CHAPTER 1

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.

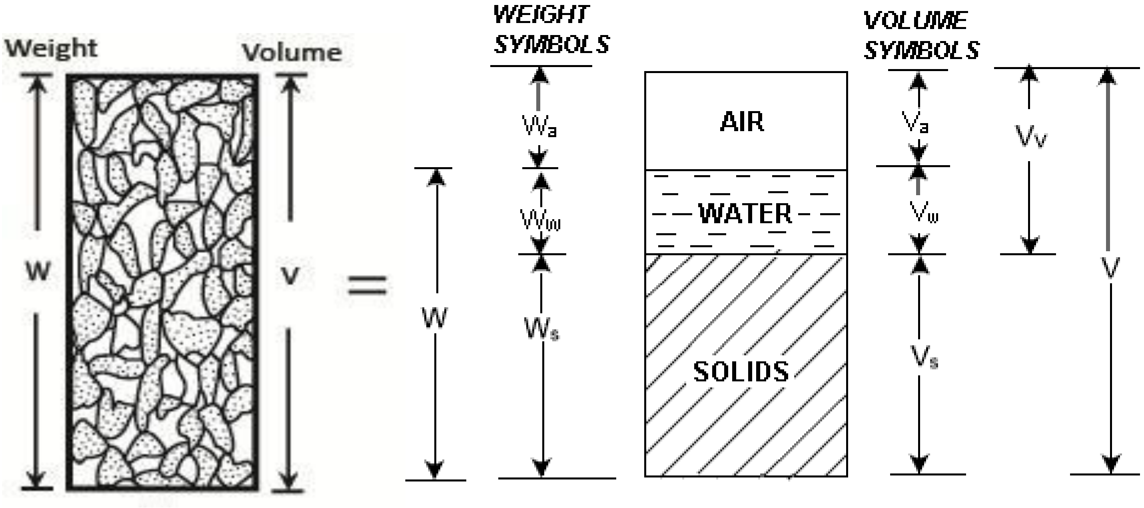


Fig. 2.1

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.

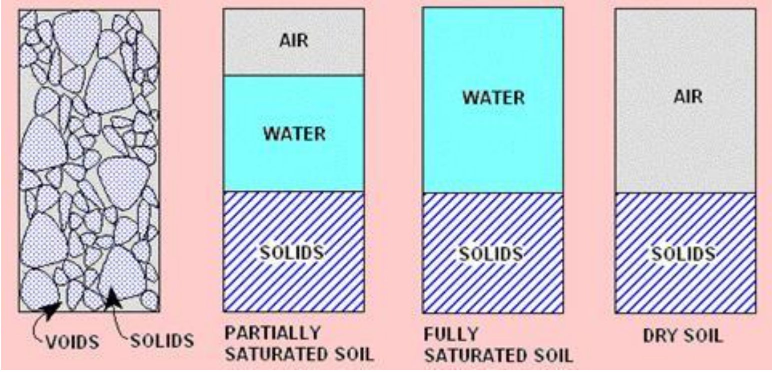


Fig. 2.2

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.

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

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

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

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.

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

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

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

$$a_c = \frac{V_a}{V_v} \qquad (2.6)$$

or $$a_c = \frac{V_v - V_w}{V_v} = 1 - S \qquad (2.7)$$

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.

$$n_a(\%) = \frac{V_a}{V} x100 \qquad (2.8)$$

or $n_a = \frac{V_v}{V} x \frac{V_a}{V_v} x100$

or $n_a = na_c \qquad (2.9)$

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.**

$$w = \frac{W_w}{W_s} x100 \qquad (2.10)$$

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.

$$\gamma_s = \frac{W_s}{V_s} \qquad (2.11)$$

$$\gamma_s = G_s \gamma_w \qquad (2.12)$$

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.

$$\gamma_d = \frac{W_s}{V} \qquad (2.13)$$

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.

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

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

$$\gamma_{sat} = \frac{W_{sat}}{V} \tag{2.15}$$

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.

$$\gamma' = \gamma_{sat} - \gamma_w \tag{2.16}$$

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

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.

$$G_s = \frac{W_s}{V_s \gamma_w} \tag{2.17}$$

$$\text{as } \gamma_s = \frac{W_s}{V_s}, \; G_s = \frac{\gamma_s}{\gamma_w} \tag{2.18}$$

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)

$$\gamma = \frac{W}{V} = \frac{M.g}{V} = \rho g \tag{2.19}$$

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, ρ_w = 1000 kg/m^3

Therefore, γ_w = 1000 x 9.81 = 9810 N/m^3 or γ_w = 9.81 kN/m^3.

Other definitions involving density

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

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

$$W = W_w + W_w$$

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

or $W_s = \frac{W}{1+w}$ (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

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

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

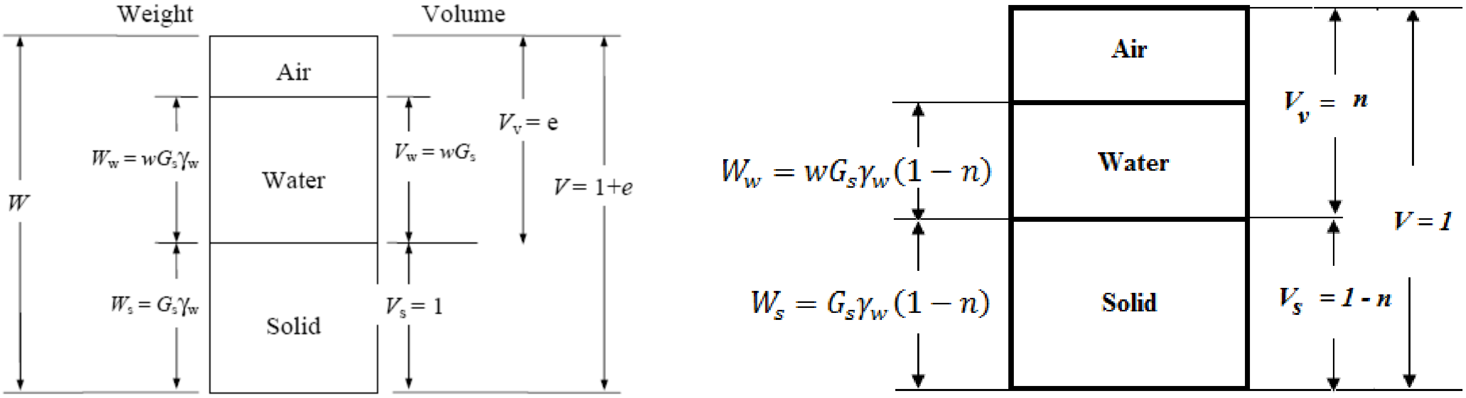


Fig. 2.3: (a) (b)

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**

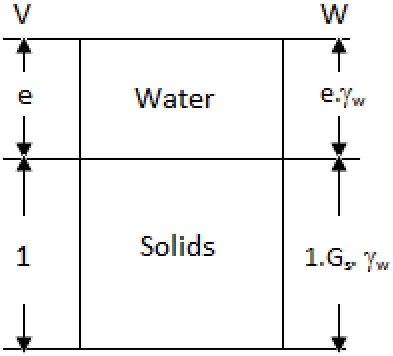


Fig. 2.4

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

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

Specific volume approach for a fully dry soil

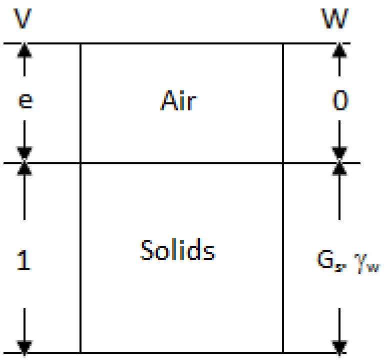


Fig.2.5

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

Index properties of soils

Index properties refer to those properties of the soil that indicate the type and condition of the soil, and provide a relationship to structural properties. Index properties are used in the identification and classification of soils. The following are the index properties of soils: (i) water content (ii) specific gravity (iii) particle shape (iv) in-situ density (v) particle size distribution (vi) consistency limits (vii) density index.

Index properties can be divided into two categories: (i) soil grain properties (ii) soil aggregate properties.

The soil grain properties are the properties of the individual particles of which the soil is composed, without reference to the manner in which these particles are arranged in a soil mass. Mineralogical composition, specific gravity of solids, size and shape of grains are soil grain properties.

The soil aggregate properties are the properties which are dependent on the soil mass as a whole and thus represent the collective behavior of soil. Soil aggregate properties are a function of stress history, mode of soil formation and the soil structure.

Determination of water content [(IS:2720 (Part – II) -1173)]

Water content of soil is an important soil parameter which influences the behavior, particularly os cohesive soils, significantly. Water content can be determined by the following methods:

i) Oven drying method
ii) Sand bath method
iii) Alcohol method
iv) Calcium carbide method
v) Pycnometer method
vi) Radiation method
vii) Torsion balance method

The standard method of determining the water content is the oven-drying method. The others are subsidiary methods.

Oven drying method:

The method consists of drying a weighed moist sample of soil in an oven at a temperature of 110 ± 5^{o}C for a period of 24 hours after which the dry weight of the sample is taken. Temperatures higher than 110^{o}C may break the crystalline structure of clay particles and result in the loss of chemically-bound water of crystallization. Lower temperature of about 60^{o}C is recommended for organic soils to avoid oxidation of organic matter present in the samples. If gypsum is present, the sample is dried at not more than 80^{o}C but for a longer time. The water content of the soil shall be reported to two significant figures.

Let,
Weight of empty can = W_1
Weight of can + moist soil = W_2
Weight of can + dry soil = W_3

Water content, $\boldsymbol{w} = \frac{W_w}{W_s} = \frac{W_2 - W_3}{W_3 - W_1}$ (3.1)

Note: The can must be covered with a lid immediately after placing the moist soil in it and then weighed to prevent moisture movement in to and out of the soil sample. The can should be placed in oven without lid. Lid of the can should be replaced when the container is taken out of the oven for weighing. A steel can is preferably used to prevent any reactions between can material, water and mineral salts present in the soil.

Calcium carbide method or Rapid moisture meter method

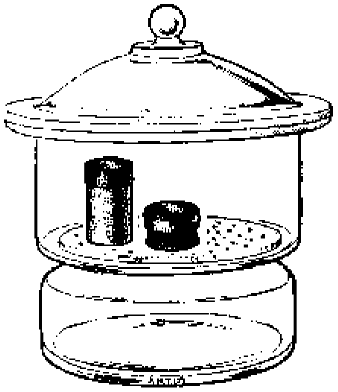

Rapid moisture meter

It is a rapid method of determination of water content of soil. It consists of an air tight container with a diaphragm and a calibrated meter. About 6 g of soil is mixed with fresh Calcium carbide. The mixture is rigorously shaken. Water in the soil reacts with Calcium Carbide to release acetylene gas. The amount of gas produced depends on available water. This gas creates a pressure on sensitive diaphragm and water content is directly recorded on the calibrated meter. The method is not very accurate, but is extremely rapid.

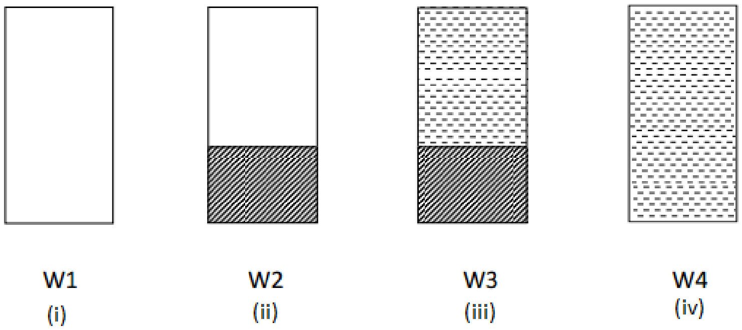
Determination of specific gravity
[IS: 2720 (Part III/Sec 1)-1980 & IS: 2720 (Part III/Sec 2)-1980]

The procedure involves weighing first an empty dried density bottle of 50 ml capacity with stopper. About 10 grams of oven dried soil passing 2 mm sieve is transferred directly from the dessicator in which it has been cooled. The weight of density bottle with dry soil is noted. Sufficient distilled water is added so that the soil in the bottle is just covered and stirred with a glass rod to remove entrapped air. The bottle is gradually filled up to the top with water, carefully removing the entrapped air. Vacuum pump may also be used to remove the entrapped air. The stoppered botlle is then weighed to the nearest 0.001 g. Finally, the density bottle is emptied completely, cleaned, dried and weighed after filling it with water up to the top.

For coarse grained a pycnometer is used with 300-400 g of oven dried soil and similar procedure outlined above is followed. Pycnometer is an approximately 900 ml capacity glass bottle provided with a conical cap. The purpose of conical top is to reduce the cross section gradually to a minimum such that any difference in level of water in different stages should not cause serious error. Further, the opening will allow any air present in the voids of soil to be expelled out.



Desiccator



Stages in the determination of specific gravity using density bottle or pycnometer

Weight of dry soil, $W_s = W_2 - W_1$
Weight of water in observation (iii) = $W_3 - W_2$
Weight of water in observation (iv) = $W_4 - W_1$
Weight of water having the same volume as that of soil solids = $(W_4 - W_1) - (W_3 - W_2)$
$= (W_2 - W_1) - (W_3 - W_4)$
$= W_s - W_3 + W_4$

Specific gravity of soil solids, $G_s = \frac{W_s}{W_s - W_3 + W_4}$
(3.2)

Specific gravity values are usually reported at 27°C. If T°C is the test temperature, the specific gravity at 27°C is given by,

$$G_{s(27^oC)} = G_{s(T^oC)} x \frac{Specific\ gravity\ of\ water\ at\ T^oC}{Specific\ gravity\ of\ water\ at\ 27^oC} \quad (3.3)$$

Determination of In-situ unit weight

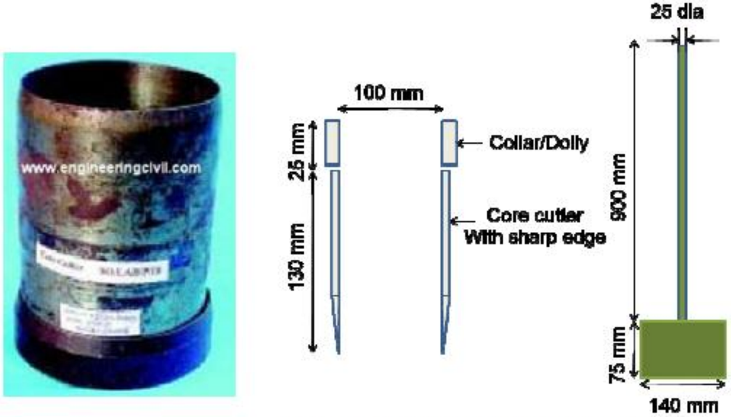
The methods commonly used for the determination of in-situ unit weight of a natural soil deposit or a compacted earth fill are:

(i) Core-cutter method
(ii) Sand replacement method
(iii) Water displacement method

Core-cutter method [IS:2720 (Part 24) – 1975]

The core-cutter method consists of driving a core-cutter of known volume (1000 cc) in to the soil after placing it on a cleaned soil surface. The core-cutter is usually provided with a 25 mm high dolly, which is mounted on top of the core-cutter and driven in to the soil with a suitable hammer. The core-cutter filled with soil is removed and the excess soil trimmed off. The core-cutter with the soil is weighed. The volume of the cutter is calculated from the dimensions of the cutter and the in-situ unit weight is determined by dividing the weight of the soil in the cutter by the volume of the cutter. Dry unit weight is then calculated after determining the water content.

Core-cutter method cannot be used in case of hard gravelly soils or cohesionless soils.



Apparatus for in-situ unit using core-cutter method

Sand replacement method [IS:2720 (Part 28) – 1974]

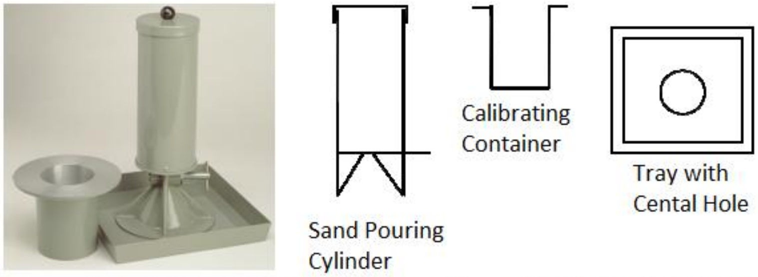
This method consists of (a) calibration of apparatus and (b) determination of soil unit weight.

(a) Calibration of apparatus

This consists of determining the weight of the sand in the cone of the pouring cylinder and determination of bulk density of sand. Clean uniformly graded natural sand passing 1 mm sieve and retained on 600 µ sieve shall be used. The sand pouring cylinder filled with sand up to 10 mm from the top is weighed (W_1) and then placed on a flat surface. The shutter is released and when no further flow of sand takes place, the shutter is closed and the sand pouring cylinder is now once again weighed (W_2). The difference (W_1 - W_2) = W_3 gives the weight of the sand in the cone of the pouring cylinder. The sand poured on flat surface is filled back in to the pouring cylinder to weigh W_1. The sand pouring cylinder is now placed centrally over the calibrating cylinder and the shutter is released to fill the calibrating cylinder and conical top. The sand pouring cylinder is now weighed (W_4) to give the weight of sand filling the calibrating cylinder and conical top (W_3). The weight of the sand filling just the calibrating cylinder is determined as ($W_4 – W_3$). The bulk unit weight of sand is obtained by dividing the weight ($W_4 – W_3$) by volume of the calibrating cylinder (determined by measuring its height and diameter).

(b) Determination of soil unit weight

The site is cleaned and a square tray with a central hole in it is placed on the cleaned surface. A hole of diameter equal to that in tray and depth of about 10-15 cm is made in the ground. The excavated soil is collected in the tray and weighed. The sand pouring cylinder filled with sand up to 10 mm from the top is weighed and then placed centrally over the hole. The shutter of the sand pouring cylinder is released and sand is allowed to run to fill the excavated hole and the conical end. When no further flow of sand takes place, the shutter is closed. Having computed the unit weight of sand, weight of sand filling the conical bottom, the weight of sand required to fill the hole is determined and thereby the volume of the hole is determined. The bulk unit weight of soil is obtained by dividing the weight of excavated soil with the volume of hole.



Apparatus for in-situ unit weight using sand replacement method

Water displacement method

This method is suitable for cohesive soil only, where it is possible to have a lump sample. A small sample is trimmed to a regular shape from a larger sample brought from the field. Weight of the trimmed moist sample is noted and then a thin layer of paraffin wax is applied all over the moist sample, to make the sample water proof. Weight of waxed sample is also noted. The waxed sample is immersed in a container with an overflow arrangement and the volume of water displaced is measured.

Let,
Weight of the trimmed moist sample = W_1
Weight of the wax coated sample = W_2
Weight of wax = $W_2 - W_1$
Unit weight of wax = γ_p
Volume of water displaced by waxed moist sample = V_w = Vol. of moist soil + Vol. of wax

Volume of moist sample alone, $\boldsymbol{V = V_w - \frac{W_2 - W_1}{\gamma_p}}$

Bulk unit weight of sample, $\boldsymbol{\gamma = \frac{W_1}{V}}$

If *w* is the moisture content of the sample, it dry unit weight is

$$\boldsymbol{\gamma_d = \frac{\gamma}{1+w}}$$

Grain shape

The shape of grains in coarse grained soils can be examined with naked eyes, whereas fine grained soils require microscopic examination. ***Bulky grains*** are characteristic of sands and gravels. All the dimensions of a bulky grain are more or less the same. Bulky grains are ***angular*** immediately after mechanical break-down of parent rock. ***Subangular*** grains result from subsequent erosion during transportation. ***Subrounded*** grains result from further erosion of subangular grains. Finally, ***rounded*** grains are formed by the erosion of subrounded grains. Alluvial sands are subangular to subrounded. River gravels and wind blown sands are usally rounded.

Flaky grains or plate shaped grains are the ones in which one dimension of grain i,e., its thickness bears no relationship with the other two lateral dimensions which are much bigger. Submicroscopic crystals of clay minerals usually exhibit this grain shape.

Needle-shaped grains are the grains in which one dimension of the grain is fully developed and is much larger than the other two. Such grains are characteristic of clay mineral kaolinite.

PARTICLE SIZE DISTRIBUTION [IS:2720 (Part 4 – 1985]

For measuring the distribution of particle sizes in a soil sample, it is necessary to conduct different **particle-size tests**.

Sieve Analysis

Wet sieving is carried out for separating fine grains from coarse grains by washing the soil specimen on a 75 micron sieve mesh.

Dry sieve analysis is carried out on particles coarser than 75 micron. Samples (with fines removed) are dried and shaken through a set of sieves of descending size for 10 minutes on a mechanical sieve shaker. The set of fine sieves for fine sieve analysis consist of 2 mm, 1mm, 600 µ, 425 µ, 300 µ, 150 µ and 75 µ.

$$\%\, retained\ on\ a\ particular\ sieve = \frac{weight\ of\ soil\ retained\ on\ that\ sieve}{total\ weight\ of\ soil\ taken} x100$$

$$Cumulative\ \%\ retained$$
$$= sum\ of\ \%\ retained\ on\ all\ sieves\ of\ larger\ sizes\ and\ the\ \%\ retained\ on\ that\ particular\ sieve$$

$$\%\ Finer\ (N)\ than\ the\ sieve\ under\ reference = 100\ \% - cumulative\ \%\ retained$$

The resulting data is presented as a distribution curve with **grain size** along x-axis (log scale) and **percentage finer** along y-axis (arithmetic scale).

Sedimentation Analysis (Stoke's Law)

Sedimentation analysis is used only for the soil fraction finer than 75 microns. Soil particles are allowed to settle from a suspension. The decreasing density of the suspension is measured at various time intervals. This analysis is based on Stoke's law, which gives the terminal velocity of a small single sphere settling in a fluid of infinite extent. When a small sphere settles in a fluid, it velocity first increases under the action of gravity, but the drag force comes into action and retards the velocity. After steady conditions are attained, the sphere attains a constant velocity called terminal velocity. The terminal velocity of a spherical particle is governed by the diameter of the particle and the properties of the suspension.

Thus, the forces acting on a sphere of radius *r* when it falls through a fluid of viscosity η are:

i) Weight of the sphere, $W = \frac{4}{3}\pi r^3 \gamma_s = \frac{4}{3}\pi r^3 \rho_s g$, where ρ_s is the density of sphere material and *g* is acceleration due to gravity.
ii) Drag force, $F_D = 6\pi\ \eta\, r\, v$
iii) Buoyant force, $U = \frac{4}{3}\pi r^3 \gamma_w = \frac{4}{3}\pi r^3 \rho_w g$

From equilibrium of forces in vertical direction,

$$W = F_D + U$$

$$\frac{4}{3}\pi r^3 \rho_s g = 6\pi \eta r v + \frac{4}{3}\pi r^3 \rho_w g$$

or $$v = \frac{2}{9}\frac{r^2}{\eta}(\rho_s - \rho_w)g$$

or $$v = \frac{1}{18}\frac{gD^2(G-1)\rho_w}{\eta} \tag{3.4}$$

where *D* is the diameter of the sphere, G is the specific gravity of sphere material.

If the particle falls through a height H_e (cm) in time *t* (minutes),

$$v = \frac{H_e}{60t}\ cm/s \tag{3.5}$$

From equations (3.4) and (3.5)

$$\frac{H_e}{60t} = \frac{1}{18}\frac{gD^2(G-1)\rho_w}{\eta}$$

or $$D_{cm} = \sqrt{\frac{0.3\,\eta H_e}{g(G-1)\rho_w t}} \tag{3.6}$$

or $$D_{cm} = M\sqrt{\frac{H_e}{t}}$$ where $M = \sqrt{\frac{0.3\,\eta}{g(G-1)\rho_w}}$

taking G = 2.67, ρ_w = 1 g/cc, g = 981 cm/s^2, and η = 10.03 x 10^{-3} poise = 0.01 poise (at a temp. of 20^{o}C), *M = 1.36 x 10*$^{-3}$

Limitations of Stoke's law

1. In Stoke's law, the particles are assumed to be free falling spheres with no collision, but the clay mineral particles are plate-like or needle shaped and collision of particles during sedimentation is unavoidable.
2. Stoke's law is applicable for spheres of diameter between 0.2 mm and 0.0002 mm. Spheres large than 2mm diameter cause turbulence and for spheres withless than 0.0002 mm diameter, Brownian movement takes place and the velocity of settlement is too small for accurate measurements.
3. An average value of specific gravity of soil grains is used, though the specific gravity of the some grains may be different from the average value.
4. Clay particles have a tendency for floc formation due to net negative charge on their surfaces. If the tendency to form flocs is not prevented, the diameter measured will be the diameter of the floc and not of the individual grain.

Theory of sedimentation

At the commencement of sedimentation, the soil particles are uniformly dispersed throughout the suspension, and the concentration of particles of different sizes is same at all depths. After a time period at a particular depth, only those particles remain which have not settled. Because all the particles of the same size have the same velocity, particles of a given size, if exist at any level, are in the same concentration as at the beginning of the sedimentation. All particles smaller than a particular size *D* will be present at a depth H_e in the same degree of concentration as at the beginning.

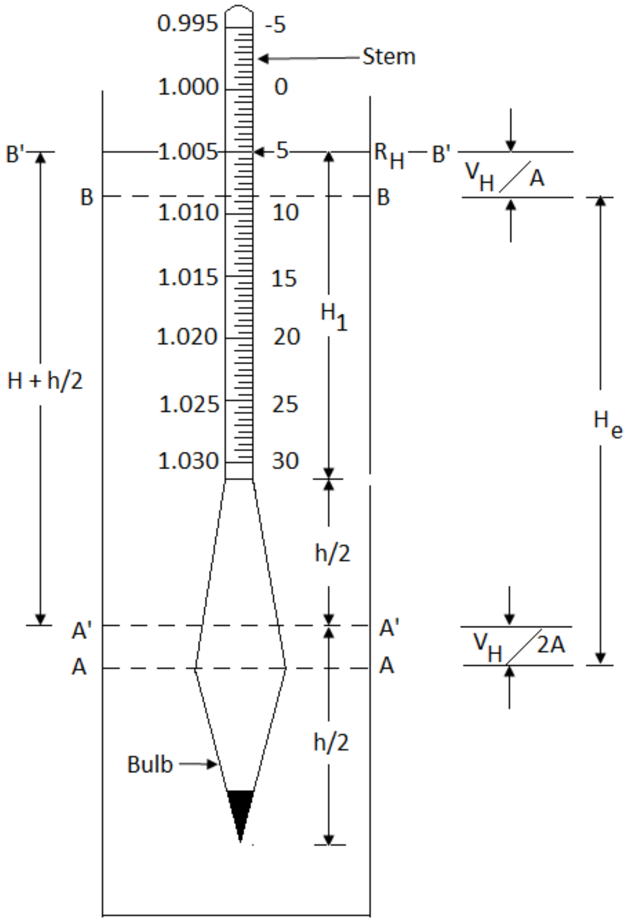
If M_D is the mass of particles per unit volume of suspension at depth H_e after time t, and M_s is the mass of particles per unit volume of suspension at the beginning of sedimentation, the percentage finer (N) than size *D* is

$$N = \frac{M_D}{M_s} x\ 100 \qquad (3.7)$$

In sedimentation analysis, equation (3.6) is used to determine the particle size (D) and equation (3.7) is used to determine the percentage finer.

Methods of sedimentation analysis

Sedimentation analysis can be carried out by **pipette method** or **hydrometer method**. Very sensitive balance to measure small weights is required in pipette analysis, making it expensive. However, calculations in pipette analysis are simple and there is no need to account for meniscus correction and effective depth of sampling. For quick particle size analysis, hydrometer method is more convenient and widely used.



Hydrometer method

Soil hydrometers are of two types: one type of hydrometer is graduated in the specific gravity of fluids and is calibrated to read the density of pure water as 1g/cm^3 at 20^{o}C. BIS recommends the use of this type of hydrometer. The other, recommended by ASTM, is graduated in grams of soil and calibrated to read 0 g/L in pure water at 20^{o}C.

The hydrometer consists of a long stem and a bulb at the bottom. The stem is graduated to read the specific gravity of fluid in the range of 0.995 to 1.030. For the analysis of the results of hydrometer method, it is first essential to calibrate the hydrometer, that is, to establish a relation between the hydrometer reading R_H on the stem and the effective depth H_e for a given hydrometer.

The **effective depth** is the distance from the surface of soil suspension to the level at which the density of soil suspension is being measured. The effective depth of the hydrometer keeps on increasing as the particles settle with time.

The markings on the hydrometer stem give the specific gravity of the suspension at the centre of the bulb. The hydrometer reading R_H is recorded after subtracting unity from the value of specific gravity and multiplying the result with 1000.

$$R_H = (Specific\ Gravity\ of\ soil\ suspension - 1)\ x\ 1000$$

or

$$R_H = \left(\rho_{suspension} - \rho_{water}\right)\ x\ 1000$$

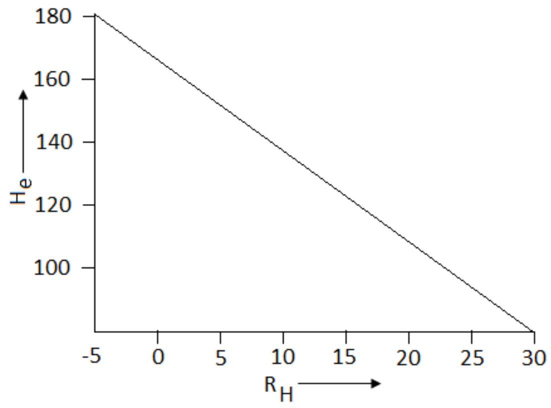
Thus, the hydrometer reading for a specific gravity of 1.005 is

$$R_H = (1.005 - 1.000)x1000 = 5$$

Let h and V_H be the height and volume of the hydrometer bulb and H_1 the distance between any hydrometer reading R_H and the neck. As the hydrometer is immersed in the jar, the water level in the jar rises. If A is the cross-section area of the jar, the surface of the soil suspension rises by V_H/A, whereas at the centre of the bulb, the rise is $V_H/2A$, if the volume of the hydrometer below the centre of the bulb is taken as approximately one-half of the total volume.

The effective depth H_e is given by

$$H_e = \left(H_1 + \frac{h}{2}\right) - \frac{V_H}{A} + \frac{V_H}{2A} = H_1 + \frac{1}{2}\left(h - \frac{V_H}{A}\right)$$



An accurate scale is used to determine the height of the bulb h and also to determine the heights H_1 to various graduations from the neck of the hydrometer. A calibration chart is obtained between the hydrometer reading R_H and the effective depth H_e. During the hydrometer test, the effective depth corresponding to the hydrometer reading is read from this chart.

Pre-treatment of soil

Before sedimentation analysis, the soil must be subjected to chemical treatment, if required. Pre-treatment of soil is required only if the soil contains soluble salts, calcium salts or organic matter. If the amount of soluble salts in the soil is more than one percent, the soil is first washed thoroughly with water while ensuring no loss of soil grains. To oxidize organic matter, the sample is treated with hydrogen peroxide. If the soil contains calcium compounds, the soil oxidized with hydrogen peroxide may further be treated with hydrochloric acid.

Test Procedure

About 50 g of oven dried soil passing 75 µ sieve is taken. The sample is put in an evaporating dish and is covered with 100 cc of distilled water. About 100 cc of deflocculating agent (33 g of sodium hexameta-phosphate and 7 g of sodium carbonate added to distilled water to make one litre of solution) is added and the sample is allowed to soak for five minutes. The sample is then transferred to a dispersion cup. The cup is filled three-fourths using distilled water. After the suspension is stirred for 10 minutes, the suspension is transferred to a 100 cc measuring cylinder of uniform cross-section. More water is added and the total volume is brought to 1000 cc. The measuring cylinder is covered with a rubber bung and the suspension is thoroughly mixed by turning the measuring cylinder upside down and back. When the suspension is well mixed, the measuring cylinder is placed on the table and the hydrometer is inserted. A stop watch is started immediately and the reading of the hydrometer is taken after 1/4, 1/2, 1 and 2 minutes. The hydrometer is taken out of the suspension. The soil suspension is again mixed thoroughly and the stop watch is restarted. Readings of the hydrometer are then taken after 5, 10, 15, 30 min, 1, 2, 4, 8 and 24 hours. The temperature of the suspension is also recorded for every hydrometer reading. About 30 seconds before each hydrometer reading, the hydrometer is inserted slowly in the suspension so that it is stable by the time reading is due. The hydrometer is taken out as soon as the reading is taken, with as little disturbance as possible and inserted in a comparison cylinder containing 100 cc of deflocculating agent mixed in 900 cc of distilled water to make a 1000 cc solution.

Corrections to hydrometer reading

(i) **Meniscus correction (+$\boldsymbol{C_m}$)**
Since the suspension is opaque, the readings are taken at the top of the meniscus. The meniscus correction is equal to the difference between the readings corresponding to the upper meniscus (top of the meniscus) and lower meniscus (level of suspension) in the comparison cylinder. As the markings on the stem increase in the downward direction, the correction is positive. The meniscus correction is constant for a given hydrometer.

(ii) **Temperature correction** $(\pm \boldsymbol{C_t})$
The hydrometers are generally calibrated at 27°C. In case the temperature of the suspension is more than 27°C, the correction is added $(+\boldsymbol{C_t})$, and if below, the correction is subtracted $(-\boldsymbol{C_t})$

(iii) **Dispersion agent correction** $(-\boldsymbol{C_d})$
The correction due to rise in specific gravity of the suspension on account of addition of the deflocculating agent is called the dispersing agent correction. $\boldsymbol{C_d}$ is always negative. The dispersing agent correction can be determined by noting the hydrometer reading in clear distilled water and again in the same water after adding the dispersing agent.

The corrected hydrometer reading, $\boldsymbol{R_c}$, is given as

$$\boldsymbol{R_c = R_H + C_m \pm C_t - C_d}$$

Relation between % Finer (N) and Hydrometer reading ($\boldsymbol{R_c}$)

Let $\boldsymbol{M_s}$ be the mass of dry soil in a suspension of volume $\boldsymbol{V}$. At the commencement of sedimentation, the soil water suspension is uniform, and therefore, the mass of solids per unit volume of suspension at any depth is $\boldsymbol{M_s/V}$.

The initial density of the suspension is given by,

$$\boldsymbol{\rho_i = \frac{M_s + mass\ of\ water\ in\ the\ suspenson}{V}}$$

or $$\boldsymbol{\rho_i = \frac{M_s}{V} + \frac{Mass\ of\ water}{Volume\ of\ suspension}} \qquad \text{(a)}$$

Mass of solids per unit volume of suspension $= \boldsymbol{\frac{M_s}{V}}$

Volume of solids per unit volume of suspension

$$\boldsymbol{= \frac{Mass\ of\ solids\ per\ unit\ volume}{Density\ of\ solids} = \frac{\frac{M_s}{V}}{G\rho_w} = \frac{M_s}{V(G\rho_w)}}$$

Volume of water per unit volume of suspension $\boldsymbol{= 1 - \frac{M_s}{V(G\rho_w)}}$

Mass of water per unit volume of suspension $\boldsymbol{= \left(1 - \frac{M_s}{V(G\rho_w)}\right)\rho_w}$

From equation (a), $\boldsymbol{\rho_i = \frac{M_s}{V} + \left(1 - \frac{M_s}{V(G\rho_w)}\right)\rho_w}$ or $\boldsymbol{\rho_i = \rho_w + \frac{M_s}{V}\left(\frac{G-1}{G}\right)}$ (b)

If $\boldsymbol{M_D}$ is the mass of solids in volume $\boldsymbol{V}$ at depth $\boldsymbol{H_e}$ after time t, equation (b) gives the density of the suspension at that depth as

$$\boldsymbol{\rho_i = \rho_w + \frac{M_D}{V}\left(\frac{G-1}{G}\right)}$$

(c)

From equation (3.7), the percentage finer is given by

$$N = \frac{m_D}{m_s} x\ 100$$

or $m_D = \frac{Nm_s}{100}$, where $m_D = \frac{M_D}{V}$ and $m_s = \frac{M_s}{V}$

therefore, equation (c) becomes

$$\boldsymbol{\rho_i = \rho_w + \frac{Nm_s}{100}\left(\frac{G-1}{G}\right)}$$

or $$\boldsymbol{\rho_i - \rho_w = \frac{Nm_s}{100}\left(\frac{G-1}{G}\right)}$$

or $$\boldsymbol{N = \left(\frac{G}{G-1}\right)\frac{(\rho-\rho_w)}{m_s} x100}$$

The corrected hydrometer reading $\boldsymbol{R_c = (\rho - \rho_w) x1000}$

Therefore, $$N = \left(\frac{G}{G-1}\right)\frac{R}{1000}\,x\,\frac{1}{m_s}\;x\;100$$

As $m_s = \frac{M_S}{V}$, $$N = \left(\frac{G}{G-1}\right)\frac{R}{1000}\,x\,\frac{V}{M_s}\;x\;100$$

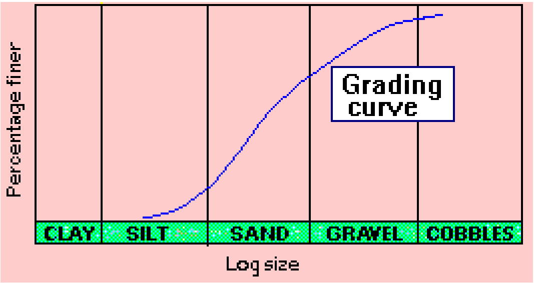
Taking V =1000 cc

$$N = \left(\frac{G}{G-1}\right)\frac{R}{M_s}\,x\;100 \qquad (3.8)$$

Where M_s is the mass of solids in a volume V of 1000 cc.

GRAIN-SIZE DISTRIBUTION CURVE

The size distribution curves, as obtained from coarse and fine grained portions, can be combined to form one complete **grain-size distribution curve** (also known as **grading curve**). A typical grading curve is shown.



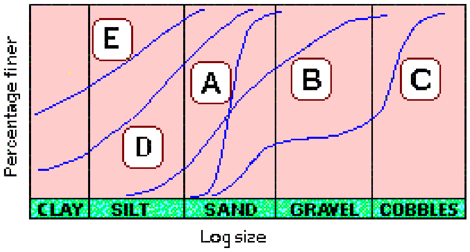
From the complete grain-size distribution curve, useful information can be obtained such as:

1. Grading characteristics, which indicate the uniformity and range in grain-size distribution.

2. Percentages (or **fractions)** of gravel, sand, silt and clay-size.

According to **gradation**, they are further grouped as well-graded (**W**) or poorly graded (**P**). If **fine soils** are present, they are grouped as containing silty fines (**M**) or as containing clayey fines (**C**).

Both the position and the shape of the grading curve for a soil can aid in establishing its identity and description. Some typical grading curves are shown.



Curve A - a poorly-graded medium SAND

Curve B - a well-graded GRAVEL-SAND (i.e. having equal amounts of gravel and sand)

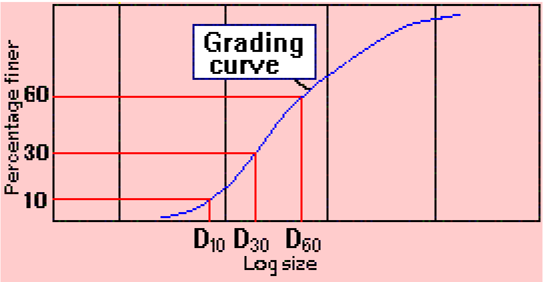
Curve C - a gap-graded COBBLES-SAND

Curve D - a sandy SILT

Curve E - a silty CLAY (i.e. having little amount of sand)

GRADING CHARACTERISTICS

A grading curve is a useful aid to soil description. The geometric properties of a grading curve are called **grading characteristics**.



To obtain the grading characteristics, three points are located first on the grading curve.

D_{60} = particle size such that 60% of soil by weight is finer than this size.
D_{30} = particle size such that 30% of soil by weight is finer than this size.
D_{10} = particle size such that 10% of soil by weight is finer than this size.

The grading characteristics are then determined as follows:

1. Effective size = D_{10}

2. Uniformity coefficient, $C_u = \frac{D_{60}}{D_{10}}$

3. Curvature coefficient, $C_c = \frac{D_{30}^2}{D_{10}D_{60}}$

The uniformity coefficient and coefficient of curvature are strictly applicable to coarse grained soils.

Minimum value of $\mathbf{C_u}$ is 1 for a single-sized soil. The larger the numerical value of $\mathbf{C_u}$**,** the more is the range of the particles. Well graded soils have $\mathbf{C_u}$ > 4, $\mathbf{C_c}$ between 1 and 3 and flat gradation curves. Poorly graded soils have $\mathbf{C_u}$ < 4 and steep gradation curves. The absence of certain grain sizes, termed gap graded, is indicated by $\mathbf{C_c}$ **<1** or **>3**, and a sudden change of slope (hump) in the GSD curve. Humps in the gradation curve indicate two or more poorly graded soils.

For sands, **C_u > 6** indicates a well graded sand. For gravels, **C_u > 4** indicates a well graded gravel.

C_c between 1 and 3 also indicates a well-graded soil.

C_u < 2 indicates a **uniform soil**, i.e. a soil which has a very narrow particle size range.

For a soil to be classified as well graded, both **C_u** and **C_c** must be satisfied.

USES OF PARTICLE SIZE DISTRIBUTION CURVE

Particle size distribution or grain size distribution (GSD) curve is extremely useful for coarse grained soils. Its use for fine grained soils is limited as the behavior of fine grained soils depends on the plasticity characteristics and not on the particle size.

1. GSD curve is used in the classification of coarse grained soils.
2. Effective size, D_{10}, is an important value in regulating flow through flows and can significantly influence the mechanical behavior of soils.
3. The higher the effective size, D_{10}, the coarser the soil and the better the drainage characteristics. An approximate value of coefficient of permeability (k) for coarse grained soils can be estimated from D_{10}.
4. GSD curve is used in the design of drainage filters
5. The particle size can be used to know the susceptibility of a soil to frost action.
6. A uniform soil indicated by steep GSD curve is more compressible.
7. A well graded compacted sand has a higher shear strength compared to a poorly graded loose sand.
8. GSD curve is useful in soil stabilization and for the design of pavements.
9. GSD curve also indicates mode of deposition of soil. A gap graded soil indicates deposition by two different agencies.