1. **What is Vadose Zone?**

   (1) Located below land surface and above groundwater level
   (2) Contains the three-phases of solid, liquid, and gas

   **Solid phase**: mineral grains (soil formed by in situ weathering, sediment transported from somewhere else, unweathered bedrock) and organic matter (the remains of plants and animals under decay)

   Mineral grains may be aggregated (peds) or unaggregated.

   Soil texture: defined by the distribution of the size fraction of mineral grains

   USDA soil texture classification

   - **Clay**: Diameter limit < 0.002mm
   - **Silt**: 0.002mm - 0.05mm
   - **Sand**: 0.05mm - 2.0mm

   Very fine sand, fine sand, medium sand, coarse sand, very coarse sand

   **Liquid phase**: water containing dissolved solutes (contaminants if polluted)

   **Gas Phase**: water vapor and other gas (natural gas)
2. Why Study Vadose Zone? An example of soil contamination at DOE Hanford Site

Location:

Hydrogeology
Soils samples at Hanford
(Core samples from Hanford fm, well 699-S20-E10)

(Core samples from Ringold fm, well 699-S20-E10)
Contamination history (June, 1953) (Picture is classified until this Spring)

Existing contamination (Dec, 2002)

Existing Contamination
Soil contamination
(Uranium concentration and hydraulic head data, Well 399-1-17A)

Conceptual model
Chemical reaction (adsorption and desorption) plays the key role
3. Definitions

Three phases: solid, liquid, and gas

What are the percentages of the three phases (in terms of space and mass), especially the liquid phase?

Porosity (-, %): \( n = \frac{V_v}{V} \)

Void ratio (-, %): \( e = \frac{V_v}{V_s} \quad e = n/(1-n) \)

Gravimetric water content (also called mass wetness) (-, %): \( _g = \frac{W_w}{W_s} \)

Volumetric water content (also called volume wetness) (-, %): \( _v = \frac{V_w}{V} \quad \text{saturated} \quad _v \leq n \)

Saturation ratio (also called degree of saturation) (-, %): \( R_s = \frac{V_w}{V_v} \)

Dry bulk density (M/L^3): \( _b = \frac{W_s}{V} \)

Particle density (M/L^3): \( _m = \frac{W_s}{V_s} \)

Some relationships

(1) Relation between volumetric water content and gravimetric water content
\( _v = \left( \frac{b}{w} \right)_g \)

\( W_w = _w V_w = _w _v V \)

\( W_w = _g W_s = _g _b V \)

\( _w _v V = _b _g V \)

(2) Relation between porosity and bulk density
\( n = 1 - \frac{b}{m} \)

\( n = V_v/V = (V-V_s)/V = 1 - V_s/V = 1 - (W_s/m)/(W_s/b) = 1 - \frac{b}{m} \)

(3) Relation between volumetric water content and void ratio
\( _v = n R_s \)

\( _v = V_w/V = R_s V_v/V = n R_s \)
5. **How to measure moisture content**

**In laboratory (direct measurement):**
Gravimetric water content (-, %): \( g = \frac{W_w}{W_s} \)
Volumetric water content (-, %): \( v = \frac{V_w}{V} \)

- \( V \): determined by placing a soil sample into a graduated cylinder and measuring the volume it occupies
- \( W_s \): measured after the sample is oven-dried at 105°C (before the organic matter is destroyed)
- \( W_m \): Moisture mass (the mass of soil sample at natural condition)
- \( W_w = W_m - W_s \) \( V_w = \frac{W_w}{\gamma_m} \)

**In field (indirect measurement)**
All the equipments must be calibrated for soil types before being used

1. Electrical resistance blocks (cells)  
2. Time domain reflectrometry (TDR)  
3. Neutron probe: radioactive and safety training is required.
6. **Capillary and capillary fringe**

**Tension or Suction**

When soil water is at hydrostatic pressure greater than atmospheric, its pressure potential is considered positive.

When it is at a pressure lower than atmospheric, the pressure potential is considered negative and the subpressure is known as tension or suction.

![Capillary and capillary fringe](image)

**Capillary and capillary fringe**

Macropore, Mesopore, and Micropore

The soil pores are analogous to water pipes. The macropores are even smaller than the inner diameter of the tubes below.

Capillary rise: 

\[ h_c = \frac{2 \cos \theta}{\gamma_{wg}R} \]

\( \gamma \): surface tension of the fluid \( \theta \): contact angle \( R \): the radius of the capillary tube

The smaller the \( R \), the larger the capillary rise \( h_c \).

The finer the soil grains, the higher the capillary fringe.

Capillarity is determined by (1) surface tension of the air-water interface and (2) molecular attraction of the liquid and surface phases.
7. **Theory of unsaturated flow**

For saturated zone: $H(\text{total head}) = h(\text{pressure head})+Z(\text{gravity head})$

$H(\text{total potential}) = h(\text{pressure potential})+Z(\text{gravity potential})$

For vadose zone: $\Phi = (\nu)+Z$

($\nu < 0$ due to the tension): moisture potential (matric potential, capillary potential)

**Measurement of soil-moisture potential using tensiometer**

The tensiometer consists of a porous cup, generally of a ceramic material, connected through a tube to a manometer, with all parts filled with water. When the cup is placed in the soil where suction measurement is to be made, the bulk water inside the cup comes into hydraulic contact and tends to equilibrate with soil water through the porous in the ceramic walls. When initially placed in the soil, the water contained in the tensiometer is generally at atmospheric pressure. Soil water, being generally at subatmospheric pressure, exercises a suction, which draws out a certain amount of water from the rigid and airtight tensiometer. Consequently, the pressure inside the tensiometer falls below atmospheric pressure. The subpressure is indicated by a manometer, which may be a simple water- or mercury-filled U tube, a vacuum gauge, or an electrical transducer.

Suction measurements by tensiometery are generally limited to matrix suction value below 1 atm, mainly due to the vacuum gauge or manometer measures a partial vacuum relative to the external atmospheric pressure.

In practice, the useful limit of most tensiometers is a maximal tension of about 0.8 atm. To measure higher suctions, use psychrometer or osmometer.

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![An example of soil moisture tension](image-url)
Soil moisture characterization curve or soil-water retention curve
The **nonlinear** relationship between moisture potential and volumetric water content

The water retention is affected by soil texture
The more the clay content, the greater the water retention, and the more gradual the slope of the curve is.

Hysteresis
The relation between matric potential and soil wetness can be obtained in two ways

(1) Drying (in desorption), start with a saturated sample and apply increasing suction, in a step-wise manner, to gradually dry the soil while taking successive measurements of wetness versus suction.

(2) Wetting (in sorption), gradually wet an initially dry soil sample while reducing the suction incrementally.
A typical hysteresis loop
A-B-C: Drying (desorption)
C-D-A: Wetting (sorption)

The hysteresis can be attributed to several causes:
1. ink-bottle effect
2. contact angle effect
3. encapsulated air in dead-end pore
4. change of soil structure

ink bottle effect

The pore consists of a relatively wide void of radius R, bounded by narrow channels of radius r<R. In the drying process, the pore drain requires a suction exceeding hc~1/r; in the wetting process, the pore-rewetting only has a suction of hc~1/R. The drying process depends on the narrow radius of the connected channels; while the wetting process depends on the maximum diameter of the large pores.

Darcy’s law
In the saturated zone: q=K H
In the vadose zone: q=K( ) H= K( ) H
The nonlinear nature of unsaturated flow:
When moisture content changes, matric suction (moisture potential) changes, and K changes, which results in the change of moisture content again.
Soil texture has significant effect on hydraulic conductivity.

8. **Redistribution of water in soils**

Factors affecting water redistribution in soils:

1. Infiltration, irrigation, or recharge
2. Evaporation and transpiration (evapotranspiration, ET)
3. Soil texture, structure, and the existence of impeding layers

**Field capacity:** The presumed water content at which internal gravity drainage allegedly ceased is termed as field capacity.

It also depends on soil texture. The sandy soil has lower field capacity than clayey soil.

**Wilting point:** If the soil moisture drops too low, the remaining moisture is too tightly bound to the soil particles for the plant roots to withdraw it. The soil-moisture content at which this first occurs is the wilting point.
9. Water table recharge

The factors affecting water table recharge:

(1) thickness of the unsaturated zone (the thinner the unsaturated zone, the faster the recharge reaches the water table)

(2) vertical unsaturated hydraulic conductivity (the larger the conductivity, the faster the recharge reaches the water table)

(3) existence of low-permeability layers (the less the low-permeability layers, the faster the recharge reaches the water table)

An example of field injection experiment at Hanford Site

Layering structure of the soil