

# **SOS513: SOIL PHYSICS**

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# SOIL SOLIDS

## 1.0 Introduction

*What is soil?*

Soil is the unconsolidated material at the earth's surface that serves as a medium for plant growth, regulator of water regime, environmental filter and functions as supporting medium. It is a dynamic 3-phase system comprised of solids, liquids and gases.

*What is Soil Physics?*

Soil physics is the application of principle of physics to the characterization of soil properties and the understanding of soil processes involving the transport of matter and energy.

Soil physicists are generally concerned with heat and mass transport in soil. Subject they considered frequently include: soil aeration, soil temperature and soil water. These are described in both static and dynamic terms.

*Static parameters:*

- Soil porosity
- Water content
- Degree of saturation
- Void ratio
- Bulk density
- Particle density
- Soil water potential, i.e. the potential energy of water

Dynamic parameters:

Mass and energy transport in soil are described using:

- Darcy's law for water
- Fourier law for heat
- Fick's law for gas

Each of these laws states that a flux density of heat or substance is proportional to a driving force. The driving are:

- Water potential gradient for water flow
- Temperature gradient for heat flow
- Concentration gradient for gas diffusion

*What are the major roles of Soil physicist?*

Although soil physicists still must remain concerned about the physical environment of plants, conservation of resources against degradation and pollution problems by agricultural and non-agricultural agents have become the responsibilities of soil physicist too. Soil physicist must be concerned with flow and transport processes in the zone between the soil surface and groundwater table, i.e. the VADOSE ZONE. So, soil physicist are increasingly becoming participants in global-scale hydrologic research cooperating with hydrologists, climatologists, geologists and other scientists who study soil from non-agricultural point.

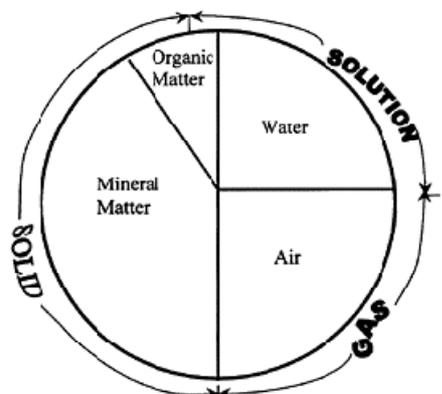
In summary, soil physicists are now interested in:

- Designing and analyzing water and solute movement using classical methods and computer aided simulation models.
- Evaluating the comparative effects of alternative soil and water management practices, and chemical application technologies on crop production and groundwater pollution.
- Soil remediation, i.e. degraded or contaminated soils.
- Risk assessment studies involving specific soil and water degradation or pollution cases.
- Prediction of water and contamination transport.
- Geostatistical documentation of soil physical properties for various uses.

## 1.1 Soil Components

The four major components or constituents of soil are:

- Mineral matter
- Organic matter
- Water and
- Air



## 1.2 Soil Phase

Phase is portion of a system with definite geometrical boundaries and uniform properties.

Soil has three majors' phases:

- Solid phase
- Liquid phase
- Gaseous phase
- Then phase interaction with external environment, i.e. soil temperature and soil colour.

Solid phase: Solid phase is the most dominant with great influence over the behaviour of other two phases. The solid phase is the soil matrix or skeleton of the soil. It is the product of weathering of parent rocks/materials and materials which they contain. The solid phase consist of mineral matter and decomposed or decomposing organic matter of all shapes, sizes and arrangement.

Liquid phase: This is primarily water, i.e. soil solution containing various ions such as  $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Cl}^-$ ,  $\text{NO}_3^-$ ,  $\text{SO}_4^{2-}$ , etc.

Gaseous phase: This is the soil air/atmosphere. It composed of  $\text{N}_2$ ,  $\text{O}_2$ ,  $\text{CO}_2$  and  $\text{H}_2\text{O}$  (vapour) mainly. Other gases in the atmosphere are also present in the soil. Others also like  $\text{CH}_4$ ,  $\text{H}_2\text{S}$  which are by-products of impeded drainage condition could be found in the soil.

*Note the following terms:*

- Dispersion (dispersibility): This refer to the degree of subdivision of the solid phase.
- Dispersed phase: i.e. the textural or mechanical separates or aggregates.
- Disperse medium: Mainly water

## **2.0 SOLID PHASE**

### **2.1 Surface Relationship**

Soil specific surface is used to describe the extent of the surface of the dispersed soil system. It is defined as the sum of the surfaces of constituent dispersed soil particles referred to unit mass or unit volume of the soil. Specific surface is a geometrical concept which is strongly dependent on the degree of dispersion of the soil, i.e. soil texture. Thus,

Specific surface of soil ( $A_m$ ) or ( $A_v$ ):

$$= \frac{\text{total surface area of soil}}{\text{Mass or Volume of soil}} = \frac{A_s}{M_s \text{ or } V_s}$$

Units:  $A_m = A_s/M_s$  ( $\text{cm}^2/\text{g}$ ) or ( $\text{L}^2/\text{M}$ )

$$A_v = A_s/V_s \text{ (cm}^2/\text{cm}^3\text{)}$$

The relationship between  $A_m$  and  $A_v$ :

From  $\rho_s = M_s/V_s$

$$M_s = \rho_s V_s$$

$$\therefore A_m = A_s / \rho_s V_s$$

$$= A_s / V_s \times 1 / \rho_s$$

$$= A_v / \rho_s$$

where  $\rho_s$  = average density of soil particle i.e.  $2.65 \text{ g cm}^{-3}$

NOTE: Most soil physical and chemical reactions occur at the surface, and the amount of these reactions is directly proportional to the specific surface.

*Factors influencing specific surface:*

- Size
- Shape
- Mineralogy of the soil or material

*(a) Particle Size:*

Side of cube (cm)	NO. of Particles in $1\text{cm}^3$	Surface of single particle ( $\text{cm}^2$ )	Total ( $\text{cm}^2$ )	Specific surface of 1 g particle where $\rho_s = 2.65 \text{ g cm}^{-3}$
1	1	6	6	$A_m = 6\text{cm}^2 / 2.65 \text{ g} = 2.26 \text{ cm}^2/\text{g}$
$10^{-1}$	$10^3$	$6 \times 10^{-2}$	60	$2.26 \times 10 \text{ cm}^2/\text{g}$
$10^{-5}$	$10^{15}$	$6 \times 10^{-10}$	$6 \times 10^5$	$2.26 \times 10^5 \text{ cm}^2/\text{g}$

(b) Particle Shape:

(i) Sphere with diameter d:

$$A_v = A_s/V_s$$

$$\text{Area of sphere} = 4\pi r^2 = \pi d^2$$

$$\text{Note: } r^2 = (d/2)^2 = d^2/4$$

$$\text{Volume of sphere} = 4/3\pi r^3 = \pi d^3/6$$

$$A_v = \pi d^2 / (\pi d^3/6)$$

$$= 6/d$$

$$A_m = A_v/\rho_s, \text{ and assume } \rho_s = 2.60 \text{ g cm}^{-3}$$

$$A_m = 2.3/d$$

(ii) Cube of edge L:

$$A_v = 6L^2/L^3 = 6/L$$

$$\therefore A_m = 2.3/L$$

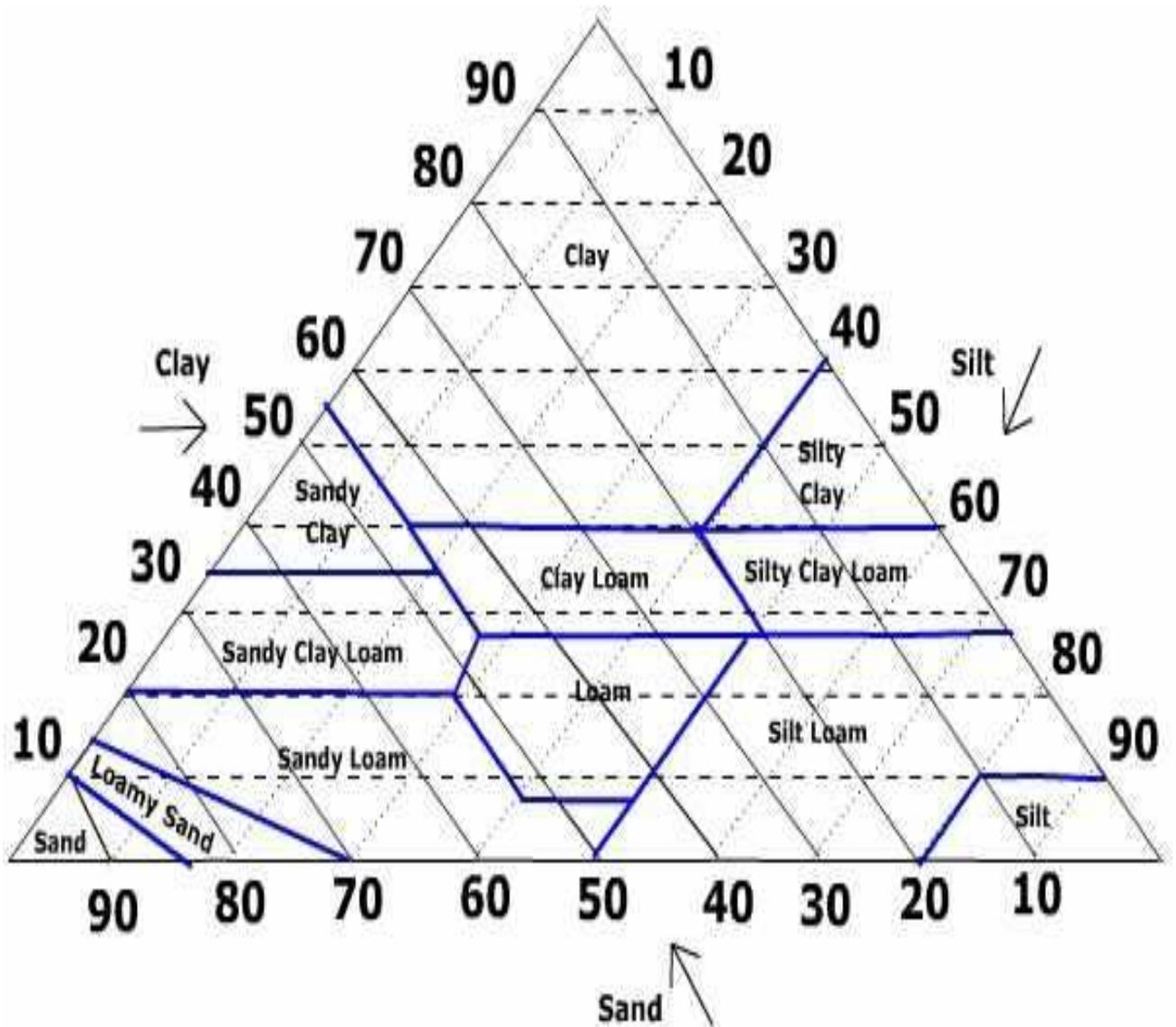
## 2.2 Soil Texture

*Definition:* Soil texture is relative proportion of different sized groups in the soil on percentage basis. It describes the sand, silt and clay composition of a soil.

*Soil Textural Class:*

Grouping based on relative proportion and specifically on % sand, silt and clay in given soil sample. The class name essentially describes the separate which most influence the sample physical/chemical/biological properties.

Common soil textural classes' identification is based on USDA textural triangle system shown below.



### *Mechanical Composition of Soil:*

The mechanical composition of soils is the basic aspect of their physical investigation useful for:

- Land use capability classification. (Best agricultural soil – about 10-20% clay, 5-10% organic matter and the rest divided equally between sand and silt).
- In the study of soil morphology, genesis, classification and mapping.
- Texture of the mineral soil determines to a large extent the physical and chemical behaviour as well as biological potential of the soil.
- Soil texture is an indicator of the type of management needed for good plant growth and for engineering purposes.

NOTE: Texture varies little with time.

### *Mechanical Analysis:*

This is the procedure for determining the particle size distribution of a soil sample.

#### **1<sup>st</sup> Step:** Dispersion

- Remove organic matter by  $H_2O_2$  where necessary
- Disperse in an aqueous solution. The common dispersing agent is Calgon solution, i.e. sodium-hexa-metaphosphate
- Deflocculate with by mechanical agitation, i.e. shaking, stirring or ultrasonic vibration.

#### **2<sup>nd</sup> Step:** Determination (Quantification) of size fractions)

1. *Sieving* (coarse fractions only):

By use of nest of sieves corresponding to desired particle size separates; e.g. 2, 1, 0.5 mm sieve.

The sieving can be dry- or wet-sieving.

2. *Sedimentation* (fine fractions)

The law which governs sedimentation of particles is called STOKES' LAW (Stokes, 1851). The law states that "resistance offered by liquid to the fall of rigid spherical particles varies with the circumference of the sphere and not with its surface". OR "the terminal velocity of a spherical particle settling under the influence of gravity in a fluid of a given density and viscosity is proportional to the square of the particle's radius".

i.e. Cause of settling (force of fall)	=	Resistance to settling
mg (wt. of material)		$\propto$ velocity = $3v$
$m = \rho V$		$\propto$ viscosity
		$\propto$ circumference of the sphere

where V = Volume of sphere

$$\therefore \frac{4}{3}\pi r^3(d_1 - d_2)g = 2\pi r\eta \cdot 3V$$

where  $d_1$  = density of particle;  $d_2$  = density of liquid

$$V = \frac{\frac{4}{3}\pi r^3(d_1 - d_2)g}{2\pi r\eta \cdot 3}$$

$$V = \frac{2r^2(d_1 - d_2)g}{9\eta}$$

In terms of particle diameter, d,  $1/4D^2$

$$V = \frac{(d_1 - d_2)gD^2}{18\eta}$$

To obtain time, t, needed for particle to fall through depth, h:

$$t = \frac{18h\eta}{(d_1 - d_2)gD^2}$$

### Examples

1. Calculate the velocity of sedimentation of silt particle 0.006 mm at 30<sup>0</sup> C. If  $\eta$  of H<sub>2</sub>O at 30<sup>0</sup> C = 0.00798 g cm<sup>-1</sup> s<sup>-1</sup> and gravity, g, = 980 cms<sup>-2</sup>

Solution:

$$D = 0.006 \text{ mm} = 0.0006 \text{ cm}$$

$$\begin{aligned} V &= \frac{(d_1 - d_2)gD^2}{18\eta} \\ &= \frac{(2.65 \text{ g cm}^{-3} - 1.0 \text{ cm}^{-3})980 \text{ cms}^{-2} \times (0.0006)^2 \text{ cm}}{18 \times 0.00798 \text{ g cm}^{-1} \text{ s}^{-1}} \\ &= \frac{5.8212 \times 10^{-4}}{0.14364} \text{ cms}^{-1} \\ &= \mathbf{4.1 \times 10^{-3} \text{ cms}^{-1}} \end{aligned}$$

2. Given:

Sampling depth = 10 cm

Particle diameter = 20  $\mu$ m and 2  $\mu$ m

Temperature = 30<sup>0</sup>C

Calculate the setting time of each particle.

Solution:

$$t = \frac{18h\eta}{(d_1 - d_2)gD^2}$$

(a) For  $D = 20 \mu\text{m} = 0.02 \text{ mm} = 0.002 \text{ cm}$

$$t = \frac{18 \times 0.00798 \text{ g cm}^{-1} \text{ s}^{-1} \times 10 \text{ cm}}{(2.65 \text{ g cm}^{-3} - 1.0 \text{ g cm}^{-3}) 980 \text{ cm}^{-2} \times (0.002)^2 \text{ cm}}$$
$$= \frac{1.4364}{6.468 \times 10^{-3}}$$

$$= \mathbf{222 \text{ seconds} = 3 \text{ min. } 42 \text{ s}}$$

(b) (b) For  $D = 2 \mu\text{m} = 0.002 \text{ mm} = 0.0002 \text{ cm}$

$$t = \frac{18 \times 0.00798 \text{ g cm}^{-1} \text{ s}^{-1} \times 10 \text{ cm}}{(2.65 \text{ g cm}^{-3} - 1.0 \text{ g cm}^{-3}) 980 \text{ cm}^{-2} \times (0.0002)^2 \text{ cm}}$$
$$= \frac{1.4364}{6.468 \times 10^{-5}}$$

$$= \mathbf{22208 \text{ seconds} = 6 \text{ hrs } 10 \text{ min. } 8 \text{ s}}$$

**PRACTICAL SECTION:** By Bouyoucous Hydrometer Method.

**QUESTIONS:**

1. Compute specific surface area of the A horizon of a UNAAB soil with the following characteristics:
  - (a) 60% sand with an average e.c.d. of 0.1 mm,  $\rho_s = 2.65 \text{ Mg/m}^3$ .
  - (b) 30% silt with an average e.c.d. of 10  $\mu\text{m}$ ,  $\rho_s = 2.65 \text{ Mg/m}^3$ .
  - (c) 10% clay with platy structure of length=200 nm, width=100 nm and  $d = 5 \text{ nm}$ ,  $\rho_s = 2.8 \text{ Mg/m}^3$ .
- (i) Calculate the relative contribution of each particle size class to the specific surface

area,

(ii) What is the textural classification of this soil? Compare it with that containing 10% sand, 30% silt and 60% clay,

(iii) What may be possible management problems of these two soils?

2. Calculate the terminal velocity of spherical particles of 2, 0.02, and 0.002 mm diameter in dilute water suspension at 20, 30 and 40°C.

*Questions adopted from Lal and Shukla (2004).*

### **2.3 Soil Structure**

*Introduction:*

The term structure relates to the arrangement of primary soil particles into groupings called AGGREGATES or PEDS. The pattern of pores and peds defined by soil structure greatly influence water movements, heat transfer, aeration and porosity in soils.

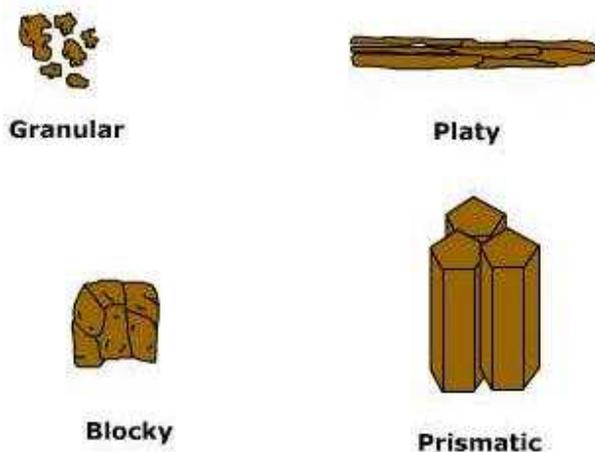
*Types of Soil Structure:*

Different types of structural peds in soils occur within horizons of soil profile. Soil structure is characterized in terms of shape (type or form), size and distinctiveness (grade) of the peds.

**GRADE:** Describes the distinctiveness of the peds (differential between cohesion within peds and adhesion between peds). It relates to the degree of aggregation or the development of soil structure. In the field a classification of grade is based on a finger test (durability of peds) or a crushing of a soil sample.

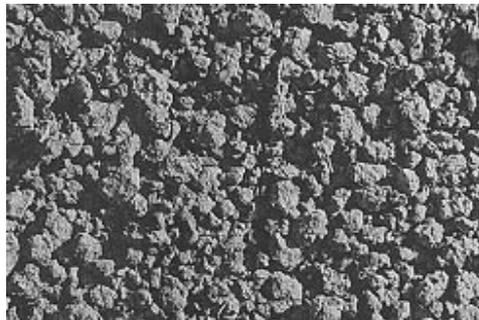
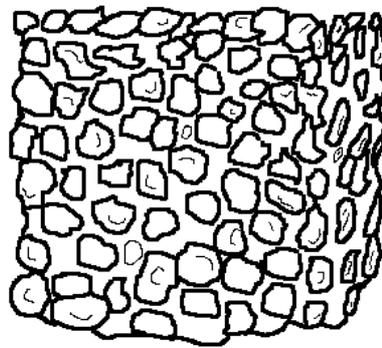
FORM: Is classified on the basis of the shape of peds, such as spheroidal, platy, blocky, or prismatic. A granular or crumb structure is often found in A horizons, a platy structure in E horizons, and a blocky, prismatic or columnar structure in Bt horizons. Massive or single-grain structure occurs in very young soils, which are in an initial stage of soil development. Another example where massive or single-grain structure can be identified is on reconstruction sites. There may two or more structural arrangements occur in a given profile. This may be in the form of progressive change in size/type of structural units with depth (e.g. A horizons that exhibit a progressive increase in size of granular peds that grade into subangular blocks with increasing depth) or occurrence of larger structural entities (e.g. prisms) that are internally composed of smaller structural units (e.g. blocky peds). In such a case all discernible structures should be recorded (i.e. more rather than less detail). The size of the particles have to be recorded as well, which is dependent on the form of the peds.

The four principal shape of soil structure are: (i) Spheroidal; (ii) Blocklike; (iii) Prismlike; and (iv) Platy.



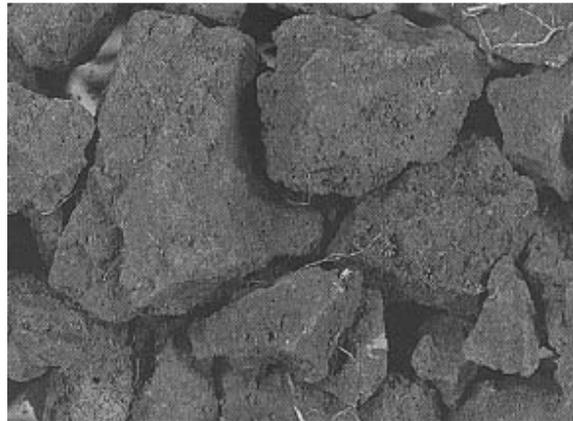
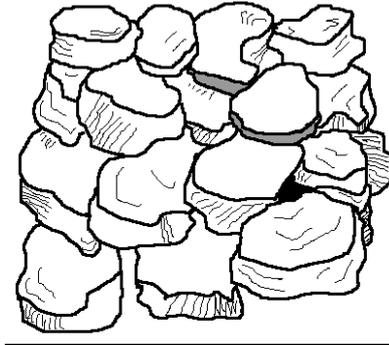
These structural types and their subtypes are illustrated as:

- (i) Spheroidal: We have (a) Granular structure and (b) crumb structure. The granular structure consists of spheroidal peds or granules that are usually separated from each other in loosely packed arrangement. When the spheroidal peds are porous, they are classified as **crumbs**. Granular and crumb structures are characteristic of many surface soils, usually the A-horizon, and particularly those high in OM. They are especially prominent in grassland soils and soils that have been worked by earthworms.

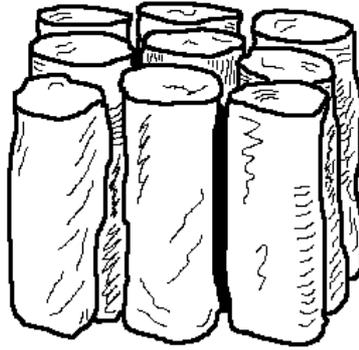


- (ii) Blocklike: Blocky peds are irregular, roughly cubelike in shape and range from about 5 to 50 mm across. The individual blocks are not shaped independently but are molded by the shapes of the surrounding blocks. When the edges of the blocks are sharp and the rectangular faces are distinct, the subtype is referred to as **angular**

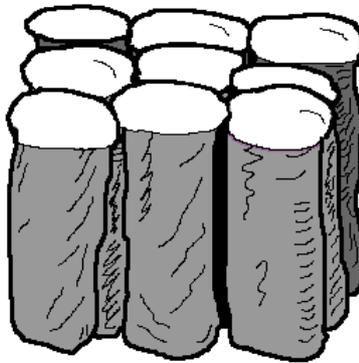
**blocky.** When the corners are round and the edges are sharp, then it is called **subangular blocky.** These types are usually found in the B-horizon of soil where they promote good drainage, aeration and root penetration.



- (iii) Prismlike: This has two sub-types namely (a) Columnar and (b) Prismatic. The horizontal axes of prismlike structure are shorter than the vertical axes. Columnar structure has pillars with distinct, rounded top and this is especially common in subsoils high in  $\text{Na}^+$ . When the tops are of the prisms are relatively angular and flat horizontally, the structure is designated as Prismatic. Both prismlike structures are often associated with swelling types of clay. They commonly occur in subsurface in arid and semiarid regions.

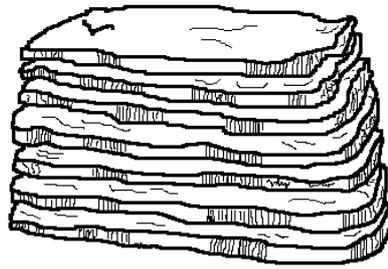


(Prismatic structure)



(Columnar structure)

- (iv) Platelike: Platy structure is characterized by relatively thin horizontal peds or plates and may be found in both surface and subsurface horizons. The horizontal axes are longer than vertical, i.e. horizontal cleavage planes predominate. NOTE: In some case, compaction of clayey soils by heavy machinery can create platy structure.



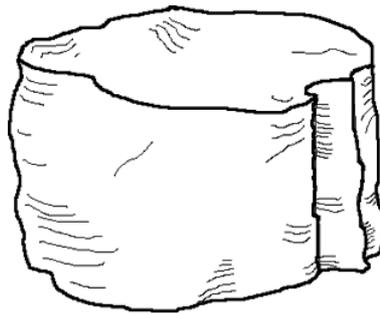
*Structureless soil:*

Single-grained: Soil is broken into individual particles that do not stick together.

Always accompanies a loose consistence. Commonly found in sandy soils.



Massive: Soil has no visible structure, is hard to break apart and appears in very large clods.





*Measurement of Soil Structure:*

Direct Measurement: this involves measuring the size and shape of aggregates and spaces or pore spaces between them. This is 3-dimensional study of undisturbed soil achieved in thin section observed with polarizing microscopes.

Indirect Measurement: This involves measurement of the parameters which are used to estimate the soil structural properties. These parameters are:

- Aggregate size distribution
- Aggregate stability
- Porosity
- Pore size distribution
- Permeability
- Infiltration
- Bulk density

Aggregate size distribution/stability:

This measured using nest of sieves and the proportion of aggregates retained on each sieve size range is calculated as %WSA or %DSA. The aggregate stability is calculated from data obtained from % stable aggregates as:

(a) 
$$MWD = \sum_{i=1}^n X_i W_i$$

Where  $X_i$  = mean diameter of a particular size range separated by sieving

$W_i$  = weight or proportion of the aggregate in the size range

MWD = mean weight diameter

(b) Other techniques include:

- Geometric mean diameter (GMD)
- Water-drop impact techniques

Example:

Give weight of soil sample = 50 g

Nest of sieves = 5-2 mm, 2-1 mm, 1-0.5 mm, 0.5-0.25 mm and <0.25 mm.

Calculate the MWD of the soil.

Solution

Size range (mm)	Wt. of soil (g)			$X_i$	$W_i$	%WSA	MWD
	I	II	θ				
5-2	15	20	17.5	3.5	0.35	35	1.275
2-1	10	15	12.5	1.5	0.25	25	0.375
1-0.5	10	5	7.5	0.75	0.15	15	0.113
0.5-0.25	10	3	6.5	0.375	0.13	13	0.049
<0.25	5	7	6.0	0.125	0.12	12	0.015
							<b><math>\Sigma</math>MWD = 1.777</b>

### 3.0 Soil Consistency

*Definition:* Soil consistency describes the state of the soil, i.e. solid, plastic and liquid states.

OR:

- Ability of soil to keep its place or maintain its form when stress is applied.
- Soil consistence (or consistency) refers to the manifestations of the physical forces of cohesion and adhesion acting within the soil at a range of soil moisture contents.

Adhesion refers to the attraction between dissimilar objects, i.e. to the attraction of water to the soil solids. While cohesion is attraction between similar objects, i.e. bonding between soil particles. Cohesive forces in soil are due to attractive forces between the particles.

These forces are due to physicochemical mechanisms including:

- van der Waals forces
- Electrostatic attraction between negatively charged clay surfaces and positively charged clay edges
- Cationic bridges,
- Cementing effects of humic substances and salts, and
- Surface tension of water

Soil consistence encompasses several attributes including friability, tilth, plasticity, stickiness, and resistance to compression.

Atterberg, a Swedish agriculturist, proposed a concept dividing the entire cohesive range of the soil into five stages and six divisions of soil wetness (Lal and Shukla, 2004). These limits, corresponding with soil moisture content from harsh consistency to viscous flow, are called Atterberg consistency limits.

***Shrinkage Limit:*** This represents the soil moisture content corresponding with the lower limit of the volume change at which there is no further decrease in soil volume as soil moisture is evaporated.

***Lower Plastic Limit:*** This refers to the moisture content corresponding with the lower limit of the plastic range. This is the moisture content at which the soil starts to crumble when rolled into a thread (3 mm diameter) under the palm of the hand. It represents the minimum soil moisture content at which the soil can be puddled.

***Cohesion Limit:*** It refers to the soil moisture content at which crumbs of soil cease to adhere when placed together or in contact with one another.

***Sticky Limit:*** This is the soil moisture content above which the mixture of soil and water will adhere or stick to a steel spatula or another object that can be wet by water.

***Upper Plastic Limit:*** This is also called the liquid limit or the lower limit of viscous flow. It signifies the moisture content at which the moisture film becomes thick, cohesion is decreased, and soil-water mixture flows under stress.

***Upper Limit of Viscous Flow:*** This is the soil moisture content above which the mixture of soil and water flows like a liquid.

***Plasticity Index (PI):*** This represents the difference in moisture content between the upper and lower plastic limits i.e.

$$PI = UPL - LPL$$

where PI is the plasticity index, and UPL and LPL refer to the moisture content at upper and lower plastic limits. This index is an indirect measure of the force required to mold the soil; indicates ease of tillage without puddling danger; and it tells us about the soil we are dealing with. Thus, high PI shows fine materials like clay or types of clay.

# Soil Air

Soil is a three-phase, porous media, composed of solids, liquids, and gases.

**Soil air** can be defined as the air that fills the soil pore spaces not occupied by water.

That is the gaseous phase of the soil not occupied by solid or liquid.

## Soil Air Composition

<i>Air Composition</i>	<i>Atmosphere</i>	<i>Soil</i>
Oxygen	21%	< 20% (10.35 – 20.03)
Carbon Dioxide	0.035%	> 0.035% (0.10 – 20.0)
Nitrogen	78%	78%
Argon	0.94	
Hydrogen	0.01	

## Gaseous Composition of Soil Air

### **Oxygen**

- Soil air is consistently lower in oxygen
- The oxygen content may be only slightly below 20% in the upper layers of a soil
- Wet soils typically have low oxygen contents.
- Once the supply of oxygen is virtually exhausted, the soil environment becomes anaerobic
- Drastic reductions in the oxygen content of soil air may occur following a heavy rain.

### **Carbon dioxide**

- Carbon dioxide typically increases in soil air.
- Carbon dioxide may become toxic to plants when it is as high as 10% in soil air.

### **Other Gases**

- Soil air is usually higher in water vapour than in the atmosphere.
- Under waterlogged conditions, the concentrations of methane (CH<sub>4</sub>), and hydrogen sulphide (H<sub>2</sub>S) are particularly higher in soil air.
- Ethylene (C<sub>2</sub>H<sub>4</sub>) gas, a product of anaerobic microbial metabolism is toxic to plant roots, even in very small concentrations.

## Soil Aeration

### Definition

Soil aeration is the ability of soil to exchange gases with the atmosphere. This involves the rate of ventilation, composition of soil air, proportion of pore space filled with air, and redox reaction potential.

### Poor Soil Aeration

1. This refers to a condition in which the availability of oxygen in the root zone is insufficient to support optimal growth of most plants and aerobic microorganisms.
2. Poor aeration becomes a serious impediment to plant growth when more than 80 to 90% of the soil pore space is filled with water, leaving less than 10 to 20 % of the pore space filled with air.
3. The high soil water content not only leaves little pore space for air storage but, more important the water blocks the pathways by which gases could exchange with the atmosphere.

### Water Saturated (Waterlogged) Conditions

- The soil is said to be *water saturated* or *waterlogged* when all or nearly all of the soil pores are filled with water. Such conditions occur naturally in wetlands.
- Plants adapted to grow in waterlogged soils are known as *hydrophytes* (water-loving plants), e.g., grasses and rice. Respiration is via hollow structures in their stems and roots known as *aerenchyma tissues*.
- When oxygen becomes depleted, soil conditions are said to be *anaerobic*. Methane, hydrogen sulphide, and ethylene are often evolved under these conditions.

### Adverse Effects of Suboptimal Aeration on Plants and Soils

1. Morphologic structure (e.g., Thin cell walls in root; Suppression of root hair formation)
2. Physiologic function (e.g., Decline in pH of plant sap; Reduction in transpiration rate)
3. Induced chemical/biochemical reactions (Denitrification; Manganese reduction; Iron reduction; Organic matter reduction)

### Factors Affecting Soil Aeration

- Drainage
- Texture
- Bulk density
- Aggregate stability
- Organic matter content
- Biopore formation
- Soil heterogeneity –(tillage)
- Seasonal differences
- Vegetation

### Mechanisms for soil aeration

**Mass flow:** This mechanism is dependent upon overall pressure gradients and is thus affected by soil water content, wind, and changes in barometric pressure.

**Diffusion:** Gases move in the direction determined by their partial pressure. Consequently, the higher concentration of oxygen in the atmosphere will result in a net movement of this particular gas into the soil. Carbon dioxide and water vapour normally move in the opposite direction, since the partial pressure of these two gases are generally higher in the soil air than in the atmosphere.

### Soil Temperature and thermal properties

Soil temperature affects :

- Soil
  - physical,
  - biological and
  - chemical processes occurring in the soil
- Growing plants

### Soil Processes Affected by Variation in Soil Temperature

In cold soil, rate of chemical and biological reactions are slow.

b. Microbial activities are slowed down at low temperatures, which bring biological decomposition to near standstill.

c. Absorption and transport of water and nutrients ions by higher plants are inhibited by low temperatures.

d. Plants and microbial processes are also inhibited by too high temperature.

e. Seed germination is most sensitive to soil temperature.

## Solar Radiation

The primary source of energy to heat soils is the solar radiation from the sun.

### Factors influencing the amount of solar radiation

- **Albedo** – This is the fraction of incident radiation that is reflected by the land surface.
- **Aspect** – The angle at which the sun's rays strike the soil
- **Rain/Irrigation water** – affect the soil temperature.
- **Soil Cover** – depends on whether the soil is bare, or is covered with vegetation or mulch.

## Soil Thermal Properties

- Specific heat (heat capacity): This is the amount of energy required to raise the temperature of a substance by 1°C.  
Unit - (cal/g) or joules per gram (J/g)
- Thermal Conductivity: The amount of heat transferred through a unit cross-sectional area of unit thickness in unit time and unit temperature gradient.
- Thermal Diffusivity: Temperature change that takes place in a portion of a given soil as heat flows into it from adjacent layer.

### Mode of Heat Transfer

- Conduction – Flow of heat through matter unaccompanied by any motion
- Convection – The transfer of heat by moving matter.
- Radiation – The transfer of heat through vacuum / space

### Modification of soil thermal regime

- Mulch
- Tillage
- Irrigation

- Drainage
- Weed control
- Plants/trees.

Most of the methods are aimed at modifying the surface intake / loss of heat.

#### Calculating the Specific Heat of Moist Soils

$$c_{moist\ soil} = \frac{c_1 m_1 + c_2 m_2}{m_1 + m_2}$$

where  $c_1$  and  $c_2$  are specific heat of the two substances and  $m_1$  and  $m_2$  are mass of the substances.

specific heat:

Water = 1.0 cal/g

dry mineral soil = 0.2 cal/g

# SOIL WATER

## Properties of Water Which Are Relevant to its Behavior in Porous Media

Water is the most common of all liquids, and it is indispensable for life. It accounts for 60-95% of the material in all organisms and it is a means of transporting nutrients dissolved or suspended in it to all parts of plants and other biological and porous bodies like soil. Water is thus a solvent to make solutions or suspension.

*In a solution*, a chemical species (the solute) breaks up into its molecules or into portions of its molecules when it is added to a pure liquid (the solvent) and the result is a homogenous solution in which it is impossible to detect the physical presence of the solute. *In a suspension*, one substance made up of the very small particles is present in a pure liquid, but the particles are a size that makes them physically distinguishable from the liquid. As the size of the particles in a suspension is reduced, we reach a state referred to as *the colloidal state*, which is half way between the true solution and a true suspension.

Water is a very unusual liquid with unique physical properties that depend on the fact that its molecules form strong bonds with one another, so that they exist in partially ordered state that has certain crystalline properties. As a chemical, it is a compound of great stability, a remarkable solvent and a powerful source of chemical energy. The concepts, which explain the physical properties of water, apply to other liquids as well as gases, necessitating the use of the word “fluid” when gases and liquid are being discussed.

### *Pressure*

A liquid is characterized by its having a definite volume but no definite shape. A given quantity of liquid will always at the same temperature fill a specific container to the same level. Some physical properties of water are:

#### Density

Liquid       $0.998 \text{ g cm}^{-3}$  or  $1000 \text{ kg m}^{-3}$

Solid         $0.910 \text{ g cm}^{-3}$

Vapor         $1.73 \times 10^{-5} \text{ g cm}^{-3}$

Surface tension       $73 \times 10^{-3} \text{ N m}^{-1}$

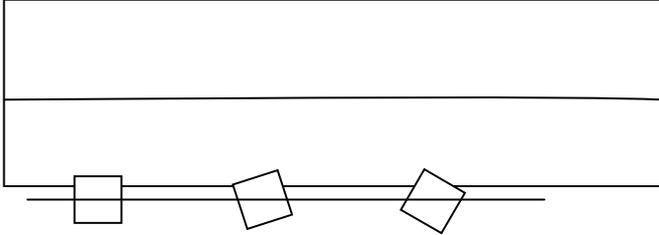
Viscosity               $100 \times 10^{-5} \text{ kg m}^{-1} \text{ s}^{-1}$  or  $1.00 \times 10^{-2} \text{ g cm}^{-1} \text{ s}^{-1}$

The derived units of density are  $\text{kg m}^{-3}$  and it is more convenient to work with relative density (specific gravity), which is defined as a density of the liquid divided by the density of pure water at  $4^\circ\text{C}$ .

*Ask the student to distinguish solution, suspension, colloid, fluid, liquid and relative density*

*e.g. Density of benzene is  $879 \text{ kg m}^{-3}$ , what is its relative density?*

$$879/1000 = 0.879$$



Consider the small disk of area  $A$  placed in a liquid. The liquid exerts a force  $F$  on both sides of the disk and this force is independent of the orientation of the disk and acts perpendicular to the surface of the disk. The pressure occupied by the disk is defined as

$$p = F/A.$$

The disk must be small enough so that the pressure does not vary appreciably over its surface.

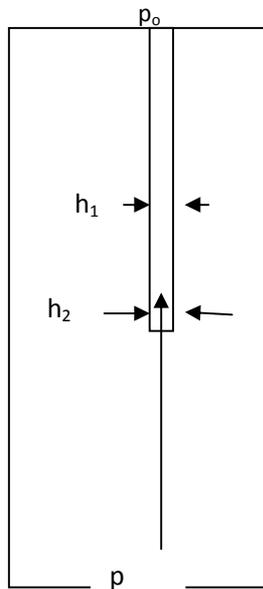
The dimensions of pressure are:

$$\text{Pressure} = \text{Force}/\text{Area} = \text{Force} \times \text{Distance}/\text{Area} \times \text{Distance} = \text{Energy}/\text{Volume}$$

This shows that pressure is alternatively an energy density.

*Note the approach in deriving formulae which is also a way of proving formulae*

The pressure in a liquid depends on the depth at which we measure it.



Consider the tank of water above at depth  $h_1$  and at depth  $h_2$ . Imagine a cylindrical column of liquid above this point reaching the surface. All the rest of the liquid exerts pressure normally over the surface of the cylindrical column, and the atmosphere on the top of the column with a pressure referred to as atmospheric pressure. All the forces resulting from the horizontal pressure cancel out and we are concerned with only the vertical forces. If the cross-sectional area of the cylinder is  $A$ , then the pressure  $p$  in the liquid at the depth  $h$  exerts on the cylinder an upward force  $pA$ , while the atmosphere exerts a downward force on the top of the cylinder of amount  $p_0A$ . The resultant upward force is  $(p-p_0)A$  and this force must exactly balance the weight of liquid in the cylinder since the whole liquid is at rest. The volume of the cylinder is

$hA$ , the mass of the liquid in the cylinder is  $\rho hA$ , and therefore the weight of this mass of a liquid is  $\rho ghA$  (note: *weight = mg*)

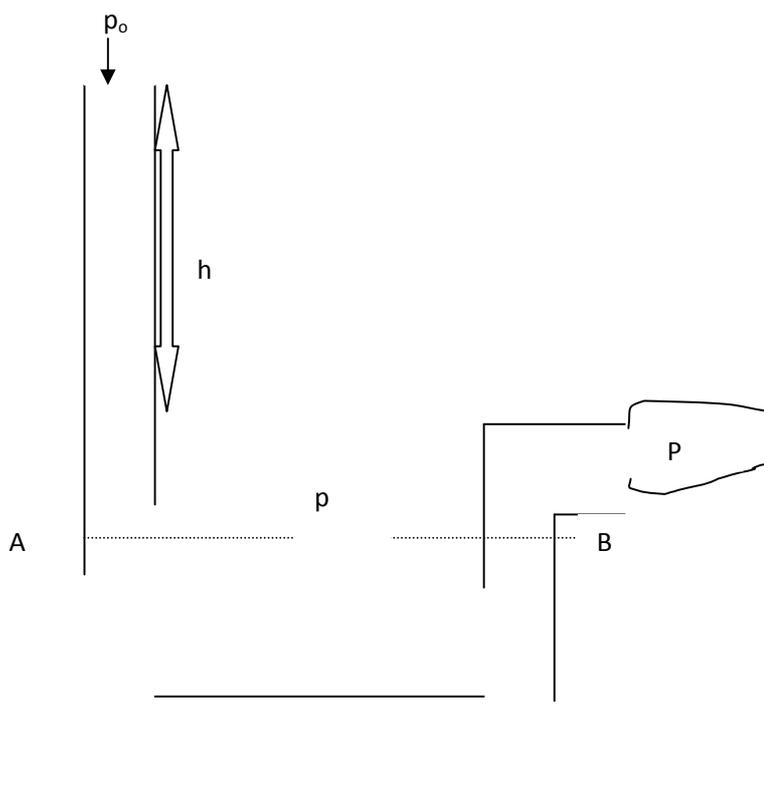
Since upward force = downward force

$$(p-p_0)A = \rho ghA$$

$$(p-p_0) = \rho gh$$

This is a fundamental hydrostatic equation

A common device for measuring pressure in liquids or gases is the manometer



It consists essentially of a U-shaped tube containing a liquid (usually mercury or water), one arm of which is open to the atmosphere, the other being connected to the vessel whose pressure we wish to measure. If the manometer shows the liquid in open arm at a height  $h$  above that in the closed arm, the pressure in the open arm at A is equal to that of the closed arm at B. Considering the open arm, we get

$P - p_0 = \rho gh$  and the height  $h$  gives a direct measure of the gage pressure. It is customary to pressure in terms of manometric height,  $h$ , using the known values of  $\rho$  and  $g$ .  $\rho$  for mercury is  $13600 \text{ kg m}^{-3}$ ,  $g = 9.8 \text{ m s}^{-2}$ ,  $\rho g = 1.33 \times 10^5 \text{ N m}^{-3}$ . Standard atmospheric pressure,  $1 \text{ atm} = 760 \text{ torr} = 1.01 \times 10^5 \text{ N m}^{-2}$  or  $10^5 \text{ N m}^{-2}$ .

### **Soil Water Content and Potential**

Quantity of water in soil is expressed by gravimetric or volumetric water content. However, water can also be characterized by describing its free energy per unit mass, which is termed potential. The tenacity with which water is held in soil solid is characterized by matric or pressure potential. When volumetric water content and matric potential are plotted graphically, the relationship is termed *Soil Moisture Characteristic Curve*.

When all soil pores are filled with water, the soil is at its maximum retentive capacity called saturation. In the field, the lowest wetness you can observe is called air-dryness and in the laboratory it is called oven-dry condition.

$$w = M_w/M_s$$

$$\theta = V_w/V_t = V_w/(V_s + V_w + V_a)$$

$$\theta = w(\rho_b/\rho_w) = w\Gamma_b$$

where  $\Gamma$  (capital letter of gamma) is the bulk specific gravity of the soil. The conversion of  $w$  to  $\theta$  is easily done in non-swelling soil where soil bulk density does not change with wetness.

Application of soil water by irrigation or rainfall is reported as the depth of water if it were accumulated in a layer. This indicates the equivalent depth,  $d_w$ , soil water would have if it were ponded over the surface

$$d_w = \theta d_t = w \Gamma_b d_t$$

$d_t$  is depth of soil per unit area

Usually  $d_w$  is given in mm, as rainfall and evaporation

To obtain the volume of water applied to a given area would require multiplication of the depth by the area, measured in the same length units.

### **Measurement of Soil Water Content**

The gravimetric water content,  $w$ , of a sample of moist soil is measured by weighing the moist soil sample, drying it to remove water, and reweighing it. The customary method of drying is to place the sample in an oven at  $105^\circ\text{C}$  for 24 h.

Calculate  $w$  given the following:

Mass of can + moist soil      180 g

Mass of can + dry soil      153 g

Mass of empty can          35 g

w = mass of water/mass

of

dry soil =  $(180 - 153) / 153 = 0.22881$

35                                      4

229

g/kg

A problem with the gravimetric method is that it is often assumed that the oven dries the soil at the control temperature when in reality the temperature varies from the desired temperature. A solution to this is to measure oven temperature regularly with a thermometer after setting the control.

### **Estimation of volumetric water content**

This is done as indicated above, if the bulk density is known. Determination of bulk density and volumetric water content in gravelly or stony soil is accompanied by low precision because of the heterogeneity or variability that occurs from point to point. A relationship which takes into account the stone or gravel content is as follows:

$$\theta = (w\rho_b/\rho_w)/(1 + M_{\text{stone}}/M_{\text{fines}})$$

$\rho_b$  = bulk density of bulk soil

$M_{\text{stone}}$  = Dry mass of stones

$M_{\text{fines}}$  = Dry mass of fines

Conventional cylindrical tube samplers may be used in some gravelly and stony soils. However, as the amount of stones increases, the utility of such sampling devices diminishes. In these kinds of soils, it is important to determine the volume sampled each time a water content determination is to be made. When large rocks and stones interfere seriously, one useful method involves sampling with a spade or shovel and determining the volume of the hole which is dug. The volume may be measured by placing a rubber or plastic membrane in the hole and filling it with water from a container filled to a known volume.

#### INDIRECT METHODS OF SOIL WATER CONTENT DETERMINATION

Indirect methods involve measurement of some property of the soil that is affected by soil water content or measurement of a property of some object placed in the soil. Indirect methods reduce labor and time required during direct methods of measurement. Furthermore, direct methods often involve destructive sampling, in which case, an experimental plot may be highly disturbed by frequent sampling. Also, point to point variations on plots may be misconstrued as temporal variation in direct methods.

##### Electrical resistance method

Materials such as porous moisture absorbers vary in their electrical and thermal conductivity and electrical capacitance with water content. Thus, electrical resistance of porous blocks such as

gypsum (plaster of Paris) blocks or fiber glass placed in soil equilibrate with soil water suction or tension. A calibration of this electrical resistance with soil water suction is used to describe soil wetness. The gypsum blocks are connected to a resistance meter using suitable electrodes.

Diagram

### ***Neutron scattering or attenuation***

An equipment called Neutron moisture meter is used to measure soil moisture in the field. It has (i) a probe and (ii) a scaler or rate meter. When the probe is inserted into soil through an access tube, fast neutrons are emitted from it into the soil from the equipment but these are slowed down as they collide with hydrogen nuclei, which are mainly found as components of soil water. The neutrons that have been slowed down are said to be thermalized. The probe is also equipped with a detector of slow neutrons which counts the neutrons, sending pulses over a measured time interval to the scaler or rate meter.

An empirical equation for water content in terms of count ratio, used over the range of water contents of interest is:

$$\theta = a + bf$$

where  $f$  is the count rate ratio,  $I/I_{\text{std}}$ . The parameter, “ $a$ ” depends in part upon the bulk density while the parameter “ $b$ ” depends upon the presence of substances in the soil such as structural water (i.e., water derived from components of the mineral lattice itself as opposed to adsorbed water which is water that is attached to the mineral lattice but is not a structural component of the lattice), and chemical materials.

Diagram

### *Gamma ray Attenuation or Absorption*

In this method, a narrow beam of gamma radiation is sent through a soil sample of known thickness and is collected beyond its exit from the sample by a detector.

#### Diagram

The gamma-ray scanner for measuring soil moisture generally consists of a source of radioactive Cesium <sup>137</sup>Cs and a detector. The gamma ray equation may be written as

$$n(L) = n_0 \exp(-v_m \rho_b L - v_w \rho_w \theta_v L)$$

where  $n(L)$  is the number of counts of gamma radiation per unit time recorded at the detector,  $n_0$  is the background count rate when soil is removed,  $v_m$  is soil mineral gamma ray absorption coefficient,  $L$  is the thickness of the soil sample.

The gamma ray absorption method is used mostly in the laboratory where the dimensions and density of the soil sample as well as ambient temperature can be precisely controlled. Since the absorption of radiation is dependent upon the entire mass intervening between the source and detectors, the readings can only be related uniquely to changing soil moisture if soil bulk density is constant or if change is monitored simultaneously.

### *Time Domain Reflectometry*

Time Domain Reflectometry (TDR) is a recent method by which volumetric water content is estimated directly. The method consists of the permittivity or dielectric number,  $\epsilon$ , of the soil and the subsequent calibration of this property with the volumetric water content. Measurement of dielectric number consists of placing a prong with two arms (usually about 30 cm long or less) forming two parallel waveguides into the soil and sending a step pulse of electromagnetic radiation along the guides. This pulse is reflected at the end of the prong and returned to the

source, where its travel time and velocity can be estimated with oscilloscope (instrument that shows variation in electrical current of a wavy line on the screen of a cathode ray tube). The permittivity or dielectric number of the soil between the waveguides causes the velocity of pulse to deviate in a known manner from the velocity of light in vacuum. Hence the permittivity can be estimated from the travel time, and the water content can be calculated by a regression equation from the permittivity.

### Capillary and Soil Water

The movement of water up a wick typifies the phenomenon of capillarity. Two forces cause capillarity (1) the attraction of water for the solid (adhesion or adsorption) and (2) the surface tension of water which is due largely to the attraction of water molecules for each other (cohesion).

The height of rise in a capillary tube is also inversely proportional to the tube radius. Capillary rise is also inversely proportional to the density of the liquid, and is directly proportional to the liquid's surface tension and the degree of its adhesive attraction to the soil surface. Considering water at a given temperature of 20°C, we can have a simple capillary equation to calculate the height of rise  $h$ :

$$h = 0.15/r$$

where both  $h$  and  $r$  are expressed in cm

Capillary forces are at work in all moist soils. However, the rate of movement and rise in height are less than one would expect because soil pores are not straight and there can be air entrapment slowing down water movement. In fine textured soils, capillary rise is high but rate of flow is slow because of frictional forces in tiny pores. In coarse-textured (sandy) soils, pores are large presenting little resistance to capillary rise but limiting the rise in capillary water.

## Energy Status of Soil Water

The difference in energy level of water from one site or one condition (e.g., wet soil) to another (e.g., dry soil) determines the direction and rate of water movement in soils and plants. In a wet soil, most of the water is retained in large pores or thick water films around particles. Therefore, most of the water molecules in wet soil are not very close to a particle surface and so are not held very tightly by the soil solids (soil matrix). In this condition, the water molecules have considerable freedom of movement, so their energy level is near that of water molecules in a pool of pure water outside the soil. In a drier soil, however, the water that remains is located in small pores and thin water films, and is therefore held tightly by the soil solids. Thus the water molecules in a drier soil have little freedom of movement, and the energy level of the water is much lower than that of water in wet soil. If wet and dry soils are brought in touch with each other, water will move from the wet soil (higher energy state) to the drier soil (lower energy).

Usually the energy status of soil water in a particular location in the profile is compared to that of pure water at a standard pressure and temperature, unaffected by the soil and located at some reference elevation. *The difference in energy* levels between this pure water in the reference state and that of soil water is termed Soil Water Potential. Thus the term potential implies a difference in energy status. Knowing the potential energy in soil can help us estimate how much work the plant must expend to extract a unit amount of water. Potential energy rather than kinetic energy is used to describe soil water flow because kinetic energy is considered negligible by virtue of slow movement of soil water.

## Components of soil water potential

The International Soil Science Society defines total potential of soil water as “the amount of work that must be done per unit quantity of pure water in order to transport reversibly and isothermally an infinitesimal quantity of water from a pool of pure water at a specified elevation at atmospheric pressure to the soil water(at the point under consideration”. Soil water is subject to a number of force fields, which cause its potential to differ from that of pure, free water. Each of these forces is a component of the total soil water potential and they result from the attraction of the solid matrix for water, as well as from the presences of solutes and the action of external gas pressure and gravitation. Thus, the total potential is the summation of the component potentials:

$$\Phi = \phi_g + \phi_w + \phi_o + \phi_a + \phi_e$$

where  $\phi_g$  = gravitational potential

$\phi_w$  = is the soil water potential

$\phi_o$  = Osmotic potential owing to the difference in chemical composition of the soil solution related to free, pure, bulk water at the same elevation.

$\phi_a$  = pneumatic potential which accounts for air pressure inside the soil pores being different from the outside atmospheric air pressure acting upon the reference water

$\phi_e$  =envelope potential. When an external mechanical pressure such as the overburden pressure of the topsoil layers acts upon the soil, the magnitude of change of the total potential is expressed by the envelope potential, which is usuall negligible for sandy soils and becomes more important for soils having greater clay contents.

In the majority of situations, the simplest definition of the total potental is

$$\Phi = \phi_w + \phi_g$$

and with the potential expressed as energy per unit weight of water

$$H = h + z$$

Thus, the total potential head of soil water (H) is the sum of the pressure potential head (h) and gravitational potential head (z). H is commonly called hydraulic head.

### **Expression of water potential**

The soil-water potential is expressible in at least 3 ways:

1. Energy per unit mass: This is often taken to be the fundamental expression of potential (J/kg) with dimensions of  $L^2T^{-2}$
2. Energy per unit volume: This is unit of pressure (Pressure = force/area = force x distance/area x distance = energy/volume). Units  $N/m^2$ , kPa.  $ML^{-1}T^{-2}$
3. Energy per unit weight (hydraulic head): Since we can express soil water in units of hydrostatic pressure, it means we can also express it in terms of an equivalent head of water, which is height of a liquid column corresponding to the given pressure. The sum of matric and gravitational (elevation) heads is generally called the hydraulic head (or hydraulic potential) and is useful in evaluating directions and magnitudes of the water-moving forces throughout the soil profile.

pF. This is the logarithm of the negative pressure (tension or suction). It is an old term analogous to the term pH. A pF of 1 is a tension head of 10 cm H<sub>2</sub>O, a pF 3 is a tension head of 1000 cm H<sub>2</sub>O etc.,.

### **Expression of gravitational potential**

The force of gravity attracts soil water to the center of the earth as it does to any other body. Mathematical, gravitational potential is

$$E_g = Mgz = \rho_w Vgz$$

Where  $\rho_w$  is the density of water and  $g$  the acceleration of gravity.

*Note: Energy = force x distance, and force = mass x acceleration*

$$\text{Therefore, } E_g = mgz$$

*Where  $M$  = mass,  $g$  is acceleration due to gravity, and  $z$  is the height above a reference*

When gravitational potential is expressed as potential energy per unit mass:

$$E_g/m = Mgz/M = \rho_w Vgz/\rho_w V = gz$$

When it is expressed in terms of energy per unit volume,

$$E_g/V = \rho_w gz.$$

### **Pressure potential**

This component accounts for the effects of soil water potential of all factors other than gravity and solute levels. It most commonly includes (i) the positive hydrostatic pressure due to the weight of water in saturated soils and aquifers and (2) the negative pressure due to the attractive forces between the water and the soil solids or soil matrix. Pressure potential and matric potential

are mutually exclusive because pressure potential occurs in saturated soil while matric potential occurs in unsaturated soil. However, soil can be saturated up to the water table and unsaturated above the water table. Pressure potential is positive and greater than atmospheric pressure while matric potential is a negative pressure lower than the atmospheric. The positive pressure potential is termed submergence potential. The hydrostatic pressure  $P$  of water with reference to the atmosphere is

$$P = \rho gh$$

(See the expression of Energy/Volume = Pressure) above

where  $h$  is the submergence depth below the free-water surface, called piezometric head. *Note that  $\rho$  and  $g$  are constant, and this makes it possible to measure pressure by measuring depth of water,  $h$ .  $h$  is the submergence depth below the free-water surface called piezometric head.*

Suction is negative pressure or negative matric potential and its values are usually written in positive terms while matric potential with similar values are expressed in negative values. Thus a matric potential of  $-9.8$  kPa is referred to as a suction of  $9.8$  kPa. In other words, a low suction is a high potential.

The movement of soil water, the availability of water to plants and the solutions to many civil engineering problems are determined to a considerable extent by matric potential.

Matric potential which results from the phenomena of adhesion (or adsorption) and of capillarity, influences soil moisture retention as well as soil water movement

### ***Osmotic potential***

The osmotic potential is attributable to the presence of solutes in the solution. The solutes may be inorganic salts or organic compounds. Their presence reduces the potential energy of water, primarily because of the reduced freedom of movement of the water molecules that cluster

around each solute ion or molecule. The greater the concentration of solutes, the more the osmotic potential is lowered. Water will tend to move to where the energy level will be lower, in this case where place where the solute concentration is high. However, liquid water will tend to move in response to differences in osmotic potential (the process termed osmosis) only if semi permeable membrane exists between the zones of high and low osmotic potential allowing water through but preventing the movement of the solute. If no membrane is present, the solute rather than the water generally moves to equalize concentrations. Soil zones are not generally separated by membranes, so the osmotic potential has little effect on the mass movement of water in soils. Its major effect is on the uptake of water by plant root cells that are isolated from the soil solution by their semi permeable cell membranes. In soils high in soluble salts,  $\Psi_o$ , may be lower (have a greater negative value) in soil solution than in plant root cells. This leads to constraints in the uptake of water by the plants. In very salty soil, the soil water osmotic potential may be low enough to cause cells in young seedlings to collapse (plasmolyze) as water moves from the cells to the lower osmotic potential zone in the soil.

The random movement of water molecules causes a few of them to escape a body of liquid water, enter the atmosphere, and become water vapor. Since the presence of solutes restricts the movement of water molecules, fewer water molecules escape into the air as the solute concentration of liquid water is increased. Therefore water vapor pressure is lower in the air over salty water than in the air over pure water. By affecting water vapor pressure, osmotic potential affects the movement of water vapor in soils.

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**Water potential expressed in different units**

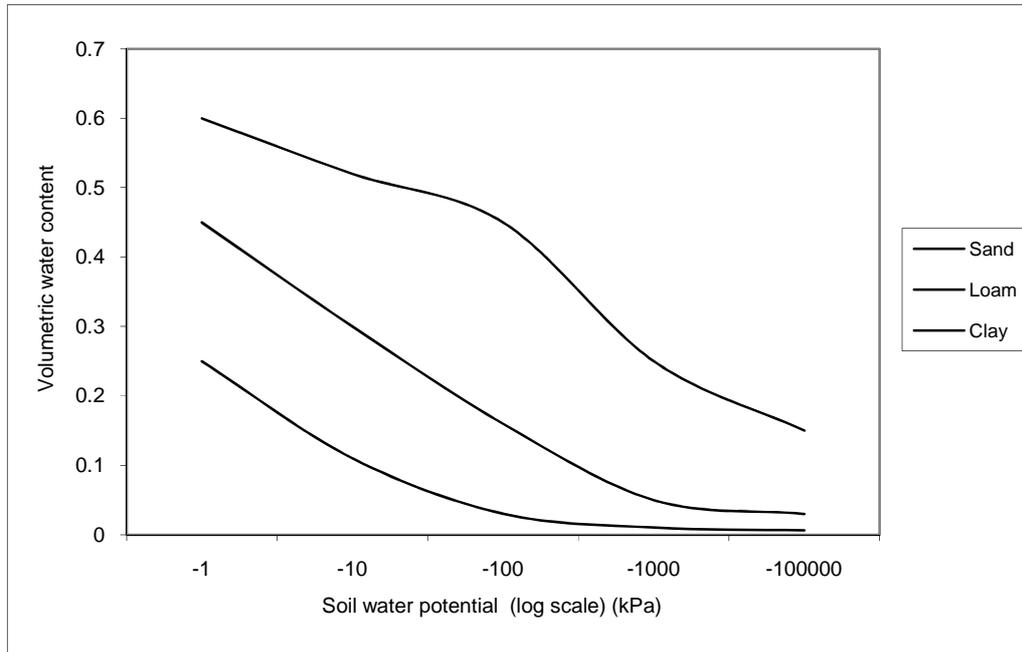
<b>pF</b>	<b>(-) cm</b>	<b>(-) bar</b>	<b>(-) kPa</b>	<b>(-)MPa</b>	<b>(-)Atmosphere</b>
<b>0.00</b>	<b>1.00</b>	<b>0.00</b>	<b>0.10</b>	<b>0.00</b>	<b>0.00</b>
0.50	3.16	0.00	0.31	0.00	0.00
1.00	10.00	0.01	0.98	0.00	0.01
1.10	12.59	0.01	1.23	0.00	0.01
1.20	15.85	0.02	1.55	0.00	0.02
1.30	19.95	0.02	1.96	0.00	0.02
1.40	25.12	0.02	2.46	0.00	0.02
1.60	39.81	0.04	3.90	0.00	0.04
1.70	50.12	0.05	4.91	0.00	0.05
1.80	63.10	0.06	6.18	0.01	0.06
1.90	79.43	0.08	7.78	0.01	0.08
<b>2.00</b>	<b>100.00</b>	<b>0.10</b>	<b>9.80</b>	<b>0.01</b>	<b>0.10</b>

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The SI unit kilopascal (kPa) is equivalent to 0.01 bars.

**Soil Moisture versus Energy Curves: Soil Water Retention**

The relationship between soil water potential  $\Psi$  and moisture content  $\theta$  plotted on semi-log scale is termed water release characteristic curve or soil moisture characteristic curve



The clay soils holds much more water at a given potential than does the loam or sand. Also clay holds water more tenaciously than loam or sand. Water in clay is held in the abundant micropores in it and this may not be readily available to plant because it is held so tightly. *Therefore, soil texture has a major influence on soil water retention.*

Soil structure also influences soil water content-energy relationships. A well-granulated soil has more total pore space and greater overall water-holding capacity than one with poor granulation or one that has been compacted. The greater total pore space indicates a greater overall water-holding capacity. The increased porosity of well-structured soils results mainly from greater amounts of large pores in which water is held with little tenacity. The compacted soil will hold less total soil water but is likely to have a higher proportion of small and medium-sized pores which hold water with greater tenacity than do large pores. Therefore, soil structure predominantly influences the shape of the water characteristic curve in the portion where the

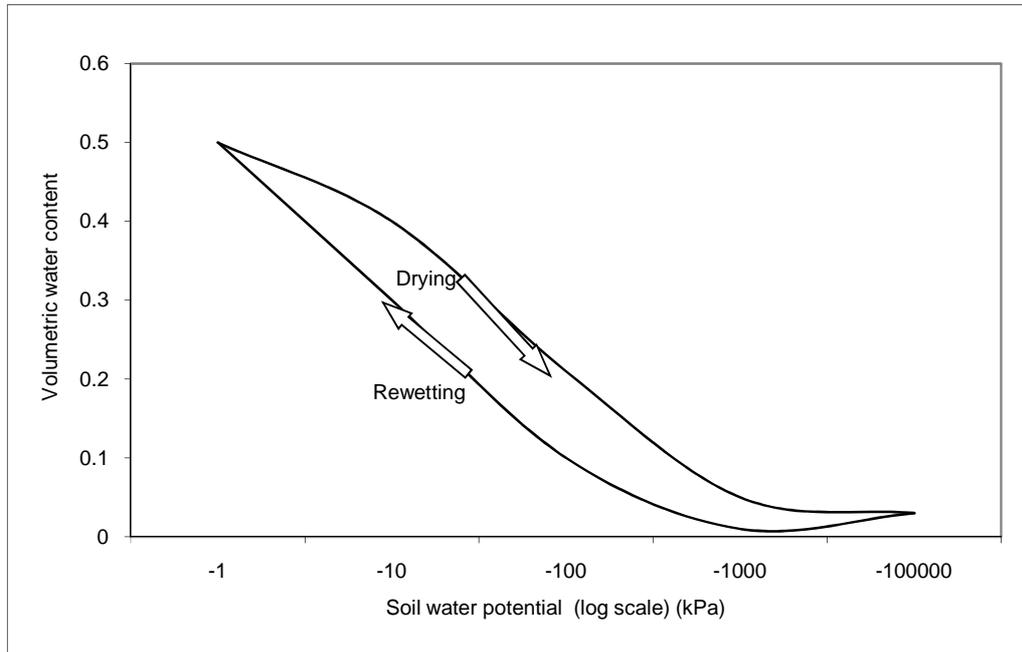
potentials are between 0 and 100 kPa. The shape of the remainder of the curve generally reflects the influence of soil texture. Increasing suction is associated with decreasing soil wetness.

There are various equations for describing soil wetness and matric suction

*Some authors plot gravimetric water content against soil water potential but the volumetric water content is preferred because it has an element of soil structure description. Emphasize difference between suction and potential* Water held in soil is expressed by water potentials (bars), a negative number. The positive number for water potential is called tension. The water held in the soil by adhesion and cohesion is called **matric potential** (go here for more reading on [Matric Potential](#))

### **Hysteresis**

The relationship between soil water content and potential, determined as soil dries out, will differ somewhat from the relationship measured as the soil is rewetted. This phenomenon describing the dependence of the equilibrium content and state of soil water upon the direction of the process leading up to it is called hysteresis.



Hysteresis is caused by a number of factors among which are:

Geometric non-uniformity of soil pores

Air entrapment which prevents water penetration

Some macropores may be surrounded by micropores creating a bottleneck effect

Consider the hypothetical pore which consists of a relatively wide void of radius  $T$ , bounded by narrow channels of radius  $r$ . If initially saturated, this pore will drain abruptly the moment the suction exceeds  $\Psi_r$  where  $\Psi_r = 2\gamma/r$ . For this pore to rewet, however, the suction must decrease to below  $\Psi_R$  where  $\Psi_R = 2\gamma/R$ , whereupon the pore fills abruptly. Since  $R > r$ , it follows that  $\Psi_r > \Psi_R$ . Desorption depends on the narrow radii of the connecting channels whereas sorption depends on the maximum diameter of the large pores.

Due to its complexity, the hysteresis phenomenon is too often ignored, and the soil moisture characteristic curve is only described with the desorption curve while the sorption curve is equally important but more difficult to determine and is seldom attempted.

## Soil Water Classification

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Soil Water is classified according to how "tightly" it is being held in the Soil.

Free water or gravitational water will drain from a soil until the soil water potential reaches **-1/3 bar**. This is called **field capacity**. Gravitational water is not considered available to plants because it is in the soil only a short time and reduces oxygen levels to the point where the plant will not be absorbing water anyway.

As the soil continues to dry--or water is used by plants--more and more energy is needed by the plants to remove the water. Eventually a point is reached where the plant can no longer remove water. This is called the **wilt point** and occurs at -15 bars water potential for most plants. From **-1/3 to -15 bars** is the zone of **available water**.

If the soil dries to an **air dry** state, the potential is **-31 bars**. (This assumes that the air has 100% relative humidity.) Plants cannot exert enough tension to pull water away from the soil. Tension is used to express water potential with positive numbers. So a tension of +15 bars equals a potential of -15 bars.

Additional drying requires putting the soil in an oven to drive off the tightly held water. Water is held in the soil like a series of beads, the farther the beads are from the soil particle, the weaker they are held by cohesion

The investigation in the laboratory will be using the soil placed in the drying cans last week. The sample in the lab was somewhere between field capacity and the wilt point (that is, between -1/3 and -15 bars).

You let the sample air dry, and later it was placed in the oven and dried, then weighed to obtain the *oven dry* weight. When working with determining % water by weight or volume, we always use the oven dry weight as the standard value with which to compare. In this investigation, we also determine the % water near the field capacity, using the **mud ball technique**.

### Water Problems

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You are required to know how to calculate the amount of water in a soil given various water potentials. This will help you understand that it is not the total amount of water in a soil that determines if water is available to plants, but is the plant available water. Seek help if you do not understand how to do these problems.

### DATA:

Soil Core Volume = 250 cc (for each soil core below)

Weight of soil core at -1/3 bar (field capacity) = **420** g (July 4, 19??)

Weight of soil core at -15 bar (wilt point) = **350** g

Weight of soil core at present field condition = **395** g (on July 10)

Weight of Oven dry soil core = **300** g

### Questions:

1) What is the Bulk Density?

*Answer:* B.D. =  $300 \text{ g} / 250 \text{ cc} = \mathbf{1.2 \text{ g/cc}}$  (remember, always use oven dry weight)

2) What is the % water by weight at field capacity?

**FC - Oven dry**

*Answer:*  $420 \text{ g} - 300 \text{ g} = 120 \text{ g of water}$

$120 \text{ g water} / 300 \text{ g soil} = .4$  (\*use oven dry weight)

$.4 \times 100 = \mathbf{40\% \text{ water by weight at field capacity}}$

3) What is the % water by volume at field capacity?

$$\text{FC} - \text{Soil Volume} =$$

*Answer:* 420 g - 300 g = 120 g of water

$$120 \text{ g water} / 250 \text{ cc soil} = .48$$

$$.48 \times 100 = \mathbf{48\% \text{ water by volume at field capacity}}$$

(Another way to calculate this is:  $\text{BD} \times \% \text{ water wt.} = \% \text{ water by volume}$ ):

$$1.2 \times 40\% \text{ water by weight} = 48\% \text{ water by volume}$$

4) What is the total possible % Available Water-holding Capacity (AWC) by volume?

$$(\text{AWC} = \text{FC} - \text{WP})$$

$$\text{FC} - \text{WP} / \text{Soil Volume} =$$

$$\text{Answer: } (420 - 350) / 250 = .28 \times 100 = \mathbf{28\%}$$

$$\mathbf{\text{available water}} \quad [(\text{FC} - \text{WP}) / \text{vol.}]$$

5) How many inches of AWC are in the upper 5 ft. of soil?

$$\text{inches of soil} \times \% \text{ AWC} =$$

$$\text{Answer: } 5 \text{ ft.} \times (12 \text{"/ft.}) \times .28 = \mathbf{16.8'' \text{ of AWC in upper 5 ft. of soil.}}$$

6) How many inches of available water are left in the soil at present field condition?

Field Cond. = 395 and Wilt Pt. = 350; therefore:

$$(395-350)/250 = 45/250 = .18 \text{ (\%AWC by Vol.)}$$

and

$$0.18 \times 60'' \text{ (of soil)} = \mathbf{10.8'' \text{ of water available in upper 5 feet.}}$$

In other words, the soil has lost 6" of water (16.8-10.8) since it was at field capacity.

7) What is the depth of wetting for a 1.5 inch rainfall event for the soil at Field Condition?

Answer : Field Capacity - Field Cond./ vol x 100 = % water by vol between field condition and Field Capacity. or  $420 - 395/250 = 25/250 = .1$  or 10%

thus 1.5 inches of rain will infiltrate ( $1.5 / .1$ ) = **15 inches.** of soil because

Inches of water = % Water vol x Soil Depth. or  $1.5 = .1 \times ?$  inches of soil

### **Measurement of Soil Water Potential**

Total water potential is often thought of as the sum of matric and osmotic (solute) potentials and is a very useful index for characterizing the energy status of soil water with respect to plant water uptake.

#### *The Tensiometer*

The tensiometer consists of a porous cup, generally ceramic material, connected through a tube to a manometer, with all parts filled with water. When the cup is placed in the soil where the suction measurement is to be made, the bulk water inside the cup comes into hydraulic contact and equilibrates with soil water through the pores 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 sub atmospheric pressure, exercises suction which draws out a certain amount of water from the rigid and airtight tensiometer thus causing a drop in its hydrostatic pressure.

This pressure is indicated by a manometer or a vacuum gauge. A tensiometer left in the soil for a long period of time tends to follow the changes in the matric suction of soil water. As moisture is depleted by drainage or plant uptake or it is replenished by rainfall or irrigation, corresponding readings occur on the gauge of the tensiometer. Since the porous cup of the tensiometer is permeable to both water and solutes, the water inside the tensiometer tends to assume solute composition and concentration as soil water, and the instrument does not indicate the osmotic suction of soil water (unless so equipped). The vacuum gage system functions within the range of 100 kPa, usually it collapses as suction reaches 80 kPa. This is however a suction range common during the wet season or during irrigation when crops are grown.

Tensiometers have long been used in guiding the timing of irrigation of field and orchard crops, as well as of potted plants. A general practice is to monitor soil suction with tensiometers placed in the root zones and irrigate when suction has reached a prescribed value.

#### *Measurement of soil moisture characteristic curves*

The fundamental relation between soil wetness and matric suction is often determined by the means of tension plate assembly in the low suction (<100 kPa or 1 bar). Tension tables can be used for measurements less than 100 cm or 0.1 bar or 10 kPa. A pressure plate or pressure membrane apparatus is needed in the higher suction range. These instruments permit the application of successive suction values as and the repeated measurement of the equilibrium soil wetness at each suction.

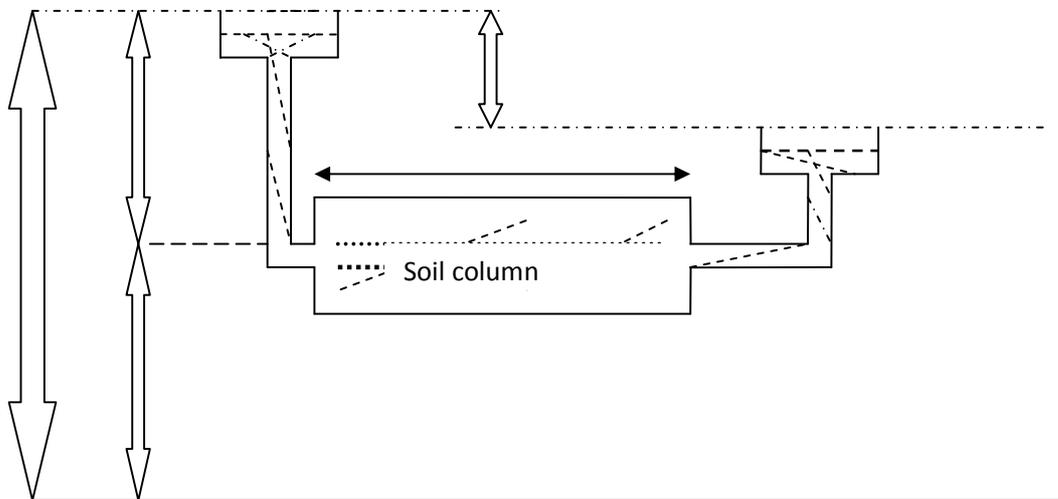
Ceramic plates generally do not hold pressures greater than about 2000 kPa but cellulose acetate membranes can be used with pressures exceeding 10000 kPa.

Soil moisture retention in the low suction range (0-100 kPa) is strongly influenced by soil structure and pore-size distribution. Hence, measurements made with disturbed sample cannot be said to represent field conditions.

### **WATER FLOW IN SATURATED SOIL**

Soil pores are highly irregular, tortuous and intricate with the consequence that the geometry of the pores restrict flow of water compared to what it would have been in straight tubes. However, the detailed flow pattern of water in soil is ignored, and it is treated as if it were a uniform medium, with flow spread over the entire cross section.

Consider the flow of water through a horizontal column of soil;



A steady flow of water is occurring from left to right, from an upper reservoir to a lower one, in each of which the water level is maintained constant.

The discharge rate,  $Q$ , being the volume  $V$  flowing through the column per unit time is directly proportional to the cross-sectional area and to the hydraulic head drop  $\Delta H$ , and inversely proportional to the length of the column:

$$Q = V/t \propto A \Delta H/L$$

$\Delta H$  is determined by measuring the head at the inflow boundary  $H_i$  and at the outflow  $H_o$ , relative to some reference level.  $\Delta H = H_i - H_o$

There will be no flow if  $\Delta H = 0$ .

The head drop per unit distance in the direction of flow ( $\Delta H/L$ ) is the hydraulic gradient, which is the driving force. The specific discharge rate  $Q/A$  (i.e., the volume of water flowing through a unit cross-sectional area per unit time  $t$ ) is called flux density (or simply flux) and is indicated by  $q$

$$Q = Q/A = Q = V/At \propto \Delta H/L$$

The proportionality factor  $K$  is generally designated as the hydraulic conductivity:

$$q = K \Delta H/L$$

This equation is known as Darcy's Law, after Henri Darcy, a French engineer

State verbally, this law indicates that the flow of a liquid through a porous medium is in the direction of, and at a rate proportional to, the driving force acting on the liquid (i.e., hydraulic gradient) and also proportional to the property of the conducting medium to transmit the liquid (namely, conductivity).

Where flow is not steady, i.e., the flux changes with time, or the soil non-uniform, the hydraulic head may not decrease linearly along the direction of flow

### Gravitational, Pressure, and Total Hydraulic Heads

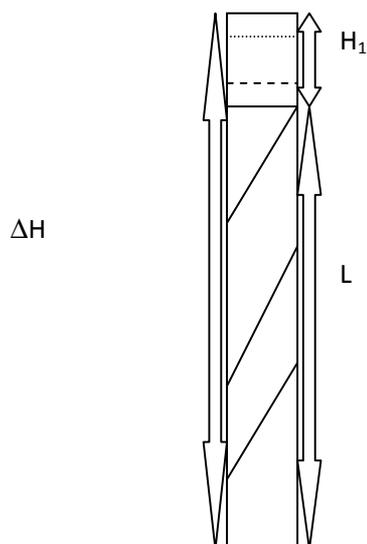
Water flow in a horizontal column occurs in response to a pressure head gradient. Flow in a vertical column can be caused by gravitation as well as pressure. The gravitational head  $H_g$  at any point is determined by the height of the point relative to some reference plane, while the pressure head is determined by the height of water column resting on that point.

The total hydraulic head  $H$  is composed of these two heads:

$$H = H_p + H_g$$

Flow in a vertical column

$$Q = K \Delta H/L = K(H_1 + L)/L = KH_1/L + K$$



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