CHAPTER 02

Properties of Soils

2.1 Introduction

Soil is essentially made up of solid particles, with spaces or voids in between. The assemblage of particles in contact is usually referred to as the 'soil matrix' or the 'soil skeleton'. The intermittent void spaces are filled up by either air or water or both air and water. This means that an element of 'soil' may be considered as a three-phase material, comprising some solid (soil grains), some liquid (pore water) and some gas (pore air).

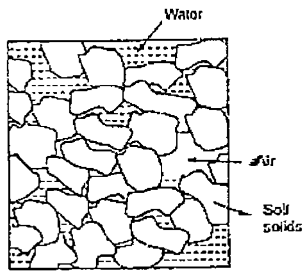


Fig. 2.1 Three phase solid-water-air system

2.2 Phase Diagram

- Soil mass, in general is a three phase system composed of solid, liquid and gaseous phase.
- Different phases present in soil mass cannot be separated. For better understanding, all three constituents are assumed to occupy separate spaces as shown in figure below.

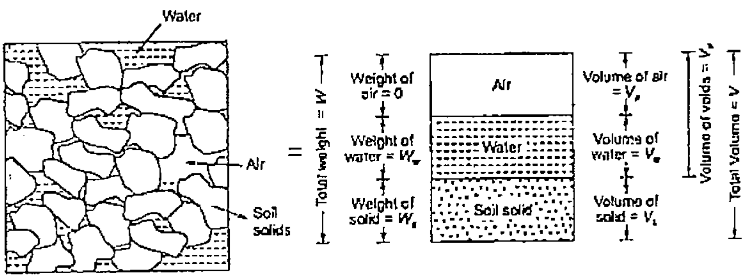
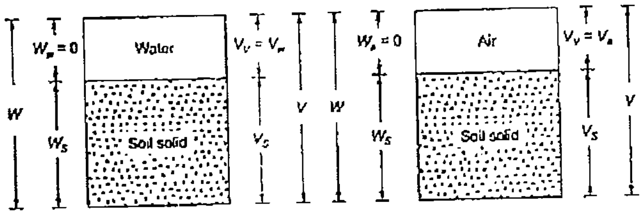


Fig. 2.2 Three Phase diagram

- The diagrammatic representation of the different phases in a soil mass is called the 'phase diagram', or 'block diagram'.
- A three-phase diagram is applicable for a partially saturated soil ($0 < S < 1$)
- When all the voids are filled with water, the sample becomes saturated and thus the gaseous phase

is absent; whereas, in oven dry soil sample the liquid phase is absent. Thus, in saturated and oven dry soils, the three phase system reduces to two phase system.



(a) Water and soil solids (Fully saturated soil, S = 1)

(b) Air and soil solids (Oven dry soil, S = 0)

Fig. 2.3 Two Phase diagram

2.3 Basic Definitions

(i) Water Content (*w*)

- Water content (*w*) is also called moisture content. It is the ratio of weight of water to the weight of soil solids.

$$w = \frac{W_w}{W_s}; \quad w \geq 0$$

- This is represented as a percentage.
- The water content of a oven dry soil is zero but natural water content for most soils is around 60%.
- There is no upper limit for water content. It can be greater than 100%.

NOTE

1. Fine-grained soils have higher values of natural moisture content as compared to coarse-grained soils.
2. There are four possible forms of water present in soil:
   (i) Gravity water (free water): Added due to rain or flooding
   (ii) Capillary water : Extracted through capillary action
   (iii) Hygroscopic water : Water absorbed by oven dried sample when it is placed in open atmosphere
   (iv) Structural water : Water bounded in crystalline structure of soil
   On oven drying, gravity water, capillary water and hygroscopic water are removed but structural water remains present in soil mass.
3. Water content in soil represents gravity water, capillary water and hygroscopic water, which can be removed on oven drying.

(ii) Degree of Saturation(S)

- Degree of saturation (*S*) of a soil is defined as the ratio of the volume of water to the volume of voids in the soil mass.

$$S = \frac{V_w}{V_v} \times 100$$

where, V_w = volume of water
V_v = volume of voids

- It is expressed in percentage.
- For dry soil, S = 0% and for fully saturated soil S = 100%, whereas partially saturated soil have $0 < S < 100\%$.

NOTE

- If soil is partially saturated, then total volume of soil and volume of void remain constant during variation of moisture content. If soil is super saturated due to further addition of water, then volume of void and total volume increases. Hence void ratio will change but degree of saturation remains constant equal to 100%.

(iii) Void Ratio (*e*)

- The void ratio (*e*) of a soil is defined as the ratio of the total volume of voids to the volume of solids.

$$e = \frac{V_v}{V_s}; \quad e > 0$$

where, V_v = volume of voids
V_s = volume of soil solids

- It is expressed in decimal.
- In general $e > 0$, i.e. no upper limit for void ratio.
- Void ratio of fine grained soils are generally higher than those of coarse grained soils.
  The individual void spaces in coarse grained soil are larger than fine grained soils; but the total void space is generally more in fine grained soils.

(iv) Porosity (*n*)

- The porosity (*n*) of a soil is defined as the ratio of volume of voids to the total volume of soil.

$$n = \frac{V_v}{V} \times 100\%$$

where, V_v = volume of voids
V = Total volume of soil

- It is expressed in percentage.
- In porosity, total volume of soil is used which includes volume of voids.
- Hence porosity (*n*) of soil cannot exceed 100%.
- The range of porosity is $0 < n < 100\%$.

NOTE

Void ratio (*e*) and porosity (*n*) both have same significance but void ratio (*e*) is more widely adopted than porosity because volume of solid which is used in void ratio is more stable than total volume used in porosity.

(v) Air Content (a_c)

- It is defined as the ratio of the volume of air to the total volume of voids present in soil.

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

where, V_a = volume of air in voids

V_v = volume of voids

- It is expressed in percentage.

(vi) Percentage Air Voids (n_a)

- Percentage air voids (n_a) is defined as the ratio of volume of air to the total volume of soil mass.

$$n_a = \frac{V_a}{V} \times 100$$

where, V_a = volume of air

V = total volume of soil

- It is expressed in percentage.

(vii) Unit Weights

(a) Bulk Unit Weight (γ_t)

- It is the ratio of total weight of soil to the total volume of soil mass.

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_w + V_s}$$

- It is expressed as $\frac{kN}{m^3}$ or $\frac{kgf}{cm^3}$

NOTE

- Bulk density is defined as the ratio of total soil mass to the total volume.

$$\rho_t = \frac{M}{V} = \frac{M_s + M_w}{V_s + V_w + V_s}$$

- It is expressed as $\frac{kg}{m^3}$

(b) Dry Unit Weight (γ_d)

- It is the ratio of total dry weight of soil to the total volume of soil mass.

$$\gamma_d = \frac{\text{Dry weight of soil}}{\text{Total volume}} = \frac{W_{dry}}{V}$$

- Dry unit weight is used as a measure of denseness of soil. More dry unit weight means more dense or compacted is the soil.

NOTE

- Dry density is defined as the ratio of total dry mass to the total volume.

$$\rho_d = \frac{M}{V} = \frac{M_{dry}}{V}$$

(c) Saturated Unit Weight (γ_{sat})

- It is defined as the ratio of total saturated weight of soil to the total volume of soil mass

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

Do You Know?

- Saturated density is defined as the ratio of total saturated soil mass to the total volume of soil mass.

$$\rho_{sat} = \frac{M_{sat}}{V}$$

(d) Submerged Unit Weight or Buoyant Unit Weight (γ'_{sub} or γ')

- It is the ratio of buoyant weight of soil to the total volume of soil mass.

$$\gamma' = \frac{W_{sub}}{V}$$

- When soil is below water i.e. in submerged condition, a buoyant force acts on the soil solids which is equal in magnitude to the weight of water displaced by the soil solids. Hence the net weight of soil is reduced and reduced weight is known as buoyant weight or submerged weight.

$$\therefore \quad \gamma' = \frac{W_{sub}}{V} = \gamma_{sat} - \gamma_w$$

- γ' is roughly $\frac{1}{2}$ of saturated unit weight (γ_{sat})

Note: Submerged density or buoyant density, $\rho' = \rho_{sat} - \rho_w$

(e) Unit Weight of Water (γ_w)

- It is the ratio of weight of water to the volume occupied by the water

$$\gamma_w = \frac{W_w}{V_w}$$

- Unit weight of water depends on its temperature. However, the unit weight of water is taken to be constant as 9.81 kN/m^3 or 1g/cc.
- It is expressed in $\frac{kN}{m^3}$ or $\frac{kgf}{cm^3}$

(f) Unit Weight of Solids (γ_s)

- It is the ratio of weight of soil solids to the volume occupied by the soil solids.

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

- It is expressed in $\frac{kN}{m^3}$ or $\frac{kgf}{cm^3}$

(viii) Specific Gravity (G)

- Specific gravity of soil solids (G) is the ratio of the weight of a given volume of solids to the weight of an equivalent volume of water at 4°C.

$$G = \frac{W_s}{V_s \gamma_w} = \frac{\gamma_s}{\gamma_w} \qquad \left[\because \gamma_s = \frac{W_s}{V_s}\right]$$

- The specific gravity of most of the inorganic soils lies in the range of 2.65 to 2.80.
- For organics soils, it lies in the range of 1.2 to 1.40.

(ix) Apparent or Mass Specific Gravity (G_m)

- Mass specific gravity is defined as the ratio of the total weight of a given volume of soil to an equivalent volume of water.
- Mass specific gravity can be defined as the ratio of bulk unit weight of soil to unit weight of water.

$$G_m = \frac{W_t}{V\gamma_w} = \frac{\gamma_t}{\gamma_w}$$

If soil is in saturated state,

$$G_m = \frac{\gamma_{sat}}{\gamma_w}$$

If soil is in dry state,

$$G_m = \frac{\gamma_d}{\gamma_w}$$

Do You Know?

- Generally, specific gravity is represented either at 27°C or at 20°C. If test temperature is different than the standard temperature, then correction has to be done as follows–

$$G = \frac{\gamma_s}{\gamma_w}$$

$\therefore$ $$G \times \gamma_w = \text{constant}$$

$\Rightarrow$ $$G_{27^\circ C} \times \gamma_{w27^\circ C} = G_{T^\circ C} \times \gamma_{wT^\circ C}$$

$\therefore$ $$G_{27^\circ C} = G_{T^\circ C} \times \frac{\gamma_{wT^\circ C}}{\gamma_{w27^\circ C}}$$

2.4 Some Important Relationships

1. Relation between W_s, W_w and W

From block diagram,

$$W = W_s + W_w + W_a$$

$$W = W_s + W_w + 0 \quad (\because W_a = 0)$$

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

$$W = W_s(1 + w) \quad \left(\because \text{Water content, } w = \frac{W_w}{W_s}\right)$$

$\therefore$ $$W_s = \frac{W}{1+w}$$

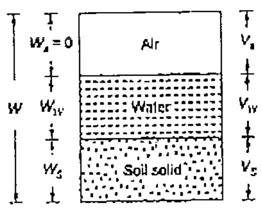


Fig.2.4

2. Relation between e and n

We know, Porosity, $$n = \frac{V_v}{V} = \frac{V_v}{V_s + V_v} = \frac{\left(\frac{V_v}{V_s}\right)}{1 + \left(\frac{V_v}{V_s}\right)}$$

$\Rightarrow$ $$n = \frac{e}{1+e} \quad \left(\because e = \frac{V_v}{V_s}\right)$$

3. Relation between e, S, w and G

We know,

$$\text{Void ratio, } e = \frac{V_v}{V_s}$$

Also, $$e = \frac{V_v}{V_s} = \frac{V_v}{V_w} \times \frac{V_w}{V_s} = \frac{V_v}{V_w} \times \frac{W_w/\gamma_w}{W_s/\gamma_s} = \frac{V_v}{V_w} \cdot \frac{W_w}{W_s} \cdot \frac{G_s\gamma_w}{\gamma_w} = \frac{1}{S}wG_s$$

$$e = \frac{wG_s}{S}$$

or $$Se = wG$$

4. Relation between γ_t, G_s, e, w and γ_w

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V_s + V_v} = \frac{W_s\left(1 + \frac{W_w}{W_s}\right)}{V_s\left(1 + \frac{V_v}{V_s}\right)}$$

But $$\frac{W_w}{W_s} = w \quad \text{and} \quad \frac{W_s}{V_s} = \gamma_s = G_s\gamma_w$$

$\therefore$ $$\gamma_t = \frac{G_s\gamma_w(1+w)}{1+e}$$

But $$w = \frac{Se}{G_s}$$

$\therefore$ $$\gamma_t = \left(\frac{G_s + Se}{1+e}\right)\gamma_w$$

Special Case (*a*): If soil is saturated, then

$$\gamma_t = \gamma_{sat} \quad \text{and} \quad S = 1$$

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

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

Special Case (*b*): If soil is dry, then

$$\gamma_t = \gamma_d \quad \text{and} \quad S = 0$$

Hence $$\gamma_d = \left(\frac{G_s + 0 \times e}{1+e}\right)\gamma_w$$

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

Special Case (*c*): If soil is submerged, then

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

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

5. Relation between γ_t, γ_d, w

$$\gamma_t = \frac{W}{V} = \frac{W_s + W_w}{V}$$

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

or $$\gamma_d = \frac{\gamma_t}{1+w} \qquad \left(\because \gamma_d = \frac{W_s}{V}\right)$$

6. Relation between γ_d, G_s, w and n_a

$$V = V_s + V_w + V_a$$

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

or $$1 - n_a = \frac{V_s}{V} + \frac{V_w}{V} = \frac{W_s / G_s\gamma_w}{V} + \frac{wW_s / \gamma_w}{V} \qquad \left(\because V_w = \frac{wW_s}{\gamma_w}\right)$$

$$= \frac{\gamma_d}{G_s\gamma_w} + \frac{wW_s / \gamma_w}{V} = \frac{\gamma_d}{G_s\gamma_w} + \frac{w\gamma_d}{\gamma_w} = \frac{\gamma_d}{\gamma_w}\left(w + \frac{1}{G_s}\right)$$

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

Special Case (a): When $n_a = 0$, then soil become fully saturated at a given water content

Hence $$\gamma_d = \frac{G_s\gamma_w}{1+wG}$$

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

7. Relation between S, w, G_s, γ_t and γ_w

$$\gamma_t = \left(\frac{G_s + Se}{1+e}\right)\gamma_w$$

$$\frac{\gamma_t}{\gamma_w} = \left(\frac{G_s + Se}{1+e}\right) = \left(\frac{G_s + wG_s}{1 + \frac{wG_s}{S}}\right)$$

$$\left(1 + \frac{wG_s}{S}\right) = \frac{G_s\gamma_w}{\gamma_t}(1+w)$$

$$\frac{1}{G_s}\left(1 + \frac{wG_s}{S}\right) = \frac{\gamma_w}{\gamma_t}(1+w)$$

$$\frac{1}{G_s} + \frac{w}{S} = \frac{\gamma_w}{\gamma_t}(1+w)$$

or $$S = \frac{w}{\frac{\gamma_w}{\gamma_t}(1+w) - \frac{1}{G_s}}$$

Summary

1. $W_s = \frac{W}{1+w}$
2. $n = \frac{e}{1+e}$
3. $Se = wG$
4. $\gamma_t = \left(\frac{G+Se}{1+e}\right)\gamma_w$
5. $\gamma_{sat} = \left(\frac{G+e}{1+e}\right)\gamma_w$
6. $\gamma_d = \frac{G\gamma_w}{1+e}$
7. $\gamma' = \left(\frac{G-1}{1+e}\right)\gamma_w$
8. $\gamma_d = \frac{(1-n_a)G\gamma_w}{1+wG}$
9. $\gamma_d = \frac{\gamma_t}{1+w}$
10. $S = \frac{w}{\frac{\gamma_w}{\gamma_t}(1+w) - \frac{1}{G}}$

Example 2.1 A soil sampler of volume 1000 cm³ is used to collect soil samples. It was found that sampler contain 2 kg soil with dry unit weight of 1800 kg/m³. If 300 g water is mixed to the soil, then what will be the water content of the sample?

Solution:

$$\gamma_d = 1800 \text{ kg/m}^3$$

Dry weight of soil (weight of soil solids),

$$W_s = V \times \gamma_d = 1000 \times 10^{-6} \times 1800 = 1.8 \text{ kg}$$

But actual weight of sample, $W = 2$ kg

∴ Weight of water before mixing additional water,

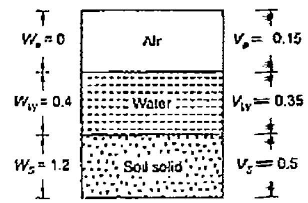
$$W_{w_1} = W - W_s = 2 - 1.8 = 0.2 \text{ kg}$$

After mixing 300 g of water, the total weight of water would be

$$W_{w_2} = 0.2 + 0.3 = 0.5 \text{ kg}$$

Thus, water content, $$w = \frac{W_{w_2}}{W_s} \times 100 = \frac{0.5}{1.8} \times 1000 = 27.8\%$$

Example 2.2 Figure shows a block diagram for a soil sample, having volumes and weights in *cc* and *g* respectively.



Consider the following statements

1. Soil is partially saturated with degree of saturation greater than 60%
2. Void ratio = 100%
3. Water content = 40%
4. Saturated unit weight = 2g/cc

Which of the above statements are TRUE?

(a) 1, 2 and 3 (b) 1, 2, 3 and 4
(c) 1, 2 and 4 (d) 2 and 3

Ans. (c)

1. Degree of saturation, $S = \frac{V_w}{V_v} \times 100 = \frac{0.35}{(0.15+0.35)} \times 100 = 70\%$

2. Void ratio, $e = \frac{V_v}{V_s} = \frac{0.15+0.35}{0.5} \times 100 = 100\%$

3. Water content, $w = \frac{W_w}{W_s} \times 100 = \frac{0.4}{1.2} \times 100 = 33.33\%$

4. Saturated unit weight, $\gamma_{sat} = \left(\frac{G+Se}{1+e}\right)\gamma_w$

Using, $Se = wG$

$$G = \frac{Se}{w} = \frac{1 \times 1}{0.333} = 3.0$$

$$\therefore \quad \gamma_{sat} = \left(\frac{3+1\times1}{1+1}\right) \times 1 = 2 \text{ g/cc}$$

Hence option (c) is correct.

Example 2.3 An oven dry soil has mass specific gravity of 1.5 g/cc. If bulk density of soil in its natural state is 2.0 g/cc, then the water content of soil in natural state will be

(a) 50% (b) 25%
(c) 100% (d) 33.33%

Ans. (d)

For oven dry soil,

Mass specific gravity, $G_m = \frac{\gamma_d}{\gamma_w} = 1.5$ g/cc

$\therefore \quad \gamma_d = 1.5$ g/cc

Given, bulk density, $\gamma_t = 2.0$ g/cc

Using, $\gamma_d = \frac{\gamma_t}{1+w}$

$$1.5 = \frac{2.0}{1+w}$$

$$w = \frac{2.0}{1.5} - 1 = 33.33\%$$

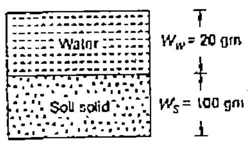
Hence option (d) is correct.

Example 2.4 Consider the phase diagram of the soil given below:

The soil is completely saturated

The specific gravity of soil solids is 2.6 (take unit weight of water as 10 kN/m³).

Match List-I (Physical properties of soil) with List II (Corresponding values) and select the correct answer using the codes given below.



List-I	List-II
1. Water content	A. 0.34
2. Void ratio	B. 0.52
3. Porosity	C. 20.53
4. Saturated density	D. 20%

Codes:

	1	2	3	4
(a)	A	C	B	D
(b)	B	A	D	C
(c)	C	A	C	D
(d)	D	B	A	C

Ans. (d)

1. Water content, $w = \frac{W_w}{W_s} \times 100 = \frac{20}{100} \times 100 = 20\%$

2. Void ratio, $e = \frac{wG}{S} = \frac{0.2 \times 2.6}{1} = 0.52$

3. Porosity, $n = \frac{e}{1+e} = \frac{0.52}{1+0.52} = 0.34$

4. We know, $\gamma_t = \left(\frac{G+Se}{1+e}\right)\gamma_w$

For saturated density, $\gamma_{sat} = \left(\frac{G+1\times e}{1+e}\right)\gamma_w = \left(\frac{2.6+0.52}{1+0.52}\right) \times 10 = 20.53 \text{ kN/m}^3$

Hence option (d) is correct.

Example 2.5 Soil sample *A* and *B* have void ratio of 0.5 and 0.7 respectively. If 1.5 m³ of soil sample *A* and 1.7m³ of sample *B* are mixed to form sample *C* having a volume of 3.2 m³, which one of the following correctly represents the porosity of sample *C*?

(a) 50% (b) 37.5%
(c) 100% (d) 33.33%

Ans. (b)

Soil *A*(1)	Soil *B*(2)	Soil *C*(3)
$e_1 = 0.5$	$e_2 = 0.7$	$V_3 = 3.2$ m³
$V_1 = 1.5$ m³	$V_2 = 1.7$ m³	

Even after mixing, volume of solids of each soil will be same in mixed sample

The solids in soil *A*, $V_{s_1} = \frac{V_1}{1+e_1} = \frac{1.5}{1+0.5} = 1 \text{ m}^3$

The solids in soil *B*, $V_{s_2} = \frac{V_2}{1+e_2} = \frac{1.7}{1+0.7} = 1 \text{ m}^3$

Total volume of solids in soil *C*, $V_{s_3} = V_{s_1} + V_{s_2} = 2 \text{ m}^3$

$\therefore$ Volume of void in soil *C*, $V_v = V_3 - V_{s_3} = 3.2 - 2 = 1.2 \text{ m}^3$

$\therefore$ Porosity, $n = \frac{V_v}{V_3} = \frac{1.2}{3.2} = 0.375$

Hence, option (b) is correct.

Example 2.6 Which one of the following is the water content of the mixed soil made from 1 kg of soil (say A) with water content of 100% and 1 kg of soil (say B) with water content of 50%?

(a) 66% (b) 71%

(c) 75% (d) 82%

***Ans.* (b)**

Soil A(1)	Soil B(2)	Soil C(3)
$W_1 = 1$ kg	$W_2 = 1$ kg	$W_3 = W_1 + W_2$
$w_1 = 100\%$	$w_2 = 50\%$	$w_3 = ?$

Water content,
$$w = \frac{W_w}{W_s} \times 100 \Rightarrow \frac{w}{100} = \frac{W_w}{W_s}$$
$$\frac{w}{100} + 1 = \frac{W_w + W_s}{W_s} \Rightarrow W = \left(\frac{w\%}{100} + 1\right)W_s = (w+1)W_s$$

Weight of solids in soil A,
$$W_{S_A} = \frac{1000}{1+1} = 500 \text{ g}$$
$$W_{w_A} = 1000 - 500 = 500 \text{ g}$$

Weight of solids in soil B,
$$W_{S_B} = \frac{1000}{(0.5+1)} = 666.7 \text{ g}$$
$$W_{w_B} = 1000 - 666.7 = 333.3 \text{ g}$$
$$W_{S,mix} = W_{S_A} + W_{S_B} = 500 + 666.7 \text{ and } = 1166.7 \text{ g}$$
$$W_{w,mix} = W_{w_A} + W_{w_B} = 500 + 333.3 \text{ g} = 833.3 \text{ g}$$
$$\therefore \quad w = \frac{W_{w,mix}}{W_{s,mix}} = \frac{833.3}{1166.7} \times 100 = 71\%$$

Example 2.7 A soil sample has void ratio of 35%. The specific gravity of solids is 2.7. Calculate the

(i) Porosity (ii) Dry density

(iii) Unit weight if the soil is 75% saturated (iv) Unit weight if the soil is submerged

Solution:

Given, Void ratio, $e = 35\%$, $G_s = 2.7$

(i) We know, Porosity, $n = \dfrac{e}{1+e}$

$$\therefore \quad n = \frac{0.35}{1+0.35} = 0.259$$

(ii) We know, $\gamma_t = \left(\dfrac{G_s + Se}{1+e}\right)\gamma_w$

For dry density, $S = 0$

$$\therefore \quad \gamma_d = \frac{G_s \gamma_w}{1+e} = \frac{2.7 \times 9.81}{1+0.35}$$
$$\Rightarrow \quad \gamma_d = 19.62 \text{ kN/m}^3$$

(iii) When soil is 75% saturated i.e. $S = 0.75$

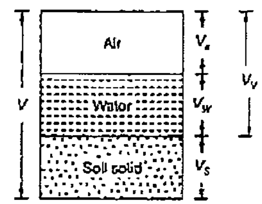
$$\therefore \quad \gamma = \left(\frac{G_s + Se}{1+e}\right)\gamma_w = \left(\frac{2.7 + 0.75 \times 0.35}{1+0.35}\right) \times 9.81 = 21.53 \text{ kN/m}^3$$

(iv) We know, $\gamma_{sub} = \gamma_{sat} - \gamma_w$

$$= \left(\frac{G_s + 1e}{1+e}\right)\gamma_w - \gamma_w = \frac{(G_s - 1)}{1+e}\gamma_w = \frac{(2.7-1)}{1+0.35} \times 9.81 = 12.35 \text{ kN/m}^3$$

Example 2.8 A sampler with a volume of 60 cm³ is filled with saturated soil sample. The specific gravity of soil solids is 2.65. When the oven dry soil is poured into a graduated cylinder filled with water, it displaces 40 cm³ of water. What is the natural moisture content and dry unit weight of soil?

Solution:



Volume of soil sample = Volume of sampler

$\therefore \quad V = 60 \text{ cm}^3$

When soil sample is poured into graduated cylinder, it displaces 40 cm³ of water

$\therefore$ Volume of soil solids, $V_s = 40 \text{ cm}^3$

$\because$ Total volume, $V = V_v + V_s$

$\Rightarrow \quad V_v = V - V_s = 60 - 40$

$\Rightarrow \quad V_v = 20 \text{ cm}^3$

$\therefore$ Void ratio, $e = \dfrac{V_v}{V_s} = \dfrac{20}{40} = 0.5$

Now, we have, $e = 0.5$, $S = 1$ and $G_s = 2.65$

Using $Se = wG_s$

Moisture content, $w = \dfrac{Se}{G_s} = \dfrac{1 \times 0.5}{2.65} = 18.86\%$

We know, $\gamma_d = \dfrac{\gamma_t}{1+w}$

where, γ_t = bulk unit weight

$$\gamma_t = \left(\frac{G + Se}{1+e}\right)\gamma_w = \left(\frac{2.65 + 1 \times 0.5}{1+0.5}\right) \times 1 = 2.1 \text{ g/cc}$$

Hence, $\gamma_d = \dfrac{2.1}{1+0.1886} = 1.76$ g/cc

Example 2.9 The void ratio and specific gravity of a sample of clay are 0.73 and 2.7 respectively. The voids are 92% saturated. Find the bulk density, dry density and the water content. What would be the water content for complete saturation, the void ratio remaining the same?

Solution:

Given, $e = 0.73$, $G = 2.7$ and $S = 92\%$

We know that,

Bulk density, $\rho_t = \left(\dfrac{G + Se}{1+e}\right)\rho_w = \left(\dfrac{2.7 + 0.92 \times 0.73}{1+0.73}\right) \times 1$ $[\because \rho_w = 1 \text{ g/cc}]$

$$\rho_t = 1.948 \text{ g/cc}$$

We know, Dry density, $\rho_d = \dfrac{\rho_t}{1+w}$ ...(i)

Using $Se = wG$

$\Rightarrow$ $w = \dfrac{Se}{G} = \dfrac{0.92\times0.73}{2.7} = 0.2487$ or 24.87%

Substituting the value of w in (i), we get,

$$\rho_d = \frac{1.948}{1+0.2487} = 1.560 \text{ g/cc}$$

Let, water content is w for full saturation at given void ratio.

Now, $S = 100\%$, $e = 0.73$

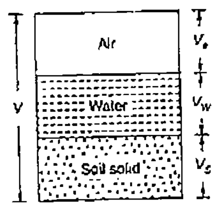
We know, $Se = wG$

$\Rightarrow$ $w = \dfrac{1\times0.73}{2.7} = 0.2703$ or 27.03%

Example 2.10 : A compacted cylindrical specimen of 50 mm diameter and 100 mm long is to be prepared from dry soil. If the specimen is required to have a water content of 15% and the percentage of air void is 20%, calculate the weight of soil and water required in the preparation of the soil whose specific gravity is 2.69.

Solution:

Volume of soil sample = Volume of cylinder



$\therefore$ $V = \dfrac{\pi}{4}D^2H = \dfrac{\pi}{4}\times(5)^2\times10 = 196.35$ cc

Water content, $w = \dfrac{W_w}{W_s} = \dfrac{V_w\times\gamma_w}{V_s\times\gamma_s} = \dfrac{V_w}{V_sG}$

$0.15 = \dfrac{V_w}{V_sG}$

$\therefore$ $V_w = 0.15\,V_s\times G = 0.15\times V_s\times2.69 = 0.40\,V_s$

Also,

% Air voids, $n_a = \dfrac{V_a}{V} = 0.2$

$\therefore$ $V_a = 0.2\,V$

$\because$ $V = V_s + V_w + V_a$

$\Rightarrow$ $V = V_s + 0.4\,V_s + 0.2\,V$

$0.8\,V = 1.4\,V_s$

$\therefore$ $V_s = \dfrac{0.8\,V}{1.4} = \dfrac{0.8\times196.35}{1.4} = 112.20$ cc

Let W_s be the weight of soil solids to prepare soil whose specific gravity is 2.69.

We know, $G = \dfrac{W_s}{V_s\times\gamma_w}$

$\therefore$ $W_s = G\times V_s\times\gamma_w = 2.69\times112.2\times1 = 301.82$ g

Weight of dry soil = Weight of solids

= 301.82 g

Let W_w be the weight of water to prepare soil whose specific gravity is 2.69.

$W_w = w\times W_s = 0.15\times301.82 = 45.27$ g

Example 2.11 A soil sample of saturated clay has a diameter of 50 mm and the height of 100 mm. The mass of saturated sample is 220 g and its mass when oven dried is 150 g. Find

(i) Water content of the clay

(ii) Void ratio

(iii) Dry density of solid

Assume specific gravity of solid as 2.7.

Solution:

Mass of saturated soil sample, $M_{sat} = 220$ g

Mass of oven dry soil sample, $M_s = 150$ g

$\therefore$ Mass of water in soil, $M_w = 220 - 150 = 70$ g

(i) Water content of sample, $w = \dfrac{W_w}{W_s}\times100 = \dfrac{M_w}{M_s}\times100$

$= \dfrac{70}{150}\times100 = 46.67\%$

(ii) Volume of sample, $V = \dfrac{\pi}{4}D^2L = \dfrac{\pi}{4}(5)^2\times10 = 196.35$ cc

and $V_w = \dfrac{M_w}{\rho_w} = \dfrac{70\text{ g}}{1\text{ g/cc}} = 70$ cc

For a saturated soil sample,

$V_v = V_w = 70$ cc

$\therefore$ $V_s = V - V_w$

$= 196.35 - 70$

$= 126.35$ cc

$\therefore$ Void radio, $e = \dfrac{V_v}{V_s} = \dfrac{70}{126.35} = 0.55$

(iii) Dry density, $\rho_d = \dfrac{G\rho_w}{1+e}$

$= \dfrac{2.7\times1}{1+0.55}$

$= 1.74$ g/cc

Example 2.12 A clayey soil with specific gravity of 2.70 has natural moisture content of 16% at 70% degree of saturation. What will be its water content if, after soaking, degree of saturation becomes 90%.

Solution:

In the first case,

Given, $G = 2.7$, $w = 16\%$ and $S = 70\%$

We know, $e = \frac{wG}{S} = \frac{0.16 \times 2.7}{0.7} = 0.617$

In the second case,

Since degree of saturation is within 100%, void ratio (e) will be same as the previous case

$$Se = wG$$

$$w = \frac{Se}{G} = \frac{0.9 \times 0.617}{2.7} = 0.2057 \text{ or } 20.57\%$$

Example 2.13 A soil sample has wet density of 20 kN/m³ and dry density of 18 kN/m³. If the specific gravity of soil is 2.67. Calculate the void ratio, porosity, moisture content and degree of saturation. Assume unit weight of water = 10 kN/m³.

Solution:

Given, $\gamma_{wet} = \gamma_t = 20\text{ kN/m}^3$, $\gamma_d = 18\text{ kN/m}^3$ and $G = 2.67$

We know, $\gamma_d = \frac{G\gamma_w}{1+e}$

$\therefore$ $18 = \frac{2.67 \times 10}{1+e}$

$\Rightarrow$ $1 + e = \frac{2.67 \times 10}{18} = 1.483$

$\therefore$ $e = 0.483$

We know that,

$$\text{Porosity, } n = \frac{e}{1+e} = \frac{0.483}{1+0.483} = 0.326$$

We have,

Dry density, $\gamma_d = \frac{\gamma_t}{1+w}$

$\therefore$ $18 = \frac{20}{1+w}$

$1 + w = \frac{20}{18} = 1.111$

$w = 0.111$ or 11.11%

Using,

$$Se = wG$$

$$S = \frac{wG}{e} = \frac{0.111 \times 2.67}{0.483} = 0.614 \text{ or } 61.4\%$$

8. Problems of Borrow Pit and Fill

Example 2.14 An embankment is to be constructed. The soil is to be compacted at maximum dry density of 18 kN/m³ at optimum moisture content = 15%. The in-situ bulk density and water content in borrow pit are 17 kN/m³ and 8% respectively. How much excavation should be carried out in the borrow pit for each cubic meter of embankment? Assume $G = 2.7$ and $\gamma_w = 10$ kN/m³.

Solution:

Borrow Pit (1)	Embankment (2)
$\gamma_1 = 17\text{ kN/m}^3$	$\gamma_{d_2} = 18\text{ kN/m}^3$
$w_1 = 0.08$	$w_2 = 0.15$
$G = 2.7$	$\gamma_w = 10\text{ kN/m}^3$

For embankment $\gamma_{d_2} = \frac{\gamma_2}{1+w_2} \Rightarrow \gamma_2 = \gamma_{d_2} \times (1+w_2) = 18 \times (1+0.15)$

$\Rightarrow$ $\gamma_2 = 20.7\text{ kN/m}^3$

Void Ratios:

Borrow Pit (1)	Embankment (2)
$\gamma_1 = \frac{G(1+w_1)}{1+e_1}\gamma_w$,	$\gamma_2 = \frac{G(1+w_2)}{1+e_2}\gamma_w$
$\therefore$ $17 = \frac{2.7(1+0.08) \times 10}{1+e_1}$,	$20.7 = \frac{2.7(1+0.15) \times 10}{1+e_2}$
$e_1 = 0.7153$ and	$e_2 = 0.5$

Volume of solids (V_s) will remain same in both borrow pit and embankment.

$\therefore$ $V_s = \frac{V_1}{1+e_1} = \frac{V_2}{1+e_2}$

$\Rightarrow$ $V_1 = \left(\frac{1+e_1}{1+e_2}\right)V_2$

$\Rightarrow$ $V_1 = \left(\frac{1+0.7153}{1+0.5}\right) \times 1 \text{ cum}$

$\Rightarrow$ $V_1 = 1.143 \text{ cum}$

Hence, the volume of excavation from borrow pit is 1.143 m³ for each cubic meter of embankment.

Example 2.15 The soil in a borrow pit has a void ratio of 0.90. A fill of volume 20000 m³ has to be constructed with an in place dry density of 19.2 kN/m³. If the owner of borrow pit to be compensated at rate 2.5 ₹ per cubic metre of excavation, determine the cost of compensation.

Take $G = 2.68$, $\gamma_w = 9.81$ kN/m³.

Solution:

Borrow Pit (1)	The fill (2)
$e_1 = 0.90$	$\gamma_2 = 18\text{ kN/m}^3$
$G = 2.68$	$\gamma_{d_2} = 19.2\text{ kN/m}^3$
$\gamma_w = 9.81$	

For fill, $\gamma_{d_2} = \frac{G\gamma_w}{1+e_2}$

$\therefore$ $1 + e_2 = \frac{G\gamma_w}{\gamma_{d2}} \Rightarrow \frac{2.68 \times 9.81}{19.2} = 1.37$

$\therefore$ $e_2 = 0.37$

volume of soil solid (V_s) will remain same in both borrow pit and fill.

$$\therefore \quad V_s = \frac{V_1}{1+e_1} = \frac{V_2}{1+e_2}$$

$$\therefore \quad V_1 = \left(\frac{1+e_1}{1+e_2}\right)V_2$$

$$\Rightarrow \quad V_1 = \left(\frac{1+0.90}{1+0.37}\right)\times 20000$$

$$\Rightarrow \quad V_1 = 27737.3\ m^3$$

Cost of compensation to be given to the owner of borrow pit,

$$= 2.50\ ₹/m^3 \times 27737.3\ m^3$$

$$= ₹\ 69343.25$$

Example 2.16 Soil is to be excavated from a borrow pit which has a density of 1.75 gm/cc and water content of 12%. The specific gravity of soil particles is 2.7. The soil is compacted so that water content is 18% and dry density is 1.65 gm/cc. For 1000 m³ of soil in fill, estimate

(i) quantity of soil to be excavated from the pit in m³,

(ii) amount of water to be added.

Also, determine the void ratios of the soil in borrow pit and fill.

Solution:

Borrow Pit (1)	The fill (2)
$\rho_1 = 1.75$ g/cc	$V_2 = 1000\ m^3$
$w_1 = 12\%$	$w_2 = 18\%$
$G = 2.7$	$\rho_{d_2} = 1.65$ g/cc

(i)
$$\rho_{d_1} = \frac{\rho_1}{1+w_1} = \frac{G\rho_w}{1+e_1}$$

$$\Rightarrow \quad \frac{1.75}{1+0.12} = \frac{2.7\times 1}{1+e_1} \quad \Rightarrow \quad e_1 = 0.728$$

and
$$\rho_{d_2} = \frac{G\rho_w}{1+e_2}$$

$$1.65 = \frac{2.7\times 1}{1+e_2} \quad \Rightarrow \quad e_2 = 0.636$$

We know that volume of solids in borrow pit and fill is same

$$\Rightarrow \quad V_s = \frac{V_1}{1+e_1} = \frac{V_2}{1+e_2}$$

$$\therefore \quad V_1 = \left(\frac{1+e_1}{1+e_2}\right)V_2$$

$$\Rightarrow \quad V_1 = \left(\frac{1+0.728}{1+0.636}\right)\times 1000$$

$$\Rightarrow \quad V_1 = 1056.23\ m^3$$

Hence, 1056.23 m³ of soil is to be excavated from the borrow pit.

(ii) We know that,

$$V_{s_2} = \frac{V_2}{1+e_2} = \frac{1000}{1+0.636} = 611.25\ m^3$$

$$\therefore \quad \text{weight of solids} = W_s = V_s\gamma_s$$

$$\Rightarrow \quad W_s = V_s G\gamma_w$$

$$\Rightarrow \quad W_s = 611.25 \times 2.7 \times 9.81$$

$$\therefore \quad W_s = 16190.18\ kN$$

Now, moisture content,
$$w_1 = \frac{W_{w_1}}{W_s}$$

$$\Rightarrow \quad W_{w_1}\ \text{(weight of water in pit)} = w_1 \times W_s = 0.12 \times 16190.18 = 1942.8$$

and $$W_{w_2}\ \text{(weight of water in fill)} = 0.18 \times 16190.18 = 2914.23\ kN$$

$$\therefore \quad \text{amount of water added} = W_{w_1} - W_{w_2}$$

$$= 2914.23 - 1942.8 = 971.43\ kN \text{ or } \frac{971.43}{9.81}\ kg$$

$$= 99.02 \times 10^3\ kg$$

2.5 Relative Density (I_D or D_r)

- Relative density is also called degree of density or density index.
- It is the index which quantifies the degree of packing between the loosest and densest packing of coarse grained soil.

$$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \quad \text{or} \quad \frac{\dfrac{1}{\gamma_{min}} - \dfrac{1}{\gamma}}{\dfrac{1}{\gamma_{min}} - \dfrac{1}{\gamma_{max}}} \times 100$$

where, e_{max} = void ratio in loosest state
e_{min} = void ratio in densest state
e = void ratio in natural state

- It is the most important property of a coarse grained soil.
- Coarse grained soil can be classified on the basis of relative density as given below.

I_D (%)	0 - 15	15 - 35	35 - 65	65 - 85	85 - 100
Classification	Very loose	Loose	Medium	Dense	Very loose

NOTE

It is better indicator of denseness of solid than void ratio and dry unit weight, as it represents the relative compactness in absolute terms.

Soils having similar shape and grain size distribution exhibit different properties if their relative density differs.

This term is not used for cohesive soils as uncertainties are involved in computation of void ratio of cohesive soils in their loosest state in the laboratory.

Example 2.17 A saturated sand deposit have natural moisture content of 30%. It was noticed that the maximum and minimum void ratios are 0.95 and 0.40 respectively. Assume specific gravity of sand solid as 2.7. The sand deposit would be classified as

(a) medium (b) dense

(c) loose (d) very dense

Ans. (c)

Given, $w = 0.30$, $S = 1$ and $G = 2.7$

$\therefore$ $$e = \frac{wG}{S} = \frac{0.30 \times 2.7}{1} = 0.81$$

Now we have, $e = 0.81$, $e_{max} = 0.95$ and $e_{min} = 0.40$

Relative density, $$I_D = \frac{0.95 - 0.81}{0.95 - 0.40} \times 100 = 25.45\%$$

Hence, sand deposit would be classified as loose.

Example 2.18 The natural void ratio of a saturated sand sample is 0.6 and its density Index is 60%. If void ratio in loosest state is 0.9, then the water content (for the sand having $G = 2.7$) corresponding to densest state will be

(a) 15% (b) 20%

(c) 30% (d) 50%

Ans. (a)

Given, $e = 0.6$, $I_D = 60\%$ and $e_{max} = 0.9$

Water content corresponding to densest state is given by,

$$w = \frac{Se_{min}}{G} \quad \text{...(i)}$$

$$\% I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

$$0.60 = \frac{0.9 - 0.6}{0.9 - e_{min}}$$

$\therefore$ $$e_{min} = 0.4$$

Hence $$w = \frac{1 \times 0.4}{2.7} = 15\%$$

Hence, option (a) is correct.

Example 2.19. A relative density test was conducted on a sandy soil. The following results were obtained:

$e_{max} = 0.95$, $e_{min} = 0.40$, $I_D = 45\%$ and $G = 2.7$

Calculate the dry density of soil. If a 5 m thickness of this stratum is densified to a $I_D = 70\%$, how much will the stratum reduce in thickness?

Solution:

$$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

$$45 = \frac{0.95 - e}{0.95 - 0.40} \times 100$$

$$0.95 - e = 0.2475$$

$$e \approx 0.70$$

We know, $$\gamma_t = \left(\frac{G + Se}{1 + e}\right)\gamma_w$$

For dry density, $S = 0$

$\therefore$ $$\gamma_d = \frac{G\gamma_w}{1 + e} = 1.588 \text{ g/cc}$$

Considering unit surface area of sample stratum,

$\because$ $$e = \frac{V_v}{V_s} = \frac{V_1 - V_s}{V_s}$$

$$0.70 = \frac{5 - V_s}{V_s} \quad [\because V_1 = 5 \times 1 \times 1 = 5 \text{ m}^3]$$

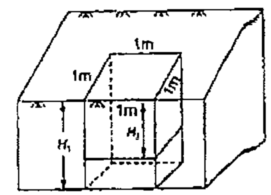
$\therefore$ $$V_s = 2.94 \text{ m}^3$$

If soil stratum is densified to 70% relative density,

$$70 = \frac{e_{max} - e}{e_{max} - e_{min}} \times 100$$

$$0.70 = \frac{0.95 - e}{0.95 - 0.40}$$

$$e = 0.565$$



Also, $$e = \frac{V_v}{V_s} = \frac{V_2 - V_s}{2.94}$$

$\therefore$ $$0.565 = \frac{V_2 - 2.94}{2.94}$$

$$1.661 = V_2 - 2.94$$

$$V_2 = 4.601 \text{ m}^3$$

Therefore, the reduction in thickness is given by

$$H_1 - H_2 = \Delta H = \left(\frac{V_1 - V_2}{A}\right) = \left(\frac{5 - 4.601}{1}\right) = 0.399 \text{ m} \simeq 0.4 \text{ m.}$$

Example 2.20 The density of a sand backfill was determined by field measurements to be 1746 kg/m³. The water content at the time of test was 8.6 percent and the unit weight of the solid constituents was 2.6 g/cm³. In the laboratory the void ratios in loosest and densest states was found to be 0.642 and 0.462 respectively. What was the relative density of the fill?

Solution:

Given, $\gamma = 1746 \text{ kg/m}^3$, $w = 0.086$, $\gamma_s = 2.6$ g/cc

$e_{max} = 0.642$ and $e_{min} = 0.462$

Specific gravity of soil solid,

$$G = \frac{\gamma_s}{\gamma_w} = \frac{2.6}{1} = 2.6$$

Void ratio of soil in natural state may be obtained by using,

$$\gamma = \frac{G(1+w)}{1+e}\gamma_w$$

$$1746 = \frac{2.6(1+0.086)}{1+e} \times 1000$$

$$1 + e = \frac{2.6(1+0.086)}{1746} \times 1000$$

$$e = 1.617 - 1 = 0.617$$

Now,

Relative density, $$I_D = \frac{e_{max} - e}{e_{max} - e_{min}} = \frac{0.642 - 0.617}{0.642 - 0.462} \times 100 = 13.89\%$$

Example 2.21 Compute the void ratio of uniformly graded coarse grained soil in

(i) loosest possible state

(ii) densest possible state

Assuming the soil particles made up of equal diameter spherical shape.

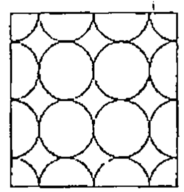
Solution:

(i) In loosest packing, each sphere makes contact with six adjacent sphere-four from side, one from bottom and one from top. Assume each sphere is fitted within a cube of side d as shown in figure.

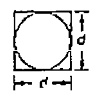
Volume of void, V_v = Volume of cube – volume of sphere

$$= d^3 - \frac{\pi d^3}{6}$$

Thus, the void ratio, $$e = \frac{V_v}{V_s} = \frac{\left[d^3 - \frac{\pi d^3}{6}\right]}{\frac{\pi d^3}{6}} = \frac{\left(1 - \frac{\pi}{6}\right)}{\frac{\pi}{6}} = 0.91$$



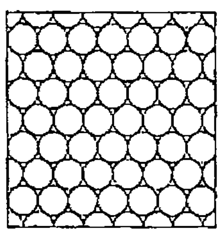
(a) Simple packing of spheres



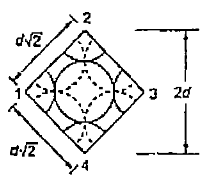
(b) Cubic element from simple packing

Thus, the void ratio in loosest state of packing is 0.91.

(ii) For densest packing, particles are packed as shown in figure.



(a) Face centered cubic packing of spheres



(b) Cubic element from face centered cubic packing

Volume of void, V_v = Volume of cube – volume of sphere within cube

$$V_v = (\sqrt{2}d)^3 - \left[4 \times \frac{\pi d^3}{6}\right] = 2\sqrt{2}d^3 - \frac{2}{3}\pi d^3$$

The void ratio, $$e = \frac{V_v}{V_s} = \frac{\left[2\sqrt{2}d^3 - \frac{2}{3}\pi d^3\right]}{\frac{2}{3}\pi d^3} = \frac{2\sqrt{2} - \frac{2}{3}\pi}{\frac{2}{3}\pi} = 0.35$$

Thus, the void ratio in densest state is 0.35.

2.6 Methods for Determination of Water Content

1. Oven Drying Method

- This is the simplest and most accurate method.
- For inorganic soils, temperature is controlled between 105-110°C.
- For soil containing organic compounds, temperature is maintained about 60°C and if Gypsum is present, then temperature should be maintained at 80°C.
- Usually 4 - 6 hrs are enough for sands to dry but 16 - 20 hrs are required for clay. Usually 24 hrs are provided for drying in the oven.
- If temperature is uncontrolled and more than 110°C, there is a danger of loss of structural water.
- Water content is calculated as follows :

  Let W_1 = weight of empty container

  W_2 = weight of container + moist soil

  W_3 = weight of container + dry soil

  W_w(weight of water) = $W_2 - W_3$

  $W_s = W_3 - W_1$

  $$\therefore \quad w = \frac{W_w}{W_s} \times 100$$

  $$\Rightarrow \quad w = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

  This method is accurate but time taking.

2. Pycnometer Method

- This is a quick method but it is less accurate than oven drying method.
- This method is used only when specific gravity of soil solids is known.
- A small weight, say 200 g to 400 g of soil is placed in a clean pycnometer whose capacity is 900 ml.
- Let W_1 = weight of empty pycnometer bottle

  W_2 = weight of pycnometer + soil

  W_3 = weight of pycnometer + soil + water

  W_4 = weight of pycnometer + water

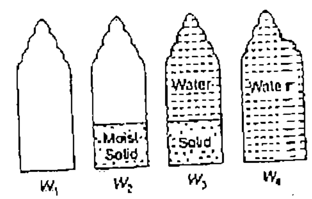


Fig. 2.5 Pycnometer method

Let G be specific gravity of soil solids.

Now, water content, $w = \frac{W_w}{W_s} \times 100$

$$\text{weight of water} = (W_2 - W_1) - W_s \quad ...(i)$$

If from W_3, the weight of solids W_s could be removed and replaced by the weight of an equivalent volume of water, the weight W_4 will be

$$W_4 = W_3 - W_s + \frac{W_s}{G\gamma_w} \cdot \gamma_w$$

$$W_s = (W_3 - W_4)\frac{G}{G-1} \quad ...(ii) \left[\because V_s = \frac{W_s}{\gamma_s} \text{ and } G = \frac{\gamma_s}{\gamma_w}\right]$$

from (i) and (ii),

$$w = \left[\frac{(W_2 - W_4)}{(W_3 - W_4)}\left(\frac{G-1}{G}\right) - 1\right] \times 100$$

NOTE

- In view of the difficulty in removing entrapped air from the soil sample, this method is more suited for cohesionless soil where this can be achieved easily.
- Pycnometer method is suitable for coarse grained soil. But if it is used for fine grained soil, then instead of water kerosene should be used because kerosene has good wetting properties.

3. Calcium Carbide Method/Rapid Moisture Meter Method

- It is very quick method, takes only 5 to 7 minutes but may not give accurate results.
- A soil sample weight 4 - 6 gms is placed in moisture testing equipment. The equipment consists of a closed chamber in which calibrated scale is connected to measure pressure exerted which is directly co-related to water content.
- Calcium carbide powder (CaC_2) is added on the moist soil sample which reacts with the water and as a result acetylene gas is removed which exerts pressure.

  $CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2 \uparrow$
- The water content recorded is expressed as a % of moist weight of soil, whereas actual water content is expressed as fraction of dry weight of soil.

  Let w_r = moisture content recorded, expressed as fraction of moist weight of soil

  w = actual water content

  Then $w = \frac{w_r}{1+w_r} \times 100\%$

4. Sand Bath Method

- It is a quick *field method.*
- This method is used when electric oven is not available.
- Soil sample is put in a container and dried by placing it on the sand bath, then it is heated over a kerosene stove.
- Water content is determined similar to oven drying method.

$$w = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

where, W_1 = weight of empty container
W_2 = weight of container + moist soil
W_3 = weight of container + dry soil

- Since temperature is uncontrolled, hence there is a change of loss of structural water.

5. Alcohol Method

- It is also a quick method adopted in field.
- In this method, methylated sprit is mixed with the soil sample in order to increase the rate of evaporation and then methylated sprit is ignited.

$$w = \frac{W_1 - W_2}{W_2} \times 100$$

where, W_1 = weight of sample
W_2 = weight of soil after cooling of soil + methylated sprit mixture

This method is very rapid but less accurate.

Note: Since alcohol is an oxidising agent, this method should not be used for organic soils and soils containing organic compounds.

6. Torsion Balance Method

- It is a laboratory method
- In this method, *Infrared radiation is used for drying soil sample.*
- In this method, drying and weighing are done simultaneously.
- This method is rapid, accurate and most suitable for soils which quickly reabsorb moisture after drying.

7. Radiation Method

- This is an in-situ method to determine water content of soil.
- In this method, radioactive isotopes are used for the determination of water content of soil.
- A radiating device containing radioactive isotopes like Cobalt 60 is placed inside a capsules and lowered in a steel casing A as shown in figure. Steel casing has a small opening on one side through which rays can come out. A detector is placed inside another steel casing B, which also has an opening facing that of A.

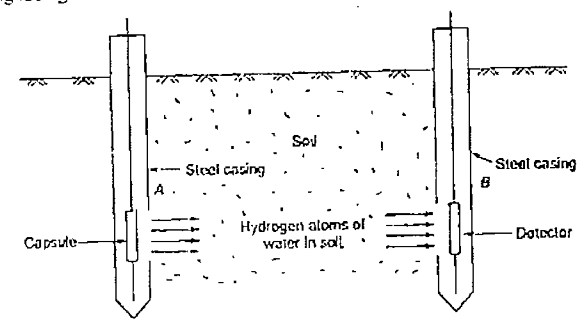


Fig. 2.6 Radiation Method

- Neutrons are emitted by the radio-active material. The hydrogen atoms in water of the soil cause scattering of neutrons. As these neutrons strike with the hydrogen atom, they lose energy. The loss of energy is proportional to the quantity of water present in the soil. The detector is calibrated to give the water contents directly.

2.7 Determination of Specific Gravity of Soil Solids

2.7.1 Pycnometer Method

- This method is similar to Pycnometer method for water content determination, but here oven dry soil is taken instead of moist soil.

Let W_1 = weight of empty pycnometer

W_2 = weight of pycnometer + soil sample (oven dry)

W_3 = weight of pycnometer + soil solids + water

W_4 = weight of pycnometer + water

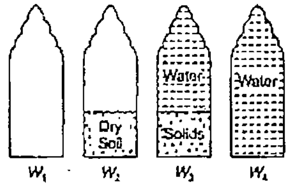


Fig. 2.7 Pycnometer method for determining specific gravity

Weight of solid, $W_s = W_2 - W_1$

Weight of equivalent volume of water

$$= (W_4 - W_1) - (W_3 - W_2)$$

$$\therefore \quad G_s = \frac{\text{weight of solid } (W_s)}{\text{weight of equivalent volume of water}}$$

$$G_s = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_4)}$$

NOTE

- Specific gravity values are generally reported at 27°C (In India)
- If T°C is the test temperature, then G at 27°C is given by

$$G_{27°C} = G_{T°C} \times \frac{\text{unit weight of water at T°C}}{\text{unit weight of water at 27°C}}$$

- If kerosene (better wetting agent) is used instead of water then,

$$G = \frac{W_2 - W_1}{(W_4 - W_1) - (W_3 - W_4)} \times K$$

where, K = specific gravity of kerosene

- G can also be determined indirectly by using shrinkage limit.

Example 2.22 A Pycnometer test for the determination of water content of soil sample having specific gravity of soil solids as 2.70 yielded following data:

weight of moist soil = 800 gm

weight of pycnometer with soil and filled with water = 1875 gm

weight of pycnometer filled with water only = 1545 gm

Calculate the water content of the soil.

Solution:

Given,

$W_2 - W_1$ = weight of moist soil = 800 gm

W_3 = weight of pycnometer + soil + water = 1875 gm

We know,

$$w = \left[\frac{(W_2 - W_1)}{(W_3 - W_4)} \cdot \left(\frac{G-1}{G}\right) - 1\right] \times 100$$

$$\Rightarrow \quad w = \left[\frac{\text{weight of moist sample}}{(W_3 - W_4)} \left(\frac{G-1}{G}\right) - 1\right] \times 100$$

$$\Rightarrow \quad w = \left[\frac{800}{(1875 - 1545)} \times \left(\frac{2.70 - 1}{2.70}\right) - 1\right] \times 100$$

$$\Rightarrow \quad w = [1.526 - 1] \times 100$$

$$w = 52.63\%$$

2.8 Determination of In-Situ Unit Weight

1. Core Cutter Method

- This method is used in the case of cohesive soil.
- This method cannot be used in case of hard and gravelly soils.
- Core-cutter is a cylindrical vessel with open at top and bottom with sharp edges usually having 10 cm dia and 12.5 cm height with volume nearly 1000 cc.
- The soil surface is prepared and levelled in field and cylindrical core-cutter is punched into ground and cylinder filled with soil is taken out, which is levelled at top and bottom.

Let, weight of empty core-cutter = W_1

weight of core cutter + soil = W_2

weight of soil, $W = W_2 - W_1$

Volume of soil sample, V = volume of core cutter = $\frac{\pi}{4} D^2 H$

The In-situ bulk unit weight is given by,

$$\gamma_t = \frac{W}{V}$$

- If water content is known in laboratory, the dry unit weight can also be computed as

$$\gamma_d = \frac{\gamma_t}{1 + w}$$

Example 2.23 A core cutter 12.6 cm in height and 10.2 cm in diameter weighs 1071 g when empty. It is used to determine the in-situ unit weight of an embankment. The weight of core cutter full of soil is 2970 g. If the water content is 6%, then

(i) What are the in-situ dry unit weight and porosity?

(ii) If the embankment gets fully saturated due to heavy rain what will be the increase in water content and bulk unit weight, if no volume change occurs?

The specific gravity of the soil solids is 2.69.

Solution:

(i) Given,

Mass of empty core cutter, $M_1 = 1071$ g

Mass of core cutter + soil sample, $M_2 = 2370$ g

∴ mass of soil sample, $M = M_2 - M_1$

$M = 2970 - 1071$

$M = 1899$ g

Volume of soil sample, V = volume of core cutter

$$= \frac{\pi}{4}D^2H = \frac{\pi}{4}\times(10.2)^2\times 12.6 = 1029.58 \text{ cc}$$

In-situ bulk density, $\rho_t = \frac{M}{V} = \frac{1899}{1029.58} = 1.844$ g/cc

Given, $w = 6\%$ or 0.06

We know, $\rho_d = \frac{\rho_t}{1+w}$

∴ $\rho_d = \frac{1.844}{1+0.06} = 1.74$ g/cc

Hence, in-situ dry unit weight is given by,

$$\gamma_d = \rho_d\times\left(\frac{\gamma_w}{\rho_w}\right) = 1.74\times\left(\frac{9.81}{1}\right)$$

$$\gamma_d = 17.07 \text{ kN/m}^3$$

(ii) Let void ratio of soil is e.

We know, $\gamma_d = \frac{G\gamma_w}{1+e}$

$$17.07 = \frac{2.69\times 9.81}{1+e}$$

$$1+e = \frac{2.69\times 9.81}{17.04} = 1.55$$

∴ $e \simeq 0.55$

When embankment is fully saturated then $S = 1$.

Let w_{sat} is moisture content of soil at saturation,

We know, $Se = w_{sat}G$

$$w_{sat} = \frac{Se}{G} = \frac{1\times 0.55}{2.69}$$

∴ $w_{sat} = 0.205$ or 20.5%

Increase in water content, $\Delta w = 20.5 - 6 = 14.5\%$

Now in-situ bulk unit weight $= \gamma_{sat}$

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

⇒ $\gamma_{sat} = \left(\frac{2.69+0.55}{1+0.55}\right)\times 9.81$

⇒ $\gamma_{sat} = 20.50$ kN/m^3

Thus increase in in-situ bulk unit weight,

$$\Delta\gamma_t = \gamma_{sat} - \gamma_t = 20.50 - 17.07$$

∴ $\Delta\gamma_t = 3.43$ kN/m^3

2. Sand Replacement Method

- This method is used in case of hard and gravelly soils where core-cutter method can not be used.
- In this method, a small pit or hole is made in the ground. The excavated soil is collected in the tray and weigted, say W. Now the pit is filled with sand which is measured through calibrated cylinder. Volume of soil, V = volume of sand required to fill pit completely.
- In-situ unit weight is obtained by dividing weight of excavated soil with volume of hole.

$$\gamma = \frac{W}{V}$$

- The water content of the excavated soil is also determined and the dry unit weight is obtained by using

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

- This method is widely adopted in construction of *highways*.

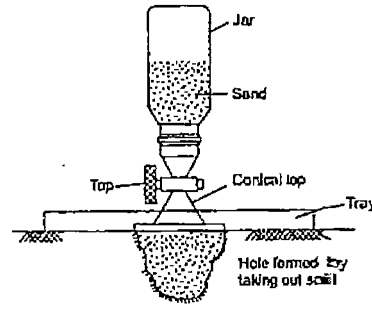


Fig. 2.8 Sand replacement method

Example 2.24 During the soil investigation for a new highway, the following observations were taken at site for the determination of unit weight by sand replacement method.

Weight of excavated soil = 452.30 g

Weight of sand + cylinder (W_1) = 10300 g

Weight of sand + cylinder after pouring the excavated hole and cone (W_2) = 9480 g

Weight of sand + cylinder after pouring for the cone only (W_3) = 9015 g

Weight of sand in calibrating can of 1000 cc after pouring from cylinder = 1580 g

Calculate the in-situ unit weight of the soil.

Solution:

Weight of sand filling the excavation hole and cone = $W_1 - W_2 = 10300 - 9480 = 820$ g

Weight of sand filling cone only = $W_2 - W_3 = 9480 - 9015 = 465$ g

Weight of sand filling hole only = $820 - 465 = 355$ g

$$\text{Unit weight of sand, } \gamma_{sand} = \frac{\text{weight of sand in cylinder}}{\text{volume of cylinder}}$$

$$\gamma_{sand} = \frac{1580}{1000} = 1.58 \text{ g/cc}$$

Volume of excavated soil = volume of hole

$$V = \frac{\text{weight of sand filled in hole}}{\gamma_{sand}} = \frac{355}{1.58} = 224.68 \text{ cc}$$

Thus, in-situ unit weight, $\gamma_{sat} = \frac{W}{V} = \frac{452.30}{224.68} = 2.01$ g/cc

3. Water Displacement Method

- This method is suitable for highly cohesive and sticky type of soil, where it is possible to have a lump sample.
- A small soil sample is taken.
  Let weight of soil sample is = W_1
- Wax is coated over the soil sample and is immersed in a water filled cylinder which displaces water equal to volume of soil + volume of wax say V_w. Let the weight of soil sample + wax = W_2.
  Let unit weight of wax is γ_{wax}. Hence volume of wax is equal to

$$V_{wax} = \frac{W_{wax}}{\gamma_{wax}} = \frac{W_2 - W_1}{\gamma_{wax}}$$

Now, volume of soil sample,

$$V = \text{Volume of water displaced} - V_{wax}$$

$$V = V_w - \frac{(W_2 - W_1)}{\gamma_{wax}}$$

Now, bulk unit weight of soil,

$$\gamma = \frac{W_1}{V}$$

Example 2.25 The weight of soil coated with thin layer of paraffin wax is 690.6 g and the soil alone weighs 683 g. When the soil sample coated with wax is immersed in water, it displaces 350 *ml* of water. The specific gravity of soil is 2.73 and that of wax is 0.89. Find the degree of saturation and void ratio if soil has water content of 17%.

Solution:

Mass of soil alone, $M_1 = 683$ g

Mass of soil + wax, $M_2 = 690.6$ g

Volume of soil + wax = volume of water displaced = V_w = 350 *ml*

∴ Mass of wax alone, $M_{wax} = M_2 - M_1 = 690.6 - 683 = 7.6$ g

Density of wax, $\rho_{wax} = G_{wax} \times \rho_{water} = 0.89 \times 1 = 0.89$ g/cc

∴ Volume of wax, $V_{wax} = \frac{M_{wax}}{\rho_{wax}} = \frac{7.6}{0.89} = 8.53$ cc

Volume of soil sample, $V = V_w - V_{wax} = 350 - 8.53 = 341.47$ cc

∴ Bulk density of soil, $\rho_t = \frac{M_1}{V} = \frac{683}{341.47} \approx 2$ g/cc

Since water content of soil sample *w* is 17%, corresponding dry density can be obtained by

$$\rho_d = \frac{\rho_t}{1+w} = \frac{2}{1+0.17} = 1.71 \text{ g/cc}$$

Also, $\rho_d = \frac{G\rho_w}{1+e}$

⇒ $1.71 = \frac{2.73 \times 1}{1+e}$

∴ $1 + e = \frac{2.73 \times 1}{1.71} = 1.596$

$e = 0.596$

Also, $Se = wG$

$S = \frac{wG}{e} = \frac{0.17 \times 2.73}{0.596}$

∴ $S = 0.778$ or 77.8%

2.9 Index Properties of Soils

In nature, soil occur in different forms. However soils exhibiting similar behaviour can be put into a particular category. Different tests are done to assess the engineering behaviour of soils.

Index properties are those properties which are used for the identification and classification of soils.

Index properties can be divided into two general types:

(i) Soil grain properties
(ii) Soil aggregate properties

The soil grain properties depend on the individual grains of soil mass whereas, soil aggregate properties depends on the soil mass as a whole i.e. soil history, mode of formation or on soil structure. Hence soil 'aggregate properties' are of great engineering importance.

(i) Soil Grain Properties

The most important soil grain properties of soil are:

(a) Grain size distribution: by sieve and sedimentation analysis
(b) Grain shape: Bulky, flaky and needle shaped etc.

(ii) Soil Aggregate Properties

The various soil aggregate properties are:

(a) Unconfined compressive strength (q_u)
(b) Consistency and atterberg's limits
(c) Sensitivity
(d) Thixotropy and soil activity
(e) Relative density

Type of Soil	Index Property
Coarse Soil	Particle size, Grain shape and Relative density
Fine Soil	Atterberg's limit and consistency, unconfined compressive strength, thixotropy and activity

2.10 Particle Size Analysis

Grain Size Distribution

- Grain size analysis of coarse grained soils is carried out by sieve analysis, whereas analysis of fine grained soils is by sedimentation method i.e. either by hydrometer or pipette method.
- Generally, most of the soil contains both coarse as well as fine grain constituents. Hence a combined analysis is usually carried out.
- In combined analysis, dry soil fraction retained on sieve size 4.75 mm is called gravel fraction which is subjected to coarse sieve analysis and soil fraction passing through 4.75 mm sieve is further subjected to fine sieve analysis.
- Fraction passing through 0.075 mm sieve is analysed by hydrometer or pipette method.

I. S. Classification

S.N.	Type of soil	Particle size	Remark
1.	Boulder	> 300 mm	Not considered as soil
2.	Cobbles	80 mm – 300 mm	
3.	Gravel	4.75 mm – 80 mm	Coarse grained soil
4.	Sand	0.075 mm – 4.75 mm	
	(4.1) Coarse sand	2 mm – 4.75 mm	
	(4.2) Medium sand	0.425 mm – 2 mm	
	(4.3) Fine sand	0.075 mm – 0.425 mm	
5.	Silt	0.002 mm – 0.075 mm	Fine grained soil
	(6.1) Coarse	0.02 mm – 0.075 mm	
	(6.2) Medium	0.01 mm – 0.02 mm	
	(6.3) Fine	0.002 mm – 0.01 mm	
6.	Clay	< 0.002 mm	

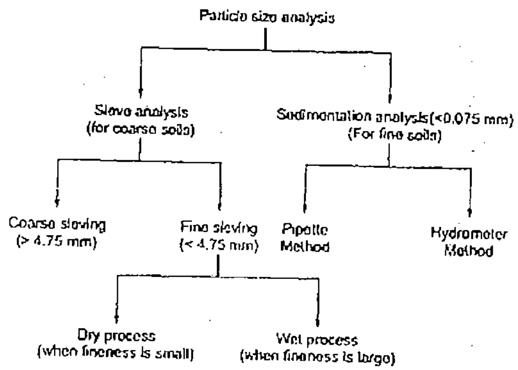


Fig. 2.9

2.10.1 Sieve Analysis

1. **Coarse Sieving**

- The fraction retained on 4.75 mm sieve is called the gravel fraction and is subjected to coarse sieve analysis.
- Sieves are represented either by their number or either by size. IS sieves have square size opening represented in mm or micrometer.
- Sieve no. represents no. of square openings in 1 inch of length. For eg. 0.075 mm size sieve has Sieve no. IS-200.
- The sieves used in coarse seiving are 80mm, 20 mm, 10mm, 4.75 mm (4 No. of sieves)

- The sample is shaken for 10 min. in the shaking machine and weight of soil retained in each sieve is found.

Let, W_i = Weight retained in the i^{th} sieve
W = Total weight of soil sample taken

$$\% \text{ weight retained on } i^{th} \text{ sieve} = \frac{W_i}{W} \times 100$$

$$\text{Cumulative \% retained} = \frac{\text{Total weight of soil retain up to } i^{th} \text{ sieve}}{\text{Total weight of soil taken}} \times 100$$

$$= \sum_{i=1}^{i} \frac{W_i}{W} \times 100$$

$$\% \text{ finer than } i^{th} \text{ sieve } (\%N) = 100 - \text{cumulative \% retained.}$$

Grain Size distribution Curve

- A graph is plotted between % finer and sieve size in semi-log paper. Sieve size (particle dia) is taken on log scale on x-axis and % finer in arithmetic scale in y-axis.
- From the grain distribution curve, size is computed corresponding to 60% finer, 30% finer and 10% finer are computed. They are represented as D_{60}, D_{30} and D_{10} respectively.
- D_{60} is that size below which 60% particles are finer than this size by weight.
- D_{30} is that size below which 30% particles are finer than this size by weight.
- D_{10} is that size below which 10% particles are finer than this size by weight. D_{10} is also called as *effective size*.
- D_{50} is called average size.
- Using D_{60}, D_{30} and D_{10}, following shape parameters are defined for the classification of coarse soils:

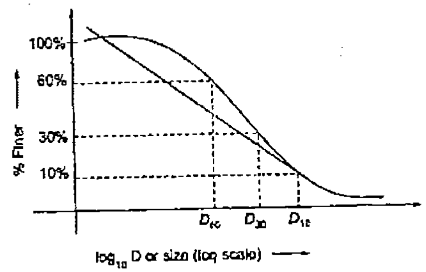


Fig. 2.10 Grain distribution curve

1. Coefficient of uniformity,

$$C_u = \frac{D_{60}}{D_{10}}$$

2. Coefficient of curvature,

$$C_C = \frac{D_{30}^2}{D_{60} \times D_{10}}$$

Typical results of a sieve analysis are shown in figure:

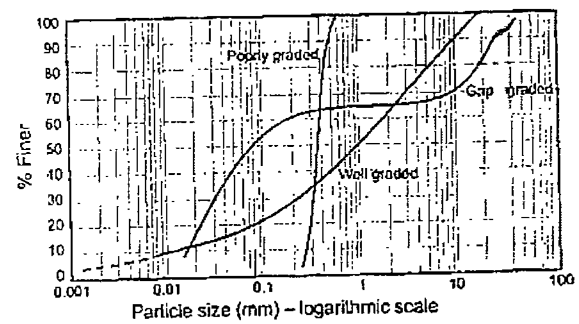


Fig.2.11 Typical Particle size distribution curve

- Well graded means soil particles of all size are present.
  - (i) For well graded gravel $C_u > 4$ and $1 \le C_C \le 3$
  - (ii) For well graded sand $C_u > 6$ and $1 \le C_C \le 3$
- Poorly graded or uniformly graded means soil particle of one size are present predominantly.
- Gap graded means soil particle of same size are missing.
- $C_u \simeq 1$ for uniformly/ poorly graded soil

2. Fine Sieving (Sand Sieving)

- Soil fraction passing through 4.75 mm sieve is subjected to fine sieve analysis.
- It can be performed either in dry state or wet state. Wet sieving is preferred when clay content is present in the sand. So sand is washed to remove the clay.
- In fine sieving, following sieves are arranged in decreasing order as 2 mm, 1 mm, 600 μ-m, 425 μ-m, 150 μ-m and 75 μm.
- The procedure of analysis is same as coarse analysis.

Example 2.26 From the results of a sieve analysis given below, plot a grain-size distribution curve and then determine.

(i) The effective size

(ii) The coefficient of uniformity

(iii) The coefficient of curvature

Weight of soil taken for sieve analysis was 500 g.

Sieve size	Weight of soil retained in each sieve, g
4.75 mm	3.8
2.40 mm	32.2
1.20 mm	52.8
0.60 mm	38.7
0.30 mm	122.5
0.15 mm	15.0
0.075 mm	26.4

Solution:

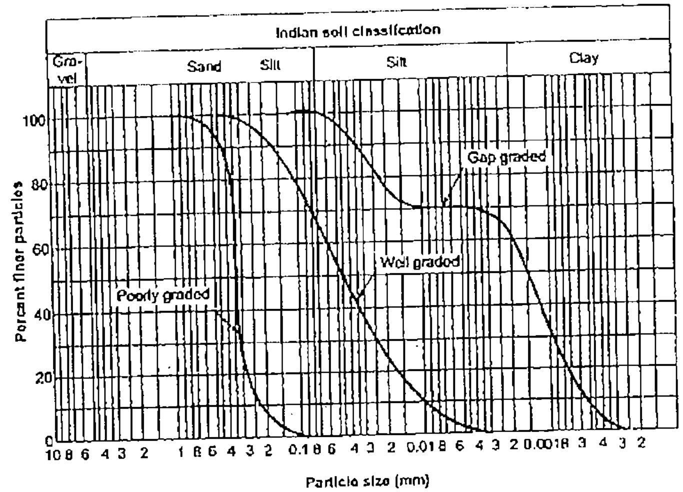
Since, total weight is 500 gm.

$$\therefore \text{Percentage retained on each sieve} = \frac{3.8 \times 100}{500} = 0.76\%$$

Similarly for every sieve size calculation will be done as:

Sieve size (mm)	Weight retained (g)	% Retained on each sieve	% Cumulative retained	% Finer
4.76 mm	3.8	0.76	0.76	99.24
2.40 mm	32.2	6.44	7.20	92.80
1.20 mm	52.8	10.56	17.76	82.24
0.60 mm	38.7	7.74	25.50	74.50
0.30 mm	122.5	24.50	50.00	50.00
0.15 mm	159.9	31.98	81.98	18.02
0.075 mm	26.4	5.28	87.26	12.74

The grain distribution curve is plotted as shown in figure below



From the curve,

(i) Effective size, $D_{10} = 0.07$ mm

(ii) $D_{30} = 0.21$ mm and $D_{60} = 0.41$ mm

$$\therefore \text{Coefficient of uniformity,} \quad C_u = \frac{D_{60}}{D_{10}} = \frac{0.43}{0.07} = 6.14$$

(iii) Coefficient of curvature,

$$C_C = \frac{D_{30}^2}{D_{60} \times D_{10}} = \frac{0.21^2}{0.43 \times 0.07} = 1.47$$

2.10.2 Sedimentation Analysis

- Sedimentation analysis is used to determine grain size distribution of the soil fraction passing through 75 μm size.
- It is based on the 'Stoke's Law'.

Stoke's Law

If a spherical particle falls through infinitely large medium, then it will achieve a constant terminal velocity

Terminal velocity is given as

$$V = \frac{(\gamma_s - \gamma_l)}{18\mu} D^2 = \frac{(\rho_s - \rho_l)}{18\eta} D^2$$

where,

γ_s = unit weight of spherical particle

γ_l = unit weight of liquid

D = dia of falling spherical particle

μ = dynamic viscosity of liquid $\frac{(N-s)}{m^2}$

η = kinematic viscosity m²/sec

Limitations of Stokes Law

1. The analysis is based on the assumption that the falling particle is spherical. But in soils, the finer particles are never truly spherical.
2. Stoke's law considers the velocity of free fall of a single sphere in a liquid of infinite extension, where as the grain size analysis is usually carried out in a glass jar in which the extent of liquid is limited.
3. The fine grains of soil carry charges on their surface and have a tendency for floc formation. If the tendency of floc formation is not prevented, the diameter measured will be the diameter of the floc and not of the individual.

NOTE

- Stokes law is applicable for spheres of diameter between 0.2 mm and 0.0002 mm.
- Spheres of diameter larger than 0.2 mm falling through water causes turbulence, whereas for spheres with diameter less than 0.0002 mm, Brownian motion takes place and the velocity of settlement is too small for accurate measurement.

Procedure of Sedimentation Analysis

First step involved is the preparation of soil sample. Soil sample is mixed with water and suspension is made.

Treatment given to soil sample

1. Pre-treatment: Treatment given before making of soil suspension to remove organic matters and calcium compounds.

   For organic matter-Oxidizing agent is used (e.g. H_2O_2)

   For calcium compounds - Acids are used (e.g. HCl)

2. Post-treatment: It is done after preparation of soil suspension to break the flocs that are formed due to presence of surface electric charges. The dispersing agents (deflocculating agent) used are sodium hexameta phosphate or calgon, sodium oxalate, etc.

   The analysis is carried out by the hydrometer or pipette method. The principle of the test is same in both methods. The difference lies only in the method of making observations.

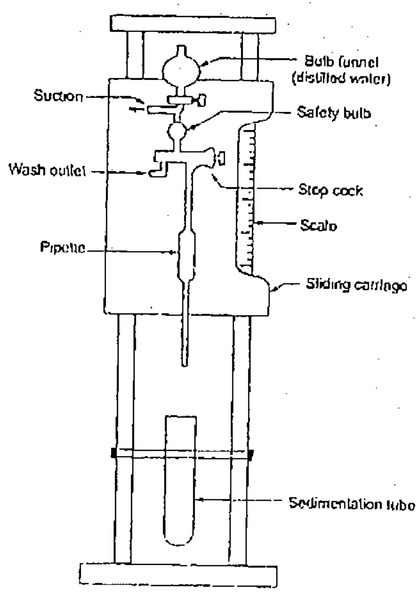


Fig. 2.12 Pipe the method

1. Pipette Method

- 10 ml sample of suspension is drawn off with a pipette from a specified depth from the surface at different time intervals
- This 10 ml sample is put in a container and is dried in oven to get dry unit weight/dry density.

Let m_d be the mass of dried sample obtained from pipette volume (V_P = 10 ml)

Hence, mass per unit volume of dried sample

$$= \frac{m_d}{\text{Volume of piple }(V_P)} = \frac{m_d}{10ml}$$

Let M is the total mass of dry soil which is used to prepare the suspension having total volume of V.

- If dispersing agent as added in the total volume V, of mass.

  Then mass per unit weight of dispersing agent is = $\frac{m'}{V}$

- The mass per unit volume of soil solids at any time interval is given by

$$= \frac{m_d}{V_P} - \frac{m'}{V}$$

- The percentage finer is given by

$$\% N = \frac{\frac{m_d}{V_P} - \frac{m'}{V}}{\frac{M}{V}} \times 100$$

- The diameter of falling particle at any instance of time is given by the Stoke's law

$$\frac{H_o}{t} = V = \frac{(\gamma_s - \gamma_f)D^2}{18\mu}$$

where, H_o = effective depth through which particle settles.

- Observation are taken at regular intervals, a graph is plotted between % finer (%N) and diameter of particle.

Note: In pipette method, sample is collected from height H_o at various time intervals i.e. H_o is fixed.

Example 2.27 In a sedimentation analysis 73 g of soil passing 75 μm is dispersed in 1,000 ml of water. In order to estimate the percentage of particle size less than 0.002 mm, how long after the commencement of sedimentation is the pipette reading to be taken? The sample was drawn 165 mm below the surface of suspension in jar. The specific gravity of soil grain is 2.72 and viscosity of water is 0.001 N-s/m².

Solution:

Given, D = 0.002 mm, μ = 0.001 N-s/m², H_o = 165 mm

Settling velocity,
$$V = \frac{(\gamma_s - \gamma_w)D^2}{18\mu} = \frac{(G_s - 1)\gamma_w D^2}{18\mu}$$

$$= \frac{(2.72 - 1) \times 9.81 \times 10^3 \times (0.002 \times 10^{-3})^2}{18 \times 0.001} = 3.7496 \times 10^{-6} \text{ m/s}$$

$$\therefore \quad V = \frac{H_o}{t}$$

$$3.7496 \times 10^{-6} = \frac{165 \times 10^{-3}}{t}$$

$$t = \frac{165 \times 10^{-3}}{3.7496 \times 10{-}6} = 44004.69 \text{ sec. or } 12.22 \text{ hrs.}$$

Example 2.28 In a pipette analysis, 25 g of soil was dispersed in water, and the suspension was made to a volume 500 m*l*. The viscosity of water is 0.0012 SI units. Seven minutes after the commencement of sedimentation, 10 m*l* of suspension was taken at a depth of 100 mm. The sampled volume was dried and found to have mass of 0.3 g and $G = 2.70$. Compute

(a) Largest size of particle remaining in suspension 7 minutes after the commencement of sedimentation at a depth 100 mm.

(b) The percentage of finer particles.

Solution:

Given, $M = 25$ g, $t = 7$ minutes or 420 sec., $V = 500$ m*l*, $V_p = 10$ m*l*

$\mu = 0.0012$, $H_e = 100$ mm, $m_p = 0.3$ g, $G = 2.70$

Using Stoke's law,
$$V = \frac{(G-1)\gamma_w D^2}{18\mu} = \frac{(G-1)g\rho_w D^2}{18\mu}$$

$$\therefore \quad \frac{H_e}{t} = \frac{(G-1)g\rho_w D^2}{18\mu}$$

$$D = \sqrt{\frac{18\mu H_e}{(G-1)g\rho_w t}} = \sqrt{\frac{18\times0.0012\times100\times10^{-3}}{(2.70-1)\times9.81\times1000\times420}}$$

$$= 1.756\times10^{-5}\ \text{m or } 0.0175\ \text{mm}$$

$$\%\ \text{finer}\ (\%N) = \frac{\frac{m_P}{V_P}-\frac{m'}{V}}{\frac{M}{V}}\times100 = \frac{\frac{0.3}{10}-0}{\frac{25}{500}}\times100 = 60\%$$

2. **Hydrometer Method**

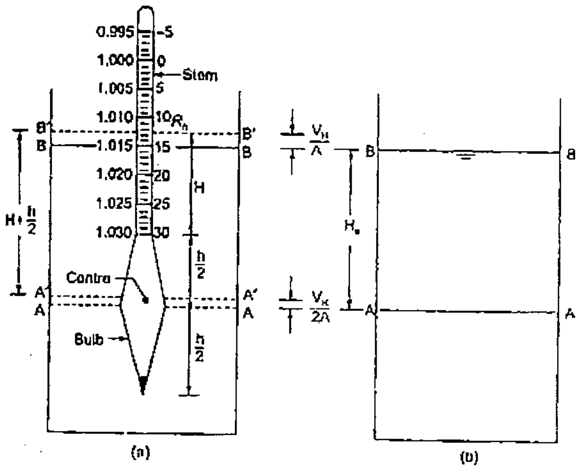


Fig. 2.13 *Hydrometer method*

- It is also based on Stoke's law.
- Hydrometer is a device used to measure specific gravity of *liquids*.
- In this method, the weight of solid present at any time is calculated directly by reading the density of soil suspension.

Calibration of hydrometer: It involves establishing a relation between the hydrometer reading R_H and effective depth (H_e).

The effective depth is the distance from the surface of the soil suspension to the level at which the density of soil suspension is being measured.

- Effective depth is calculated as

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

where, H_1 = distance (cm) between any hydrometer reading and neck

h = length of hydrometer bulb

V_H = volume of hydrometer bulb

A_j = area of the cross section of the jar

- Reading of hydrometer is related to specific gravity or density of soil suspension as :

$$G_{SS} = 1 + \frac{R_H}{1000}$$

Thus a reading of $R_H = 25$ means, $G_{SS} = 1.025$

and a reading of $R_H = -25$ means, $G_{SS} = 0.975$

- % finer is given as :

$$\%\ N = \frac{G}{G-1}\rho_w\left(\frac{V}{W}\right)\left(\frac{R_H}{10}\right)\%$$

where, $G = G_{SS}$ = Specific gravity of soil solids

R_H = Final corrected reading of Hydrometer

V = Total volume of soil suspension

W = Weight of soil mass dissolved in g

Corrections to Hydrometer Reading

Hydrometer readings observed in the test are further corrected for following:

1. Meniscus Correction (C_m)
   - Hydrometer reading is always corresponding to the upper level of meniscus.
   - Therefore, meniscus correction is always positive.
2. Temperature Correction (C_t)
   - Hydrometers are generally calibrated at 27°c. If the test temperature is above the standard (27°C) the correction is added and if below, it is subtracted.
3. Dispersing/Deflocculating agent Correction (C_d)
   - The correction due to rise in specific gravity of the suspension on account of the addition of the deflocculating agent is called dispersing agent correction (C_d)
   - C_d is always negative
   - The corrected hydrometer reading is given by

$$R_{HC} = R_H + C_m \pm C_t - C_d$$

Example 2.29 The corrected hydrometer reading in 1000 ml of soil suspension, 60 minute after commencement of sedimentation is 20. The effective depth from the calibrations is 165 mm. If the particle specific gravity is 2.74 and the viscosity of water is 0.01 poise, calculate

(i) The smallest particle size which would have settled during this interval of 60 minutes.

(ii) % of particle finer than this size.

The total weight of the soil sample taken was 48 grams.

Solution:

Given,

$$V = 1000\,ml$$
$$t = 60 \text{ min or } 3600 \text{ sec.}$$
$$\mu = 0.01 \text{ poise} = 0.01 \times 10^{-1}\,N\text{-}s/m^2$$
$$H_e = 165\,mm$$

(i)
$$\frac{H_e}{t} = \frac{(G-1)\gamma_w D^2}{18\mu}$$

$$D = \sqrt{\frac{18\mu H_e}{(G-1)\gamma_w t}} = \sqrt{\frac{18\times 0.01\times 10^{-1}\times 165\times 10^{-3}}{(2.74-1)\times 9.81\times 3600}}$$

$$= 2.198\,m\times 10^{-5} \text{ or } 0.022\,mm$$

(ii) Percentage finer than particle of size D is given by,

$$\%\,N = \frac{G}{(G-1)}\rho_w\times\left(\frac{V}{W}\right)\times\left(\frac{R_H}{10}\right)\%$$

where, G = sp.gravity of solid

V = volume of soil sample = 1000 ml or 1000 cc.

W = weight of dry soil used to make suspension = 48 g

R_H = corrected Hydrometer reading = 20

$\therefore$
$$\%\,N = \frac{2.74}{(2.74-1)}\times 1\times\left(\frac{1000}{48}\right)\times\left(\frac{20}{10}\right)\% = 65.61\%$$

Example 2.30 In a hydrometer analysis, 45 gm of soil is mixed with distilled water to make 1200 ml suspension. After 45 sec. the reading of hydrometer is 1.015. The depth of suspension below the reading is found to be 140 mm. The dimension of hydrometer are :

Volume of hydrometer = 75 cc

The internal area of jar of Hydrometer = 60 cm^2

Assuming ρ_w = 1g/cc, μ = 0.001 N-s/m^2 and G_s = 2.7

Find out the co-ordinate of the point on the grain size plot.

Solution:

Given,

$$V_H = 75 \text{ cc}, \quad A = 60 \text{ cm}^2$$

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

Here
$$\left(H+\frac{1}{2}h\right) = \text{Depth of suspension below the hydrometer reading}$$
$$= 140 \text{ mm or } 14 \text{ cm}$$

$\therefore$
$$H_e = 14 - \frac{75}{2\times 60} = 13.375 \text{ cm}$$

By Stoke's law, we have
$$D = \sqrt{\frac{18\mu H_e}{(G-1)\gamma_w t}} = \sqrt{\frac{18\times 0.001\times 13.375\times 10^{-2}}{(2.7-1)9.81\times 45}}$$

$$D = 1.7910\times 10^{-4} \text{ m or } 0.179 \text{ mm}$$

Percentage finer (% N) is given by,

$$\%N = \frac{G}{G-1}\rho_w\left(\frac{V}{W}\right)\left(\frac{R_H}{10}\right)\%$$

Since reading of Hydrometer is 1.015 which is density of suspension at the time of observation,

$\therefore$
$$1.015 = 1 + \frac{R_H}{1000}$$

$$\frac{R_H}{1000} = 0.015$$

$\therefore$
$$R_H = 15$$

Hence
$$\%N = \frac{2.7}{(2.7-1)}\times 1\times\left(\frac{1200}{45}\right)\times\left(\frac{15}{10}\right)\% = 63.52\%$$

Thus the coordinate of the point on the grain size curve is (0.179 mm, 63.52)

2.11 Consistency of Clays (Atterberg's Limits)

- Consistency represents relative ease with which a soil can be deformed.
- In practice, consistency is a property associated only with fine grained soils, especially clays.
- Consistency of clays is related to the water content.
- Depending on percentage water content, four stages of consistency are used to describe the state of a clayey soil :
  1. Solid State
  2. Semi Solid State
  3. Plastic State
  4. Liquid State
- The boundary between any two states is called consistency limit. They are also known as Atterberg limits after Swedish scientist Atterberg, who first demonstrated the significance of these limits.

where, V_d = Volume of dry soil mass

= Volume of soil at shrinkage limit

V_P = Volume of soil at plastic limit

V_L = Volume of soil at liquid limit

w_L = Liquid limit

w_P = Plastic limit

w_S = Shrinkage limit

Slope,
$$\frac{dy}{dx} = \text{constant}$$

$$\Rightarrow \quad \frac{V_l - V_P}{w_L - w_P} = \frac{V_P - V_d}{w_P - w_S}$$

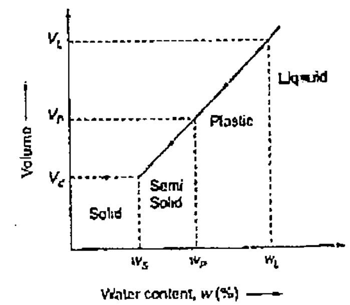


Fig. 2.14 States of clayey soil and consistency limits

- For change in water content corresponding to change in degree of saturation from 0 to 100%, there is no change in total volume of soil. But for water content increasing greater than shrinkage limit (S = 100%), then with change in water content total volume of soil also changes.
- At shrinkage limit all the pores of soil are just filled by water. Hence degree of saturation (S) is 100%.
- Naturally existing soils have water content between w_L and w_P.
- On increase in water content shear strength of soil decreases.
- At liquid limit, all soils have negligible and equal shear strength.

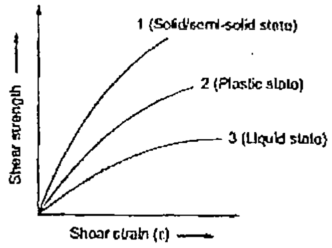


Fig. 2.15 Shear strength behaviour at different soil states

2.11.1 Liquid Limit (w_L)

It is that minimum water content at which soil has tendency to flow. At liquid limit, consistency of soil changes from plastic state to liquid state.

At liquid limit all soil have nearly negligible shear strength of 2.7 kN/m² approximately.

Determination of Liquid Limit: Liquid limit is found out by the following two methods:

(a) Casagrande's apparatus.

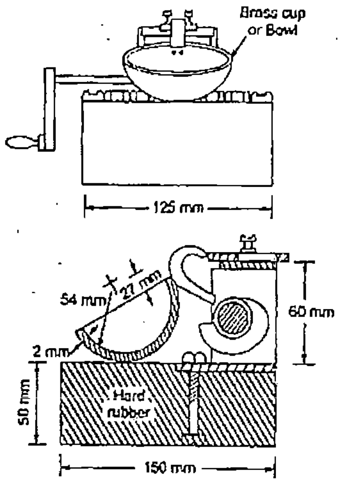
(b) Cone penetration.

(a) Casagrande's apparatus

- About 120 g oven dried soil is taken and mixed with water (say w_1 %) to attain putty like consistency.
- Paste is placed inside casagrande apparatus cup and levelled.
- A groove of 2 mm size is cut and apparatus is given blows over a rubber pad and no. of blows required to close the 2 mm groove is noted as N_1.
- Now same soil is mixed with water content w_2 and no. of blows required to close the 2 mm groove is noted say N_2.
- Same process is repeated with different water content.
- A graph is plotted between % water content and No. of blows in semi log scale.
- The above curve is called flow curve and the slope of above curve is called flow index (I_f).

$I_f = \tan\theta$

$$= \frac{w_1 - w_2}{\log_{10} N_2 - \log_{10} N_1} = \frac{w_1 - w_2}{\log_{10}\left(\frac{N_2}{N_1}\right)} = \text{constant}$$



Standard liquid limit test apparatus

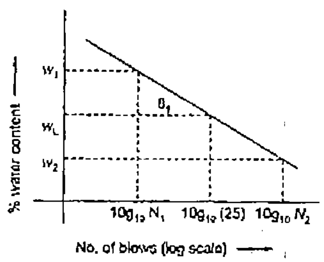


Fig. 2.16 Flow Curve

- If a soil has greater flow index, it means that the rate of loss of shear strength with increase in water content is high.

> **NOTE**
> The Compressibility of soil directly depends on liquid limits. Greater the liquid limit, greater is the compressibility of the soil.
> e.g. For soil X, w_L = 42 %
> soil Y, w_L = 56 %
> Soil Y is more compressible than soil X.
> - Clay have more liquid limit than silt.

(b) Cone Penetrometer Method

The cone penetrometer test is another method recommended by the Indian standards to find the liquid limit.

- To find liquid limit, the penetration of standard cone into soil sample is measured for 30 sec. If the penetration is less than 20 mm, the wet soil is taken out and mixed thoroughly with water and test is repeated till the penetration is between 20 and 30 mm.
- The test is repeated for a variety of water contents, and the *water content corresponding to a penetration of 25 mm is taken as the liquid limit of the sample.*

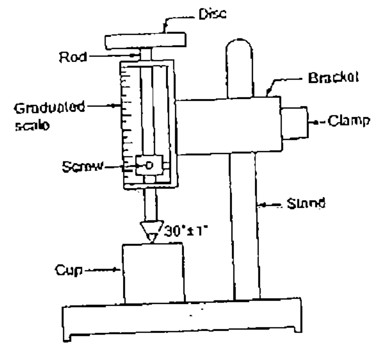


Fig.2.17 Cone Pentrometer

Example 2.31 The relationship between water content (w%) and number of blows (N) in soils, as obtained from casagrande's liquid limit apparatus is given by

$$w = 20 - \log_{10} N$$

The liquid limit of soil is

(a) 15.6 %
(b) 16.6 %
(c) 17.6 %
(d) 18.6 %

Ans. (d)

Liquid limit is also defined as the "water content corresponding to 25 blows to close the 2 mm groove". It means, for liquid limit of soil,

$$N = 25$$

$$\therefore \quad w_L = 20 - \log_{10} 25 = 20 - \log_{10}(5)^2$$

$$w_L = 20 - 2\log_{10} 5 = 20 - 2 \times 0.698 = 18.60\ \%$$

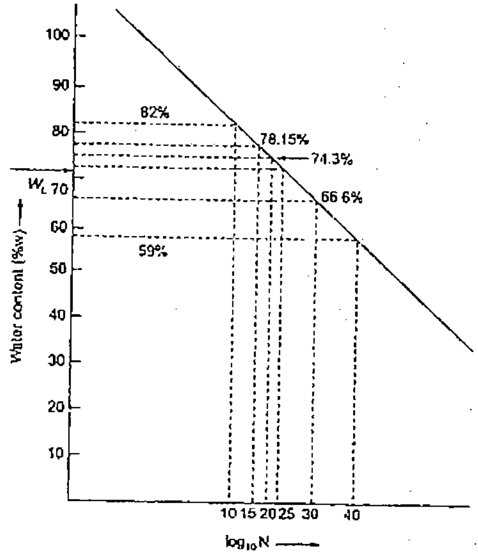
Example 2.32 The results were obtained from a liquid limit test of soil.

No. of blows	10	15	20	30	40
Water content	82.0%	78.15%	74.3%	66.6%	59%

(a) Plot the flow curve and determine liquid limit.

(b) Flow index of soil.

Solution:



(i) From the graph,

$$w_L = w_{20} + \frac{w_{30} - w_{20}}{\log\left(\frac{30}{20}\right)} \log\left(\frac{25}{20}\right)$$

$$w_L = 74.3 + \frac{66.6 - 74.3}{30 - 20} \times 5$$

$$w_L = 74.3 - 4.23 = 70.07\ \%$$

(ii) Flow index,

$$I_f = \frac{w_1 - w_2}{\log_{10}N_2 - \log_{10}N_1} = \frac{82 - 59}{\log_{10}\left(\frac{40}{10}\right)}$$

$$I_f = \frac{23}{2\log_{10}2} = 38.2\%$$

2.11.2 Plastic Limit (w_p)

- The water content at which soil sample changes from semi-solid to plastic state is known as Plastic Limit.
- Plastic limit is also defined as the water content at which soil would just begin to crumble when rolled into a thread of approximately 3 mm diameter.
- Clays have high plastic limit and liquid limit.

  but $LL >> PL$

- Coarse grained soil like sand and gravel have less liquid limit and plastic limit generally.

  $w_L \simeq w_P$

Eg.

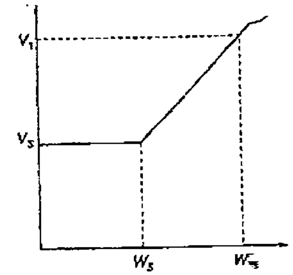
Type of soil	Liquid limit (w_L)	Plastic limit (w_p)
Black cotton soil	400 - 500%	200 - 250%
Alluvial soil (sand)	10 - 50%	10 - 15%

- Plastic limit depends upon amount and type of clay mineral in soil. Hence clay containing fine soils have more plastic limit.

NOTE

- If organic matter is mixed with soil then LL and PL both increases but increase in LL > increase in PL
- If sand is mixed in clays then LL and PL both reduces but decrease in LL > decrease in PL

2.11.3 Shrinkage Limit (w_s)



- A state when the decrease in moisture content leads to solid state, no change in volume of soil mass is observed, the consistency of soil changes from semi-solid to solid state. The boundary water content is called shrinkage limit.
- Shrinkage limit is the smallest value of water content at which soil mass is completely saturated. It means that below shrinkage limit, soil is partially saturated.

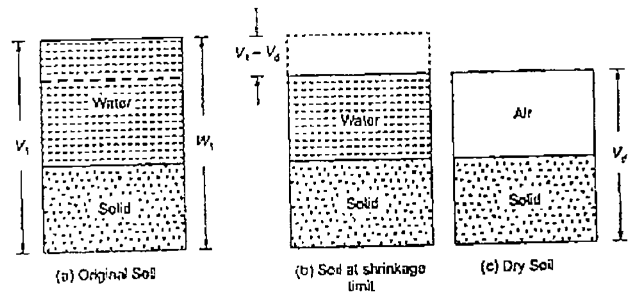


Fig. 2.18 Determination of Shrinkage limit

where,
V_1 = original volume of soil
V_d = dry volume of soil
W_1 = original weight of soil
W_d = W_s = dry weight of soil (solids)
w_1 = natural water content

Shrinkage limit,

$$w_s = \frac{W_w}{W_s} = \frac{(W_1 - W_s) - (V_1 - V_d)\gamma_w}{W_d} = \frac{(W_1 - W_s)}{W_d} - \frac{(V_1 - V_d)\gamma_w}{W_d}$$

$$w_s = w_1 - \left(\frac{V_1 - V_d}{W_d}\right) \times \gamma_w$$

- Shrinkage limit test can be used to determine sp.gravity of soil solids

$$G = \frac{1}{\left(\frac{\gamma_w}{\gamma_d} - \frac{w_s}{100}\right)}$$

where, γ_w = unit weight of water
γ_d = dry unit weight of soil
w_s = % shrinkage limit

- If specific gravity G and void ratio e are known, then

$$w_s = \frac{Se}{G} = \frac{e}{G} \qquad (\because S = 1)$$

- **Shrinkage ratio (R) :** It is defined as the ratio of a given volume change in a soil, expressed as a percentage of the dry volume to the corresponding change in water content above the shrinkage limit.

$$R = \frac{\left(\frac{V_1 - V_2}{V_d}\right) \times 100}{w_1 - w_2}$$

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.

- Special case: At shrinkage limit.

$$w_2 = w_s \text{ and } V_2 = V_d$$

$$\therefore \quad R = \frac{\left(\frac{V_1 - V_d}{V_d}\right) \times 100}{w_1 - w_s}$$

- Shrinkage ratio can also be defined as,

$$R = \frac{\gamma_d}{\gamma_w}$$

- **Volumetric Shrinkage :** It is the percentage loss in volume of soil on drying

$$V_s = \frac{V_1 - V_d}{V_d} \times 100$$

or $\qquad V_s = R(w_1 - w_s)$

- **Degree of shrinkage :** It is the percentage loss in volume of soil on drying corresponding to initial volume.

$$D.O.S. = \frac{V_i - V_d}{V_i} \times 100$$

where, V_i = initial volume of soil sample
V_d = Dry volume of soil sample

Degree of shrinkage	< 5%	5 - 10%	10 - 15%	> 15%
Plasticity	Good	Medium	Poor	Very poor

- **Linear Shrinkage :** It refers to decrease in one dimension of soil expressed as % of initial dimension.

$$L_s = \left[1 - \left(\frac{100}{100 + V_s}\right)^{1/3}\right] \times 100$$

V_s = volumetric shrinkage.

Stress-strain curve for different consistency states :

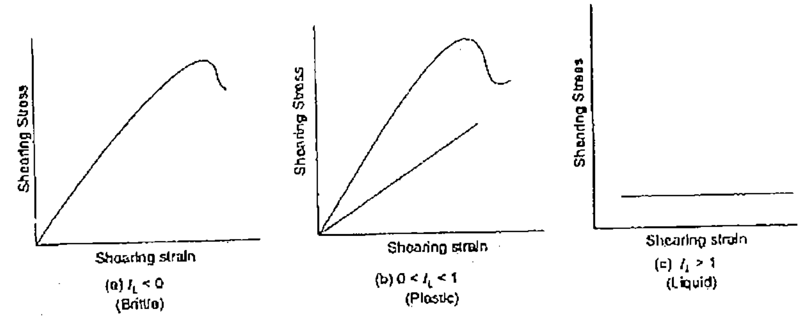


Fig.2.19

Example 2.33 An oven dry soil sample of 200 cm³ weighs 360 g. If the specific gravity is 2.7, determine the void ratio and shrinkage limit. What will be the water content which will fully saturate the sample and cause an increase in volume equal to 10% of the original dry volume.

Solution:

V_d = 200 cm³

Weight of dry soil sample, W_d = 360 g

Specific gravity, G = 2.7

Dry density of sample, $\gamma_d = \frac{W_d}{V_d} = \frac{360}{200} = 1.8$ g/cc

We know, $\gamma_d = \frac{G\gamma_w}{1+e}$

$$1.8 = \frac{2.7 \times 1}{1+e}$$

$\therefore \quad e = 0.5$

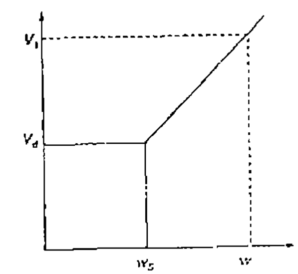
At shrinkage limit, soil is saturated.

$\therefore \quad S = 1$

Using, $S.e = w.G$

At shrinkage limit w = shrinkage limit (w_s)

$$\therefore \quad w_s = \frac{Se}{G} = \frac{1 \times 0.5}{2.7} = 0.185$$



Let w be the water content which will fully saturate the sample and cause an increase in volume equal to 10%.

$\therefore \quad V_1 = 1.1 V_d = 1.1 \times 200 = 220 \text{ cm}^3$

We know,

Shrinkage limit, $w_s = w_1 - \left(\frac{V_1 - V_d}{W_d}\right) \times \gamma_w$

$$0.185 = w - \left(\frac{20}{360}\right) \times 1$$

$\therefore \quad w = 0.24$ or 24 %

Example 2.34 A soil sample of volume 320 cm³ weighs 600 g. On oven drying, the weight of sample reduced to 90% and volume reduced by 12%. Calculate (i) shrinkage limit (ii) specific gravity of solids (iii) shrinkage ratio

Solution:

Given,

$$V_1 = 320 \text{ cm}^3$$
$$W_1 = 600 \text{ g}$$
$$V_d = V_2 = 0.92 \times 320 = 294.4 \text{ cm}^3$$
$$W_d = W_2 = 0.88 \times 600 = 528 \text{ g}$$

(i) Shrinkage limit, $w_s = w_1 - \left(\frac{V_1 - V_d}{W_d}\right)\gamma_w$

where $w_1 = \frac{W_w}{W_s} = \frac{W_1 - W_2}{W_2}$

$$\therefore \quad w_s = \left(\frac{W_1 - W_2}{W_2}\right) - \left(\frac{V_1 - V_d}{W_d}\right)\gamma_w$$

$$= \left(\frac{600 - 528}{528}\right) - \left(\frac{320 - 294.4}{528}\right) \times 1$$

$$= 0.087 \text{ or } 8.78\ \%$$

(ii) $$G = \frac{1}{\left(\frac{\gamma_w}{\gamma_d} - \frac{w_s}{100}\right)}$$

Here, $\gamma_d = \frac{W_d}{V_d} = \frac{528}{294.4} = 1.79$ g/cc

$$\therefore \quad G = \frac{1}{\frac{1}{1.79} - 0.087} = 2.12$$

(iii) Shrinkage ratio, $R = \frac{\gamma_d}{\gamma_w} = \frac{1.79}{1} = 1.79$

Example 2.35 The mass specific gravity of a fully saturated specimen of clay having a water content of 40% is 1.88. On oven drying, the mass specific gravity drops to 1.74. Calculate the specific gravity of clay and its shrinkage limit.

Solution:

For saturated clay,

Mass specific gravity, $G_m = \frac{\gamma_t}{\gamma_w} = \frac{\gamma_{sat}}{\gamma_w}$

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

$$\therefore \quad G_m = \frac{\frac{(G+e)\gamma_w}{(1+e)}}{\gamma_w} = \frac{(G+e)}{1+e}$$

$$\therefore \quad \frac{G+e}{1+e} = 1.88 \qquad \text{...(i)}$$

At saturation, $S = 1$ and $w = 40\ \%$ (given)

$$S.e = w.G$$

$$\therefore \quad e = \frac{w.G}{S} = \frac{0.4G}{1}$$

$$e = 0.4\,G \qquad \text{...(ii)}$$

Substituting value of 'e' in (i), we get

$$\frac{G+0.4G}{1+0.4G} = 1.88$$

$$\therefore \quad G = 2.9$$

Now, mass sp.gravity for dry soil, $G_m = \frac{\gamma_t}{\gamma_w} = \frac{\gamma_d}{\gamma_w}$

$$\therefore \quad \frac{\gamma_d}{\gamma_w} = 1.74 \qquad \text{...(iii)}$$

If specific gravity of soil solids is known, then shrinkage limit may be obtained from the relation,

$$G = \frac{1}{\frac{\gamma_w}{\gamma_d} - \frac{w_s}{100}}$$

$$2.9 = \frac{1}{\left(\frac{1}{1.74}\right) - \left(\frac{w_s}{100}\right)}$$

$$1.67 - \frac{2.9\,w_s}{100} = 1$$

$$\frac{2.9\,w_s}{100} = 0.67$$

$$w_s = \frac{0.67 \times 100}{2.9} = 23.10\%$$

Example 2.36 The values of liquid limit, plastic limit and shrinkage limit of a soil were reported as below : $w_L = 60\ \%$, $w_P = 30\%$ and $w_S = 20\%$. If a sample of this soil at liquid limit has a volume of 40 cc and its volume measured at shrinkage limit was 23.5 cc, determine the specific gravity of the solids. What is the shrinkage ratio and volumetric shrinkage?

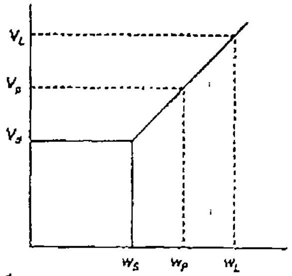
***Solution*:**

Given,

$w_L = 60\%$, $V_L = 40$ cc

$w_S = 20\%$, $V_d = 23.5$ cc

$w_P = 30\%$



Specific gravity of solids,
$$G = \frac{1}{\frac{\gamma_w}{\gamma_d} - \frac{w_s}{100}}$$

The ratio $\frac{\gamma_d}{\gamma_w}$ is known as shrinkage ratio R

$$\therefore \quad G = \frac{1}{\frac{1}{R} - \frac{w_s}{100}} = \frac{1}{\frac{1}{R} - \frac{20}{100}} = \frac{1}{\left(\frac{1}{R} - \frac{1}{5}\right)}$$

$$G = \frac{1}{\frac{1}{R} - 0.2} \quad ...(i)$$

The shrinkage ratio may be given as,
$$R = \frac{\frac{V_1 - V_d}{V_d} \times 100}{w_2 - w_s}$$

Here $V_1 = V_L$ and $w_2 = w_L$

$$\therefore \quad R = \frac{\frac{V_L - V_d}{V_d} \times 100}{w_L - w_s} = \frac{\frac{40 - 23.5}{23.5} \times 100}{60 - 20} = 1.75$$

Substituting value of R in (i), we have
$$G = \frac{1}{\frac{1}{1.75} - 0.2} = 2.70$$

Volumetric Shrinkage,
$$V_s = \frac{V_1 - V_d}{V_d} \times 100$$

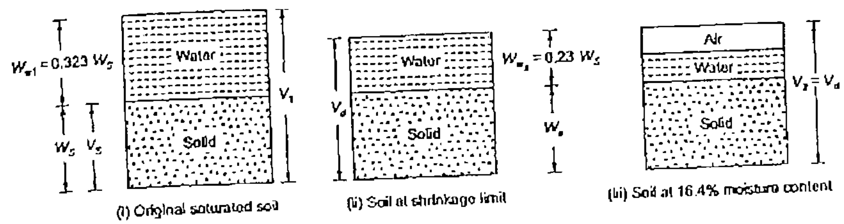
Here, $V_1 = V_L$

$$\therefore \quad \frac{V_L - V_d}{V_d} \times 100 = \frac{40 - 23.5}{23.5} \times 100 \Rightarrow V_s = 70.2\ \%$$

Example 2.37 The natural moisture content of a fully saturated clay is 32.3%. The specific gravity of soil is 2.65. Calculate the percentage decrease to be expected in the unit volume of clay when its moisture content is reduced by evaporation to 16.4%. The shrinkage limit of clay is 23%.

***Solution*:**

Volume of soil at natural condition,
$$V_1 = V_s + V_{w1}$$
$$w = 32.3\ \% \text{ or } 0.323 = \frac{W_{w1}}{W_s}$$
$$\therefore \quad W_{w1} = 0.323\ W_s$$



(i) Original saturated soil (ii) Soil at shrinkage limit (iii) Soil at 16.4% moisture content

$$\Rightarrow \quad V_{w1} = \frac{0.323\ W_s}{\gamma_w} = \frac{0.323\ W_s}{1} \quad [\gamma_w = 1\text{ g/cc}]$$

Thus
$$V_1 = V_s + 0.323\ W_s$$

Similarly, volume of soil at shrinkage limit
$$V_d = V_s + 0.23\ W_s$$

If water content of soil is reduced to 16.4%, it is below the shrinkage limit. Hence the volume of soil at this water content will remain same as shrinkage limit.

$$\therefore \quad V_2 = V_d$$

$$\%\text{ Volume reduction} = \frac{V_1 - V_2}{V_1} \times 100$$

$$= \frac{(V_s + 0.323W_s) - (V_s + 0.23W_s)}{V_s + 0.323\,W_s} \times 100$$

$$= \frac{9.3W_s}{V_s + 0.323W_s} = \frac{9.3W_s}{W_s\left(\frac{V_s}{W_s} + 0.323\right)}$$

$$= \frac{9.3}{\frac{V_s}{W_s} + 0.323} = \frac{9.3}{\left(\frac{V_s}{V_s\gamma_s}\right) + 0.323}$$

$$= \frac{9.3}{\left(\frac{1}{G\gamma_w}\right) + 0.323} = \frac{9.3}{\left(\frac{1}{2.65 \times 1} + 0.323\right)} = 13.28\% \quad \left[\because G = \frac{\gamma_s}{\gamma_w}\right]$$

Example 2.38 An oven dry sample of clay has volume of 250 cc and weight 410 g. If specific gravity of soil solids is 2.74, determine the void ratio and shrinkage limit. Also find % increase in volume of dry soil, when the sample is fully saturated at a water content 32%.

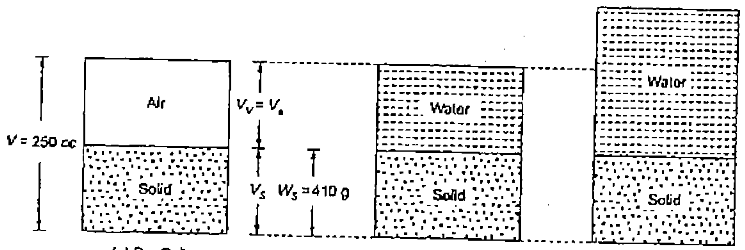
***Solution*:**

Given,

$V_d = 250$ cc

$W_d = 410$ g

$G = 2.74$



(a) Dry Soil (b) Soil at Shrinkage limit (c) Soil at 32% water content

We know,
$$G = \frac{W_s}{V_s\gamma_w}$$

∴ Volume of solid,
$$V_s = \frac{W_s}{G\gamma_w} = \frac{410}{2.74\times 1} = 149.63 \text{ cc}$$

Volume of void,
$$V_v = V - V_s$$

⇒
$$V_v = 250 - 149.63 = 100.37 \text{ cc}$$

∴ Void ratio,
$$e = \frac{V_v}{V_s} = \frac{100.37}{149.63} = 0.67$$

We know,
$$S.e = wG$$

at shrinkage limit,
$$S = 1 \text{ and } w = w_s$$

∴
$$w_s = \frac{e}{G} = \frac{0.67}{2.74} = 0.2448 \text{ or } 24.48\ \%.$$

Volume of soil at 32% moisture,
$$V_2 = V_s + V_w$$
$$w = \frac{W_w}{W_s} = \frac{V_w\times\gamma_w}{W_s}$$

∴
$$V_w = \frac{w\times W_s}{\gamma_w} = \frac{0.32\times 410}{1} = 131.2 \text{ cc}$$

∴
$$V_2 = 149.63 + 131.2 = 280.83 \text{ cc}$$

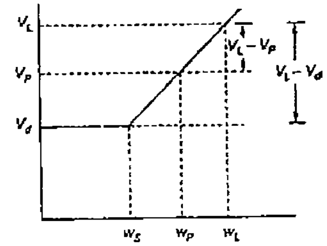
$$\%\ \text{increase in volume} = \frac{V_2 - V_1}{V_1}\times 100 = \frac{280.83-250}{250}\times 100 = 12.33\%$$

Example 2.39: The plastic limit and liquid limit of a soil are 30% and 42 % respectively. The percent volume change from the liquid limit to the dry state is 35% of the dry volume similarly, the percentage volume change from the plastic limit to the dry state is 22% of the dry volume. Determine the shrinkage limit and shrinkage ratio.

Solution:

Given,
$$w_p = 0.30 \text{ and } w_L = 0.42$$
$$V_L - V_d = 0.35\, V_d$$
$$V_P - V_d = 0.22\, V_d$$

From the figure,
$$\frac{dy}{dx} = \text{slope} = \text{constant}$$



$$\frac{V_L - V_P}{w_L - w_P} = \frac{V_L - V_d}{w_L - w_S}$$

$$\frac{1.35V_d - 1.22V_d}{0.42-0.30} = \frac{1.35V_d - V_d}{0.42 - w_S}$$

$$\frac{0.13V_d}{0.12} = \frac{0.35V_d}{0.42 - w_s}$$

$$(0.42 - w_s) = \frac{0.35\times 0.12}{0.13} = 0.323$$

$$w_s = 0.42 - 0.323 = 0.097 \text{ or } 9.7\ \%$$

$$\text{Shrinkage ratio, } R = \frac{\frac{V_1 - V_2}{V_d}\times 100}{w_1 - w_2}$$

Here,
$$V_1 = V_L,\ V_2 = V_P$$

and
$$w_1 = w_L,\ w_2 = w_P$$

∴
$$R = \frac{\frac{V_L - V_P}{V_d}\times 100}{w_L - w_P} = \frac{\frac{1.35V_d - 1.22V_d}{V_d}}{42-30}\times 100 = 1.08$$

2.11.4 Plasticity Index

- It is the range of moisture content over which a soil exhibits plasticity. It is equal to the difference between LL and PL.

$$I_P = w_L - w_P$$

where,
w_L = Water content at LL
w_P = Water content at PL

- This is due to presence of clay minerals.
- For coarse grained soils, there is no plastic zone. Hence LL coincides with PL

∴ $I_P = 0$

- If $PL \geq LL$, then I_P is reported as zero. I_P can never be Negative.

Soil classification based on Plasticity Index

I_P(%)	Soil description
0	Non Plastic
1 to 5	Slight Plastic
5 to 10	Low Plastic
10 to 20	Medium Plastic
20 to 40	Highly plastic
> 40	Very highly plastic

Note: Clay soils possessing high values of liquid limit and plasticity index are referred to as highly plastic or fat clays, and those with low values are described as lean clays.

Plasticity Index of Mixed Soil

Let X_1 % of a soil A having plasticity index I_{P_1}, is mixed with X_2 % of soil B having plasticity index I_{P_2}. Then, I_P of mixed soil will be

$$I_P = \frac{X_1 I_{P_1} + X_2 I_{P_2}}{X_1 + X_2}$$

2.11.5 Shrinkage Index (I_S)

It represents semi-solid state of consistency.

$$I_S = w_P - w_S$$

where, w_P = water content at plastic limit

w_S = water content at shrinkage limit

2.11.6 Consistency Index / Relative Consistency (I_C)

It is defined as a ratio of the difference between the liquid limit and the natural water content of the soil to the plasticity index.

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

where, w_P = water content at PL

w_L = water content at LL

w = natural water content.

% I_c	% Water Content	Consistency
$I_c < 0$	$w > w_L$	Soil is in Liquid State
$0 < I_c < 1$	$w_P < w < w_L$	Soil is in Plastic state
$I_c > 1$	$w < w_P$	Soil is in Solid/semi solid

2.11.7 Liquidity Index (I_L)

It is defined as the ratio of the difference between the natural water content of a soil and its plastic limit to its plasticity index.

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

% I_L	% Water Content	Consistency
$I_L < 0$	$w < w_L$	Solid/semi solid state
$0 < I_L < 1$	$w_P < w < w_L$	Plastic state
$I_L >$	$w > w_L$	Liquid state

Note: Sum of consistency index and liquidity index is always unity.

$\therefore \quad I_C + I_L = 1$

2.11.8 Toughness Index (I_t)

- It is defined as the ratio of plasticity index to the flow index.

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

- It gives an idea about the shear strength of a soil at plastic limit. For the same value of plasticity index, two soils exhibit different toughness based on flow index.
- For most of the soil :

$$0 < I_t < 3$$

- When $I_t < 1$, the soil is easily crushed (friable) at the plastic limit.

2.12 Sensitivity (S_t)

Consistency of a clay sample is altered even at the same water content on its remoulding. This change in consistency or loss of strength takes place due to the following:

(i) Due to permanent destruction of soil solids on remoulding.

(ii) Due to change in orientation of the water molecules in the adsorbed layer of soil solids.

Sensitivity is defined as the ratio of the unconfined compressive strength of an undisturbed specimen of the soil to the unconfined compressive strength of a specimen of the same soil after remoulding at unaltered water content.

$$S_t = \frac{(q_u)\text{undisturbed}}{(q_u)\text{remoulded}}$$

It represents degree of disturbance achieved on remoulding.

Soil classification based on sensitivity:

Sensitivity	% Water Content	Consistency
1 - 4	Normal	Gravel, Coarse sand
4 - 8	Sensitive	Sand
8 - 15	Extra Sensitive	Flocculant structure soil
> 15	Quick	Fine clay

2.13 Thixotropy

It is that property of soil due to which loss in shear strength due to remoulding at unaltered moisture content may be regained.

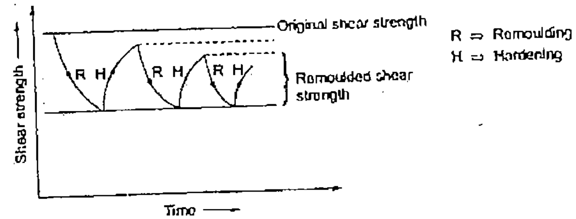


Fig. 2.20

Cohesive soils have greater thixotropy than cohesionless soils.

Higher the sensitivity, larger the thixotropic hardening.

2.14 Unconfined Compressive Strength (q_u)

Defined as the load per unit area at which unconfined cylindrical specimen of standard dimension fails in a simple compression test.

$$q_u = 2C_u$$

where, C_u = cohesion of pure clay

q_u is related to consistency of clays.

q_u (kN/m²)	< 25	25 - 50	50 - 100	100 - 200	200 - 400	> 400
Consistency	Very soft	Soft	Medium	Stiff	Very stiff	Hard

2.15 Activity (A_C)

The behaviour of clay with change in water content is influenced by the presence, magnitude and type of clay minerals.

According to Skempton, Activity is defined as

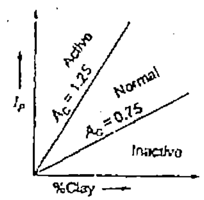
$$A_C = \frac{\% I_P}{\% C}$$

where, I_P = plasticity index

$\%C$ = % of particles which are of clay size i.e. smaller than 2 μm.

Classification of clays, based on Activity

Activity (A_C)	Consistency
< 0.75	Inactive
$0.75 < A_C < 1.25$	Normal
$A_C > 1.25$	Active



- Higher activity means soil is more compressible and represents more change in volume due to moisture variation, hence high active soils are not preferred for foundation works.
- Activity of clay minerals :

Type of minerals	Activity (A_C)
Kaolinite	0.38
Illite	0.90
Montmorillonite	7.2

Note: Black cotton soil and bentonite soils have high content of montmorillonite mineral. Hence they are highly active.

2.16 Collapsibility

- Soils which show large decrease in volume with increase in its water content at same pressure are termed as collapsible soil. For example: Loess.
- Collapsibility of the soil is analysed in terms of a parameter termed as collapse potential.
- Collapse potential is defined as the ratio of change in volume of the soil with increase in water content to its original volume.
- Collapse potential can be determined by performing a simple plate load test in the field.

Collapse potential, $CP = \frac{\Delta V}{V_0} = \frac{\Delta H}{H_0} = \frac{\Delta e}{1+e_0}$

CP%	-	Effect on Structure
0 - 1	-	No trouble
1 - 5	-	Moderate
5 - 10	-	Trouble
10 - 20	-	Severe trouble
> 20	-	Very severe trouble

2.17 Relationship between Atterberg Limits and Engineering Properties

Characteristics	Equal LL (w_L) and Increasing I_P	Equal I_P and Increasing LL (w_L)
Dry Strength	I	D
Toughness	I	D
Compressibility	-	I
Permeability	D	I
Rate of volume change	D	I

where, D = decrease

I = Increase

Example 2.40 A soil has liquid limit 40% and plastic limit of 25 %. Determine the toughness index of soil if flow index is 20%.

(a) 1 (b) 0.25

(c) 0.5 (d) 0.75

Ans. (d)

$$I_P = w_L - w_P$$

$$\Rightarrow I_P = 40 - 25 = 15\ \%$$

$$\text{Toughness index, } I_t = \frac{I_P}{I_f}$$

$$\Rightarrow I_t = \frac{15}{20} = 0.75$$

Hence option (d) is correct.

Example 2.41 A sample of the soil has following properties ;

Liquid Limit = 45 %

Plastic Limit = 25 %

Shrinkage Limit = 17%

Natural Moisture Content = 30%

The consistency index of the soil is

(a) $\frac{15}{20}$ (b) $\frac{12}{20}$

(c) $\frac{8}{20}$ (d) $\frac{5}{20}$

Ans. (a)

Plasticity index,
$$I_P = w_L - w_P$$
$$I_P = 45 - 25 = 20\%$$

Consistency index,
$$I_C = \frac{w_L - w}{I_P} = \frac{45-30}{20} = \frac{15}{20}$$

Hence option (a) is correct.

Example 2.42 A soil has following properties :

Liquid Limit = 35

Plastic Limit = 20

Natural Moisture Content = 25%

Match List -I with List-II and select the correct answer using the code given below :

	List-I		List-II
1.	Liquidity index	A.	15
2.	Plasticity index	B.	33
3.	Shrinkage index	C.	10

Codes :

	1	2	3
(a)	A	B	C
(b)	B	A	C
(c)	C	B	A
(d)	B	C	A

Ans. (b)

Plasticity index,
$$I_P = w_L - w_P$$
$\Rightarrow$
$$I_P = 35 - 20 = 15\%$$

Liquidity index,
$$I_L = \frac{w - w_P}{I_P}$$
$\Rightarrow$
$$I_L = \frac{25-20}{15} = 33\%$$

Shrinkage index,
$$I_s = w_P - w_S$$
$\Rightarrow$
$$I_s = 20 - 10 = 10\%$$

Hence option (b) is correct.

Example 2.43

Atterberg's limit	Soil A	Soil B
Liquid limit	40	0
Plastic limit	15	0

Soil A and Soil B are mixed to prepare a clayey soil of plasticity index of 12, the percentage of sand in the mix should be

(a) 50 (b) 60

(c) 52 (d) 43

Ans. (c)

$$I_{P1} = w_L - w_P = 40 - 15 = 25$$
$$I_{P2} = 0$$

Let percentage of B to be mixed is x

$\therefore$
$$X_2 = x \text{ and } X_1 = 100 - x$$
$$I_{P\,mix} = \frac{X_1 I_{P1} + X_2 I_{P2}}{X_1 + X_2}$$
$$12 = \frac{(100-x)\times 25 + x \times 0}{100}$$
$$1200 = 2500 - 25x$$
$$x = 52\%$$

Hence option (c) is correct.

Example 2.44 The liquid limit and plastic limit of sample are 60% and 30% respectively. The percentage of the soil fraction with grain size finer than 0.002 mm is 20. The activity ratio of the soil sample is

(a) 0.50 (b) 1.00

(c) 1.50 (d) 2.00

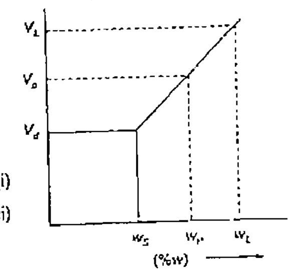
Ans. (c)

$$A_C = \frac{I_P}{\%C} = \frac{w_L - w_P}{\%C}$$
$\Rightarrow$
$$A_C = \frac{60-30}{20} = 1.5$$

Hence option (c) is correct.

Example 2.45 The plastic limit of a soil is 24% and its plasticity index is 8%. When the soil is dried from its state at plastic limit, the volume change is 26% of its volume at plastic limit. The corresponding volume change from the liquid limit to dry state is 35% of its volume at liquid limit. Determine the shrinkage limit and the shrinkage ratio.

Solution:



Given,
$$w_P = 0.24$$
$$I_P = 0.08$$
$$I_P = w_L - w_P = 0.08$$
$\therefore$
$$w_L = 0.08 + 0.24 = 0.32$$
$$V_P - V_d = 0.26\, V_P \text{(given)} \quad ...(i)$$
$$V_L - V_d = 0.35\, V_L \text{ (given)} \quad ...(ii)$$

Substracting (ii) from (i), we get
$$V_P - V_L = 0.26\, V_P - 0.35\, V_L$$
$$1.26\, V_P = 0.65\, V_L$$
$$V_L = 1.138\, V_P \quad ...(iii)$$

From geometry,
$$\frac{dy}{dx} = \text{slope} = \text{constant}$$

$$\frac{w_P - w_S}{V_P - V_d} = \frac{w_L - w_P}{V_L - V_P}$$

$$\frac{0.24 - w_S}{0.26V_P} = \frac{0.32 - 0.24}{1.138V_P - V_P}$$

$$\frac{0.24 - w_S}{0.26} = \frac{0.08}{0.138}$$

or $0.24 - w_S = 0.15$

or $w_S = 0.09$ or 9%

Shrinkage ratio, $$R = \frac{\frac{V_1 - V_2}{V_d} \times 100}{w_1 - w_2} = \frac{\frac{V_L - V_P}{V_d} \times 100}{w_L - w_P}$$

$\Rightarrow$ $$R = \frac{1.38V_P - V_P}{0.74V_P \times (0.32 - 0.24)}$$

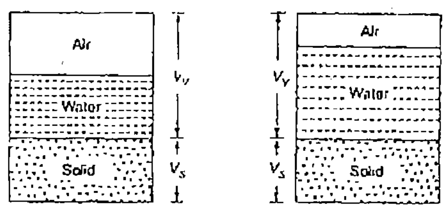
$\Rightarrow$ $$R = \frac{0.138}{0.74 \times 0.08} = 2.33$$

Illustrative Examples

Example 2.46 A clayey soil has saturated moisture content of 15.8%. The specific gravity is 2.72. Its saturation percentage is 70.8%. The soil is allowed to absorb water. After some time, the saturation increased to 90.8%. Find the water content of the soil in the later case.

Solution:

$$G = 2.72,\ S = 70.8,\ w = 15.8\%$$



(a) case I (b) case II

In Case I,

Void ratio, $$e = \frac{wG}{S} = \frac{0.158 \times 2.72}{0.708} = 0.607$$

Since degree of saturation is within $0 < S < 100\%$. Hence volume of void remain same.

$\therefore$ $e_1 = e_2$

$\therefore$ $$w = \frac{0.908 \times 0.607}{2.72} = 0.2036 \text{ or } 20.36\%$$

Example 2.47 A cohesive soils yields maximum dry density of 1.8 g/cc at an optimum moisture content of 16%. If $G_s = 2.65$, then find the degree of saturation. Also determine the maximum dry density which can be possible to achieved.

Solution:

Given, $\rho_{d,\,max} = 1.8$ g/cc

$w = 16\%$ or 0.16

$G = 2.65$

We know, $$\rho_d = \frac{G\rho_w}{1+e}$$

$\therefore$ $$e = \frac{2.65 \times 1}{1.8} - 1 = 0.472$$

Also, $S.e = wG$

$$S = \frac{wG}{e} = \frac{0.16 \times 2.65}{0.472} = 0.89 \text{ or } 89\%$$

Theoritical maximum dry density will be achieved when all the air present in the voids escaped out. i.e. all voids are just filled by water only.

$\therefore$ For condition of theoritical maximum dry density,

$S = 100\%$ or 1

$S.e = w.G$

$$e = \frac{wG}{S} = \frac{0.16 \times 2.65}{1} = 0.424$$

$\therefore$ Theoritical maximum density, $$\rho_{d,max} = \frac{G\rho_w}{1+e} = \frac{2.65 \times 1}{1 + 0.424} = 1.86 \text{ g/cc}$$

Example 2.48 You are a project engineer on a large dam project that has a volume of 800,000 m³ of selected fill, compacted such that the final void ratio in the dam is 0.80. The project manager delegates to you the important decision of buying the earth fill from one of the three suppliers. Which one of the three suppliers is the most economical and how much will you save.

Supplier *A*	sells fill at 5 ₹/m³	with	e = 1.50
Supplier *B*	sells fill at 10 ₹/m³	with	e = 0.20
Supplier *C*	sells fill at 12 ₹/m³	with	e = 1.60

Solution:

Without considering void ratio, it would appear that supplier *A* is cheaper than *B* by 5 ₹/m³.

Volume of solid needed for dam site, $$V_s = \frac{V}{1+e} = \frac{800{,}000}{1+0.80} = 444{,}444 \text{ m}^3$$

Volume of soil required to be taken out from suppliers,

Supplier *A*, $V_A = V_s(1+e) = 4444{,}44\ (1 + 1.50) = 1{,}111{,}110 \text{ m}^3$

Supplier *B*, $V_B = V_s(1+e) = 444.444\ (1 + 0.2) = 544{,}442 \text{ m}^3$

Supplier *C*, $V_C = V_s(1+e) = 444{,}444\ (1 + 1.6) = 1155{,}555 \text{ m}^3$

Cost of bills,

Supplier *A*, $A = 1{,}111{,}110 \times 5 = 5{,}555{,}550$ ₹

Supplier *B*, $B = 533{,}332 \times 10 = 5{,}333{,}320$ ₹

Supplier C, $C = 1155,555 \times 12 = ₹\ 13,866,660$

Therefore supplier B is more economical, and we save

$₹ = 5,555,550 - 5,333,320 = 222,230$

Example 2.49 **The fines fraction of a soil to be used for a highway near Hapur was subjected to a hydrometer analysis be placing 25 g of dry soil in 100 ml solution of water (μ = 0.01 poise at 20°c). The specific gravity of the solid was 2.65.**

(a) Estimate the maximum diameter D of the particle found at a depth of 5 cm after a sedimentation of 4 hour has elapsed, if the solution's concentration has reduced to 2 g/lit at the level.

(b) What % of the sample would have a diameter smaller than D?

Solution:

Given,

$$W_1 = 25\text{ g},\ V = 1000\text{ m}l \text{ or } 1000\text{ cc}$$

$$t = 4\text{ hrs} = 14,400\text{ sec},\ H_e = 5\text{ cm},\ \mu = 0.01\text{ Poise} = 0.001\text{ Ns/m}^2$$

(a) Using Stoke's law,

$$V = \frac{\gamma_w (G-1)}{18\mu} D^2 = \frac{H_e}{t}$$

$$\therefore \quad D = \sqrt{\frac{18\mu H_e}{\gamma_w (G-1) t}} = \sqrt{\frac{18 \times 0.001 \times 5 \times 10^{-2}}{9.81 \times (2.65-1) \times 14400}}$$

$$= 6.2 \times 10^{-5}\text{ m} = 0.062\text{ mm}$$

(b) Concentration of solution $= \frac{2g}{l}$ = 2g soil solids in 1 litre

unit weight of solution after 4 hrs,

$$\gamma = \frac{\text{weight of solution}}{\text{volume of solution}} = \frac{W_S + W_w}{V} = \frac{W_s + (V - V_S)\gamma_W}{V}$$

$$\gamma = \frac{2g + \left[V - \frac{W_S}{G\gamma_w}\right] \times \gamma_w}{V} \qquad \left[\because G = \frac{W_S}{V_S \gamma_w}\right]$$

$$\gamma = \frac{2 + \left[1000 - \frac{2}{2.65 \times 1}\right] \times 1}{1000} = 1.001\text{ g/cc}$$

But

$$\gamma = 1 + \frac{R_H}{1000}$$

$$\therefore \quad R_H = 1.245$$

% finer than particle of size 0.0615 m

$$\% = \frac{G}{G-1} \gamma_w \left(\frac{V}{W_1}\right)\left(\frac{R_H}{10}\right)\%$$

$$= \frac{2.65}{2.65-1} \times 1 \times 1\left(\frac{100}{25}\right) \times \left(\frac{1.245}{10}\right) = 8\%$$

Summary

- Soil mass in general is a three phase system composed of solid, liquid and gas.
- Fine grained soils have higher values of natural moisture content as compared to coarse grained soils.
- Void ratio of fine grained soils are generally higher than those of coarse grained soils.
- The unit weight /density of soil (dry, saturated or submerged) is a function of void ratio and moisture content.
- Consistency limits or Atterberg limits viz. liquid limit, plastic limit, and shrinkage limit are the water content at the change of states from liquid to plastic, plastic to semi-solid and semisolid to solid state respectively.
- Plasticity Index refers to the range over which soil exhibit plasticity.
- The sum of consistency index and liquidity index is always unity.
- Thixotropy of soil is that property of soil due to which soil regains some part of its lost strength during remoulding.

Objective Brain Teasers

Q.1 In its natural condition, a soil sample has a mass of 2290 gm and a volume of 1.15×10^{-3} m³. After being completely dried in an oven, the mass of the sample is 2035 gm. The value of G for the soil is 2.68. Match List-I (Property) with List-II (Values) and select the correct answer using the codes given below:

List-I	List-II
A. Void ratio	1. 0.510
B. Porosity	2. 0.337
C. Degree of saturation	3. 0.657
D. Air content	4. 0.343

Codes:

	A	B	C	D
(a)	1	3	2	4
(b)	1	2	3	4
(c)	2	4	3	1
(d)	4	3	2	1

Q.2 A mass of soil coated with a thin layer of paraffin wax weighs 700 gm and soil alone weighs 650 gm. When soil sample is immersed in water it displaces 400 mL of water. The specific gravity of soil is 2.65 and that of wax is 0.9 and water content is 20%, ρ_w = 1000 kg/m³. Void ratio of soil is

(a) 0.81 (b) 0.59
(c) 0.73 (d) 0.69

Q.3 Sieve analysis is done on a soil sample and following observation were made:

Size of sieve	% Retained
4.75 mm	36
75 micron	90

Size of particle for which 60% particles are finer = 5 mm

Size of particle for which 30% particles are finer = 3 mm

Size of particle for which 10% particles are finer = 1 mm

On further testing the finer particles, it was found that:

Liquid limit = 50%

Plastic limit = 35%

Based on the above information, according to Indian soil classification system, the soil is

(a) SW – SC (b) SP – SM
(c) GW – GC (d) None of these

Answers

1. (b) 2. (d) 3. (d)

Hints and Explanations:

1. (b)

Mass of the soil solid,

$$m_s = 2290 \text{ gm}$$

Mass of dry soil

$$m_d = 2035 \text{ gm}$$

Specific gravity

$$G = 2.68$$

Volume, $V = 1.15 \times 10^{-3} \text{ m}^3$

∴ Density of dry soil

$$\gamma_d = \frac{2035 \times 10^{-3}}{1.15 \times 10^{-3}} = 1769.565 \text{ kg/m}^3$$

$$\because \quad \gamma_d = \frac{G\gamma_w}{1+e}$$

$$\Rightarrow \quad 1769.565 = \frac{2.66 \times 1000}{1+e}$$

$$\Rightarrow \quad e = 0.51$$

∴ Void ratio, $e = 0.51$

Porosity $n = \frac{e}{1+e} = 0.338$

Water content

$$w = \frac{m_w}{m_d} = \frac{2290 - 2035}{2035} = 0.125$$

$$m_d = \frac{m}{1+w}$$

$$\Rightarrow \quad 2035 = \frac{2290}{1+w}$$

$$\Rightarrow \quad w = 0.125$$

$$\therefore \quad wG = eS$$

$$\Rightarrow \frac{0.125 \times 2.68}{0.51} = S$$

$$\Rightarrow \quad S = 0.657$$

∴ Degree of saturation = 0.657

Air content, $= 1 - S = 1 - 0.657 = 0.343$

2. (d)

$$M_{wax} = 700 - 650 = 50 \text{ gm}$$

$$\gamma_{wax} = 0.9 \times 1 = 0.9 \text{ gm/cc}$$

$$V_w = V_1 + V_{wax}$$

$$V_1 = V_w - V_{wax} = 400 - \frac{M_{wax}}{\gamma_{wax}}$$

$$V_1 = 400 - \frac{50}{0.9} = 344.4 \text{ ml.}$$

$$\rho = \frac{M}{V_1} = \frac{650}{344.4} = 1.89 \text{ gm/cc}$$

$$\rho_d = \frac{\rho}{1+w} = \frac{1.89}{1.20} = 1.57 \text{ gm/cc}$$

$$\rho_d = \frac{G\rho_w}{1+e}$$

$$1.57 = \frac{2.65 \times 1}{1+e}$$

$$e = 0.69$$

3. (d)

% retained on 75 micron sieve is 90%

∴ Soil is coarse

% Gravel = 36

% Sand = 90 − 36 = 54

More than half of coarse fraction is sand

$$D_{60} = 5 \text{ mm}$$

$$D_{30} = 3 \text{ mm}$$

$$D_{10} = 1 \text{ mm}$$

$$C_u = \frac{D_{60}}{D_{10}} = \frac{5}{1} < 6$$

Finer analysis: It is poorly graded

$$I_p = \text{Liquid limit} - \text{Plastic limit} = 50 - 35 = 15\%$$

A-line, $I_p = 0.73(w_L - 20) = 0.73(50 - 20) = 21.9$

This will lie above A-line, therefore, it is clay.

Soil is SP - SC.

Student's Assignments

Q.1 A soil sample with specific gravity of solids 2.70 has a mass specific gravity of 1.84. Assuming the soil to be perfectly dry, determine the void ratio.

[Ans. 0.47]

Q.2 An oven dry soil sample of volume 250 cc weight 430 g. If the specific gravity of solids is 2.70, what is the water content when the soil becomes fully saturated without any change in its volume? What will be the water content which will fully saturate the sample and also cause an increase in volume equal to 10% of the original dry volume? Use phase diagram.

[Ans. 21.1%, 26.9%]

Q.3 An airport runway fill needs 600,000 m³ of soil compacted to a void ratio of 0.75. There are two borrow pits A and B from where the required soil can be taken and transported to the site.

Borrow pit	In situ void ratio	Transportation cost
A	0.80	₹ 10/m³
B	1.70	₹ 5/m³

Which of the two borrow pits would be more economical?

[Ans. ₹ 6171430, ₹ 4628570]

Q.4 An undisturbed sample of clay brought from the field was noted to have a volume of 18.0 cc and weight of 30.8 g. On over drying, the weight of the sample was reduced to 20.5 g. The volume of dried sample as obtained by displacement of mercury was 12.5 cc. Calculate the shrinkage limit and the specific gravity of solids. What is the shrinkage ratio?

[Ans. 1.64]

Q.5 A natural soil deposit has a bulk unit weight of 18 kN/m³ and a water content of 5%. Calculate the amount of water in litres required to be added to 1 cu m of soil to raise the water content to 15%. Assume the void ratio to remain constant. What will be the degree of saturation? Take $G_s = 2.60$.

[Ans. 174 liters; S = 79.6%]

Q.6 The dry unit weight of a 4 m thick stratum of coarse sand is 15 t/m³. Calculate the quantity of cement grout slurry required per meter run for providing a 2 m thick grout curtain through this stratum. G_s of sand grains = 2.68.

[Ans. 3.43 m³]

Q.7 A sample of soil with a liquid limit of 72.8% was found to have a liquidity index of 1.21 and water content of 81.3%. What are its plastic limit and plasticity index? Comment on the consistency of the soil.

[Ans. 32.3%, 40.5%]

Q.8 A soil has a liquid limit of 50% and plasticity index of 20. When the soil at its liquid limit was dried, the percentage decrease in volume was 40% of its dry volume. When it was dried from its plastic limit, the percentage decrease in volume as 20% of its dry volume. Determine the shrinkage limit of the soil and its shrinkage ratio.

[Ans. 10%, 1.0]

Q.9 A sample of sand from a natural deposit has a porosity of 35%. For a volume of 495 cc, the dry weight in the densest and loosest states are 950 and 700 g, respectively. Compute the relative density of sand assuming the specific gravity of solids to be 2.65.

[Ans. 67.9%]