Unit - I

INTRODUCTION TO SOIL MECHANICS

The term "**soil**" is defined as the un-cemented aggregate (or granular material) of mineral grains and decayed organic matter along with the liquid and gas that occupy empty spaces between the solid particles.

It is a material that can be:

- **built on:** foundations of buildings, bridges
- **built in:** basements, culverts, tunnels
- **built with:** embankments, roads, dams
- **supported:** retaining walls

Soil Mechanics is the branch of engineering of Civil Engineering that deals with the engineering properties of the soil and its behavior under stresses and strains.

Soil Mechanics is the application of laws of mechanics and hydraulics to engineering problems dealing with sediments and other unconsolidated accumulations of solid particles, which are produced by the mechanical and chemical disintegration of rocks, regardless of whether or not they contain an admixture of organic constituents.

Soil consists of a multiphase aggregation of solid particles, water, and air. This fundamental composition gives rise to unique engineering properties, and the description of its mechanical behavior requires some of the most classic principles of engineering mechanics.

Engineers are concerned with soil's mechanical properties: permeability, stiffness, and strength. These depend primarily on the nature of the soil grains, the current stress, the water content and unit weight.

FORMATION OF SOILS

In the Earth's surface, rocks extend upto as much as 20 km depth. The major rock types are categorized as igneous, sedimentary, and metamorphic.

- **Igneous rocks**.

  Igneous rocks are formed from the solidification of molten rock material. There are two basic types.

  Intrusive igneous rocks crystallize below Earth's surface and the slow cooling that occurs there allows large crystals to form. Examples of intrusive igneous rocks are diorite, gabbro, granite, pegmatite, and peridotite.

  Extrusive igneous rocks erupt onto the surface where they cool quickly to form small crystals. Some cool so quickly that they form an amorphous glass. These rocks include andesite, basalt, obsidian, pumice, rhyolite, scoria, and tuff.

  Based on silica content igneous rocks may be classified as acidic or basic. **Acid igneous rocks** are those with high silica contents. They are light colored. Rhyolite and the granites are typical acid igneous rocks. **Basic igneous rocks** are those with less silica content. Basic igneous rocks include basalt, dolerite and gabbro.

- **Sedimentary rocks**

  Sedimentary rocks are formed by the accumulation of sediments. **Clastic sedimentary rocks** such as breccia, conglomerate, sandstone, siltstone, and shale are formed from mechanical weathering debris. **Chemical sedimentary rocks**, such as rock salt, iron ore, chert, flint, some dolomites, and some limestones, form when dissolved materials precipitate from solution. **Organic sedimentary rocks** such as coal, some dolomites, and some limestones, form from the accumulation of plant or animal debris.

- **Metamorphic rocks**

  Metamorphic rocks are formed by the alteration of existing rocks by heat, pressure and chemical processes, usually while buried deep below Earth's surface. Exposure to these extreme conditions has alters the mineralogy, texture and chemical composition of the rocks.

  There are two basic types of metamorphic rocks. **Foliated metamorphic rocks** such as gneiss, phyllite, schist, and slate have a layered or banded appearance that is produced by exposure to heat and directed pressure. **Non-foliated metamorphic rocks** such as hornfels, marble, quartzite, and novaculite do not have a layered or banded appearance.

The nature and structure of a given soil depends on the processes and conditions that formed it:

- **Breakdown** of parent rock: weathering, decomposition, erosion.
- **Transportation** to site of final deposition: gravity, flowing water, ice, wind.
- **Environment** of final deposition: flood plain, river terrace, glacial moraine, lacustrine or marine.
- **Subsequent conditions** of loading and drainage: little or no surcharge, heavy surcharge due to ice or overlying deposits, change from saline to freshwater, leaching, contamination.

All soils originate, directly or indirectly, from different rock types.

Physical weathering reduces the size of the parent rock material, without any change in the original composition of the parent rock. Physical or mechanical processes taking place on the earth's surface include the actions of water, frost, temperature changes, wind and ice. They cause disintegration and the products are mainly coarse soils.

The main processes involved are exfoliation, unloading, erosion, freezing, and thawing. The principal cause is climatic change. In exfoliation, the outer shell separates from the main rock. Heavy rain and wind cause erosion of the rock surface. Adverse temperarture changes produce fragments due to different thermal coefficients of rock minerals. The effect is more for freeze-thaw cycles.

Chemical weathering not only breaks up the material into smaller particles but alters the nature of the original parent rock itself. The main processes responsible are hydration, oxidation, and carbonation. New compounds are formed due to the chemical alterations.

Rain water that comes in contact with the rock surface reacts to form hydrated oxides, carbonates and sulphates. If there is a volume increase, the disintegration continues. Due to leaching, water-soluble materials are washed away and rocks lose their cementing properties.

Chemical weathering occurs in wet and warm conditions and consists of degradation by decomposition and/or alteration. The results of chemical weathering are generally fine soils with altered mineral grains.

The effects of weathering and transportation mainly determine the basic ***nature*** of the soil (size, shape, composition and distribution of the particles).

The environment into which deposition takes place, and the subsequent geological events that take place there, determine the ***state*** of the soil (density, moisture content) and the ***structure*** or fabric of the soil (bedding, stratification, occurrence of joints or fissures).

Transportation agencies can be combinations of gravity, flowing water or air, and moving ice. In water or air, the grains become sub-rounded or rounded, and the grain sizes get sorted so as to form poorly-graded deposits. In moving ice, grinding and crushing occur, size distribution becomes wider forming well-graded deposits.

In running water, soil can be transported in the form of suspended particles, or by rolling and sliding along the bottom. Coarser particles settle when a decrease in velocity occurs, whereas finer particles are deposited further downstream. In still water, horizontal layers of successive sediments are formed, which may change with time, even seasonally or daily.

Wind can erode, transport and deposit fine-grained soils. Wind-blown soil is generally uniformly-graded.

A glacier moves slowly but scours the bedrock surface over which it passes.

Gravity transports materials along slopes without causing much alteration.

Soils as they are found in different regions can be classified into two broad categories:

(1) Residual soils
(2) Transported soils

Residual Soils
Residual soils are found at the same location where they have been formed. Generally, the depth of residual soils varies from 5 to 20 m.

Chemical weathering rate is greater in warm, humid regions than in cold, dry regions causing a faster breakdown of rocks. Accumulation of residual soils takes place as the rate of rock decomposition exceeds the rate of erosion or transportation of the weathered material. In humid regions, the presence of surface vegetation reduces the possibility of soil transportation.

As leaching action due to percolating surface water decreases with depth, there is a corresponding decrease in the degree of chemical weathering from the ground surface downwards. This results in a gradual reduction of residual soil formation with depth, until unaltered rock is found.

Residual soils comprise of a wide range of particle sizes, shapes and composition.

Transported Soils

Weathered rock materials can be moved from their original site to new locations by one or more of the transportation agencies to form transported soils. Tranported soils are classified based on the mode of transportation and the finaldeposition environment.

(a) Soils that are carried and deposited by rivers are called ***alluvial deposits.***

(b) Soils that are deposited by flowing water or surface runoff while entering a lake are called ***lacustrine deposits.***Atlernate layers are formed in different seasons depending on flow rate.

(c) If the deposits are made by rivers in sea water, they are called ***marine deposits.*** Marine deposits contain both particulate material brought from the shore as well as organic remnants of marine life forms.

(d) Melting of a glacier causes the deposition of all the materials scoured by it leading to formation of ***glacial deposits.***

(e) Soil particles carried by wind and subsequently deposited are known as ***aeolian deposits.***

Soils are formed from materials that have resulted from the disintegration of rocks by various processes of physical and chemical weathering. Rocks get disintegrated into boulder, gravel, sand, silt and clay with reducing particle size.

Rocks, whose chief mineral is quartz mineral with high silica content, decompose to predominantly sandy or gravelly soil with little clay. *Acidic rocks decompose to sands and gravels*. *Basic rocks decompose to fine textured silt and clayey soils*. Clays are not small fragments of the original materials that existed in the parent rocks, but they are the result of primary rock forming minerals decomposing to form secondary minerals.

CHAPTER 2

PHASE RELATION OF SOILS

Soil is not a coherent solid material like steel and concrete, but is a particulate material. Soils, as they exist in nature, consist of solid particles (mineral grains, rock fragments) with water and air in the voids between the particles. The water and air contents are readily changed by changes in ambient conditions and location.

As the relative proportions of the three phases vary in any soil deposit, it is useful to consider a soil model which will represent these phases distinctly and properly quantify the amount of each phase. A schematic diagram of the three-phase system is shown in terms of weight and volume symbols respectively for soil solids, water, and air. The weight of air can be neglected.

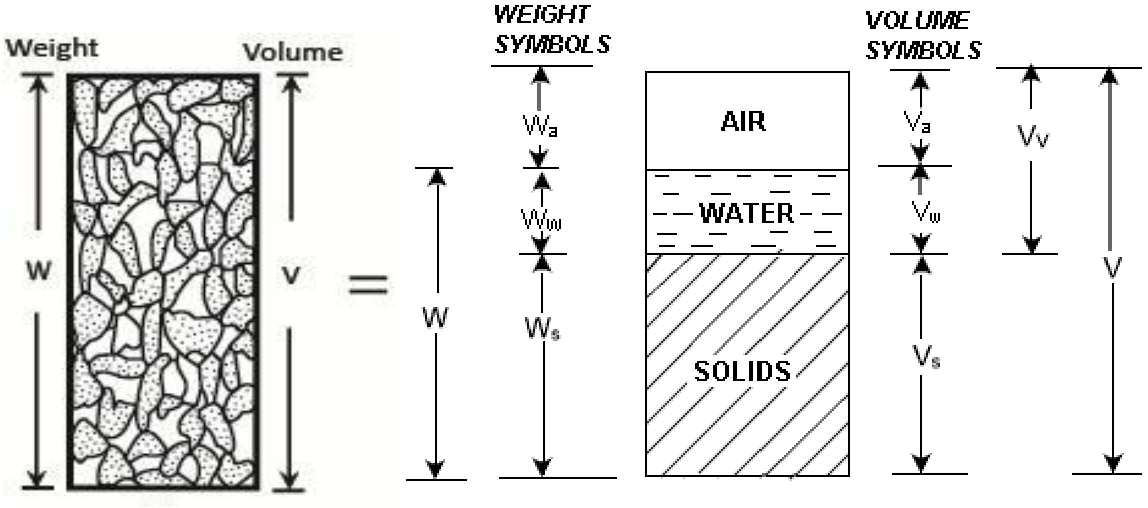


Fig. 2.1

The soil model is given dimensional values for the solid, water and air components.

Total volume, $V = V_s + V_w + V_v$; total weight, $W = W_w + W_s$

Also $V_v = V_a + V_w$

where V_s = Volume of soil solids

V_w = Volume of water

V_a = Volume of air

V_v = Volume of voids

W_w = Weight of water

W_s = Weight of soil solids

The weight of air (W_a) is assumed to be zero.

Soils can be partially saturated (with both air and water present), or be fully saturated (no air content) or be perfectly dry (no water content).

In a saturated soil or a dry soil, the three-phase system thus reduces to two phases only, as shown.

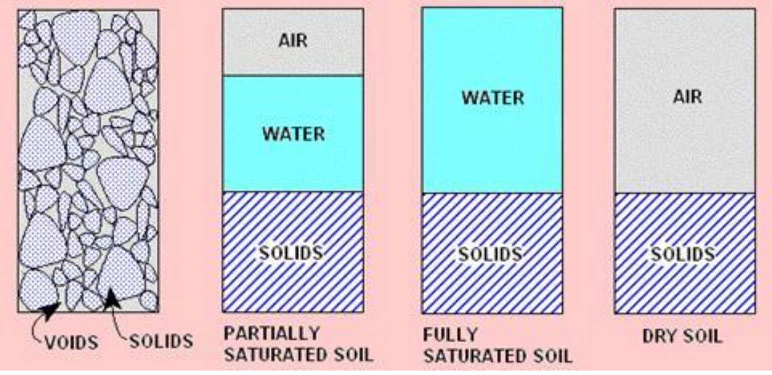


Fig. 2.2

For the purpose of engineering analysis and design, it is necessary to express relations between the weights and the volumes of the three phases.

The various relations can be grouped into:

- **Volume relations**
- **Weight relations**
- **Inter-relations**

VOLUME RELATIONS

As the amounts of both water and air are variable, the volume of solids is taken as the reference quantity. Thus, several relational volumetric quantities may be defined. The following are the **basic volume relations:**

1. Void ratio (e) is the ratio of the volume of voids (V_v) to the volume of soil solids (V_s), and is expressed as a decimal.

$$e = \frac{V_v}{V_s} \tag{2.1}$$

Even though the individual void sizes are larger in coarse-grained soils, the void ratios of fine-grained soils are generally higher than those of coarse-grained soils. In general, it can be written that e > 0, since a soil has to contain some voids but there cannot be an upper limit to the void volume.

2. Porosity (n) is the ratio of the volume of voids to the total volume of soil (V), and is expressed as a percentage.

$$n\ (\%) = \frac{V_v}{V} x\ 100 \tag{2.2}$$

Porosity of a soil cannot exceed 100 percent. Thus it can be written as 0 < n < 100.

3. Relation between e and n.

$$V = V_v + V_s$$

$$\therefore\ n = \frac{V_v}{V_v + V_s}$$

$$n = \frac{\frac{V_v}{V_s}}{\frac{V_s}{V_s} + \frac{V_v}{V_s}}$$

or $n = \frac{e}{1+e}$
(2.3)

also, $e = \frac{n}{1-n}$ (2.4)

In soil mechanics, void ratio is more favoured for use. This is due to the fact that any change in the volume of soil mass is a direct consequence of a similar change in volume of voids while the volume of solids remain the same. Hence, it is more convenient to use void ratio in which only the numerator (V_v) changes when the volume of a soil changes while in porosity, both the numerator (V_v) and the denominator (V) change.

4. The volume of water (V_w) in a soil can vary between zero (i.e. a dry soil) and the volume of voids. This can be expressed as the **degree of saturation (S)** in percentage.

$$S(\%) = \frac{V_w}{V_v} x100 \tag{2.5}$$

For a dry soil, S = 0%, and for a fully saturated soil, S = 100%. For a partially saturated soil, 0 ≤ S ≤ 100.

5. Air content (a_c) is the ratio of the volume of air (V_a) to the volume of voids.

$$a_c = \frac{V_a}{V_v} \tag{2.6}$$

or $$a_c = \frac{V_v - V_w}{V_v} = 1 - S \tag{2.7}$$

6. Percentage air voids (n_a) is the ratio of the volume of air voids expressed as a percentage of the total volume of soil mass.

$$n_a(\%) = \frac{V_a}{V} x 100 \tag{2.8}$$

or $$n_a = \frac{V_v}{V} x \frac{V_a}{V_v} x 100$$

or $$n_a = n a_c \tag{2.9}$$

WEIGHT RELATIONS

Density is a measure of the quantity of mass in a unit volume of material. Unit weight is a measure of the weight of a unit volume of material. Both can be used interchangeably. The units of density are ton/m^3, kg/m^3 or g/cm^3. Unit weight is expressed in kN/m^3. The following are the **basic weight relations:**

1. Water content (w): The ratio of the mass of water present to the mass of solid particles is called the **water content (w)**, or sometimes the **moisture content.**

$$w = \frac{W_w}{W_s} x 100 \tag{2.10}$$

Its value is 0% for dry soil and its magnitude can exceed 100%. In general, it may be written as $w \geq 0$, since there can be no upper limit to water content.

2. Particle unit weight or Unit weight of soil solids (γ_s): It is the ratio of the weight of soil solids to the volume of soil soilds. It is also expressed in terms of **specific gravity** (**G_s**) of the soil grain solids.

$$\gamma_s = \frac{W_s}{V_s} \tag{2.11}$$

$$\gamma_s = G_s \gamma_w \tag{2.12}$$

where γ_w = Unit weight of water

For most inorganic soils, the value of G_s lies between 2.60 and 2.80. The presence of organic material reduces the value of G_s.

3. Dry unit weight (γ_d): Dry unit weight is a measure of the amount of solid particles per unit of total volume.

$$\gamma_d = \frac{W_s}{V} \tag{2.13}$$

The dry unit weight is used as a measure of denseness of a soil. A high value of dry unit weight indicates that more solids are packed ina unit volume of the soil and hence a more compact soil.

4. Bulk unit weight (γ_t or γ): Bulk unit weight is a measure of the amount of solid particles plus water per unit total volume.

$$\gamma_t = \gamma = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_w + V_a} \quad (2.14)$$

5. Saturated unit weight (γ_{sat}) is equal to the bulk density when the total voids are filled up with water.

$$\gamma_{sat} = \frac{W_{sat}}{V} \quad (2.15)$$

6. Buoyant unit weight or **submerged unit weight** or **effective unit weight** (γ'): It is the effective weight per unit volume when the soil is submerged below standing water or below the ground water table.

$$\gamma' = \gamma_{sat} - \gamma_w \quad (2.16)$$

$$\gamma' \cong \frac{1}{2}\gamma_{sat}$$

When a soil mass is submerged below the ground water table, a buoyant force acts on the soil solids which is equal in magnitude to the weight of the water displaced by the solids. The net weight of solids is reduced; the reduced weight is known as the submerged weight or the buoyant weight.

7. Specific Gravity of solids (G_s): Specific gravity of solids is defined as the ratio of the weight of a given volume of solids to the weight of an equivalent volume of water at 4°C.

$$G_s = \frac{W_s}{V_s \gamma_w} \quad (2.17)$$

$$\text{as } \gamma_s = \frac{W_s}{V_s}\ ,\ G_s = \frac{\gamma_s}{\gamma_w} \quad (2.18)$$

at 4°C, $\gamma_w = 9.81$ kN/m^3.

Bulk mass density or wet mass density or bulk density or density (ρ) is defined as the total mass per unit total volume. The SI units of mass density is kg/m$^{3.}$

Relation between unit weight (γ) and Density(ρ)

$$\gamma = \frac{W}{V} = \frac{M.g}{V} = \rho g \quad (2.19)$$

g = acceleration due to gravity = 9.81 m/s^2.

Thus, unit weight in N/m^3 = mass density in kg/m^3 x 9.81

For example, $\rho_w = 1000$ kg/m^3

Therefore, $\gamma_w = 1000 \times 9.81 = 9810$ N/m^3 or $\gamma_w = 9.81$ kN/m^3.

Other definitions involving density

Mass density of solids (ρ_s)	$\rho_s = \dfrac{M_s}{V_s}$
Dry mass density (ρ_d)	$\rho_d = \dfrac{M_s}{V}$
Bulk mass density (ρ)	$\rho = \dfrac{M}{V}$
Saturated mass density (ρ_{sat})	$\rho_{sat} = \dfrac{M_{sat}}{V}$
Submerged mass density (ρ')	$\rho' = \dfrac{M_{sub}}{V}$
	$\rho' \cong \dfrac{1}{2}\rho'$

BASIC RELATIONSHIPS

Basic relationships can be established from the basic definitions of one of the key parameters involved. Alternatively, they can also be established using two approaches

(i) Specific volume approach ($V_s = 1$)
(ii) Unit volume approach ($V = 1$)

In specific volume approach, the volume of solids is taken as unity, while in unit volume approach, the total volume is taken as unity.

1. Relation between W_s, W and w

$$W = W_w + W_w$$

$$\text{or } W = W_s\left(1 + \frac{W_w}{W_s}\right) = W_s(1 + w)$$

$$\text{or } W_s = \frac{W}{1+w} \tag{2.20}$$

2. Relation between e, w, G_s and S

$$e = \frac{V_v}{V_s} = \frac{V_v}{V_w} x \frac{V_w}{V_s}$$

$$= \frac{V_v}{V_w} x \frac{W_w/\gamma_w}{W_s/\gamma_s}$$

$$= \frac{V_v}{V_w} x \frac{W_w}{W_s} x \frac{G_s \gamma_w}{\gamma_w}$$

$$= \frac{1}{S} . wG_s$$

or $eS = \ wG_s$ (2.21)

3. Relation between γ, G$_s$, e, w and γ_w

$$\gamma = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{W_s(1 + W_w/W_s)}{V_s(1 + V_V/V_s)}$$

$$= \ \gamma_s \frac{1+w}{1+e}$$

or $\gamma = G_s \gamma_w \left(\frac{1+w}{1+e}\right)$ (2.22)

since $w = \frac{eS}{G_s}$, $\ \gamma = \gamma_w \left(\frac{G_s + eS}{1+e}\right)$

when the soil is dry, $S = 0 \ and \ \gamma = \ \gamma_d$

therefore, $\gamma_d = \frac{G_s \gamma_w}{1+e}$ (2.23)

Substituting for *e* from eq. 2.21 in eq. 2.23

$$\gamma_d = \frac{G_s \gamma_w}{1 + \frac{wG_s}{S}}$$

When the soil becomes fully saturated (*S* = 1) at a given water content, the dry unit weight for such a condition is known as “***Zero Air Voids Unit Weght”*** and is given by

$$\gamma_d = \frac{G_s \gamma_w}{1 + wG_s} \quad (2.24)$$

The zero air voids unit weight given eq. 2.24 is useful in the study of compaction behavior of soils.

when the soil is saturated, $S = 1 \ and \ \gamma = \gamma_{sat}$

therefore, $\gamma_{sat} = \gamma_w \left(\frac{G_s + e}{1+e}\right)$ (2.25)

also $\gamma' = \gamma_{sat} - \gamma_w$

therefore, $\gamma' = \gamma_w \left(\frac{G_s + e}{1+e}\right) - \gamma_w$

or $$\gamma' = \gamma_w \left(\frac{G_s - 1}{1+e}\right) \tag{2.26}$$

4. Relation between γ_d, γ and w

$$\gamma = \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{W_s(1 + W_w/W_s)}{V}$$

$$= \gamma_d(1+w)$$

or $$\gamma_d = \frac{\gamma}{1+w} \tag{2.27}$$

5. Relation between γ_d, G_s, w and n_a

$$V = V_s + V_w + V_a$$

$$1 = \frac{V_s}{V} + \frac{V_w}{V} + \frac{V_a}{V}$$

$$= \frac{V_s}{V} + \frac{V_w}{V} + n_a$$

$$1 - n_a = \frac{V_s}{V} + \frac{V_w}{V}$$

$$= \frac{W_s/G_s\gamma_w}{V} + \frac{W_w/\gamma_w}{V}$$

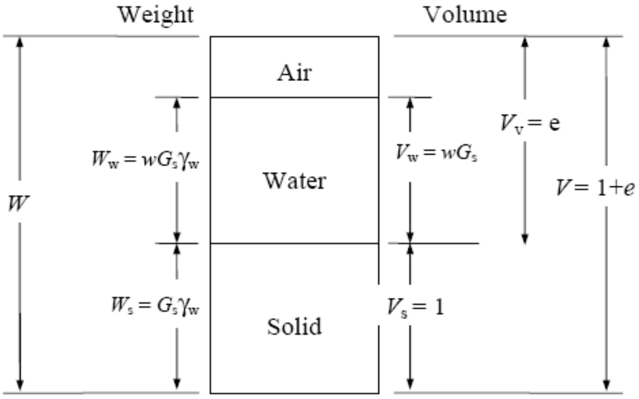
$$= \frac{\gamma_d}{G_s\gamma_w} + \frac{wW_s/\gamma_w}{V} = \frac{\gamma_d}{G_s\gamma_w} + \frac{w\gamma_d}{\gamma_w}$$

or $$\gamma_d = \frac{(1-n_a)G_s\gamma_w}{1+wG_s} \tag{2.28}$$

Phase diagrams for specific volume approach (V_s = 1) and unit volume approach (V =1)

Specific volume approach for a partially saturated soil

1. **Relation between e and n**



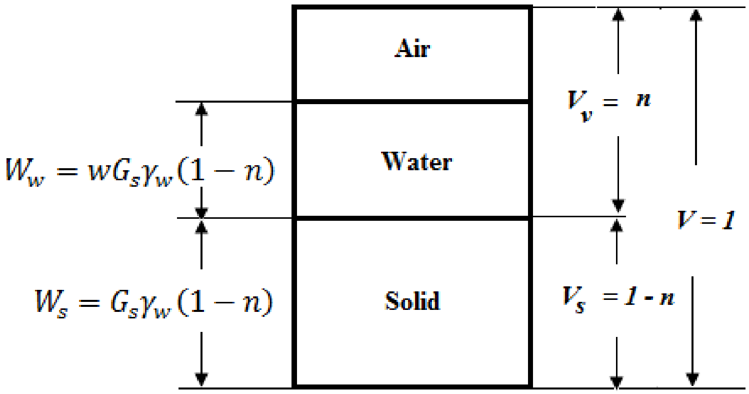


Fig. 2.3: (a) (b)

Figure 2.3 (a) shows the three phase diagram in which the volume of solids is taken as unity and (b) shows the three phase diagram in which total volume is taken as unity.

From the definition of void ratio, *e*

$$e = \frac{V_v}{V_s}$$, since $V_s = 1$, $e = V_v$ and total volume $V = 1 + e$

Porosity, $n = \frac{V_v}{V} = \frac{e}{1+e}$

From fig.2.4 (b)

$$e = \frac{V_v}{V_s} = \frac{n}{1-n}$$

In a total volume of soil equal to (1 + e), the volume of solids is 1 and the volume of voids is e. Thus, if the total volume of a soil is V,

$$V_s = \frac{V}{1+e} \quad \text{and} \quad V_v = \frac{e}{1+e}.V$$

2. **Relation between e, S, w and G_s**

$$V_s = 1;\ V_v = e;\ V_w = Se$$

$$W_{s=}V_s\ x\ \gamma_s = 1\ x\ G_s\gamma_w$$

$$W_w = V_w\ x\ \gamma_w = eS\gamma_w$$

$$W_w = w.W_s = wG_s\gamma_w$$

$$w = \frac{W_w}{W_s} = \frac{eS\gamma_w}{G_s\gamma_w}\ or\ w = \frac{eS}{G_s}$$

3. **Relation between γ, G_s, e, w and γ_w**

$$\gamma = \frac{W}{V} = \frac{W_s+W_w}{V_s+V_v} = \frac{G_s\gamma_w+eS\gamma_w}{1+e}\ or\ \frac{G_s\gamma_w+wG_s\gamma_w}{1+e}$$

or $\gamma = \left(\frac{G_s+eS}{1+e}\right)\gamma_w = \frac{G_s\gamma_w(1+w)}{1+e}$

Specific volume approach for a fully saturated soil

4. **Relation between γ_{sat}, G_s, e and γ_w**

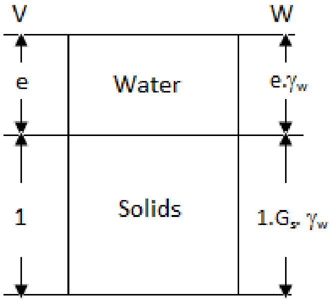


Fig. 2.4

$$\gamma_{sat} = \frac{W}{V} = \frac{W_s+W_w}{V_s+V_v} = \frac{G_s\gamma_w+e\gamma_w}{1+e}$$

$$\gamma_{sat} = \left(\frac{G_s+e}{1+e}\right)\gamma_w$$

Specific volume approach for a fully dry soil

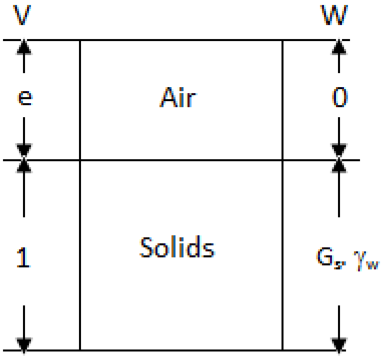


Fig.2.5

5. Relation between γ_d, G_s, e and γ_w

$$\gamma_d = \frac{W}{V} = \frac{W_s}{V} = \frac{W_s}{V_s+V_v}$$

$$\gamma_d = \frac{G_s\gamma_w}{1+e}$$

Typical porosity, void ratio, and unit weight values for soils in their natural state (after Peck, Hanson, and Thornburn, 1974)

Soil Type	Porosity	Void Ratio	Water Content	γ_d kN/m^3	γ_{sat} kN/m^3
Uniform sand (loose)	0.46	0.85	32%	14.1	18.5
Uniform sand (dense)	0.34	0.51	19%	17.1	20.4
Well-graded sand (loose)	0.40	0.67	25%	15.6	19.5
Well-graded sand (dense)	0.30	0.43	16%	18.2	21.2
Windblown silt (loose)	0.50	0.99	21%	13.4	18.2

Glacial till	0.20	0.25	9%	20.7	22.8
Soft glacial clay	0.55	1.2	45%	11.9	17.3
Stiff glacial clay	0.37	0.6	22%	16.7	20.3
Soft slightly organic clay	0.66	1.9	70%	9.1	15.4
Soft very organic clay	0.75	3.0	110%	6.8	14.0
Soft montmorillonitic clay	0.84	5.2	194%	4.2	12.6

Typical values of Specific Gravity of Soil Solids (G_s)

Soil Type	**Specific Gravity**
Clean sands and gravel	2.65 - 2.68
Silt and silty sands	2.66 - 2.70
Inorganic clays	2.70 - 2.80
Soils high in mica and iron	2.75 - 2.85
Organic soils	Quite variable May fall below 2.0

Plasticity of Soils

The plasticity of a soil is its ability to undergo deformation without cracking or fracturing. Plasticity is an important index property of fine grained soils, especially clayey soils. Plasticity is due to the presence of clay minerals.

The clay particles carry a negative charge on their surfaces. The water molecules are dipolar (dipoles) and are attracted towards the clay surface. This phenomenon is known as adsorption of water. The water so attracted to the clay surface is called adsorbed water. Plasticity of the soil is due to adsorbed water. Adsorbed water cannot be removed by oven drying and is considered to be part of the soil particles.

The clay particles are separated by layers of adsorbed water which allow them to slip over one another. When the soil is subjected to deformations, the particles do not return to their original positions. Thus the deformations are plastic or irreversible.

The presence of adsorbed water is necessary to impart plasticity characteristics to the soil. The soil does not become plastic when it is mixed with a non-polarizing liquid such as kerosene or paraffin oil.

Consistency

The consistency of a fine grained soil is the physical state in which the soil exists. Consistency is the degree of firmness of a soil and is often directly related to strength.

As the water content reduced from a soil from the stage of almost a suspension, the soil passes through states of consistency.

The water contents at which the soil changes from one state to the other are known as consistency limits or Atterberg's limits.

Atterberg mentioned that a fine grained soil can exist in four states – liquid, plastic, semi-solid and solid state.

The water content alone is not an important index property of a soil. At the same water content, one soil may be relatively soft, whereas another may be hard. However, soils with the same consistency limits behave somewhat in a similar manner.

A soil containing high water content is in a liquid state. It has no shear resistance, and therefore, the shear strength is equal to zero. As the water content is reduced, the soil becomes stiffer and starts developing resistance to shear deformation. At some water content the soil becomes plastic.

The water content at which the soil changes from liquid state to plastic state is known as Liquid Limit (LL or w_L). At the liquid limit, the soil ceases to be a liquid and possesses a small shearing strength.

Plastic limit (w_P) the arbitrary limit of water content at which the soil tends to pass from the plastic state to the semi-solid state of consistency.

Liquid limit and plastic limit are known as Atterberg limits

The numerical difference between liquid limit and plastic limit is known as Plasticity Index (PI or I_P). It is the range in which the soil is in a plastic state.

$$PI = LL - PL$$

The soil remains plastic when the water content is between liquid limit and plastic limit.

When the water content is reduced below the plastic limit, the soil attains a semi-solid state. The soil cracks when moulded. At the plastic limit, the soil loses its plasticity.

In the semi-solid state, the volume of the soil decreases with a decrease in water content till a stage is reached when further reduction of water content does not cause any reduction in the volume of the soil. The soil is said to have reached a solid state.

The water content at which a soil changes from semi-solid state to solid state is known as shrinkage limit (SL or w_S). Below the shrinkage limit, the soil does not remain saturated.

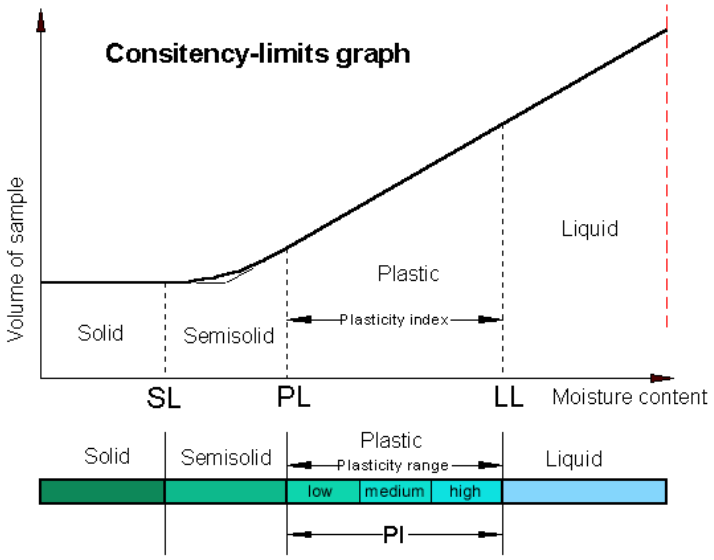
Shrinkage limit is the water content at which the soil stops shrinking further and attains a constant volume. It is also defined as the maximum water content at which a reduction of water content will not cause a decrease in the volume of the soil mass.

The shrinkage limit may also be defined as the lowest water content at which the soil is fully saturated.

Water Content

Phase	Solid State	Semi-Solid State	Plastic State	Liquid State	Suspension
Description	Hard to Stiff	Workable	Sticky	Slurry	Water-held suspension

Shear Strength (kPa)



Plasticity Index	Plasticity
0	Non-Plastic
1 -5	Slight
5 – 10	Low
10 -20	Medium
20 – 40	High
>40	Very High

Shrinkage Index (SI or I_s)

Shrinkage Index is defined as the difference between the plastic limit and shrinkage limit. It is the range in which the soil is in a semi-solid state of consistency.

$$SI = PL - SL$$

Consistency Index (CI or I_C)

Consistency Index is the ratio of the difference between liquid limit and the natural water content to the plasticity index of the soil.

$$I_C = \frac{w_L - w}{I_P}$$

w = natural water content of the soil.

If $I_C = 0$, $w = w_L$

$I_C = 1$, $w = w_P$

$I_C > 0$, the soil is in semi-solid state and is stiff

$I_C < 0$, the natural water content is greater than LL, and the soil behaves like a liquid.

Liquidity Index (LI or I_L)

Liquidity Index or water-plasticity ratio is the ratio of the difference between natural water content and the plastic limit to the plasticity index.

$$I_L = \frac{w - w_P}{I_P}$$

Below plastic range, LI is negative.

If $I_L = 0$, w = PL
$I_L = 1$, w = LL
$I_L > 1$, the soil is in a liquid state
$I_L < 0$, the soil is in semi-solid state and is stiff.

$$I_L + I_C = 1$$

Determination of Liquid Limit

Liquid limit is determined in the laboratory by Casagrande apparatus. The device consists of a brass cup which drops through a height of 1 cm on a hard base when operated by the handle. The device is operated by turning the handle which raises the cup and lets it drop on the rubber base.

About 120 g of air-dried sample passing through 425 µ sieve is taken in a dish and mixed with distilled water to form a uniform paste.

The paste is place in the cup of the liquid limit device and the surface is smoothened and leveled with a spatula to a maximum depth of 1 cm.

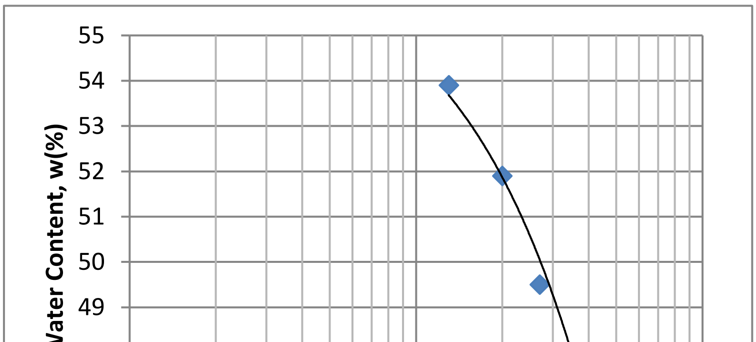
With a Casagrande tool, a groove is cut through the sample along the symmetrical axis of the cup, preferably in stroke.

The handle is turned at the rate of 2 revolutions per second until the two parts of the soil sample come into contact at the bottom of the groove along a distance of 12 mm. The number of blows required for this is noted.

The groove should close by flow of the soil and not by slippage between the soil and the cup. The test is repeated for at least 4 different water contents and the numbers of blows for each content is noted.

A plot is made between water content (y-axis, natural scale) and number of blows (x-axis, logarithmic scale). The plot is approximately a straight line known as flow curve.

The liquid limit is obtained from the plot corresponding to 25 blows.



No of Blows	Water Content
38	47.5
27	49.5
20	51.9
13	53.9

Flow Index (I_f) is the slope of the flow curve.

$$I_f = \frac{w_1 - w_2}{Log_{10} \frac{N_1}{N_2}}$$

N_1 = no of blows at water content w_1
N_2 = no of blows at water content w_2

Flow index is the rate at which a soil mass loses its shear strength with an increase in water content.

The soil with a greater value of flow index has a steeper slope and possesses lower shear strength as compared to a soil with a flatter slope.

Toughness Index (I_t) is defined as the ratio of the plasticity index to the flow index.

$$I_t = \frac{I_P}{I_f}$$

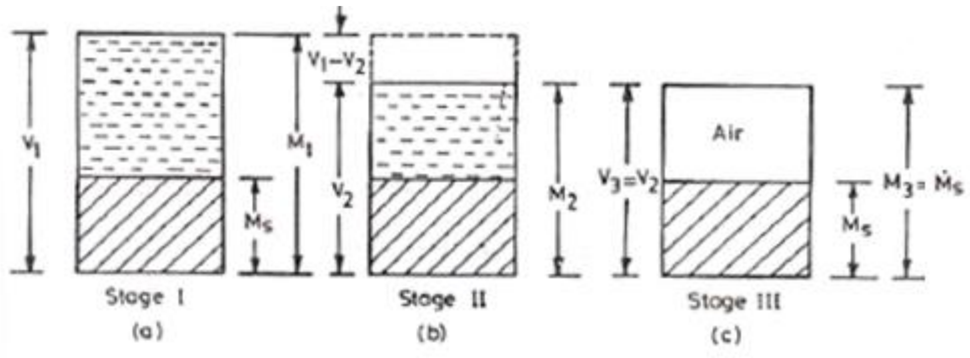
Toughness index is a measure of the shearing strength of soil at plastic limit. For most soils, toughness index lies between 0 and 3. If $I_t < 1$, it indicates that the soil is friable at the plastic limit.

Plastic limit

30 g of soil passing 425 µ sieve is taken in a dish and mixed with distilled water to form a uniform paste plastic enough to be easily shaped into a ball. The ball is rolled between fingers and a glass plate with just enough pressure to roll the soil mass into a thread of 3 mm diameter. The soil is then kneaded back to a uniform mass and rolled again. This process of rolling and kneading is continued till the thread of 3 mm diameter just begins to crumble. The pieces of crumbled threads of soils are collected and the moisture content is determined, which is the plastic limit.

Shrinkage Limit

The figure(a) below shows the block diagram of a soil sample when it is fully saturated and has the water content greater than the expected shrinkage limit. Figure (b) shows the sample at shrinkage limit. Figure (c) shows the sample after oven drying.



Let V_1 = initial volume of soil sample
V_2 = volume of soil sample at shrinkage limit
$V_3 = V_2$ = volume of completely dry soil sample
M_1 = mass of soil solids

Mass of water in stage I = $M_1 - M_s$
Loss of mass of water from stage I to stage II = $(V_1 - V_2)\rho_w$
Mass of water in stage II = $(M_1 - M_s) - (V_1 - V_2)\rho_w$
Shrinkage limit = water content in stage II

$$w_S = \frac{(M_1 - M_s) - (V_1 - V_2)\rho_w}{M_s}$$

$$w_S = w_1 - \frac{(V_1 - V_2)\rho_w}{M_s}$$

50 g of soil passing 425 µ sieve is taken for the test.

Shrinkage parameters

Shrinkage Index (I_s): Shrinkage Index is the numerical difference between liquid limit and shrinkage index.

$$I_s = w_L - w_S$$

Shrinkage Ratio (SR): Shrinkage ratio is defined as the ratio of a given volume change expressed as a percentage of dry volume, to the corresponding change in water content.

$$SR = \frac{(V_1 - V_2)/V_d}{w_1 - w_2} \ x\ 100$$

Where V_1 = Volume of soil mass at water content w_1
V_2 = Volume of soil mass at water content w_2
V_d = volume of dry soil mass

When the volume V_2 is at the shrinkage limit

$$SR = \frac{(V_1 - V_d)/V_d}{w_1 - w_S} \, x\, 100$$

Also

$$w_1 - w_s = \frac{(V_1 - V_d)\rho_w}{M_s} \, x\, 100$$

Therefore,

$$SR = \frac{\frac{(V_1 - V_d)}{V_d}}{\frac{(V_1 - V_d)\rho_w}{M_s} \, x\, 100} \, x\, 100$$

Or

$$SR = \frac{M_s}{V_d \rho_w}$$

Or

$$SR = \frac{\rho_d}{\rho_w} = G_m = Mass\ Specific\ gravity\ in\ dry\ state$$

Also

$$w_s = \left(\frac{\rho_w}{\rho_d} - \frac{1}{G}\right)$$

Therefore,

$$w_s = \left(\frac{1}{SR} - \frac{1}{G}\right)$$

Volumetric Shrinkage (VS): The Volumetric shrinkage(VS), or volumetric change, is defined as the change in volume expressed as a percentage of the dry volume when the water content is reduced from a given value to the shrinkage limit.

$$VS = \frac{(V_1 - V_d)}{V_d} \, x\, 100$$

But from the definition of shrinkage ratio

$$\frac{(V_1 - V_d)}{V_d} \, x\, 100 = SR(w_1 - w_S)$$

$$\therefore VS = SR(w_1 - w_S)$$

Linear Shrinkage (LS): Linear shrinkage (LS) is defined as the change in length divided by the initial length when the water content is reduced to the shrinkage limit. It is expressed a s percentage and reported to the nearest whole number.

$$LS = \frac{Initial\ Length - Final\ Length}{Initial\ Length}\ x\ 100$$

A soil sample of about 150 g passing through 425 µ sieve is taken in a dish. It is mixed with distilled water to form a smooth paste at water content greater than the liquid limit. The sample is placed in a brass mould, 140 mm long and with a semi-circular cross-section of 25 mm diameter.

The sample is allowed to first allowed to dry slowly in air and then in an oven. The sample is cooled and final length is measured.

$$LS = 1 - \ \frac{Length\ of\ oven\ dry\ sample}{Initial\ Length}\ x\ 100$$

It is assumed that the length of oven dry sample is the same as that at shrinkage limit.

Also

$$LS = 100\left[1 - \left(\frac{100}{VS + 100}\right)^{1/3}\right]$$

Activity

Plasticity index of a soil increases linearly with the percentage of clay-size fraction (% finer than 2 µ by mass).

Activity is the slope of the line correlating PI and % finer than 2 µ. Activity may be expressed as

$$A = \frac{PI}{\%\ of\ clay - size\ fraction\ by\ mass}$$

Activity is used as an index for identifying the swelling potential of clay soils. Higher the activity value, greater is the swelling potential.

For a soil of specific origin, the activity is constant. The PI increases a sthe amount of clay fraction increases.

Highly active minerals, such as montmorillonite, can produce a large increase in PI even when present in small quantity.

Mineral	**LL**	**PL**	**A**
Kaolinite	35-100	20-40	0.3 – 0.5
Illite	60-120	35-60	0.5 - `1.2
Montmorillonite	100-900	50-100	1.5 – 7.0
Halloysite (hydrated)	50-70	40-60	0.1 – 0.2
Halloysite(dehydrated)	40-55	30-45	0.4 – 0.6
Attapulgite	150-250	100-125	0.4 – 1.3
Allophane	200-250	120-150	0.4 – 1.3