CIVIL ENGINEERING

Soil Mechanics and Foundation Engineering

Comprehensive Theory
with Solved Examples *and* Practice Questions

MADE EASY
Publications

Soil Mechanics and Foundation Engineering

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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 of some solid (soil grains), some liquid (pore water) and some gas (pore air). The proportion of these phases affects the properties of soil.

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.
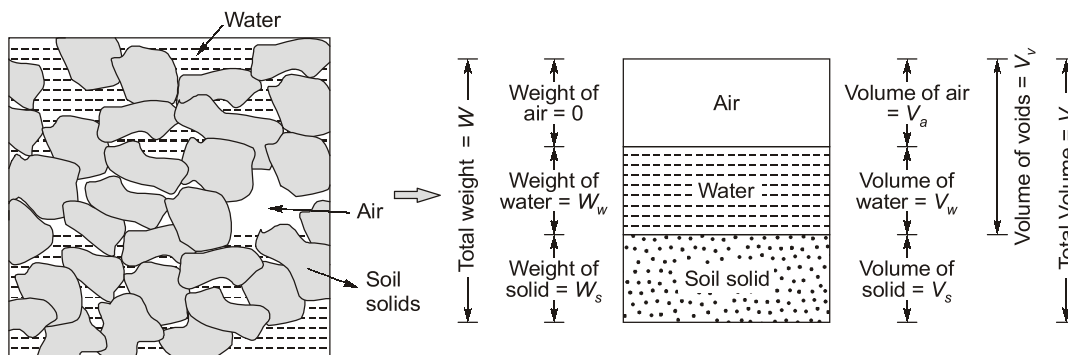
Fig. Three Phase diagram

- In phase diagrams, the weight of air is negligible as compared to soil solid and water and is thus assumed to be zero.
- 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)
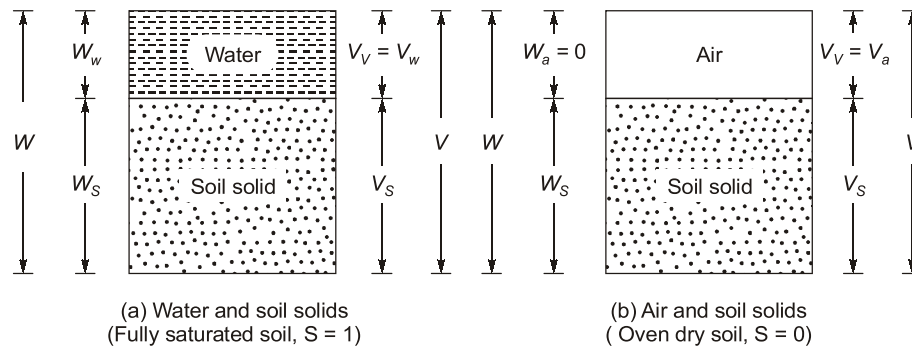
Fig. Two Phase diagram

2.3 BASIC DEFINITIONS

2.3.1 Water Content (*w*)

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

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

- It is generally 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.
> 4. Water content can also be represented in terms of total weight of soil mass.
>
> $$w' = \frac{\text{weight of water}}{\text{Total weight of soil mass}} \times 100$$
>
> $$w' = \frac{W_w}{W} \times 100 = \frac{M_w}{M} \times 100$$
>
> Range of *w'* is $0 \leq w' < 100\%$
> If we consider *w'* =100%, i.e., $W_w = W$ which is not possible in soil mass, hence, $w' \neq 100\%$.

Relationship between *w* and *w′*:

$$w' = \frac{W_w}{W} = \frac{W_w}{W_w + W_S} = \frac{W_w}{W_w \left[1 + \dfrac{W_S}{W_w}\right]} = \frac{1}{1 + \dfrac{1}{w}}$$

$$\therefore \qquad w' = \frac{w}{1 + w} \quad \text{or } w = \frac{w'}{1 - w'}$$

Total weight of soil mass changes with change in weight of water. Hence engineering significance of '*w*' is more than *w*' because solids are stable quantity.

2.3.2 Void Ratio (*e*)

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

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

- It is generally expressed in decimal.
- In general *e* > 0, i.e. no upper limit for void ratio.
- Void ratio of fine grained soils is generally higher than that of coarse grained soils.

> **NOTE**
> 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.

2.3.3 Porosity (*n*)

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

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

- It is generally 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.

2.3.4 Degree of Saturation(S)

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

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

- It is generally expressed in percentage.
- For dry soil, *S* = 0% and for fully saturated soil, *S* = 100%, whereas partially saturated soil has 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 addition of water beyond saturation, then volume of void and total volume increases. Hence void ratio will change but degree of saturation remains constant equal to 100%.

2.3.5 Air Content (a_c)

- It is defined as the ratio of the volume of air (V_a) to the total volume of voids (V_v) 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.

NOTE
(i) For dry condition : $S = 0\%$ and $a_c = 100\%$
(ii) For saturated condition : $S = 100\%$ and $a_c = 0\%$
(iii) For partially saturated condition : $0 < S < 100\%$ and $0 < a_c < 100\%$.

Relationship between S and a_c

$$S = \frac{V_w}{V_v} = \frac{V_v - V_a}{V_v} = 1 - \frac{V_a}{V_v} = 1 - a_c$$

$$\therefore \qquad a_c + S = 1$$

2.3.6 Percentage Air Voids (n_a)

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

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

- It is generally expressed in percentage.

Relation between n_a and a_c

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

$$n_a = n \times a_c$$

2.3.7 Unit Weights

(a) Bulk Unit Weight (γ_t or γ_b or γ)

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

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

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

> **NOTE**
> - Bulk density is defined as the ratio of total soil mass to the total volume.
> $$\rho_t = \frac{M}{V} = \frac{M_s + M_w}{V_s + V_w + V_a}$$
> - It is generally expressed as $\frac{kg}{m^3}$ or g_{cc}.

(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. If dry unit weight value is more, it means the soil is more dense or compacted for same type of soil solids.

> **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

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

> **NOTE**
> - Saturated density is defined as the ratio of total saturated soil mass to the total volume of soil mass.
> $$\rho_{sat} = \frac{M_{sat}}{V}$$
> - If the exiting condition is dry, then its bulk unit weight will be same as of its dry unit weight.
> $\therefore$ If $S = 0$, $\gamma_t = \gamma_d$
> - If the existing condition is fully saturated then its bulk unit weight will be same as of its saturated unit weight.
> $\therefore$ If $S = 100\%$, $\gamma_t = \gamma_{sat}$

(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.

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

- γ' is roughly half of saturated unit weight (γ_{sat})

> **NOTE**
> - Submerged density or buoyant density is defined as the total mass of soil submerged to the total volume of soil mass, $\rho' = \rho_{sat} - \rho_w$
> - Soil in submerged condition will be in saturated condition also, but soil in saturated condition need not to be in submerged condition.
> - Soil mass below the water table is saturated as well as submerged but soil mass in capillary zone is in saturated condition only.

(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/m³ or 1g/cc for soil conditions.

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

(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 $\dfrac{kN}{m^3}$ or $\dfrac{kgf}{cm^3}$

> **NOTE**
> Order of unit weight of soil.
> ∴ $\gamma_S > \gamma_{sat} > \gamma_t > \gamma_d > \gamma'$

2.3.8 True/absolute Specific Gravity (G or G_s)

- 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.

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

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

> **NOTE**
> $[G]_{\text{fine grained}} > [G]_{\text{coarse grained}}$
> ∵ Fine grained soil contains Al^{3+}, Fe, mg in clay minerals.

2.3.9 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,

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

REMEMBER

- 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–

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

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

$$\Rightarrow \qquad G_{27°C} \times \gamma_{w\,27°C} = G_{T°C} \times \gamma_{w,\,T°C}$$

$$\therefore \qquad G_{27°C} = G_{T°C} \times \frac{\gamma_{w,T°C}}{\gamma_{w,27°C}}$$

2.4 SOME IMPORTANT RELATIONSHIPS

2.4.1 Relation between W_s, W_w and w

From block diagram,

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

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

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

$$\therefore \qquad W_s = \frac{W}{1 + w}$$
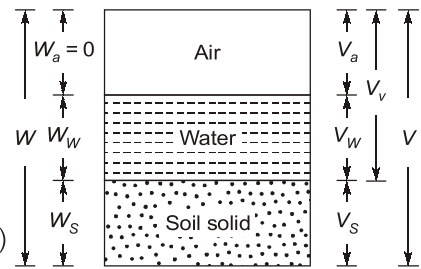
Fig. Three phase diagram

2.4.2 Relation between e and n

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

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

or $$e = \frac{n}{1 - n}$$

2.4.3 Relation between e, S, w and G_s

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

$$Se = wG_s$$

2.4.4 Relation between γ_t, G_s, e, w and γ_w

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

But

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

$\therefore$

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

But

$$wG_s = S_e$$

$\therefore$

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

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

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

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

$\therefore$

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

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

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

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

$\therefore$

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

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

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

$\therefore$

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

2.4.5 Relation between γ_t, γ_d and w

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

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

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

2.4.6 Relation between γ_d, G_s, w and n_a

$$V = V_s + V_w + V_a$$

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

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

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

$$\therefore \qquad \gamma_d = \frac{(1-n_a)G_s\gamma_w}{1+wG_s}$$

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

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

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

2.4.7 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
$$S = \frac{w}{\dfrac{\gamma_w}{\gamma_t}(1+w) - \dfrac{1}{G_s}}$$

2.4.8 Relation between e, V_s and V_T

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

$$1 + e = 1 + \frac{V_v}{V_s}$$

$$1 + e = \frac{V_s + V_s}{V_s} = \frac{V_T}{V_s}$$

$$\therefore \qquad V_s = \frac{V_T}{1+e}$$

NOTE

1. $W_s = \dfrac{W}{1+w}$

2. $n = \dfrac{e}{1+e}$ or $e = \dfrac{n}{1-n}$

3. $Se = wG$

4. $\gamma_t = \left(\dfrac{G+Se}{1+e}\right)\gamma_w$

5. $\gamma_{sat} = \left(\dfrac{G+e}{1+e}\right)\gamma_w$

6. $\gamma_d = \dfrac{G\gamma_w}{1+e}$

7. $\gamma' = \left(\dfrac{G-1}{1+e}\right)\gamma_w$

8. $\gamma_d = \dfrac{(1-n_a)G\gamma_w}{1+wG}$

9. $\gamma_d = \dfrac{\gamma_t}{1+w}$

10. $S = \dfrac{w}{\dfrac{\gamma_w}{\gamma_t}(1+w) - \dfrac{1}{G}}$

11. $V_s = \dfrac{V_T}{1+e}$

12. $n_a = n \cdot a_c$

13. $S + a_c = 1$

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 b 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, $\qquad W = 2$ kg

$\therefore$ 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,
$$w = \frac{W_{w_2}}{W_s} \times 100 = \frac{0.5}{1.8} \times 100 = 27.8\%$$

Example 2.2   Consider the following statements in relation to the given sketch:

Volume (cc)		Weight (g)
0.2	Air	0
0.3	Water	0.3
0.5	Solids	1.0

1. Soil is partially saturated at degree of saturation = 60%
2. Void ratio = 40%
3. Water content = 30%
4. Saturated unit weight = 1.5 g/cc

Which of these statements are correct?

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

Ans. (b)

1. Degree of saturation, $S = \dfrac{V_w}{V_v} \times 100 = \dfrac{0.3}{(0.3 + 0.2)} \times 100 = 60\%$

2. Void ratio, $e = \dfrac{V_v}{V_s} = \dfrac{(0.3 + 0.2)}{0.5} \times 100 = 100\%$

3. Water content, $w = \dfrac{W_w}{W_s} \times 100 = \dfrac{0.3}{1} \times 100 = 30\%$

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

$$G = \frac{\gamma_s}{\gamma_w} = \left(\frac{W_s / V_s}{\gamma_w}\right) = \left(\frac{1/0.5}{1}\right) = 2$$

$\therefore$ $\gamma_{sat} = \left(\dfrac{2 + 1 \times 1}{1 + 1}\right) \times 1 = \dfrac{3}{2} = 1.5 \text{ g/cc}$

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, $G_m = \dfrac{\gamma_d}{\gamma_w} = 1.5$

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

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

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

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

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

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/m^3).

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	B	D
(d)	D	B	A	C
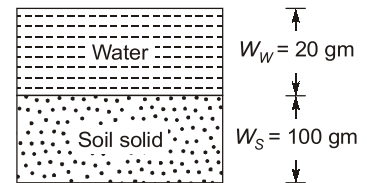
Ans. (d)

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

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

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

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

   For saturated density, $\gamma_{sat} = \left(\dfrac{G + 1 \times e}{1+e}\right)\gamma_w$

   $= \left(\dfrac{2.6 + 0.52}{1 + 0.52}\right) \times 10 = 20.53$ kN/m^3

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%, $\rho_w = 1000$ 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

Q.4 A soil sample has a void ratio of 0.75, moisture content = 15%, $G_s = 2.6$ and $\gamma_w = 9.81$ kN/m³. The amount of water (in kN) required to be added per m³ to make it saturated is _____ kN.

Q.5 An embankment having a volume 200000 m³ is to be constructed at a void ratio of 0.6.
The soil is required to be excavated from a pit having a natural deposit void ratio of 1.0.
Estimate the volume of excavated soil from the borrow pit in m³.
(a) 160000 m³   (b) 100000 m³
(c) 200000 m³   (d) 250000 m³

Q.6 The mass specific gravity of a fully saturated specimen of clay having a water content of 35% is 1.90. On oven drying, the mass specific gravity drops to 1.75. The specific gravity of clay particles and the shrinkage limit are respectively
(a) 2.65 and 21%   (b) 2.77 and 21%
(c) 2.77 and 28%   (d) 2.65 and 28%

Q.7 A clayey soil has saturated moisture content of 18%. The saturation percentage is 70%. The soil is allowed to absorb water and saturation increased to 92% after some time. Assuming specific gravity of soil to be 2.72, the water content of soil is latter case is
(a) 20.26   (b) 23.66
(c) 21.24   (d) 25.61

Q.8 A dry soil has mass specific gravity of 1.42. If the specific gravity of soil solids is 2.6, then the void ratio will be _____.

Q.9 A sample of saturated clay has a porosity of 0.562. The void ratio of the clay is _____.

Q.10 The pavement of a road is to be laid on a base course 500 mm thick. The base course has void ratio of 60% and degree of saturation, 50%. The

amount of rainfall needed to fully saturate the base course is
(a) 93.75 mm   (b) 60.15 mm
(c) 130.20 mm   (d) 150 mm

Q.11 Consider the following statements in relation to the given table

Component	Volume (cm^3)	Weight (g)
Air	0.1	0.0
Water	0.3	0.3
Solids	0.6	1.50

Which of the following statements are CORRECT?
1. Soil is partially saturated at degree of saturation = 50%
2. Void ratio = 66.7%
3. If $G = 2.65$, water content = 18.87%

(a) 1 and 2   (b) 2 and 3
(c) 1 and 3   (d) 3 only

Q.12 In a wet soil mass, air occupies one eighth of its volume and water occupies one third of its volume. The void ratio and the air content of the soil are respectively:
(a) 54% and 50%   (b) 54% and 27.27%
(c) 60% and 25.0%   (d) 85% and 27.27%

Q.13 A saturated soil sample has a volume of 26 cm^3 at liquid limit. The shrinkage limit and liquid limit are 18% and 40% respectively. The specific gravity of solids is 2.6 and unit weight of water is 10 kN/m^3.
The minimum volume which can be attained by the soil is _____ cm^3.

Q.14 An embankment having a volume 200000 m^3 is to be constructed at a void ratio of 0.6. The soil is required to be excavated from a pit having a natural void ratio of 1.0. Estimate the volume of excavated soil from the borrow pit in m^3.
(a) 160000 m^3 (b) 100000 m^3
(c) 300000 m^3 (d) 250000 m^3

Q.15 With the increased value of plasticity index of a soil, the quantity of lime required for its stabilisation will

(a) increase
(b) decrease
(c) sometimes increase and sometimes decrease
(d) remain unaffected

Q.16 A sample of saturated clay has a porosity of 0.562. The void ratio of the clay is _____.

Q.17 The insitu void ratio of a granular soil deposit is 0.55. The maximum and minimum void ratios obtained for the same soil in the laboratory are 0.65 and 0.45 respectively. If specific gravity of solids is 2.67, then the relative density will be _____ %.

Q.18 The mass of a saturated soil sample is 150 g and its mass when oven dried is 90 g. The water content of the soil sample is _____ %.

Q.19 If w_L = Liquid limit, w_P = Plastic limit, I_P = Plasticity index, w = natural moisture content, then consistency index for a clayey soil (I_C) will be
(a) $\dfrac{w_L - w}{I_P}$ (b) $\dfrac{w - w_L}{I_P}$
(c) $w_L - w_P$ (d) $0.5\,w$

Q.20 **Assertion (A):** A compacted abutment of volume 250000 m^3 is to be made from a soil taken from a borrow pit whose void ratio is 0.8. Void ratio in abutment is 0.6. Volume of soil taken from borrow pit is 281250 m^3.
Reason (R): In both the volume of soil have equal number of solids.
Codes:
(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

Q.21 **Assertion (A):** In oven drying method, for soils containing significant amount of organic matter, a temperature range of 60°C – 80°C is recommended.

Reason (R): At higher temperature, organic matter in the soil tends to get oxidized.

Codes:
(a) Both A and R are true and R is the correct explanation of A
(b) Both A and R are true but R is not the correct explanation of A
(c) A is true but R is false
(d) A is false but R is true

ANSWER KEY

1. (b)	2. (d)	3. (d)	4. (2.02)
5. (d)	6. (b)	7. (b)	8. (b)
9. (1.283)	10. (a)	11. (b)	12. (d)
13. (18.7)	14. (d)	15. (a)	16. (1.28)
17. (50)	18. (66.67)	19. (a)	20. (a)
21. (a)			

HINTS & 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

$$\gamma_d = \frac{2035 \times 10^{-3}}{1.15 \times 10^{-3}}$$
$$= 1769.565 \text{ kg/m}^3$$

∵ $$\gamma_d = \frac{G\gamma_w}{1+e}$$

⇒ $$1769.565 = \frac{2.68 \times 1000}{1+e}$$

⇒ $$e = 0.51$$
∴ Void ratio, $e = 0.51$

Porosity $\quad n = \dfrac{e}{1+e} = 0.338$

Water content

$$w = \frac{m_w}{m_d}$$

$$= \frac{2290 - 2035}{2035} = 0.125$$

$$m_d = \frac{m}{1+w}$$

⇒ $$2035 = \frac{2290}{1+w}$$

⇒ $$w = 0.125$$
∴ $$wG = eS$$

⇒ $$\frac{0.125 \times 2.68}{0.51} = S$$

⇒ $$S = 0.657$$
∴ Degree of saturation = 0.657
Air content, $\quad = 1 - S$
$$= 1 - 0.657$$
$$= 0.343$$

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.

4. (2.02)

We know that $\gamma_{sat} = \left(\dfrac{G+e}{1+e} \right) \gamma_w$

$$\Rightarrow \quad \gamma_{sat} = \left(\frac{2.60+0.75}{1+0.75} \right) \times 9.81 = 18.78$$

kN/m^3

we know, $e = \dfrac{wG}{S}$

$$\Rightarrow \quad S = \frac{wG}{e}$$

$$\Rightarrow \quad S = \frac{0.15 \times 2.6}{0.75} = 0.52$$

Also, $\gamma = \left(\dfrac{G+eS}{1+e} \right) \gamma_w$

$$\Rightarrow \quad \gamma = \left(\frac{2.6+0.75 \times 0.52}{1+0.75} \right) \times 9.81$$

$$\Rightarrow \quad \gamma = 16.76 \text{ kN/m}^3$$

So water to be added in 1 m^3 of soil to make it saturated is

$$\gamma_{sat} - \gamma = 18.78 - 16.76$$

$$= 2.02 \text{ kN}$$

5. (d)

Let V_1 and V_2 are the volumes of embankments and pit and e_1 and e_2 are their void ratios, V_{s1} and V_{s2} are the volumes of their soil solids.

$$e_1 = \frac{V_{v1}}{V_{s_1}} \Rightarrow 1 + e_1 = 1 + \frac{V_{v1}}{V_{s_1}}$$

$$\Rightarrow \quad 1 + e_1 = \frac{V_{s_1} + V_{v_1}}{V_{s_1}}$$

$$\Rightarrow \quad 1 + e_1 = \frac{V_1}{V_{s_1}} \Rightarrow V_{s_1} = \frac{V_1}{1+e_1}$$

Similarly, $V_{s_2} = \dfrac{V_2}{1+e_2}$

$$\therefore \quad V_{s_1} = \frac{V_1}{1+e_1} = \frac{200000}{1+0.6} = \frac{200000}{1.6}$$

and $V_{s_2} = \dfrac{V_2}{1+e_2} = \dfrac{V_2}{1+1.0} = \dfrac{V_2}{2.0}$

$$\because \quad V_{s_1} = V_{s_2}$$

$$\Rightarrow \quad \frac{200000}{1.6} = \frac{V_2}{2.0}$$

$$\Rightarrow \quad V_2 = 250000 \text{ m}^3$$

6. (b)

For fully saturated soil $S = 1$

We know that, $e = wG = 0.35 \, G$

Also, $\dfrac{\gamma}{\gamma_w} = \left(\dfrac{G+eS}{1+e} \right)$

$$\Rightarrow \quad 1.9 = \frac{G+e}{1+e}$$

Since, $e = 0.35 \, G$

Since volume of solids are constant

$$\frac{V_{\text{borrow pit}}}{1+e_1} = \frac{V_{\text{abutment}}}{1+e_2} = \frac{250000}{1+0.6}$$

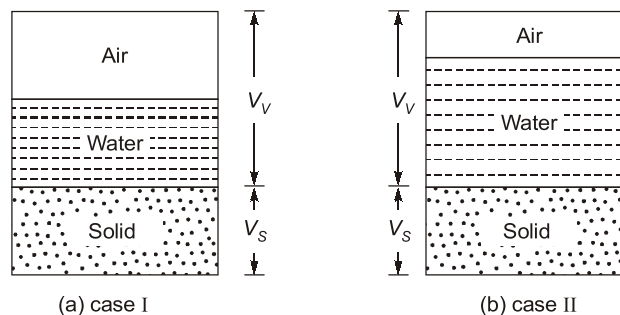$$V_{\text{borrow pit}} = \frac{250000 \times 1.8}{1.6} = 281250 \text{ m}^3$$

CONVENTIONAL BRAIN TEASERS

Q.1 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.

$$\therefore \qquad e_1 = e_2$$

$$\therefore \qquad w = \frac{0.908 \times 0.607}{2.72} = 0.2036 \text{ or } 20.26\%$$

Q.2 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,

$$\rho_{d, \text{ max}} = 1.8 \text{ g/cc}$$
$$w = 16 \% \text{ or } 0.16$$
$$G = 2.65$$

We know,

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

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

Also, $\qquad S.e = wG$

$$S = \frac{wG}{e} = \frac{0.16 \times 2.65}{0.472} = 0.8983 \text{ or } 89.83\%$$

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,

$$S = 100 \% \text{ or } 1$$
$$S.e = w.G$$

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

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

Q.3 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 per m³   with   e = 1.50
Supplier *B*   sells fill at ₹ 10 per m³ with   e = 0.20
Supplier *C*   sells fill at ₹ 12 per m³ with   e= 1.60

Solution:

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

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

Volume of soil required to be taken out from suppliers,

Supplier *A*, $\qquad\qquad\qquad\qquad V_A = V_s(1 + e) = 4444,44 \ (1 + 1.50) = 1,111,110 \text{ m}^3$
Supplier *B*, $\qquad\qquad\qquad\qquad V_B = V_s(1 + e) = 444,444 \ (1 + 0.2) = 544,442 \text{ m}^3$
Supplier *C*, $\qquad\qquad\qquad\qquad V_C = V_s(1 + e) = 444,444 \ (1 + 1.6) = 1155,555 \text{ m}^3$

Cost of bills,

Supplier *A*, $\qquad\qquad\qquad\qquad A = 1,111,110 \times 5 = ₹ 5,555,550$
Supplier *B*, $\qquad\qquad\qquad\qquad B = 533,332 \times 10 = ₹ 5,333,320$
Supplier *C*, $\qquad\qquad\qquad\qquad C = 1155,555 \times 12 = ₹ 13,866,660$

Therefore supplier *B* is more economical, and we save

$$= ₹ 5,555,550 - ₹ 5,333,320 = ₹ 222,230$$

Q.4 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 m*l* solution of water ($\mu = 0.01$ 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*?