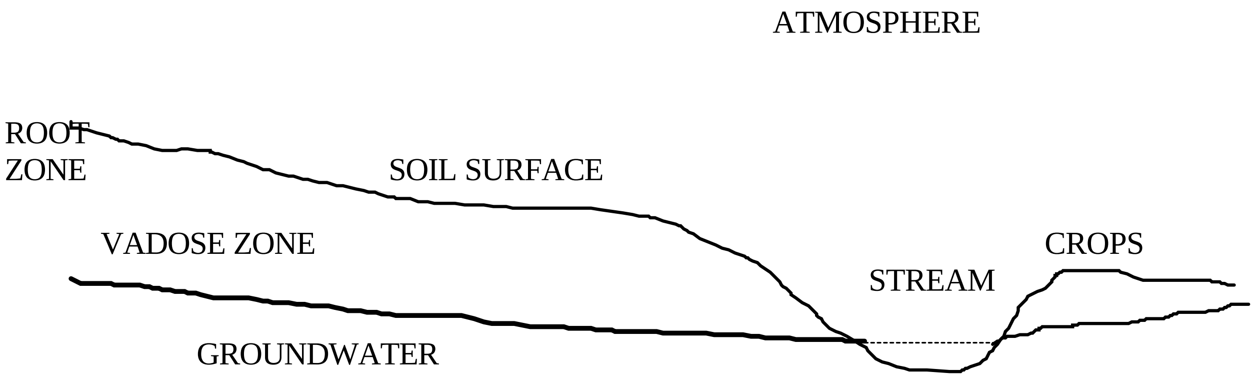
CHAPTER 1. SOIL PHYSICAL PROPERTIES

Contents:

- Soil physics
- Soil texture
- Soil surface area
- Soil structure
- Volume and mass relationships
- Water content measurements
- Units

SOIL PHYSICS: THE STUDY OF THE STATE AND TRANSPORT OF ALL FORM OF MATTER AND ENERGY IN SOILS

✪ Why study soil physics ???

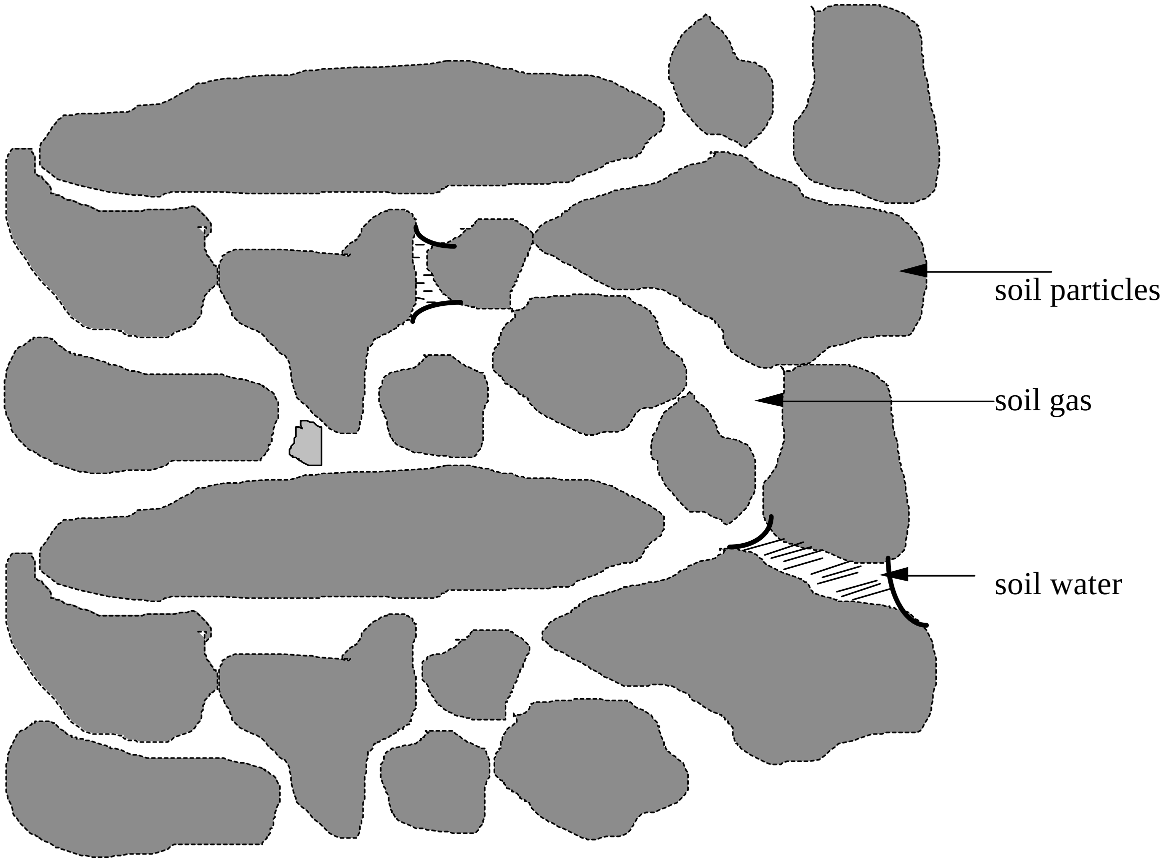


SOILS:

- SOURCE OF NUTRIENTS AND WATER FOR CROP AND PLANT GROWTH
- CONDUIT BETWEEN SOIL SURFACE AND GROUNDWATER
- ACT AS FILTER AND A BUFFER

Soils are extremely complex, hence we often simplify to study and understand soil physical principles, e.g.,

- soil particles are spherical
- soil pores are composed of capillary tubes
- soil is homogeneous



SOIL SOLID PHASE IS CHARACTERIZED BY

- SOIL TEXTURE - SIZE DISTRIBUTION OF SOIL PARTICLES
- CHEMICAL AND MINERALOGICAL PROPERTIES
- SHAPE AND SURFACE AREA OF SOIL PARTICLES
- SOIL STRUCTURE - ARRANGEMENT OF INDIVIDUAL SOIL PARTICLES

Soil texture:

Has a large influence on water holding capacity, water conducting ability and chemical soil properties

Soil Texture Classification:

Soil separate		equivalent diameter size (mm)
gravel		> 2 mm
Sand		0.05 - 2 mm
	very coarse	1 - 2 mm
	coarse	0.5 - 1 mm
	medium	0.25 - 0.5 mm
	fine	0.1 - 0.25 mm
	very fine	0.05 - 0.1 mm
Silt		0.002 - 0.05 mm
Clay		< 0.002 mm (< 2 micrometer)

✪ How to measure soil particle size ???

1. Mechanical sieving, if size > 0.05 mm

2. Sedimentation - Stokes' law, if size < 0.05 mm

   Hydrometer method
   Pipette method

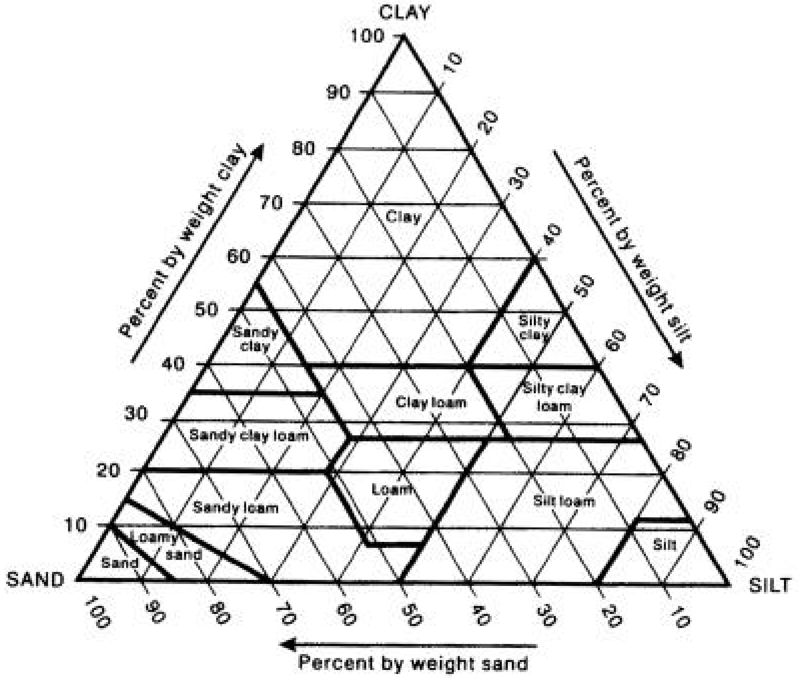
      Soil is dispersed, and mixed with water (soil suspension);

      Settling velocity of individual particles depends on particle diameter;

      Forces acting on soil particle are gravitation, buoyancy and drag forces, and all depend on particle size;

      The larger particles settle first → Stokes law

Since soils are a mixture of different size particles, soil's are classified using the so-called **soil textural triangle**.



Soil Textural Triangle

Soil mineralogical composition:

- Primary minerals: present in original rock from which soil is formed. These occur predominantly in sand and silt fractions, and are weathering resistant (quartz, feldspars);
- Secondary minerals: formed by decomposition of primary minerals, and their subsequent weathering and recomposition into new ones (clay minerals).
- Humus or organic matter (decomposed organic materials)

Mineral type has large influence on soil behavior:

- Ion exchange, related to cation exchange capacity
- Hydration and swelling; dehydration and shrinking
- Flocculation and dispersion
- Preferential flow, as through soil cracks
- Barrier to flow, as by swelling clays
- Chemical adsorption of contaminants and nutrients, both in liquid and gas phase

Soil's specific surface area (s, m^2/g):

Depends on shape of soil particle.
For example, if spherical (r = radius and ρ = density)

Surface area (a) = $4\pi r^2$

Mass (m) = $\rho V = \rho[4\pi r^3/3]$

Thus, specific surface area (s=a/m): $s = 3/\rho r$ (inversely proportional to radius)

✪ How to approximate surface area of a clay particle ???

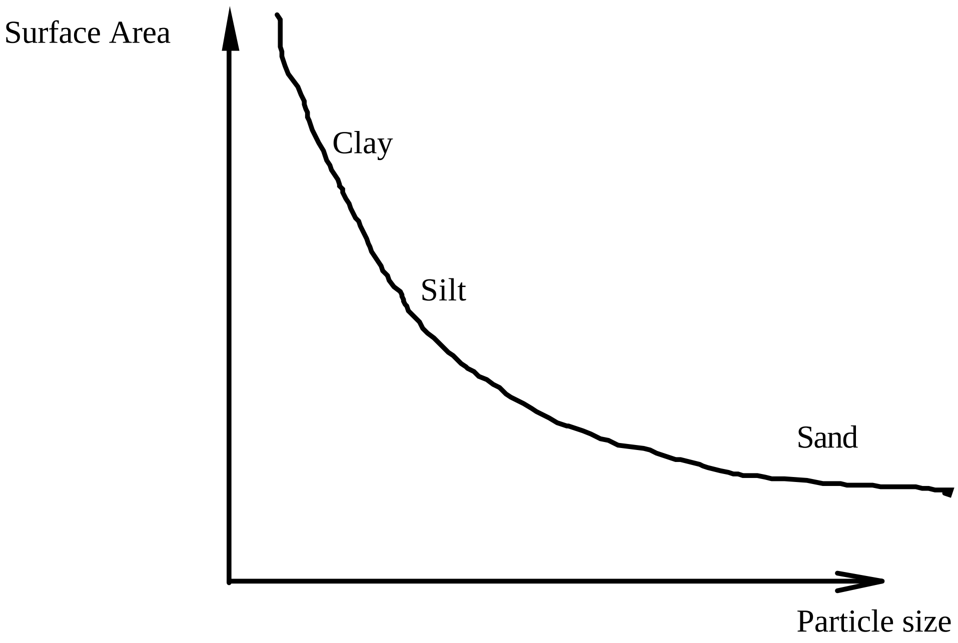
Surface area of soil affects its physical and chemical properties and is largely determined by amount of clay present in soil:

Specific surface area of soil particles

Particle	Effective Diameter (cm)	Mass (g)	Area (cm^2)	Specific Surface Area ($cm^2\ g^{-1}$)
Gravel	2×10^{-1}	1.13×10^{-2}	1.3×10^{-1}	11.1
Sand	5×10^{-3}	1.77×10^{-7}	7.9×10^{-5}	444.4
Silt	2×10^{-4}	1.13×10^{-11}	1.3×10^{-7}	11.1×10^{4}
Clay[a]	2×10^{-4}	8.48×10^{-15}	6.3×10^{-8}	7.4×10^{6}

[a] Thickness = 10^{-7} cm

✪ Compute the surface area of 1 gram of clay in m^2 .



✪ Which physical and chemical properties are largely affected by surface area ???

<u>Soil Structure:</u>

The arrangement and organization of soil particles in the soil, and the tendency of individual soil particles to bind together in aggregates;

Aggregation creates intra-aggregrate and inter-aggregate pore space, thereby changing flow paths for water, gases, solutes and pollutants;

Effects on plant growth operates through:

1. Aeration
2. Soil compaction
3. Water relations
4. Soil temperature

Structure development is influenced by:

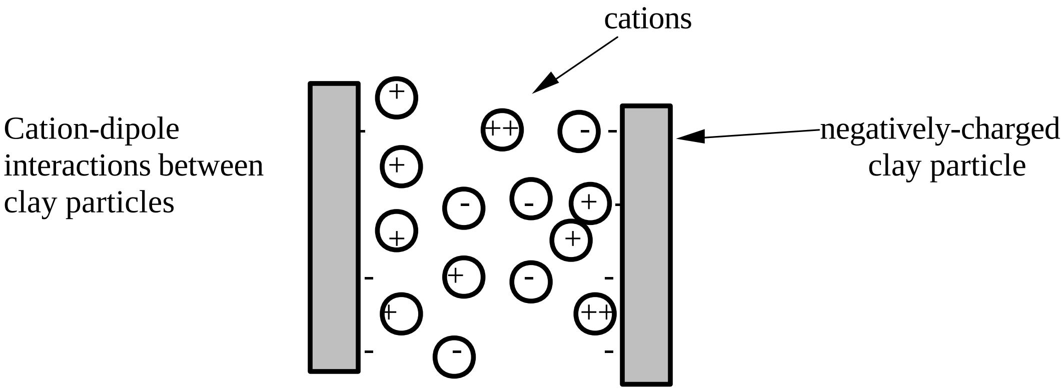
- Amount and type of clay, as well as the exchangeable ions on the clay (also water acts as bridge between clay particles)

- Amount and type of organic matter, since it provides food for soil fungi and bacteria and their secretion of cementing agents (polysaccharides)

- Presence of iron and aluminum oxides (cementing agents).

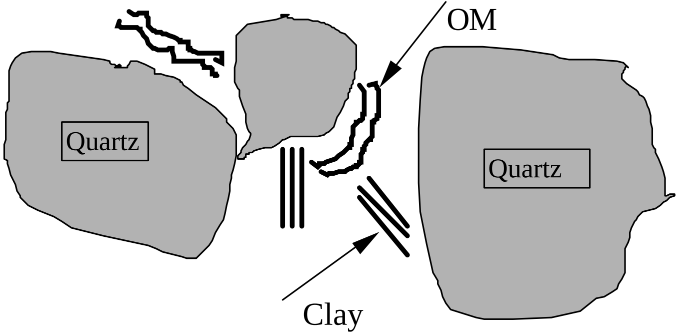
- Binding between organic and inorganic compounds (aluminium oxides, cations, clays)

- Vegetation: produces OM, roots act as holding soil together, and protects soil surface



TOTAL CHARGE MUST BALANCE

Clay - quartz - OM interactions

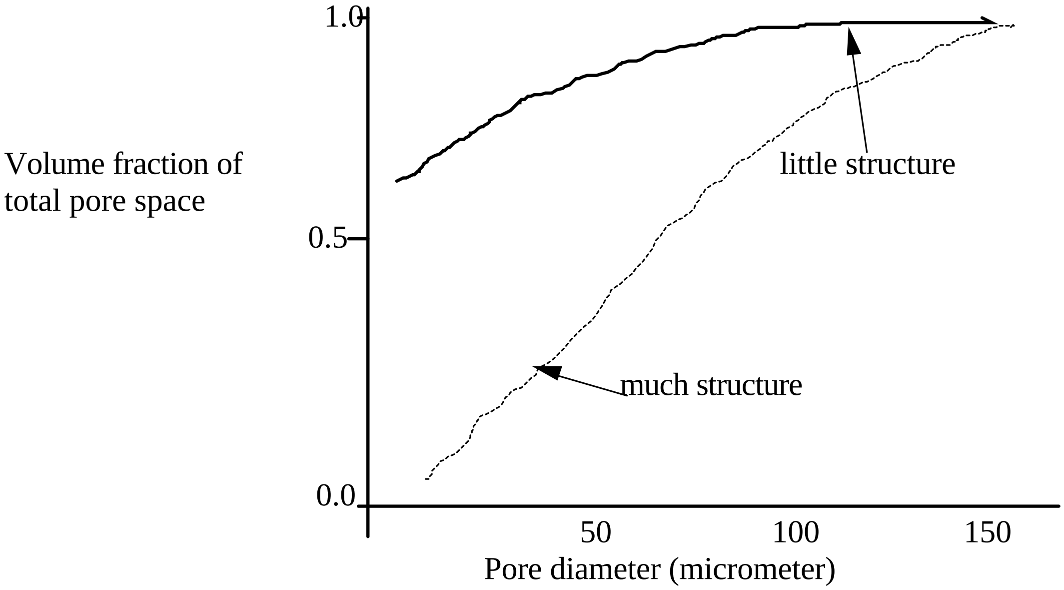


Types of soil structure:
1. Single-grained (windblown particles such as silt; sand) - highly erodable
2. Massive (heavy clays)

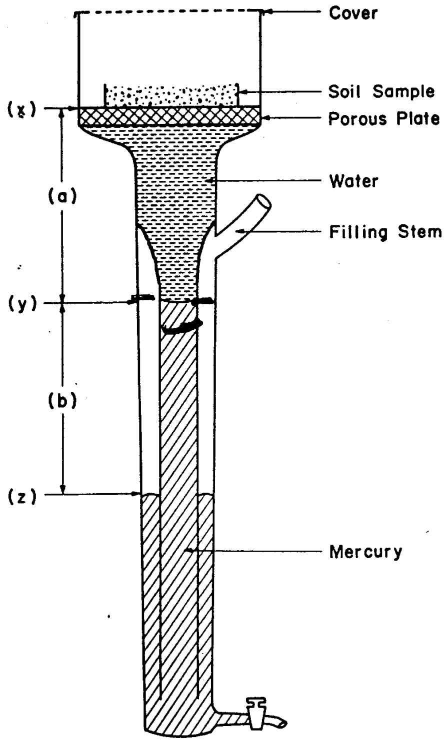
3. Aggregated (ideal soil structure)

<u>Characterization of soil structure:</u> (mostly qualitative, since is a function of time)

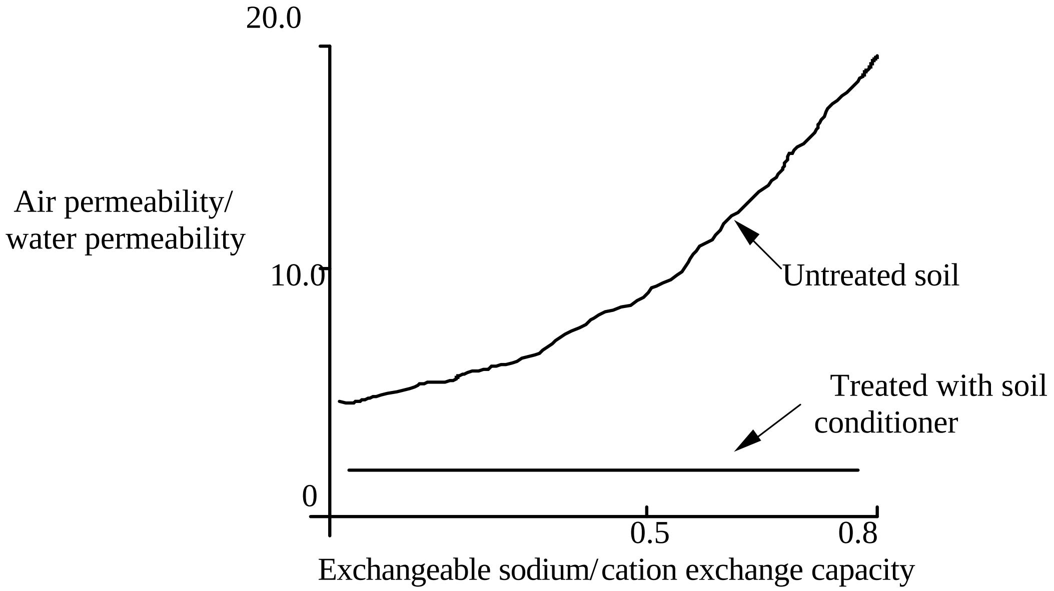
1. Size
    - Particles (particle size distribution)
    - Aggregates (dry-sieving; water stability test by wet-sieving)
    - Porosity
2. Morphological
    - Blocky
    - Plately
    - Prismatic
3. Physical
    - Pore size distribution - water desorption method



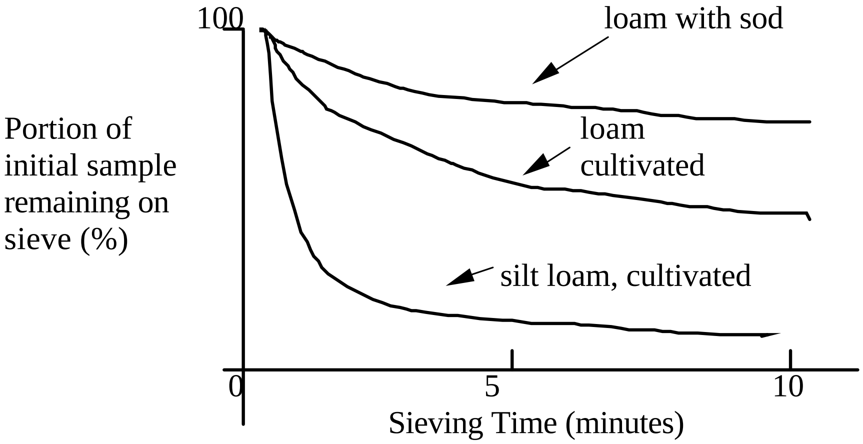
Funnel apparatus for determining pore-size distribution



- Water permeability (ratio of permeability to air and water)



- Stability upon wetting (wet sieving)

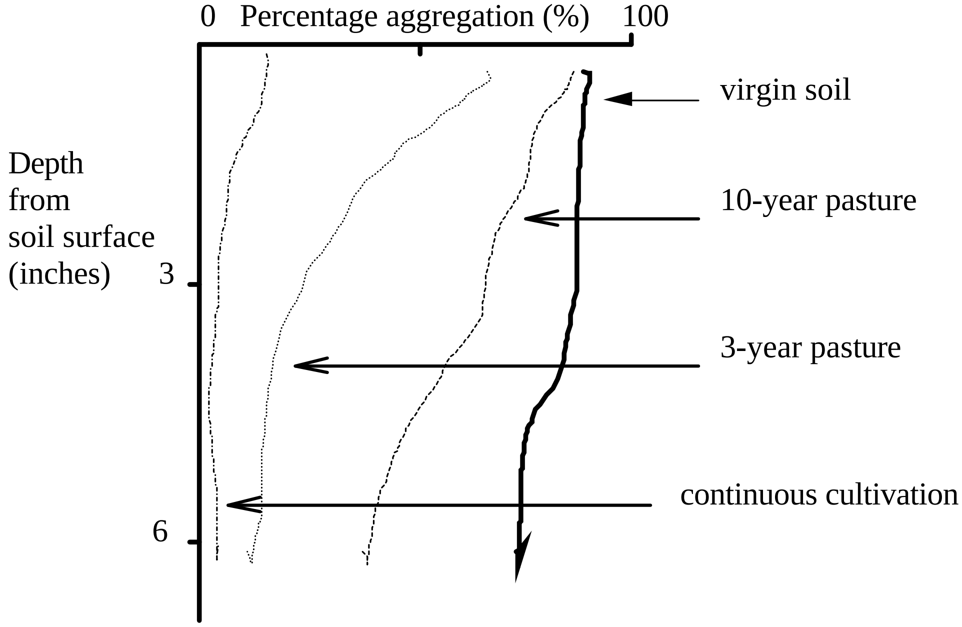


- Ability to reform upon drying
- Hardness
- Mechanical impedance (cone-penetrometer tests)
- Crusting (infiltration measurements)
- Compaction (bulk density measurements)

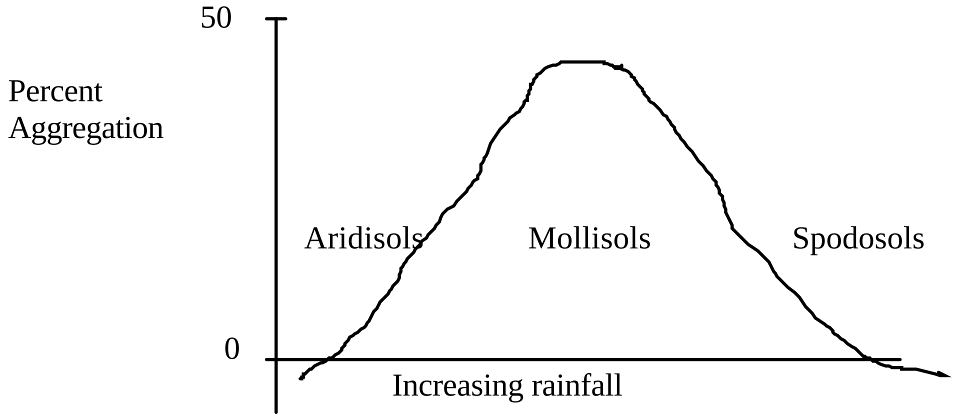
<u>Soil structure deterioration by:</u>

1. Tillage and cultivation
2. Decrease in organic matter
3. Silt and salt in irrigation water

The following graph from Greacen (1958), shows the influence of exposure time to microbial decomposition of OM on soil structure (percentage aggregation):

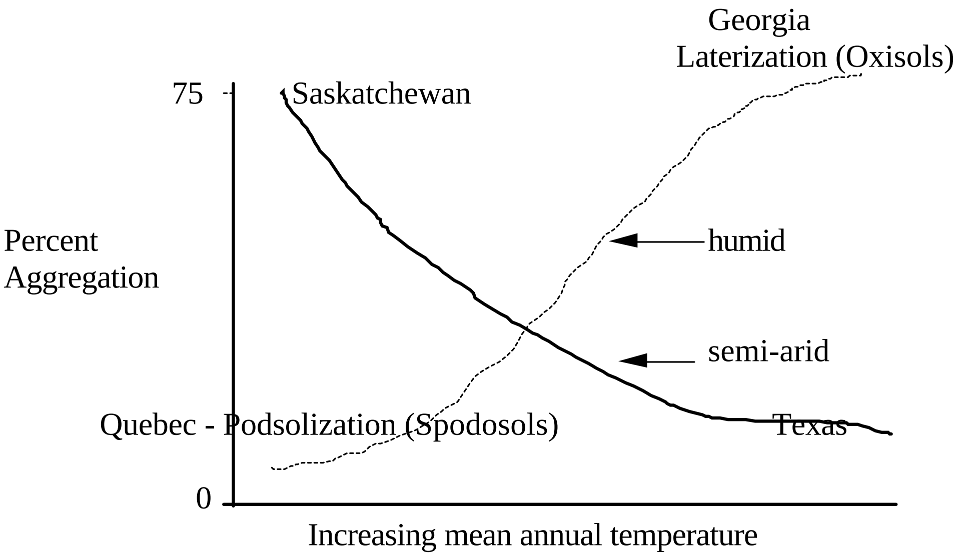


Tendency of soil aggregation is also largely influenced by climate (West to East in US):

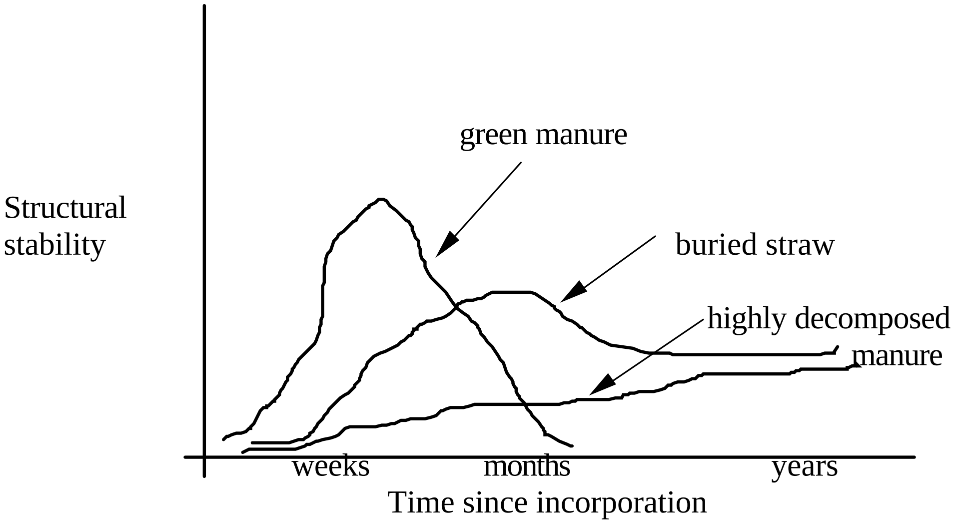


Temperature also affects aggregration:

Stable aggregation is caused by OM (arid soils) or oxides (humid soils):

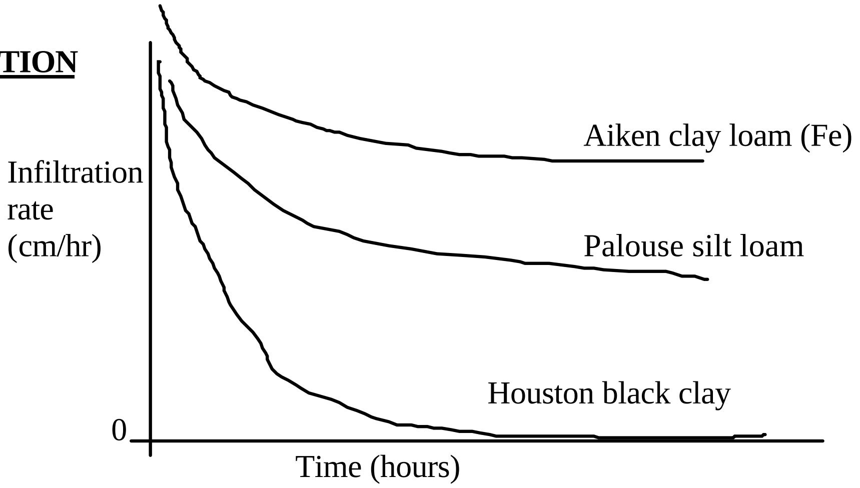


Structural stability or resistance of soil to disintegrative forces (rain, cultivation, soil swelling), depends on type of organic matter and its changing from low to high C/N as a result of microbial breakdown of OM:

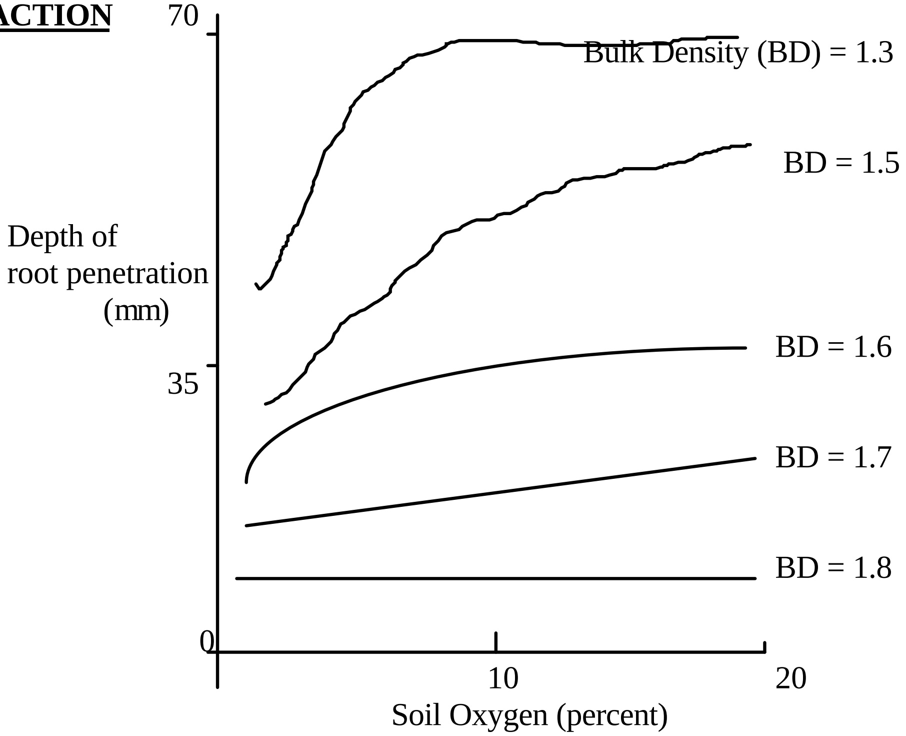


Soil structure detoriation causes soil compaction, reduced gaseous exchange between atmosphere and soil (aeration), and reduction in infiltration:

INFILTRATION



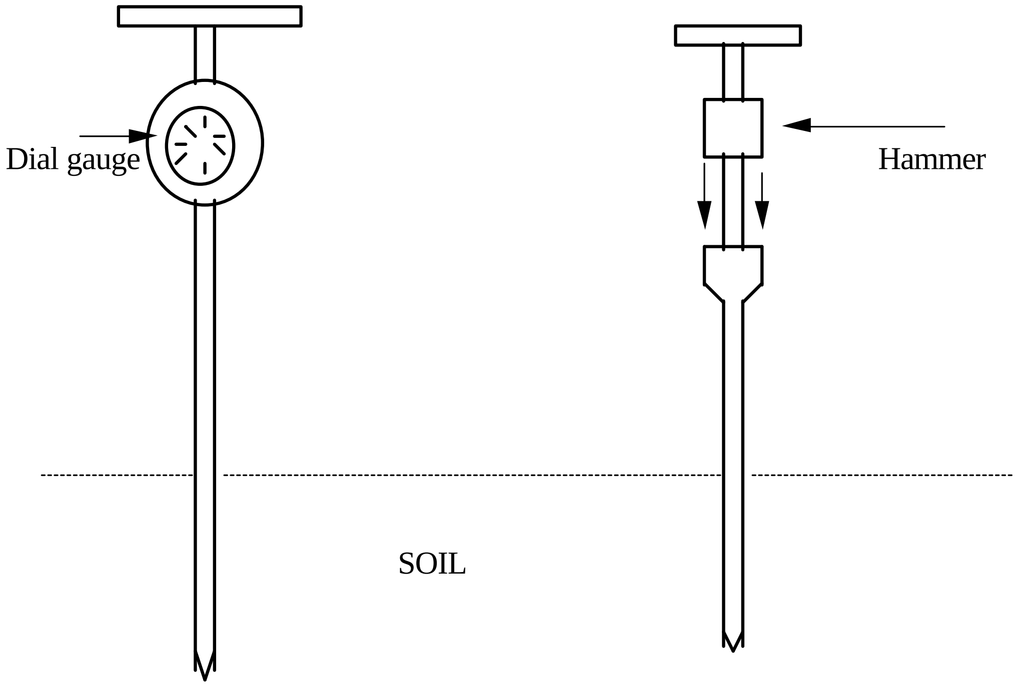
AERATION AND COMPACTION

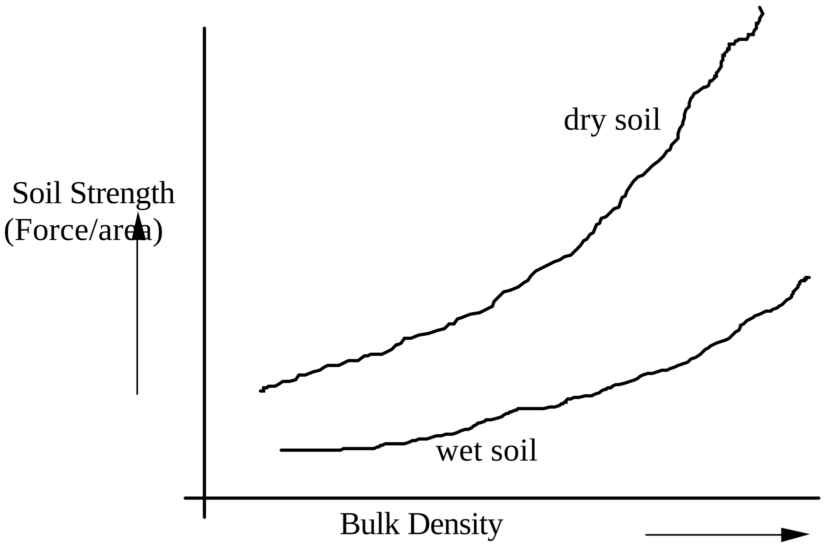


Soil Compaction:

- Compression of an unsaturated soil, resulting in reduction of fractional air volume
- Natural and human-induced compaction:
    - Surface crusts
    - Hardpans
    - Clay pans
    - Carbonates
    - Tillage pans
    - Trampling by animals
    - Machinery
- Compaction measurements
    - Bulk density
    - Penetrometer (indirect, and measures soil strength)

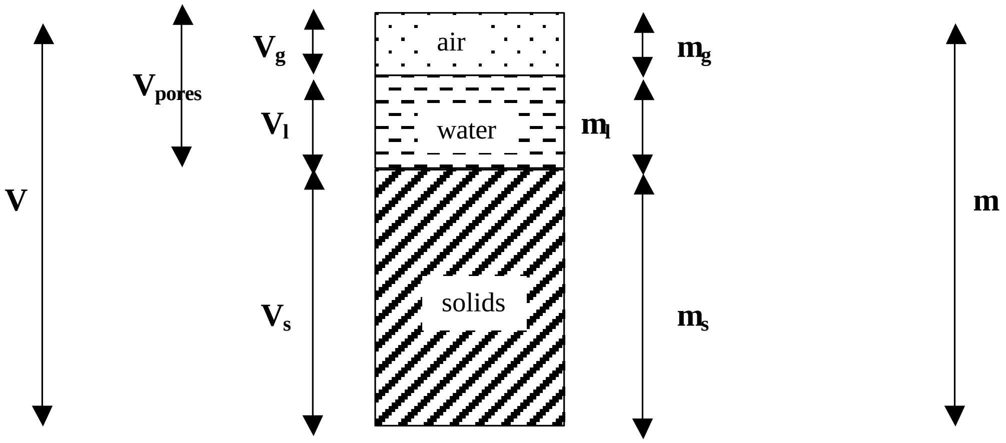
Gauge and hammer-type penetrometers:





Volume and Mass Relationships in Soils (comprising of solid (s), liquid (l) or water (w) and gas (g) phase:

Volume relations **Mass Relations**



$V = = V_s + V_l + V_g$ and $m = m_s + m_l + m_g$

$V_{pores} = V_l + V_g$ and Porosity (f)= V_{pores} / V
V = bulk volume of soil (total soil volume)

Porosity in soils varies between 0.3 (sands, silts) to 0.45 (clays) to 0.7 (peat), and is largely determined by the soil bulk density:

$\rho_b = m_s/V$,

and includes dry mass only (Dry bulk density), its units are in g/cm^3 (or Mg/m^3) and varies between <1 (peat) to 1.3 (clays) to 1.7 g/cm^3 (sands)

✪ What is density of organic matter ?

Sometimes, we use wet bulk density, and it is defined as

$$\rho_{wb} = (m_l + m_s)/V$$

Moreover, we define density of each of the specific phases, or

$\rho_m = m_s/V_s$ **varies between 2.6-2.65 for most mineral soils (mineral density)**

$\rho_l = m_l/V_l$ **is about 1.0 for water and assumed constant (water density)**

$\rho_g = m_g/V_g$ **approximately zero, relative to other phases (gas density)**

Hence: $\rho_{wb} = m/V = m_g/V + m_s/V + m_l/V$ **, hence**

$$\rho_{wb} = m_g/V_g * V_g/V + m_s/V_s * V_s/V + m_l/V_l * V_l/V \text{ , or}$$

$$\rho_{wb} = \alpha\rho_g + (1-\phi)\rho_m + \theta\rho_l = \rho_b + \theta \quad \text{(cgs units)}$$

where $\alpha = V_g/V$ **(volumetric gas content) and** $\theta = V_l/V$ **(volumetric water content)**

✪ Show that $\phi = 1 - \rho_b/\rho_m$

$$\phi = (V - V_s)/V = 1 - V_s/V = 1 - (m_s/\rho_m)/(m_s/\rho_b) = 1 - \rho_b/\rho_m$$

✪ What are the units of ϕ, θ, **and** α **?**

Water content measures:

1. **Water content by mass (gravimetric water content:**

q_g **= mass of water / mass of dry soil - (kg/kg)**

q_g **= (wet soil –dry soil) / dry soil**

2. **Water content by volume:**

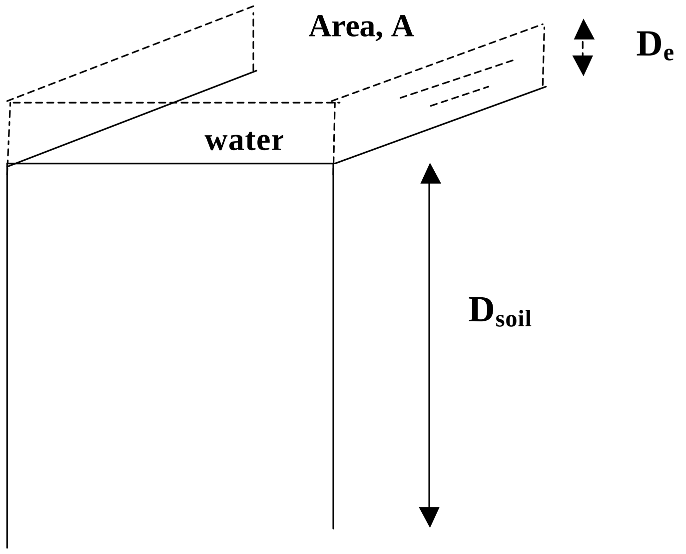
q_v**= volume of water / volume of bulk soil - (m^3/m^3)**

$$q_v = q_g \; r_b / r_l \; = r_b \, q_g$$

3. Volume of water in soil is also often expressed by equivalent depth of water, D_e:

D_e = Volume water / Soil Surface area (units in cm, m, inches, feet)

$$q_v = V_l / V = (D_e A) / (D_{soil} A) = D_e / D_{soil}$$



4. Degree of saturation, S : S $= q_v/f = q_v/q_{sat}$

Water content measurements:

- **Direct measurement**

Gravimetric method using soil cores

1. If soil cores of known volume are used

θ_v = volume of water/volume of core

where volume of water is equal to difference in mass between wet and ovendry soil sample

2. Determine dry bulk density of soil first, independently

- Extract soil core with known bulk volume and oven-dry

ρ_b = mass dry soil / volume soil core

- Extract subsequent soil samples of unknown volume and determine wet mass (mass wet soil), and then oven dry (oven dry mass) the soil sample

θ_g = mass of water / mass of dry soil

$\theta_v = \rho_b \times \theta_g$ Porosity (ϕ) = $1 - \rho_b/\rho_m$

✪ Solve the following two problems.

1. An undisturbed soil core is 10 cm in diameter and 10 cm in length. The wet soil mass is 1320 g. After oven drying the core, the dry soil mass is 1100 g. The mineral density of the soil is 2.6 g cm^{-3}.

Calculate:

a. Dry soil bulk density
b. Water content on a mass basis
c. Water content on a volume basis

d. Soil porosity
e. Equivalent depth of water (cm) contained in a 1 m soil profile, if the undisturbed core is representative of the 1 m soil depth

2. Consider a 1.2 m depth soil profile with 3 layers. The dry bulk density of each layer (top, center, bottom) is 1.20, 1.35, and 1.48 g/cm^3. The top 30-cm layer has a water content of 0.12 g/g, the center 50-cm layer has a water content of 0.18 g/g, and the bottom 40 cm layer has a water content of 0.22 g/g.

a. What is the total amount of water in the whole profile in mm and in inches ?
b. How much water (mm and inches) do you need to apply to bring the 1.2 m soil profile to a volumetric water content of 0.35 cm^3 / cm^3 ?

- **Indirect soil moisture measurements**

  Neutron probe

  Time Domain Reflectometry (TDR)

NEUTRON PROBE SOIL MOISTURE MEASUREMENT

<u>Principle of operation</u>:

Based on emission of neutrons (^{1}n) by a radioactive source

These so-called fast neutrons (about 5 MeV) collide with atoms in surrounding soil

Since hydrogen has mass equal to a neutron, loss of energy of neutron is most effective by elastic collision with hydrogen atoms of water molecules

Detector is sensitive to measurement of low-energy neutrons (thermal neutrons)

Result: Count rate of thermal or slow neutrons is proportional to the density

of hydrogen atoms in the vicinity of the radioactive source. Hence, a relation between count rate and volumetric water content can be obtained (calibration curve).

Fast neutron source:

Use ^{214}Americium-Be source, where Am produces ^{4}He (alpha-particles)

which subsequently interact with the ^{9}Be to yield nuclear reaction:

$$^{9}Be + {}^{4}He \rightarrow {}^{1}n + {}^{12}C + energy$$

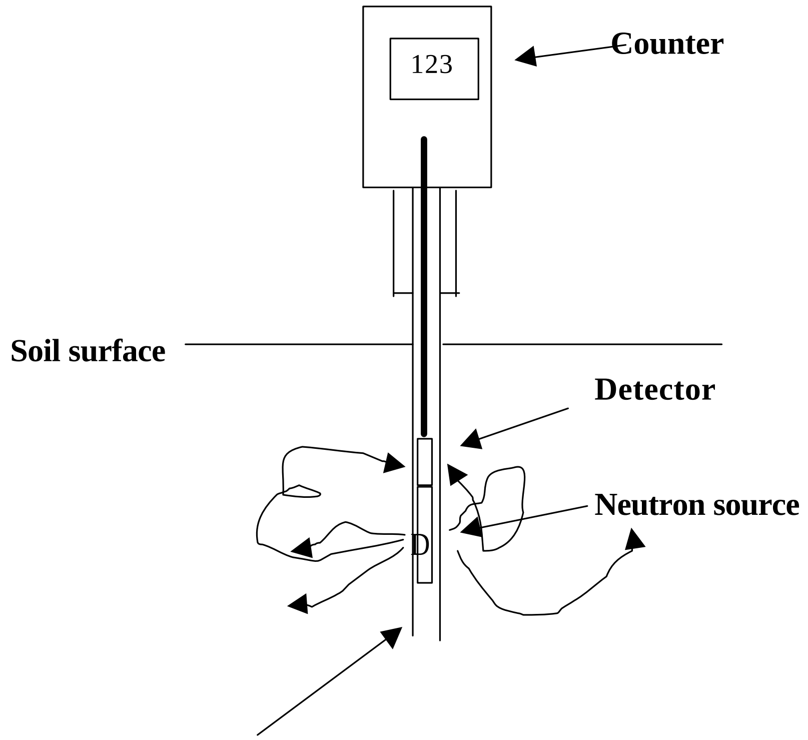
Along with this reaction, gamma radiation is also emitted

Fast neutrons are emitted radially into the soil away from the source and collide with nuclei of various soil elements. Part of neutrons are scattered and reduced in energy by hydrogen atoms, after which these move at reduced speed in a random motion. Thus a fraction of these thermalized neutrons will be detected by scintillator, close to source.

However, a fraction of the thermal neutrons will be adsorbed by heavy atoms in soil (Boron, Chloride, Iron)

Slow neutrons are counted by light flashes (scintillation counter), which occur if thermalized neutrons interact with chemical (^{6}Li)

Experimental setup (exclusively in the field):



- Use 2-inch PVC access tube

- Drill hole slightly smaller than diameter of access tube, so as to insure tight fit

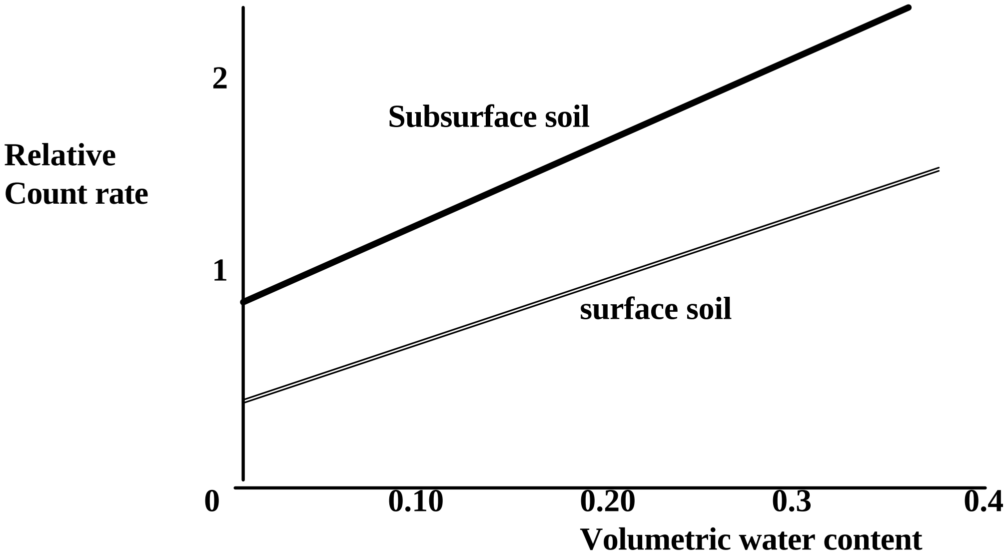
- If saturated soil conditions could occur (permanent or perched water table), close bottom of tube off with rubber stopper

Calibration:

Often relative counts rather than total counts are used in the calibration. That is, count rate is divided by a standard count rate (e.g. source in shield material), to account for electronic drift, instability of electronics, and radioactive decay of neutron source.

Standard deviation of counts is proportional to square root of total counts (Poisson distribution). Hence, instrument precision increases by taking longer counts. However, instruments available now do not require longer than 16 sec counts to obtain 1 volume percent precision.

Of course, accuracy depends on other factors, such as number of calibration points, and errors in gravimetric sampling



<u>Advantages:</u>

- **Nondestructive**
- **Rapid**
- **Repeated measurements of same soil volume**
- **Measurement integrates over relatively large soil volume**
- **Portable, rugged and largely automated**
- **Accuracy of about 2 volume percent**

<u>Limitations:</u>

- **Measurement responds to total hydrogen content, and thus will vary with organic matter content**
- **Measurement is slightly affected by soil bulk density and soil chemical composition, thus calibration for specific site is often needed**
- **Radioactive source causes restrictions on its use**
- **Operator must be present at all times**
- **Only for field use**
- **Measured soil volume is large (sphere of influence with radius 15-25 cm), and thus is not useful to make measurements at narrow depth intervals**
- **Effective measurement volume is function of water content and is larger as soil contains less water**

- **Special calibration for measurements near soil surface is required.**

TIME DOMAIN REFLECTOMETRY (TDR)

TDR is relatively new method, with first applications reported in early 1980's.

Advantages:

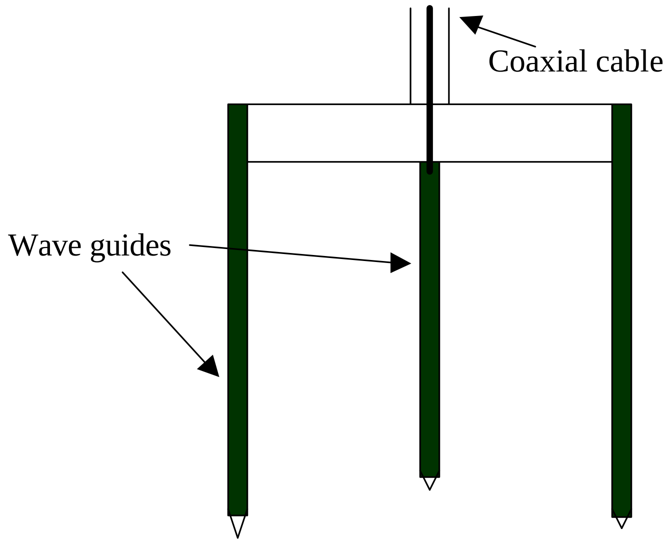
- **Minimal calibration requirements**
- **No radiation hazards**
- **Excellent spatial and temporal resolution**
- **Simple measurement provides continuous measurements of soil water through automation and multiplexing**
- **Accuracy is 1 – 2 volume percent**

Electromagnetic (EM) waves are launched in air (RADAR) or along conductors (cable tester), and amplitude of their reflection (voltage signal) is measured. Measurement of propagation velocity of EM waves and their amplitude yields information on position of object (RADAR) or break in cable (Cable tester - Tektronix).

The dielectric constant is the extend to which charges present in a material are polarized by the application of an externally imposed electro-magnetic (EM) field (Coulomb's law). As a consequence of the polarization, the imposed electric field is reduced.

The minimum value of the dielectric constant (K_a) is 1 (as in vacuum), and is about 80 for water (high polarizability).

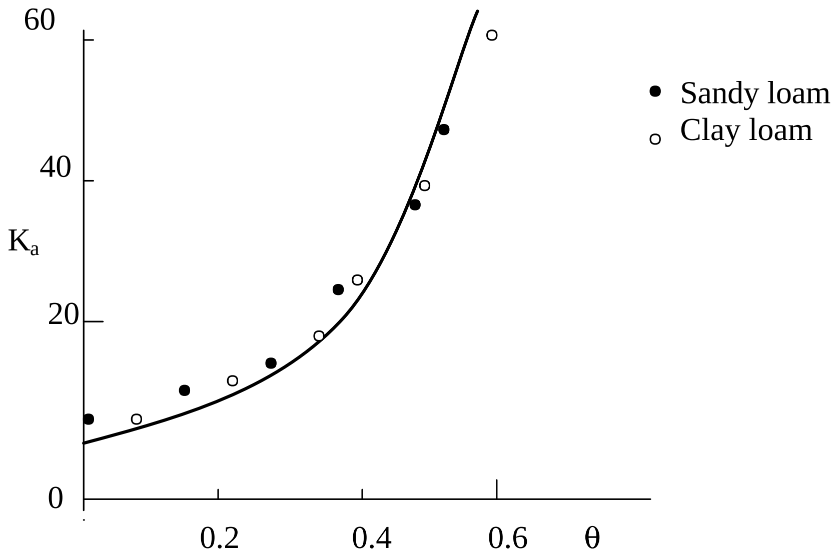
In TDR, the Electro-Magnetic field is generated by voltage signal, which is guided by conductors of a transmission line wave guides).



The speed (v) at which the EM wave moves along the conductors and through the soil is reduced as the dielectric constant of the soil is higher. Hence, an increase in water content increases the soil's dielectric, and subsequently increases the travel time of the EM wave. The TDR method measures the travel time through the soil.

Calibration

- **Obtain independent water content measurements**
- **Plot travel time (t) or dielectric constant (K_a) versus** q_v



- **Fit calibration curve through data:**

$$\mathbf{K_a = 3.03 + 9.3\, q_v + 146.0\, q_v^2 - 76.7\, q_v^3}$$

- **Appeared satisfactory for most mineral soils, but does not appear to be valid for all soils:**
  - **Clayey soils (water close to electrical-charged surfaces has different dielectric constant)**
  - **Organic soils (low bulk density)**

Units:

cgs (cm, g, sec) or SI (m, kg, sec)

Additional Fundamental Units:

Force: $F = m\,a$ (Newton's second law), where m (kg) is mass and a (m sec^{-2}) denotes acceleration

So that units of Force are kg m sec^{-2} = Newton (N)

For gravitational field: $a = g = 9.8$ m sec^{-2}

and

Weight: $W = mg$, where g is acceleration due to gravity (do not confuse with gram)

✪ How is g computed ??

Gravitational force:

$$F = \frac{Gmm'}{r^2} = mg$$

where

G = universal gravitational constant = 6.67×10^{-8} dyne cm^2/g^2 = 6.67×10^{-11} Nm^2/kg^2

g = acceleration due to gravity, and m' is the mass of the earth (or any other body in space)

<u>Pressure:</u> P = F/A = N/m^2 (Pa) = dynes/cm^2 (cgs)

1 bar= 10^5 Pa = 100 kPa = 1021 cm H_2O column

1 bar = 10^6 dynes/cm^2 = 0.987 atm

Relationship between Pressure and height of water comes from:

P = F/A = mg/A = r_wVg/A = $r_w$gh,
where h denotes equivalent height of water.

✪ **A 5-m tall column with an area (A) of 1 m^2 is completely filled with water. Compute the pressure at the bottom of the column in N/m^2 and in units of cm of water.**

<u>Work:</u> W = Fs [Nm = J (SI) or dyne cm = erg (cgs)]

Potential energy is defined as ability for doing work (J)