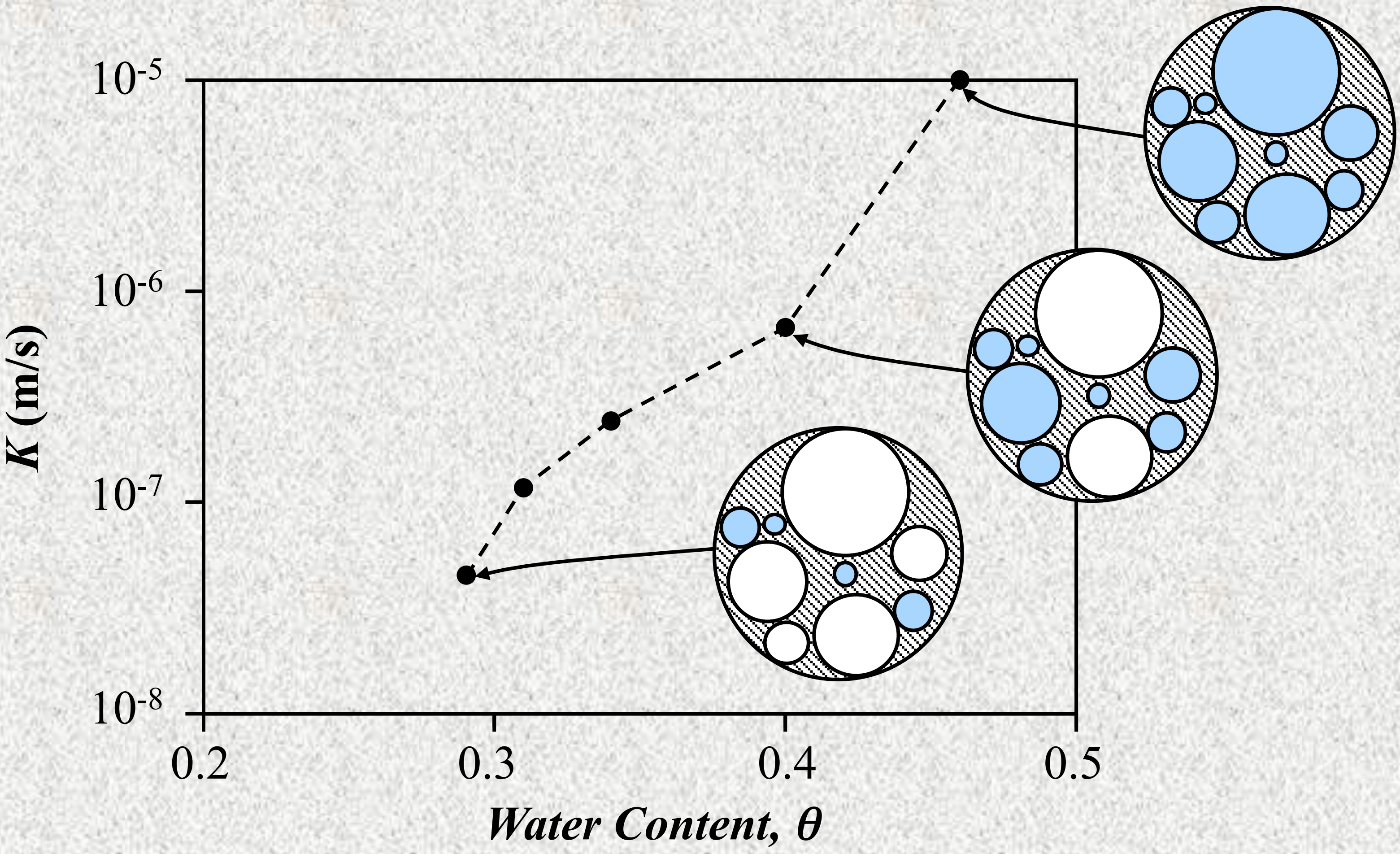
Vadose Zone Hydraulic Conductivity

In vadose zone flow, a portion of the pore space is taken up by water and a portion by air. Because of the reduction in pore space for each phase, hydraulic conductivity is reduced.

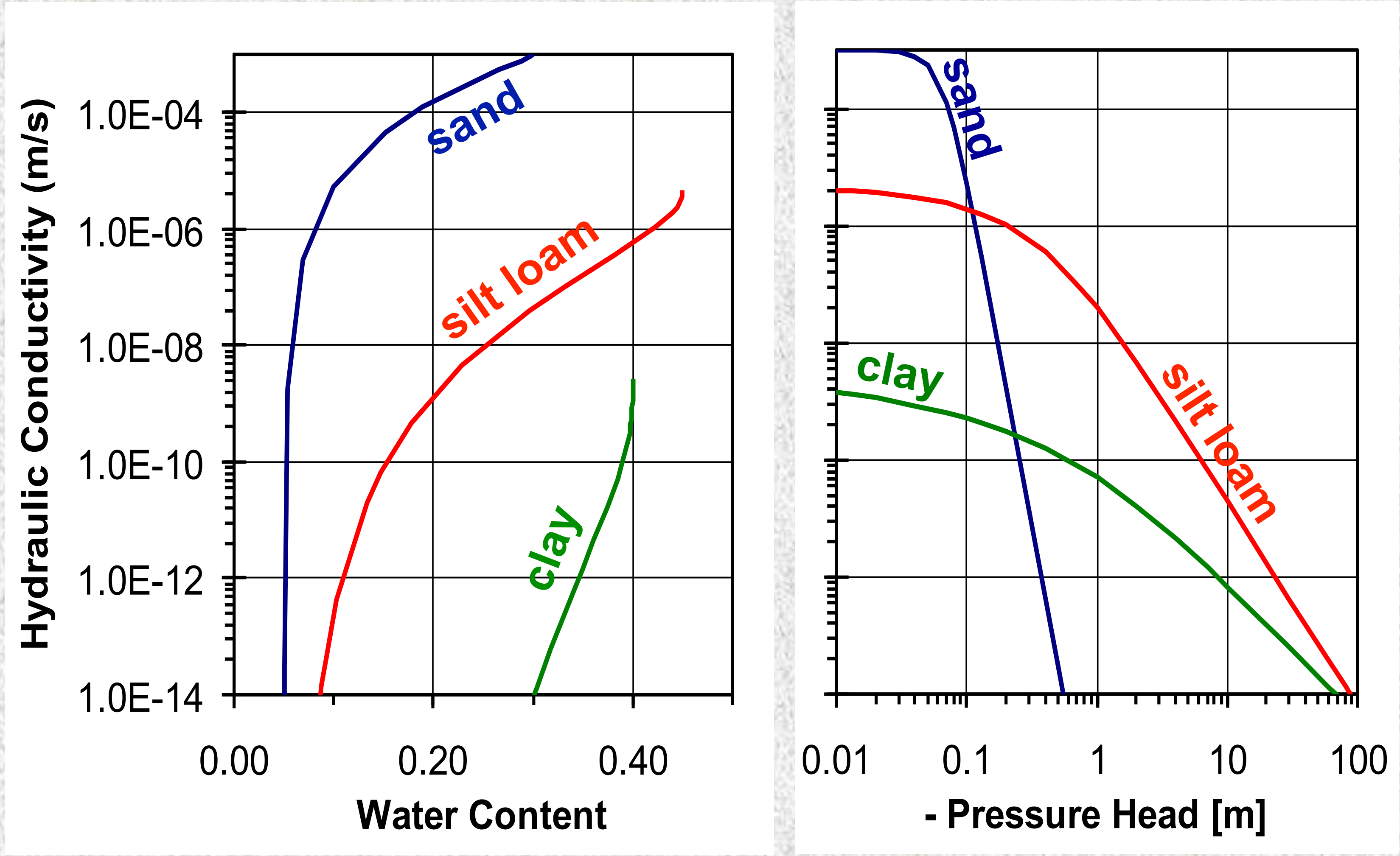
Remember that K of saturated sediments is roughly proportional to (pore radius)^2. As the soil becomes unsaturated, the larger pores drain first. The remaining pores have smaller radii and hence *K* decreases dramatically as water content (or ψ) decreases.

> **Key result:** K becomes a function of water content or pressure head in the vadose zone.

K-θ Relationship



Hydraulic conductivity can be expressed as a function of either pressure head (ψ) or water content (θ).



Darcy's Law in Vadose Zone

Darcy's Law needs to be adjusted to account for the dependence on either θ or ψ.

$$q_z = -K_z(\theta)\frac{\partial h}{\partial z}$$

$$q_z = -K_z(\psi)\frac{\partial h}{\partial z}$$

Therefore, K is dependent on the variable h ($= \psi + z$) itself. This is called a non-linear dependence of K on h, and has a major influence on vadose zone flow.

Vadose Zone Flow Equation

Remember the groundwater flow equation:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)=S_s \frac{\partial h}{\partial t}$$

In the vadose zone, the flow equation can be written as:

$$\frac{\partial}{\partial x}\left(K_x(\psi) \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y(\psi) \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z(\psi) \frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial t}$$

Note that the hydraulic conductivity is given as a function of pressure head. Also notice that the storage term on the right is expressed as changes in water content with time (i.e., compressibility is neglected).

We can express θ as a function of ψ;

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial t}[\theta(\psi)] = \frac{d\theta}{d\psi}\frac{\partial \psi}{\partial t} = \frac{d\theta}{d\psi}\frac{\partial h}{\partial t} = C_w(\psi)\frac{\partial h}{\partial t}$$

where C_w ($= d\theta/d\psi$) is called the <u>soil water capacity</u>. The flow equation in the vadose zone is thus written:

$$\frac{\partial}{\partial x}\left(K_x(\psi)\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_y(\psi)\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_z(\psi)\frac{\partial h}{\partial z}\right) = C_w(\psi)\frac{\partial h}{\partial t}$$

The saturated and unsaturated flow equations are similar except for the non-linear dependence of K and C_w on ψ. This non-linearity makes the equations very difficult to solve, even numerically.

Groundwater Recharge and Discharge

Recharge: net inflow across the water table into groundwater

Discharge: net outflow across the water table