UNIT-I
INTRODUCTION

The word "soil" is derived from the latin word solium which according to webster's diction-ary means the upper layer of the earth that may be dug or plowed : specifically the loose surface material of the earth in which plants grow.

The term 'soil' in the soil engineering is defined as an unconsolidated material composed of solid particles produced by the disintegration of rocks. The void space between the particles may contain air, water or both. The solid particles may contain organic matter. The soil particles can be sepa-rated by such machanical means as agitation in water.

Soil Engineering & Geotechnical Engineering :-

Soil engineering in an applied science dealing with the applications of principles of soil mechanics to partical problems. It has a much wider scope than soil mechanics, as it deals with all engineering problems realted with soils. It includes site investigations, design and construction of foundations, earth - retaining structures and earth structures.

Geotechnical engineering is a broader term which includes soil engineering, rock mechanics and geology. This term is used synonymously with soil engineering in this text. The term "soil mechanics" was coined by Dr. Karl Terzaghi in 1925

FORMATION OF SOILS :-

Soils are formed by either

A) physical disintegration

B) chemical decomposition of rocks.

A) Physical disintergration :-

Physical disintergration or mechanical weathering of rocks occurs due to the following physical processes :

1. <u>Temperature changes</u> :- Different minerals of rocks have different co-efficients of thermal expansion. Unequal expansion and contraction of these minerals occur due to temperature changes. When the stresses induced due to such changes are repeated many

times, the particles get detached from the rock and the soils are formed.

2. Wedging action of Ice :- water in the pores and minute cracks of rocks gets frozen in very cold climates. As the volume of Ice formed in more than that of water, expansion occurs. Rocks get broken into pieces when large stress develop in the cracks due to weding action of the ice formed.

3. spreading of roots of plants :- As the roots trees and shrubs grow in the cracks and fissures of the rocks, forces act on the rocks. The segments of the rocks are forced apart and disintegration of rocks occurs.

4. Abrasion :- As water, wind and glaciers move over the surface of rocks, abrasion and scouring takes place. It results in the formation of soil.

In all the process of physical disintegration, there is no change in the chemical composition. The soil formed has the properties of the parent rocks. Coarse grained soils, such as gravel and sand, are formed by the process of physical disintegration.

B) Chemical Decomposition :- When chemical decomposition or chemical weathering of rocks takes places original rocks minerals are transformed into new minerals by chemical reactions. The soils formed do not have the properties of the parent rocks. The following chemical processes generally occur in nature.

1. Hydration :- In hydration, water combines with the rocks minerals and results in the formation of a new chemical compound. The chemical reaction causes a change in volume and decomposition of rocks into small particles.

2. Carbonation :- It is a type of chemical decomposition in which carbon dioxide in the atmosphere combines with water to form carbonic acid. The carbonic acid reacts chemically with rocks and causes their decomposition.

3. Oxidation :- Oxidation occurs when oxygen ions combine with minerals in rocks. Oxidation results in decomposition of rocks. Oxidation of rocks is some what similar to rusting of steel.

4. <u>Solution</u>:- Some of the rock minerals from a solution with water when they get dissolved in water. Chemical reaction takes place in the solution and the soils are formed.

5. <u>Hydrolysis</u> :- It is a chemical process in which water gets dissociated into H^+ and OH^- ions. The hydrogen cations replace the matalic ions such as calcium, sodium and potassium in the rock minerals and soils are formed with anew chemical decomposition.

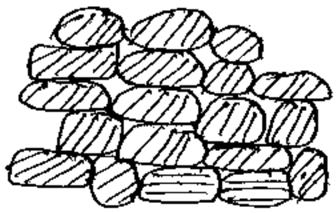
chemical decomposition of rocks results in formation of clay minerals. These clay minerals imparts plastic properties to soils. clayey soils are formed by chemical decomposition.

SOIL STRUCTURES :-

The geometrical arrangement of soil particles with respect to one another is known as soil structure. The soil in nature have different structures depending upon the particle size and the mode of formation. The following types of structures are usually found. The first two types are for coarse grained soils and types ③ and ④ for clays. Types ⑤ and ⑥ are for mixed soils.

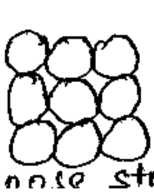
1. Single - grained structure :-

Cohesionless soils, such as gravel and sand are composed of bulky grains in which the gravitational forces are more predominant that surface forces. When decomposition of these soils occurs, that particles settle under gravitational forces and take an equilibrium position as shown in the below figure. Each particle is in contact with those surrounding it. The soil structure so formed is known as single grained structure.

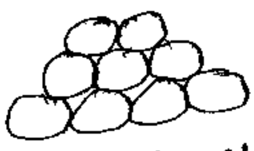


1. single grained structure

Depending upon the relative position of the particle the soil may have a loose structure or a dense structure. Loosest condition, the void ratio is 0.90 and the densest condition the void ratio is 0.35



a) Loose structure

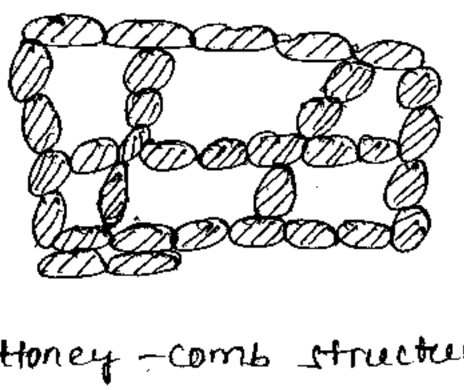


b) Dense structure.

2. Honey - comb structure :-

It is possible for fine sands or silts to get deposited such that the particles when setting develop a particle - to - particle contact that bridges over large voids in the soil mass. The particles wedge between one another into a stable condition and form a skelton like an arch to carry the weight of overlying material. The structure so formed is known as honey comb structure.

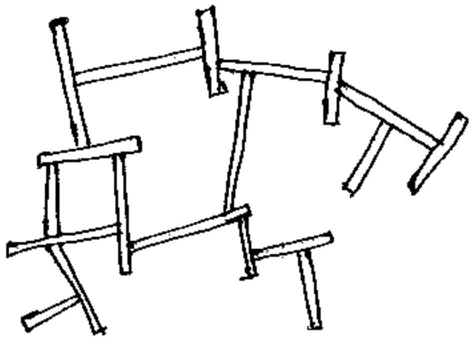
The honey - comb structure usually develops when the particles size is between 0.002 mm and 0.02 mm



Honey - comb structure.

3. Flocculated structure :-

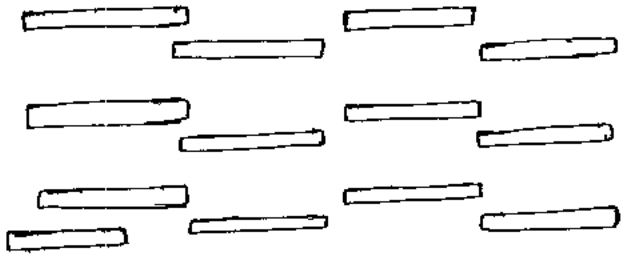
Flocculated structure occurs in clays. The clay particles have large surface and therfore, the electrical forces are important in such soils. The clay particles have a negative charge on the surface and a positive charge on the edges. Interparticle contact develops between the positevly changed edges and the negatively charged faces. This results in a flocculated structure.



Flocculated structure.

4. Dispersed structure :-

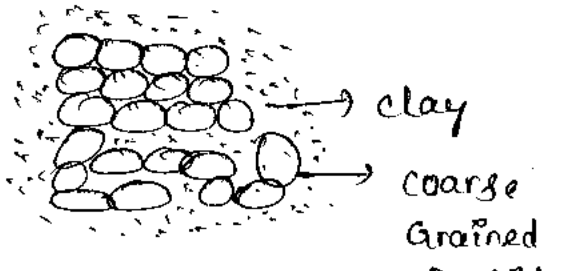
Dispersed structure develops in clays that have been reworked or remoulded. The particles develop more or less a parallel orientation. clay deposits with a flocculent structure when transported to other places by nature or man get remoulded. Remoulding converts the edge-to-face orientation to face-to-face orientation. The dispersed structure is formed in nature when there is a net repulsive fore between particles.



Dispersed structure.

5. <u>coarse-grained skeleton</u> :-

~~A~~ coarse grained skeleton is a composite structure which is formed when the soil contains particles of different types. when the amount of bulky, cohesionless particles is large compared with that of fine-grained clayey particles, the bulky grains are in particle-to-particle contact. These particles form a formwork or skelton. The space between the bulky grains is occupied by clayey particles known as binders



a) coarse grained skeleton

b) clay matrix.

6. <u>clay matrix</u> :- clay matrix is also a composite structure formed by soil of different types However, in this case, the amount of clay particles is very large as compared with bulky coarse-grained particles. The clay forms a matrix in which bulky grains appear floating without touching one another.

The soil with a clay matrix structure have atmost the same properties as clay. Their behaviour is similar to that of an ordinary clay deposite. However, they are more stable as disturbance has very little effect on the soil formation with a clay-matrix structure.

Weight - volume relationships :-

1. <u>Bulk unit weight (γ)</u> :- It is defined as the ratio of weight per unit volume of the soil mass. It is defined by 'γ' (Gama)

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

Units :- N/m^3 (or) kN/m^3

2. Unit weight of solids (γ_s):-

It is defined as the ratio of weight of soil solids to that of the volume of soil solids

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

It is also called as absolute unit weight of soil.

3. Unit weight of water (γ_w):-

It is the ratio of the weight of water to the volume of water.

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

$w = 1000 \ kg/m^3$ (or) $9.81 \ kN/m^3$

4. Dry unit weight (γ_d):-

It defined as the ratio of weight of soil solids per unit total volume.

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

5. Saturated unit weight:-

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

The saturated unit weight is the bulk unit weight when the soil is saturated.

6. <u>Submarged unit weight</u>:-

It is defined as the ratio of the submarged weight of soil solids to that of the unit total volume of the soil.

$$\gamma' = \frac{(W_s)_{sub}}{V}$$

$(W_s)_{sub}$ = weight of solid particles in air weight of water displaced by the solids

$$= W_s - V_s \gamma_w$$

$$= W - W_w - V_s \gamma_w$$

$$= W - \gamma_w V_w - \gamma_w V_s$$

$$= W - \gamma_w (V_w + V_s)$$

$$(W_s)_{sub} = W - V\gamma_w$$

Dividing throughout by V

$$\frac{(W_s)_{sub}}{V} = \frac{W}{V} - \frac{V\gamma_w}{V}$$

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

$$\gamma_s > \gamma_{sat} > \gamma > \gamma_d > \gamma'$$

ADSORBED WATER :-

The water held by electro-chemical forces existing on the soil surface is adsorbed water. As the adsorbed water is under the influence of electrical forces, its properties are different from that of normal water. It is much more viscous, and its surface tension is also greater. It is heavier than normal water. The boiling point is higher, but the freezing point is lower than that of the normal water.

The thickness of the adsorbed water layer is about 10 to 15A° for colloids but may be upto 200A° for silts. The attractive forces between the adsorbed water and the soil surface decrease exponentially with the distance until the double layer merges into normal water. The adsorbed water exists in an almost solidified state. The pressure required to pull away the adsorbed water layer from the soil surface is very high it may be as high as 10,000 atmospheres.

Adsorbed water imparts plasticity characteristics to soils. The adsorbed water depends upon the clay minerals present in the soil. The presence of highly active clay minerals in necessary to give the soil plasticity. The fine-grained soil with out clay minerals may develop cohesion if the particle size is very small, but these soils cannot be moulded into small threads as these are not plastic.

RELATIVE DENSITY:-

The most important index aggregate property of a cohesionless soil is its relative density. The engineering properties of a mass of cohesionless soil depend to a large extent on its relative density (D_r) also known as density index (I_D). The relative density is defined as

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

where e_{max} = Maximum void ratio of the soil in the loosest condition

e_{min} = Minimum void ratio of the soil in the densest condition

e = void ratio in the nutral state.

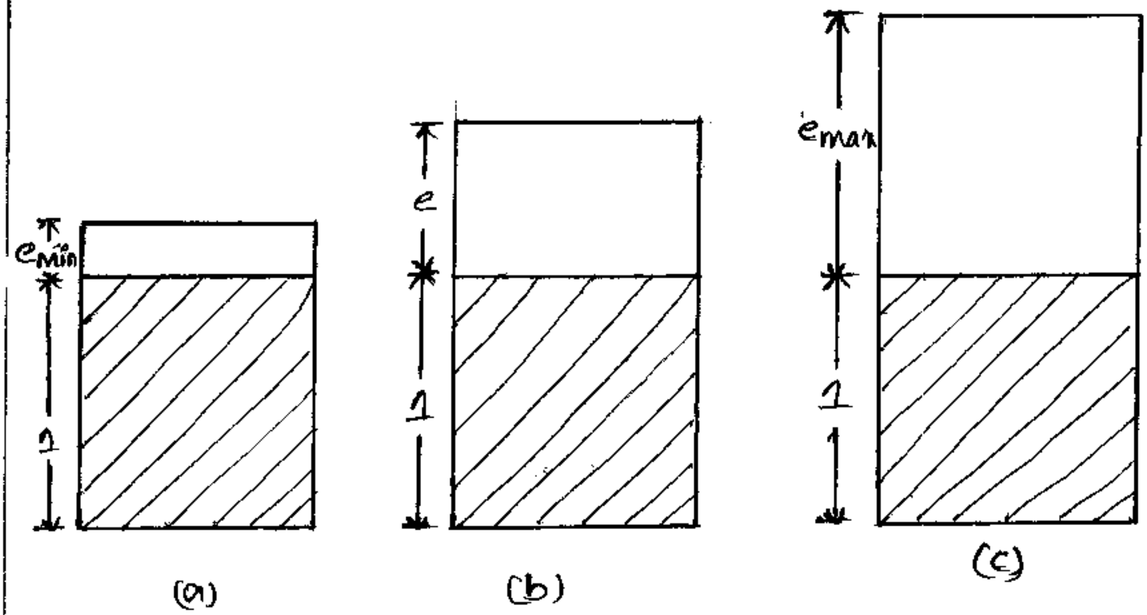
The relative density of a soil gives a more clear idea of the denseness than does the void ratio. Two types of sand having the same void ratio may have entirely different state of denseness and engineering properties. However, if the two sands have the same relative density, they usually behave in identical manner.

The relative density of a soil indicates how it would behave under loads. If the deposits is dense. It can take heavy loads with very little settlements. Depending upon the relative density, the soils are generally divided into 5 categories.

Denseness	very Loose	Loose	medium Dense	Dense	very Dense
Dr(%)	<15	15 to 35	35 to 65	65 to 85	85 to 100.

Determination of relative density :-

The below fig show the soil in the densest natural and loosest states. As it is difficult to measure the void ratio directly. However, it is convenient to express the void ratio in terms of dry density (ρ_d)



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

Representing the dry density in the loosest, densest and natural conditions as ρ_{min}, ρ_{max} and ρ_d

we know $D_r = \dfrac{e_{max} - e}{e_{max} - e_{min}} \times 100$

$$D_r = \frac{\left[\dfrac{G\rho_w}{\rho_{min}} - 1\right] - \left[\dfrac{G\rho_w}{\rho_d} - 1\right]}{\left[\dfrac{G\rho_w}{\rho_{min}} - 1\right] - \left[\dfrac{G\rho_w}{\rho_{max}} - 1\right]}$$

$$D_r = \frac{\rho_{max}}{\rho_d}\left[\frac{\rho_d - \rho_{min}}{\rho_{max} - \rho_{min}}\right]$$

Volumetric relationships :-

1. Void ratio (e) :-

It is defined as the ratio of the volume of voids to the volume of solids

$$e = \frac{V_v}{V_s} \longrightarrow (1)$$

It can be expressed by decimals such as 0.4, 0.5 for the coarse grained soil, the void ratio is generally smaller than that for fine-grained soils.

2. Porosity (n) :-

It is defined as the ratio of the volume of the voids to the total volume. Then

$$n = \frac{V_v}{V} \longrightarrow (2)$$

porosity generally expressed as percentage. However in equations it is used as a ratio. For example a porosity of 50% will be used as 0.5 in equations. The porosity can not exceed 100% as it would mean V_v is greater than V. porosity is also known as percentage voids.

An inter-relationship can be found between the void ratio and the porosity as under from ② $\frac{1}{n} = \frac{V}{V_V} = \frac{V_V + V_S}{V_V}$

$$\frac{1}{n} = 1 + \frac{1}{e} = \frac{1+e}{e} \longrightarrow (i)$$

$$n = \frac{e}{1+e} \longrightarrow ③$$

from (i) $\frac{1}{e} = \frac{1}{n} - 1 = \frac{1-n}{n}$

$$e = \frac{n}{1-n} \longrightarrow ④$$

In eqs ③ & ④ the porosity should be expressed as a ratio (and not percentage)

3. <u>Degree of saturation (S)</u> :-

The degree of saturation is the ratio of the volume of water to the volume of voids.

Thus $S = \frac{V_W}{V_V} \longrightarrow ⑤$

The degree of saturation is generally expressed as a percentage. It is equal to zero when the soil is absolutely dry and 100% when the soil fully saturated. In expressions the degree of saturation is used as a decimal.

4. Percentage air voids (na):-

It is the ratio of the volume of air to the total volume

$$n_a = \frac{V_a}{V} \longrightarrow (6)$$

As the name indicates it reprasented as a percentage

5. Air content (ac):-

Air content is defined as the ratio of the volume of the air to the volume of voids.

$$a_c = \frac{V_a}{V_v} \longrightarrow (7)$$

ac is usually expressed as a percentage.

Both air content and the percentage air voids are zero when the soil is saturated ($V_a = 0$)

An inter relationship between na & ac is

from (6) $n_a = \frac{V_a}{V} = \frac{V_a}{V_v} \times \frac{V_v}{V}$

$$\boxed{n_a = n a_c} \longrightarrow (8)$$

Volume - mass Relationship :-

The volume - mass relationship are in terms of mass density. The mass of soil per unit volume is known as mass density. In soil engineering the following 5 different mass densities are used.

1. **Bulk mass density :-** The bulk mass density (ρ) is defined as the total mass (m) per unit total volume (V)

$$\rho = \frac{m}{V} \longrightarrow (1)$$

The bulk mass density is also known as the wet mass density (or) simply bulk density or density. It is expressed in kg/m^3, gm/ml (or) Mg/m^3

Obviously 1 Mg/m^3 = 1000 kg/m^3 = 1 gm/ml.

2. **Dry mass density :-**

It is defined as mass of solids per unit total volume

$$\rho_d = \frac{M_s}{V} \longrightarrow (2)$$

The dry mass density is also known as dry density. The dry mass density is used to express the denseness of the soil. A high value of dry mass density indicates that the soil is in a compact condition.

3. Saturated mass density :-

The saturated mass density (ρ_{sat}) is the bulk mass density of the soil when it is fully saturated

$$\rho_{sat} = \frac{M_{sat}}{V} \longrightarrow (3)$$

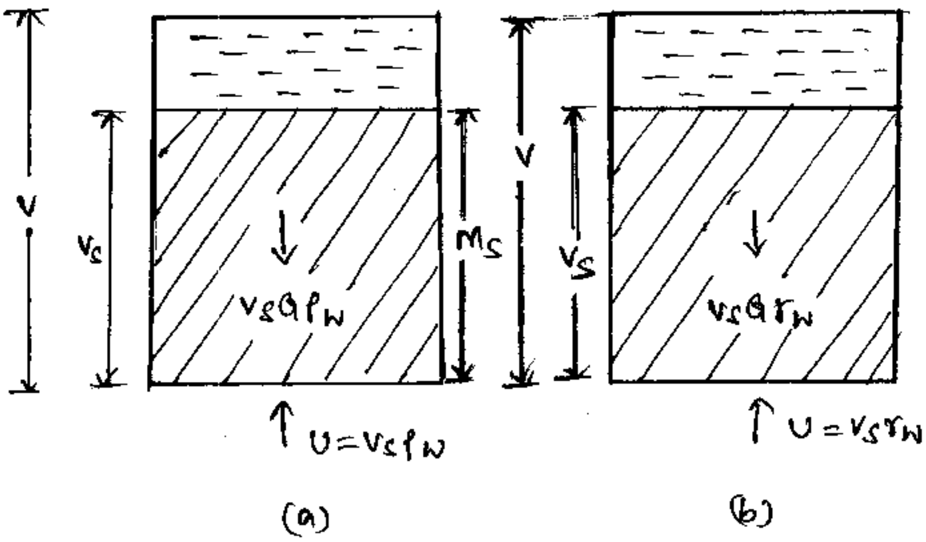
4. Submerged Mass density :-

When the soil exists below water it is in a submerged condition.

The submerged mass density (ρ') of the soil is defined as the submerged mass per unit of total volume

$$\rho' = \frac{M_{sub}}{V} \longrightarrow (4)$$

The submerged density is also expressed as ρ_{sub} in some texts. It is also known as the buoyant mass density (ρ_b).



$$U = V_s \rho_w$$

$$M_{sub} = M_s - U$$

$$= V_s G \rho_w - V_s \rho_w$$

$$\rho' = \frac{V_s \rho_w (G-1)}{V}$$

Alternatively, we can also consider the equilibrium of the entire volume (V). In this case, the total downward mass, including the mass of voids, is given by

$$M_{sat} = M_s + V_v \rho_w$$

The total upward thrust, including that on the water in voids, is given by

$$U = V \rho_w$$

∴ The submerged mass is given by

$$M_{sub} = (M_s + V_v \rho_w) - V \rho_w$$

$$\rho' = \frac{(M_s + V_v \rho_w) - V \rho_w}{V} = \frac{M_{sat} - V \rho_w}{V}$$

$$= \frac{M_{sat}}{V} - \rho_w$$

$$\rho' = \rho_{sat} - \rho_w$$

Specific Gravity of solids :-

It is defined as the ratio of the unit weight of solids to the unit weight of water at a standard temparature at 4°c.

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

It is also defined as the ratio of mass of volume of solids to the mass of an equal volume of water at 4°c

$$G = \frac{\rho_s}{\rho_w}$$

Mass specific Gravity :-

It is defined as the ratio of mass (or) bulk unit weight of soil to the unit weight of water at standard temparature 4°c

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

It is also known as bulk specific gravity or apperent specific Gravity

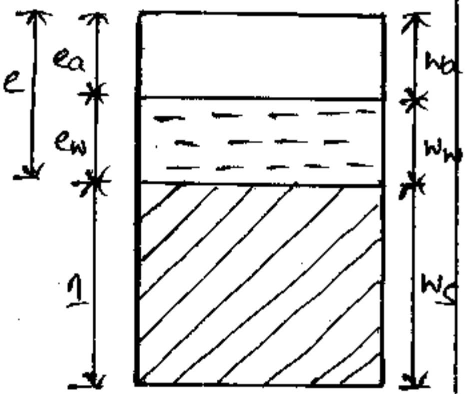
$$G > G_m$$

Three phase diagram in terms of void ratio :-

For convience the volume of solids is taken as unity.

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

$e = V_v \quad (\because V_s = 1)$



$\therefore$ total volume $(V) = 1+e$

Let volume of air $= e_a$

volume of water $= e_w$

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

Degree of saturation $S = \frac{V_w}{V_v} = \frac{e_w}{e}$

$$\boxed{e_w = Se} \longrightarrow (1)$$

$\therefore$ volume of air $V_a = e_a = e - e_w = e - Se \quad \{\because (1)\}$

$$\boxed{V_a = e(1-S)} \longrightarrow (2)$$

percentage of air voids $n_a = \frac{V_a}{V}$

$$n_a = \frac{e(1-S)}{1+e} \longrightarrow (3)$$

Air content $a_c = \frac{V_a}{V_v} = \frac{e(1-S)}{e}$

$$\boxed{a_c = 1-S} \longrightarrow (4)$$

Functional Relationships :-

i) Relationship between e, G, w and s :-

we know $s = \frac{V_w}{V_v} = \frac{e_w}{e}$ $\{\because V_v = e\}$

$$\boxed{e_w = se} \longrightarrow (1)$$

we know water content $w = \frac{W_w}{W_s}$

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

$$W_w = V_w \gamma_w = se\gamma_w \qquad \{V_w = e_w = se\}$$

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

$$W_s = V_s \gamma_s = V_s G \gamma_w = G\gamma_w \qquad \{\because \gamma_s = G\gamma_w\}$$

$$w = \frac{se\gamma_w}{G\gamma_w} \qquad \{\because V_s = 1\}$$

$$w = \frac{se}{G}$$

$$\boxed{se = wG} \longrightarrow (2)$$

2. Relation between γ_d, G & e (or) n :-

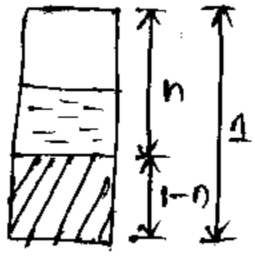
we know $\gamma_d = \frac{W_s}{V}$

$$\gamma_d = \frac{\gamma_s V_s}{V} \qquad \left\{\because \gamma_s = \frac{W_s}{V_s}\right\}$$

$$\gamma_d = \frac{\gamma_s}{1+e} \qquad \{\because V = 1+e \text{ from fig}\}$$

but we know $\gamma_s = G\gamma_w$

$$\boxed{\gamma_d = \frac{G\gamma_w}{1+e}} \longrightarrow (3)$$



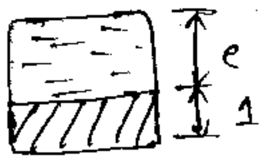
$$\boxed{e = \frac{G\gamma_w}{\gamma_d} - 1} \longrightarrow (4)$$

In case of n

$$\gamma_d = \frac{W_s}{V} = \frac{\gamma_s V_s}{V} = \frac{G\gamma_w(1-n)}{1}$$

$$\boxed{\therefore \gamma_d = G\gamma_w(1-n)} \longrightarrow (5)$$

3. <u>Relation between γ_{sat}, G and e :-</u>



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

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

$$= \frac{\gamma_w V_w + \gamma_s V_s}{V}$$

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

$$\boxed{\gamma_{sat} = \frac{(G+e)\gamma_w}{1+e}} \longrightarrow (6)$$

$\left\{ \gamma_w = \frac{W_w}{V_w},\ W_w = \gamma_w V_w,\ \gamma_s = \frac{W_s}{V_s},\ W_s = \gamma_s V_s \right\}$

4. <u>Relation between γ, G, e and S :-</u>

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

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

$$\gamma = \frac{\gamma_w V_w + \gamma_s V_s}{V}$$

$$= \frac{\gamma_w (es) + G\gamma_w (1)}{V}$$

$$\boxed{\gamma = \frac{\gamma_w (es + G)}{1+e}} \longrightarrow (7)$$

$\therefore \left\{ \begin{array}{l} V_w = e_w = es \\ V_s = e_s = 1 \end{array} \right\}$

$\left\{ \begin{array}{l} G = \frac{\gamma_s}{\gamma_w} \\ V_s = G\gamma_w \end{array} \right\}$

5. Relationship between γ', G and e

We know $\gamma' = \gamma_{sat} - \gamma_w$

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

$$= \gamma_w \left[\frac{G+e-1-e}{1+e} \right]$$

$$\boxed{\gamma' = \frac{(G-1)\gamma_w}{1+e}} \longrightarrow (8)$$

6. Relation between γ_d, γ and w :-

We know $w = \frac{W_w}{W_s}$

Both sides add '1'

$$1 + w = \frac{W_s + W_w}{W_s}$$

$$= \frac{W}{W_s}$$

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

$$\gamma_d = \frac{W_s}{V} = \frac{W}{(1+w)} \times \frac{1}{V} = \frac{\gamma}{1+w} \quad \left\{ \because \frac{W}{V} = \gamma \right\}$$

$$\boxed{\gamma_d = \frac{\gamma}{1+w}} \longrightarrow (9)$$

7. Relationship between γ_d, G, w and S :-

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

We know $Se = wG$

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

$$\therefore \gamma_d = \frac{G\gamma_w}{1+\frac{wG}{S}} \longrightarrow (10)$$

8. Relation between γ_{sat}, γ, γ_d and S :-

We prove

$$\gamma = \frac{(G+Se)\gamma_w}{1+e} \quad \{\because \text{from eq } (7)\}$$

$$= \frac{G\gamma_w}{1+e} + \frac{Se\gamma_w}{1+e}$$

$$= \gamma_d + S\left[\frac{(G+e)\gamma_w}{1+e} - \frac{G\gamma_w}{1+e}\right]$$

$$\gamma = \gamma_d + S[\gamma_{sat} - \gamma_d] \longrightarrow (11)$$

9. Relation between γ_d, G, w, n_a :-

We know

$$V = V_a + V_w + V_s$$

$$= V_a + \frac{W_s}{\gamma_s} + \frac{W_w}{\gamma_w} \quad \left\{ \gamma_s = \frac{W_s}{V_s} \quad \gamma_w = \frac{W_w}{V_w} \right\}$$

dividing both sides with 'V'

$$\frac{V}{V} = \frac{V_a}{V} + \frac{W_w}{V\gamma_w} + \frac{W_s}{V\gamma_s}$$

$$1-\frac{V_a}{V} = \frac{w \cdot W_s}{V \cdot \gamma_w} + \frac{W_s}{V\gamma_s}$$

$$1-n_a = \frac{\gamma_d w}{\gamma_w} + \frac{\gamma_d}{\gamma_s}$$

$$1-n_a = \frac{\gamma_d}{\gamma_w}\left(w+\frac{1}{G}\right)$$

$$\frac{(1-n_a)\gamma_w}{w+\frac{1}{G}} = \gamma_d$$

$$\boxed{\gamma_d = \frac{(1-n_a)G\gamma_w}{wG+1}} \longrightarrow (12)$$

List of formulaes :-

1. $n = \frac{e}{1+e}$

2. $e = \frac{n}{1-n}$

3. $n_a = n a_c$

4. $\gamma = \frac{(G+se)\gamma_w}{1+e}$

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

6. $\gamma_{sat} = \frac{\gamma_w(G+e)}{1+e}$

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

8. $se = wG$

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

10. $\gamma_d = \frac{(1-n_a)\, G\gamma_w}{1+wG}$

11. $\gamma = \frac{(G+Se)\gamma_w}{1+e} = \frac{(G+wG)\gamma_w}{1+e} = \frac{G\gamma_w(1+w)}{1+\frac{wG}{S}}$

12. If soil is saturated $S=1$

$$\gamma_{sat} = \frac{G\gamma_w(1+w)}{1+wG}$$

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

13. $V_v = n$

14. $V_s = 1-n$

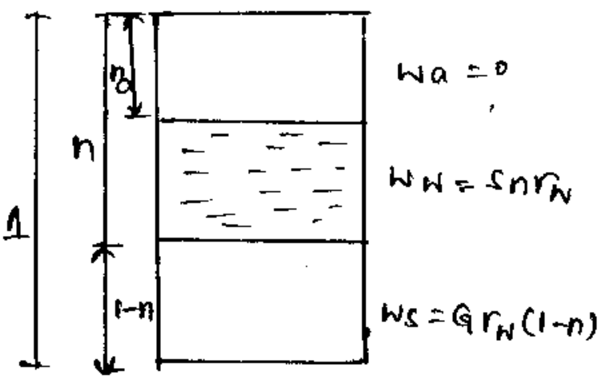
15. $e = \frac{n}{1-n}$

16. $\gamma = \gamma_w\,(G(1-n)+Sn)$

17. $\gamma_d = G\gamma_w(1-n)$

18. $\gamma_{sat} = [G(1-n)+n]\,\gamma_w$

19. $\gamma' = [(G-1)(1-n)]\,\gamma_w$



Problems :-

1. Determine water content, Dry density, bulk density, void ratio and degree of saturation from the following data. Sample size 3.81 cm ϕ × 7.62 cm ht, wet weight 1.668 N oven dry weight = 1.400 N & sp. gravity (G) is 2.7.

Sol:- Water content $w = \frac{W_w}{W_s} = \frac{1.668 - 1.400}{1.4} \times 100$

$= \frac{0.268}{1.4} \times 100$

$= 19.14\%$

Volume of the sample $V = A \times h$

$= \frac{\pi}{4} \times 3.81^2 \times 7.62$

$= 86.88\ cm^3$

$\gamma_w = 1 g/c$
$= 1000\ kg/m^3$
$= 9.8\ kN/m^3$
$\gamma_w = 9810\ N/m^3$

Dry density $(\gamma_d) = \frac{W_s}{V} = \frac{1.4}{86.88} = 0.01611$

$= 16.11\ kN/m^3$

Bulk unit weight $(\gamma) = \frac{W}{V} = \frac{1.668}{86.88}$

$= 0.0192\ N/cm^3$

$= 19.2\ N/m^3$

$\gamma_d = \frac{G\gamma_w}{1+e} = \frac{2.7 \times 9.81}{1+e}$

$16.11 = \frac{2.7 \times 9.81}{1+e}$

$1+e = 1.644$

$e = 0.645$

Degree of saturation (S)

We know $Se = wG$

$$S = \frac{0.1914 \times 2.7}{0.645} \times 100$$

$$S = 80.12\%$$

8. A partially saturated soil sample obtained from a earth fill has a natural moisture content of 22% and unit weight of 19.62 kN/m³ of G = 2.7 and unit weight of water = 9810 N/m³ compute

a) Degree of saturation b) void ratio

c) If subsequently the soil gets saturated, find its unit weight.

Sol:- $w = 22\%$ $\gamma = 19.62\ kN/m^3$ $G = 2.7$

$\gamma_w = 9810\ N/m^3 = 9.81\ kN/m^3$

$$\gamma = \frac{G\gamma_w(1+w)}{1+e} = \frac{2.7 \times 9.81(1+0.22)}{1+e}$$

$$1+e = \frac{26.487(1.22)}{19.62}$$

$$1+e = 1.647$$

$$e = 0.647$$

$$Se = wG$$

$$S = \frac{0.22 \times 2.7}{0.647} = 0.9188 = 91.88\%$$

soil gets saturated then $S = 1$

$$\gamma_{sat} = \frac{(G+e)\gamma_w}{1+e} = \frac{(2.7+0.647) \times 9.81}{1+0.647} = 19.92\ kN/m^3$$

5. A sample of saturated soil has a water content of 38%. G = 2.65. Determine void ratio, porosity, saturated unit weight and dry unit weight.

Given sample is saturated than S = 1

$w = 38\%$

$G = 2.65$

$Se = wG$

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

$= 0.38 \times 2.65 = 1.007$

Porosity $n = \frac{e}{1+e}$

$= \frac{1.007}{1+1.007} = 0.5017$

$= 50.17\%$

Taking $\gamma_w = 9.81\ kN/m^3$

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

$= \frac{(2.65+1.007)9.81}{1+1.007}$

$= 17.88\ kN/m^3$

$\gamma_d = \frac{G\gamma_w}{1+e} = \frac{2.65 \times 9.81}{1+1.007} = 12.952\ kN/m^3$

4. A sand sample has porosity of 28% and specific gravity of solids 2.65 find

a) Dry unit weight of sand b) unit weight of sand if $S = 0.56$

c) unit wt of saturated sand.

d) U.W in submerged condition

Sol:

$n = 28\%$, $G = 2.65$

$$e = \frac{n}{1-n} = \frac{0.28}{1-0.28} = 0.388$$

a) $$\gamma_d = \frac{G\gamma_w}{1+e} = \frac{2.65 \times 9.81}{1+0.388} = \frac{25.9965}{1.388} = 18.729 \text{ kN/m}^3$$

b) $S = 0.56$

$$\gamma = \frac{(G+Se)\gamma_w}{1+e} = \frac{(2.65+0.56\times0.388)\times9.81}{1+0.388}$$

$$= \frac{28.128}{1.388} = 20.2651 \text{ kN/m}^3$$

c) $S = 1$

$$\gamma_{sat} = \frac{(G+e)\gamma_w}{1+e} = \frac{(2.65+0.388)\times9.81}{1+0.388} = 21.471 \text{ kN/m}^3$$

$$Se = wG \Rightarrow w = \frac{Se}{G} = \frac{0.56\times0.388}{2.65} = 0.081$$

$$= 8.1\%$$

d) unit weight in submerged condition

$$\gamma' = \frac{(G-1)\gamma_w}{1+e} = \frac{(2.65-1)\times9.81}{1+0.388} = 11.661 \text{ kN/m}^3$$

(or)

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

$$= 21.471 - 9.81 = 11.661 \text{ kN/m}^3$$

5. A saturated clay has a water content 39.3% and a bulk sp. gravity of 1.84 final void ratio and sp. gravity of particles.

Sol:

$w = 39.3\%$ $G_m = 1.84$

We know $G_m = \frac{\gamma}{\gamma_w}$

$\gamma = G_m \cdot \gamma_w$

$= 1.84 \times 9.81 = 18.05 \ kN/m^3$

(or)

$\gamma = 1.84 \times 1 = 1.84 \ kN/m^3$ $(\because \gamma_w = 1 \ g/cc)$

Since it is saturated than $\gamma = \gamma_{sat}$

$= 1.84 \ g/cc$

$Se = wG$

$e = wG$

$$\gamma_{sat} = \frac{(G+e)\gamma_w}{1+e} = \frac{(G+wG)\gamma_w}{1+e}$$

$$1.84 = \frac{G(1+0.393)\times 1}{1+0.393\times G}$$

$$= \frac{1.393G}{1+0.393G}$$

$1 + 0.393G = 0.757G$

$0.364G = 1.$

$$\boxed{G = 2.747}$$

$e = wG$

$= 0.393 \times 2.747$

$e = 1.0795$

6. A soil has porosity of 40% and G = 2.65 and water content 12% determine mass of water to added to 100 m^3 of this soil for full saturated.

Sol:

$n = 90\%$ $w = 12\%$ $G = 2.65$

let us take volume of solids = 1 m^3

wt of solids $(W_s) = V_s \gamma_s = G \gamma_w V_s$

$= 2.65 \times 1000 \times 1$

$= 2650$ kg

$\therefore$ wt of water $= W_w = w \times W_s$

$= 0.12 \times 2650 = 318$ kg

volume of water $V_w = \frac{318}{1000} = 0.318\ m^3$

$$e = \frac{n}{1-n} = \frac{0.4}{1-0.4} = 0.667$$

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

$$V_v = e \times V_s = 0.667 \times 1 = 0.667\ m^3$$

volume of air $V_a = V_v - V_w = 0.349\ m^3$

volume of addition water for full saturation $= 0.349\ m^3$

$\therefore$ Total volume $V = V_w + V_s + V_a$

$= 0.318 + 1 + 0.349 = 1.667\ m^3$

$1.667 \rightarrow 0.349$

$100\ m^3 \rightarrow \frac{100 \times 0.349}{1.667} = 20.935\ m^3$

volume of water required for 100 m^3 of soil

$= 20.935\ m^3$

$= 20935$ kg

COMPACTION

compaction is a process of changing the state of the soil by expelling the air in the voids.

compaction process is important in study of earthend dam. construction seepage analysis and in stability of solids.

other definistion of compaction is pressing the soil particles close to eachother by mechanical methods this is part of soil stabilization Air during the compaction is expelled from the void space in the soil. Therefore the massdensity is increased. compaction is the process done for improving engineering properties of soil. The Compaction process may be accumplished by rolling, tanping, (or) vibration.

compaction is some what different from consolidation. while consolidation is a gradual process of volume reduction under sustained loading, compaction refers to a more or less rapid reduction mainly in the air void under a loading of short duration.

Difference between compaction and consolidation :-

Consolidation	Compaction
(1) consolidation is the process that changes the state of the soil by expelsion of water.	(1) compaction is the process that changes the state of the soil by expelsion of air.
(2). consolidation is a slow process.	(2) compaction is a rapid process.
(3) settlement are slower	(3) settlements are faster.
(4) consolidation occurs in all three dimensions But we study consolidation in one direction only.	(4) Since the boundaries in other direction this confined compaction occurs in 1-D only.
(5) consolidation occurs in field when saturated soils are subiected to static load.	(5) compaction is artificially done to construct embackment and earthen dams.

Factors affecting the compaction:-

The dry density of the soil is increased by compaction. The increase in dry density depends upon the following factors.

1. Water content:-

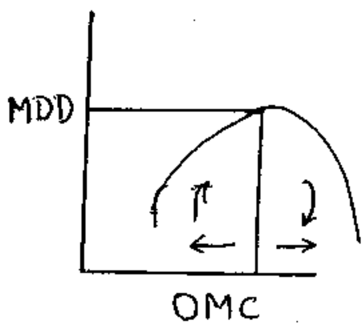
At low water content the soil is stiff and offers more resistence to compaction. As water is increased the soil particles gets lubricated. The soil mass becomes more workable and the particles have closer packing.

The dry density of the soil increases with an increase in water content. Fill the optimum water content is reached.

At the stage the air voids attain approximately a constant volume.

Further increase in water content the air voids donot decrease. But the total voids (air + water) increase and the dry density decrease.

The higher drydensity is achieved upto the optimum water content. Due to forcing in air out of the soil from the soil

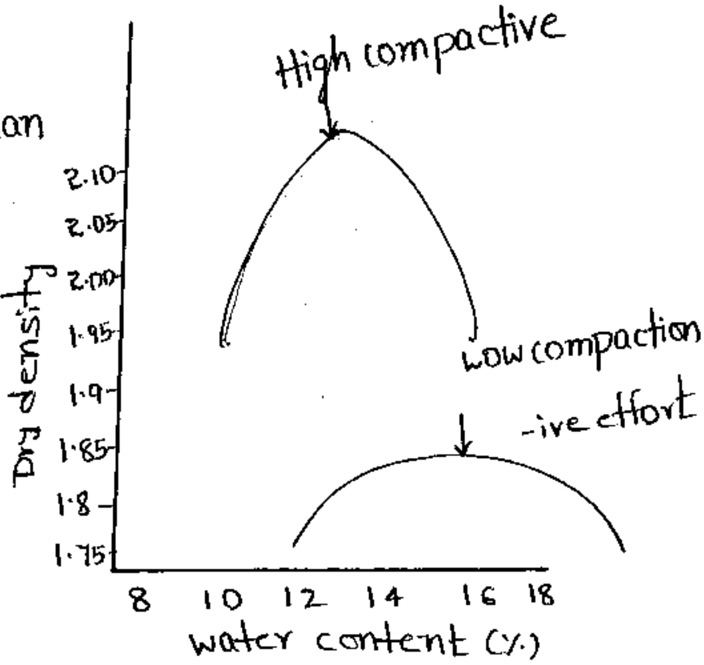


After the optimum water content is reached it becomes more difficult to force air out of the soil. Then we have to increase the moisture content to reduce the dry density.

2) Amount of compaction (or) compactive affort:-

The effect of increase in the amount of compactive effort is "to increase the maximum dry density and to reduce the optimum water content

This is shown in figure.



The water content lessthan the optimum the effect of increased compaction is more predominant.

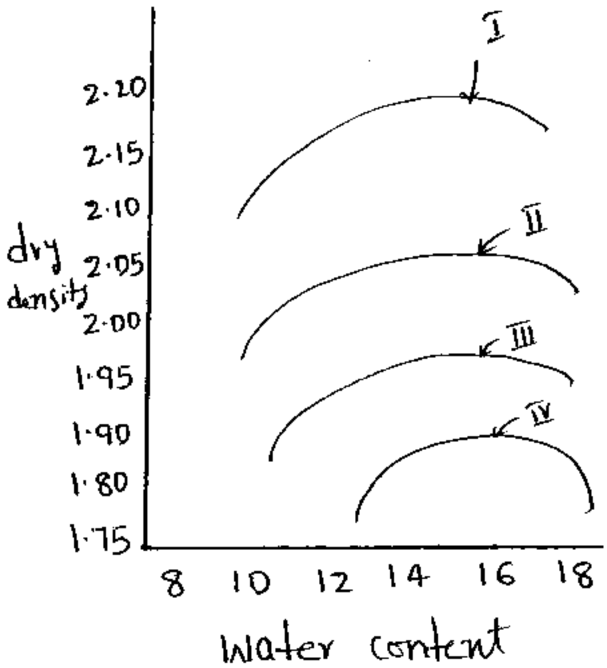
At a water content morethan the optimum the volume of air voids becomes almost constant and the effects of increased compaction is not significant.

From this we can inform that compaction is kevior on dry of optimum and it is lighter on wet of optimum.

3. Type of soil :-

The dry density achived depends on the type of soil. In general coarse grain soil can be compacted to higher drydensity than fine grain soils. With the addition of even a small quantity of fines to a coarse grain soils the soils obtained much higher dry density for the same compactive effort.

I - Well graded sand
II - Low plasticity silt
III - Low plasticity clay
IV - High plasticity clay



4. Method of compaction :-

The dry density achieved depends not only compactive effort but also on the method of compaction.

For the amount of compactive affort the drydensity will depends upon wheather the method of compaction utilised kneading action (or) Dynamic action (or) static action.

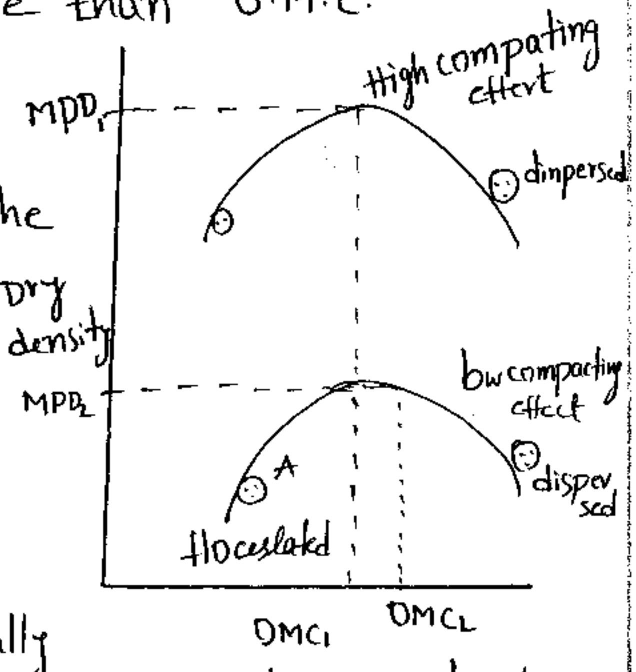
Effect of compaction on properties of soils:-

The engineering property of the soil are improved by compaction. when we are constructing an embankment the desirable properties are achieved by proper selection of type.

The following properties are changed due to compaction of soil. The following discussion the phase "dry of optimum" means the water content is less the optimum moisture content, and the phase 'wet of optimum means the water content is more than O.M.C.

(i) Soil structure:-

The water content in the compacted soils plays an vital role in changing the properties of the soil.



soils compacted at a water content lessthan OMC generally have a floccuated structure.

soils compacted at a water content less than OMC generally have a flocculated structure.

soil compacted at a water content more than the optimum water content usually have a dispersed structure. The structure won't depend on the type of compaction.

If OMC_1 and MDD_1 are the soil parameters at high compacting effort and OMC_2, MDD_2 are the soil parameters at low compacting effort. Then OMC_1 is lesser than OMC_2 and MDD_1 is greater than MDD_2.

$$OMC_1 < OMC_2$$

$$MDD_1 > MDD_2$$

In figure the point A on dry side of the optimum the water content is so low that the attractive force's are more predoments than the repulsive forces. this results in flocculated structure.

2. <u>permeability</u>:- The permeability of a soil depends upon the size of voids. The permeability of soil decreases with an increase in water content on the dry side of the optimum water content. There is an improved orientation of the particles and corresponding reduction in

the size of voids which cause a decrease in permeability. The minimum permeability occurs at or slightly above the optimum water content. After that stage, the permeability, slightly increase, but it always remains much less than that on the dry side of the optimum. The slight increase in the drydensity is more pronounced than the effect of improved orientation.

3) Swelling:- A soil compacted dry of the optimum water content has high water deficiency and more random orientation of particles. Consequently, it imbibes more water than the sample compacted wet of the optimum, and has, therefore more swelling.

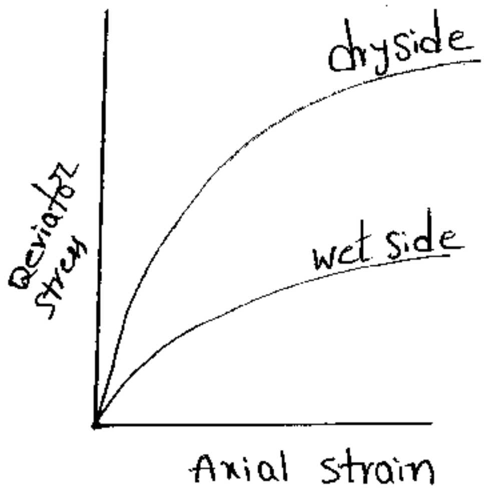
4. pore water pressure:- A sample compacted dry of the optimum has low water content. The pore water pressure developed for the soil compacted dry of the optimum is therefore less than that for the same soil compacted wet of the optimum.

(5) compressibility:- The flocculated structure developes on the dry side of the optimum offers greater resistance to compression than the dispersed structure on the wet side consequently, the soils on the dry side of the optimum are less compressible.

(6) stress - strain Relationship:-

The soils compacted dry of optimum has steeper stress - strain curve.

The modulus of elasticity for the soils compacted dry of optimum is high.



Such soils have brittle failure. Like dense sands and over consolidated soils.

The soils compacted on wet of optimum will having relatively flater stress-strain curve, and it will have lower modulus of elasticity.

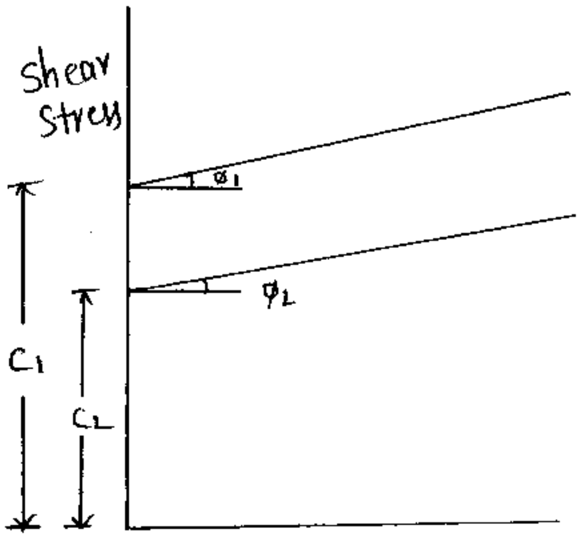
The failure in this case occurs at a large strain and it is of plastic in nature.

7) <u>Shear strength</u> :-

Since shear strength is a function of wherion and bulk density. The change in water contant changes the bulkdensity so as shear strength.

In general at a given water content the shear strength of the soil increases with an increase in the compactive effort till a critical degree of saturation is reached.

The shear strength of compacted soils depends upon the soil type, the moduler water content, drainage conditions and method of compaction.



The soil compacted dry of optimum have a higher shear strength at low strains. However, at large strain the flocculated structure for the on the dry side in broken and the ultimate strength is approximately eaual for both samples.

On wet side the shear strength is further reduced. If compaction is reduced.

Problems

(1) The OMC of a soil is 16.5% and its maximum dry density is 1.57 g/cc. The specific gravity of solids is 2.65. Determine (i) the degree of saturation and percentage of air voids of the soil at OMC. (ii) Theoritical dry density at O.M.C corresponding to zero air voids.

Sol:- (i) $\gamma_d = 1.57 \text{ g/cc}$

$\omega = 16.5\%$, $G = 2.65$

$$\gamma_d = \frac{G\gamma_w}{1+\frac{WG}{S}}$$

$eS = WG$

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

$$1.57 = \frac{2.65\times 1}{1+\frac{165\times 2.65}{S}}$$

$$1+\frac{0.165\times 2.65}{S} = \frac{2.65}{1.57}$$

$$\frac{0.437}{S} = 0.687$$

$$S = 0.636$$

$$= 63.6\%$$

The soil at OMC has a moisture of 16.5% and dry density of 1.57 g/cc.

percentage of air voids = 100 − S

= 100 − 63.6

= 36.4%

(ii) At zero air voids the soil is fully saturated

i.e $S=1$

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

$$Se = WG$$

$$e = WG \quad (\because S=1)$$

$$\gamma_d = \frac{G\gamma_w}{1+WG} = \frac{2.65\times 1}{1+0.165\times 2.65}$$

$$\gamma_d = 1.843 \text{ g/cc.}$$

(2) During the construction of an embankment the density attained by field compaction was investigated by sand jar method. A test pit was excavated in the newly compacted soil and wass filled up by pouring sand. The following observations were made. weight of soil excavated from pit equal to 2883g. Bulk density of sand equal to 1.52g/cc. Moisture content of embankment soil = 16%. Determine the dry density of the compacted soil.

Sol: The volume of sand required to fill up the pit

$$= \text{volume of pit} = \frac{\text{wt. of sand}}{\text{bulk density of sand}}$$

$$V = \frac{2883}{1.52}$$

$V = 1897 cm^3$

Wt of the soil excavated from the pit = 2883g

$\gamma = \frac{\text{wt of soil}}{\text{volume}} = \frac{2883}{1897} = 1.51 g/c.c$ $\quad w = 16\% = 0.16$

$\therefore$ Dry density $= \gamma_d = \frac{\gamma}{1+w} = \frac{1.51}{1+0.16} = 1.30 g/cc.$

3. It is required to construct an embackment by compacting a soil excavated from near by barrow area. The optimum moisture content and maximum drydensity of the soil for determine in the laboratory and were found to be 22.5% and 1.66g/cc respectively. However, the natural moisture content and bulkdensity of soil were 9% and 1.75g/cc respectively. Final out the quantity of the soil to be excavated and the quantity of water to be added to it for every $100m^3$ of finished embankment.

Sol: The embankment should be constructed by compacting the soil obtained from barrow area which is at the OMC and corresponding dry density. But the natural moisture content of the existing soil is less than its OMC. Hence a certain amount of water is to be added to the soil prior to the compaction.

Maximum dry density is given as 1.66 g/cc

$$= \frac{1.66 \times 10^{-3} \times 10^{-3} t}{10^{-6}}$$

$= 1.66$ tone/m^3

$[1 g/cc = 1 t/m^3]$

$[1 g/cc = \frac{10^{-3} kg}{10^{-6} m^3}]$

$$= \frac{10^{-3} \times 10^{-3}}{10^{-6} m^3}.$$

But $\gamma_d = \frac{W_d}{V} \Rightarrow W_d = \gamma_d V.$

In the problem 1 unit of embakment is given as $100 m^3$ of finished embankment.

From this wt. of dry soil for $100 m^3$ embankment. $W_d = 1.66 \times 100 = 166$ tones.

The weight of water reauired to get the optimum moisture content.

$$W = \frac{W_w}{W_d}$$

$$W_w = W \times W_d$$

$$= 0.225 \times 166$$

$$= 37.35 \text{ tones}.$$

But the Bulk of the

But the bulk density of the existing soil (or) transported soil = 1.78 g/cc = 1.78 t/m³ and the moisture content is 9%.

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

$$= \frac{1.78}{1+0.09} = 1.633 \, t/m^3$$

The volume of soil V_b to be obtained from barrow area in order to obtained 166 tones of dry soil.

$$V_b = \frac{\text{wt. of dry soil excavated}}{\gamma_d \text{ in natural in condition.}}$$

$$V_b = \frac{166}{1.633} = 101.65 m^3$$

volume of extra soil to be added = $1.65 m^3$

weight of the water avilable from the soil in natural condition = wt. of dry soil × Natural water content

= 166 × 0.09 = 14.94 tones

weight of water avilable per unit embankment = 37.35 tones.

quantity of water to be added = 37.35 − 14.94

= 22.41 tones.

volume of water to be added = $\frac{\text{wt. of water}}{\text{density of water}}$

$= \frac{22.41}{1\ t/m^3} = 22.41 m^3$

We know that 1 litre $= 10^{-3} m^3$

$1 m^3 = 1000$ lts.

$22.41 m^3 = 22.41 \times 1000$ lts

$= 22410$ lts.

To construct $100 m^3$ of embankment $101.65 m^3$ of soil is to be excavated from the barrow pit and 22410 litres of water is added.

7. An embankment was constructed by compacting at a moisture content of 15.5% and dry density of 1.72 g/cc. If the specific gravity of solid soils be 2.68 Determine the void ratio and degree of saturation of embankment of soils.

Sol:-

$W = 15.5\% = 0.155$

$G = 2.68$

We have $\gamma_d = 1.72$

$$\frac{G\gamma_w}{1+e} = 1.72$$

$$1+e = \frac{2.68 \times 1}{1.72} = 1.558$$

$$e = 0.558$$

$Se = WG$

$$S = \frac{WG}{e} = \frac{0.155 \times 2.68}{0.558} = 0.744 = 74.4\%.$$

The required degree of saturation $= 74.4\%$.

5. The rock contant in a filled is 80% dry weight. The rock can be compacted to a minimum void ratio of 0.73. The man dry unit weight to which the soil fraction can be compacted is 1.63g/cc What is the maximum dry density to which the fill can be compacted Given specific gravity of rock is 2.56.

Sol:- When the rock present in the fill is compacted to the densest state its dry unit weight is given by

$$\gamma_{dmax} = \frac{G \gamma_w}{1 + e_{dense}}$$

$$\gamma_{dmax} = \frac{2.56 \times 1}{1 + 0.73} = 1.479 \, g/cc$$

For the soil $\gamma_{dmax} = 1.63$ (Given in problem)

Let us now consider 1unit soil of the given fill (1g of soil is taken as unit in fill)

According to the question the weight of soil and rock present in the given sample are 0.2g and 0.8g respectively.

Now volume of 0.8g of rock $= \frac{\text{weight}}{\text{density}}$

$= \frac{0.8}{1.48} = 0.54\,cc$

volume of 0.2g of dry soil $= \frac{0.2}{1.63} = 0.122\,cc.$

Total volume of 1g of fill $= 0.54 + 0.112$

$= 0.662\,c.c$

Maximum dry density of composite fill

$= \frac{\text{Dry weight}}{\text{volume}}$

$= \frac{1\,gm}{0.662} = 1.508\,g/cc.$

6) In order to determine the relative density of sand sample, its natural moisture content and bulkdensity were determined in the field, and were found to be 7% and 1.61g/cc respectively. Samples of this soil were then compacted in proctor's mould of 1/30 cubic feet capacity at loosest and densest state the following data were obtained.

weight of the empty mould = 2100g

weight of the mould + soil in the loosest state: 3363.6gm

weight of mould + soil in the densest state:

= 3857.4g

moisture content of the sample used in test = 11%.

Determine the relative density of the sand and coment on its type.

Sol:

volume of the mould $= \frac{1}{30}$ cu.ft

$$= \frac{1 ft^3}{30} = \frac{(12)^3 \times 2.54^3}{30}$$

$$= 943.89 \, c.c$$

The bulk density in the loosest state

$$\gamma_1 = \frac{3363.6 - 2100}{943.89}$$

$$= 1.339 \, g/cc$$

Dry density in the loosest state $= \gamma_{d\,min}$

$$\gamma_{d\,min} = \frac{\gamma}{1+w} = \frac{1.339}{1+0.11} = 1.206 \, g/cc$$

Bulk density in the densest state $= \frac{3857.4 - 2100}{943.89}$

$$\gamma_2 = 1.861 \, g/cc$$

Dry density in the denses state $= \gamma_{d\,max}$

$$\gamma_{d\,max} = \frac{1.861}{1+0.11} = 1.67 \, g/cc$$

Natural bulk density is given as

$$\gamma = 1.61 \, g/cc$$

and natural moisture content is given as 7%.

∴ Insitu dry density (or) Natural dry density

$$\gamma_d = \frac{1.67}{1+0.07} = 1.504\ g/cc$$

Relative density $= \frac{\gamma_{d\,max}}{\gamma_d} \times \frac{\gamma_d - \gamma_{d\,min}}{\gamma_{d\,max} - \gamma_{d\,min}}$

$$= \frac{1.67}{1.504} \times \frac{1.504 - 1.206}{1.67 - 1.206}$$

$$= 0.713 = 71.3\%$$

Field compaction Methods / Equipment :-

Several methods are used for compaction of soil in field. The choice of the method will depend upon the soil type, the maximum dry density required, and economic consideration. Some of the more commonly used conventional methods are disscussal below.

1) Tampers :- A hand-operated tamper (or rammer) consists of a block of iron (or stone), about 3 to 5 kg in mass, attached to a wooden rod. The rammer is lifted for about 0.30m and dropped on the soil to be compacted. A mechanical rammer is operated by compressed air gasoline

power. It is much heavier, about 30 to 150kg. Mechanical rammers have been used upto a mass of 1000kg in some special cases.

Tampers are used to compact soil adjacent to existing structure or confined areas, such as trenches and behind the bridge abutments where other methods of compaction cannot be used. Owing to very low output, tampers are not economical where large quantities of soils are involved. Tampers can be used for all types of soils.

(2) Rollers:- Rollers of different types are used for compaction of soils. The compaction depends upon the following factors.

(i) contact pressure:- In general, the compaction increases with an increase in the contact pressure. For a smooth-wheel roller, the contact pressure, pressure depends upon the load per unit width and the diameter of the roller.

(ii) Number of passes:- The compaction of a soil increases with an increases in the number of passes made. However, beyond a certain limit, the increases in the density with an increase in the number of passes in not applicable. From economy consideration, the number of passes generally restricted to a reasonable limit between 5 to 15.

(iii) Layer thickness:- The compaction of a soil increases with a decrease in the thickness of the layer. However, for economy consideration, the thickness is rarely kept lessthan 15cm.

(iv) Speed of roller:- The compaction depends upon the speed of the roller. The speed should be so adjusted that the maxi-mum effect is achieved.

Types of Rollers:-

(a) Smooth-wheel rollers:-

A smooth wheel rollers generally consists of three wheels, two large wheels in the rear and one small wheel in the front. A tandem type smooth wheel roller consists of only two drums; one in the rear and one in the front. The mass of a smooth wheel roller generally varies between 2 to 15 Mg. These roller are operated by internal combustion engines.

(b) Rubber tyred roller:- (or) (pneumatic-tyred roller)

The maximum weight of this roller may reach 2000 kN. The smaller rollers usually have 9 to 11 tyres on two axles with the tyres spaced so that a complete coverage is obtained with each pass. The tyre loads of the smaller roller are in the 7.5 kN and the tyre pressure in the order of 200 kN/m². The large rollers have tyre loads ranging from 100 to 500 kN per tyre, and tyre pressure range from 400 to 1000 kN/m².

(c) sheep foot roller:-

Sheep foot rollers are avilable in drum widths ranging from 120 to 180cm and in drum diameters ranging from 90-180cm. projections like a sheeps foot are fixed on the drums. The lengths of these projection range from 17.5cm - 23cm. The contact area of the tamping foot ranges from 35 to 56cm². The loaded weight per drum ranges from about 30KN for the smaller Sizes to 130kg/ 130KN for the layer Sizes.

(d) vibratory roller:-

The weight of vibratory rollers range from 120 to 300kN. In some units vibration is produced by weights placed eccentrically on a rotating shaft in such a manner that the forces produced by the rotating weights are essentially in a vertical direction. vibratory rollers are effective for compacting granular soils.