

**C.V. RAMAN POLYTECHNIC, BHUBANESWAR**



**C.V.Raman Polytechnic**

*Quality Education for the New Millenium*

**LECTURE NOTE**

**GEOTECHNICAL ENGINEERING,  
(Th.2)**

**SEM-3<sup>rd</sup>**

**BRANCH- CIVIL ENGINEERING**

**Prepared by**

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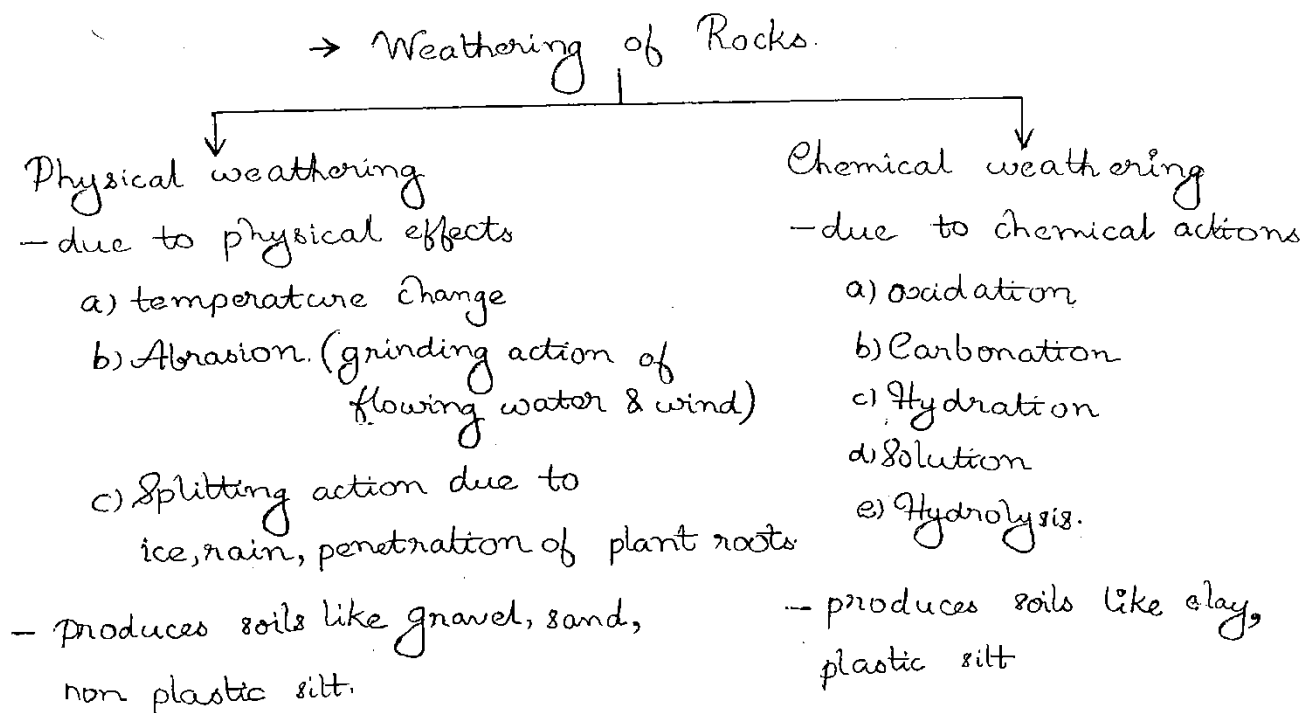
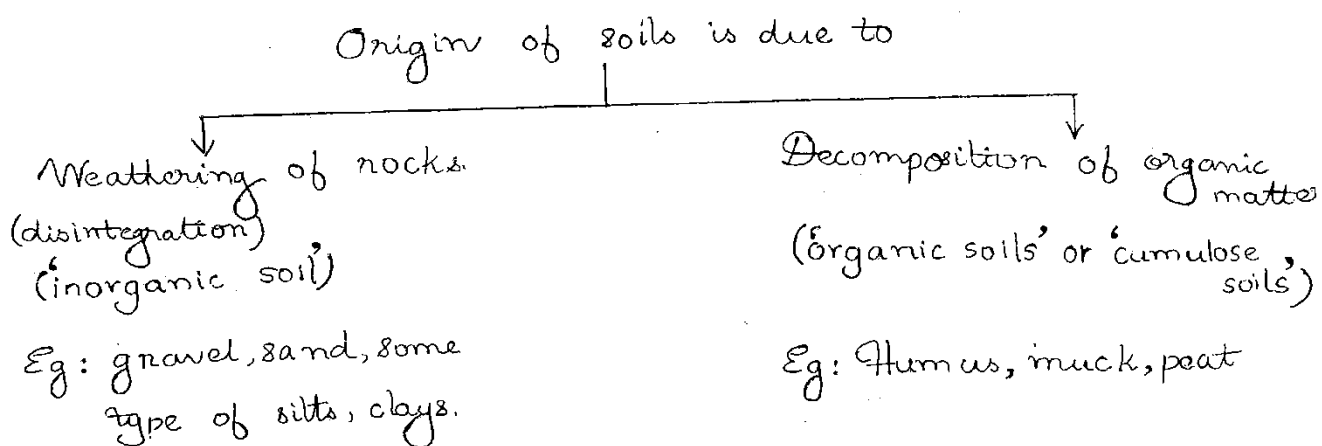
# GEO TECHNICAL ENGINEERING

(12 marks)

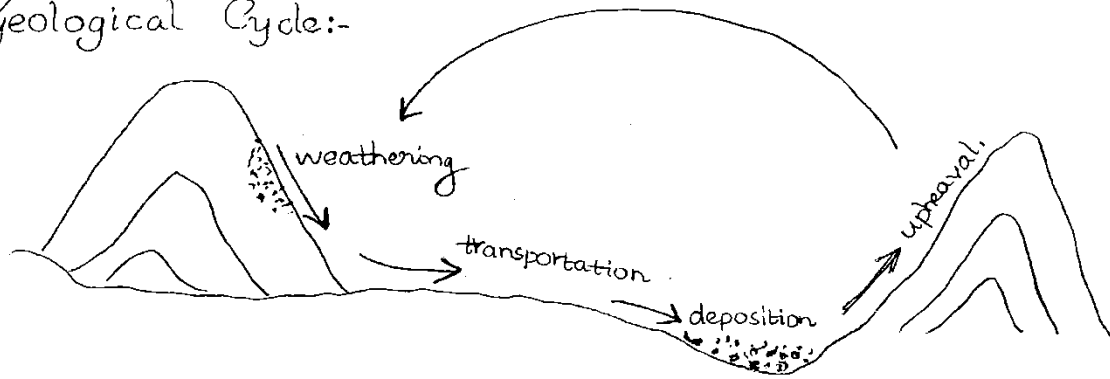
## 1. ORIGIN OF SOILS

Soil is a naturally occurring unconsolidated earth material present above the bed rock. - Terzaghy.

Karl Terzaghy - Father of Soil Mechanics.



→ Geological Cycle:-



Pedogenesis : It is a process of formation of soil.

→ Transportation of Soil :

It is due to -

- a) Wind - Aeolian Soil : transported & deposited by wind.
- b) Water - Alluvial Soil : transported by water & deposited along river & lake.
- c) Glacier - Glacier deposit : transported by glacier
- d) Gravity - Colluvial Soil : transported & deposited by Gravity.

Lacustrine Soil :- transported by water & deposited in lakes

Marine Soil :- transported by water & deposited in sea

\* Classification of Soils.

a) Residual Soils. :- soil which remains at or near the (Sedentary Soil). parent rock.

b) Transported Soil :- transported away from parent rock

→ Forces acting on the Soil Particles :

(i) Gravitational Force or Body Force.

(ii) Surface force

Body Force

- (i) It is proportional to mass
- (ii) Eg: weight.
- (iii) It is predominant in gravel & sand

Surface Force.

- (i) It is proportional to surface <sup>area</sup>
- (ii) Eg: cohesion, electrochemical force.
- (iii) It is predominant in clay. (Clay behaviour is mainly controlled by surface force).

In the case of silty soil both body force and surface force <sup>3</sup> are equally important.

→ Popular Field names of Soils.

1. Black Cotton soil (BC Soil):— a residual clayey soil.

— highly plastic.

— exhibits high swelling & shrinkage due to presence of "Montmorillonite" clay mineral.

— parent rock is Basalt or trap.

2. Loam :— a mix of sand, silt & clay

3. Moorum :— a gravel mixed with red clay

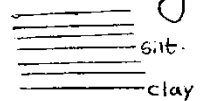
4. Bentonite :— a decomposed volcanic ash.

— a clayey soil, highly plastic, highly water absorb

— bentonite slurry is called "Drilling Mud"

5. Varved Clay :— contains alternate thin layers of silt & clay

— lacustrine deposits.



6. Loess :— Aeolian deposit.

— contains silt sized particles

— weakly cemented by  $\text{CaCO}_3$  particles.

7. Sand dunes :— Aeolian deposit.

— particle size is same.

8. Humus :— half decomposed organic soil.

— amorphous in nature. (amorphous x crystalline)

9. Muck :— contains fine inorganic particles with decomposed organic material.

— black in colour.

10. Peat :— highly decomposed organic matter.

— fibrous in nature.

— dark brown to black colour

— bad odour.

11. Fill :- a manually deposited soil. (a man made deposit)

## 2. DEFINITIONS & PROPERTIES OF SOIL

\* Partially saturated soil : solids + water + air (3 phase system)

Fully saturated soil : solids + water. (2 phase system)

Dry soil : solids + air

\* Frozen soil : solids + water + ice + air. (4 phase system)

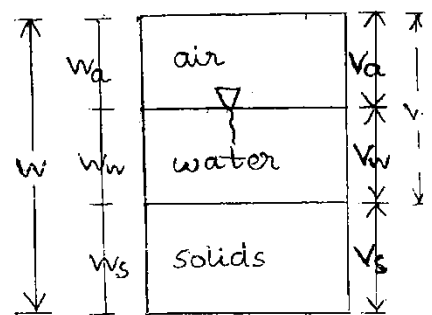
$V_s \rightarrow$  volume of solids.

$V \rightarrow$  volume of soil.

$V_v \rightarrow$  volume of voids.

$$V_v = V_w + V_a.$$

$$V = V_s + V_w + V_a.$$



Phase Diagram  
OR  
Block Diagram

\* Void Ratio,  $e$

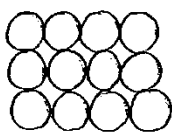
$$e = \frac{V_v}{V_s}$$

Range :- more than zero, it can have any value (no limit)

- For coarse grained soil,  $e < 1$  generally.

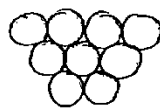
- For fine grained soil,  $e > 1$  generally

- The 'e' of FG soil is generally more than that of a coarse grained soil.



Cubical array  
(loosest state)

$$e_{\max} = 0.91$$



Diagonal array  
(densest state)

$$e_{\max} = 0.35$$

## \* Specific Gravity of Soil Solids, $G$

$$G = \frac{\gamma_s}{\gamma_w} \quad ; \quad \gamma_w \rightarrow \text{distilled water (pure water)}$$

Also called 'True Specific gravity of soil'

For soils,  $G : 2.60 - 2.85$  generally, (inorganic).

\* Mass Specific Gravity of soil. (or) Bulk Sp. Gr. of soil  
(or) Apparent Specific Gravity of soil,  $G_m$ .

$$\text{For a dry soil, } G_m = \frac{\gamma_d}{\gamma_w}$$

$$\text{For a partially saturated soil, } G_m = \frac{\gamma}{\gamma_w}$$

$$\text{For a fully saturated soil, } G_m = \frac{\gamma_{sat}}{\gamma_w}$$

$$\boxed{G_m < G}$$

For cement :-

$$\text{True sp. gravity, } G = 3.15$$

$$\text{Apparent sp. gravity, } G_m = 1.44$$

$$\text{For cement, } \gamma_s = 3150 \text{ kgf/m}^3$$

$$\gamma_d = 1440 \text{ kgf/m}^3$$

$$n \approx 44\%$$

Important Relationships:

$$1. \quad e = \frac{wG}{S_r}$$

$$2. \quad \gamma = \gamma_w \left( \frac{G + eS_r}{1 + e} \right)$$

$$3. \quad \gamma_{sat} = \gamma_w \left( \frac{G + e}{1 + e} \right)$$

$$4. \quad \gamma_d = \frac{\gamma_w G}{1 + e}$$

$$5. \quad \gamma_d = \frac{\gamma}{1 + w}$$

$$6. \quad \gamma_d = \frac{(1 - na)\gamma_w G}{1 + wG}$$

$$7. \quad \gamma = \gamma_d + S_r(\gamma_{sat} - \gamma_d)$$

\* Saturated unit weight of Soil,  $\gamma_{sat}$ .

(4)

It is the bulk unit weight of soil in a saturated condition.  $\Rightarrow \gamma_{sat} > \gamma$

For partially saturated soil,  $\gamma_{sat}$  use  $\gamma$

For fully saturated soil, use  $\gamma_{sat}$ .

\* Dry unit weight of Soil,  $\gamma_d$ .

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

It can be used irrespective of saturation level of soil.

\* Unit weight of Solids,  $\gamma_s$

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

\* Submerged Unit Weight of Soil,  $\gamma_{sub}$  or  $\gamma'$

It is the submerged wt. of soil per unit volume of soil.

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

$$\begin{cases} \gamma_{sat} \downarrow - \text{gravity force} \\ \gamma_w \uparrow - \text{buoyant force.} \end{cases}$$

1<sup>st</sup> Aug,  
MONDAY

Submerged weight of Soil is based on Archimedes Principle.

$\gamma_w$  = unit weight of water

$$= 1 \text{ g/cc} = 1 \text{ ton/m}^3 = 1000 \text{ kgf/m}^3$$

$$= 9.81 \text{ kN/m}^3 \approx 10 \text{ kN/m}^3$$

$$\boxed{\gamma_s > \gamma_{sat} > \gamma_{bulk} > \gamma_{dry} > \gamma'}$$

For a given soil,  $\gamma_s$  remains a constant

\* Porosity,  $n$  (also called 'Percentage voids')

4<sup>10</sup>

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

Range:  $0 < n < 100\%$  ( $V_v \neq 0$  for soil,  $\therefore n \neq 0$ ).

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

\* Degree of Saturation,  $S_r$

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

For a dry soil,  $S_r = \frac{0}{V_v} \times 100 = 0$  ( $V_w = 0$ )

For a saturated soil,  $S_r = \frac{V_v}{V_v} \times 100 = 100$  ( $V_w = V_v$ )

Range:  $0 \leq S_r \leq 100\%$

\* Air content,  $a_c$

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

For a saturated soil,  $a_c = \frac{0}{V_v} = 0$  ( $V_a = 0$ ).

For a dry soil,  $a_c = \frac{V_v}{V_v} = 1$ . ( $V_a = V_v$ ).

Range:  $0 \leq a_c \leq 1$

\* % air voids,  $n_a$

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

For a saturated soil, ( $V_a = 0$ ),  $n_a = 0$

For a dry soil,  $n_a = n$  ( $V_a = V_v$ ).

Range:  $0 \leq n_a \leq n$ .

$$a_c + S_r = \frac{V_a}{V_v} + \frac{V_w}{V_v}$$

$$= \frac{V_a + V_w}{V_v} = \frac{V_v}{V_v} = 1.$$

$$\therefore \boxed{a_c + S_r = 1}$$

$$n a_c = \frac{V_v}{V} \times \frac{V_a}{V_v} = \frac{V_a}{V} = n_a.$$

$$\boxed{n \cdot a_c = n_a}$$

$W_s \rightarrow$  weight of solids.

$W \rightarrow$  weight of soil.

$$W = W_s + W_w \quad (W_a \text{ is negligible})$$

$W_d \rightarrow$  <sup>total.</sup> weight of soil in dry condition. ( $= W_s$ ).

\* Water Content,  $w$

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

For dry soil,  $w = \frac{0}{W_s} \times 100 = 0$

For a saturated soil,  $w > 0$ .

(i.e., water content <sup>can</sup> have any value greater than zero  
Sometimes  $> 100\%$ , sometimes  $< 100\%$ )

\* Bulk unit weight of Soil,  $\gamma$

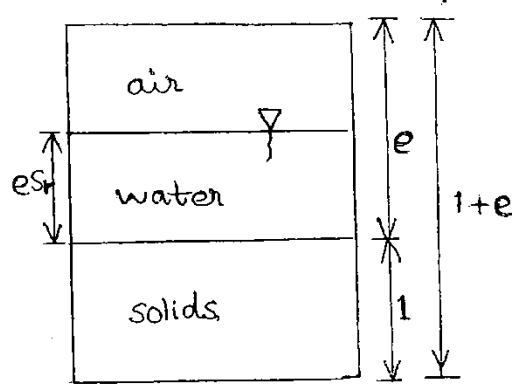
- it is the total weight of soil per unit volume of soil.

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

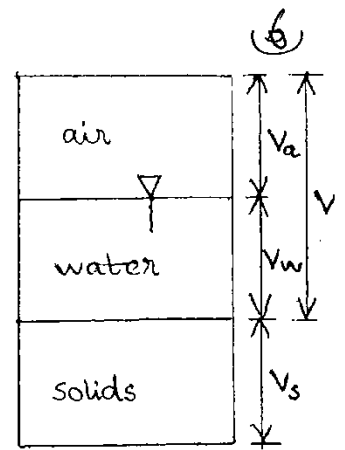
In a unit phase diagram,

lets take  $V_s = 1$

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



Unit Phase diagram.



Phase Diagram

If  $V_s = 1$ , then

$$e = V_v$$

$$S_r = \frac{V_w}{V_v} \Rightarrow V_w = V_v \cdot S_r = e \cdot S_r$$

⊙ To derive  $n$  &  $e$  relationship:

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

⊙ To derive  $e = \frac{\omega G}{S_r}$

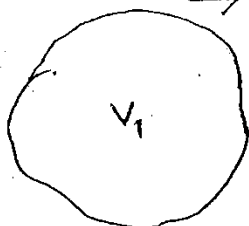
$$\omega = \frac{w_w}{w_s} = \frac{V_w \gamma_w}{V_s \gamma_s} = \frac{e S_r}{1 \cdot G}$$

$$\Rightarrow e = \frac{\omega G}{S_r}$$

⊙ To derive  $\gamma = \gamma_w \left( \frac{G + e S_r}{1 + e} \right)$

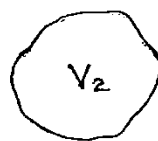
$$\begin{aligned} \gamma &= \frac{w_s + w_w}{V} = \frac{\gamma_s w_s + \gamma_w V_w}{V} \\ &= \frac{\gamma_s + \gamma_w e \cdot S_r}{1 + e} \end{aligned}$$

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



Before compaction

$e_1, \gamma_{d1}, w_s$



After compaction

$e_2, \gamma_{d2}, w_s$

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

$$\therefore V \propto (1+e)$$

$$\gamma_d = \frac{W_s}{V} \Rightarrow \gamma_d \propto \frac{1}{V}$$

$$\frac{V_2}{V_1} = \frac{\gamma_{d1}}{\gamma_{d2}}$$

Q. Due to compaction, the void ratio of a soil reduced from 1 to 0.6. What is the % volume loss.

$$\frac{V_2}{V_1} = \frac{1+0.6}{1+1} = \frac{1.6}{2}$$

$$V_2 = 0.8 V_1$$

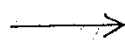
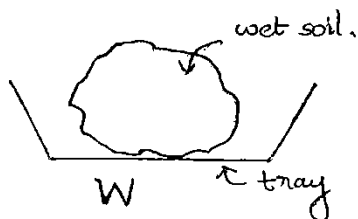
$\therefore$  vol. reduced to 80%.

vol. reduced by 20%  $\Rightarrow$  volume loss is 20%.

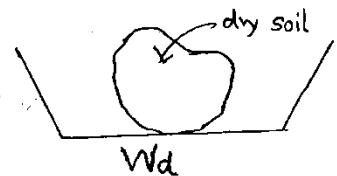
\* To Find Water Content of Soil :

- Overdrying Method.  $\rightarrow$  most accurate method.
- Pycnometer Method  $\rightarrow$  can be used only if 'G' is known
- Sand bath method  $\rightarrow$  quick field method. (approx. value).
- Calcium Carbide method  $\rightarrow$  quick method.
- Torsion balance method  $\rightarrow$  to find w.c at different depths below G.L

a) Oven Drying method :



in oven  
for 24 hours  
105° - 110° C.

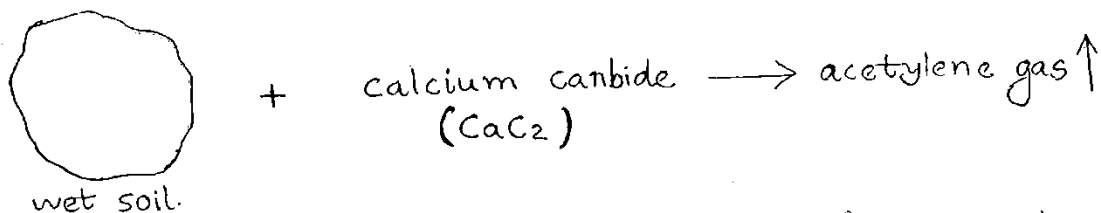


$W \rightarrow$  wt. of wet soil  
 $W_d =$  wt. of dry soil =  $W_s$

$$w = \frac{W_w}{W_s} \times 100 = \frac{W - W_d}{W_d} \times 100$$

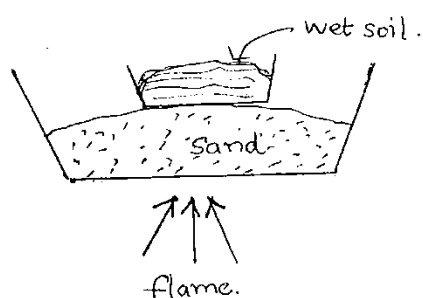
## b) Calcium Carbide method.

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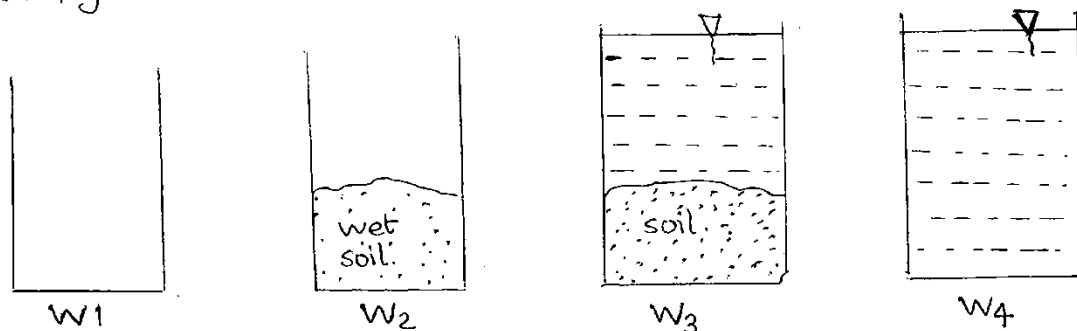
Amount of acetylene gas produced is directly proportional to water content of soil.

## c) Sand Bath method.



It's a crude method used in the field.

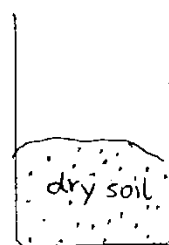
## d) Pycnometer Method



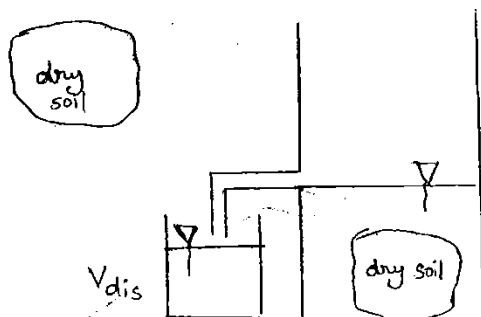
$$\text{Water content, } \omega = \left[ \frac{W_2 - W_1}{W_3 - W_4} \left( \frac{G - 1}{G} \right) - 1 \right] \times 100$$

① To find Specific Gravity,  $G$ , replace second container with dry soil

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



② To find volume:



$V_{dis} \rightarrow$  volume of water displaced

① If dry soil is immersed, then

$$V_{dis} = V_s \text{ (vol. of solids)}$$

② If partially saturated soil is immersed,

$$V_{dis} = V_s + V_w$$

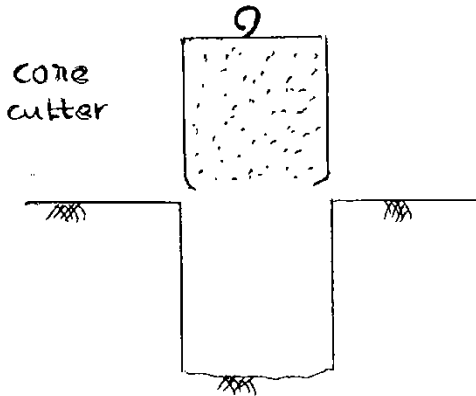
⊙ Partially saturated soil with wax coating, then

$$V_{dis} = \text{total volume of soil} = V + \text{vol. of wa}$$

\* To determine in-situ  $\gamma_d$  and  $e$

(i) Core Cutter Method.  $\rightarrow$  suitable for clays only (cohesive).

(ii) Sand Replacement method.  $\rightarrow$  suitable for any soil



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

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

12<sup>th</sup> Aug,  
TUESDAY

P-8.

1.

$$V_a = \frac{V}{6}, \quad V_w = \frac{V}{3}$$

$$V_a + V_w = V_v$$

$$\therefore V_v = \frac{V}{6} + \frac{V}{3} = \frac{V}{2}$$

$$V_s = V - V_v = \frac{V}{2}$$

$$\therefore e = \frac{V_v}{V_s} = \frac{0.5V}{0.5V} = \underline{\underline{1}}$$

2.  $\gamma_1 = 1.8 \text{ g/cc.}$  at  $w_1 = 5\%$  'e' remains constant.  
 $\gamma_2 = ?$  at  $w_2 = 10\%$

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

$$\therefore \gamma \propto (1+w) \quad (e \text{ is constant})$$

$$\frac{1.8}{\gamma_2} = \frac{1.05}{1.1}$$

$$\underline{\underline{\gamma_2 = 1.886 \text{ g/cc}}}$$

4. Volume of soil = vol. of sampler.

$$V = 45 \text{ cc.}$$

Given  $V_s = 25 \text{ cc.}$

$$e = \frac{V - V_s}{V_s} = \frac{20}{25} = \underline{0.8}$$

5. Initial wt. of soil = 0.18 kg.

Water added = 0.02.

$\therefore$  Total weight,  $w = 0.2 \text{ kg.}$

Vol. of soil,  $V = 10^{-4} \text{ m}^3$ . (initial volume assumed to be constant)

$$\gamma = \frac{w}{V} = \frac{0.2}{10^{-4}} = 2000 \text{ kg/m}^3$$

$$\gamma_d = 1600 \text{ kg/m}^3$$

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

$$1600 = \frac{2000}{1+w}$$

$$w = 0.25 = \underline{25\%}$$
 (method is valid only if  $V$  remains const. after adding water)

(OR)

Initial weight,  $w = 0.18 \text{ kg}$ ,  $V = 10^{-4} \text{ m}^3$ ,  $\gamma_d = 1600 \text{ kg/m}^3$

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

$$W = W_s + W_w$$

$$\therefore W_w = 0.02 \text{ kg.}$$

$$1600 = \frac{W_s}{10^{-4}} \Rightarrow W_s = 0.16 \text{ kg.}$$
 (water present in)

Water added additionally, = 0.02 kg.

$$W_w = 0.02 + 0.02 = 0.04 \text{ kg.}$$

$$\text{Final water content} = \frac{0.04}{0.16} \times 100 = \underline{25\%}$$

6.  $W = 34.62 \text{ g}$ ,  $V = 24.66 \text{ cm}^3$ ,  $W_d = W_s = 20.36 \text{ g}$

$$G = 2.68 \quad ; \quad e = ? \quad S_r = ?$$

$$\omega = \frac{W - W_d}{W_d} \times 100 = 70\%$$

$$e = \frac{\omega G}{S_r} = \frac{0.7 \times 2.68}{S_r} \longrightarrow \textcircled{1}$$

$$\gamma = \frac{W}{V} = \frac{34.62}{24.66} = 1.40 \text{ g/cc.}$$

$$\gamma = \gamma_w \left( \frac{G + e S_r}{1 + e} \right) \Rightarrow 1.4 = \frac{1 (2.68 + 0.7 \times 2.68)}{1 + e}$$

$$\therefore e = 2.25$$

$$S_r = \frac{0.7 \times 2.68}{2.25} = \underline{\underline{83.4\%}}$$

(OR)

$$\gamma_d = \frac{W_d}{V} = \frac{20.36}{24.66} = 0.825 \text{ g/cc}$$

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

$$e = \underline{\underline{2.25}}$$

819.  $\omega = 18\%$ ,  $\gamma = 2.05 \text{ g/cc.}$ ,  $G = 2.67$ ,

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

$$\frac{2.67 \times 1}{1 + e} = \frac{2.05}{1.18}$$

$$e = \underline{\underline{0.54}}$$

$$e = \frac{\omega G}{S_r} \Rightarrow S_r = \frac{0.18 \times 2.67}{0.54} = \underline{\underline{89.52\%}}$$

8.  $\omega = 39.3\%$ ,  $G_m = \frac{\gamma_{sat}}{\gamma_w} = 1.84$  (Soil is saturated)

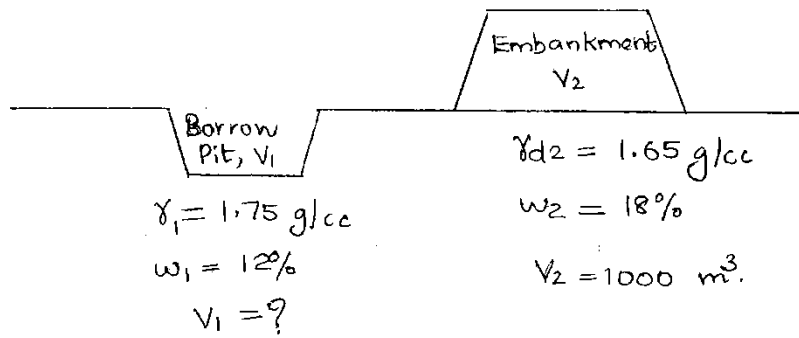
$$e = \frac{\omega G}{S_r} = 0.393 G$$

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

$$1.84 = \frac{G + 0.393 G}{1 + 0.393 G} \Rightarrow G = 2.70, e = 0.393 G = \underline{\underline{1.08}}$$

10.

9 (8)



$$\gamma_{d1} = \frac{\gamma_1}{1 + w_1} = \frac{1.75}{1 + 0.12} = 1.57$$

$$\frac{V_1}{V_2} = \frac{\gamma_{d2}}{\gamma_{d1}}$$

$$\rightarrow 1 \text{ g/cc} = 1 \text{ ton/m}^3$$

$$V_1 = \frac{1.65}{1.57} \times 1000 = \underline{\underline{1056 \text{ m}^3}}$$

To raise w.c from  $w_1 \rightarrow w_2$ :

$$\text{Weight of water to be added} = \gamma_d V (w_2 - w_1)$$

$$= \frac{1.65}{\text{g/cc}} \times 1000 \times 1000 (0.18 - 0.12)$$

$$= 99000 \text{ kg} = \underline{\underline{99 \text{ tons}}}$$

$$\gamma_{\text{borrow}} = 1.66$$

$$\gamma_{\text{truck}} = 1.15$$

$$\gamma_{\text{AU}} = 1.82$$

$$w_b = 8$$

$$w_t = 6$$

$$w_f = 14$$

$$V_b = ?$$

$$V_t = ?$$

$$V_f = 100 \text{ m}^3$$

$$\gamma_{d1} = 1.54$$

$$\gamma_{d2} = 1.08$$

$$\gamma_{d3} = 1.25$$

$$\frac{V_2}{V_3} = \frac{\gamma_{d3}}{\gamma_{d2}}$$

$$V_2 = \frac{1.25}{1.08} \times 100 = 147 \text{ m}^3$$

$$\text{No. of truck loads} = \frac{147}{6} = 24.6 \text{ no.s} = \underline{\underline{25 \text{ no.s}}}$$

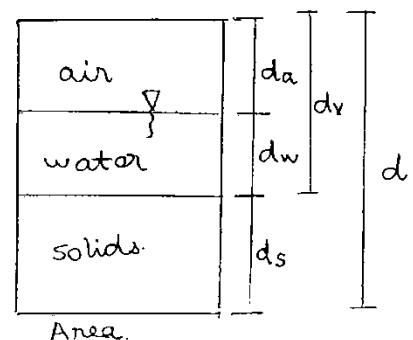
13.

$$\text{If } d_w = 1 \text{ m, } d = ?$$

$$\text{Given: } e = 0.5, S_r = 80\%$$

$$S_r = \frac{d_w}{d_v}$$

$$d_v = \frac{1}{0.8} = \underline{\underline{1.25 \text{ m}}}$$



depth of voids,  $d_v = 1.25 \text{ m}$ .

$$e = \frac{d_v}{d_s} \Rightarrow d_s = \frac{1.25}{0.5} = \underline{\underline{2.5 \text{ m}}}$$

Total depth of soil,  $d = d_s + d_v = \underline{\underline{3.75 \text{ m}}}$

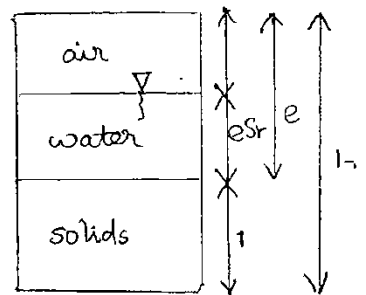
(OR) based on Unit Phase Diagram.

Given, depth of water = 1 m

$$e \cdot S_r = 0.5 \times 0.8 = 0.4 \text{ m}.$$

$$1 + e = 1 + 0.5 = 1.5 \text{ m}.$$

0.4 m depth of water makes 1.5 m depth of soil 80% saturated.



$$\text{Depth of soil} = \frac{1.5}{0.4} \times 1 = \underline{\underline{3.75 \text{ m}}}$$

14.  $n = 40\%$ ,  $G = 2.5$ ,  $w = 12\%$

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

$$e = \frac{n}{1-n} = \frac{0.4}{1-0.4} = 0.666.$$

$$e = \frac{wG}{S_r} = wG \text{ (at full saturation)}.$$

$$w = \frac{e}{G \times 2.5} = 26.6\%$$

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

Take  $\gamma_w = 1 \text{ ton/m}^3. \Rightarrow \gamma_d = 1.5 \text{ t/m}^3.$

Weight of water to be added to achieve full saturation

$$= 1.5 \times 100 \left( \frac{26.6 - 12}{100} \right)$$

$$= \underline{\underline{21.9 \text{ tons}}}.$$

16. Let  $e_2$  be void ratio at increased volume of soil

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

$$\frac{1.05 V_1}{V_1} = \frac{1+e_2}{1+0.667} \Rightarrow e_2 = \underline{\underline{0.75}}$$

Let  $w_3$  be water content at increased volume,

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$$e_2 = \frac{w_3 G}{S_r}$$

$$0.75 = \frac{w_3 \times 2.5}{S_r = 1}$$

$$\Rightarrow w_3 = \underline{\underline{30\%}}$$

17.  $w_d = w_s = 135 \text{ g.}$

Wet weight,  $w = 195 \text{ g.}$

Total vol. of ~~solid~~ <sup>soil</sup>,  $V = 5^3 = 125 \text{ cm}^3.$

$$w = \frac{w - w_d}{w_d} \times 100 = \frac{60}{135} \times 100 = \underline{\underline{44.44\%}}$$

$$e = \frac{wG}{S_r} \Rightarrow e = 0.446$$

$$\gamma_{\text{sat}} = \frac{w}{V} = \frac{195}{125} = 1.56 \text{ g/cc.}$$

$$\gamma_{\text{sat}} = \gamma_w \left( \frac{G+e}{1+e} \right) \Rightarrow 1.56 = 1 \left( \frac{G+0.44G}{1+0.44G} \right) \\ = 2.07.$$

$$e = 0.446 = \underline{\underline{0.92}}$$

(OR)

$$V = 125 \text{ cm}^3.$$

$$\text{Wt. of water added} = 195 - 135 = 60 \text{ g}$$

$$\therefore \text{Vol. of water} = \frac{w_w}{\gamma_w} = \frac{60}{1} = \underline{\underline{60 \text{ g/cc}}}$$

Vol. of voids = vol. of water added

$$\Rightarrow V_v = 60 \text{ cc.} \quad \therefore V_s = 125 - 60 = 65 \text{ cm}^3.$$

$$e = \frac{V_v}{V_s} = 0.92.$$

$$\gamma_s = \frac{w_s}{V_s} = \frac{135}{65} = 2.07 \text{ g/cc} \Rightarrow G = \frac{\gamma_s}{\gamma_w} = \frac{2.07}{1} = \underline{\underline{2.07}}$$

Q. 100 g of dry soil having  $G = 2.7$  is mixed with water and 1 L of soil slurry is prepared. What is the unit weight of soil slurry in g/cc.

$$G = \frac{\gamma_s}{\gamma_w} \Rightarrow \gamma_s = 2.7 \text{ g/cc}$$

$$\gamma_s = \frac{W_s}{V_s} \quad \therefore V_s = \frac{W_s}{\gamma_s} = \frac{100}{2.7} = 37.037 \text{ cc}$$

$$V = 1 \text{ L} = 1000 \text{ cm}^3$$

$$\Rightarrow V_w = V - V_s = 1000 - 37.037 = 962.963$$

$$\begin{aligned} \gamma_{\text{sat}} &= \frac{W}{V} = \frac{W_s + W_w}{V} = \frac{100 + V_w \times \gamma_w}{V} \\ &= \frac{100 + 962.963 \times 1}{1000} = \underline{\underline{1.063 \text{ g/cc}}} \end{aligned}$$

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Q

A marine soil has sp. gr. of solids as 2.7 and void ratio as 0.8. If sp. gr. of sea water is 1.03, calculate  $\gamma_{\text{sat}}$  of the soil. Take  $\gamma_w$  of fresh water as  $9.81 \text{ kN/m}^3$ .

$$G = 2.7$$

$$\Rightarrow \gamma_{\text{sat}} \gamma_s = 2.7 \text{ g/cc.}$$

$$e = 0.8.$$

$$\gamma_{\text{sat}} = \frac{\gamma_w (G + e)}{1 + e} = \frac{9.81 (2.7 + 0.8)}{1 + 0.8} = 19.64 \quad (\text{valid only if pure water is used!})$$

$$G = \frac{\gamma_s}{\gamma_w} \rightarrow \text{pure water}$$

$$\begin{aligned} \gamma_{\text{sea}} &= 1.03 \times 9.81 \\ &= 10.1043 \text{ g/cc} \end{aligned}$$

$$\begin{aligned} \gamma_{\text{sat}} &= \frac{W_w + W_s}{V} = \frac{V_s \gamma_s + V_w \gamma_{\text{sea water}}}{V} \\ &= \frac{1 \times G \gamma_w + e \cdot S_r \times 10.1043}{1 + e} \\ &= \frac{9.81 \times 2.7 \times 1 + 0.8 \times 1 \times 10.1043}{1 + 0.8} \\ &= \underline{\underline{19.206 \text{ kN/m}^3}} \end{aligned}$$

$$\left. \begin{aligned} V_s &= 1 \\ V_w &= e S_r \\ V &= 1 + e \end{aligned} \right\} \text{unit phase.}$$

- Q The mass of an empty pycnometer is 0.498 kg. when completely filled with water, its mass is found to be 1.528 kg. An oven dried soil of mass 0.198 kg is placed in the pycnometer and water is added to fill the pycnometer and total mass is found to be 1.653 kg. Determine sp. gravity of soil particles

$$w_1 = 0.498, \quad w_2 = 0.198, \quad w_3 = 1.653, \quad w_4 = 1.528.$$

$$G = \frac{w_2 - w_1}{(w_2 - w_1) - (w_3 - w_4)} = \frac{0.198}{0.198 - 0.125} = \underline{\underline{2.712}}$$

$$\begin{aligned} \text{Wt. of dry soil} &= w_2 - w_1 \\ &= 0.198 \end{aligned}$$

- Q A sample of clay, was coated with paraffin wax and the total mass of soil and wax was found to be 700 g. The sample was immersed in water and the vol. of water displaced was found to be 355 mL. The mass of the sample without wax was 690 g. and water content of the soil was 18%. Determine bulk density, dry density, void ratio and degree of saturation. Take sp. gr. of soil solids as 2.7. and that of wax as 0.89.

$$355 \times 1 = \frac{690 \times 1}{2.7} + \frac{10}{0.89}$$

$$\text{Weight of wax} = 700 - 690 = 10 \text{ g.}$$

$$\text{Density of wax} = 0.89 \times 1 = 0.89 \text{ g/cc.}$$

$$\text{Volume of wax} = \frac{10}{0.89} = 11.236 \text{ cc.}$$

$$\begin{aligned} \text{Volume of soil} &= \text{vol. of water displaced} - \text{vol. of wax} \\ &= 355 - 11.23 = \underline{\underline{343.77 \text{ cm}^3}} \end{aligned}$$

$$\gamma = \frac{W}{V} = \frac{690}{343.77} = 2.007 \text{ g/cc.}$$

$$\gamma_d = \frac{\gamma}{1+w} = \frac{2.007}{1.18} = 1.7 \text{ g/cc}$$

$$\gamma_d = \frac{G\gamma_w}{1+e} \Rightarrow \underline{\underline{e = 0.588}}$$

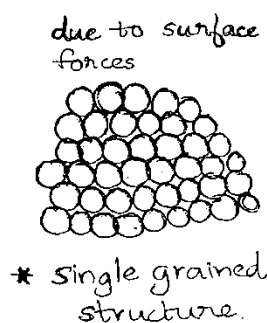
$$e = \frac{wG}{S_r} \Rightarrow \underline{\underline{S_r = 82.65\%}}$$

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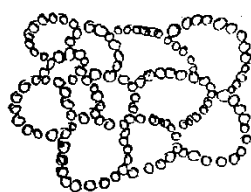
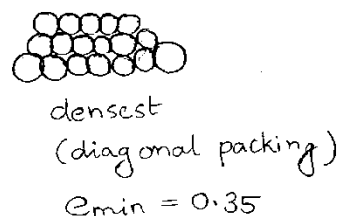
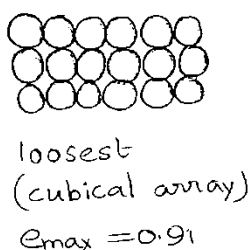
### 3. SOIL STRUCTURES & CLAY MINERALOGY

#### → Types of Structures

1. Single Grained Structure → in gravel & coarse sand
2. Honey comb structure → in fine sand & silt
3. Flocculent structure → in clays
4. Dispersed structure → in remoulded clays
5. Combined structure → in soil mixtures



2 extreme cases.

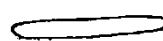


\* Honey Comb Structure

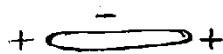
- very sensitive to vibrations (decreases in vol. due to vibrations)
- it collapses on wetting (volume decreasing)
- collapsible soils. Eg: loess, fine sand, silt

#### → Particle Shapes.

- (i) Angular: gravel & sand (ii) Rounded: gravel & sand (iii) Flaky: clay soils.

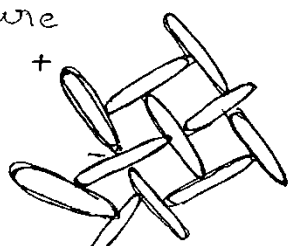


The clay particle is electrically charged as shown below.  
(-ve charge on surface)



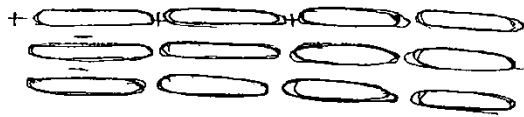
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#### \* Flocculent Structure



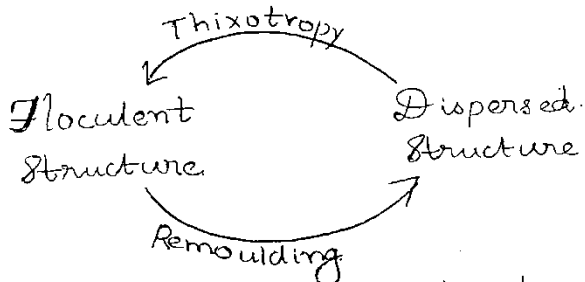
- > relatively more strength
- > stable.
- > edge to face orientation
- > net attraction.

## \* Dispersed Structure.



- > relatively low strength
- > Unstable
- > Face-to-face orientation
- > net repulsion

Thixotropy: The phenomenon of regaining of strength with passage of time under const. water content is called Thixotropy



In clay,

Due to remoulding, strength decreases.

Due to thixotropy, strength regains.

Marine clay → floculent structure.  
(Sea water)

Lake clay → dispersed structure  
(Fresh water)

The presence of salts in seawater and due to its alkaline nature, salts acts as flocculating agents. The marine clay has floculent structure.

## → Minerals.

### (i) Rock Minerals.

- no surface activity.
- Eg: Quartz, mica, feldspar.

### (ii) Clay Minerals.

- have surface activity. (like cohesion, electrostatic, chemical forces)
- Eg: Kaolinite, Illite, Montmorillonite, Holloysite.

## \* Kaolinite

- causes no swelling & no shrinkage.
- it is present in china clay (used to make earthenware utensils)

\* Illite:

- causes medium swelling & shrinkage
- present in most of the clays

\* Montmorillonite:

- causes large swelling and large shrinkage.
- present, Bentonite clay & B.C soil.

\* Halloysite:

- similar to Kaolinite

NOTE:

- ⊙ Plasticity of Kaolinite < Plasticity of Illite < Plasticity of Montmorillonite.
  - ⊙ SSA of Kaolinite < SSA of Illite < SSA of montmorillonite
- SSA - Specific Surface Area (S.A per unit weight).

→ Specific Surface Area (SSA).

1. It is the surface area per unit weight  $\Rightarrow \frac{A}{W}$
2. It is the surface area per unit volume  $\Rightarrow \frac{A}{V}$

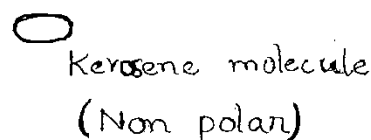
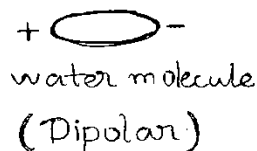
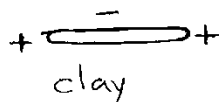
$$SSA = \frac{A}{V} = \frac{4\pi r^2}{\frac{4}{3}\pi r^3} = \frac{3}{r}$$

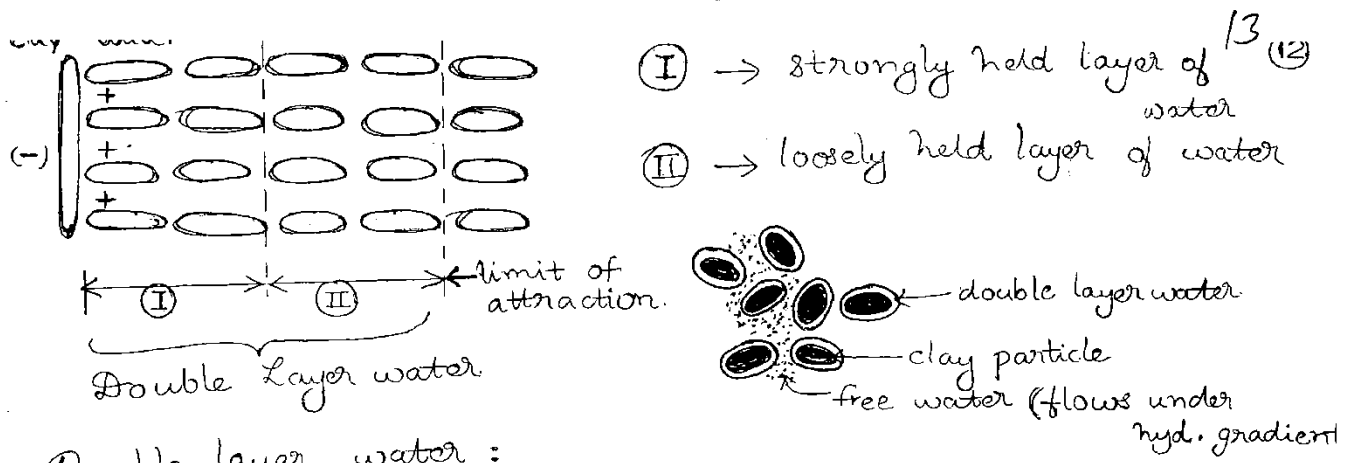
$$\Rightarrow \boxed{SSA \propto \frac{1}{\text{size of soil particle}}}$$

Gravel → least SSA  
Sand  
Silt  
Clay → highest SSA

↓ increasing order

→ Diffuse Double Layer Water (or Adsorbed Water)





Double layer water :

- present only in clays
- causes plasticity property to the clay.

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## 4. INDEX PROPERTIES OF SOILS

### Soil Properties

#### 1. Index Properties

— indicative of behaviour of soil.

Eg:— grain size distribution,  
relative density, atterberg limits.

#### 2. Engineering Properties

— used for engg. applications

Eg:— permeability, shear strength  
compressibility.

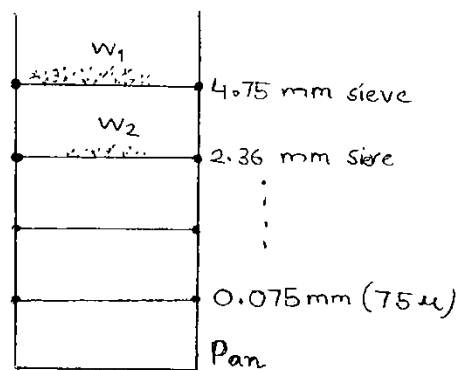
#### → Grain Size Distribution.

— by (i) Sieve analysis → used if size > 75  $\mu$

(ii) Sedimentation analysis → used if size < 75  $\mu$

#### \* Sieve Analysis.

Size (mm)	% retained.	cumulative %	% finer.
4.75	$P_1 = \frac{W_1}{W} \times 100$	$P_1 = P_1$	$100 - P_1$
2.36	$P_2 = \frac{W_2}{W} \times 100$	$P_2 = P_1 + P_2$	$100 - P_2$
...			
0.075			



size vs % finer graph is plotted.

#### \* Sedimentation Analysis

— an indirect method.

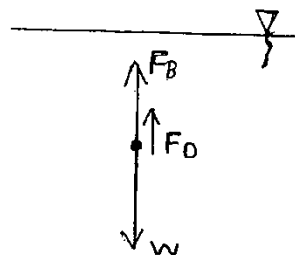
— based on "Stoke's Principle"

Settling velocity of particle,

$$V_s = \frac{g}{18} (\rho_s - \rho) \frac{d^2}{\mu} \rightarrow \text{Stoke's equation.}$$

$$V_s \approx 900 \frac{d^2}{\mu} \rightarrow \text{approximate stoke's eqn}$$

(mm/s)                  (mm)

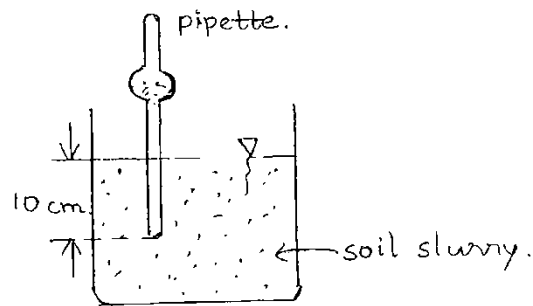


## Assumptions:

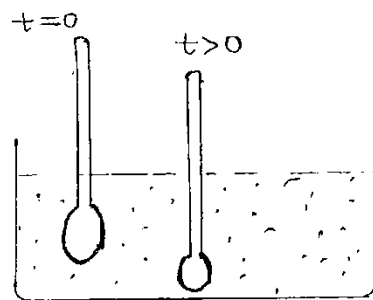
- laminar flow
- particle settle independently without interference.
- Stokes law is valid only if size is between  $0.2\mu - 0.2\text{ mm}$ 
  - If size  $> 0.2\text{ mm}$ , it will cause turbulent condition
  - If size  $< 0.2\mu$ , there will be 'Brownian movement' (zig-zag movement).

## \* Sedimentation Analysis methods:

## 1. Pipette Method.

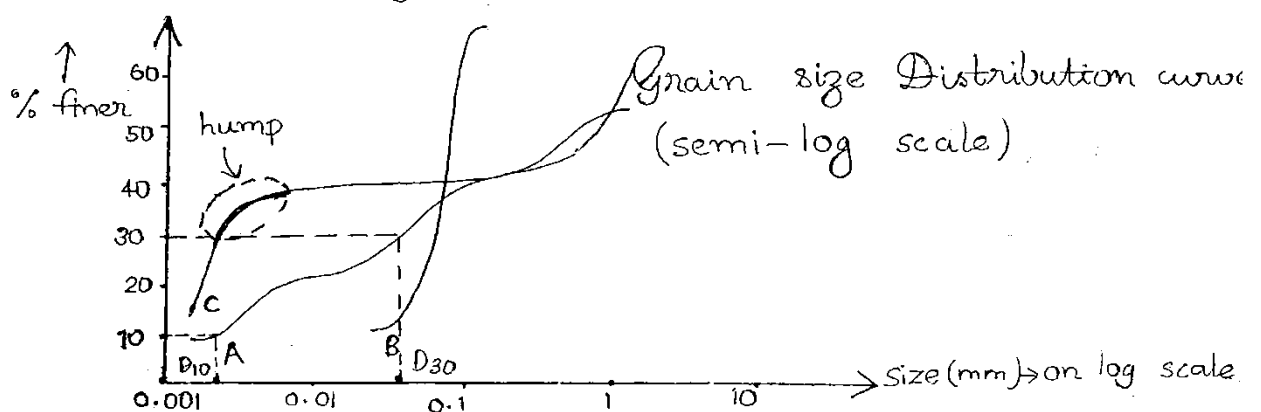


## 2. Hydrometer method.



## &gt; Corrections for Hydrometer reading.

- (i) Temperature correction (if temp  $\neq 27^\circ\text{C}$ )
- (ii) Meniscus correction
- (iii) Dispersion agent correction (Sodium hexametaphosphate)



'Log Scale' is used because:

- There is large range of data. ( $\frac{10}{0.001} = 10000$  times)
- to get straight line.

A  $\rightarrow$  well graded soil - has different sizes

B  $\rightarrow$  uniformly graded soil - same size of particles. (sand dune)

C  $\rightarrow$  gap graded soil - certain sizes are missing.

B & C  $\rightarrow$  poorly graded soil.

$\rightarrow$  Important size of Soil Particle.

- $D_{10}$   $\rightarrow$  effective size of soil.
- $D_{30}$
- $D_{60}$

D : diameter & 10, 30, 60  $\rightarrow$  % finer

$\rightarrow$  Coefficient of Uniformity ( $C_u$ )

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

For well graded gravel,  $C_u > 4$

For well graded sand,  $C_u > 6$

If  $C_u$  lies b/w 1 & 2, it is called "Uniformly Graded"

$\rightarrow$  Coefficient of Curvature ( $C_c$ )

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

> For a well graded soil,  $1 < C_c < 3$

>  $C_c$  represents shape of curve.

NOTE:

Grain size distribution curve is useful only for cohesionless soil (gravel, sand). In the case of clay, grain size distribution curve is not useful,  $\because$  the clay behaviour is mainly controlled by consistency limits.

→ Relative Density, or Density Index,  $I_D$

$$I_D = \left( \frac{e_{\max} - e}{e_{\max} - e_{\min}} \right) \times 100$$

$$e_{\min} \leq e \leq e_{\max}$$

$e_{\max}$  → max. void ratio in the loosest state.

$e_{\min}$  → min. void ratio in the densest state.

$e$  → natural or insitu void ratio.

If the soil is in the loosest state ( $e = e_{\max}$ ),  $I_D = 0$ .

If the soil is in the densest state ( $e = e_{\min}$ ),  $I_D = 100\%$

$$0 \leq I_D \leq 100\%$$

•  $I_D < 15\%$  → Very loose state

$15 \leq I_D < 35\%$  → loose state

$35 \leq I_D < 65\%$  → medium dense state.

$65 \leq I_D < 85\%$  → dense state

$I_D \geq 85\%$  → very dense state.

The more the  $I_D$  value, more will be the density.

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

$$\Rightarrow I_D = \left[ \frac{\frac{1}{\gamma_{d\min}} - \frac{1}{\gamma_d}}{\frac{1}{\gamma_{d\min}} - \frac{1}{\gamma_{d\max}}} \right] \times 100$$

→ Consistency Limits or Atterberg Limits

- exist only for cohesive soil.

- depending upon water content of soil;

1. Liquid state.

2. Plastic state

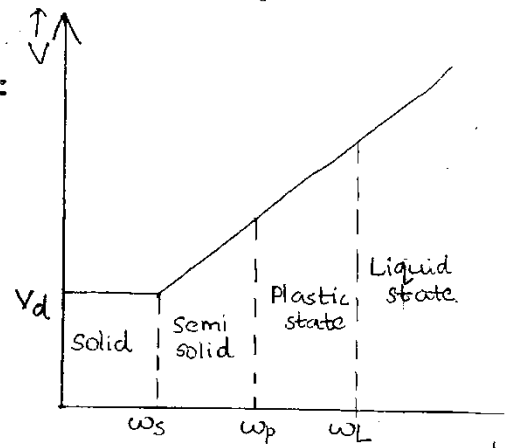
3. Semi-solid state

4. Solid state.

\* Atterberg Limits : these are the boundary w/c b/w two different states of soil.

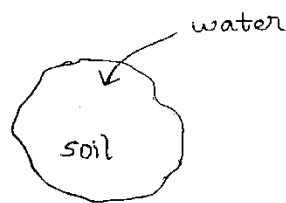
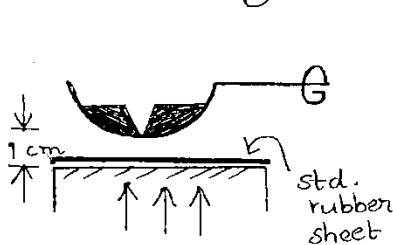
\* Types of Atterberg Limits:

1. Liquid limit, LL or  $w_L$
2. Plastic limit, PL or  $w_p$
3. Shrinkage limit, SL or  $w_s$

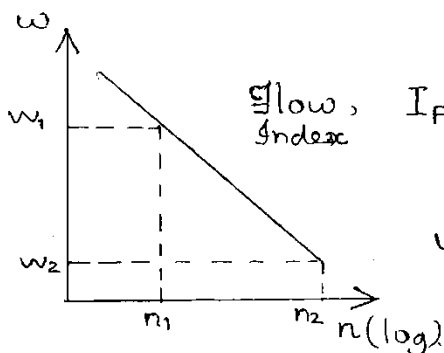
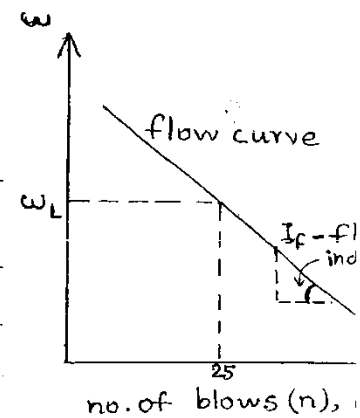


26<sup>th</sup> Aug, TUESDAY → To find  $w_L$

- Casagrande's Liquid limit test.



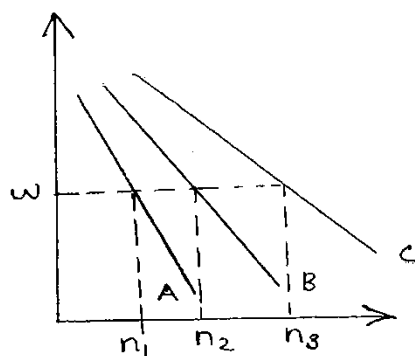
w	n
...	...
...	...
...	...
...	...
...	...



Flow, Index

$$I_F = \frac{w_1 - w_2}{\log_{10} \left( \frac{n_2}{n_1} \right)} ; \text{slope of the flow curve.}$$

$w_L$  - w/c at which 25 no. of blows can close the groove of the apparatus



Flat Flow curve has relatively more shear strength compared to a steep flow curve.

(  $n_1 < n_2 < n_3$ , more no. of blows required to close the groove.  
 $\therefore$  Shear strength of  $A < B < C$  )

$$\text{Shear strength} \propto \frac{1}{I_F}$$

\* Instead of <sup>standard</sup> rubber sheet, if hard rubber sheet is used, then  $w_L$  decreases. If soft rubber sheet is used, then  $w_L$  increases.

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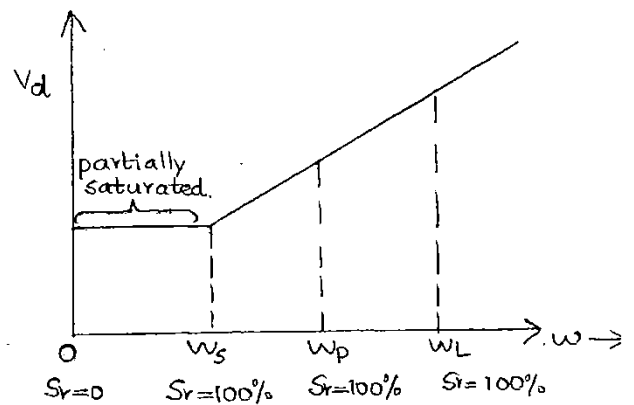
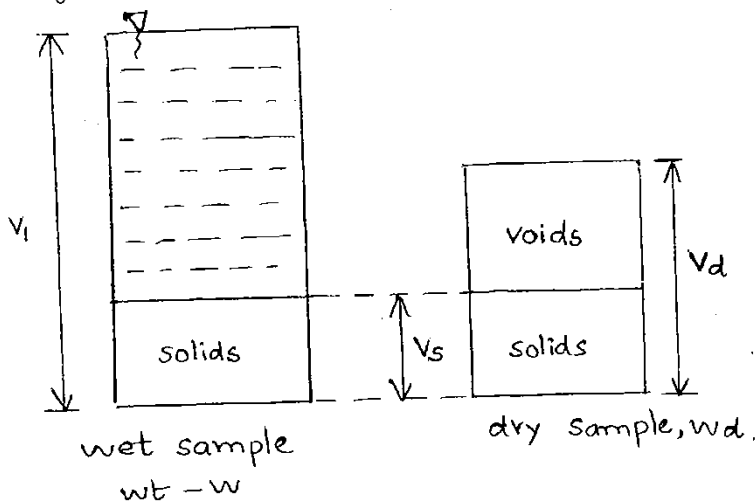
\* At liquid limit condition, shear strength of soil is  $2.7 \text{ kN/m}^2$  and is same for all soils. (Shear strength is zero for all soils in the liquid state)

→ Plastic Limit Test. (or Thread Test)

Plastic limit is the minimum w/c at which soil can be rolled into a thread of 3mm diameter without crumbling.

→ Shrinkage Limit.

Shrinkage limit is the minimum w/c that can make the soil fully saturated ( $S_r = 100\%$ ). or it is the min. w/c that can be filled in the voids of soil with 100% desaturation



$$1. \quad w_s = \frac{(V_d - V_s) \gamma_w}{w_d} \times 100$$

$$\begin{aligned} w_s &= \left( \frac{1}{\gamma_d} - \frac{1}{\gamma_s} \right) \gamma_w \times 100 \\ &= \left( \frac{1}{G_m} - \frac{1}{G} \right) \times 100 \end{aligned}$$

$$2. \quad w_s = \left( \frac{1}{G_m} - \frac{1}{G} \right) \times 100$$

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

$$e = \frac{w_s G}{1}$$

3.  $w_s = \frac{e}{G} \times 100$  ;  $e \rightarrow$  void ratio at saturation level or dry condition.

4.  $w_s = \left( w_1 - \frac{(V_1 - V_d) \gamma_w}{w_d} \right) \times 100$

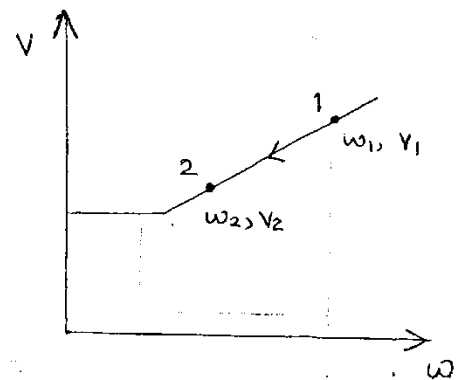
$w_1 \rightarrow$  initial water content  $= \frac{w - w_d}{w_d}$

$\rightarrow$  Shrinkage Ratio (SR).

$$SR = \frac{\frac{V_1 - V_2}{V_d} \times 100}{w_1 - w_2}$$

If  $V_2 = V_d$ ,  $w_2 = w_s$ ,

$$SR = \frac{(V_1 - V_d) / V_d \times 100}{w_1 - w_s}$$



$\rightarrow$  Volumetric Shrinkage (VS)

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

$$\therefore \boxed{SR = \frac{VS}{w_1 - w_s}}$$

$$\left\{ \begin{aligned} SR &= \frac{\frac{(V_1 - V_d)}{V_d}}{\frac{(V_1 - V_d) \gamma_w}{w_d}} = \frac{\gamma_d}{\gamma_w} \end{aligned} \right.$$

Also  $SR = \frac{\gamma_d}{\gamma_w}$  ;  $\gamma_d = \frac{w_d}{V_d}$

SR is the mass specific gravity in dry condition.

→ Plasticity Index,  $I_p$

$$I_p = w_L - w_p$$

If  $I_p = 0$  ; non plastic soil.

$I_p < 7$  ; low plastic soil.

7-17 ; medium plastic soil.

$> 17$  ; high plastic soil.

→ Shrinkage Index,  $I_s$

$$I_s = w_p - w_s$$

→ Toughness Index,  $I_T$

$$I_T = \frac{I_p}{I_f}$$

Shear strength  $\propto I_T$

→ Consistency Index,  $I_c$

$$I_c = \frac{w_L - w}{I_p} \times 100$$

→ Liquidity Index,  $I_L$

$$I_L = \frac{w - w_p}{I_p} \times 100$$

;  $w \rightarrow$  natural  $w/c$  of soil.

$$I_c + I_L = 1 \text{ or } 100\%$$

⊙ If  $I_L > 1$ , the soil is in liquid state.

( $w > w_L \rightarrow$  liquid state)

⊙ If  $I_L$  is -ve, the soil is either in semi-solid or solid state

( $w < w_p$ ).

→ Activity Number, A

$$A = \frac{I_p}{C} ; C = \% \text{ of clay particles.}$$

⊙ For a given soil, A is constant.

'A' indicates swelling and shrinkage characteristics.

If  $A < 0.75$  ; inactive soil.

0.75 - 1.25 ; normal active soil.

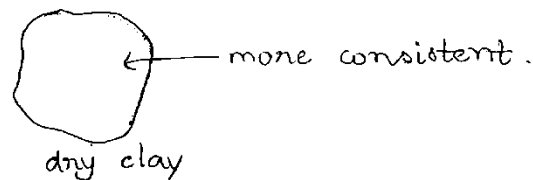
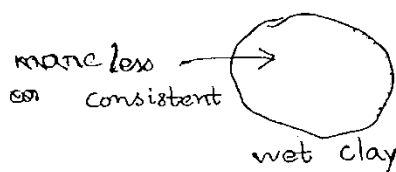
> 1.25 ; active soil. (Bentonite & Bc soil)

→ Effect of Size of Particle.

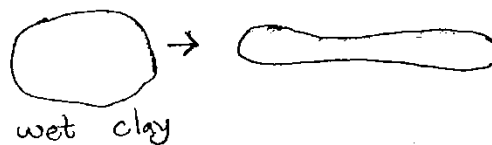
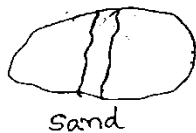
⊙ If size of particle decreases,  $w_L$  increases  
 $w_p$  <sup>increases</sup> ~~decreases~~ ⇒  $I_p$  increases

⊙ If silt or fly ash is added to clay,  $w_L$  decreases  
non-plastic  $w_p$  ~~decreases~~ ⇒  $I_p$  decreases

⊙ consistency : resistance against deformation, depends on water content. More the w/c, less the consistency.



⊙ plasticity : property due to which soil deforms plastically without rupture is called plasticity.

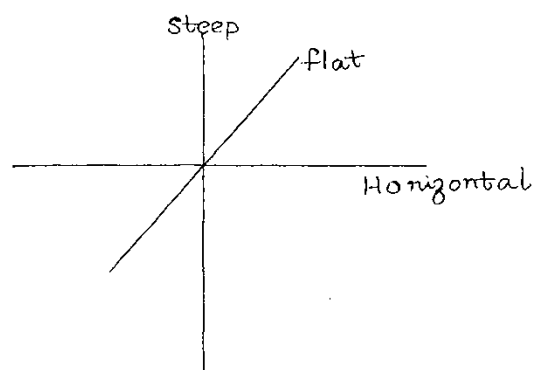


⊙ If lime is added to clay,  $w_L$  decreases,  $w_p$  increases and  $I_p$  decreases.

P-17

2. Fat Clay  $\rightarrow$  highly compressible clay. :  $w_L > 50\%$

22

29<sup>th</sup> Aug,

FRIDAY

P-19.

1.  $\gamma = 1746 \text{ kg/m}^3$  ;  $w = 8.6\%$

$$\gamma_d = \frac{\gamma}{1+w} = \frac{1746}{1.086} = 1607 \text{ kg/m}^3 \quad ; \quad \gamma_s = 2.6 \text{ g/cc}$$

$$\therefore G = 2.6.$$

$$\gamma_d = \frac{G\gamma_w}{1+e} \Rightarrow e = 0.617.$$

$$I_D = \frac{e_{\max} - e}{e_{\max} - e_{\min}} = \frac{0.642 - 0.617}{0.642 - 0.462} = \underline{\underline{13.9\%}}$$

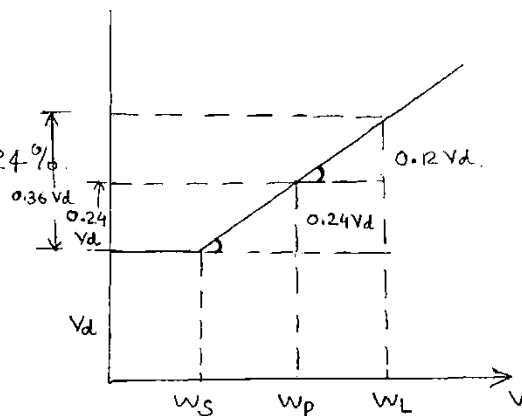
2.  $w_L = 45\%$  ;  $w_p = 33\%$

$$\frac{V_L - V_d}{V_d} \times 100 = 36\% \quad ; \quad \frac{V_p - V_d}{V_d} \times 100 = 24\%$$

$$\frac{0.36 V_d - 0.24 V_d}{w_L - w_p} = \frac{0.24 V_d}{w_p - w_s}$$

$$\frac{0.12}{45 - 33} = \frac{0.24}{33 - w_s}$$

$$\therefore w_s = \underline{\underline{9\%}}$$



3.  $SR = \frac{V_L - V_d}{V_d} \times 100$

$$= \frac{36}{45 - 9} = \underline{\underline{1}}$$

$$4. \quad G_m = \frac{\gamma_{sat}}{\gamma_w} = 1.88$$

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

$$G_m = \frac{\gamma_d}{\gamma_w} = 1.74$$

$$1.88 = \frac{G+0.46G}{1+0.46}$$

$$e = \frac{wG}{S_r} = 0.46$$

$$\underline{\underline{G = 2.9}}$$

$$5. \quad w_s = \left( \frac{1}{G_m} - \frac{1}{G} \right) 100 = \left( \frac{1}{1.74} - \frac{1}{2.9} \right) 100 = \underline{\underline{23\%}}$$

$$6. \quad SR = \frac{\gamma_d}{\gamma_w} = \underline{\underline{1.74}}$$

$$7. \quad W = 95.6 \text{ gm} ; V_1 = 68.5 \text{ cc}$$

$$W_d = 43.5 \text{ g} ; V_d = 24.1 \text{ cc.}$$

$$\begin{aligned} \text{Initial water content of soil, } w_1 &= \left( \frac{W - W_d}{W_d} \right) \times 100 \\ &= 119.77\% \end{aligned}$$

$$\begin{aligned} \text{Shrinkage limit, } w_s &= \left( w_1 - \frac{(V_1 - V_d)\gamma_w}{W_d} \right) 100 \\ &= \left( 1.197 - \frac{(68.5 - 24.1)1}{43.5} \right) 100 \\ &= \underline{\underline{17.7\%}} \end{aligned}$$

$$8. \quad w_s = \left( \frac{1}{G_m} - \frac{1}{G} \right) 100$$

$$G_m = \frac{\gamma_d}{\gamma_w} ; \quad \gamma_d = \frac{W_d}{V_d} = 1.804$$

$$G_m = 1.804$$

$$17.7\% = \left( \frac{1}{1.804} - \frac{1}{G} \right) 100$$

$$\underline{\underline{G = 2.65}}$$

9. To find initial void ratio,  $e_1$ :

$$e_1 = \frac{w_s G}{S_r} = \frac{1.197 \times 2.65}{1} = \underline{\underline{3.15}}$$

(OR)

$$\gamma_{d1} = \frac{w_s}{V_1} = \frac{43.5}{68.5} = 0.635 \text{ g/cc}$$

$$\gamma_{d1} = \frac{\gamma_w G}{1+e_1} \Rightarrow e_1 = \underline{\underline{3.15}}$$

(OR)

$$\gamma_{sat} = \gamma_w \left( \frac{G+e_1}{1+e_1} \right)$$

$$\frac{w}{V_1} = \left( \frac{2.65 + e_1}{1+e_1} \right) = \frac{95.6}{68.5}$$

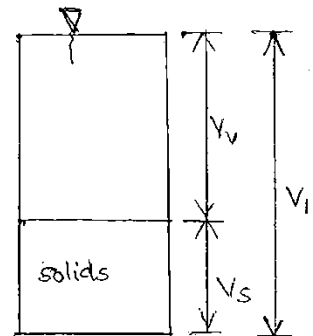
$$e_1 = \underline{\underline{3.15}}$$

(OR)

$$V_s = \frac{w_s}{\gamma_s} = \frac{43.5}{G\gamma_w} = 16.42 \text{ cm}^3$$

$$V_v = V_1 - V_s = 52.08 \text{ cm}^3$$

$$e_1 = \frac{V_v}{V_s} = \frac{52.08}{16.42} = \underline{\underline{3.17}}$$



To find final void ratio,  $e_2$ :

$$e_2 = \frac{w_s G}{S_r}$$

$$= \frac{17.7 \times 2.65}{100} = \underline{\underline{0.47}}$$

(OR)

$$\gamma_{d2} = \frac{w_s}{V_2} = 1.804 \text{ g/cc}$$

$$\gamma_{d2} = \frac{\gamma_w G}{1+e_2}$$

$$e_2 = \underline{\underline{0.47}}$$

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(OR)

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

$$\frac{24.1}{68.5} = \frac{1+e_2}{1+3.15}$$

$$e_2 = \underline{\underline{0.47}}$$

10. Let  $e_1$  be void ratio of  $w_1$  of 30%.

$$e_1 = \frac{w_1 G}{S_r} = \frac{0.3 \times 2.72}{1} = 0.816$$

$$V_1 = 100 \text{ cc.}$$

Let  $e_2$  be void ratio at  $w_s$ .

$$e_2 = w_s G = 0.489.$$

$$\frac{V_1}{V_d} = \frac{1+e_1}{1+e_2}$$

$$\frac{100}{V_2} = \frac{1+0.816}{1+0.489} \Rightarrow V_2 = \underline{\underline{82 \text{ cc}}} = V_d$$

For all  $w < w_s$ ,  $V_2 = V_d$

(OR)

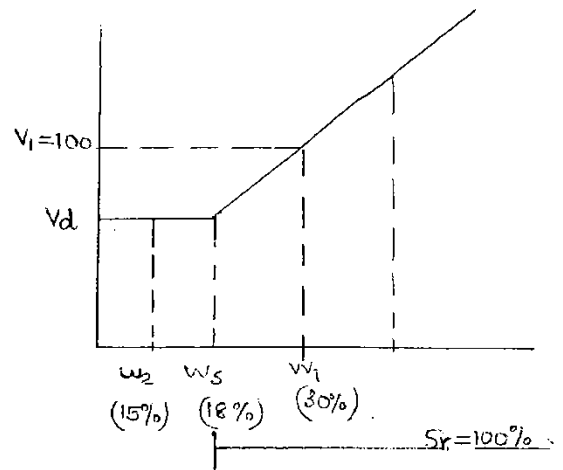
$$w_s = w_1 - \frac{(V_1 - V_d)\gamma_w}{w_d} \quad (\text{lengthy})$$

$$11. \gamma_d = \frac{w_d}{V} = \frac{890}{225} = 1.733 \text{ g/cc.}$$

$$\gamma_d = \frac{\gamma_w G}{1+e_1} \Rightarrow e_1 = 0.56.$$

Let  $e_2$  be void ratio at increased volume.

$$\frac{V_2}{V_1} = \frac{1+e_2}{1+e_1} \Rightarrow \frac{1.08 \gamma_1}{\gamma_1} = \frac{1+e_2}{1+0.56} \quad \therefore e_2 = \underline{\underline{0.684}}$$



$$e_2 = \frac{w_2 G}{S_r} \Rightarrow 0.47 = w_2 \times 2.7$$

$$w_2 = \underline{\underline{25.4\%}}$$

$$12. C_u = \frac{D_{60}}{D_{10}} = 4$$

$$D_{60} = 4 D_{10}$$

$$C_c = \frac{D_{30}^2}{D_{60} \times D_{10}} = 1$$

$$\frac{D_{30}^2}{4 D_{10}^2} = 1 \Rightarrow \frac{D_{30}}{D_{10}} = \underline{\underline{2}}$$

$$13. I_p = w_L - w_p$$

$$15 = 56 - w_p$$

$$\therefore w_p = 41\%$$

$\therefore$  given natural water content ( $w=45\%$ ) lies b/w liquid limit & plastic limit, the soil is in plastic state.

## 5. SOIL CLASSIFICATION

→ IS Particle Size Classification System

\* Grain Size only - criteria

2 $\mu$	75 $\mu$	4.75mm	80mm	300mm	
Clay	Silt.	Sand.	Gravel.	Cobble	Boule

The colloidal soil particle size is less than the clay size. However in our Indian code of practice, colloidal soil is not recognized.

But the Indian classification based on size alone is not always true. For eg:- Rock dusts or rock powder's particle size is less than 2 $\mu$  and hence belong to clay as per Indian system. But rock dust has no plasticity.

→ HRB Soil Classification System.

- HRB - Highway Research Board.

\* Criteria: a) Grain size distribution.

b) Consistency or Atterberg limits.

- This system is more useful for pavement design.

- In this system, soils are given group numbers like

A<sub>1</sub>, A<sub>2</sub>, A<sub>3</sub> . . . . A<sub>7</sub>, A<sub>8</sub>.

- The smaller the group number, the better the soil for pavement purpose. i.e. A<sub>1</sub> is better than A<sub>2</sub>. A<sub>2</sub> is better than A<sub>3</sub> and so on.

A<sub>8</sub> group - highly organic soil (worst soil for construction)

A<sub>7</sub> group - black cotton soil.

- Group Index, GI: an index value calculated by an empirical equation. GI value depends on -

- % of soil passing 75  $\mu$  sieve.
- $w_L$
- $w_p$  or  $I_p$

GI values ranges from 0 to 20

If GI value is found to be negative from equation, it is reported as 'zero'.

GI indicates quality of soil within its own group.

The smaller the GI value, the better the soil for pavement purpose.

- Symbol: A5 (6)  
                    ↑      ↓  
                    Group no.      GI

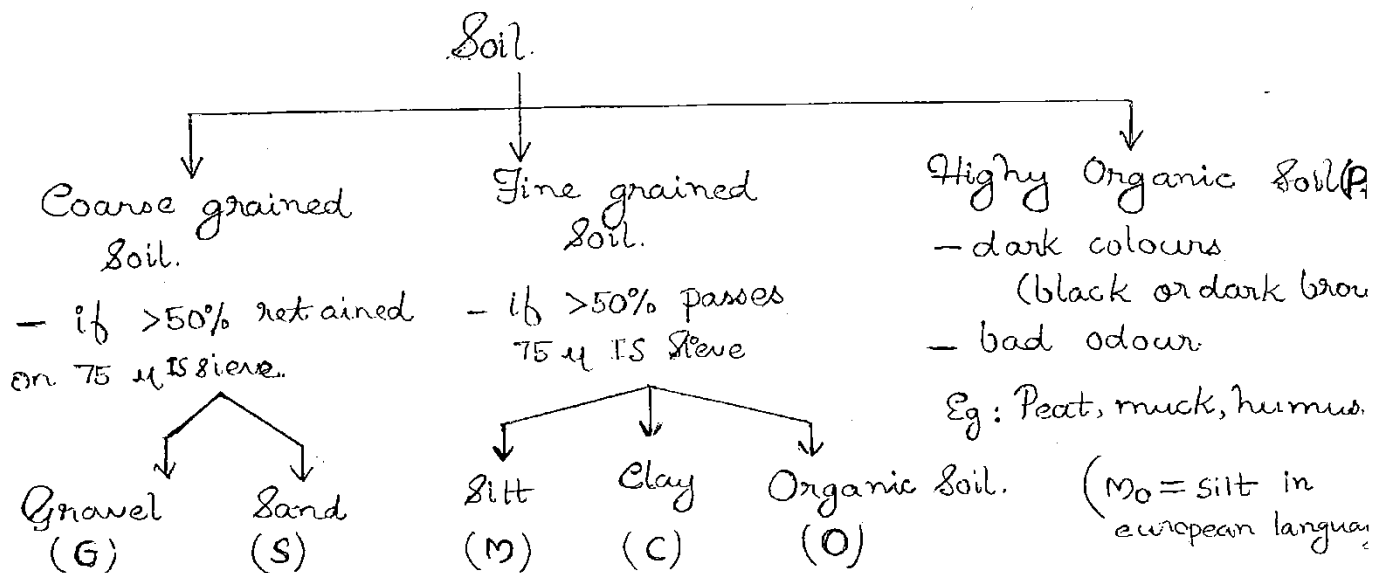
→ Unified Soil Classification System.

- most popular in European countries.

- criteria:
- grain size distribution data.
  - consistency limits
  - compressibility characteristics.

→ IS Soil Classification System.

- followed by all engineering departments in India.



Gravel — if more than 50% of coarse fraction retained on 4.75 mm sieve.

Sand — if > 50% coarse fraction passes 4.75 mm sieve.

— Gravel:

- a) Well graded Gravel — GW
- b) Poorly graded Gravel — GP
- c) Silty gravel. — GM
- d) Clayey gravel. — GC

— Sand:—

- a) Well graded sand — SW
- b) Poorly graded sand — SP
- c) Silty gravel sand — SM
- d) Clayey gravel sand — SC

- ⊙ Clayey sand  
⇒ clay qty < sand qty
- ⊙ Silty Clayey gravel  
⇒ silt qty < clay qty < gravel qty
- ⊙ Sandy clay.  
⇒ sand qty < clay qty.

— Silt:—

- a) Low compressible silt — ML
- b) Intermediate compressible silt — MI
- c) Highly compressible silt. — MH

— Clay:—

— Organic Soil

- a) CL
- b) CI
- c) CH

- a) OL
- b) OI
- c) OH

— Total group symbols = 8 + 9 + 1 = 18 groups.  
(coarse) (fine) (pt)

- If  $w_L < 35\%$  — Low compressible
- $35\% < w_L < 50\%$  — Intermediate compressible.
- $w_L > 50\%$  — Highly Compressible.

30<sup>th</sup> Aug,  
SATURDAY → Plasticity Chart.

22

- to classify the fine grained soils.

\* To identify Organic Soils:

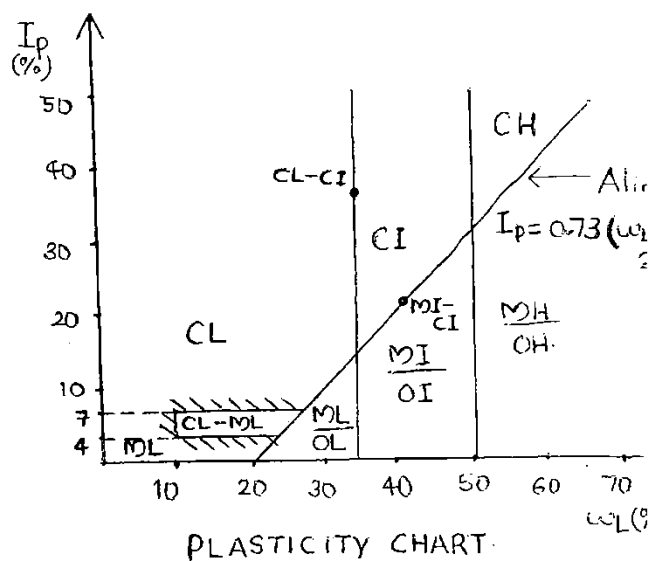
a) Colour test

Dark colours (black or dark brown)

b) Odour test.

Bad odour.

c).  $w_L$  test before and after oven drying.



For organic soils,  $w_L$  decreases (by more than one fourth of initial value) after oven drying.

\* Boundary Classifications:

- (i)  $CL-Cl$ ,  $Cl-CH$ .

- (ii)  $ML - MI$ ,  $MI - MH$

- (iii)  $OL - OI$ ,  $OI - OH$ .

- (iv)  $MI-Cl$ ,  $MH-CH$ . (coarser particle should be given preference)  
•  $MI-Cl$  ✓

∴ MI-CI ✓  
CI-MIX

Q.1 Classify the fine grained soil with  $w_L = 60\%$ ,  $w_p = 20\%$ .

$I_p$  of soil  $= 60 - 20 = 40\%$

$$I_p \text{ of A-line} = 0.73(w_L - 20) = 29.2\%$$

Since  $I_p$  of soil is  $> I_p$  of A line, the point plots above

A line  $\Rightarrow$  clay.

$w_L > 50 \Rightarrow$  highly compressible.

Soil is CH.

Q.  $w_L = 20\%$ ,  $w_p = 15\%$

$I_p = 5\%$  (blw 4 & 7)

$w_L = 20\%$

$\Rightarrow \underline{\underline{CL-ML}}$

— Equation of  $I_p$  vs  $w_L$  is called A-line because A is the surname of A. Casagrande.

$\rightarrow$  GW : (i) if fines  $< 5\%$  (ii)  $C_u > 4$  (iii)  $C_c$  lies blw 1 & 2

GP : if (i) fines  $< 5\%$  (ii) not meeting above gradation requirements ( $C_c$  &  $C_u$ ).

GM : if (i) fines  $> 12\%$  (ii)  $I_p$  value  $< 4\%$  or Atterberg limits fall below A-line.

GC : if (i) fines  $> 12\%$  (ii)  $I_p > 7\%$  with Atterberg limit fall above A-line.

If fines lies between 5% & 12%, it is a border line case requiring dual symbol.

For eg: GW-GC, GP-GM, GP-GC, GW-GM

If  $I_p$  lies blw 4 & 7%, it is a border line case requiring dual symbol. For eg:- GM-GC.

Q. Fines = 15%,  $I_p = 6\%$

$\Rightarrow$  GM-GC.

Q. Fines = 3%,  $C_u = 5$ ,  $C_c = 2$

$\Rightarrow$  GW.

Q. Fines = 15%,  $I_p = 2\%$   $\Rightarrow$  GM.

Q. Fines = 10%,  $C_u = 5$ ,  $C_c = 2$ ,  $I_p = 5\%$

$\Rightarrow$  GW-GM

In case of border line cases, the coarser one is to be favour (or) the coarser one is given priority.

- Between organic soil and clay, the organic one is coarser on

CI - OI ✗

OI - CI ✓

→ In the case of sand, all the conditions are same except  $C_u > 6$ .

→ Single Clay Particle } not visible to  
Single silt particle } naked eye

P-24.

2.

Size	% Retained	Cumulative %	% Finer
600 $\mu$	$\frac{245}{600} \times 100 = 40\%$	40%	60%
500 $\mu$	$\frac{300}{600} \times 100 = 50\%$	90%	10%
425 $\mu$	10%	100%	0

$D_{60}$  = diameter corresponding to 60% finer  
= 600  $\mu$ .

$D_{10}$  = 500  $\mu$

$$C_u = \frac{D_{60}}{D_{10}} = \frac{600}{500} = \underline{\underline{1.2}}$$

3.

$C_u < 6$

$\Rightarrow \underline{\underline{SP}}$

4.

$W_L = 42\%$  ie b/w 35% & 50%  $\Rightarrow$  intermediate, I

MI

5.

$$\text{Fines} = \frac{250}{1000} \times 100 = 25\%$$

Coarse fraction =  $100 - 25 = 75\% \Rightarrow$  coarse grained soil.

$$I_p = 42 - 20 = 22\% > 12\%$$

$$I_p \text{ of A line} = 0.73(w_L - 20) = 16.06\%$$

$I_p > I_p \text{ of A line} \therefore \text{pt. lies above A line.}$

$\therefore \underline{\underline{SC}}$

6.  $\text{Fines} = 30\%$  (silt + clay)

$$\therefore \text{Coarse fraction} = 100 - 30 = 70\% \text{ (gravel + sand).}$$

$\therefore$  It is coarse grained soil.

$$\text{Gravel fraction} = 100 - 60 = 40\% \text{ (more than 50\% of 70\%)}$$

$$\left\{ \begin{array}{l} \text{Gravel + sand} = 70\% \\ \therefore \text{Sand fraction} = 30\% \end{array} \right\}$$

$\therefore$  soil is gravel. ( $\because$  gravel % > sand %)

$$I_p \text{ of soil} = 35 - 27 = 8\%$$

$$I_p \text{ of A line} = 0.73(w_L - 20) = 10.95\%$$

$\therefore$  point falls below A-line.  $\Rightarrow \underline{\underline{GM}}$

7.  $C_u = \frac{D_{60}}{D_{10}} = 1.78$

$$C_u = \frac{D_{30}^2}{D_{60} \cdot D_{10}} = 0.95$$

} poorly graded.

$$D_{60} = 0.41 \text{ mm.} \Rightarrow 60\% \text{ passing } 0.41 \text{ mm. (or } 4.75 \text{ mm)}$$

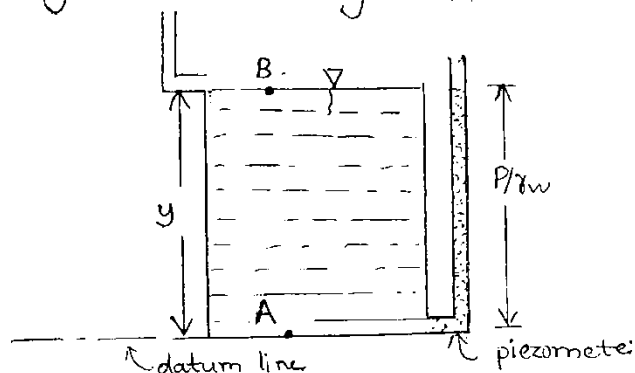
$\therefore \underline{\underline{\text{sand}}}$

SP

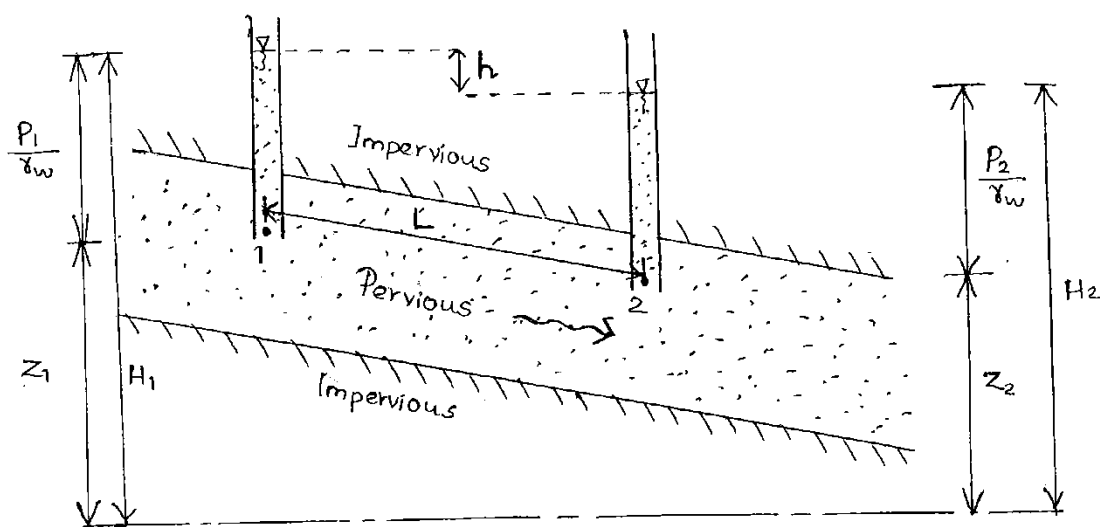
## 6. PERMEABILITY

- Flow occurs only when there is difference in the total heads b/w the two points.
- Pressure head difference alone or elevation difference alone may not cause the flow.
- In the case of soils the velocity head is neglected (negligible),

At point A	At point B
$\frac{P}{\gamma_w} = y$	$\frac{P}{\gamma_w} = 0$
$z = 0$	$z = y$
Total head, $H = y$	Total head, $H = y$



∴ total head is same ( $=y$ ) at both A & B, no flow occurs b/w A & B.



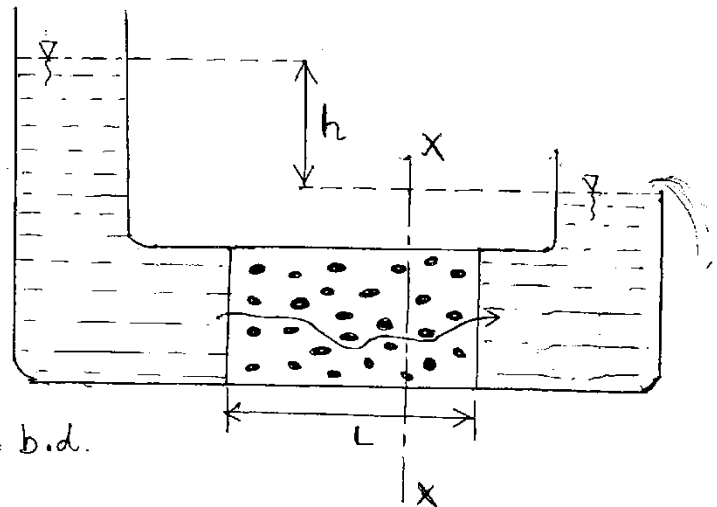
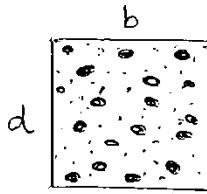
∴ Total head difference or total head loss,  $h = H_1 - H_2$

The total head loss b/w any two points in a soil mass is equal to the difference in the elevations of water in the two piezometers kept at those two points.

Hydraulic gradient,  $i = \frac{h}{L}$  ;  $L \rightarrow$  seepage length.

Hydraulic gradient is the head loss per unit seepage length.

c/s at xx :



Total c/s area of soil,  $A = b.d$ .

Area of voids or  
Actual area of flow }  $= A_v = nA$  ;  $n \rightarrow$  porosity of soil.

Discharge velocity or  
Apparent velocity }  $V = \frac{Q}{A}$

Actual velocity or  
Seepage velocity }  $V_s = \frac{Q}{A_v}$

$$Q = AV = A_v V_s$$

$$V_s = \frac{V}{n}$$

$n < 1$  always,  $\Rightarrow V_s > V$ .

$\rightarrow$  Darcy's Law

Discharge velocity  $\propto$  Hydraulic Gradient.

$$V \propto i$$

DARCY'S  
EQUATION

$$V = ki$$

$k \rightarrow$  Coefficient of Permeability of soil.

If  $i=1$ ,  $v=k \Rightarrow$  Coefficient of velocity permeability is the (24)  
discharge velocity occurring under unit hydraulic gradient. 25

Units of  $k$ : cm/s. or m/s or m/hour.

If  $k > 10^{-1}$  cm/s  $\Rightarrow$  'Permeable Soil'

$k < 10^{-7}$  cm/s  $\Rightarrow$  'Impermeable Soil'

Permeable soil — gravel, coarse sand.

Impermeable soil — stiff clays.

Soil	Gravel	Sand	Silt	Clay.
$K_{(cm/s)}$	$10^0$ ( $10^{-1} - 10^1$ )	$10^{-2}$ ( $10^{-1} - 10^{-3}$ )	$10^{-4}$ ( $10^{-3} - 10^{-5}$ )	$10^{-6}$ ( $10^{-5} - 10^{-7}$ )

• Darcy's Law is valid for Laminar flow only  
In soils, if Reynold's number,  $Re \leq 1$ , it is laminar.

$$Re = \frac{\rho v d}{\mu}$$

$$Re \propto v \propto k$$

$\therefore$  as  $k \downarrow$ ,  $Re \downarrow$  and flow becomes laminar.

• Clay, silt & fine sand — flow is laminar.

$$v = ki$$

$$v_s = K_p i$$

$K_p \rightarrow$  coefficient of percolation.

$$K_p = \frac{k}{n}$$

$$K = C \cdot D_{10}^2 \frac{e^3}{1+e} \cdot \frac{\gamma_w}{\mu}$$

$C \rightarrow$  shape constant ( $C=1$  for perfectly spherical particle)

$\mu \rightarrow$  dynamic viscosity.

→ Factors affecting  $k$  of Soil:

- shape of particle
- size of particle
- void ratio
- properties of fluid
- degree of saturation
- organic matter
- specific surface area
- stratification etc.

\* Effect of Size,  $D_{10}$ .

$$K \propto D_{10}^2$$

\* Effect of Specific Surface Area

$$K \propto \frac{1}{SSA}$$

\* Effect of shape.

$K$  of rounded particles is more compared to angular particle since SSA of rounded particle is less.

\* Effect of void ratio

$$K \propto \frac{e^3}{1+e}; \quad \text{also } K \propto e^2$$

$$\text{also } \log K \propto e \text{ (latest one)}$$

The more the void ratio, more will be permeability. But this cannot explain <sup>the</sup> reason for clay's low permeability and clay has low permeability though it has high void ratio.

$$K \propto \frac{ce^3}{1+e}$$

Clay has lowest value of  $c$ . So the product of  $c$  &  $e$  will be low.

$$K \propto \gamma_w$$

$$K \propto \frac{1}{\mu} \propto \text{temperature} \quad \mu \propto \frac{1}{\text{temp}}$$

$$\Rightarrow K \propto \text{temperature}$$

$$\therefore K \propto \frac{\gamma_w}{\mu}$$

$\Rightarrow$

$$\boxed{\frac{K_2}{K_1} = \frac{\gamma_{w2}}{\gamma_{w1}} \cdot \frac{\mu_1}{\mu_2}}$$

During summer season day, permeability will be more.

## \* Effect of Degree of Saturation

26 (25)

k of partially saturated soil is relatively less compared to fully saturated soil. (air blocking)

## \* Effect of Organic matter.

Organic matter decreases k of soil. Due to low specific gravity of organic matter, it flows along with water and fills the voids.

$$k = \underbrace{C.D_{10}^2}_{\text{soil property}} \cdot \frac{e^3}{1+e} \cdot \underbrace{\frac{\gamma_w}{\mu}}_{\text{fluid properties}}$$

$$k = k_o \cdot \frac{\gamma_w}{\mu}$$

$k_o \rightarrow$  intrinsic permeability of soil (inherent property)

Units of  $k_o$  :  $\text{cm}^2$  or  $\text{m}^2$  or darcys

$$1 \text{ darcy} = 9.87 \times 10^{-13} \text{ m}^2$$

$\rightarrow$  Tests to Determine k of soil.

- |                                  |               |
|----------------------------------|---------------|
| 1. Constant Head Test.           | } lab test.   |
| 2. Variable Head test            |               |
| 3. Capillarity Permeability test |               |
| 4. Consolidation test            | } Field test. |
| 5. Pumping out test              |               |
| 6. Pumping in test.              |               |

Pumping out test : most accurate, used for large engg. projects.

Consolidation test : suitable for impermeable clays.

Capillarity Permeability test : for partially saturated soils.

Constant head test : for coarse grained soils

Variable head test : for fine grained soils

Pumping in test : to find k of individual layer of soil.

2<sup>nd</sup> Sept,  
TUESDAY

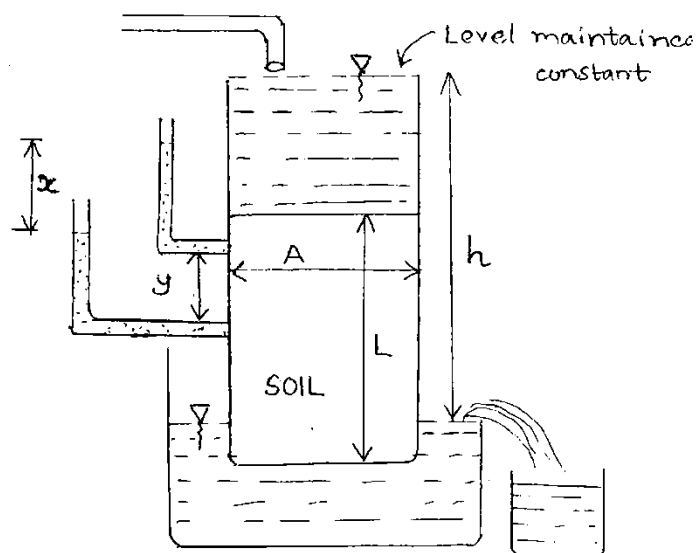
## → Constant Head Test.

$$Q = k i A$$

$$Q = k \frac{h}{L} A$$

$$i = \frac{h}{L} = \frac{x}{y}$$

$$k = \frac{QL}{Ah}$$



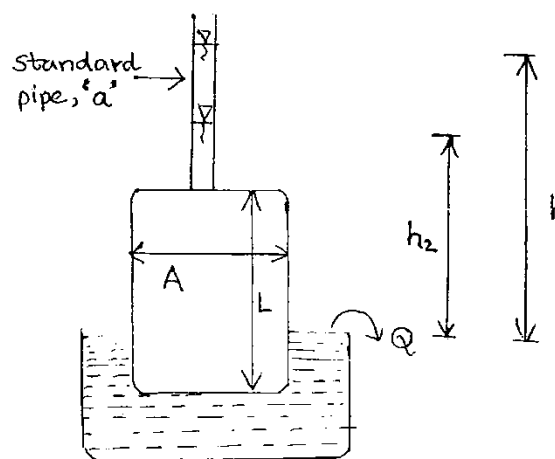
## → Variable Head Test.

$$a dh = Q \cdot dt$$

$$= k \frac{h}{L} A \cdot dt$$

$$\int_{h_2}^{h_1} \frac{dh}{h} = \frac{kA}{La} \int_0^t dt$$

$$\therefore k = \frac{aL}{At} \log_e \left( \frac{h_1}{h_2} \right)$$



## → Flow Parallel to Bedding Plates.

Total head loss =  $h$

Let  $h_1, h_2, h_3 \rightarrow$  head losses in layers 1, 2 & 3 resp'tly.

$$h_1 = h_2 = h_3 = h$$

$$\therefore i_1 = i_2 = i_3 = i = \frac{h}{L}$$

$$Q = q_1 + q_2 + q_3$$

$$q_1 = k_1 i_1 A_1$$

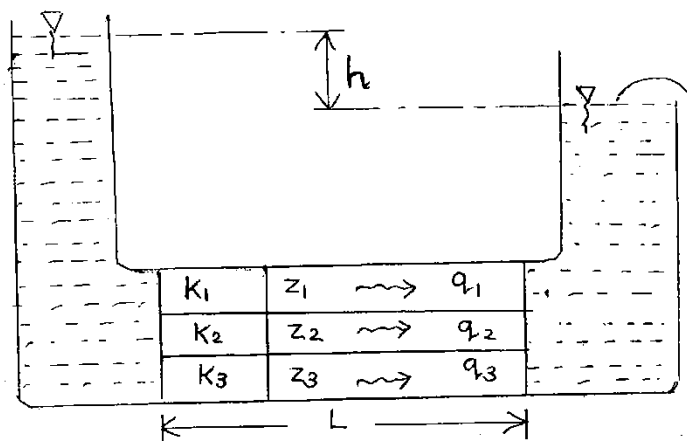
$$q_2 = k_2 i_2 A_2$$

$$q_3 = k_3 i_3 A_3$$

$$= k_1 \frac{h_1}{L} \cdot (z_1 \times 1)$$

$$= k_2 \cdot \frac{h_2}{L} \cdot (z_2 \times 1)$$

$$= k_3 \cdot \frac{h_3}{L} \cdot (z_3 \times 1)$$



Let  $K_H$  be average permeability for entire soil as a whole. (26)  
27

$$Q = K_H \cdot i \cdot A$$

$$= K_H \cdot \frac{h}{L} \cdot (z_1 + z_2 + z_3) \times 1$$

$$K_H \cdot i \cdot A = k_1 \cdot i_1 \cdot A_1 + k_2 \cdot i_2 \cdot A_2 + k_3 \cdot i_3 \cdot A_3$$

$$K_H \cdot (z_1 + z_2 + z_3) \cdot 1 = k_1 \cdot z_1 \cdot 1 + k_2 \cdot z_2 \cdot 1 + k_3 \cdot z_3 \cdot 1$$

$$\therefore K_H = \frac{k_1 z_1 + k_2 z_2 + k_3 z_3}{z_1 + z_2 + z_3}$$

→ Flow Perpendicular to Bedding Plane.

$h \rightarrow$  total head loss.

$$h = h_1 + h_2 + h_3$$

$$q_1 = q_2 = q_3 = Q$$

Let  $K_V$  be average permeability for entire soil.

$$q_1 = k_1 \cdot i_1 \cdot A_1$$

$$= k_1 \cdot \frac{h_1}{z_1} \cdot A$$

$$q_2 = k_2 i_2 A_2 \quad ; \quad q_3 = k_3 \cdot \frac{h_3}{z_3} \cdot A$$

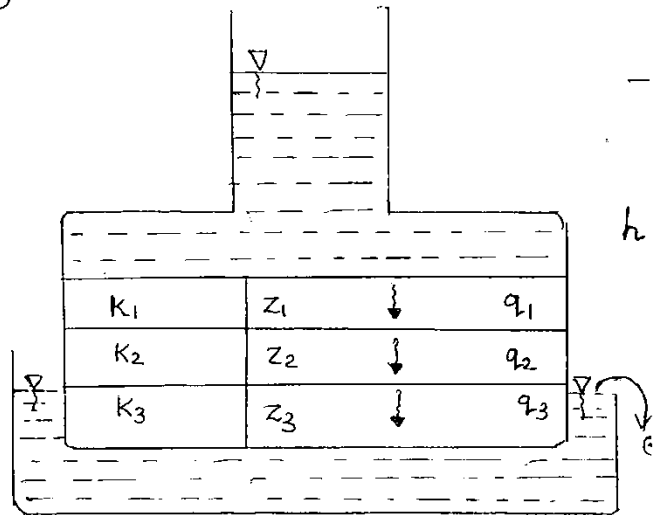
$$= k_2 \cdot \frac{h_2}{z_2} \cdot A$$

$$Q = K_V \cdot i \cdot A$$

$$= K_V \cdot \frac{h}{z_1 + z_2 + z_3} \cdot A$$

$$\therefore K_V = \frac{z_1 + z_2 + z_3}{\frac{z_1}{K_1} + \frac{z_2}{K_2} + \frac{z_3}{K_3}}$$

$$K_H > K_V$$



$$1. \quad \frac{k_2}{k_1} = \frac{\gamma_{w2}}{\gamma_{w1}} \cdot \frac{\mu_1}{\mu_2}$$

$$= \frac{0.9 \gamma_{w1}}{\gamma_{w1}} \cdot \frac{\mu_1}{0.75 \mu_1} = 1.2$$

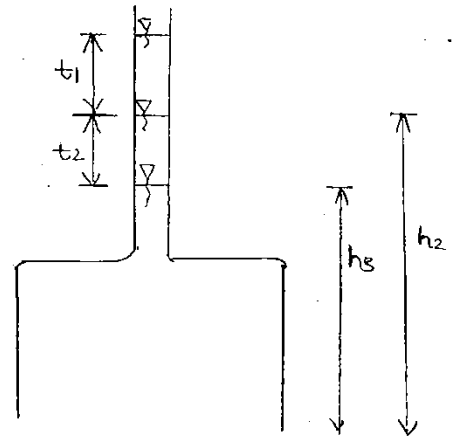
$$k_2 = 1.2 k_1 \Rightarrow 20\% \text{ increase.}$$

$$2. \quad \text{Given } t_1 = t_2.$$

$$\frac{aL}{AK} \log_e \frac{h_1}{h_2} = \frac{aL}{A \cdot K} \log_e \frac{h_2}{h_3}$$

$$\frac{h_1}{h_2} = \frac{h_2}{h_3}$$

$$h_2^2 = h_1 h_3$$



$$3. \quad \begin{array}{ll} k_1 = 2 & z_1 = 2 \\ k_2 = 3 & z_2 = 1 \\ k_3 = 1 & z_3 = 2. \end{array}$$

$$K_v = \frac{z_1 + z_2 + z_3}{\frac{z_1}{k_1} + \frac{z_2}{k_2} + \frac{z_3}{k_3}} = \frac{5}{1 + \frac{1}{3} + 2} = \underline{\underline{\frac{3}{2}}}$$

$$4. \quad k_v = \frac{6 + 6 + 6}{\frac{6}{30 \times 10^{-5}} + \frac{6}{4 \times 10^{-4}} + \frac{6}{6 \times 10^{-4}}} = 2.667 \times 10^{-4} \text{ cm/s}$$

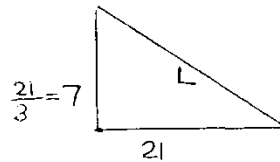
$$t = \frac{aL}{A \cdot K_v} \log_e \frac{h_1}{h_2} = \frac{2 \times 18}{22 \times 2.667 \times 10^{-4}} \log_e \frac{25}{10}$$

$$= 3748.46 \text{ s}$$

$$= \underline{\underline{62.474 \text{ min}}}$$

$$L = \sqrt{21^2 + 7^2}$$

$$= 22.135 \text{ m.}$$

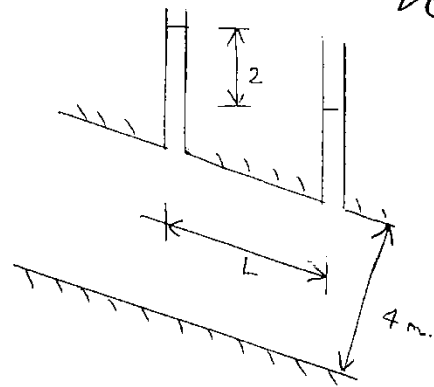


$$Q = kiA$$

$$= k \frac{h}{L} \cdot dx1$$

$$\frac{5}{1000} = k \cdot \frac{2}{22.135} \times 4 \times 1$$

$$k = 0.0138 \text{ m/hr} = 3.85 \times 10^{-6} \text{ m/s}$$



06. Total head loss =  $0.8 + 0.4 = 1.2 \text{ m.}$

Total seepage length =  $0.8 + 0.4 = 1.2 \text{ m.}$

$$i = \frac{h}{L} = \frac{1.2}{1.2} = 1$$

For a seepage length of  $y$ ,

$$\text{head loss} = i \times y = 1 \times 0.8 = \underline{0.8 \text{ m}}$$

$$\therefore \text{Pressure head at R} = 1.2 - 0.8 = \underline{0.4 \text{ m}}$$

$\therefore$  datum line is not given, let us assume,  
datum line at the d/s water surface

If d/s water surface is datum, then datum head at R = 0.

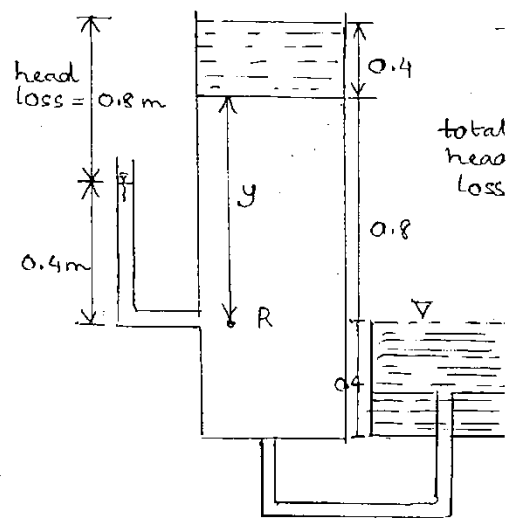
$$\text{Total head at R} = \text{Pressure head} + \text{datum head}$$

$$= 0.4 + 0 = \underline{0.4 \text{ m}}$$

\* If datum is taken to be bottom of soil,  
datum head at R = 0.4 m.

$$\text{Total head at R} = \text{pressure head} + \text{datum head}$$

$$= 0.4 + 0.4 = \underline{0.8 \text{ m}}$$



07 Discharge velocity,  $V = ki = k.$

$$\text{Seepage velocity, } V_s = \frac{V}{n} = \frac{k}{0.5} = \underline{\underline{2k}}$$

→ Allen Hazen's Equation:

$$K \approx 100 D_{10}^2$$

$D \rightarrow \text{cm}$

$K \rightarrow \text{cm/s}$

- Q The hydraulic conductivity of a soil at a void ratio of 0.8 is 0.047 cm/s. Estimate the hydraulic conductivity at a void ratio of 0.5.

At  $e_1 = 0.8$ ,  $K_1 = 0.047$

$e_2 = 0.5$ ,  $K_2 = ?$

$$K \propto \frac{e^3}{1+e} \Rightarrow \frac{K_1}{K_2} = \frac{e_1^3 / (1+e_1)}{e_2^3 / (1+e_2)}$$

$$\frac{0.047}{K_2} = \frac{0.8^3 / 1.8}{0.5^3 / 1.5}$$

$$K_2 = \underline{\underline{0.0137 \text{ cm/s}}}$$

If  $K \propto e^2$ ,  $K_2 = \underline{\underline{0.01835 \text{ cm/s}}}$

- Q. In fig. shown below, the soil X has a permeability of  $4 \times 10^{-3} \text{ cm}$ , and the head loss in soil Y is 9 times the head loss in soil X. a) What is the permeability of the soil Y?

b) What is seepage rate per hour?

c) To what elevation would water rise in a piezometer inserted in soil Y at elevation 5 cm?

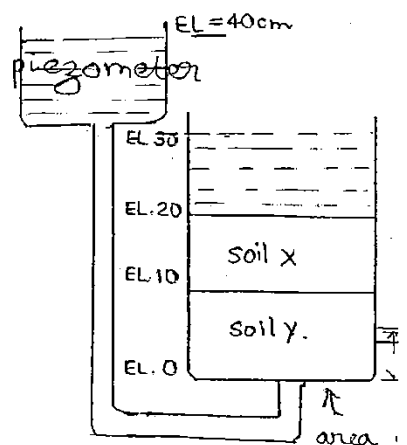
a) Total head loss,  $h = 40 - 30 = 10 \text{ cm}$ .

$$h_x + h_y = h = 10 \text{ cm} \rightarrow \textcircled{1}$$

Given,  $h_y = 9 h_x$

$$\therefore h_x = 1 \text{ cm}$$

$$h_y = 9 \text{ cm}$$



$$Q_x = Q_y$$

$$k_x \cdot \frac{h_x}{z_x} \cdot A_x = k_y \cdot \frac{h_y}{z_y} \cdot A_y$$

$$4 \times 10^{-3} \times \frac{1}{10} \times 10 = k_y \cdot \frac{9}{10} \cdot 10$$

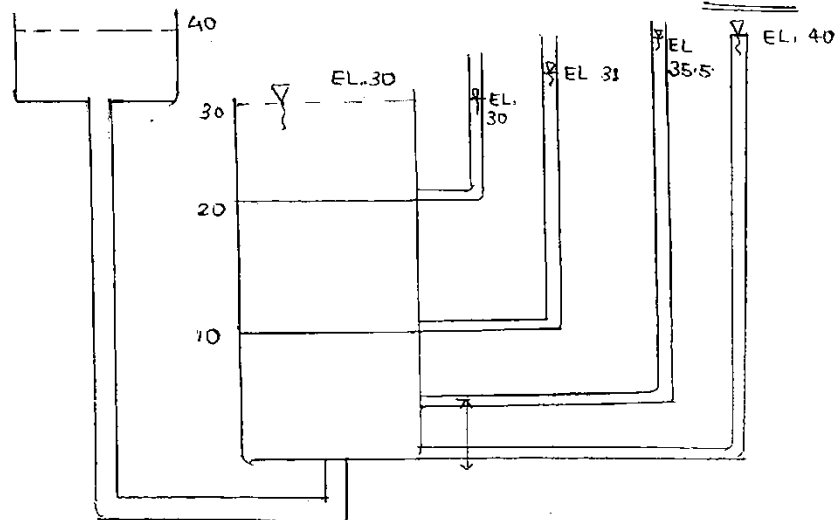
$$k_y = 4.4 \times 10^{-4} \text{ cm/s}$$

$$b) Q_x = k_x \cdot \frac{h_x}{z_x} \cdot A_x = Q$$

$$= 4 \times 10^{-3} \times \frac{1}{10} \times 10 = 4 \times 10^{-3} \text{ cm}^3/\text{s}$$

$$= 4 \times 10^{-3} \times 60 \times 60 = \underline{\underline{14.4 \text{ cm}^3/\text{hr}}}$$

c)



Pressure head = height of water column in piezometer.

H

8<sup>th</sup> Sept,  
WEDNESDAY

## 7. EFFECTIVE STRESS

→ Total Stress ( $\sigma$ )

It is the stress due to total load.

\* Neutral Stress or Pore water Pressure ( $u$ )

It is the pressure in the water.

\* Effective Stress ( $\sigma'$ )

It is the total stress minus neutral stress.

It is also called intergranular pressure. It is the stress which controls the behaviour of soil, shear strength of soil and volume change of soil.

$$\sigma = u + \sigma'$$

$$\sigma' = \sigma - u$$

$$\sigma = \frac{W}{A}$$

where  $W \rightarrow$  total load (external load + self wt. of soil)

$A \rightarrow$  total c/s area of soil

$$u = \gamma_w h$$

where  $h \rightarrow$  pressure head = depth of water in piezometer

$\therefore \sigma$  &  $u$  can be measured, but  $\sigma'$  can't be measured

However it can be computed using  $\sigma$  &  $u$  values.

$$\sigma = \frac{W}{A}$$

$$= \frac{A \cdot z \cdot \gamma_{sat}}{A}$$

$$\therefore \boxed{\sigma = z \cdot \gamma_{sat}}$$

$$u = \gamma_w h$$

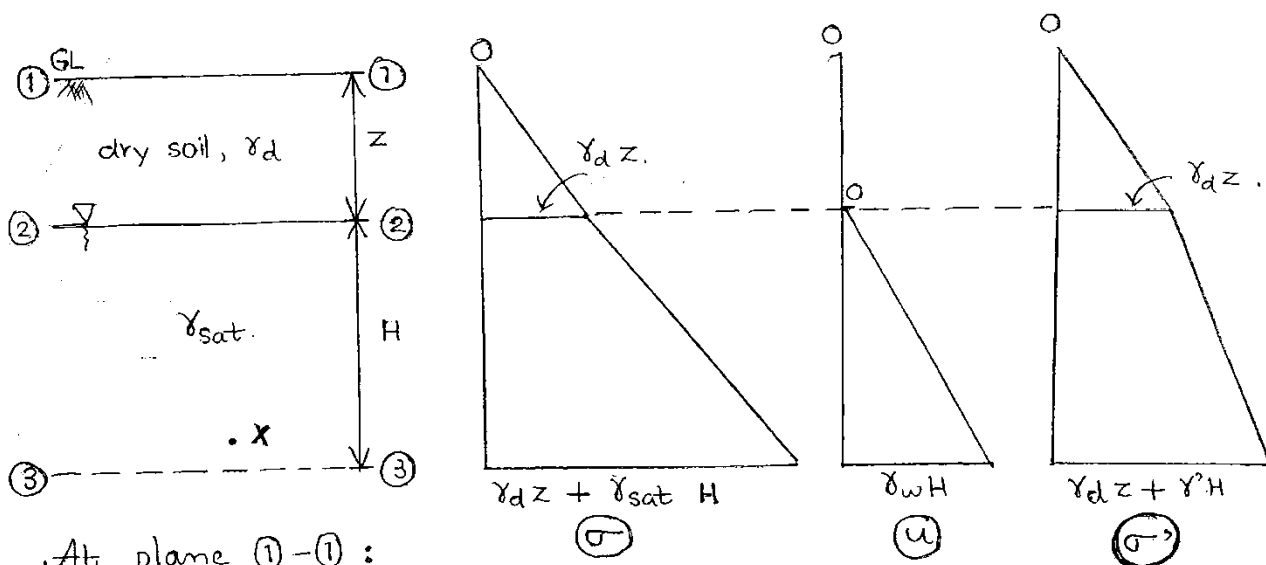
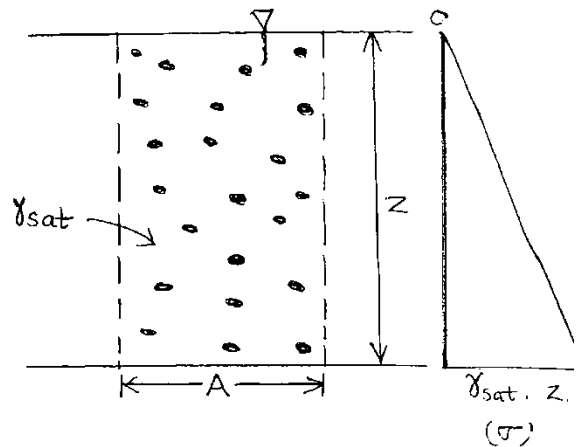
$$\therefore \boxed{u = \gamma_w \cdot z}$$

$$\sigma' = \sigma - u$$

$$= \gamma_{sat} z - \gamma_w z$$

$$= (\gamma_{sat} - \gamma_w) z$$

$$\therefore \boxed{\sigma' = \gamma' z}$$



At plane ①-①:

$$\sigma = 0; u = 0; \sigma' = 0$$

At plane ②-②:

$$\sigma = \gamma_d \cdot z; u = 0; \sigma' = \gamma_d z$$

At plane ③-③:

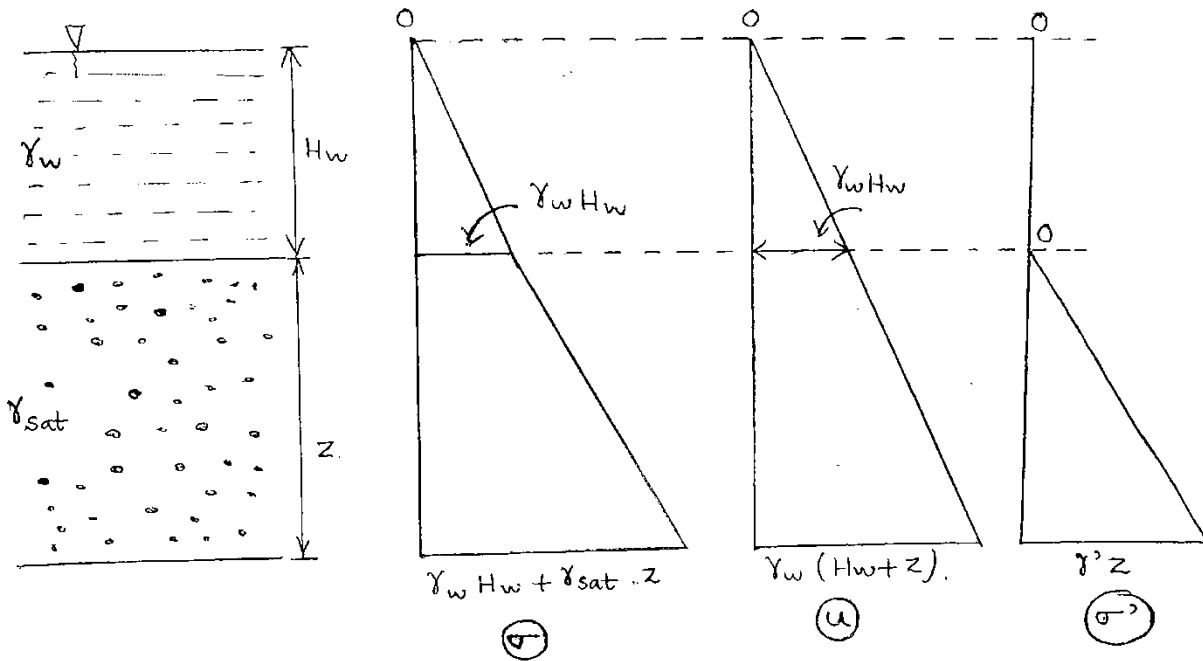
$$\sigma = \gamma_d \cdot z + \gamma_{sat} \cdot H$$

$$u = \gamma_w \cdot H$$

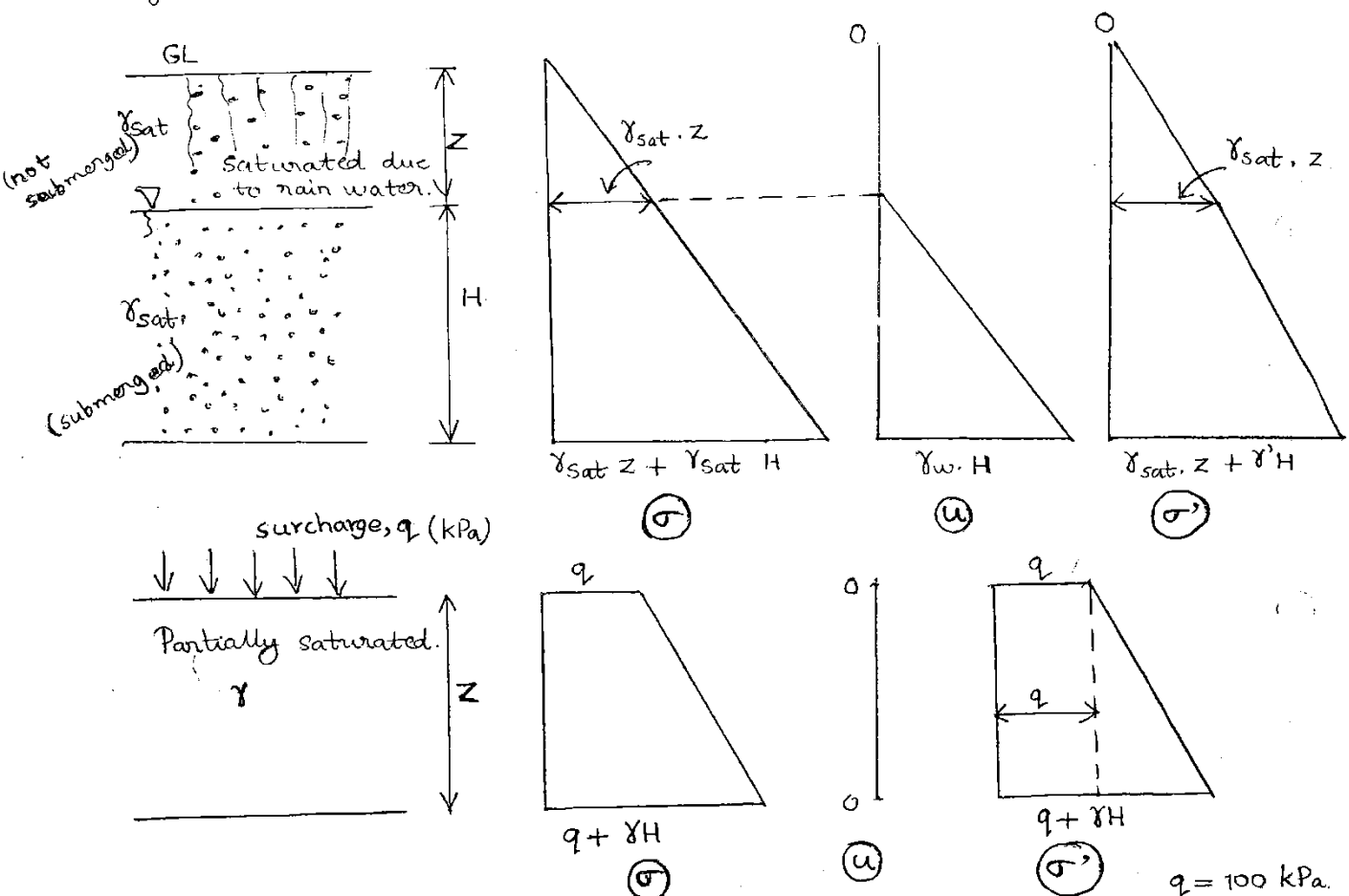
$$\sigma' = \gamma_d z + \gamma' H$$

• If WT rises, then  $\sigma$  &  $u$  increase, but  $\sigma'$  decreases.

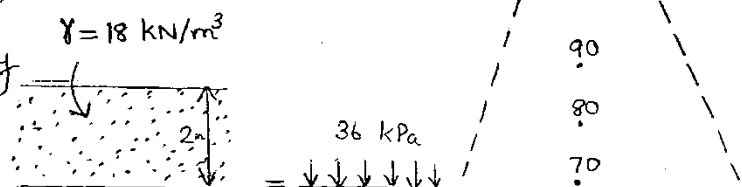
• If WT falls, then  $\sigma$  &  $u$  decrease but  $\sigma'$  increases.



Effective stress below the bed level is totally independent of depth of water ( $H_w$ ) above bed level.



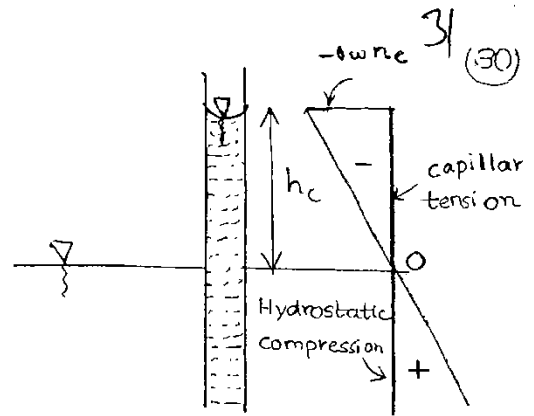
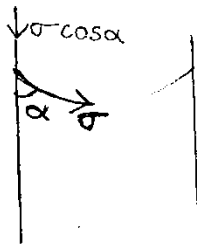
Above stress distribution diagrams are possible only if surcharge is infinite



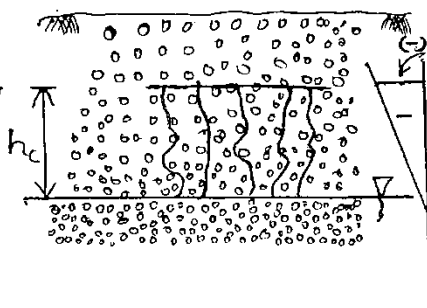
## → Capillarity

Due to capillarity, the capillary water is under tension whereas the wall of capillary tube is under compression.

' $\sigma \cos \alpha$ ' causing compression on the walls.



th Sept,  
THURSDAY



In soils, capillarity rise,  $h_c \approx \frac{0.3}{d}$

where  $d$  - diameter of void (cm)

$h_c$  - capillary height (cm)

$$d \propto D_{10} \Rightarrow h_c \propto \frac{1}{D_{10}}$$

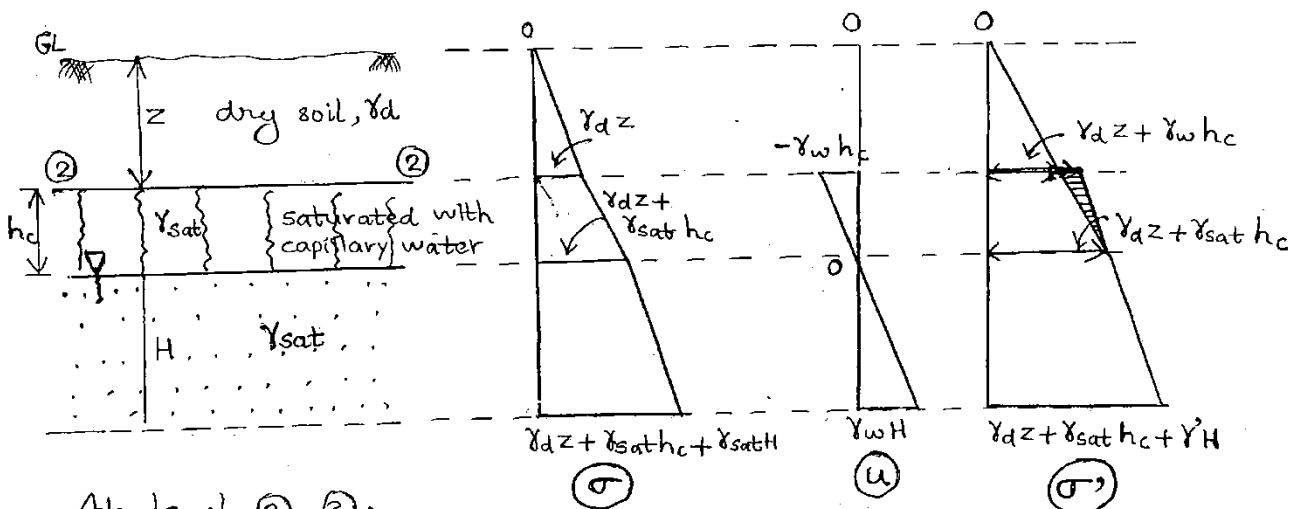
variation

- For gravel & coarse sand,  $h_c$  is negligible.

-  $h_c$  is highest for clay.

$$d \propto e D_{10} \Rightarrow h_c \propto \frac{1}{e D_{10}}$$

For clay, effect of size of particle on capillary height is more than that of void ratio.



At level ②-②:

a) Just above

$$\sigma = \gamma_d z$$

$$u = 0$$

$$\sigma' = \gamma_d z - 0 = \gamma_d z$$

b) Just below

$$\sigma = \gamma_d z$$

$$u = -\gamma_w h_c$$

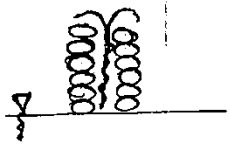
$$\sigma' = \gamma_d z - (-\gamma_w h_c) = \gamma_d z + \gamma_w h_c$$

$$\sigma' = \sigma - u$$

$\sigma' = \sigma$  if  $u = 0 \rightarrow$  dry & partially saturated soil

$\sigma' < \sigma$  if  $u$  is +ve  $\rightarrow$  below WT

$\sigma' > \sigma$  if  $u$  is -ve  $\rightarrow$  in capillary zone



Soil molecules act like walls of the capillary tube and they are under compression.  $\therefore \sigma'$  inc in capillary zone.

Frost heave & Frost boil are disadvantages of capillary action  
(night time) (day time)

But capillary increases the shear strength of soil. ( $s = c + \sigma' \tan \phi$ )

2.  $\sigma' = \gamma' z$

$$100 = \gamma' z$$

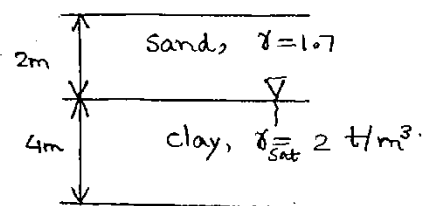
Taking  $\gamma' = 10$ ,  $z = \underline{10 \text{ m}}$

3. At centre of clay,

$$\sigma = 2\gamma + 2\gamma_{\text{sat}} = 7.4 \text{ t/m}^2$$

$$u = 2\gamma_w = 2 \text{ t/m}^2$$

$$\sigma' = \sigma - u = 7.4 - 2 = \underline{5.4 \text{ t/m}^2}$$



(OR)

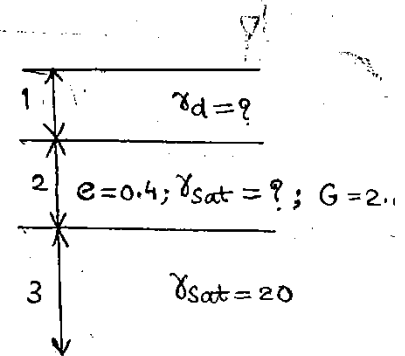
$$\begin{aligned} \sigma' &= 2\gamma + 2\gamma' \\ &= 2 \times 1.7 + 2(2-1) = \underline{5.4 \text{ t/m}^2} \end{aligned}$$

4.  $\sigma' = 3 \times 18 + 7 \times 10 = \underline{124 \text{ t/m}^2}$

5.  $\gamma_d = \frac{G\gamma_w}{1+e} = 18.93 \text{ kN/m}^3$

$$\gamma_{\text{sat}} = \gamma_w \left( \frac{G+e}{1+e} \right) = 21.78 \text{ kN/m}^3$$

$$\sigma' = 1 \times 18.93 + 2(21.78 - 10) + 3(20 - 10) = \underline{72.49 \text{ kN/m}^2}$$



Q. 7 b) Calculate  $\sigma^2$  at a depth of 2.4 m below GL for the above capillarity case.

$$\sigma_{(9m)}^2 = 17 \times 3 + (20 - 9.81) \times 1 + (18 - 9.81) \times 5 = \underline{\underline{102.14 \text{ kN/m}^2}}$$

7. a) After capillary rise,

At 9 m depth,

$$\sigma = 2 \times 17 + 20 \times 2 + 5 \times 18 = 164$$

$$u = 6 \gamma_w = 58.86$$

$$\sigma^2 = \sigma - u = 105.14 \text{ kPa}$$

$$\Delta \sigma^2 = 105.14 - 102.14 = \underline{\underline{3 \text{ kPa}}}$$

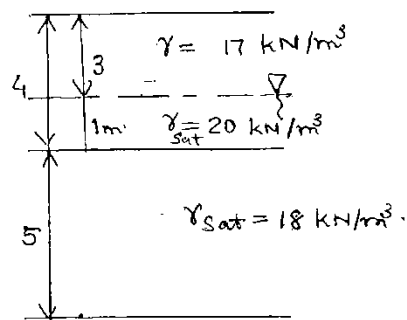
b) At 2.4 m depth,

$$\sigma = 2 \gamma_d + 0.4 \gamma_{sat}$$

$$= 2 \gamma_d + 0.4 \times 20 = \underline{\underline{42 \text{ kPa}}}$$

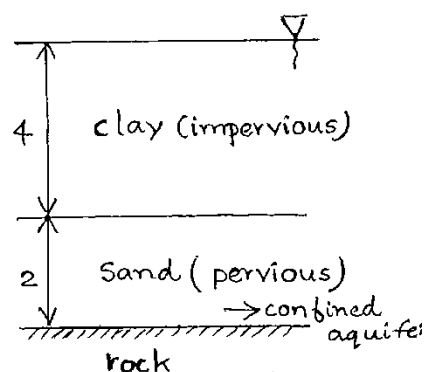
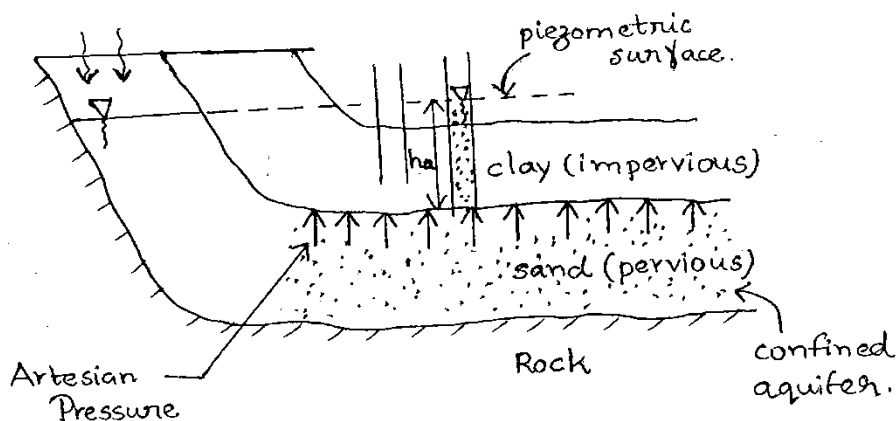
$$\sigma^2 = \sigma - (-u) = 42 + (3 - 2.4) 9.81$$

$$= \underline{\underline{47.886 \text{ kPa}}}$$



Sept,  
URDAY

8.



$h_a \rightarrow$  artesian pressure head.

$$\boxed{\text{Artesian pressure} = \gamma_w h_a}$$

Springs are developed only when piezometric surface is above GL.

8. Effective stress at a depth of 6m =  $\gamma'_{\text{clay}} \times 4 + \gamma'_{\text{sand}} \times 2 - \gamma_w h_a$

a)

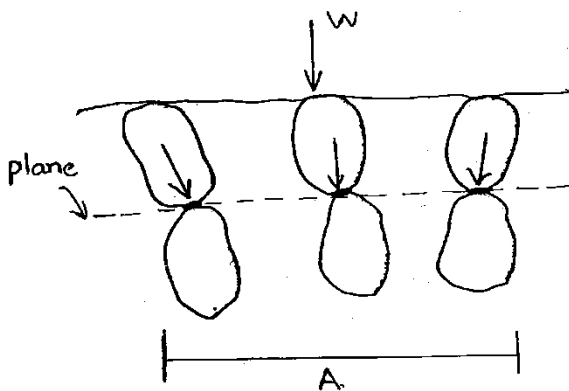
$$= (19.5 - 10) \times 4 + (18.5 - 10) \times 2 - 10 \times 2$$

$$= \underline{\underline{35 \text{ kPa}}}$$

b). When  $h_a = 1$ ,

$$\sigma' = 55 - 10 \times 1 = 45 \text{ kPa}$$

$$\Delta \sigma' = \underline{\underline{\frac{10}{35} \text{ kPa}}}$$



$A_c \rightarrow$  area of contact.

$A_w \rightarrow$  area of water

$A \rightarrow$  total area of soil.

$A_c$  is very small.

$$A = A_w + A_c \approx A_w$$

$$W = u A_w + \sum N_v$$

Dividing by  $A$ ,

$$\frac{W}{A} = u \frac{A_w}{A} + \frac{\sum N_v}{A}$$

$$\Rightarrow \sigma = u + \frac{\sum N_v}{A}$$

3992  
VAG/11

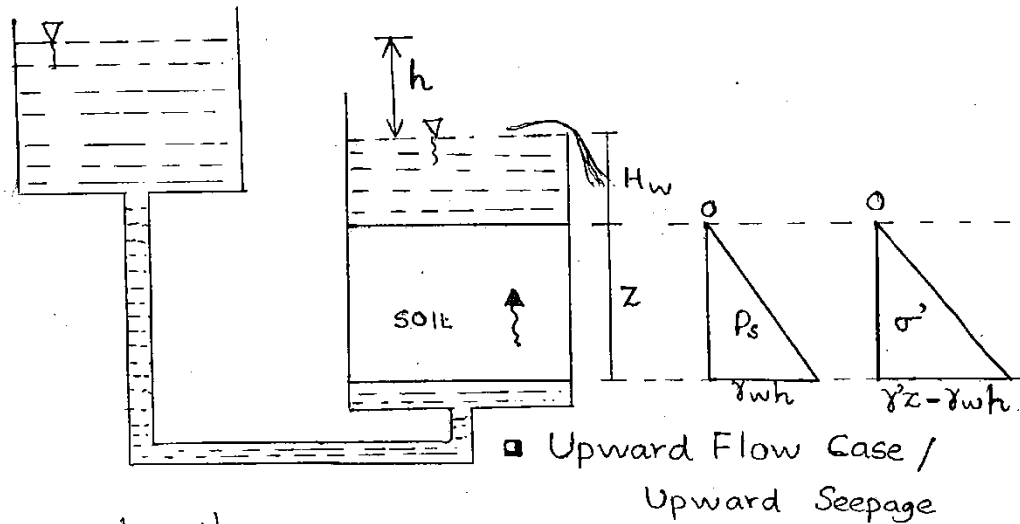
Comparing above equation with,  $\sigma = u + \sigma'$

$$\therefore \sigma' = \frac{\sum N_v}{A}$$

It is equal to the total vertical reaction force transmitted at the points of contact of soil grains divided by the total area, including that occupied by water.

It is much smaller than actual contact stress.  $\left( \frac{\sum N_v}{A_c} \right)$

## 8. SEEPAGE PRESSURE & CRITICAL HYDRAULIC GRADIENT

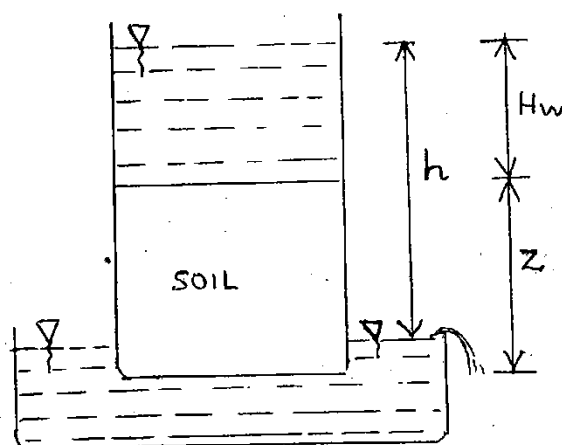


At bottom of soil:

$$\sigma = \gamma_w H_w + \gamma_{sat} \cdot z$$

$$u = \gamma_w (z + H_w + h)$$

$$\begin{aligned} \sigma' &= \sigma - u \\ &= \gamma' z - \gamma_w h \end{aligned}$$



Downward Seepage.

$$\sigma = \gamma_w H_w + \gamma_{sat} \cdot z$$

$$u = \gamma_w (H_w + z)$$

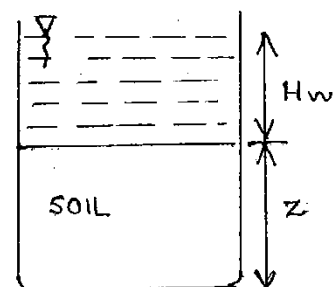
$$\sigma' = \sigma - u = \underline{\gamma' z}$$

At bottom of soil:

$$\sigma = \gamma_w H_w + \gamma_{sat} z$$

$$u = \gamma_w (z + H_w - h)$$

$$\begin{aligned} \sigma' &= \sigma - u \\ &= \gamma' z + \gamma_w h \end{aligned}$$



$\therefore$  when there is seepage,  $\sigma' = \gamma'z \pm \gamma_w h$

use -ve sign for upward seepage

+ve sign for downward seepage

$$\boxed{\text{Seepage pressure, } P_s = \gamma_w h.}$$

The pressure caused by the seepage water on the soil particle is called seepage pressure.

The seepage pressure always acts in the direction of flow.

Upward Flow:  $\gamma'z \downarrow$        $\gamma_w h \uparrow$

Downward Flow:  $\gamma'z \downarrow$        $\gamma_w h \downarrow$

Hydraulic Gradient,  $i = \frac{h}{z}$ .

$$\therefore P_s = \gamma_w h \\ = \gamma_w i z$$

$$\text{Seepage force, } P_s = P_s \cdot A. \\ = \gamma_w \cdot i \cdot z \cdot A.$$

$A \rightarrow$  area at bottom of soil.

$\therefore$  Seepage force per unit volume of soil =  $\gamma_w i$

$\rightarrow$  Critical Hydraulic Gradient;  $i_c$

It is the hydraulic gradient at critical condition. ( $\sigma' = 0$ ).

In an upward seepage,  $\sigma' = \gamma'z - \gamma_w h$ .

At critical condition ( $\sigma' = 0$ );  $\gamma_w h = \gamma'z$

$$\Rightarrow \frac{h}{z} = \frac{\gamma'}{\gamma_w}$$

$$\therefore \boxed{i_c = \frac{\gamma'}{\gamma_w}}$$

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

For soils,  $i_c \approx 1$ . ( $G = 2.6 - 2.85$  &  $e = 0.6 - 0.85$ )

→ Quick Sand & Quick Condition or Boiling Condition.

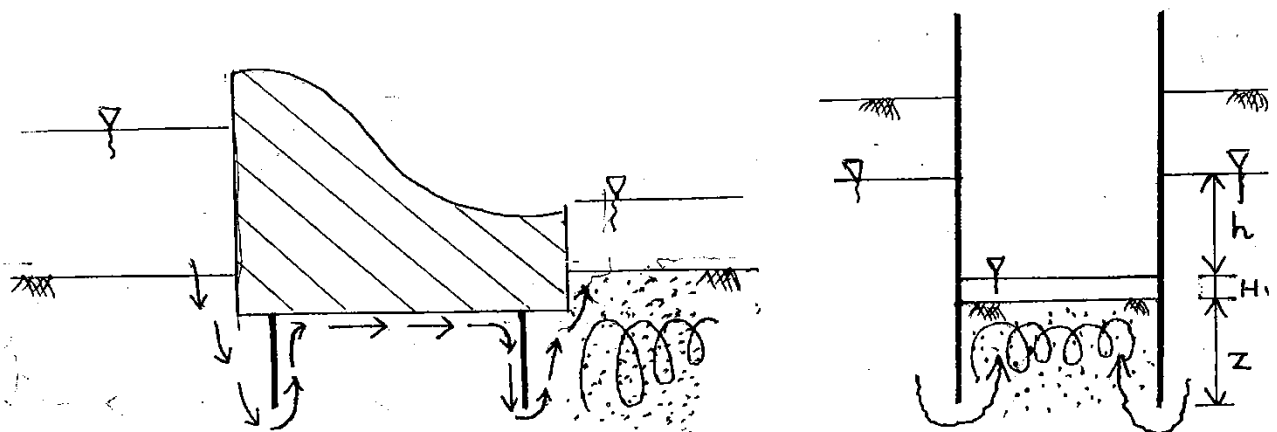
$$\text{Shear strength, } S = c' + \sigma' \tan \phi'$$

$$\text{For cohesionless soils, } S = \sigma' \tan \phi'$$

In an upward seepage,  $\sigma' = \gamma' z - \gamma_w h$ .

At critical condition ( $\sigma' = 0$ ), shear strength of cohesionless soil becomes zero and the soil behaves like a boiling liquid. This phenomenon is called Quick Condition. It occurs only in cohesionless soils.

Quick condition is generally observed in fine sand and silts. In the case of gravel and coarse sand, though they are cohesionless, quick sand condition is not common, since these are highly permeable.



Practically, quick sand condition occurs at the bottom or d/s side of hydraulic structures. This is also experienced during construction activities in regions where WT is closer to GL.

\* To prevent Quick Condition

- Provide more depth of sheet piles and reduce the hydraulic gradient.
- Keep some depths of water ( $H_w$ ) in the trench without completely dewatering.
- Lower down the surrounding WT.
- + Apply some surcharge load intensity ( $q$ ) on top of soil, at D/S of hydraulic structures.

Let  $i$  be actual hydraulic gradient ( $= \frac{h}{z}$ )

$i_c$  be critical hydraulic gradient of soil ( $= \frac{G-1}{1+e}$ ).

If  $i \geq i_c$ , quick condition occurs.

To avoid quick condition,  $i$  must be kept less than  $i_c$ .

$\therefore$  FOS against quick condition,  $F = \frac{i_c}{i}$

\* The minimum head required to cause quick condition,

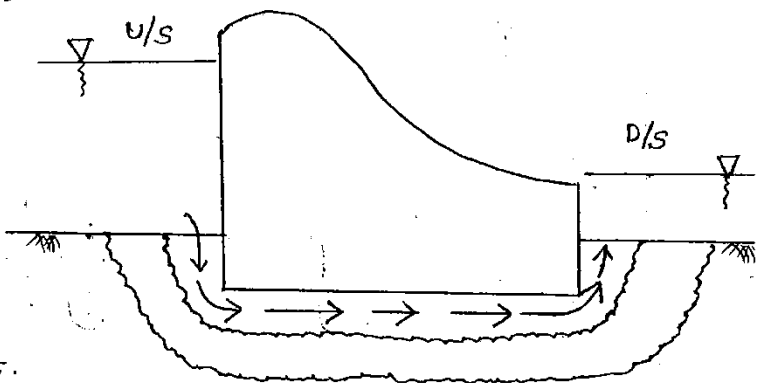
$$h = i_c \cdot z.$$

9th Sept,  
TUESDAY

→ Piping: (undermining)

- gradual erosion of soil particles.

- It occurs when  $\sigma' = 0$  in case of cohesionless soils like fine sand and silt.



Let  $i_{exit}$  be hydraulic gradient at exit point.

$$\text{FOS against piping} = \frac{i_c}{i_{exit}}$$

\* To prevent Piping:

(34)

35

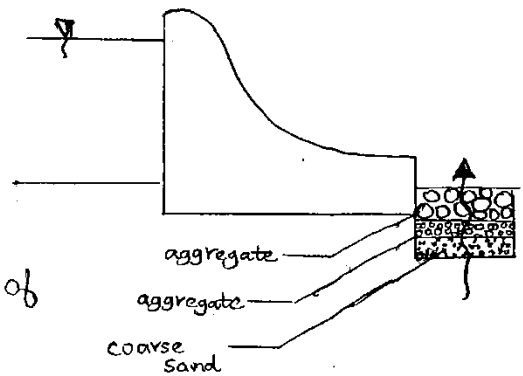
— provide sheet piles in the foundation to reduce the hydraulic gradient.

— provide inverted filter on D/S.

■ Terzaghi's criteria for design<sup>of</sup> filter:

(i)  $\frac{(D_{15})_{\text{filter}}}{(D_{15})_{\text{base}}} \geq 5$  ; to allow escape of water

(ii)  $\frac{(D_{15})_{\text{filter}}}{(D_{85})_{\text{base}}} \leq 5$  ; to prevent escape of soil particles.

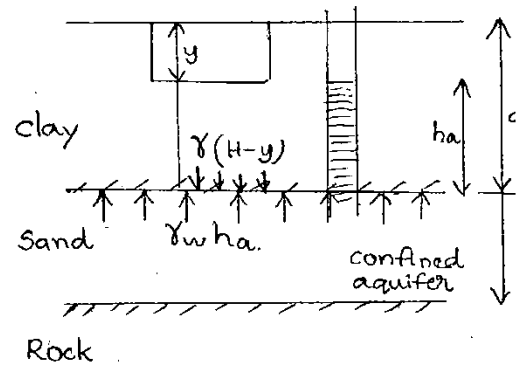


1. At critical condition,  
downward pr. = uplift pressure.

$$\gamma(H-y) = \gamma_w h_a$$

$$20(9-y) = 10 \times 6$$

$$y = 9 - 3 = \underline{6\text{ m}}$$



2. If  $y = 7\text{ m}$ ,

$$\gamma(H-y) = \gamma_w h_a$$

$$20(9-7) = 10 h_a$$

$$\therefore h_a = 4\text{ m}$$

$\therefore$  Water is to be lowered by  $6 - 4 = \underline{2\text{ m}}$

3.

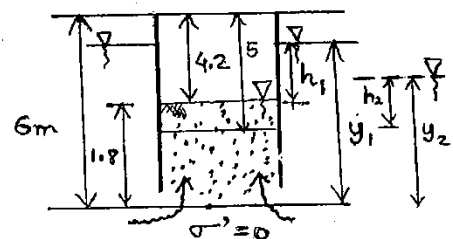
$$\sigma' = \gamma' z - \gamma_w h_1$$

$$0 = 11 \times 1.8 - 10 \times h_1$$

$$\therefore h_1 = 1.98\text{ m}$$

$$y_1 = 1.8 + 1.98 = \underline{3.78\text{ m}}$$

When depth of excavation increased to 5m,



$$0 = 11x_1 - 10h_2$$

$$h_2 = 1.1 \text{ m}$$

$$y_2 = 1 + 1.1 = 2.1 \text{ m}$$

$$y_1 - y_2 = 3.78 - 2.10 = \underline{\underline{1.68 \text{ m}}}$$

$$\Delta z \cdot \gamma_{\text{sat}} = \Delta h \cdot \gamma_w$$

$$(1.8 - 1)(11 + 10) = \Delta y \cdot 10$$

$$0.8 \times 2.1 = \Delta y$$

$$\therefore \underline{\underline{\Delta y = 1.68 \text{ m}}}$$

04.  $e = 0.8, G = 2.65, z = 10 \text{ cm}.$

$$I_c = \frac{G-1}{1+e} = \frac{1.65}{1.8} = 0.916$$

$$h = I_c \cdot z = \underline{\underline{9.16 \text{ cm}}}$$

05.  $Q = kiA.$

$$0.04 = 2 \times 10^{-3} \times i \times 45$$

$$i = 0.44.$$

$$h = iz = 0.44 \times 10 = \underline{\underline{4.4 \text{ cm}}}$$

06.  $\sigma' = \gamma'z - \gamma_w h.$

$$= (1.93 - 1) \times 10 - 1(4.4)$$

$$= \underline{\underline{4.86 \text{ g/cm}^2}}$$

## 9. SEEPAGE ANALYSIS

\* Flow Line or Stream line.

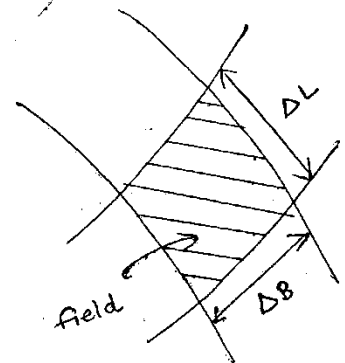
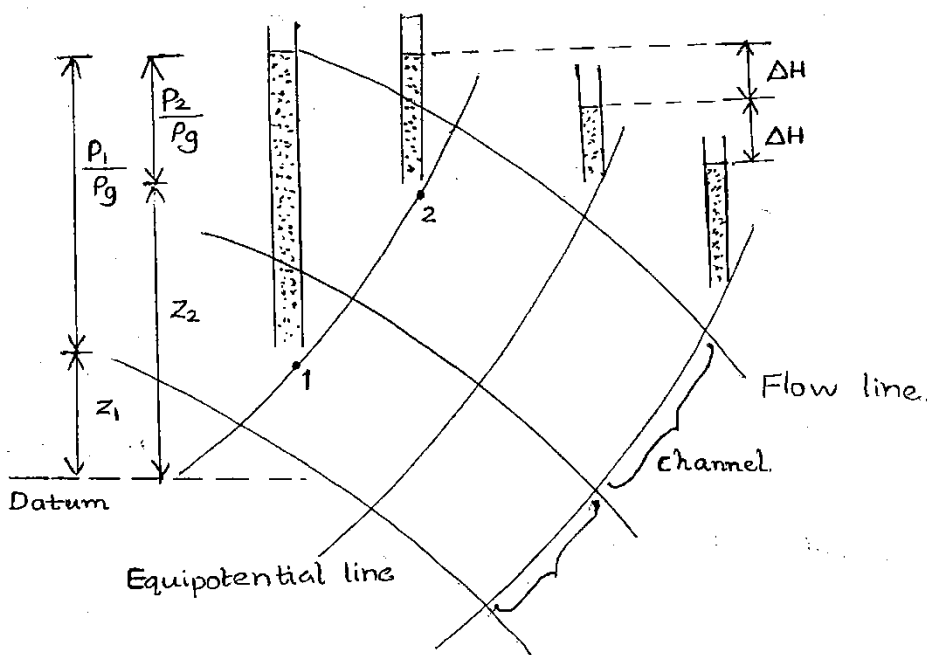
Line which shows the direction of seepage or flow.

\* Equipotential Line

Total Head or potential remains the same at all points in an equipotential line.

\* Flow net

Network of equipotential lines and flow line.



(i) Total head remains the same at all points in an equipotential line.

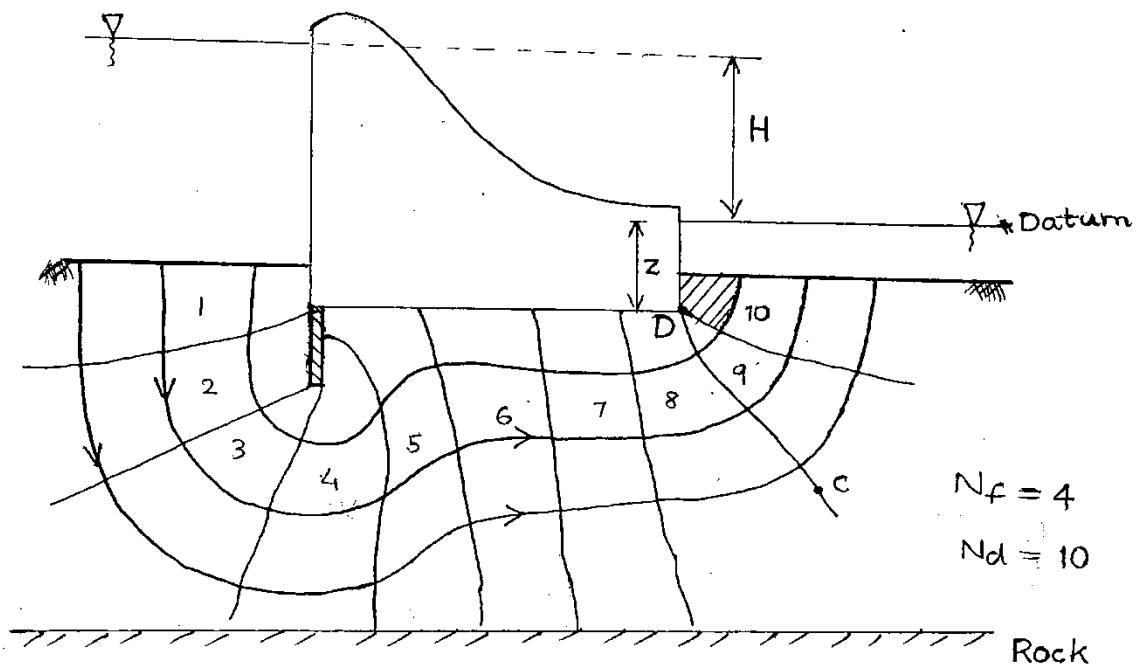
(ii) Head loss remains the same b/w two adjacent equipotential lines. ( $\Delta H$  is same)

(iii)  $\Delta Q$  remains the same for channel.

(iv) For every field,  $\frac{\Delta L}{\Delta B}$  ratio must be same.

### \* Applications of Flow net.

- (i) To find seepage loss rate.
- (ii) To find seepage pressure.
- (iii) To find uplift pressure.
- (iv) To find exit gradient



$H =$  seepage head (or) head causing flow. (or) total head loss

(i) Seepage Loss Rate,  $Q$

important

$$Q = k H \cdot \frac{N_f}{N_d} \left( \frac{\Delta B}{\Delta L} \right) \quad ; \text{ for rectangular fields}$$

$$= k H \cdot \frac{N_f}{N_d} \quad ; \text{ for square fields.}$$

$N_F \rightarrow$  No. of flow channels.

$N_d \rightarrow N_0$ : of potential drops.

$$\frac{N_F}{N_d} = \text{shape factor of flow net (a constant)}$$

(ii) Seepage Pressure,  $P_s$

$$P_s = \gamma_w h.$$

$h \rightarrow$  balance seepage head at point C.

$$h = \text{total seepage head} - \text{head loss upto point C.} \\ = H - h_f$$

$$h_f = n \Delta H \quad ; \quad n \rightarrow \text{no. of potential drops upto C.}$$

$\Delta H \rightarrow$  head loss b/w two adjacent equipotential lines.

$$\Delta H = \frac{H}{N_d} \Rightarrow h = H - \frac{nH}{N_d}$$

(iii) Uplift Pressure,  $P_u$

$$P_u = \gamma_w h_w$$

$h_w \rightarrow$  pressure head at point D.

Total head = Pressure head + Elevation head.

$$h = h_w + z$$

$$h_w = h - (-z)$$

$$h_w = h + z$$

(iv) Exit Gradient,  $i_{\text{exit}}$

$$i_{\text{exit}} = \frac{\Delta H}{\Delta L}$$

$\Delta L \rightarrow$  length of field at exit. (hatched field)

A flow net is shown in the fig. If coefficient of permeability of soil is  $2 \times 10^{-3}$  cm/s, determine the seepage loss rate in  $\text{m}^3/\text{day}$  per m length of the weir.

$$N_f = 4 \quad H = 10.5 - 0.5 = 10 \text{ m}, \quad z = 0.5 + 0.8 = 1.3 \text{ m}$$

$$N_d = 14 \quad K = 2 \times 10^{-3} \text{ cm/s}, \quad \Delta L = 1.2 \text{ m.}$$

Determine the seepage pressure and uplift pressure at point D shown in the fig, take depth of foundation as 0.8 m. Also determine the exit gradient if length of the field at the exit point is 1.2 m.

Seepage }  $Q = KH \frac{N_f}{N_d}$   
loss rate

$$= 2 \times 10^{-3} \times 10^{-2} \times 10 \times \frac{4}{14} \times 60 \times 60 \times 24.$$

$$K = \underline{1.728} \text{ m/day} \quad \& \quad Q = 4.937 \text{ m}^3/\text{day.m}$$

Seepage pressure,  $P_s = \gamma_w h$ .

$$= \gamma_w \left( H - \frac{nH}{N_d} \right)$$

$$= 10 \left( 10 - \frac{9 \times 10}{14} \right) = \underline{35.714} \text{ kPa}$$

Uplift pressure,  $P_u = \gamma_w h_w$

$$= \gamma_w (h + z).$$

$$= 10 (3.5714 + 1.3) = \underline{48.714} \text{ kPa}$$

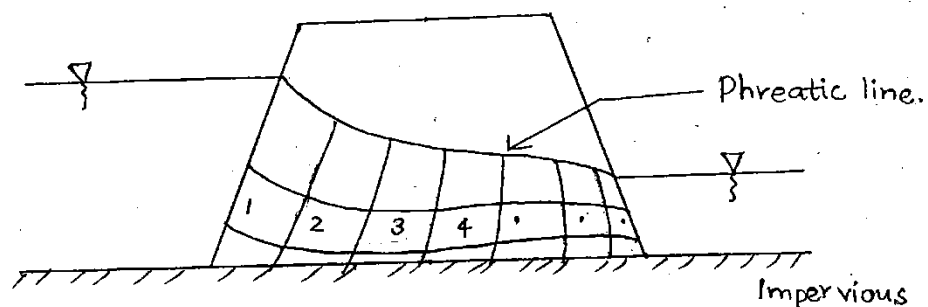
Exit gradient,  $i_{\text{exit}} = \frac{\Delta H}{\Delta L} = \frac{10/14}{1.2} = 0.595 \text{ m.}$

→ Earthen Embankment

$$N_f = 3$$

$$N_d = 7$$

$$Q = KH \frac{N_f}{N_d}$$



\* Phreatic Line:

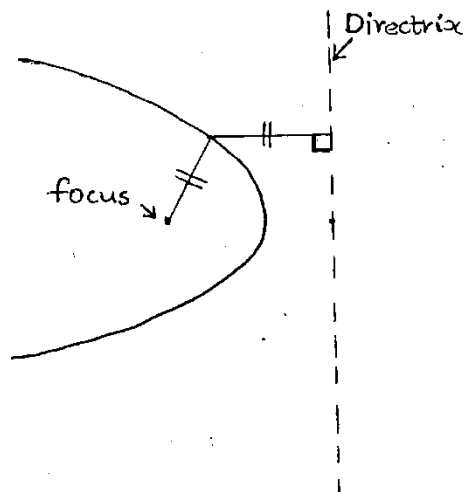
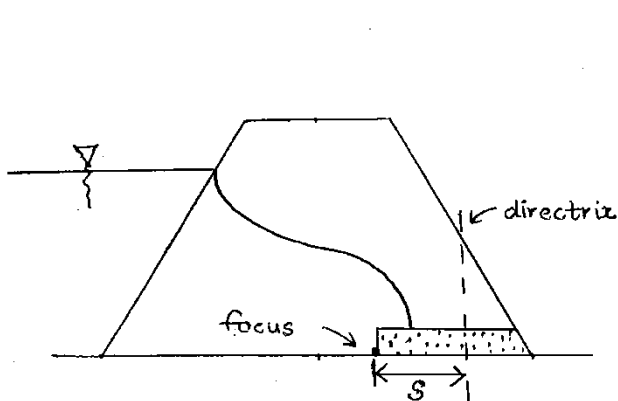
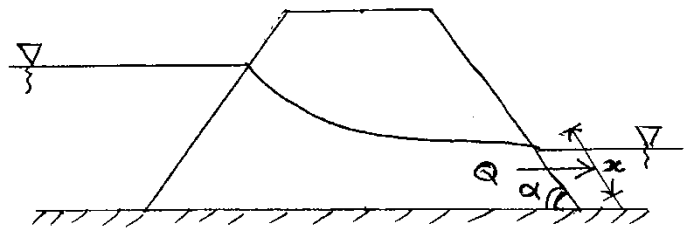
- topmost flow line
- On the phreatic line, pressure head is zero.
- Parabolic shape

■ If  $\alpha < 30^\circ$ ,

$$Q = k \cdot x \cdot \sin \alpha \cdot \tan \alpha$$

If  $30^\circ \leq \alpha \leq 60^\circ$ ,

$$Q = k \cdot x \cdot \sin^2 \alpha$$

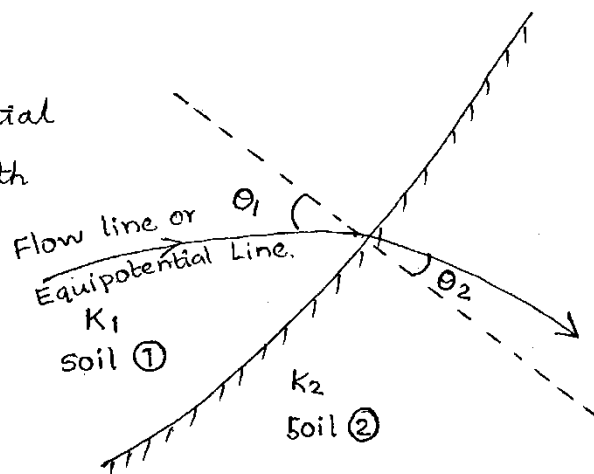


Kozney's Equation:

$$Q = K \cdot S$$

→ Anisotropic Soil:

Flow lines or equipotential lines are generally smooth lines. But whenever permeability changes, there will be deflection.



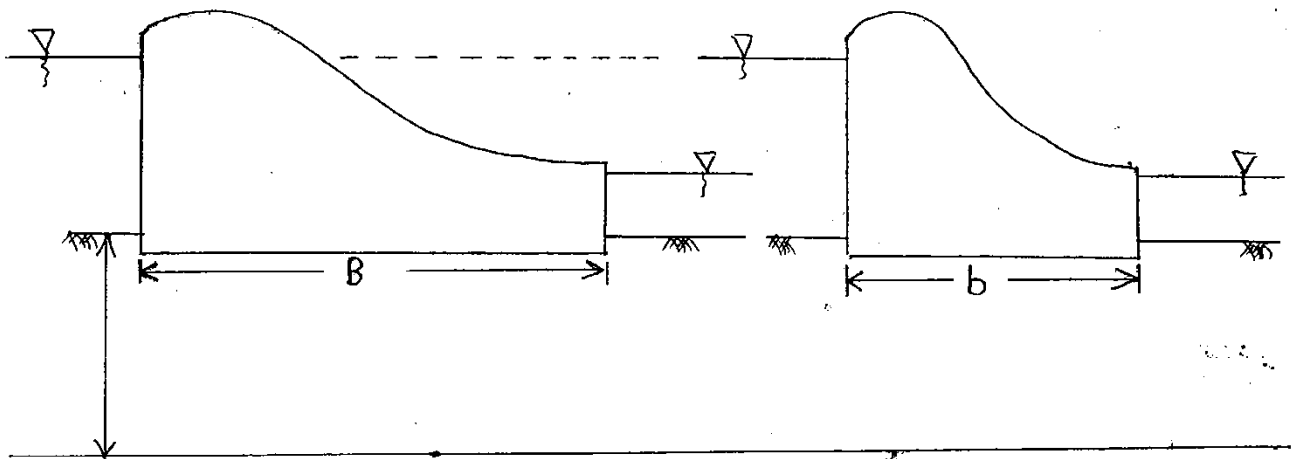
$$\frac{\tan \theta_1}{\tan \theta_2} = \frac{k_1}{k_2}$$

In the case of anisotropic soils ( $k_x > k_y$ ), the flow net is to be drawn to the transformed section which is obtained by reducing the horizontal dimensions and keeping vertical dimensions unchanged. The horizontal dimension is reduced by multiplying with a reduction coefficient of

$\sqrt{\frac{k_y}{k_x}}$ . The seepage loss rate is computed by taking average permeability ( $k'$ ) as follows:

$$Q = k' H \frac{N_f}{N_d}$$

where  $k' = \sqrt{k_x \cdot k_y}$



$$b = B \sqrt{\frac{k_y}{k_x}} = 65.8 \text{ m}$$

Scale factor = 1:25

$$= \frac{65.8}{25} = \underline{\underline{2.63 \text{ m}}}$$

$$2. \quad K = 100 D_{10}^2 = 100 \times (0.01)^2 = 10^{-4} \text{ cm/s} = 10^{-6} \text{ m/s}$$

(cm/s) (cm)

$$Q = KH \cdot \frac{N_f}{N_d} = \underline{\underline{1.5 \times 10^{-4} \text{ m}^3/\text{s}}} \text{ per metre length}$$

$$3. \quad K = 3.8 \times 10^{-6} ; H = 6.3 \text{ m} ; N_f = 3 ; N_d = 10$$

$$Q = KH \frac{N_f}{N_d} = 7.18 \times 10^{-6} \text{ m}^3/\text{s} \text{ per m length}$$

$$= 7.18 \times 10^{-6} \times 10^6 \text{ cm}^3/\text{s} \text{ per m length}$$

$$= \underline{\underline{7.18 \text{ cm}^3/\text{s}}}$$



04.

$$\Delta H = \frac{H}{Nd} = \frac{18}{9} = 2m$$

$$n = 3.$$

$$\therefore h_f = n \Delta H = 6m$$

$$h = H - h_f = 18 - 6 = \underline{\underline{12m}}$$

38  
39

11<sup>th</sup> Sept,  
THURSDAY

## 10. STRESS DISTRIBUTION

### → Boussinesq's Theory

#### \* Assumptions :

- Soil is homogenous.
- Isotropic soil.
- Semi infinite.
- Elastic medium.
- Point load.

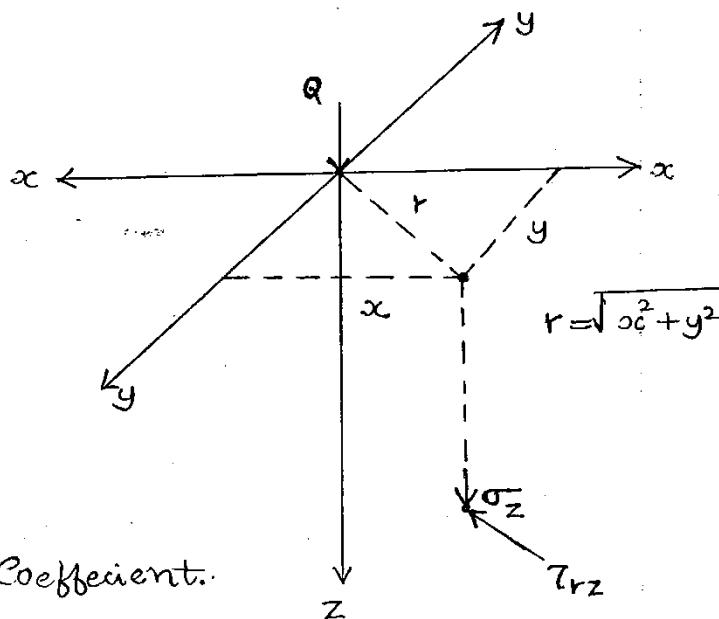
Homogenous means at different locations, soil has same elastic properties in same direction. (same  $E, \mu$ )

Isotropic means at a single point, soil has same elastic properties in different directions.

Semi-infinite means material bounded by a horizontal plane and extending to infinite length in all directions to one side of horizontal plane.

Vertical stress;

$$\sigma_z = \frac{Q}{z^2} \cdot \frac{3}{2\pi} \left[ \frac{1}{1 + \left(\frac{r}{z}\right)^2} \right]^{5/2}$$



$$\sigma_z = \frac{Q}{z^2} \cdot K_B$$

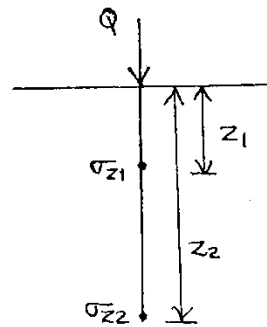
$K_B \rightarrow$  Boussinesq Influence Coefficient.

- If  $r = 0$  (vertically below the load).

$$\sigma_z = \frac{Q}{z^2} \cdot \frac{3}{2\pi}$$

$$\Rightarrow \sigma_z \propto \frac{1}{z^2}$$

$$\frac{\sigma_{z1}}{\sigma_{z2}} = \left( \frac{z_2}{z_1} \right)^2$$



(39)  
40

- Radial Shear Stress,

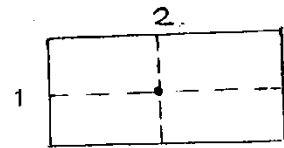
$$\tau_{rz} = \sigma_z \cdot \frac{r}{z}$$

Vertically below the load,  $\tau_{rz} = 0$ .

- Q. A rectangular footing  $1\text{ m} \times 2\text{ m}$  size has a load intensity of  $10\text{ t/m}^2$  on the ground surface. Determine the vertical stress at  $3\text{ m}$  below ground level a) below CG of the footing b) below the corner of footing, using Boussinesq's Theory.

a) below CG of footing,

$$Q = 10 \times 1 \times 2 = 20\text{ t. (acting at CG)}$$



$$\sigma_z = \frac{Q}{z^2} \cdot \frac{3}{2\pi}$$

$$= \frac{20}{3^2} \cdot \frac{3}{2\pi} = 1.06\text{ t/m}^2$$

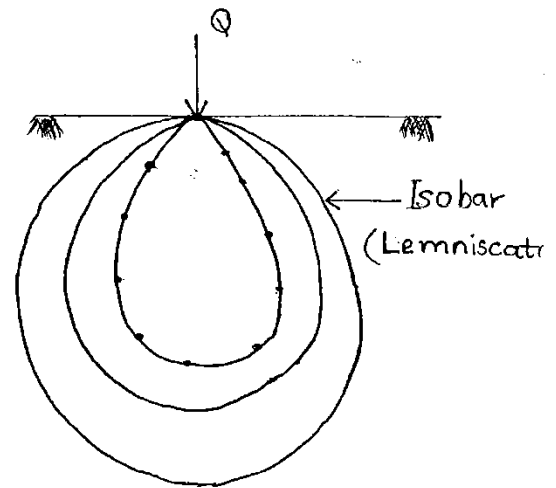
b) below corner of footing,

$$r = \sqrt{0.5^2 + 1^2} = 1.11\text{ m.}$$

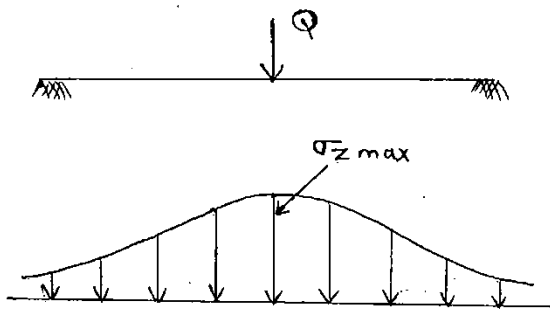
$$\begin{aligned} \sigma_z &= \frac{Q}{z^2} \cdot \frac{3}{2\pi} \left( \frac{1}{1 + \left( \frac{r}{z} \right)^2} \right)^{5/2} = \frac{20}{9^2} \cdot \frac{3}{2\pi} \left( \frac{1}{1 + \left( \frac{1.118}{3} \right)^2} \right)^{5/2} \\ &= \underline{\underline{0.7665\text{ t/m}^2}} \end{aligned}$$

→ Isobar

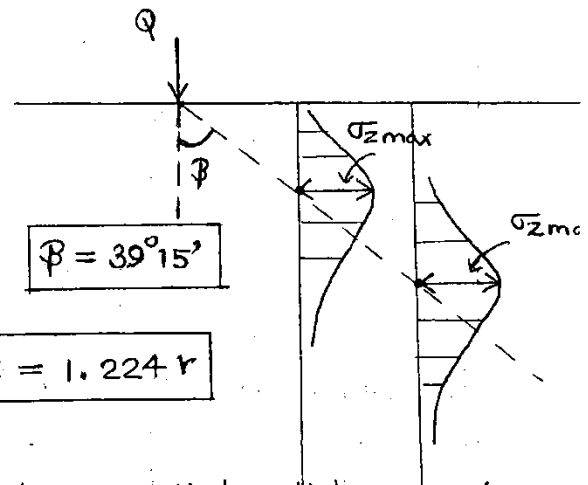
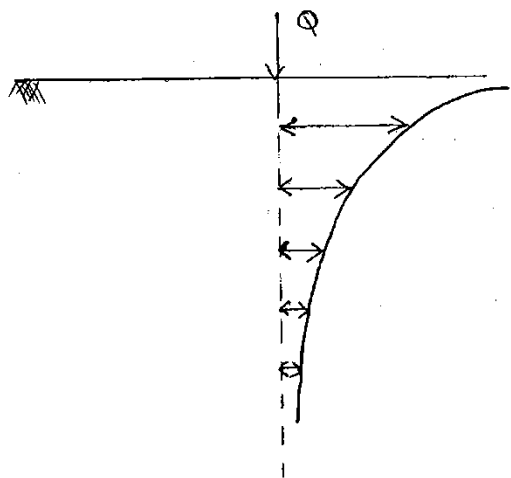
It is a curve or contour connecting all points below the ground surface of equal vertical stress.



\*  $\sigma_z$  variation on a Horizontal Plane.



\*  $\sigma_z$  variation on a Vertical Plane Passing through Load

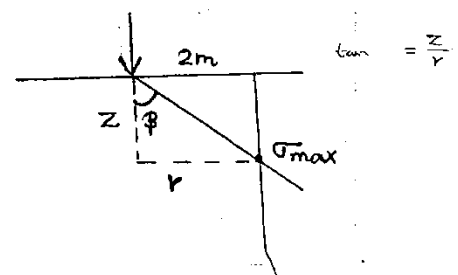


Q If a vertical plane is drawn at a radial distance of 2 m away from a vertical load at what depth more  $\sigma_z$  occurs.

$$\tan \beta = \frac{r}{z}$$

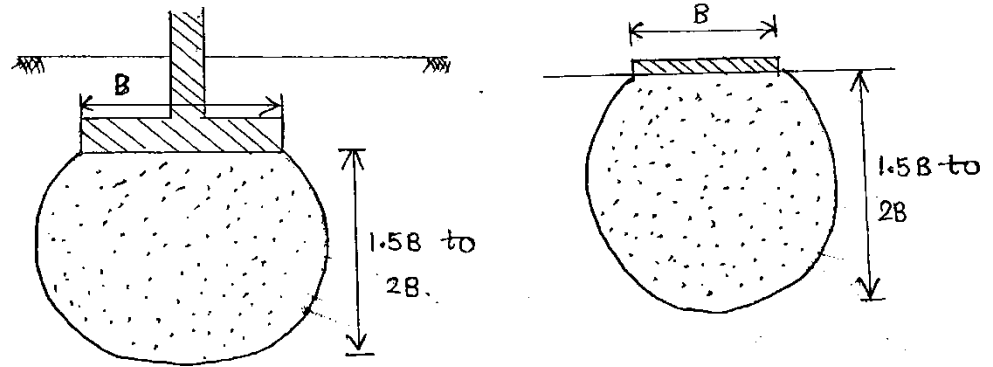
$$z = \frac{r}{\tan \beta} = 1.224 r$$

$$= 1.224 \times 2 = 2.447$$



## → Pressure Bulb.

It is the zone of the soil in which there is significant stress. Beyond the pressure bulb, stress in the soil is negligible. In the case of footings, the depth of the pressure bulb is taken as  $1.5B$  to  $2B$  (as shown in the fig) below the footing.

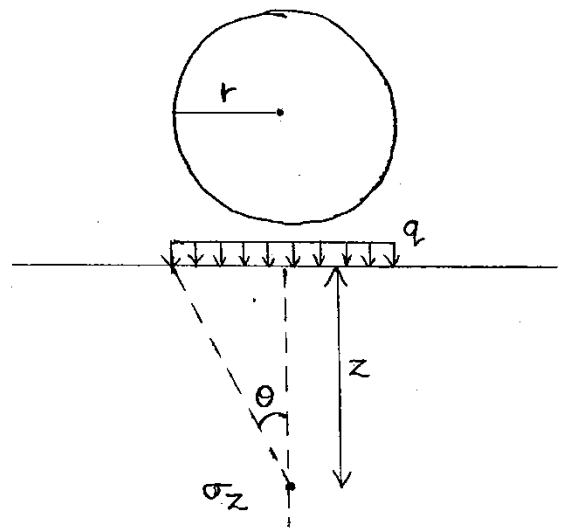


## → Circular Loaded Areas.

$$\sigma_z = q \left[ 1 - \left\{ \frac{1}{1 + \left( \frac{r}{z} \right)^2} \right\}^{3/2} \right]$$

OR

$$\sigma_z = q (1 - \cos^3 \theta)$$



## Sept, → Newmark's Influence Chart

DAY

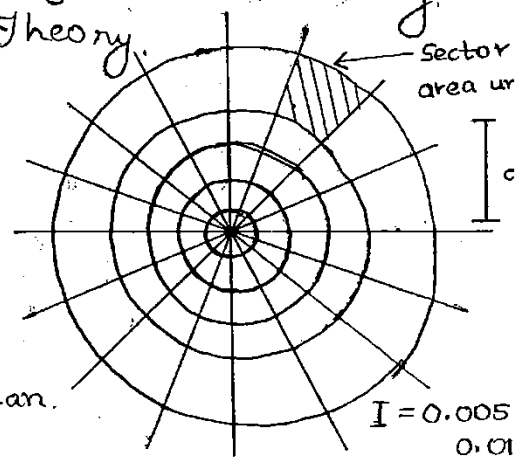
- to find  $\sigma_z$  at any point under any shape of loading.
- prepared based on Boussinesq's Theory.
- Each sector causes equal stress at the centre of the chart.

$$\sigma_z = I n q$$

I → influence coefficient of chart.

n → no. of sectors covered by footing plan.

q → load intensity of footing.



Q. In a Newmark's influence chart depth line is 5cm. If the stress is required at a depth of 10m, what scale is to be used to draw the fig on the tracing paper?

Scale: Depth line = Z.

$$5 \text{ cm} = 10 \text{ m}$$

$$1 \text{ cm} = 2 \text{ m}$$

$$1 \text{ cm} = 200 \text{ cm}$$

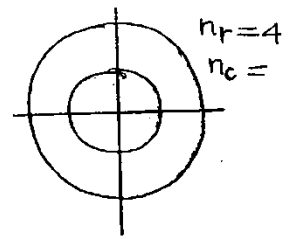
$$\text{or } \underline{\underline{1:200}}$$

$$* I = \frac{1}{\text{Total no. of sectors of chart}}$$

Total no. of sectors of chart = No. of concentric circles  $\times$  no. of radial lines.

If no. of circles = 10 & no. of radial lines = 20

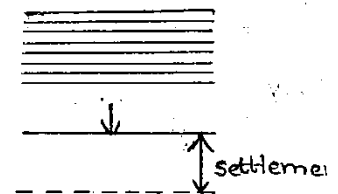
$$I = \frac{1}{10 \times 20} = \underline{\underline{0.005}}$$



→ Westergaard's Method:

\* Assumptions :-

- (i) Point Load.
- (ii) Soil consists of no. of thin layers.
- (iii) Applicable for stratified soils (or) sedimentary soils. or varved clay



$$\sigma_z = \frac{Q}{z^2} \cdot \frac{1}{\pi} \left[ \frac{1}{1 + 2\left(\frac{r}{z}\right)^2} \right]^{3/2}$$

- For  $\frac{r}{z} < 1.5$ , Boussinesq's eqn gives higher stresses compared to Westergaard's eqn.

- For  $\frac{r}{z} = 1.5$  both equations give the same stress value
- For  $\frac{r}{z} > 1.5$ , Westergaard's eqn gives slightly higher value compared to Boussinesq eqn.

### → Newmark's Method.

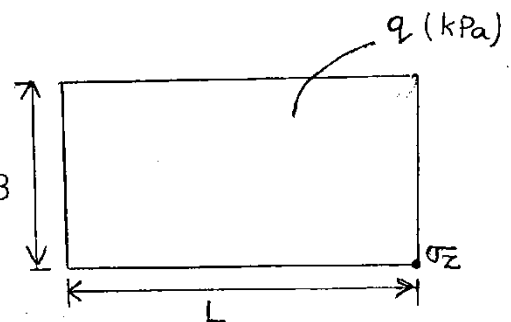
- to find  $\sigma_z$  at corner of rectangular loaded area

$$\sigma_z = I q$$

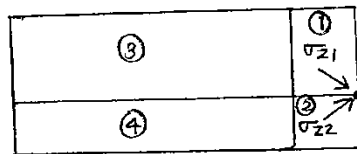
$I \rightarrow$  influence coefficient which depends on  $m$  &  $n$  coefficients.

$$m = \frac{L}{z} \quad \& \quad n = \frac{B}{z}$$

$m$  &  $n$  values are available in the form of charts or tables

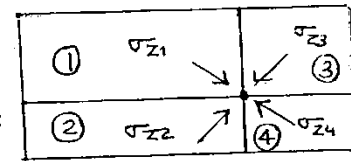


Pt. outside footing:



$$\sigma_z = \sigma_{z3} + \sigma_{z4} - \sigma_{z1} - \sigma_{z2}$$

Pt. inside footing:

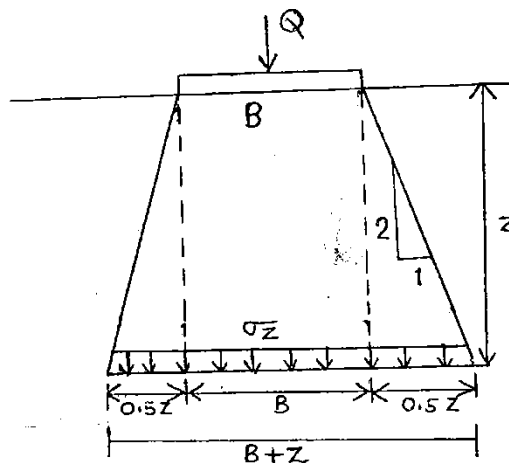
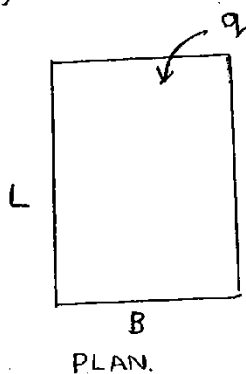


$$\sigma_z = \sigma_{z1} + \sigma_{z2} + \sigma_{z3} + \sigma_{z4}$$

### → Approximate Method:

- Load dispersion angle is assumed to be as 2v to 1H or 1:2 load dispersion.

(H:V)



$$Q = LBq$$

$$\sigma_z = \frac{Q}{(B+z)(L+z)} ;$$

for rectangular footing

$$\sigma_z = \frac{Q}{(B+z)^2} ;$$

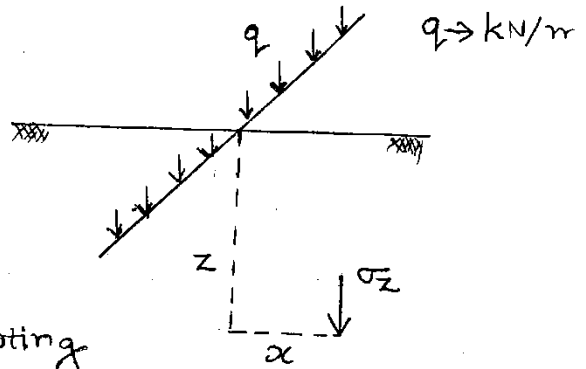
for square foot

$$\sigma_z = \frac{Q}{(B+z)^1} ; \text{ for continuous footing}$$

$$Q = (B \times 1) q ; Q \rightarrow \text{load per unit length.}$$

→ Vertical Stress due to Line Load,

$$\sigma_z = \frac{q}{z} \frac{2}{\pi} \left[ \frac{1}{1 + \left( \frac{\alpha}{z} \right)^2} \right]^2$$

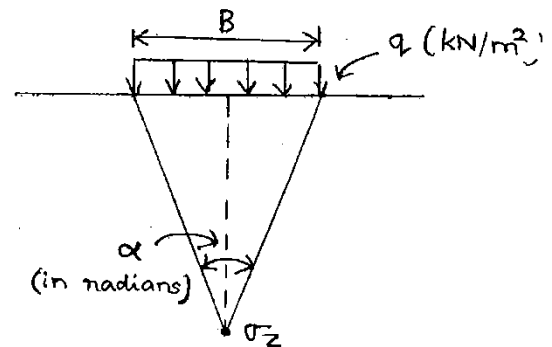


Eg:- Railway lines, sewer pipes etc.

→ Vertical Stress due to Strip footing  
(Continuous footing)

$$\sigma_z = \frac{q}{\pi} (\alpha + \sin \alpha)$$

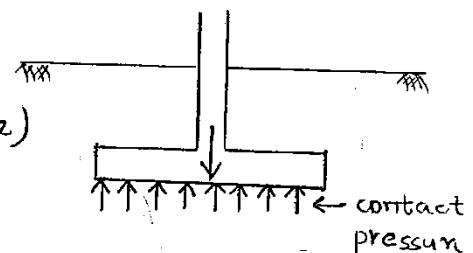
(below CG of loading)



→ Contact Pressure

Variation depends upon :-

- (i) Type of footing (rigid or flexible)
- (ii) Type of soil.

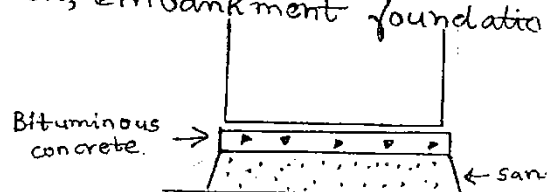


Rigid Footing (Eg: RCC footing)

Flexible Footing

- (i) uniform settlement.
- (ii) non-uniform contact pressure
- (i) Non uniform settlement.
- (ii) Uniform contact pressure.

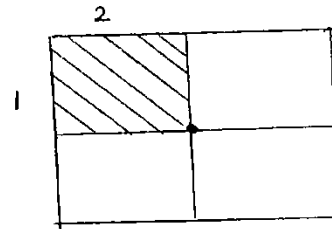
Flexible footing :- oil tank foundation, embankment foundation



For the hatched rectangle,

$$l = 2m, b = 1m.$$

$$\left. \begin{aligned} m &= \frac{l}{Z} = 0.4 \\ n &= \frac{b}{Z} = 0.2 \end{aligned} \right\} I = 0.0328$$



$$\sigma_z = 4 \cdot Iq = 4 \times 0.0328 \times 8 = \underline{\underline{1.05 \text{ t/m}^2}}$$

To find  $\sigma_z$  below the corner,

$$\left. \begin{aligned} m &= \frac{L}{Z} = \frac{4}{5} = 0.8 \\ n &= \frac{2}{5} = 0.4 \end{aligned} \right\} I = 0.0931.$$

$$\sigma_z = Iq = 0.0931 \times 8 = \underline{\underline{0.74 \text{ t/m}^2}}$$

$\sigma_{z1}$  = stress under column ①, due to  $q_1$

$\sigma_{z2}$  = stress under column ① due to  $q_2$

$\sigma_{z3}$  = " due to  $q_3$ .

$$Q_1 = \frac{200}{3} = 66.67 = Q_2 = Q_3.$$

$$Z = 2m, r = 0. (\text{for } \sigma_{z1}).$$

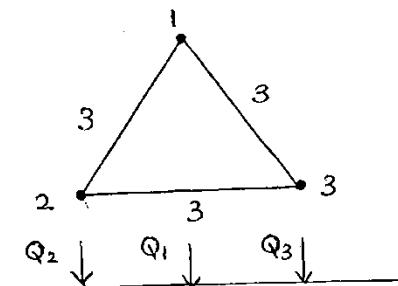
$$\sigma_{z1} = \frac{66.67}{4} \cdot \frac{3}{2\pi} = 7.96 \text{ t/m}^2$$

$$\sigma_{z2} = \frac{Q_2}{Z^2} \cdot \frac{3}{2\pi} \left( \frac{1}{1 + \left(\frac{r}{Z}\right)^2} \right)^{5/2}$$

$$= \frac{66.67}{4} \cdot \frac{3}{2\pi} \left( \frac{1}{1 + \left(\frac{3}{2}\right)^2} \right)^{5/2}$$

$$= \underline{\underline{0.418 \text{ t/m}^2}} = \sigma_{z3}$$

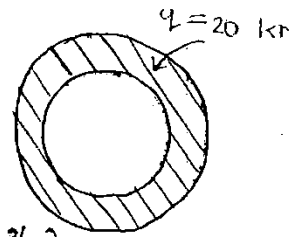
$$\begin{aligned} \sigma_z &= \sigma_{z1} + \sigma_{z2} + \sigma_{z3} = 7.96 + 0.418 \times 2 \\ &= \underline{\underline{8.796 \text{ t/m}^2}} \end{aligned}$$



4.

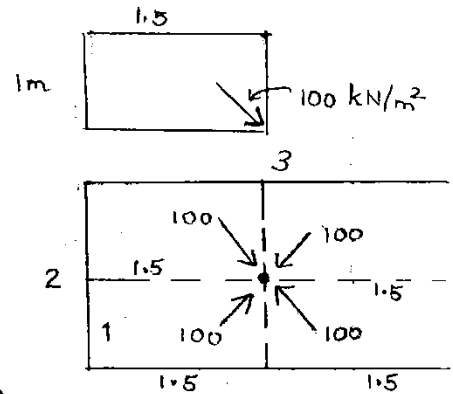
$$\sigma_z = q \left\{ 1 - \left( \frac{1}{1 + \left( \frac{r}{z} \right)^2} \right)^{3/2} \right\}$$

$$\begin{aligned} \sigma_z &= 20 \left\{ 1 - \left( \frac{1}{1 + \left( \frac{4}{10} \right)^2} \right)^{3/2} \right\} - 20 \left\{ 1 - \left( \frac{1}{1 + \left( \frac{3}{10} \right)^2} \right)^{3/2} \right\} \\ &= \underline{\underline{1.56 \text{ kN/m}^2}} \end{aligned}$$



5.

$$\sigma_z = 4 \times 100 = \underline{\underline{400 \text{ kN/m}^2}}$$



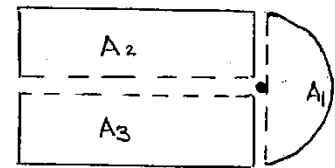
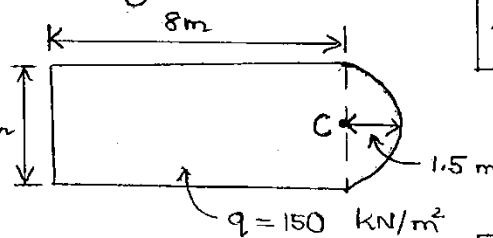
Q. A footing is shown in fig below.

Determine the vertical stress at the point C shown in the fig. at a depth of

3 m. Use the following coefficients.

$$m = 0.5 \quad n = 2.67 \quad I = 0.1365$$

$$m = 1 \quad n = 2.67 \quad I = 0.2028$$



Stress due to area A<sub>1</sub>: (semicircular area)

$$\begin{aligned} \sigma_z &= \frac{1}{2} \cdot q \left( 1 - \left\{ \frac{1}{1 + \left( \frac{r}{z} \right)^2} \right\}^{3/2} \right) = \frac{1}{2} \times 150 \left( 1 - \left( \frac{1}{1 + \left( \frac{1.5}{3} \right)^2} \right)^{3/2} \right) \\ &= 21.33 \text{ kN/m}^2 \end{aligned}$$

Stress due to A<sub>2</sub>:

$$\left. \begin{aligned} m &= \frac{L}{z} = \frac{8}{3} = 2.67 \\ n &= \frac{B}{z} = \frac{1.5}{3} = 0.5 \end{aligned} \right\} I = 0.1365$$

$$\sigma_{z2} = Iq = 20.47 \text{ kN/m}^2 = \sigma_{z3}$$

$$\sigma_z = \sigma_{z1} + \sigma_{z2} + \sigma_{z3} = \underline{\underline{62.28 \text{ kN/m}^2}}$$

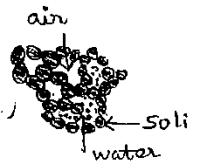
## 11. CONSOLIDATION

### → Compression

Compressibility is the property of soil due to which compression occurs. Clay has relatively more compressibility compared to gravel, sand and silt.

Compression of soil is due to:-

- compression and escape of air from voids → Compaction
- escape of pore water; whereas compression of solid grains and water is negligible. → consolidation



∴ compression depends upon volume of voids. More the vol. of voids, more will be the compression.

### → Consolidation

- It is the compression of soil due to expulsion of water under static long term loading.
- It is a slow process.
- It occurs in low permeable soil.

$u$  = pore water pressure (or)

Hydrostatic pressure.

$\bar{u}$  = excess pore water pressure (or)

hydrodynamic pressure.

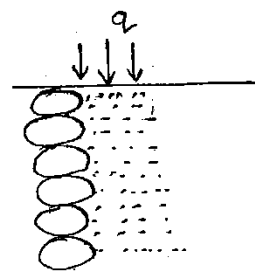
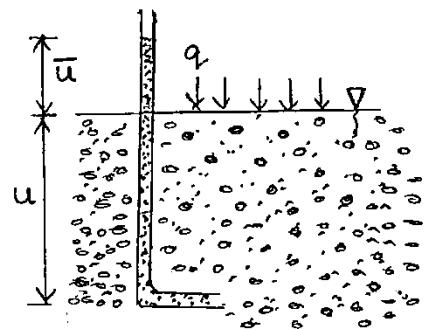
Hydro static → due to self wt.

Hydrodynamic → due to external load.

$k_w$  → stiffness of water under confined condition

$k_s$  → stiffness of soil grain structure.

$$k_w \gg k_s$$



At beginning,  $\bar{u} = q$

At end of consolidation,  $\bar{u} = 0$

Immediately after  
Loading

$$\begin{aligned}\bar{u} &= q \\ \sigma' &= 0 \\ \bar{u} + \sigma' &= q\end{aligned}$$

During Consolidation

$$\begin{aligned}\bar{u} &< q \\ \sigma' &> 0 \\ \bar{u} + \sigma' &= q\end{aligned}$$

At the end of  
consolidation

$$\begin{aligned}\bar{u} &= 0 \\ \sigma' &= q \\ \bar{u} + \sigma' &= q\end{aligned}$$

During consolidation, excess pore pressure ( $\bar{u}$ ) decreases, effective stress ( $\sigma'$ ) increases, but total stress ( $\sigma$ ) remains constant.

th Sept,  
TURDAY

During Consolidation,

Properties which  
decrease.

$\bar{u}$ , Permeability,  
Compressibility,  
water content,  
void ratio.

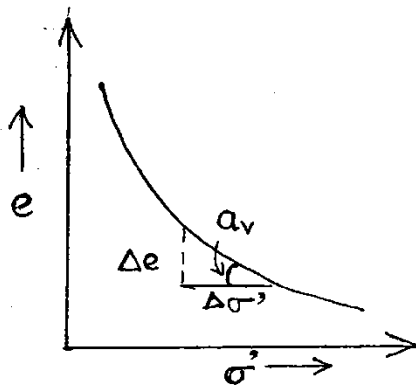
Properties which  
increase

$\sigma'$ ,  $\gamma_d$ ,  
settlement,  
shear strength.

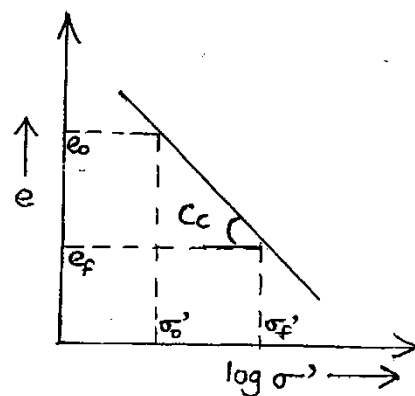
Properties which  
remains same

$\sigma$ ,  $S_r (= 100\%)$

→  $e - \sigma'$  curve.



→  $e - \log \sigma'$  curve



\* Coefficient of Compressibility,  $a_v$

$$a_v = \frac{\Delta e}{\Delta \sigma'}$$

\* Compression Index,  $C_c$

(44)  
45

Coefficient of compression index,  $C_c = \frac{e_0 - e_f}{\log \left( \frac{\sigma_f'}{\sigma_0'} \right)}$

$$C_c = \frac{\Delta e}{\log_{10} \left( \frac{\sigma_f'}{\sigma_0'} \right)}$$

$$\Rightarrow \Delta e = C_c \log_{10} \left( \frac{\sigma_f'}{\sigma_0'} \right)$$

$C_c = 0.007 (w_L - 10)$  ; for remoulded clay

$C_c = 0.009 (w_L - 10)$  ; for field consolidation  
(OR)  
normally consolidated clay

\* Coefficient of Volume Change (or)

Coefficient of Volume compressibility

$$m_v = \frac{\Delta V}{V_0 \cdot \Delta \sigma'}$$

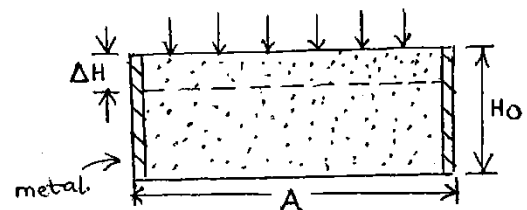
It is the volumetric strain per unit change of effective stress  
If soil is laterally confined (area remains same),

$$\frac{\Delta V}{V_0} = \frac{\Delta H}{H_0}$$

We have,  $V \propto 1 + e$

$$\frac{\Delta V}{V_0} = \frac{\Delta e}{1 + e_0}$$

$$\Rightarrow \frac{\Delta H}{H_0} = \frac{\Delta e}{1 + e_0}$$



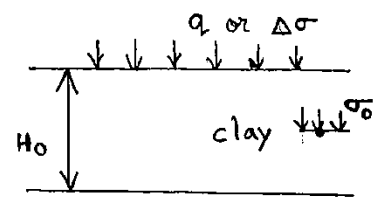
$$m_v = \frac{\Delta v}{v_o \cdot \Delta \sigma'} = \frac{\Delta e}{(1+e_o) \Delta \sigma'}$$

$$= \frac{a_v}{1+e_o} = \frac{\Delta H}{H_o \cdot \Delta \sigma'}$$

\* To find ultimate or final consolidation settlement,  $S_f$  or  $\Delta H$

$$(i) \frac{\Delta H}{H_o} = \frac{\Delta e}{1+e_o}$$

$$\therefore \Delta H \text{ or } S_f = H_o \left( \frac{\Delta e}{1+e_o} \right)$$



$$(ii) \Delta H \text{ or } S_f = H_o \cdot \frac{C_c}{(1+e_o)} \log_{10} \left( \frac{\sigma_F'}{\sigma_o'} \right)$$

$$\sigma_F' = \sigma_o' + \Delta \sigma'$$

$\sigma_o' \rightarrow$  original or initial effective stress in the clay  
(due to self weight) at the centre of clay

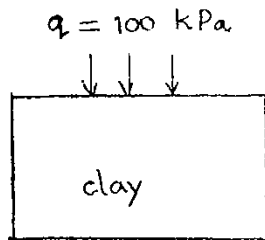
$$(iii) m_v = \frac{\Delta H}{H_o \cdot \Delta \sigma'}$$

$$\therefore \Delta H \text{ or } S_f = m_v \cdot H_o \cdot \Delta \sigma'$$

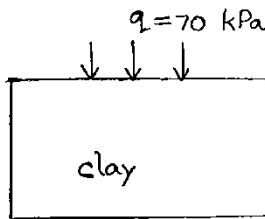
(ii)<sup>nd</sup> equation is always preferred. because for a given soil,  $a_v$  &  $m_v$  are not constant; these decrease with increase in  $\sigma'$ . But  $C_c$  is always constant.

$\rightarrow$  Depending upon Stress history, the States of Soil are:

- Normally Consolidated soil (NC soil)
- Over Consolidated soil (OC soil)
- Under Consolidated soil (UC soil)



At the end of consolidation,  $\sigma' = 100$  kPa  
(Pre consolidated stress,  $\sigma_c' = 100$  kPa)



Overconsolidated soil (or)  
preconsolidated soil.

Overconsolidated soil :- if the soil has ever been subjected to a pressure greater than existing pressure.

Normally consolidated soil :- if the soil has never been subjected to a pressure more than existing pressure.

Under consolidated soil :- when the soil is under consolidation.

→ Over Consolidation Ratio, OCR

$$OCR = \frac{\sigma_c'}{\sigma'}$$

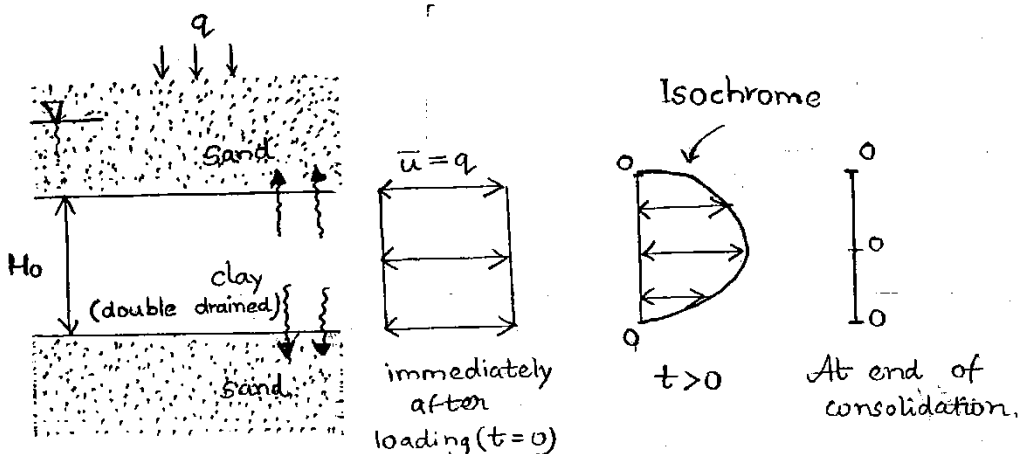
It is the ratio of preconsolidation stress to present effective stress in the soil.

For NC soil,  $OCR = 1$ .

For OC soil,  $OCR > 1$

For UC soil,  $OCR < 1$

→ Terzaghi's Theory of 1-D Consolidation:



Water tends to escape in vertical direction (to sand has higher permeability), one direction,  $\therefore$  called 1D consolidation.  
 Water near the sand escapes first (lesser drainage distance) and  $\bar{u}=0$ . Since there is sand in both sides of clay, it is called double drained clay.

\* Slope of Isochrone  $= \frac{\bar{u}}{z} = \frac{h}{z} = i = \text{hydraulic gradie.}$

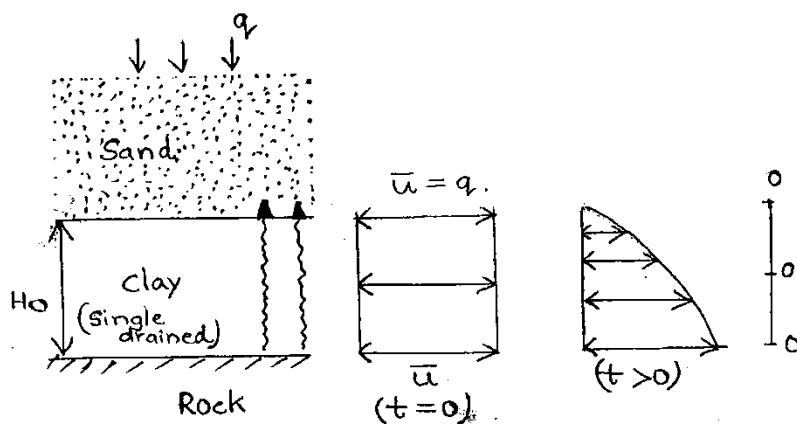
But  $\bar{u}$  varies with time and depth.  $\therefore$  slope is not constant.

\* Drainage path,  $d$

$$d = \frac{H_0}{2} ; \text{ for double drained condition}$$

$$d = H_0 ; \text{ for single drained condition}$$

Drainage path is the max distance that the water has to travel to escape.



$$\frac{\partial \bar{u}}{\partial t} = \frac{k}{m_v \gamma_w} \frac{\partial^2 \bar{u}}{\partial z^2}$$

DIFFERENTIAL EQUATION  
OF 1D CONSOLIDATION

$$\frac{\partial \bar{u}}{\partial t} = C_v \cdot \frac{\partial^2 \bar{u}}{\partial z^2}$$

→ Coefficient of Consolidation,  $C_v$

$$C_v = \frac{k}{m_v \gamma_w}$$

Units:  $\text{m}^2/\text{sec}$ ,  $\text{cm}^2/\text{sec}$

$$\frac{\partial \bar{u}}{\partial t} = C_v \frac{\partial^2 \bar{u}}{\partial z^2}$$

(46)  
47

Solution is given in terms of (i) Time factor,  $T_v$   
(ii) Degree of consolidation,  $U$

\* Time factor,  $T_v = \frac{C_v t}{d^2}$

$t \rightarrow$  time of consolidation.

\* Degree of consolidation,  $U = \frac{S}{S_f} \times 100$

$S \rightarrow$  settlement occurred upto certain time,  $t$

$S_f \rightarrow$  final settlement.

At beginning,  $S=0$  ;  $U=0$   $0 \leq U \leq 100\%$

At end,  $S=S_f$  ;  $U=100\%$

Also,  $U = \frac{\text{dissipated excess pore pressure}}{\text{initial excess pore pressure}} \times 100$

$$= \frac{\bar{u}_i - \bar{u}}{\bar{u}_i} \times 100$$

$\bar{u}_i \rightarrow$  initial excess pore pressure

$\bar{u} \rightarrow$  excess pore pressure after certain time,  $t$

or  $U = \frac{\sigma'}{\bar{u}_i} \times 100$  ;  $\sigma' = \bar{u}_i - \bar{u}$

\* Relation b/w  $U$  &  $T_v$

(i)  $T_v = \frac{\pi}{4} \left( \frac{U\%}{100} \right)^2$  ;  $U \leq 60\%$

(ii)  $T_v = 1.781 - 0.933 \log_{10}(100 - U\%)$  ;  $U > 60\%$

## → Consolidation Test (Oedometer Test)

- undisturbed sample is used
- diameter of sample  $\geq 3 \times$  thickness.

\* To find 'e' in Consolidation test:

(i) Change in void ratio method:-

Final moist void ratio,  $e_f = w_f G$

$$\frac{\Delta e}{1+e_f} = \frac{\Delta H}{H_f}$$

Initial void ratio,  $e_o = e_f \pm \Delta e$

(ii) Height of Solids method:-

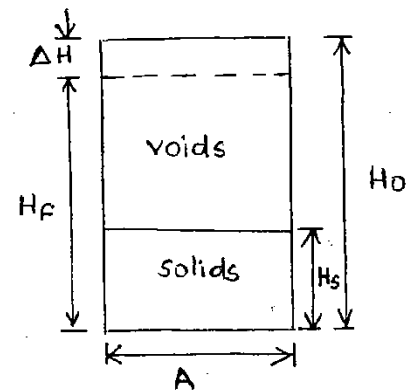
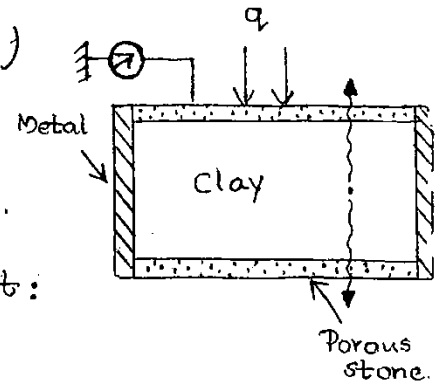
$H_s \rightarrow$  Height of solids

$$H_s = \frac{w_d}{G \gamma_w \cdot A}$$

$$e_o = \frac{H_o - H_s}{H_s}$$

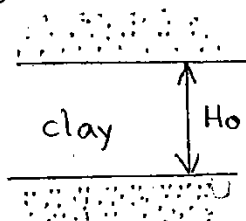
$$H_f = H_o - \Delta H$$

$$e_f = \frac{H_f - H_s}{H_s}$$

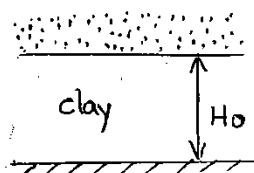


NOTE:

- ① For same loading and same clay properties, the ultimate consolidation settlement remains the same for both double drain clay condition and single drained clay condition.



$$d = \frac{H_o}{2}; S_{f1}$$



$$S_{f2}; d = H_o$$

$$S_{f1} = S_{f2}$$

$$\Delta H = H_o \left( \frac{\Delta e}{1+e_o} \right) \Rightarrow \Delta H \propto H_o$$

⑦ For a given clay,  $C_v$  is constant (assumed).

For a given clay, to undergo same degree of consolidation the time required for a double drained condition is  $\frac{1}{4}$ th time required for a single drained condition

$$T_v = \frac{C_v t}{d^2}$$

If  $C_v$  &  $U$  (or  $T_v$ ) are same,  $t \propto d^2 \Rightarrow \frac{t_1}{t_2} = \left(\frac{d_1}{d_2}\right)^2$

$$t \propto \frac{d^2 m_v}{k}$$

$$t = \frac{T_v d^2}{C_v} = \frac{T_v d^2 m_v \gamma_w}{k}$$

$\therefore$  For same degree of consolidation,  $t \propto \frac{d^2 m_v}{k}$

$$\frac{t_2}{t_1} = \left(\frac{d_2}{d_1}\right)^2 \left(\frac{m_{v2}}{m_{v1}}\right) \frac{k_1}{k_2}$$

5<sup>th</sup> Sept,  
MONDAY

P-58

Q1 From 1 to 2  $\text{kg/cm}^2$ ,  $\Delta H = 1 \text{ cm} \Rightarrow \Delta \sigma' = 2 - 1 = 1$ ;  $\frac{\sigma'_f}{\sigma'_o} = \frac{2}{1} = 2$

From 2 to 4  $\text{kg/cm}^2$ ,  $\Delta H = ? \Rightarrow \Delta \sigma' = 4 - 2 = 2$ ;  $\frac{\sigma'_f}{\sigma'_o} = \frac{4}{2} = 2$

$$\Delta H = H_0 \cdot \frac{C_c}{1+e_0} \log_{10} \left( \frac{\sigma'_f}{\sigma'_o} \right)$$

Since  $\frac{\sigma'_f}{\sigma'_o}$  ratio is same,  $\Delta H$  is also same.

$$\therefore \underline{\underline{\Delta H = 1 \text{ cm}}}$$

Q2 In  $t_1 = 4 \text{ years}$ ;  $S_1 = 80 \text{ mm}$

$t_2 = 9 \text{ years}$ ;  $S_2 = ?$

$$T_v = \frac{C_v t}{d^2}$$

$$\frac{\pi}{4} u^2 = \frac{C_v t}{d^2} \Rightarrow t \propto u^2$$

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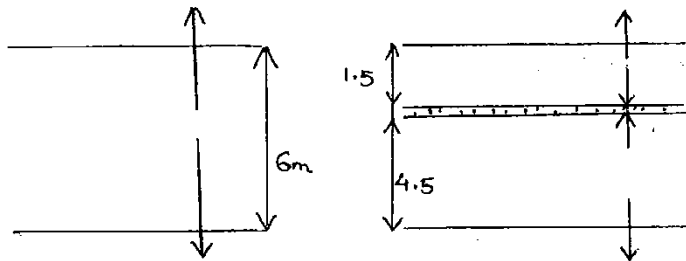
$$u = \frac{S}{S_f} \Rightarrow u \propto S$$

$$\therefore \boxed{t \propto S^2}$$

$$\frac{t_1}{t_2} = \left(\frac{S_1}{S_2}\right)^2 \quad (\text{valid only when } u < 60\%)$$

$$\frac{4}{9} = \left(\frac{80}{S_2}\right)^2 \Rightarrow S_2 = \frac{80 \times 3}{2} = \underline{\underline{120 \text{ mm}}}$$

3.



Two drainage paths.

4 drainage paths

But ultimate settlement remains the same.

4.

$$H_0 = 4 \text{ m}, C_c = 0.36$$

$$e_0 = 0.92$$

$$\sigma'_0 = \left(2 + \frac{4}{2}\right) \gamma' = \underline{\underline{37.2 \text{ kPa}}}$$

$$\Delta \sigma' = \frac{Q}{(B+z)^2}$$

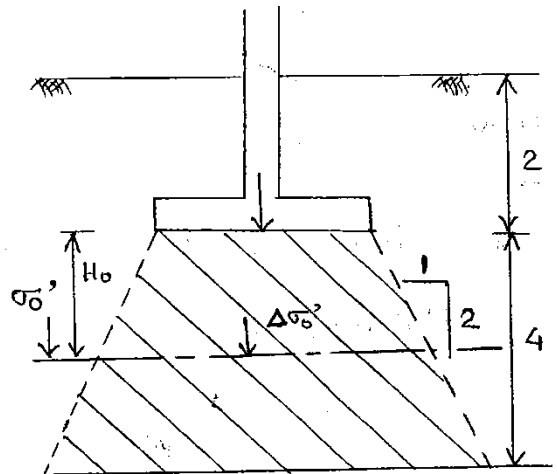
$z$ : distance b/w pt. where load is acting & pt. where  $\Delta \sigma'$  is required.

$$\Delta \sigma' = \frac{500}{(B+2)^2}$$

$$S_f = H_0 \cdot \frac{C_c}{1+e_0} \log_{10} \left( \frac{\sigma'_0 + \Delta \sigma'}{\sigma'_0} \right)$$

$$0.12 = 4 \times \frac{0.36}{1+0.92} \log_{10} \left( \frac{37.2 + \frac{500}{(B+2)^2}}{37.2} \right)$$

$$\Rightarrow \underline{\underline{B = 3.5 \text{ m}}}$$



05.  $H_0 = 4m$  ;

$$C_c = 0.009 (w_L - 10) = 0.495$$

$$e_0 = \frac{wG}{S_r} = 0.5 \times 2.65 = \underline{\underline{1.325}}$$

$$\begin{aligned} \sigma'_0 &= 2\gamma' + 2\delta' \\ &= 2(1.9 - 1) + 2(1.71 - 1) \\ &= \underline{\underline{3.2 \text{ t/m}^2}} \end{aligned}$$

For clay,  $\gamma_{sat} = \gamma_w \frac{(G + e_0)}{1 + e_0} = \underline{\underline{1.71 \text{ t/m}^3}}$ .

$$\Delta\sigma' = q = 4 \text{ t/m}^2$$

$$S_f = 4 \times \frac{0.495}{1 + 1.325} \log_{10} \left( \frac{3.2 + 4}{3.2} \right) = \underline{\underline{29.8 \text{ cm}}}$$

06.  $u_1 = 25\%$  ,  $t_1 = 10 \text{ min}$

$u_2 = 50\%$  ,  $t_2 = ?$

$$\frac{t_1}{t_2} = \left( \frac{25}{50} \right)^2 \quad (t \propto u^2)$$

$$\frac{10}{t_2} = \frac{1}{4} \Rightarrow t_2 = \underline{\underline{40 \text{ min}}}$$

07.  $U = \frac{\bar{u}_i - \bar{u}}{\bar{u}_i} \times 100 = \frac{2 - 0.6}{2} \times 100 = \underline{\underline{70\%}}$

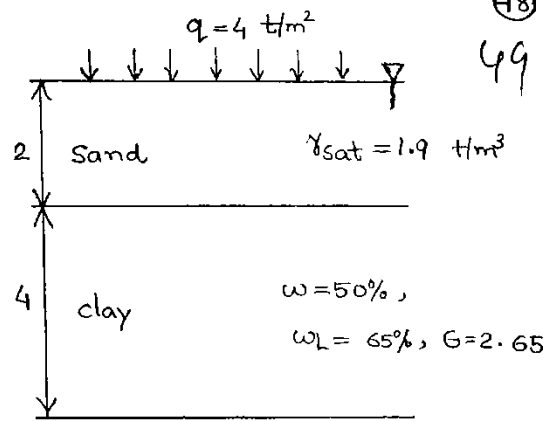
$$U = \frac{S}{S_f} \times 100$$

$$70 = \frac{S}{20} \times 100 \Rightarrow \underline{\underline{S = 14 \text{ mm}}}$$

08.  $t \propto \frac{d^2 m_v}{k}$

$$\frac{t_2}{t_1} = \left( \frac{d_2}{d_1} \right)^2 \left( \frac{m_{v2}}{m_{v1}} \right) \left( \frac{k_1}{k_2} \right)$$

$$= \left( \frac{2d_1}{d_1} \right)^2 \left( \frac{4m_{v1}}{m_{v1}} \right) \left( \frac{k_1}{3k_1} \right) = \frac{16}{3} \Rightarrow t_2 = \frac{16}{3} \times 15 = \underline{\underline{80 \text{ ye}}}$$



9. Lab specimen Field Clay

$$H_1 = 20 \text{ mm}$$

$$H_2 = 10 \text{ mm}$$

$$d_1 = \frac{H_1}{2} = 10 \text{ mm}$$

$$d_2 = \frac{H_2}{2} = 5000 \text{ mm}$$

$$U_1 = 50\%$$

$$U_2 = 50\%$$

$$t_1 = 45 \text{ min.}$$

$$t_2 = ?$$

For same  $C_v$  &  $u$ ,  $t \propto d^2$

$$\frac{t_2}{t_1} = \left(\frac{d_2}{d_1}\right)^2$$

$$\frac{t_2}{45} = \left(\frac{5000}{10}\right)^2$$

$$t_2 = \underline{\underline{21.4 \text{ years}}}$$

10. If field clay is single drained = 4 times of 21.4 years  
= 85.6 years

Q. 11. In the laboratory . . . . . Find the time required to undergo 70% consolidation of a field clay of 3m thick and double drained?

Lab Specimen:

$$H_1 = 25 \text{ mm}$$

$$d_1 = H_1 = 25 \text{ mm (single drained)}$$

$$U_1 = 50\%$$

$$t_1 = 11 \text{ min.}$$

Field Clay:

$$H_1 = 3 \text{ m}$$

$$d_1 = \frac{H_1}{2} = 1.5 \text{ m} = 1500 \text{ mm (double drain)}$$

$$U_2 = 70\%$$

$$t_2 = ?$$

For same  $C_v$ ,  $t \propto d^2 T_v$ .  
(same soil)

$$\frac{t_2}{11} = \frac{0.405}{0.197} \times \left(\frac{1500}{25}\right)^2$$

$$t_2 = \underline{\underline{56.5 \text{ days}}}$$

12. Double drainage

Single drainage

(49)

10

H

H

$$d_1 = \frac{H}{2}$$

$$d_1 = H$$

$$t_1 = 5 \text{ years.}$$

$$t_2 = 5 \text{ years.}$$

$$S_1 = 9 \text{ cm.}$$

$$S_2 = ?$$

$$S_f = 45 \text{ cm}$$

$$S_f = 45 \text{ cm.}$$

$$T_v = \frac{\pi}{4} U^2$$

$$\frac{C_v t}{d^2} = \frac{\pi}{4} U^2 \Rightarrow U \propto \frac{1}{d}$$

$$U \propto S \Rightarrow \boxed{S \propto \frac{1}{d}} \quad (\text{when } u < 60\%).$$

$$\frac{S_1}{S_2} = \frac{d_2}{d_1}$$

$$\frac{9}{S_2} = \frac{2H}{H} \Rightarrow S_2 = \underline{\underline{4.5 \text{ cm}}}$$

13. For  $t_1 = 4 \text{ years.}; S_1 = 80 \text{ mm.}$

For  $t_2 = 9 \text{ years.}; S_2 = ?$

$$U_1 = \frac{S_1}{S_f} \times 100 = 26.67\%$$

$$T_{v1} = \frac{\pi}{4} \left( \frac{U_1}{100} \right)^2 = \underline{\underline{0.0558}}$$

$$T_v = \frac{C_v t}{d^2} \Rightarrow t \propto T_v$$

$$\frac{t_2}{t_1} = \frac{T_{v2}}{T_{v1}}$$

$$\frac{9}{4} = \frac{T_{v2}}{0.0558} \Rightarrow T_{v2} = \underline{\underline{0.1255}}$$

$$\text{From the table given, } T_{v2} = \frac{\pi}{4} \left( \frac{U_2}{100} \right)^2$$

$$0.125 = \frac{\pi}{4} \times \left( \frac{U_2}{100} \right)^2 \Rightarrow U_2 = 40\%$$

$$U_2 = \frac{S_2}{S_f}$$

$$0.4 = \frac{S_2}{80} \Rightarrow S_2 = \underline{\underline{120 \text{ mm}}}$$

14.

$$\frac{T_{v2}}{T_{v1}} = \frac{t_2}{t_1}$$

$$\frac{T_{v2}}{0.0558} = \frac{25}{4} \Rightarrow T_{v2} = 0.348$$

$$\therefore U_2 = 65\% \quad (\text{from table})$$

$$U_2 = \frac{S}{300} \Rightarrow S = 300 \times 0.65 = \underline{195 \text{ mm}}$$

15

$$U_2 = \frac{S_2}{S_f} \times 100 = 70\%$$

$$\therefore T_{v2} = 0.403 \quad (\text{from table})$$

$$\frac{t_2}{t_1} = \frac{T_{v2}}{T_{v1}} \Rightarrow \frac{t_2}{4} = \frac{0.403}{0.0558}$$

$$\therefore t_2 = \underline{28.8 \text{ years}}$$

16.

Consolidation time is measured from the middle of construction period. (1958)

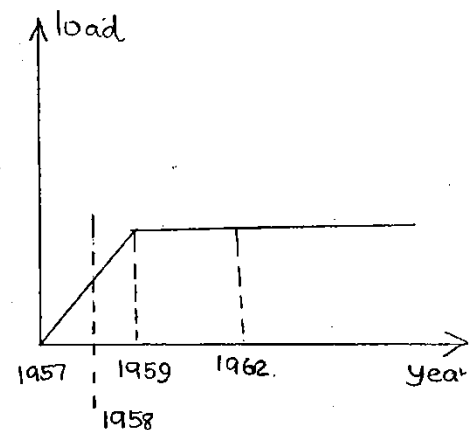
$$t = 1962 - 1958 = 4 \text{ years} ; S_1 = 90 \text{ mm}$$

$$t = 1967 - 1958 = 9 \text{ years} ; S_2 = ?$$

$$\frac{t_2}{t_1} = \left( \frac{S_2}{S_1} \right)^2$$

$$\frac{9}{4} = \left( \frac{S_2}{90} \right)^2$$

$$\underline{S_2 = 135 \text{ mm}}$$



17.

Immediately after loading

$$\sigma = q + 5\gamma_{\text{sat}} + 3\gamma_{\text{sat}}$$

$$= 76 + 5 \times 18 + 3 \times 20$$

$$= 226 \text{ kPa.}$$

$$\text{Total } U = U_{\text{st}} + \bar{U}$$

$$= (5+3)10 + 76$$

$$= 156 \text{ kPa}$$

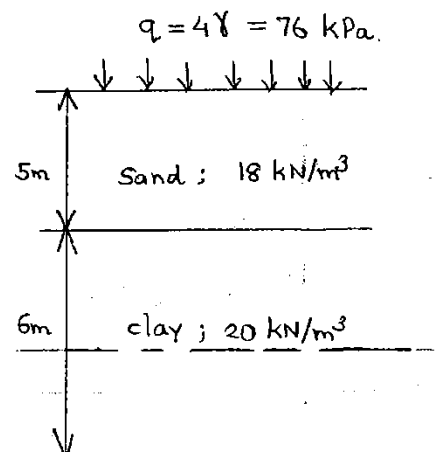
After many (at end of years consolidation)

$$\sigma = 226 \text{ kPa.}$$

$$\text{Total } \bar{U} = U_{\text{static}}$$

$$= 80 \text{ kPa.}$$

$$\sigma^2 = 226 - 80 = \underline{146 \text{ kPa}}$$



$$\begin{aligned}\sigma'_2 (\text{immediately after loading}) &= 5\gamma' + 3\delta' \\ &= 5 \times (18 - 10) + 3(20 - 10) \\ &= \underline{\underline{70 \text{ kPa}}}\end{aligned}$$

50

57

$$\sigma'_2 (\text{after many years}) = \sigma'_0 + \Delta\sigma = 70 + 76 = \underline{\underline{146 \text{ kPa}}}$$

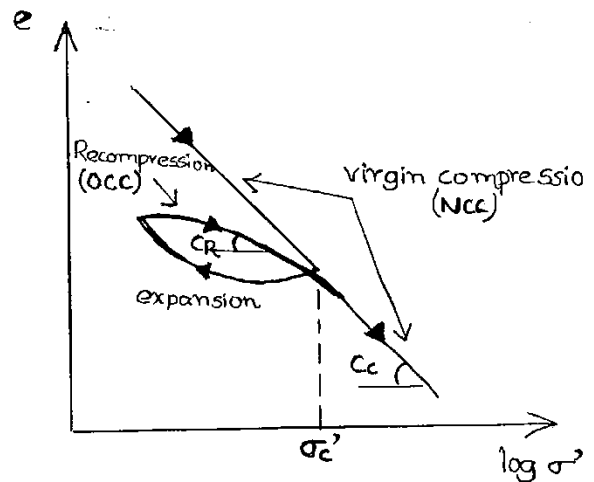
→ Recompression Index,  $C_R$

Slope of recompression curve (occ) is called  $C_R$ .

$$C_R \approx \frac{1}{5} C_c$$

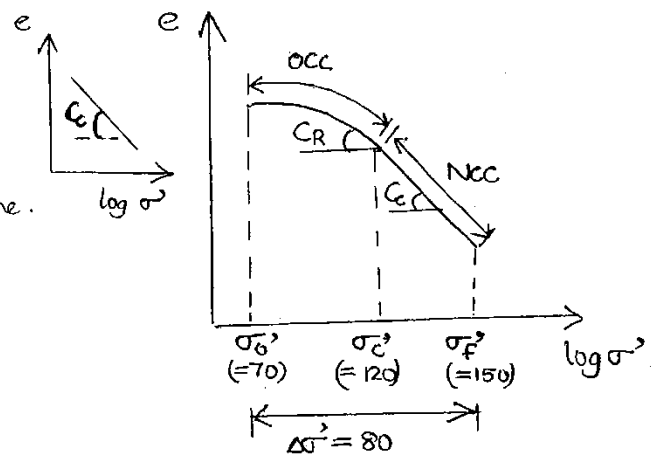
Straight line portion is called Virgin compression or NCC.

UCC cannot be marked in 'e-log  $\sigma'$ ' as eqbm void ratios are used (ie void ratio at the end of consolidation)



$$20. S_f = H_0 \times \frac{C_c}{1+e_0} \times \log_{10} \left( \frac{\sigma'_f}{\sigma'_0} \right)$$

Above eqn is used only when 'e-log  $\sigma'$ ' curve is a straight line.



$$\therefore S_f = H_0 \cdot \frac{C_R}{1+e_0} \log_{10} \frac{\sigma'_c}{\sigma'_0} +$$

$$H_0 \cdot \frac{C_c}{1+e_0} \log_{10} \frac{\sigma'_f}{\sigma'_c}$$

$$= 5 \times \frac{0.03}{(1+0.9)} \log_{10} \left( \frac{120}{70} \right) + 5 \times \frac{0.27}{(1+0.9)} \times \log_{10} \left( \frac{150}{120} \right)$$

$$= 0.087 \text{ m} = \underline{\underline{87.34 \text{ mm}}}$$

## → Stages of Consolidation

### (i) Initial Consolidation.

Settlement that occurs immediately after loading due to elastic nature and escape of air.

### (ii) Primary Consolidation

Due to expulsion of pore water

### (iii) Secondary Consolidation (Creep)

due to <sup>plastic</sup> readjustment of particles and escape of some double layer water or highly viscous water.

## → Elastic (or Immediate) Settlement :

$$S_i = \frac{q_n}{E_s} \cdot B \cdot (1 - \mu^2) \cdot I$$

where  $q_n \rightarrow$  net pressure intensity.

$E_s \rightarrow$  Young's Modulus of Soil.

$\mu \rightarrow$  Poisson's Ratio of Soil.

$B \rightarrow$  Characteristic linear dimension

(usually width of footing or diameter of footing)

$I \rightarrow$  Influence factor

Influence factor, (I) depends on stiffness, shape,  $\frac{L}{B}$  ratio of footing and location of point.

NOTE: The immediate settlement of a rigid footing is about 0.8 times the maximum settlement of an equal flexible footing (at the centre).

For a circular footing,

— Flexible

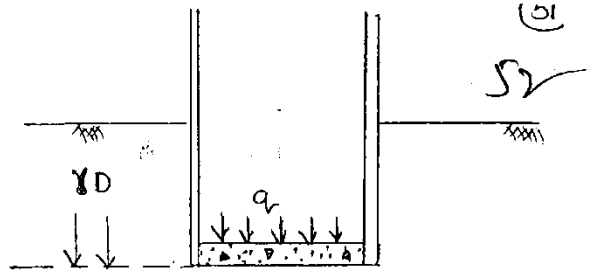
Centre = 1.0

Corner = 0.64 Average = 0.8

— Rigid

0.8

$$q_n = q - \gamma D$$



21. Oil tank foundation  $\rightarrow$  flexible footing.  
 $I_{(\text{centre})}$  for circular flexible footing = 1.

$$q_n = q - \gamma D = 250 - 22 \times 3 = 184 \text{ kN/m}^2$$

$$B = \text{diameter} = 20 \text{ m.}$$

$$u = 0.45$$

$$\Rightarrow S_i = \frac{q_n B (1-u^2) I}{E_s} = \frac{184 \times 20 (1-0.45^2) \times 1}{6 \times 10^4} = 0.04891 \text{ m} = \underline{\underline{48.9 \text{ mm}}}$$

Q. The average effective overburden pressure on a 10m thick saturated clay layer is 150 kPa. Consolidation test on an undisturbed soil sample taken from clay layer showed that void ratio decreased from 0.6 to 0.5, By increasing the stress intensity from 100 kPa to 300 kPa. Determine the initial void ratio of clay layer. Also determine the total consolidation settlement of the clay layer due to construction of a structure imposing additional stress intensity of 200 kPa.

$$C_c = \frac{\Delta e}{\log \frac{\sigma'_f}{\sigma'_o}} = \frac{0.6 - 0.5}{\log_{10} \left( \frac{300}{100} \right)} = \underline{\underline{0.209.}}$$

$$C_c = \frac{0.6 - e}{\log_{10} \frac{150}{100}} \Rightarrow e = \underline{\underline{0.563}}$$

$$\Delta H = H_o \cdot \frac{C_c}{1+e_o} \log_{10} \left( \frac{\sigma'_o + \Delta \sigma'}{\sigma'_o} \right) = 10 \times \frac{0.209}{1+0.563} \log_{10} \left( \frac{150 + 200}{150} \right) = \underline{\underline{0.492 \text{ m}}}$$

16<sup>th</sup> Sept,  
TUESDAY

## 12. COMPACTION

- Compaction of soil is due to compression and escape of air.
- It is a quick process.
- under short term loading, moving loads etc

→ Effect of Compaction:

- shear strength increases.
- compressibility decreases
- permeability decreases.

② During compaction, some amount of water is generally added to have a lubrication effect b/w the particles to facilitate easy compaction.

→ Compaction Tests:

The purpose of compaction test is :

- to find omc
- to find compactive energy.

1. IS Light Compaction Test (Std. Proctor's test)

This test is performed for ordinary roads, earthen dams.

2. IS Heavy Compaction Test (Modified Proctor's test)

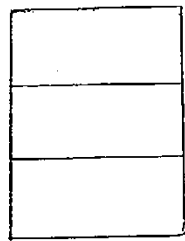
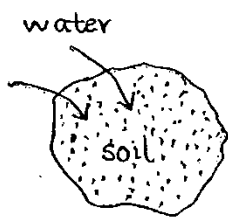
This test is performed for expressways, runways etc

	Wt. of Rammer	Ht. of fall.	No. of blow per each layer	No. of Layers
Heavy test	4.90 kg	45 cm	25	5
Light test	2.60 kg	31 cm	25	3

① Total energy ratio =  $\frac{4.90 \times 45 \times 25 \times 5}{2.60 \times 31 \times 25 \times 3} = \underline{\underline{4.55}}$

② Mould Capacity = 1 L generally or 2.25 L.  
(if soil has % retc on 4.75 mm > 20%)

For 1 L mould → 25 blows per each layer } for both tests.  
For 2.25 L mould → 56 blow per each layer }



Mould.

$W$  = wt. of soil

$V$  = vol. of soil.

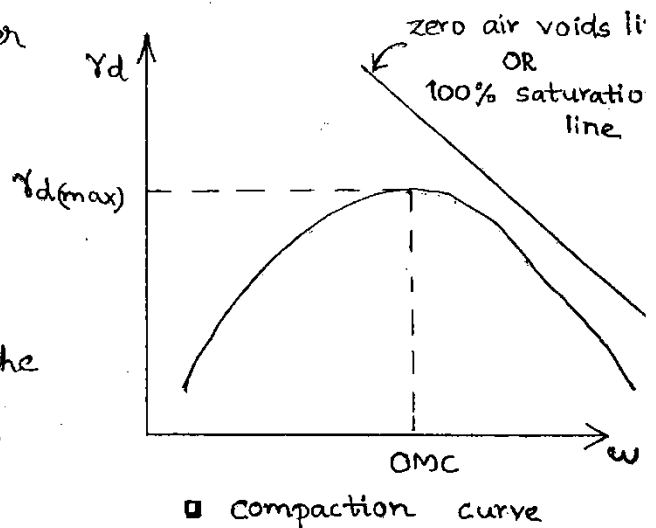
$$\gamma = \frac{W}{V}$$

$w$  → obtained by oven drying.

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

The test is repeated for <sup>diff</sup> water contents and  $\gamma_d$  is obtained in each case. A graph is plotted b/w  $\gamma_d$  &  $w$ .

OMC:— Optimum Moisture <sup>Content</sup> is the water content at which max. dry density is obtained.



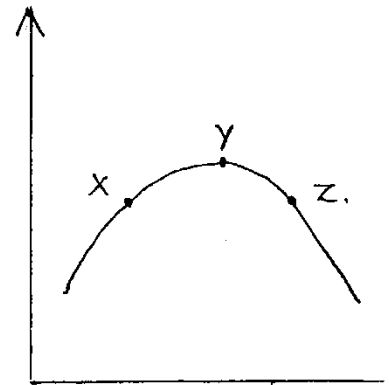
$$\gamma_d = \frac{(1 - n_a) G \gamma_w}{1 + wG} ; n_a = \% \text{ air voids} \rightarrow \text{Equation of Compaction cur}$$

$$(\gamma_{dmax})_{theo.} = \frac{G \gamma_w}{1 + wG} \rightarrow \text{Equation of Zero Air Voids line}$$

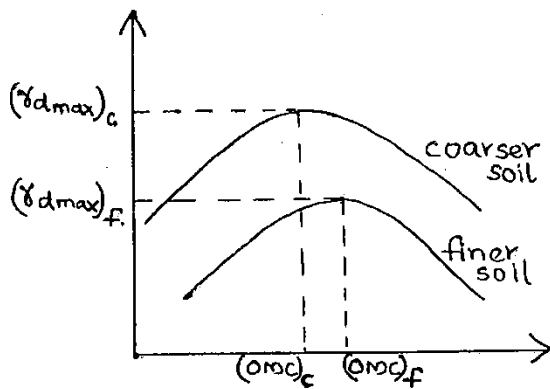
- Zero air voids line is used to compare and understand the level of compaction.

-  $K$  at  $Y$  is least (as least no. of voids due to optimum compaction)

-  $K$  at  $Z$  is relatively less than  $K$  at  $X$ .



\* Same Test but soils are Different

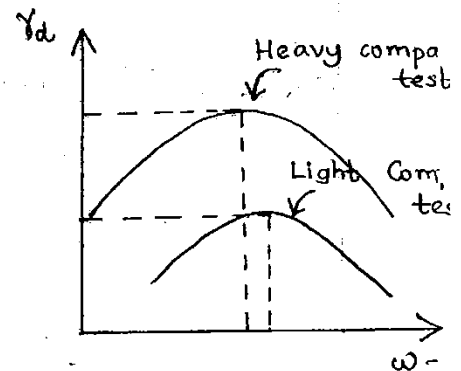


Finer soil has relatively more  $wmc$  and less  $(\gamma_d)_{max}$  compared to coarser soil.

Finer soils have more surface area and hence more  $wmc$ . Also,  $\gamma_d = \frac{G\gamma_w}{1+e} \Rightarrow$  finer soils having larger void ratio ( $e$ ) will be having lesser  $(\gamma_d)_{max}$ .

\* Same soil but tests are Different.

As the compactive energy increases,  $\gamma_{dmax}$  increases but  $wmc$  decreases.

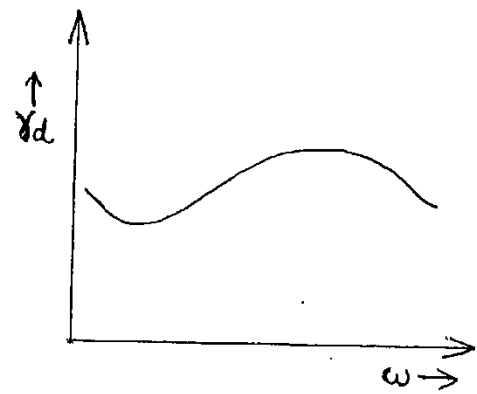


→ Factors affecting Compaction:

- water content ( $w.c$ )
- compactive energy
- type of soil.

In the case of pure sand without fines, there is no well defined OMC and the curve is shown below.

∴ For the above soil, the compaction curve is not useful.



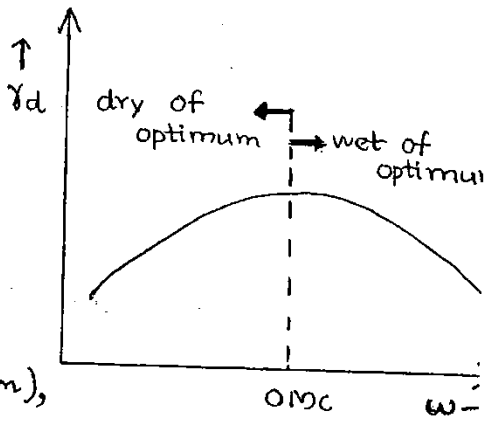
Relative density (or density index) is used to indicate the level of compaction achieved.

### Dry of Optimum

- Flocculent struct.
- more shear strength
- more swelling type

### Wet of Optimum

- dispersed struct.
- less shear strength
- less swelling type.



- To avoid swelling of soil (below the floors, pavements, core of earthen dam), soil is compacted wet of optimum.

- To have more strength (road embankments & casing of earthen dams), the soil is compacted dry of optimum.

- Placement water content :- w/c actually used at site

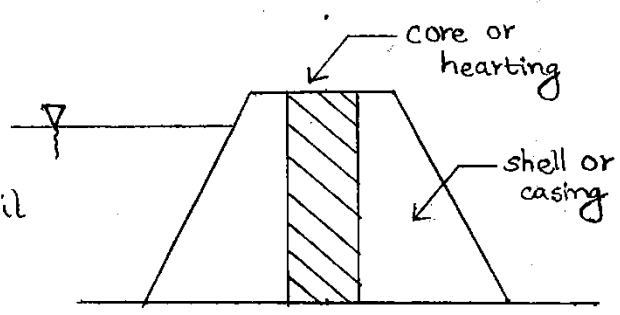
### → Earthen Dam:

#### \* Core :-

- to check seepage
- made up of impermeable soil
- wet of optimum (clay)

#### \* Shell :-

- to provide stability
- made up of soil other than clay.
- dry of optimum.



## → Compaction Equipment :

- Tampers → manual compaction (for inaccessible areas, trenches, behind retaining walls)
- Smooth wheel roller → to have smooth surface.
- Pneumatic Tyred roller → for all soils
- Sheep foot roller → best suitable for clays
- vibratory roller → best suitable for sands

Kneading action : best for compaction of clay.

Vibratory : best for compaction of sand.

## → Relative Compaction

$$\text{Relative compaction} = \frac{\gamma_d \text{ of field}}{\gamma_{d \max} \text{ in lab}} \times 100$$

Generally 90-95% is acceptable.

## → Proctor's Needle

To measure in-situ w.c and  $\gamma_d$  (approximate)

P-64

01.  $\gamma_d = 1.8 \text{ g/cc} ; w = 16\% ; G = 2.65$

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

$$1.8 = \frac{2.65}{1+e} \Rightarrow e = 0.472$$

$$e = \frac{wG}{S_r} \Rightarrow 0.472 = \frac{0.16 \times 2.65}{S_r}$$

$$\therefore S_r = \underline{\underline{89.7\%}}$$

$$a_c + S_r = 100\%$$

$$n_a = n_{ac}$$

$$\therefore a_c = \underline{\underline{10.3\%}}$$

$$= \frac{e}{1+e} \cdot 10.3 = \underline{\underline{3.27\%}}$$

$$(\gamma_{dmax})_{theo.} = \frac{G\gamma_w}{1+wG} = \underline{\underline{1.86 \text{ g/cc}}}$$

(54)

55

2. Vol. of soil = volume of cutter

$$= \frac{\pi}{4} d^2 h =$$

$$\text{wt. of soil} = 30.10 - 10.8 = 19.30 \text{ N.}$$

$$= 0.0193 \text{ kN}$$

$$\gamma_d = \frac{\gamma}{1+w} = \frac{w/V}{1+w} = \frac{13.65}{1+0.122}$$

$$= 12.16 \text{ kN/m}^3.$$

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

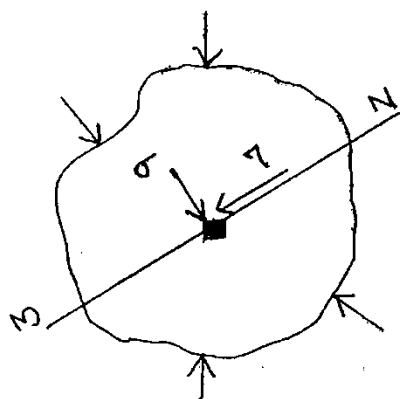
$$12.16 = \frac{2.65 \times 9.81}{1+e} \Rightarrow e = \underline{\underline{1.136}}$$

13.  $\swarrow S_r$  100% saturation line &  $\nwarrow n_a$  0% air voids line are same.
- $\swarrow S_r$  95% saturation line & 5% air voids line are different.  
 $\searrow n_a$

$$\underline{\underline{S_r + a_c = 100\%}}$$

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TUESDAY

# 13. SHEAR STRENGTH



$\sigma$  or  $\sigma_n \rightarrow$  Normal Stress.

$\tau \rightarrow$  Shear Stress

3 - Principal planes,  $\perp^n$  to each other

3 - Principal Stresses,  $\perp^n$  to each other.

$\sigma_1, \sigma_2, \sigma_3 \rightarrow$  Principal stresses. ( $\tau = 0$  in principal plane)

$$\sigma_1 \geq \sigma_2 \geq \sigma_3$$

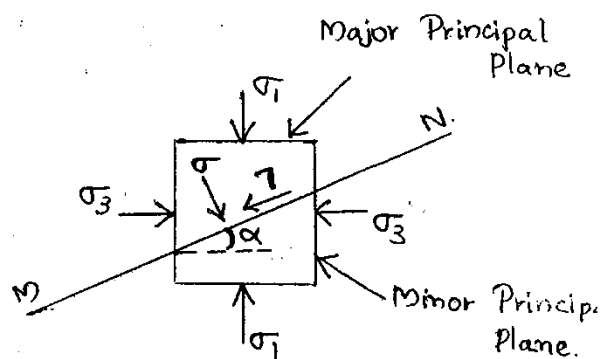
$\sigma_1 \rightarrow$  Major Principal Stress

$\sigma_2 \rightarrow$  Intermediate Principal Stress

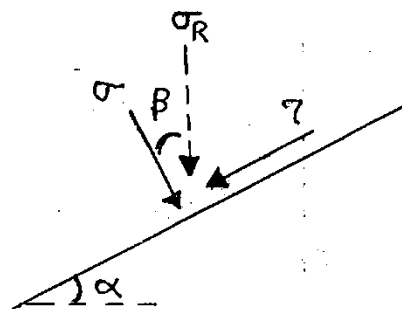
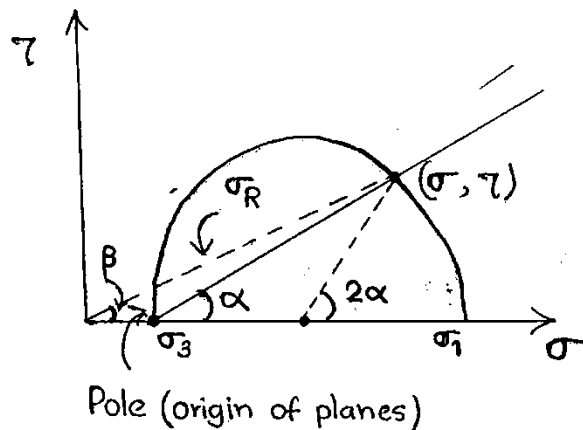
$\sigma_3 \rightarrow$  Minor Principal Stress

Analytical:

$\sigma = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha$
$\tau = \frac{\sigma_1 - \sigma_3}{2} \sin 2\alpha$



Graphical: (Mohr Circle)



$$\sigma_R = \text{Resultant stress} = \sqrt{\sigma^2 + \tau^2}$$

$\beta =$  angle of obliquity (angle b/w  $\sigma$  &  $\sigma_R$ )

③ For failure plane, angle of obliquity will be maximum (3)  
JB

$S \rightarrow$  shear strength or shear resistance

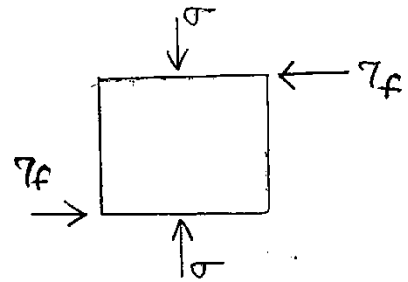
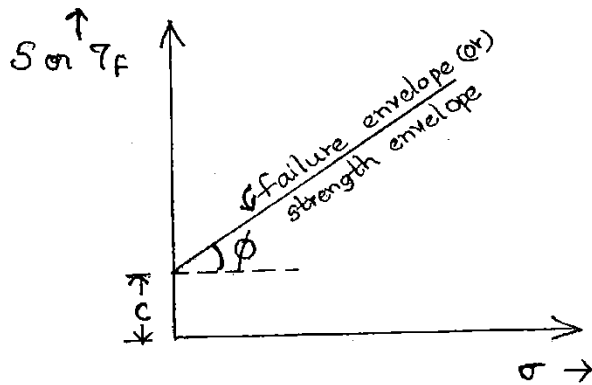
$\tau \rightarrow$  shear stress

$\tau_f \rightarrow$  failure shear stress.

- If  $\tau < S$ , no shear failure.

$$\tau_f = S$$

$\rightarrow$  Coulomb's Law



COULOMB'S EQUATION  $\Rightarrow$

$$S = c + \sigma \tan \phi$$

$\sigma \rightarrow$  Normal stress on the plane

$c \rightarrow$  Cohesion

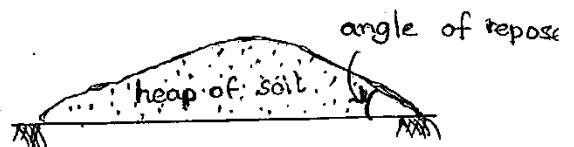
$\phi \rightarrow$  angle of internal friction (or) angle of shearing resistance.

• Angle of Repose :- Natural slope of a soil heap.

Angle of repose & angle of shearing resistance are not equal to each other.

However, for a loose sand, these two are nearly equal

Angle of Shearing Resistance : angle of inclination of failure envelope.

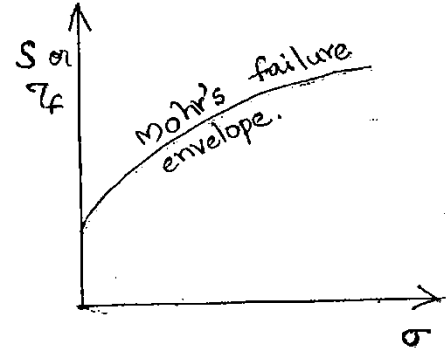


## → Mohr's Theory

- Soil fails essentially due to shear.
- Failure shear stress depends on  $\sigma$ .
- $\sigma_2$  has no effect on the behaviour of soil

$$S = f(\sigma)$$

- As per Mohr's theory,  
Mohr's failure envelope is curvilinear



\* Nowadays,

$$S = c + \sigma \tan \phi ; \text{ Mohr-Coulomb Equation.}$$

## → Terzaghi's Concept

- $S$  depends on effective normal stress ( $\sigma'$ )

$$\Rightarrow S = c' + \sigma' \tan \phi'$$

$c' \rightarrow$  effective cohesion (or drained cohesion)

$\phi' \rightarrow$  effective angle of internal friction.  
(or drained angle of internal friction)

- Another equation:-

$$S = c_u + \sigma \tan \phi_u$$

$\sigma \rightarrow$  total normal stress.

$c_u \rightarrow$  apparent cohesion (or) total cohesion (or) undrained cohesion.

$\phi_u \rightarrow$  apparent angle of int. friction (or)  
total angle of int. friction (or)  
undrained angle of int. friction.

$$S = c + \sigma \tan \phi$$

- general equation
- not used nowadays.

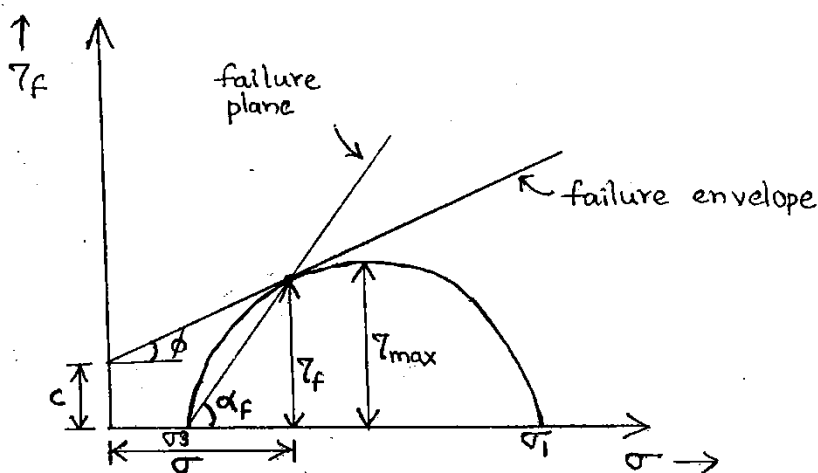
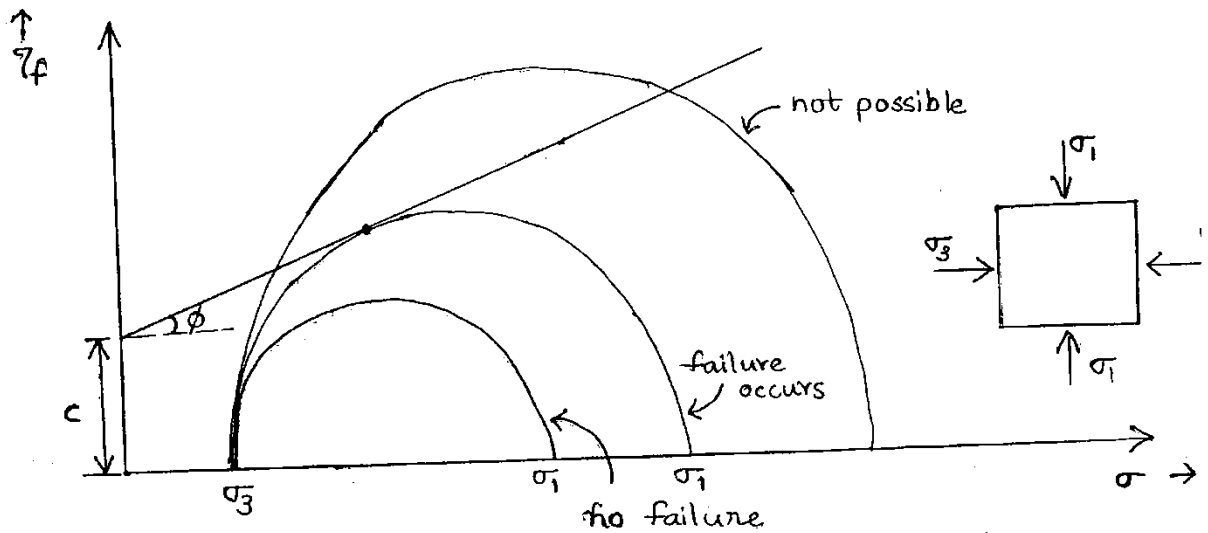
$$S = c' + \sigma' \tan \phi'$$

- in terms of effective stress.
- $c'$  &  $\phi'$  are called 'effective shear strength parameters'.
- used for drained conditions of soil.

(56)

$$S = c_u + \sigma \tan \phi_u$$

- in terms of total stress.
- $c_u$  &  $\phi_u$  are called 'total shear strength parameters'.
- used for undrained conditions of soil.

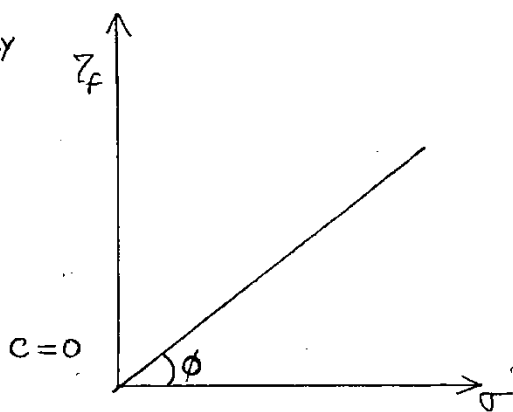


$\alpha_f \rightarrow$  failure plane inclination with major principal plane

$$\alpha_f = 45 + \phi/2$$

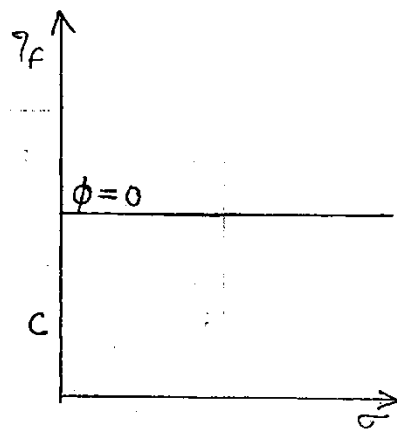
$$\tau_{max} = \frac{\sigma_1 - \sigma_3}{2} ; \tau_f \leq \tau_{max}.$$

17<sup>th</sup> Sept  
WEDNESDAY



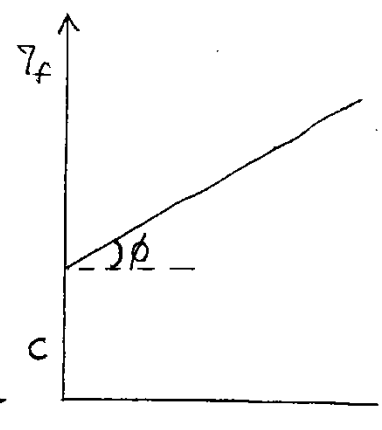
Cohesionless soil (or)  
Granular Soil.

Eg:- Dry sand.



Cohesive Soil.

Eg: Plastic soil.  
clay.



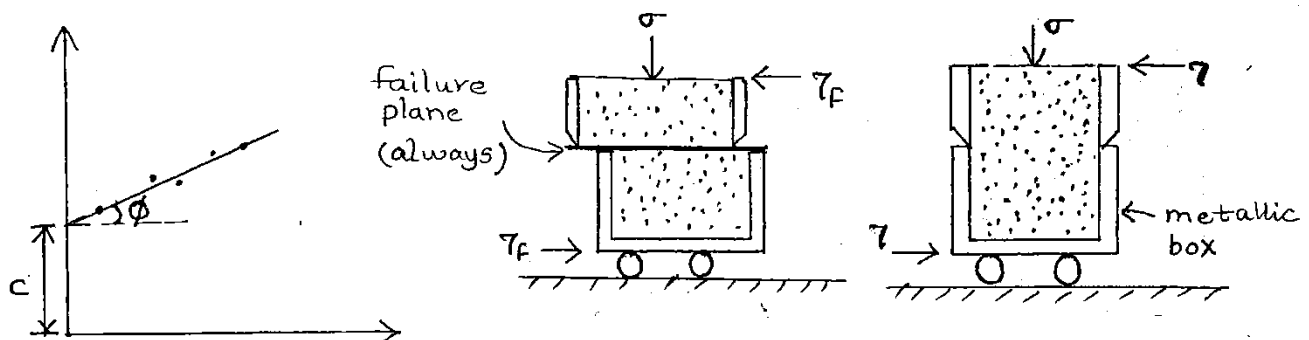
c-φ soil.

Eg: Clayey sand  
clayey gravel  
silty clay.

→ Tests to find c & φ Parameters

1. Direct Shear Test.
2. Triaxial Shear Test.
3. Unconfined Compression Test.
4. Vane Shear Test.

\* Direct Shear Test (or) Box Shear Test.



To find analytically c & φ :

$$\tau_f = c + \sigma \tan \phi$$

$$8 = c + 10 \tan \phi \rightarrow \textcircled{1}$$

$$15 = c + 20 \tan \phi \rightarrow \textcircled{2}$$

Solving we get c & φ values.

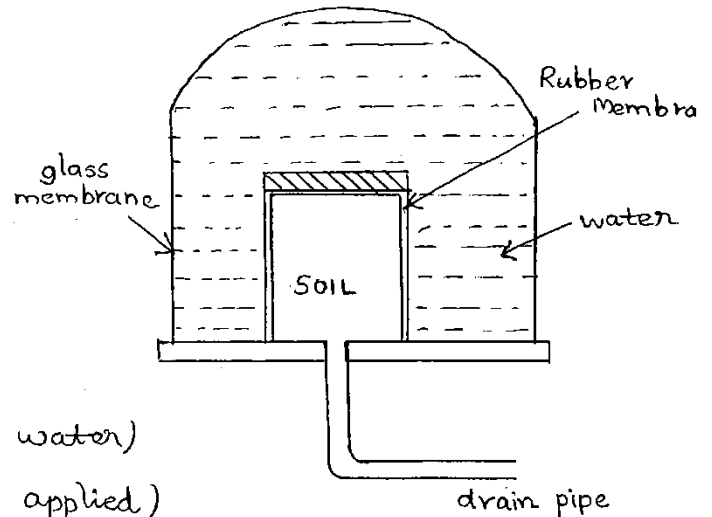
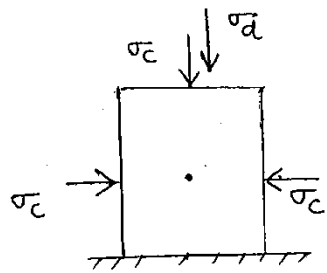
$\sigma$	$\tau_f$
10	8
20	15
30	22
40	29

- This test is generally used for cohesionless soils. (5)

- The main disadvantage of the test is that pore pressure cannot be measured directly.

- Depending on the drainage conditions provided, value of cohesion and angle of shearing resistance may be  $c'$  or  $c_u$  and  $\phi'$  or  $\phi_u$ .

### \* Triaxial Shear Test.

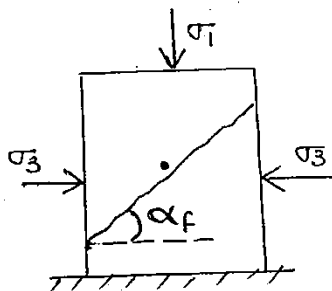


$\sigma_c$  : confining pressure (due to water)

$\sigma_d$  : Deviator stress (externally applied)

Water and wind always exerts normal force.

$\sigma_c$  = confining pressure or cell pressure or chamber pressure or consolidation pressure or around pressure



$$\sigma_3 = \sigma_c$$

$$\sigma_1 = \sigma_c + \sigma_d$$

$$\sigma_2 = \sigma_c$$

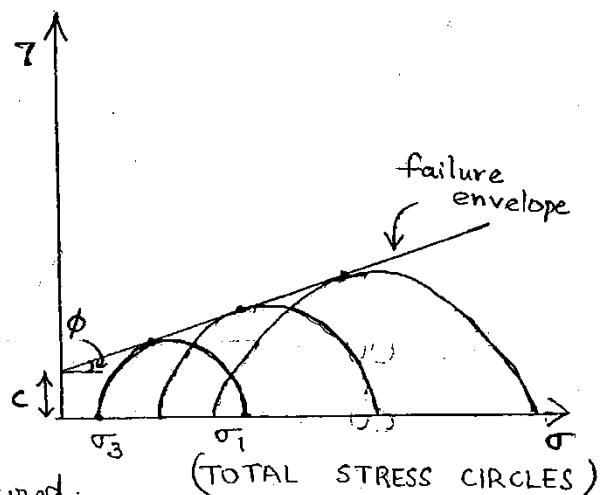
$\sigma_3$	$\sigma_1$	$u$
10	19	5
20	36	9
30	54	13
40	70	18

Keeping  $\sigma_3$  constant, determine the deviator stress required to cause shear failure. Using  $\sigma_d$ , determine  $\sigma_1$

- Open the valve of drain pipe to drain out pore water, which gives  $c'$  &  $\phi'$

- Close the drain pipe valve to obtain  $c_u$  &  $\phi_u$  (undrained)

When the test is performed under undrained conditions, pore water pressure can be measured.



$$\sigma_3' = \sigma_3 - u \quad \& \quad \sigma_1' = \sigma_1 - u.$$

- using  $\sigma_3'$  &  $\sigma_1'$ , draw the effective stress circles. A failure envelope tangential to the effective stress circles is drawn and  $c'$  &  $\phi'$  are obtained.

- Pore pressure developed in the case of drained test is zero

### → Plastic Equilibrium

A material is said to be in plastic equilibrium if every point of soil is at verge of failure.

\* Plastic Equilibrium equations:

$\sigma_1 = \sigma_3 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) + 2c_u \tan \left( 45 + \frac{\phi}{2} \right)$
$\sigma_1' = \sigma_3' \tan^2 \left( 45 + \frac{\phi'}{2} \right) + 2c' \tan \left( 45 + \frac{\phi'}{2} \right)$

→ Depending upon drainage condition, types of SHEAR TESTS :

- (i) Unconsolidated Undrained Test (UU test)
- (ii) Consolidated Undrained Test (CU test)
- (iii) Consolidated Drained Test (CD test)

\* Stages of Shear test:

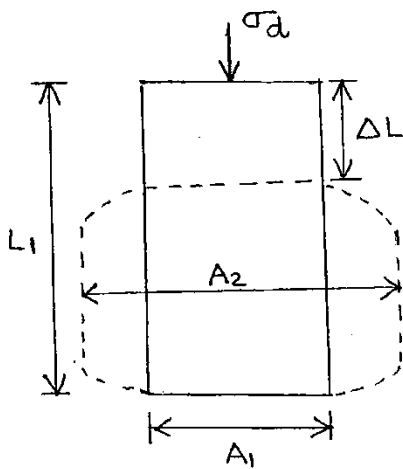
- 1<sup>st</sup> stage or consolidation stage (application of  $\sigma_c$ )
- 2<sup>nd</sup> stage or shearing stage. (application of  $\sigma_d$ )

⊙ When the valve of drain pipe is opened, when  $\sigma_c$  is applied (1<sup>st</sup> stage), pore water escapes and soil gets consolidated. Otherwise, it remains unconsolidated.

⊙ When the valve is open during application of  $\sigma_d$ , drained condition is obtained.

- ⊙ UU test : Drain valve is always kept closed. (Quick test)
- ⊙ CU test : Valve is open in 1<sup>st</sup> stage & closed in 2<sup>nd</sup> stage
- ⊙ CD test : Valve is always kept open (Slow test)

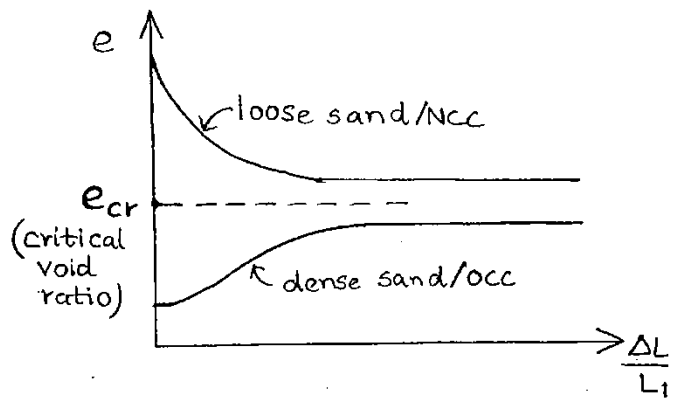
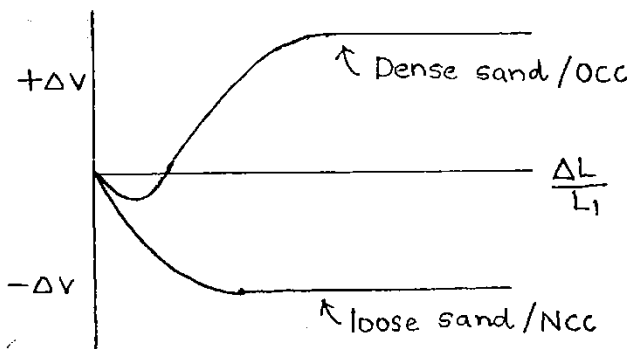
-  $c$  &  $\phi$  are shear strength parameters and not the property of soil. It varies with drainage conditions and test performed. (58) 54



$$\sigma_d = \frac{\text{axial load}}{\text{area at failure}} = \frac{Q_a}{A_2}$$

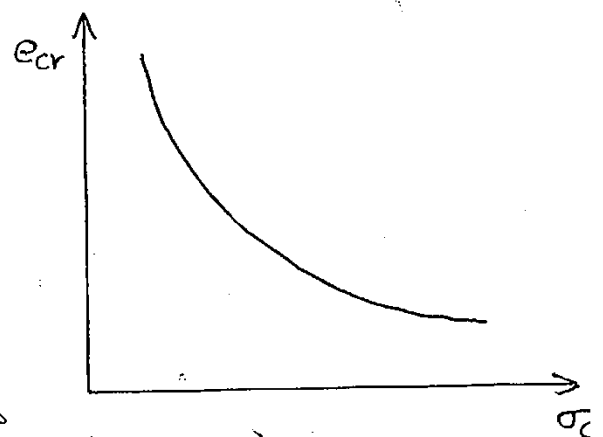
$$A_2 = \frac{V_1 \pm \Delta V}{L_1 - \Delta L}$$

$\Delta V = 0$  ; undrained test

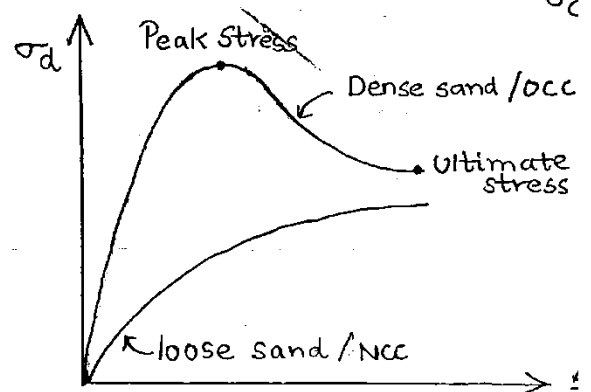


- Dilation :- The phenomenon of increase in volume of soil during shearing is called dilation. This is exhibited by dense sand and OCC.

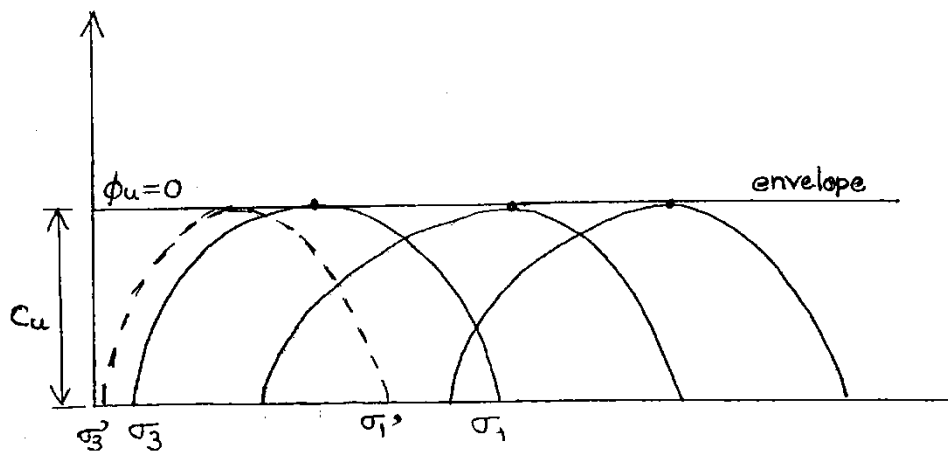
- Critical void ratio ( $e_{cr}$ ) decreases with increase in confining pressure ( $\sigma_c$ )



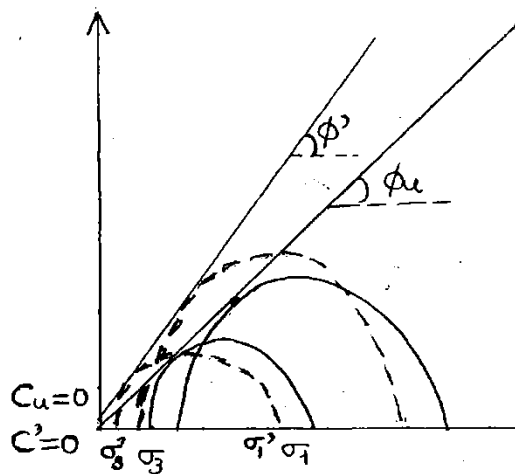
- Peak stress and ultimate stress



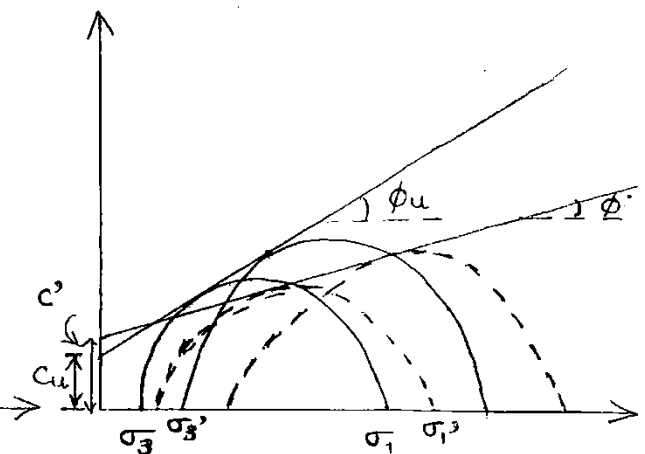
20<sup>th</sup> Sept,  
SATURDAY → Triaxial test Curves:



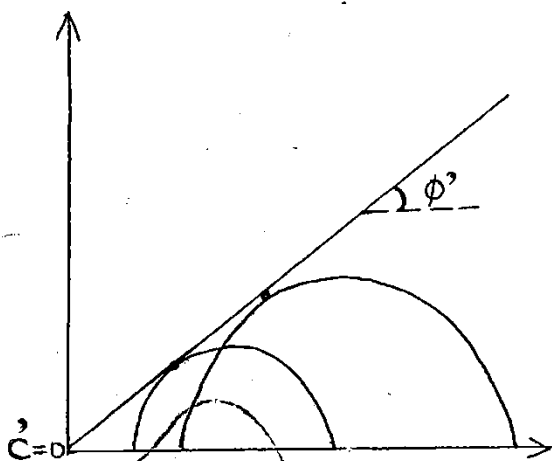
■ UU test on NCC & OCC



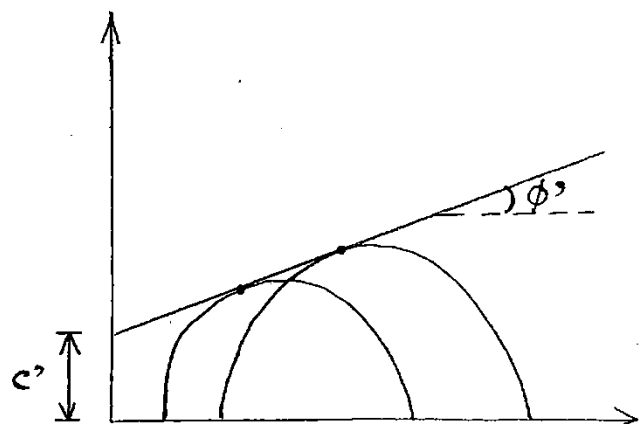
■ CU test on NCC



■ CU test on OCC



■ CD test on NCC



■ CD test on OCC

## \* Unconfined Compression Test (UCC test)

(59)

60

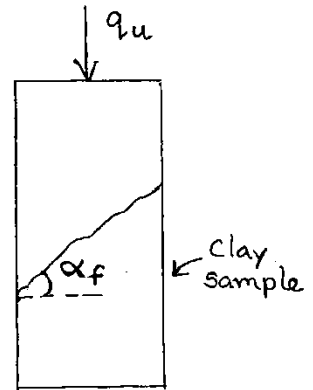
- It is a special type of triaxial test with  $\sigma_3 = 0$
- conducted quickly to have undrained condition.
- Suitable for undrained, saturated clays. ( $\phi_u = 0$ )

$q_u$  : unconfined compressive stress.

$$\sigma_1 = \sigma_3 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) + 2 C_u \tan \left( 45 + \frac{\phi_u}{2} \right)$$

In UCC test,  $\sigma_3 = 0$  &  $\sigma_1 = q_u$

$$\therefore q_u = 2 C_u \tan \left( 45 + \frac{\phi_u}{2} \right)$$



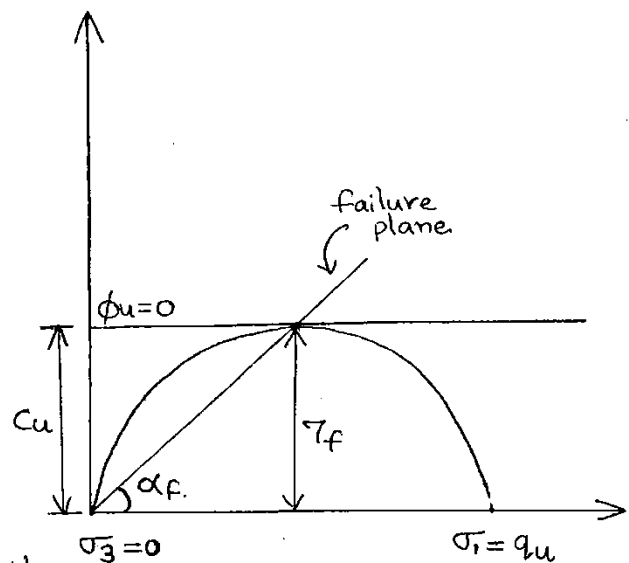
If soil is undrained saturated clay, then  $\phi_u = 0$

$$\Rightarrow C_u = \frac{q_u}{2}$$

If  $\phi = 0 \Rightarrow \alpha = 45^\circ$

$\tau_f = \tau_{max}$

- UCC is the only test in which Mohr's Circle passes through the origin.



$$\text{Sensitivity} = \frac{\text{undisturbed strength}}{\text{remoulded strength}}$$

If sensitivity = 1; soil is called "insensitive"

If sensitivity > 16; soil is called "quick soil" (Eg:- marine clay)

Quick soil is a type of soil whereas quick sand is a hydraulic condition.

- UCC is not suitable for fissured clay (cracked)

Soil will fail along the existing crack and does not exhibit the real strength.

### \* Vane Shear Test :

— can be conducted in lab or field.

— suitable for undrained saturated clays for which

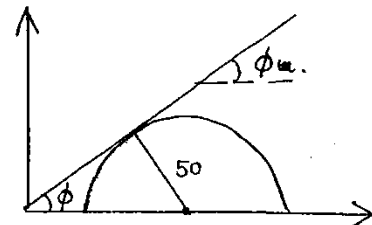
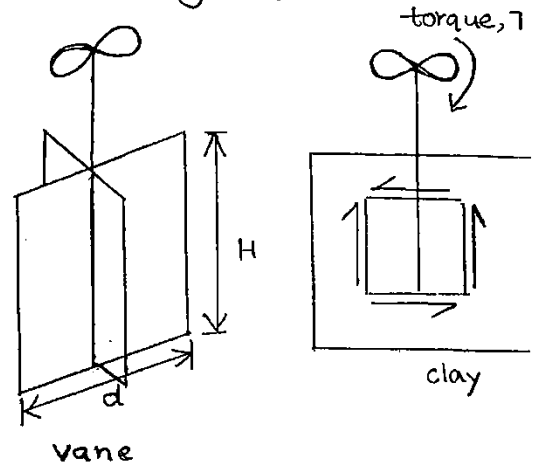
$$\phi_u = 0 \quad (\Rightarrow s = c)$$

$$T = \pi d^2 \cdot C_u \left( \frac{H}{2} + \frac{d}{6} \right)$$

(OR) when both bottom & top part take in shear

$$T = \pi d^2 \cdot C_u \left( \frac{H}{2} + \frac{d}{12} \right)$$

when bottom face takes part in shear



P-73

01.  $\sin \phi = \frac{50}{150} = \frac{1}{3}$

$$\phi = \sin^{-1} \left( \frac{1}{3} \right)$$

02.  $\tau_f = \frac{\sigma_1 - \sigma_3}{2} \cdot \sin 2\alpha$

$$0.9 = \frac{5 - 3.2}{2} \sin 2 \left( 45 + \frac{\phi}{2} \right)$$

$$\phi = 0$$

(OR)

$$\tau_{\max} = \frac{\sigma_1 - \sigma_3}{2}$$

Since  $\tau_f = \tau_{\max}$ ,  $\phi = 0$

03.  $\sigma_1 = 200$ ,  $\sigma_3 = 60$ ,  $c' = 5 \text{ kN/m}^2$ ,  $\phi' = 25^\circ$ ,  $u = 20$

$$\sigma_1' = \sigma_1 - u = 200 - 20 = 180 \text{ kPa}$$

$$\sigma_3' = \sigma_3 - u = 60 - 20 = 40 \text{ kPa}$$

If  $\sigma_3' = 40$ , the required  $\sigma_1'$  to cause failure:

$$\begin{aligned} \sigma_1' &= \sigma_3' \tan^2 \left( 45 + \frac{\phi'}{2} \right) + 2c' \tan \left( 45 + \frac{\phi'}{2} \right) \\ &= 40 \tan^2 \left( 45 + \frac{25}{2} \right) + 2 \times 5 \tan \left( 45 + \frac{25}{2} \right) \end{aligned}$$

$$\sigma_1' = 114 \text{ kPa.}$$

6/ (60)

Since the proposed effective stress (180 kPa) is more than 114 kPa, the sample will definitely fail.

04. Compressive strength = deviator stress. =  $\sigma_d$ .

$$c' = 15 \text{ kN/m}^2, \phi' = 20^\circ, \sigma_3' = 60$$

$$\begin{aligned} \sigma_1' &= \sigma_3' \tan^2 \left( 45 + \frac{\phi}{2} \right) + 2c' \tan \left( 45 + \frac{\phi}{2} \right) \\ &= 60 \tan^2 \left( 45 + \frac{20}{2} \right) + 2 \times 15 \tan \left( 45 + \frac{20}{2} \right) \\ &= \underline{\underline{165.2 \text{ kPa}}} \end{aligned}$$

$$\sigma_d = \sigma_1' - \sigma_3' = 165.2 - 60 = \underline{\underline{105.2 \text{ kPa}}}$$

05.  $q_u = 1.2 \text{ kg/cm}^2$ .

$$\alpha_f = 50^\circ$$

$$45 + \frac{\phi}{2} = \alpha_f$$

$$\phi = (50 - 45) \times 2 = \underline{\underline{10^\circ}}$$

06.  $q_u = 2c_u \tan \alpha_f$

$$\therefore c_u = \frac{1.2}{2 \tan 50} = \underline{\underline{0.503 \text{ kg/cm}^2}}$$

07.  $\sigma = 20 \text{ kN/m}^2$  ;  $\tau_f = 16 \text{ kN/m}^2$

$$c = 8 \text{ kN/m}^2$$
 ;  $\phi = 20^\circ$

$$\sigma = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2\alpha_f$$

$$20 = \frac{\sigma_1 + \sigma_3}{2} + \frac{\sigma_1 - \sigma_3}{2} \cos 2 \left( 45 + \frac{20}{2} \right) \rightarrow \textcircled{1}$$

$$\tau_f = \frac{\sigma_1 - \sigma_3}{2} \sin 2\alpha_f$$

$$16 = \frac{\sigma_1 - \sigma_3}{2} \sin 2 \left( 45 + \frac{20}{2} \right) \rightarrow \textcircled{2}$$

Solving ① & ②,

$$\sigma_1 = 42.85 \text{ kPa} \quad \& \quad \sigma_3 = 8.7 \text{ kPa.}$$

$$\sigma_1 - \sigma_3 = 34.15$$

$$\sigma_1 + \sigma_3 = 51.55$$

08. For NCC soil, in CU test,  $C_u = 0$  &  $c' = 0$ .

To find  $\phi_u$ ,

$$\sigma_1 = \sigma_3 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) + 2C_u \tan \left( 45 + \frac{\phi_u}{2} \right).$$
$$200 + 150 = 200 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) + 0$$

$$\phi_u = \underline{\underline{15.826^\circ}}$$

To find  $\phi'$ ,

$$\sigma_1' = \sigma_3' \tan^2 \left( 45 + \frac{\phi'}{2} \right) + 2c' \tan \left( 45 + \frac{\phi'}{2} \right).$$
$$(200 + 150 - 75) = (200 - 75) \tan^2 \left( 45 + \frac{\phi'}{2} \right) + 0$$

$$\phi' = \underline{\underline{22^\circ}}$$

10.  $\sigma_d = 200 \text{ kN/m}^2$ ,  $\sigma_3 = 100 \text{ kN/m}^2$

In an undrained test,  $\phi_u = 0$ .

$$\sigma_1 = \sigma_3 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) + 2C_u \tan \left( 45 + \frac{\phi_u}{2} \right).$$

$$\sigma_1 = \sigma_3 + 2C_u.$$

$$C_u = \frac{\sigma_1 - \sigma_3}{2} = \frac{\sigma_d}{2} = \frac{200}{2} = \underline{\underline{100 \text{ kPa}}}$$

11. For dry sand,  $c = 0$

$$\sigma_3 = 50 \text{ kPa}, \quad \sigma_d = 100 \text{ kPa.}$$

$$\sigma_1 = \sigma_3 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) + 2C_u \tan \left( 45 + \frac{\phi_u}{2} \right).$$

$$\sigma_1 = 50 \tan^2 \left( 45 + \frac{\phi_u}{2} \right).$$

$$150 = 50 \tan^2 \left( 45 + \frac{\phi_u}{2} \right) \Rightarrow \phi = \underline{\underline{38^\circ}}$$

12  $\phi = 37^\circ, \sigma_3 = 200 \text{ kN/m}^2, c = 0.$

$$\sigma_1 = \sigma_3 \tan^2\left(45 + \frac{\phi}{2}\right) + 2c \tan\left(45 + \frac{\phi}{2}\right).$$

$$200 + \sigma_d = 200 \tan^2\left(45 + \frac{37}{2}\right) + 0.$$

$$\sigma_d = \underline{\underline{604.56 \text{ kPa}}}$$

13.  $\sigma_3' = 150 \text{ kN/m}^2$

Principle effective stress ratio,  $\frac{\sigma_1'}{\sigma_3'} = 4.2.$

$$\sigma_1' = \sigma_3' \tan^2\left(45 + \frac{\phi'}{2}\right) + 2c \tan\left(45 + \frac{\phi'}{2}\right).$$

$$4.2 = \tan^2\left(45 + \frac{\phi'}{2}\right).$$

$$\Rightarrow \phi' = \underline{\underline{37.97^\circ}}$$

14  $\sigma_d = \sigma_1' - \sigma_3' = \sigma_3' \left(\frac{\sigma_1'}{\sigma_3'} - 1\right).$

$$= 150 (4.2 - 1) = \underline{\underline{480 \text{ kPa}}}$$

→ Skempton's Pore Pressure Parameters (A & B)

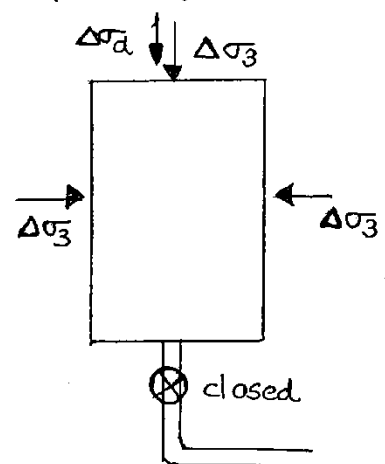
$$\Delta u_3 = B \Delta \sigma_3.$$

$B = 0$  ; for dry soil.

$B = 1$  ; for saturated soil.

$$0 \leq B \leq 1$$

$$\Delta u_d = AB \Delta \sigma_d$$



At failure,  $A \rightarrow A_f.$

○  $A_f$  is -ve for dense sand/OCC.

$A_f$  is +ve for loose sand/NCC

$$\text{Total, } \Delta u = \Delta u_3 + \Delta u_d$$

$$= B \Delta \sigma_3 + AB \Delta \sigma_d$$

$$\therefore \boxed{\Delta u = B (\Delta \sigma_3 + A \Delta \sigma_d)}$$

→ Shear Failures:

(i) Brittle Failure.

(ii) Plastic Failure



Plastic Failure.



Brittle Failure

■ Quick sand is due to upward seepage; liquefaction is due to compaction caused by vibrations

09.  $\Delta \sigma_3 = 100 - 0 = 100 \text{ kN/m}^2$ .

$$\Delta u_3 = 10 - (-60) = 70 \text{ kN/m}^2$$

$$\Delta u_3 = B \Delta \sigma_3$$

$$\therefore B = \frac{70}{100} = \underline{0.7}$$

$$\Delta \sigma_d = 500 \text{ kN/m}^2$$

$$\Delta u_d = -70 - 10 = -80 \text{ kN/m}^2$$

$$\begin{array}{l} \left. \begin{array}{l} -60 \\ 10 \\ -70 \end{array} \right\} \begin{array}{l} \text{1st stage} \\ \text{(consolidation)} \\ \text{2nd stage} \\ \text{(shearing)} \end{array} \end{array}$$

$$\Delta u_d = AB \Delta \sigma_d$$

$$-80 = A \times 0.7 \times 500$$

$$\therefore A = \underline{-0.23}$$

B → depends on degree of saturation,  $S_r$

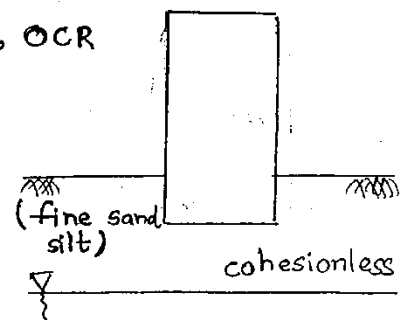
A → depends on over consolidation ratio, OCR

→ Liquefaction:

$$S = \sigma' \tan \phi' = (\sigma - u) \tan \phi'$$

Due to vibrations caused by earthquakes or pile drivings, soil gets compacted and  $u \uparrow$ .

At  $u = \sigma$ ,  $S = 0$  (soil behaves as a liquid)

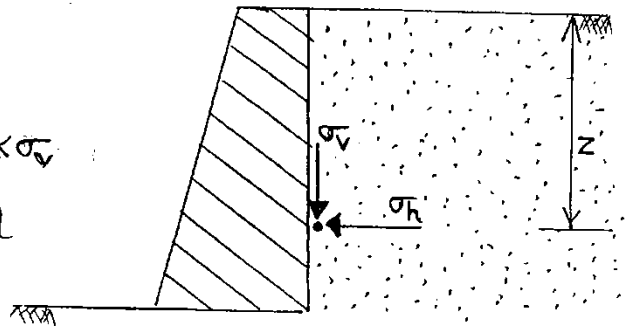


## 14. EARTH PRESSURE

$$\sigma_v = \gamma z$$

Lateral Earth Pressure,  $\sigma_h = k\sigma_v$

where  $k \rightarrow$  coefficient of lateral earth pressure.



$$k = \frac{\sigma_h}{\sigma_v}$$

$\rightarrow$  Types of Lateral Earth Pressures.

1. At-rest Earth pressure ( $P_0$ )
2. Active Earth pressure ( $P_a$ )
3. Passive Earth pressure ( $P_p$ )

\* At-rest Earth Pressure :-

- It arises when there is no movement of wall.
- No yielding of soil.
- elastic equilibrium; theory of elasticity is used to find  $\sigma_h$ .

At rest earth pressure,  $P_0 = k_0 \cdot \sigma_v$

where  $k_0 \rightarrow$  coefficient of at-rest earth pressure.

$$k_0 = \frac{\mu}{1 - \mu}; \mu \rightarrow \text{poisson's ratio of soil.}$$

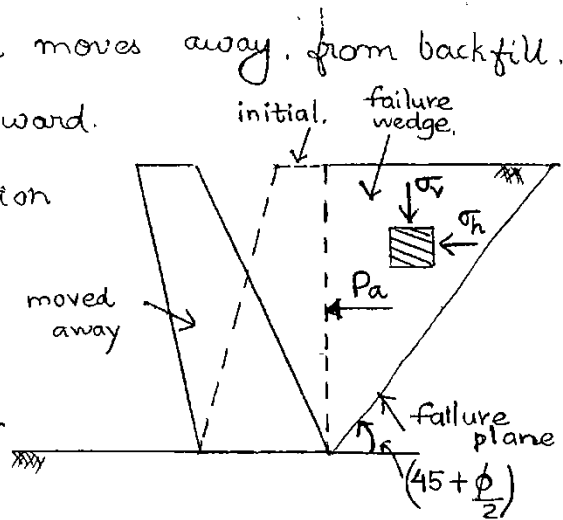
also  $k_0 = 1 - \sin \phi$ ; for cohesionless soils.

## \* Active Earth Pressure.

- It arises when the wall moves away from backfill.
- Failure wedge moves downward.
- It is a plastic eqbm condition

Here  $\sigma_v = \sigma_1$  &  $\sigma_h = \sigma_3$

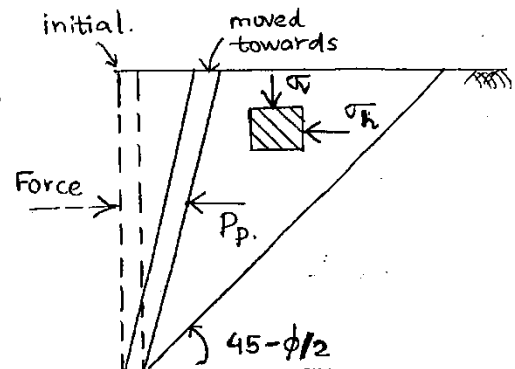
Failure plane makes an angle of  $(45 + \phi/2)$  with Major principal plane.



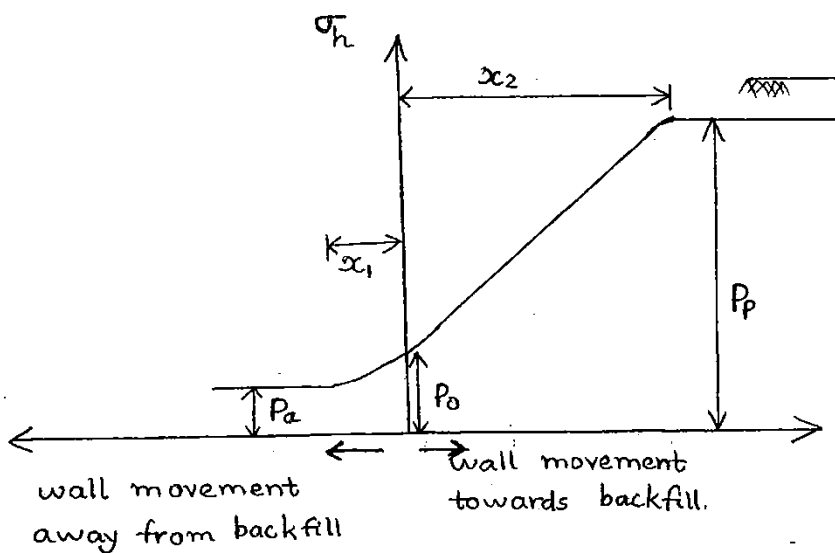
## \* Passive Earth Pressure

- It arises when the wall moves towards the backfill.
- Failure wedge moves upwards.
- It is a plastic eqbm condition.

Here  $\sigma_v = \sigma_3$  &  $\sigma_h = \sigma_1$



22<sup>nd</sup> Sept,  
MONDAY

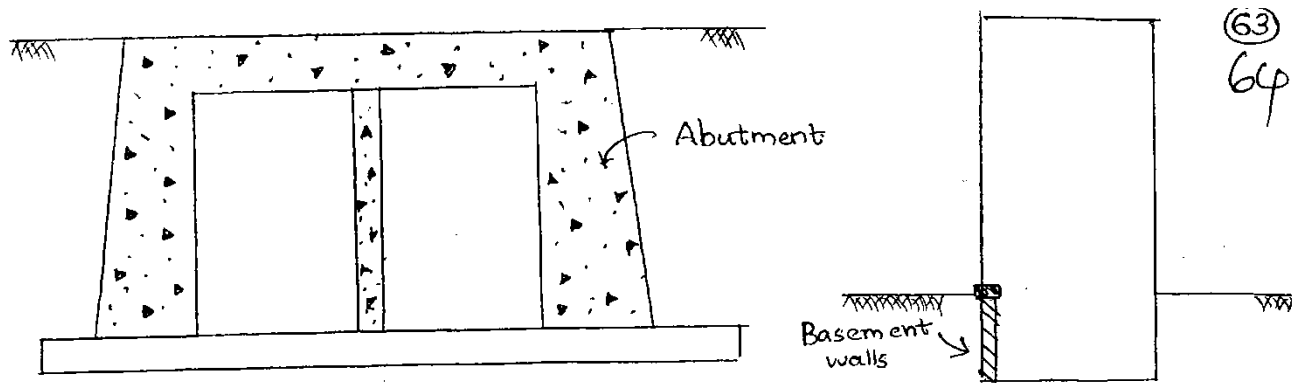


⊙  $P_p > P_o > P_a$

⊙  $x_1 < x_2$

## → Practical Applications:

- For design of ordinary retaining wall, - active pressure is used
- For design of bridge abutments and basement walls  
- at rest earth pressure is used



(iii) For design of sheet piles - both active & passive pre. used.

→ Rankine's Theory:

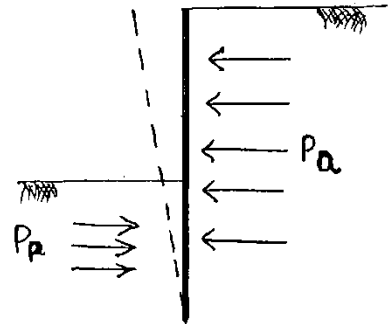
- to find  $P_a$  &  $P_p$ .

\* Assumptions:-

(i) Soil is dry and cohesionless.

(ii) The back of the wall is vertical and smooth.

(iii) Plastic equilibrium.



Plastic equilibrium equation:-

$$\sigma_1 = \sigma_3 \tan^2 \alpha_f + 2c \tan \alpha_f$$

for cohesionless soil,

$$\sigma_1 = \sigma_3 \tan^2 \alpha_f$$

In active case,  $\sigma_1 = \sigma_v$  &  $\sigma_3 = \sigma_h$ .

$$\therefore \sigma_v = \sigma_h \tan^2 \alpha_f$$

$$\sigma_h = \frac{\sigma_v}{\tan^2 \alpha_f}$$

$$\text{or } \boxed{P_a = K_a \sigma_v}$$

where  $K_a \rightarrow$  coefficient of active earth pressure.  $\left( = \frac{1}{\tan^2 \alpha_f} \right)$

$$K_a = \frac{1}{\tan^2 \alpha_f} = \frac{1}{\tan^2 (45 + \phi/2)} = \tan^2 (45 - \phi/2)$$

$$\text{or } \boxed{K_a = \frac{1 - \sin \phi}{1 + \sin \phi}}$$

Similarly,

$$P_p = K_p \cdot \sigma_v$$

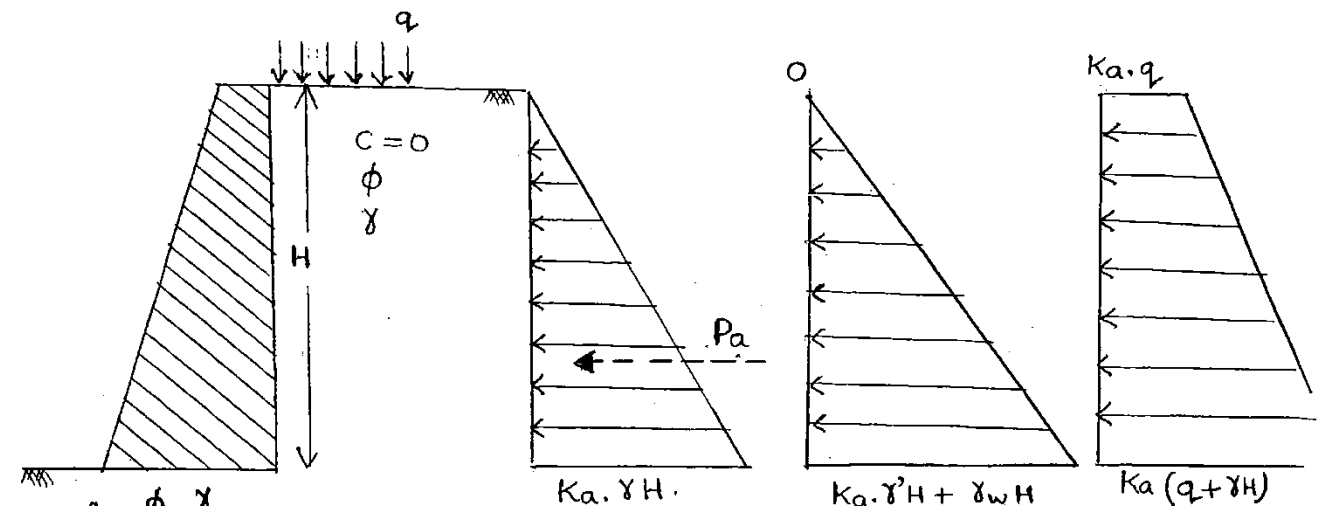
$K_p \rightarrow$  coefficient of passive earth pressure.

$$K_p = \frac{1 + \sin \phi}{1 - \sin \phi} = \frac{1}{K_a}$$

$P_o = K_o \sigma_v \rightarrow$  for both cohesive & cohesionless soils

$P_a = K_a \sigma_v$   
 $P_p = K_p \sigma_v$

$\} \rightarrow$  cohesionless soils



case 1:  $\phi, \gamma$

At top;  $\sigma_v = 0$

$$P_a = K_a \sigma_v = 0.$$

At bottom,  $\sigma_v = \gamma H$ .

$$P_a = K_a \gamma H.$$

Let  $P_a =$  total active force.

$=$  area of pressure diagram.

$$P_a = \frac{K_a \gamma H^2}{2} ; \text{ at } \frac{H}{3} \text{ from base}$$

case 2:  $\phi, \gamma_{sat}, \text{ WT on ground.}$

At top;  $P_a = 0$

At bottom;  $\sigma_v' = \gamma' H$

$$P_a = K_a \sigma_v' + \gamma_w H$$

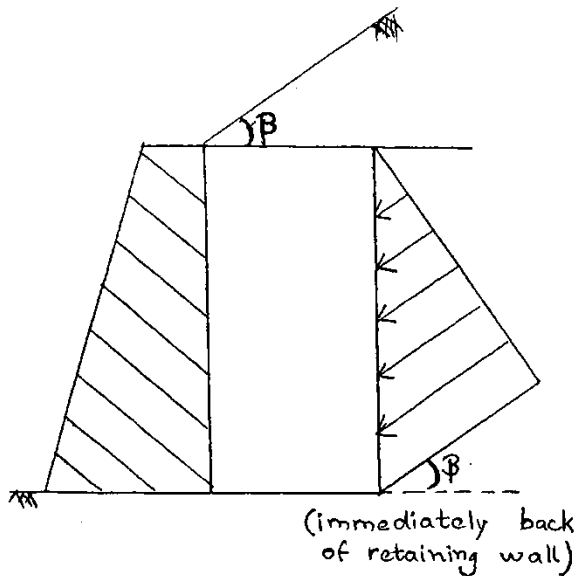
Case 3: surcharge loading,  $q$

At top;  $\sigma_v = q$ .

$$P_a = K_a \sigma_v = K_a q$$

At bottom;  $\sigma_v = q + \gamma H$

$$P_a = K_a \sigma_v = K_a (q + \gamma H)$$



Here  $K_p \neq \frac{1}{K_a}$

$$P_a = K_a \cdot \sigma_v$$

$$P_p = K_p \cdot \sigma_v$$

$$K_a = \cos \beta \left( \frac{\cos \beta - \sqrt{\cos^2 \beta - \cos^2 \phi}}{\cos \beta + \sqrt{\cos^2 \beta - \cos^2 \phi}} \right)$$

$$K_p = \cos \beta \cdot \left( \frac{\cos \beta + \sqrt{\cos^2 \beta - \cos^2 \phi}}{\cos \beta - \sqrt{\cos^2 \beta - \cos^2 \phi}} \right)$$

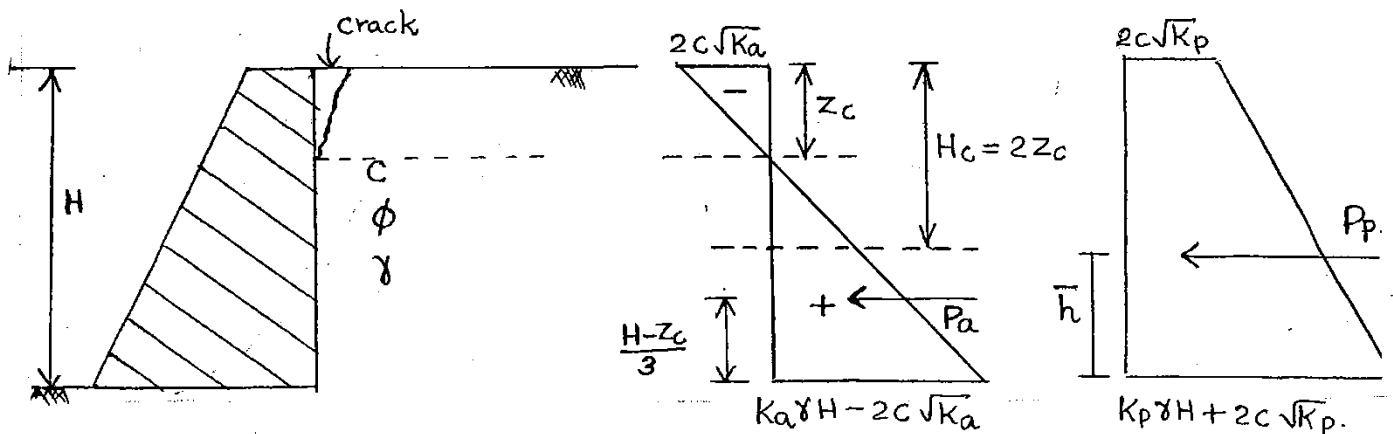
→ C-φ Soils

$$P_a = K_a \cdot \sigma_v - 2c \sqrt{K_a}$$

$$P_p = K_p \cdot \sigma_v + 2c \sqrt{K_p}$$

⇒ BELL'S EQUATIONS

• Cohesion decreases active pressure but increases passive pressure



At top;  $\sigma_v = 0$

$$P_a = K_a \sigma_v - 2c\sqrt{K_a} \\ = -2c\sqrt{K_a} \text{ (tension)}$$

At bottom;  $\sigma_v = \gamma H$ .

$$P_a = K_a \gamma H - 2c\sqrt{K_a}$$

$Z_c$  : depth of tension zone (or) depth of tension crack

\* To find  $Z_c$  :-

At a depth of  $Z_c$ ,

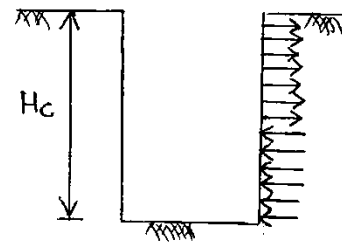
$$P_a = K_a \gamma Z_c - 2c\sqrt{K_a}$$

$$0 = K_a \gamma Z_c - 2c\sqrt{K_a}$$

$$\therefore Z_c = \frac{2c}{\gamma \sqrt{K_a}}$$

$$= \frac{2c}{\gamma} \tan(45 + \phi/2)$$

$$= \frac{2c}{\gamma} ; \text{ for pure clay } (\phi=0)$$



$H_c$  : critical height or depth of unsupported vertical trench.

$$\begin{aligned} * H_c &= 2Z_c = \frac{4c}{\gamma \sqrt{K_a}} = \frac{4c}{\gamma} \tan(45 + \frac{\phi}{2}) \\ &= \frac{4c}{\gamma} ; \text{ for pure clay} \end{aligned}$$

\* To find total active force,  $P_a$

(a). Before formation of crack.

$$P_a = \int_0^H P_a \cdot dz = \text{total algebraic sum of area of pressure diagram.}$$

$$P_a = K_a \cdot \frac{\gamma H^2}{2} - 2c\sqrt{K_a} \cdot H$$

(b) After formation of crack

$$P_a = \int_{Z_c}^H P_a \cdot dz = \text{area of +ve portion only.}$$

$$P_a = K_a \cdot \frac{\gamma H^2}{2} - 2c\sqrt{K_a} H + \frac{2c^2}{\gamma}$$

65  
66

\* To find total Passive force,  $P_p$ .

$$P_p = K_p \sigma_v + 2c\sqrt{K_p}$$

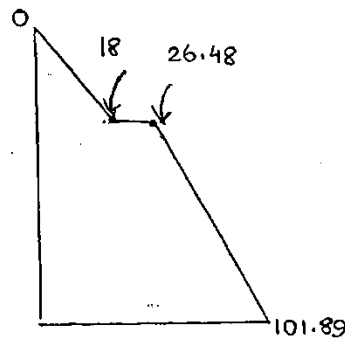
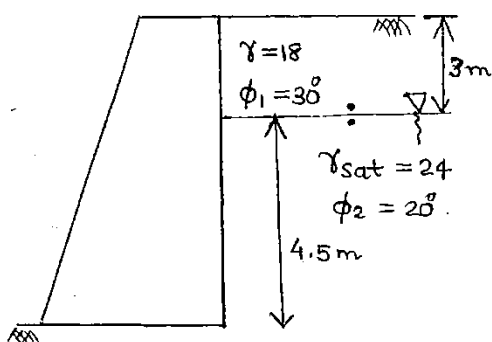
At top;  $\sigma_v = 0$ .  $\therefore P_p = 2c\sqrt{K_p}$

At bottom;  $\sigma_v = \gamma H$ .  $\therefore P_p = K_p \gamma H + 2c\sqrt{K_p}$

passive  
Total pressure force,  $P_p$  = area of pressure diagram.

$$P_p = K_p \frac{\gamma H^2}{2} + 2c\sqrt{K_p} H$$

Q1.  $H = 7.5 \text{ m}$ ;



$$K_{a1} = \frac{1 - \sin \phi_1}{1 + \sin \phi_1} = 0.33$$

$$K_{a2} = \frac{1 - \sin 20}{1 + \sin 20} = 0.49$$

At top;  $\sigma_v = 0$

$$P_a = K_{a1} \cdot \sigma_v = 0.$$

At 3m depth,  $\sigma_v = 18 \times 3 = 54$

$P_a$  = a) Just above 3m depth

$$P_a = K_{a1} \sigma_v = 18 \text{ kPa}$$

b) Just below 3m depth,

$$P_a = K_{a2} \sigma_v = 0.49 \times 54 = 26.48 \text{ kPa}$$

At bottom;  $\sigma_v = 18 \times 3 + (24 - 9.81) \times 4.5$   
 $= 117.855 \text{ kPa}$

$$P_a = K_{a2} \sigma_v' + \gamma_w h$$

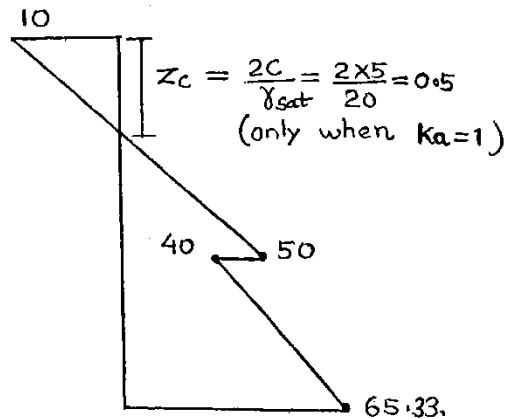
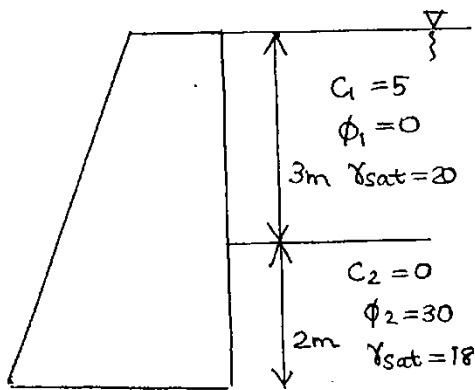
$$= 0.49 \times 117.855 + 9.81 \times 4.5$$

$$= 101.89 \text{ kPa}$$

$$\begin{aligned} \text{Total force, } P_a &= \frac{1}{2} \times 18 \times 3 + \left( \frac{26.46 + 101.89}{2} \right) \times 4.5 \\ &= \underline{\underline{315.832 \text{ kN/m}}} \end{aligned}$$

② Area of Pressure force diagram = Force per unit length.

02.



$$K_{a1} = \frac{1 - \sin \phi}{1 + \sin \phi} = \underline{\underline{1}}$$

$$K_{a2} = \frac{1 - \sin 30}{1 + \sin 30} = \underline{\underline{\frac{1}{3}}}$$

At top;

$$\sigma_v = 0$$

$$\begin{aligned} P_a &= K_{a1} \sigma_v - 2c_1 \sqrt{K_{a1}} \\ &= 0 - 2 \times 5 \times 1 = -10 \text{ kPa (tension)}. \end{aligned}$$

At 3m depth;

$$\sigma_v' = (20 - 10) \times 3 = 30 \text{ kPa.}$$

a) Just above 3m depth,

$$\begin{aligned} P_a &= \sigma_v' K_{a1} - 2c_1 \sqrt{K_{a1}} + \gamma_w h \\ &= 30 \times 1 - 2 \times 5 + 10 \times 3 = 50 \text{ kPa.} \end{aligned}$$

b) Just below 3m depth,

$$\begin{aligned} P_a &= \sigma_v' K_{a2} - 2c_2 \sqrt{K_{a2}} + \gamma_w h \\ &= 30 \times \frac{1}{3} - 0 + 30 = 40 \text{ kPa.} \end{aligned}$$

$$\begin{aligned} \text{At bottom; } \sigma_v' &= 10 \times 3 + 8 \times 2 = 46. \\ P_a &= 46 \times \frac{1}{3} + 10 \times 5 \\ &= \underline{\underline{65.33 \text{ kPa.}}} \end{aligned}$$

To find  $z_c$ :

At a depth of  $z_c$ ,  $P_a = 0$ .

$$P_a = K_{a1} \gamma' z_c - 2c_1 \sqrt{K_{a1}} + \gamma_w z_c$$

$$0 = 1 \times 10 z_c - 2 \times 5 \times \sqrt{1} + 10 z_c$$

$$z_c = \frac{10}{20} = \underline{0.5 \text{ m}}$$

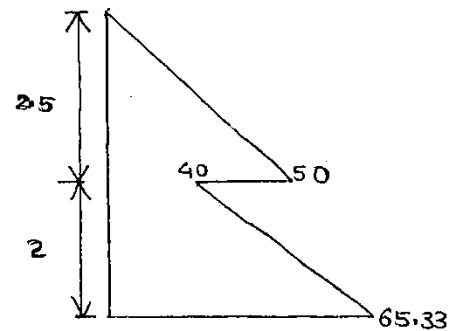
(OR)

From similar triangles,

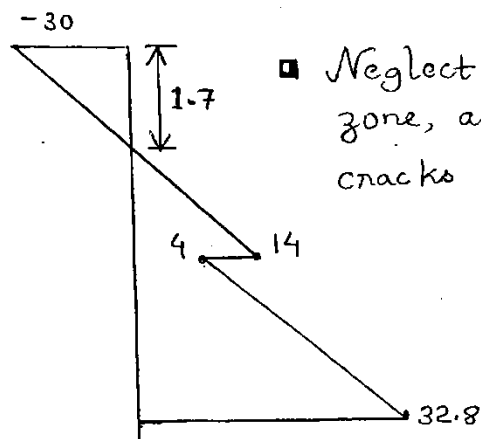
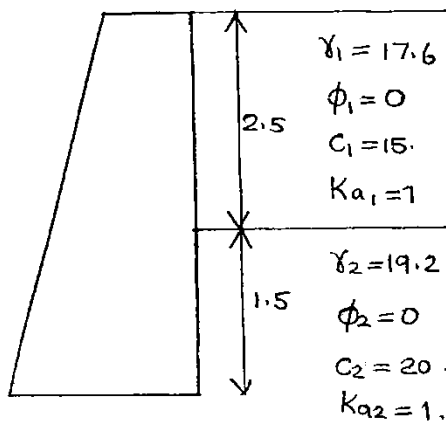
$$\frac{10}{z_c} = \frac{50}{3 - z_c} \Rightarrow z_c = \underline{0.5 \text{ m}}$$

Neglecting tension zone:

$$P_a = \frac{1}{2} \times 50 \times 2.5 + 2 \left( \frac{40 + 65.33}{2} \right) \times 2 = \underline{167.8 \text{ kN/m}}$$



03.



■ Neglect tension zone, as tension cracks develop.

At top:  $\sigma_v = -2c \sqrt{K_{a1}} = \underline{-30}$

$$P_a = K_{a1} \sigma_v = -30 \text{ kPa.}$$

At 2.5 m depth:

$$\begin{aligned} \sigma_v^* &= \gamma \times 2.5 \\ &= 17.6 \times 2.5 = \underline{44 \text{ kPa.}} \end{aligned}$$

a) Just above,

$$\begin{aligned} P_a &= K_{a1} \sigma_v^* - 2c_1 \sqrt{K_{a1}} \\ &= 44 - 2 \times 15 = 14 \text{ kPa.} \end{aligned}$$

b) Just below,

$$P_a = 1 \times 44 - 2 \times 20 = 4 \text{ kPa.}$$

At bottom:

$$\begin{aligned} \sigma_v &= 17.6 \times 2.5 + 19.2 \times 1.5 \\ &= 72.8. \end{aligned}$$

$$\begin{aligned} P_a &= 72.8 - 2 \times 20 \\ &= \underline{32.8 \text{ kPa.}} \end{aligned}$$

Total active force,  $P_a$

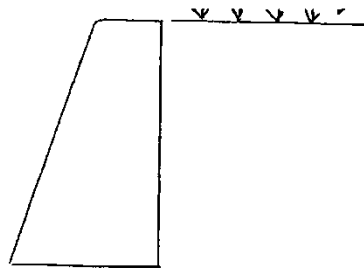
$$\begin{aligned} &= (2.5 - 1.7) \times 14 \times 0.5 + \\ &\quad 0.5(4 + 32.8) \times 1.5 \\ &= \underline{33.168 \text{ kPa}} \end{aligned}$$

04.

$$P_a = K_a \sigma_v - 2c \sqrt{K_a}$$

$$0 = K_a \cdot q - 2c \sqrt{K_a}$$

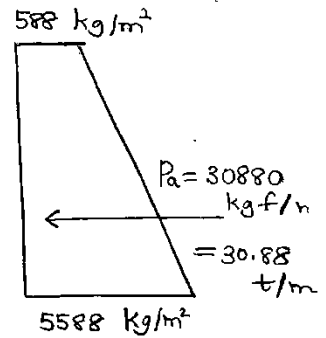
$$q = \frac{2c}{\sqrt{K_a}} = 2c \tan \alpha_f$$



05. When there is no surcharge,  
at bottom,  $P_a = K_a \gamma H$ .

$$5000 = K_a \cdot 1700 \times 10$$

$$K_a = 0.294$$



If there is surcharge,  
at <sup>top</sup> bottom,  $P_a = K_a \sigma_v$

$$= K_a \cdot q = 0.294 \times 2000$$

$$= \underline{588 \text{ kg/m}^2}$$

at bottom,  $\sigma_v = q + \gamma H$

$$P_a = K_a \cdot \sigma_v$$

$$= K_a (q + \gamma H) = \underline{5588 \text{ kg/m}^2}$$

Maximum earth pressure = 5588 kg/m<sup>2</sup>

Resultant force on the wall =  $\frac{1}{2} (5588 + 588) \times 10$

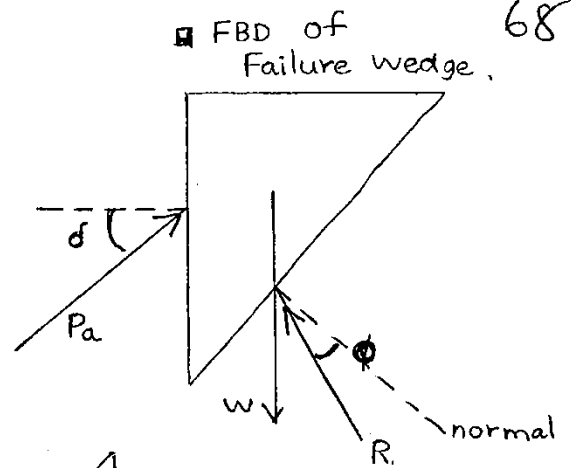
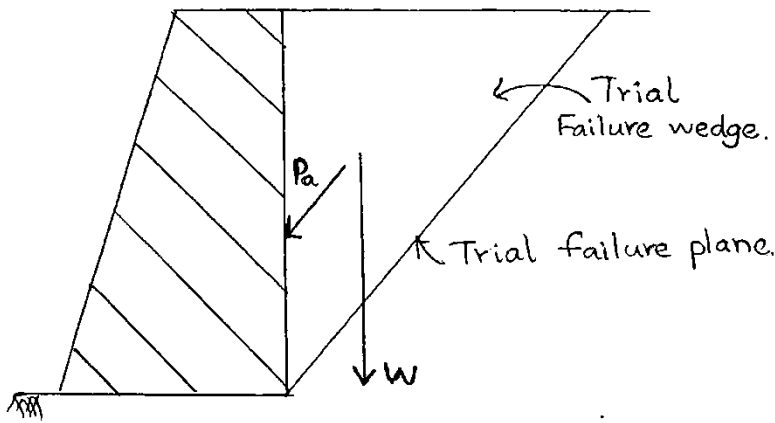
$$= 30880 \text{ kgf/m}$$

$$= \underline{30.880 \text{ t/m}}$$

## → Coulomb's Theory

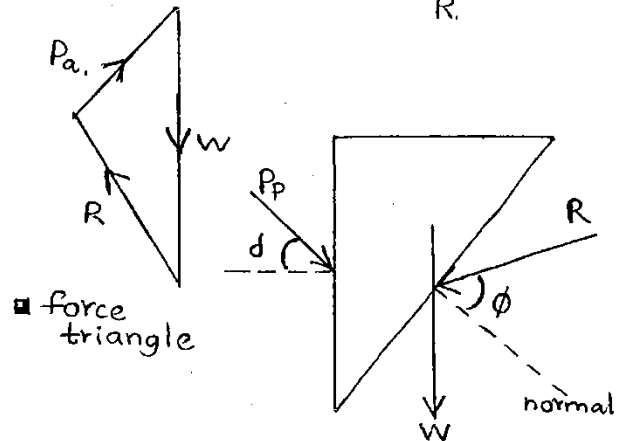
\* Assumptions:

- (i) Soil is dry and cohesionless.
- (ii) Back of the wall is rough



$\delta \rightarrow$  angle of wall friction.

Coulomb's theory is a graphical trial & error method of computing lateral earth pressures ( $P_a$  &  $P_p$ ).



NOTE: Effect of wall friction:-

① The wall friction reduces active pressure but increases passive pressure; both are advantageous.

② For RCC retaining walls, Rankine's Theory can be used.  
For stone masonry retaining walls, Coulomb's Theory is used.

\*Rebhan's Method & Culman's Method - graphical method of computing  $P_a$  &  $P_p$  using Coulomb's theory.

16. When soil is compacted,  $\phi \uparrow \Rightarrow K_a \downarrow$

$$P_a = K_a \gamma H \quad (\downarrow).$$

$$K_a \downarrow > \gamma \uparrow$$

26. Cohesive soils are poor for backfilling as they cause more lateral pressure. due to following reasons:

- (i) for clays  $\phi$  is less, Hence  $K_a$  is more.
- (ii) Swelling of clays.
- (iii) Clays have poor drainage properties.
- (iv) Compaction of clays behind the wall is difficult.

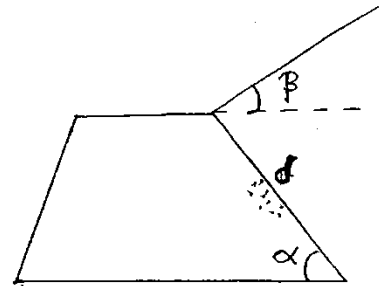
For backfilling behind the walls, cohesionless soils like gravel and sand are best.

$\uparrow K_a$  due to above factors is more than the  $\downarrow K_a$  due to cohesion. ( $P_a = K_a \sigma_v - 2c\sqrt{K_a}$ ).

→ Solution for Coulomb's Theory.

$$\text{Force, } P_a = K_a \frac{\gamma H^2}{2}$$

where  $K_a$  depends on  $\alpha, \beta, \delta, \phi$



• For vertical wall and horizontal backfill and if  $\delta = \phi$ ,

$$\text{then, } K_a = \frac{\cos \phi}{(1 + \sqrt{2} \sin \phi)^2}; \quad K_p = \frac{\cos \phi}{(1 - \sqrt{2} \sin \phi)^2}$$

## 15. STABILITY OF SLOPES

→ Forces which cause failure of Slopes:

- (i) Gravitational Force.
- (ii) Seepage force.
- (iii) Earthquake Force.
- (iv) Construction equipment loads.

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→ Types of Slopes:

- (i) Infinite slope. Eg: mountain slope.
- (ii) Finite slope. Eg: embankment of roads, earthen dams, canals etc.

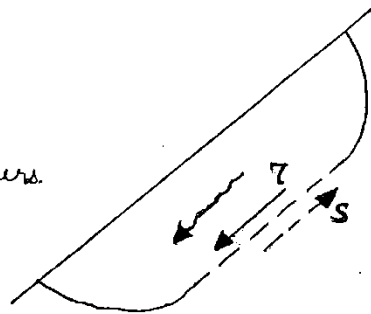
→ Types of Slope Failures:

- (i) Translational failure.
- (ii) Rotational Failure.
- (iii) Wedge Failure.
- (iv) Compound Failure.

\* Translational Failure.

If  $\tau > s$ , translational failure occurs.

∴ to avoid failure,  $\tau$  must be kept less than  $s$ .



$$\boxed{FOS = \frac{s}{\tau}}$$

if

$FOS > 1$  ; it is safe.

$FOS < 1$  ; unsafe.

$FOS = 1$  ; critical

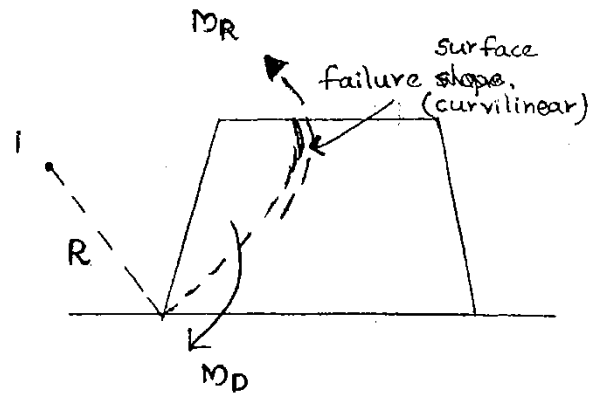
## \* Rotational Failure

$M_D$  = driving moment.

$M_R$  = resisting moment.

If  $M_D > M_R$ , failure occurs

$$\therefore FOS = \frac{M_R}{M_D}$$

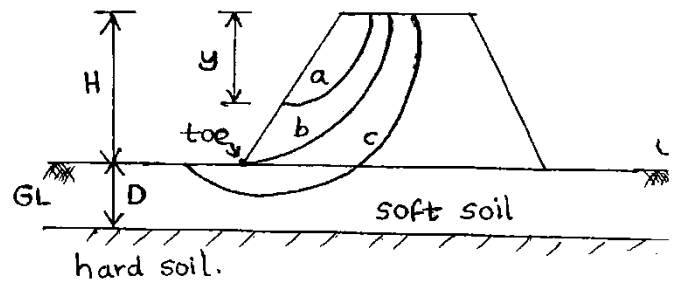


— types of rotational failures:—

a) Face failure

b) Toe failure.

c) Base failure.



Depth factor,  $D_F = \frac{H+D}{H}$

For base failure,  $D_F > 1$  (when there is soft soil)

For toe failure,  $D_F = 1$  (when there is no soft soil).

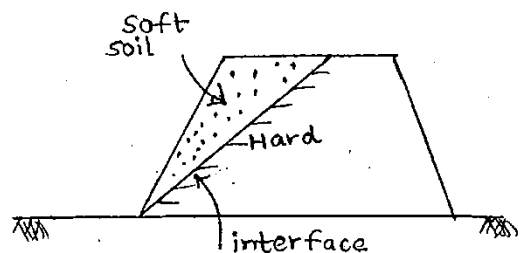
For face failure,  $D_F < 1$

Depth factor,  $D_F = \frac{y}{H}$

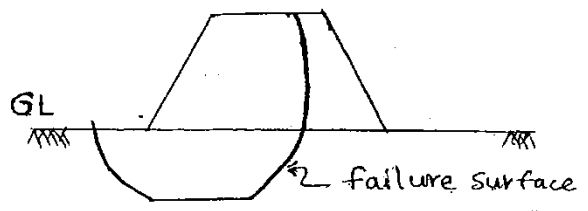
where  $y \rightarrow$  vertical depth of point where failure surface passes as shown.

## \* Wedge Failure

The soft soil above the interface b/w soft soil and hard soil will fail as a wedge.



## \* Compound Failure.



→ Infinite Slope:

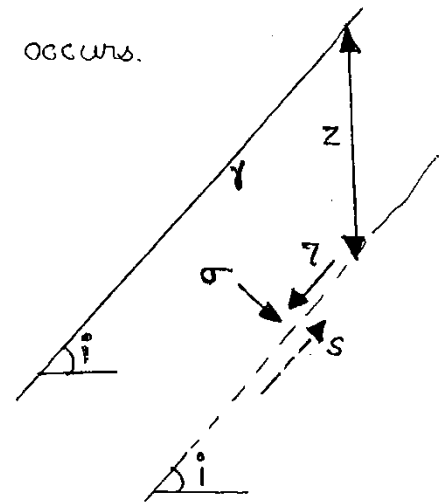
- generally, translational failure occurs.

$$FOS = \frac{S}{\tau}$$

$$S = c + \sigma \tan \phi$$

$$\sigma = \gamma z \cos^2 i$$

$$\tau = \gamma z \cos i \cdot \sin i$$



\* Infinite Slope in  $c-\phi$  soil:-

a) Dry or Partially Saturated Soil.

$$FOS = \frac{c + \sigma \tan \phi}{\tau} = \frac{c + \gamma z \cos^2 i \tan \phi}{\gamma z \cos i \cdot \sin i}, \text{ (at a depth } z \text{)}$$

b) Fully submerged soil. (mountain in ocean).

$$FOS = \frac{c' + \gamma' z \cos^2 i \cdot \tan \phi'}{\gamma' z \cos i \cdot \sin i}$$

c) If there is seepage parallel to slope. (rainwater seeping).

$$FOS = \frac{c' + \gamma' z \cos^2 i \cdot \tan \phi'}{\gamma_{sat} \cdot z \cdot \cos i \cdot \sin i}$$

\* Infinite Slope in Cohesionless soils ( $c=0$ )

imp

a) Dry or Partially Saturated Soil.

$$FOS = \frac{\tan \phi}{\tan i} \text{ (if } i > \phi; \text{ it fails)}$$

b) For fully submerged slope.

$$FOS = \frac{\tan \phi'}{\tan i}$$

c) Seepage parallel to slope,

$$FOS = \left( \frac{\gamma'}{\gamma_{sat}} \right) \frac{\tan \phi'}{\tan i}$$

→ Finite Slope

- generally, rotational failure occurs.

- methods of analysis:

1.  $\phi_u = 0$  Analysis.
2. Method of slices.
3. Bishop's method.
4. Friction circle method.
5. Stability number method.

\*  $\phi_u = 0$  Analysis:

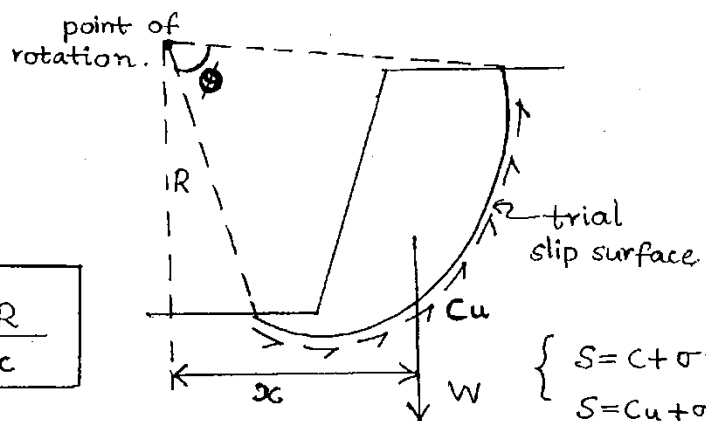
- suitable only for undrained saturated clays.

- graphical method based on trial & error.

$$\therefore M_D = W \cdot x$$

$$M_R = C_u \cdot \hat{L} \times 1 \times R$$

$$\boxed{FOS = \frac{M_R}{M_D} = \frac{C_u \hat{L} R}{W \cdot x}}$$



$$\begin{cases} S = c + \sigma \tan \phi \\ S = C_u + \sigma \tan \phi \\ \Rightarrow S = C_u \end{cases}$$

$\hat{L} \rightarrow$  arc length.

$$\hat{L} = R \theta \cdot \frac{\pi}{180}$$

$W \rightarrow$  weight of trial failure wedge.

$$W = a \times 1 \times \gamma ; a \rightarrow \text{area of trial failure wedge.}$$

→ use  $\gamma'$  for submerged slope.  
(canal running full)

use  $\gamma_{sat}$  for sudden drawdown condition

$$FOS \propto \frac{1}{W} ; \text{ but } W \propto \gamma$$

$$\Rightarrow FOS \propto \frac{1}{\gamma}$$

$\therefore$  for a canal slope, the critical condition is sudden drawdown condition.

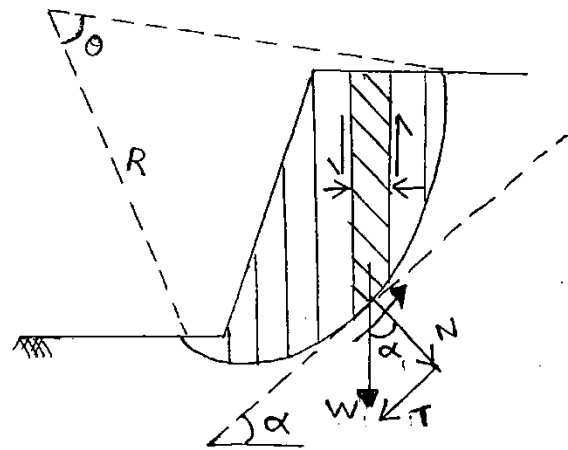
⑦ Canal will have more FOS when running full compared to sudden drawdown condition. 70

During sudden drawdown,  $\gamma$  increases to  $\gamma_{sat}$  and  $\therefore$  FOS decreases.

⑧ Among the various trials, the trial slip surface which gives min. factor of safety is called 'Critical Slip Surface' and that min. FOS is taken as the FOS of the slope.

### \* Method of Slices:

- used for all soils.
- trial and error.
- forces acting on the sides of slices are neglected.



$$N = W \cos \alpha$$

$$T = W \sin \alpha$$

$$F = \frac{cL + \sum N \tan \phi}{\sum T}$$

⑨ When there is seepage,

$$F = \frac{c'L + \sum (N - u) \tan \phi'}{\sum T}$$

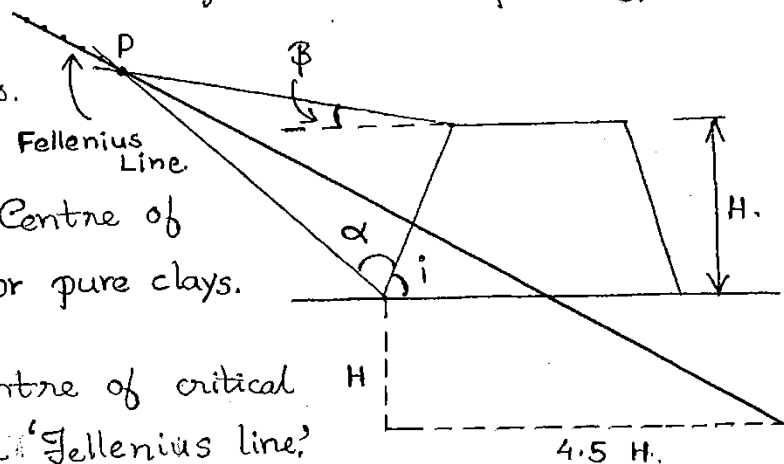
$\sum u \rightarrow$  sum of neutral forces.

⑩ Fellenius method to identify Critical Slip Circle:-

$\alpha, \beta \rightarrow$  direction angles.  
(depend on  $i$ )

Point 'P' represents Centre of Critical Slip circle for pure clays.

For  $c-\phi$  soils, the centre of critical slip circle lies on the 'Fellenius line'.



### \* Bishop's Method.

- forces acting on the sides of slices are also considered
- trial and error

### \* Friction Circle Method.

- trial and error

$c$  = cohesion

$c_m$  = mobilised cohesion.

$\phi$  = angle of internal friction.

$\phi_m$  = mobilised angle of internal friction.

$S$  = shear strength.

$S_m$  = mobilised shear strength.

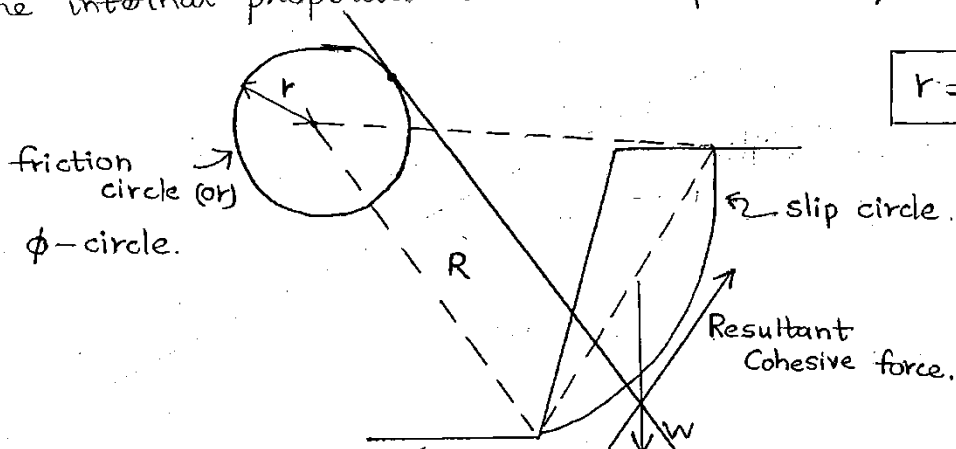
◉ 'Mobilised' means actually developed to keep system in eqbm. (wedge)

FOS wrt cohesion,  $F_c = \frac{c}{c_m}$

FOS wrt friction,  $F_\phi = \frac{\tan \phi}{\tan \phi_m}$

FOS wrt shear strength,  $F = \frac{S}{S_m} = \frac{c + \sigma \tan \phi}{c_m + \sigma \tan \phi_m}$

$\sigma$  remains the same as its related to weight, whereas  $c$  &  $\phi$  are internal properties which develops as required.



$$r = R \sin \phi$$

- ◉ For pure clay, ( $\phi = 0$ )  $\Rightarrow r = 0$
- ◉ Resultant of frictional force and normal reaction will be tangential to the friction circle.

## \* Taylor's Stability Number Method.

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— developed based on Friction Circle method.

$$\text{Stability number, } S_n = \frac{C}{F_c \cdot \gamma H}$$

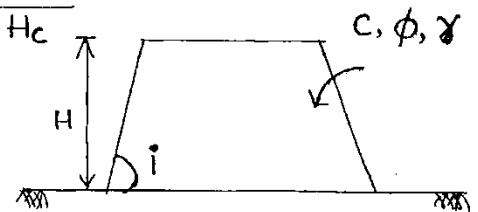
where  $F_c = \frac{C}{C_m} = \frac{H_c}{H}$ ;  $H_c \rightarrow$  critical height.

$H_c \rightarrow$  max. permitted height which can be provided for given soil against failure.

$H \rightarrow$  safe or actual height.

$$\Rightarrow S_n = \frac{C_m}{\gamma H} = \frac{C}{\gamma H_c}$$

$$\therefore F_c = \frac{C}{S_n \gamma H}$$



•  $S_n$  depends on  $i$  &  $\phi_m$  (or)  $i$  & depth factor

Knowing  $F\phi$  &  $\phi$  value,  $\phi_m$  can be calculated by:-

$$F\phi = \frac{\tan \phi}{\tan \phi_m}$$

Max. value of  $S_n = 0.261$  (for  $i = 90^\circ$  &  $\phi_m = 0$ )

• Except for cohesionless soil, this method is suitable for all soils. (for cohesionless,  $c = 0 \Rightarrow F_c = 0$ ; meaningless)

• For submerged slope, use  $\gamma'$

For sudden draw down condition, use  $\gamma_{sat}$  &  $\phi_m = \phi_w$

$$\phi_w = \text{weighted friction angle} = \frac{\gamma'}{\gamma_{sat}} \cdot \phi$$

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01.  $F = \frac{c + \gamma z \cos^2 i \tan \phi}{\gamma z \cos i \sin i} \rightarrow \text{for } c-\phi \text{ soil.}$

$i$  can be greater than  $\phi$ .

03.  $S_n = \frac{c}{F_c \gamma H} \Rightarrow F_c \propto \frac{1}{\gamma}$

04.  $F = \frac{\gamma' \tan \phi'}{\gamma_{sat} \tan i}$

$$1.5 = \frac{19 - 9.81}{9.81} \frac{\tan 36}{\tan i}$$

$$\underline{i = 13.18^\circ}$$

If no seepage,

$$F = \frac{\tan \phi}{\tan i} \Rightarrow F = \underline{3.10^\circ}$$

05. Ignoring the crack,

a)  $\theta = 109 + 12 = 121^\circ$

$$\hat{L} = R \theta \frac{\pi}{180} = 14.5 \times 121 \times \frac{\pi}{180} = 30.62$$

$$w = a \times 1 \times \gamma$$

$$= 110 \times 1 \times 18 = 1980$$

$$\bar{x} = 3.75 \text{ m.}$$

$$FOS = \frac{c \hat{L} R}{w \bar{x}} = \frac{27 \times 30.62 \times 14.5}{1980 \times 3.75} = \underline{1.61}$$

b).  $\theta = 109^\circ$ ,

$$L = R \theta \times \frac{\pi}{180} = 27.585$$

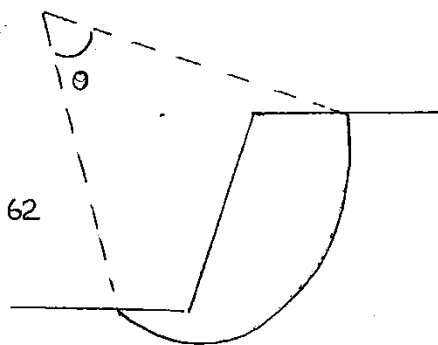
$$w = a \times 1 \times \gamma \quad \bar{x} = 3.75 \text{ m.}$$

$$= (110 - 1.5) \times 18$$

$$= 1953$$

$$F = \frac{c_u \hat{L} R}{w \bar{x}}$$

$$= \frac{27 \times 27.585 \times 14.5}{1953 \times 3.75} = \underline{1.47}$$



6.  $H = 25\text{m}$ ,  $C = 35$ ,  $\phi = 15^\circ$

a)  $\gamma = 20$ .

$$F_\phi = \frac{\tan \phi}{\tan \phi_m}$$

$$1.5 = \frac{\tan 15}{\tan \phi_m} \Rightarrow \phi_m \approx 10^\circ$$

For  $\phi_m = 10^\circ$ ,  $S_n = 0.06$ .

$$S_n = \frac{C}{F_c \gamma H}$$

$$0.06 = \frac{35}{F_c \times 20 \times 25} \Rightarrow F_c = \underline{\underline{1.167}}$$

b) If  $F_c = 1.5$ ,  $F_\phi = ?$

$$S_n = \frac{C}{F_c \gamma H} = 0.05$$

$$\phi_m = 12.5^\circ \text{ (From table given).}$$

$$F_\phi = \frac{\tan \phi}{\tan \phi_m} = \frac{\tan 15^\circ}{\tan 12.5^\circ} = \underline{\underline{1.208}}$$

7. Canal running full, (submerged condition)

a)  $S_n = \frac{C}{F_c \gamma' H}$

Since  $F_\phi$  is not given, take  $\phi_m = \phi$ .

$$\therefore \phi_m = 15^\circ \rightarrow S_n = 0.083.$$

$$S_n = \frac{C}{F_c \gamma' H}$$

$$0.083 = \frac{1.4}{F_c \times 0.945 \times 5}$$

$$\Rightarrow F_c = \underline{\underline{3.56}}$$

b) For suddenly draw down,

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$$S_n = \frac{C}{F_c \gamma_{sat} \cdot H}$$

$$\phi_m = \phi_w$$

$$\phi_w = \frac{\gamma'}{\gamma_{sat}} \phi \approx 7.5^\circ \Rightarrow S_n = 0.122$$

$$\Rightarrow 0.122 = \frac{1.4}{F_c \times 1.945 \times 5}$$

$$\therefore F_c = \underline{\underline{1.18}}$$

$$8. F_c = \frac{C}{C_m} = \frac{30}{22} = \underline{\underline{1.36}}$$

$$F_\phi = \frac{\tan \phi}{\tan \phi_m} = \frac{\tan 15}{\tan 12} = \underline{\underline{1.26}}$$

$$F = \frac{S}{S_m} = \frac{C' + \sigma \tan \phi'}{C_m + \sigma \tan \phi_m} = \frac{62.17}{47.5} = \underline{\underline{1.308}}$$

\* To find  $F_\phi$  when  $F_c = 1$ :

$$S_m = C_m + \sigma \tan \phi_m$$

$$47.5 = \frac{C}{F_c} + \frac{120 \tan \phi'}{F_\phi}$$

$$= \frac{30}{1} + \frac{120 \tan 15}{F_\phi}$$

$$\Rightarrow F_\phi = \underline{\underline{1.829}}$$

Similarly, to find  $F_c$  when  $F_\phi = 1$ .

$$47.5 = \frac{C}{F_c} + \frac{120 \tan \phi'}{1}$$

$$F_c = \underline{\underline{1.95}}$$

- Q A granular soil possesses  $\gamma_{\text{sat}} = 20 \text{ kN/m}^3$ . If  $\phi' = 35^\circ$ , and the designed FOS is 1.5, what is safe angle of slope for this soil when seepage occurs parallel to slope surface

$$F = \frac{\gamma'}{\gamma_{\text{sat}}} \frac{\tan \phi'}{\tan i}$$

$$1.5 = \frac{10}{20} \frac{\tan 35}{\tan i}$$

$$\Rightarrow i = \underline{\underline{13.14^\circ}}$$

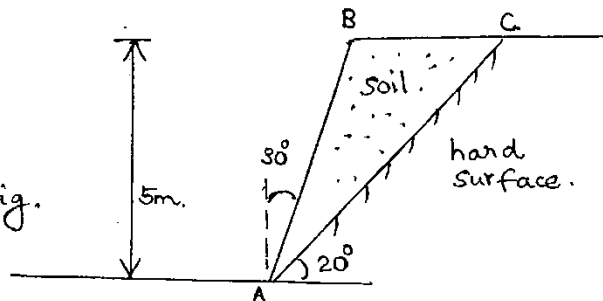
- Q  $C = 15 \text{ kN/m}^2$   
 $\phi = 20^\circ$   
 $\gamma = 18 \text{ kN/m}^3$

A slope is shown in the fig.

If the properties of soil

are as above, find the

FOS against possible wedge failure at the interface.



$$F = \frac{CL + N \tan \phi}{T}$$

$L$  = length of AC

$N$  = normal component of weight,  $w$  ;  $N = w \cos 20$

$w \rightarrow$  weight of wedge, ABC.

$T = w \sin 20$

$T$  = Tangential component of weight,  $w$ .

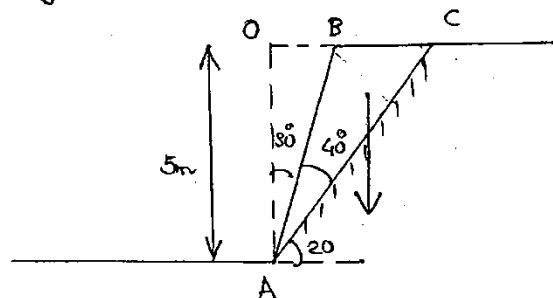
$$\tan 70^\circ = \frac{OC}{5}$$

$$OC = 13.73 \text{ m.}$$

$$\tan 30^\circ = \frac{OB}{5}$$

$$OB = 2.88 \text{ m.}$$

$$BC = OC - OB = 13.73 - 2.88 = 10.85 \text{ m.}$$



$$AC = \sqrt{5^2 + 13.73^2} = 14.61 \text{ m}$$

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$$W = \left( \frac{1}{2} \times 10.85 \times 5 \right) \gamma = 488.25 \text{ kN}$$

area of wedge

$$N = 488.25 \cos 20 = 458.805$$

$$T = 488.25 \sin 20 = 166.99$$

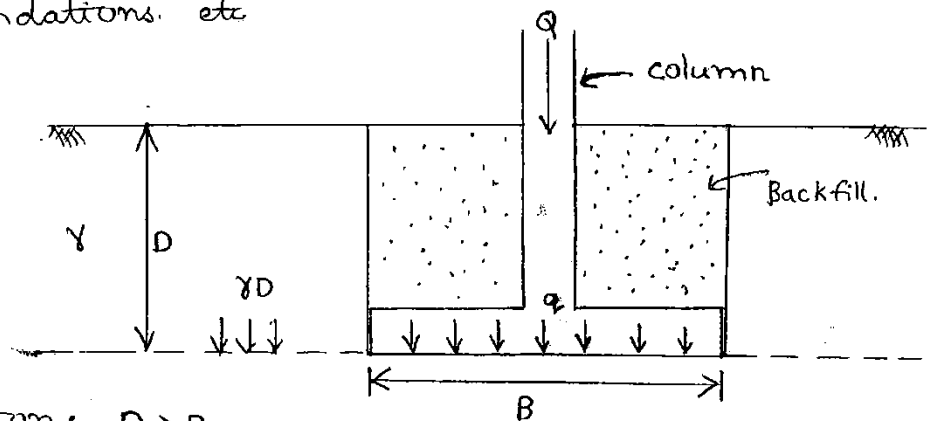
$$F = \frac{CL + N \tan \phi}{T} = \frac{15 \times 14.61 + 458.805 \tan 20}{167}$$
$$= \underline{\underline{2.31}}$$

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## 16. BEARING CAPACITY

\* Shallow Foundation :  $D \leq B$

Eg: Spread footings  
Raft foundations. etc



\* Deep Foundation:  $D > B$

Eg: Pile foundation  
Well foundation.

\* Original overburden pressure due to self weight of soil  
 $= \gamma D$

Gross Pressure  $= q$

Net Pressure,  $q_n = q - \gamma D$

\* Gross Ultimate BC of soil  
or Ultimate BC of soil }  $q_u$

Min. gross pressure required to cause shear failure

of soils

\* Net Ultimate BC of soil,  $q_{nu} = q_u - \gamma D$ .

Min. net pressure required to cause shear failure

of soils.

\* Net safe BC of soil,  $q_{ns} = \frac{q_{nu}}{F}$  ( $F=3$ )

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\* Gross safe BC of soil  
or Safe BC of soil }  $q_s = q_{ns} + \gamma D$

\* Net safe settlement pressure,  $q_{np}$ .

It is the <sup>max.</sup> net pressure which the soil can carry without exceeding allowable settlement.

\* Net Allowable BC of soil,  $q_{na} = \text{Smaller of } q_{ns} \text{ or } q_{np}$

$q_{ns} \rightarrow$  based on shear failure criteria

$q_{np} \rightarrow$  based on settlement criteria.

It is the net pressure at which soil neither fails in shear nor undergoes excessive settlement.

$\rightarrow$  Condition to be satisfied for Design of Foundation

The external pressure on soil  $\leq$  net allowable BC of soil

$$q_n \leq q_{na}$$

\* If footing is backfilled,

$$q_n \approx \frac{Q}{A}$$

where  $Q =$  column load.

$A =$  area of footing

\* If footing is not backfilled, (raft)

$$q_n = \frac{Q}{A} - \gamma D$$

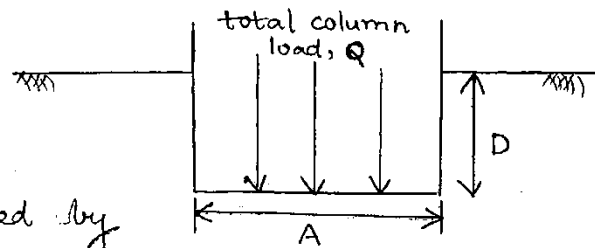
It is based on the assumption that self weight of concrete is equal to unit weight of soil ( $\gamma_c = 25$ ;  $\gamma_s = 20$ )

## → Compensated Raft Foundation. (Floating Raft)

$$q_n = \frac{Q}{A} - \gamma D.$$

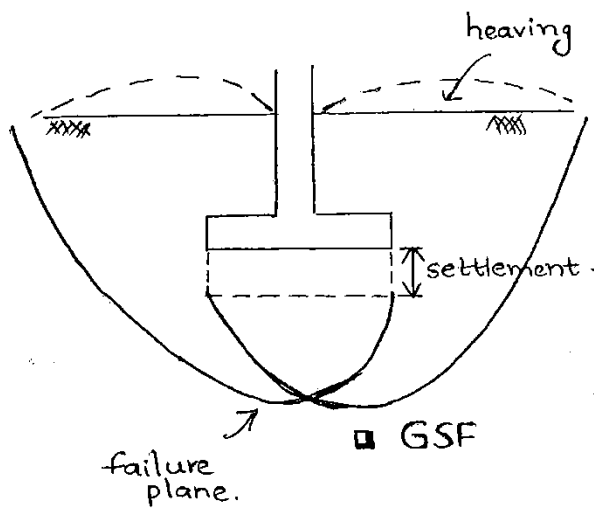
$$\text{If } \gamma D = \frac{Q}{A}; q_n = 0$$

Pressure applied is just balanced by pressure released.

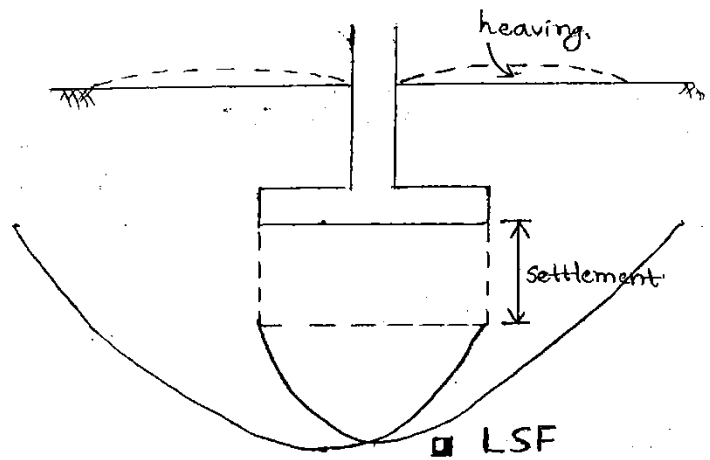


## → Types of Shear Failure:

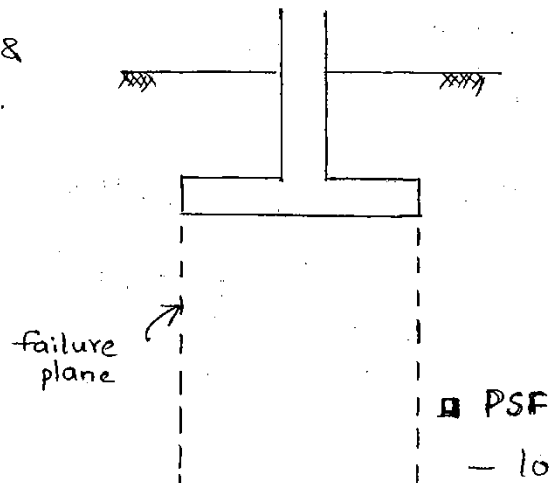
1. General Shear Failure (GSF)
2. Local Shear Failure (LSF).
3. Punching Shear Failure (PSF).



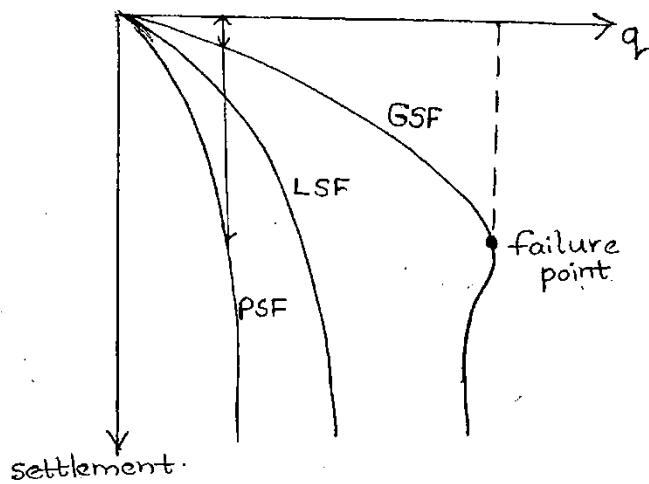
- dense sand & stiff clays.



- medium dense sand & medium clays.



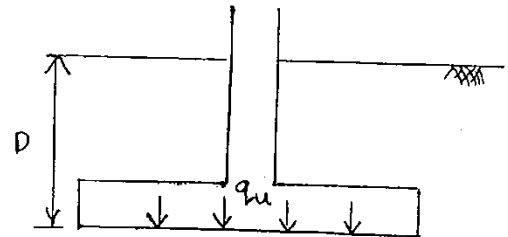
- loose sand & soft clays.



- For GSF, there will be a definite failure point.
- For the same load intensity,  $(\text{Settlement})_{\text{PSF}} > (\text{Settlement})_{\text{GSF}}$

### → Rankine's Theory

- Soil is cohesionless.
- Footing base is smooth.
- Plastic equilibrium.



$$q_u = \gamma D \left( \frac{1 + \sin \phi}{1 - \sin \phi} \right)^2$$

To avoid shear failure of soil, the min. depth of foundation required,

$$D_{\min} = \frac{q}{\gamma} \left( \frac{1 - \sin \phi}{1 + \sin \phi} \right)^2$$

$$D_{\min} = \frac{q}{\gamma} k a^2$$

However, as per this equation, as  $D=0$ ,  $q_u=0$ ; which is not possible. So this equation is not used to calculate bearing capacity.

### → Terzaghi's Theory

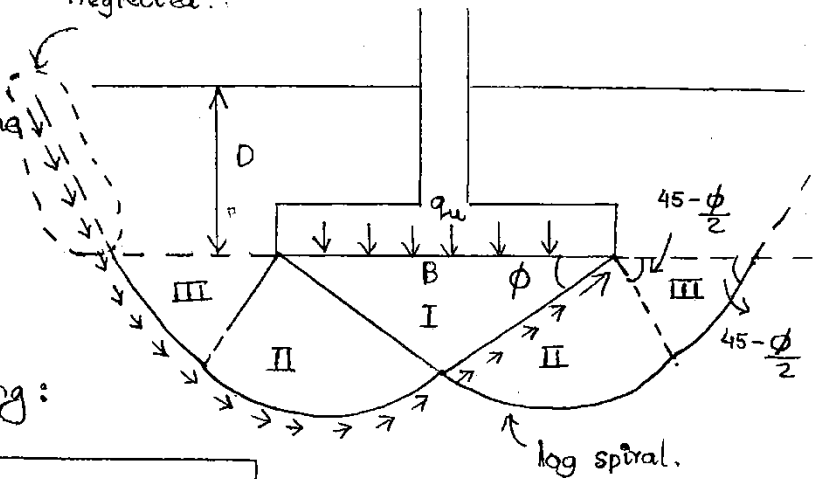
- Footing base is rough.
- shallow foundation
- Continuous footing (Strip footing,  $L \gg B$ )
- General Shear Failure.

Zone I: Elastic Zone

Zone II: Radial Shear Zone

Zone III: Rankine Passive Zone

neglected.



\* for Continuous footing:

$$q_u = C N_c + \gamma D N_q + 0.5 \gamma B N_\gamma$$

$N_c, N_q, N_\gamma \rightarrow$  Bearing Capacity Factors of Soil.  
(depends on  $\phi$ -value only)

$\phi$	$N_c$	$N_q$	$N_\gamma$

If  $\phi = 0$  (Pure Clay),

$$N_c = 5.7$$

$$N_q = 1$$

$$N_\gamma = 0$$

$\therefore$  For pure clay,

$$q_u = 5.7 C + \gamma D$$

$$q_{nu} = q_u - \gamma D.$$

$$\Rightarrow q_{nu} = 5.7 C$$

$q_{nu}$  is independent of B & D of foundation for pure clay.

$$q_u = C N_c + \gamma D N_q + 0.5 \gamma B N_\gamma$$

$$q_{nu} = q_u - \gamma D.$$

$$= C N_c + \gamma D (N_q - 1) + 0.5 \gamma B N_\gamma$$

$$\Rightarrow q_{ns} = \frac{q_{nu}}{F}$$

$$\therefore q_s = q_{ns} + \gamma D$$

\* for circular footing

$$q_u = 1.3 C N_c + \gamma D N_q + 0.3 \gamma B N_\gamma$$

where, B  $\rightarrow$  diameter of footing

\* for square footing

$$q_u = 1.3 C N_c + \gamma D N_q + 0.4 \gamma B N_\gamma$$

0.3, 0.5, 1.3, 0.4 are called 'shape factors'

\* for rectangular footing

$$q_u = \left(1 + 0.3 \frac{B}{L}\right) C N_c + \gamma D N_q + \left(1 - 0.2 \frac{B}{L}\right) 0.5 \gamma B N_\gamma$$

All the above equations are for GSF.

- For LSF, use  $C_m$  &  $\phi_m$  to find BC of soil.

$$C_m = \frac{2}{3} C \quad \& \quad \tan \phi_m = \frac{2}{3} \tan \phi$$

$$\therefore q_u = C_m N_c' + \gamma D N_q' + 0.5 \gamma B N_\gamma'$$

$N_c'$ ,  $N_m'$ ,  $N_\gamma'$  are based on  $\phi_m$  value.

- If  $\phi > 36^\circ \Rightarrow$  GSF

$\phi < 28^\circ \Rightarrow$  LSF

- If failure strain  $< 5\% \Rightarrow$  GSF

failure strain 10 to 20%  $\Rightarrow$  LSF

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$\rightarrow$  Effect of Water Table on Bearing Capacity of Soil:

$$q_u = \underset{\text{I}}{C N_c} + \underset{\text{II}}{\gamma D N_q} + \underset{\text{III}}{0.5 \gamma B N_\gamma}$$

$\swarrow$   
cohesion effect

$\swarrow$   
Depth effect

$\swarrow$   
width effect.

1. When water table is at or above GL

$$q_u = c'N_c + \gamma' D N_q + 0.5 \gamma' B N_\gamma$$

2. When water table is at footing level.

$$q_u = c'N_c + \gamma D N_q + 0.5 \gamma' B N_\gamma$$

3. When water table is at a level ③-③

⊙ No effect of water table.

4. When water table is at level ④-④

$$q_u = c'N_c + \gamma_a D N_q + 0.5 \gamma' B N_\gamma$$

$$\gamma_a = \frac{z_{w1} \gamma + (D - z_{w1}) \gamma'}{D}$$

5. When water table is at level ⑤-⑤

$$\gamma_a = \frac{z_{w2} \gamma + (B - z_{w2}) \gamma'}{B}$$

$$q_u = c'N_c + \gamma D N_q + 0.5 \gamma_a B N_\gamma$$

\* Approximate Method:

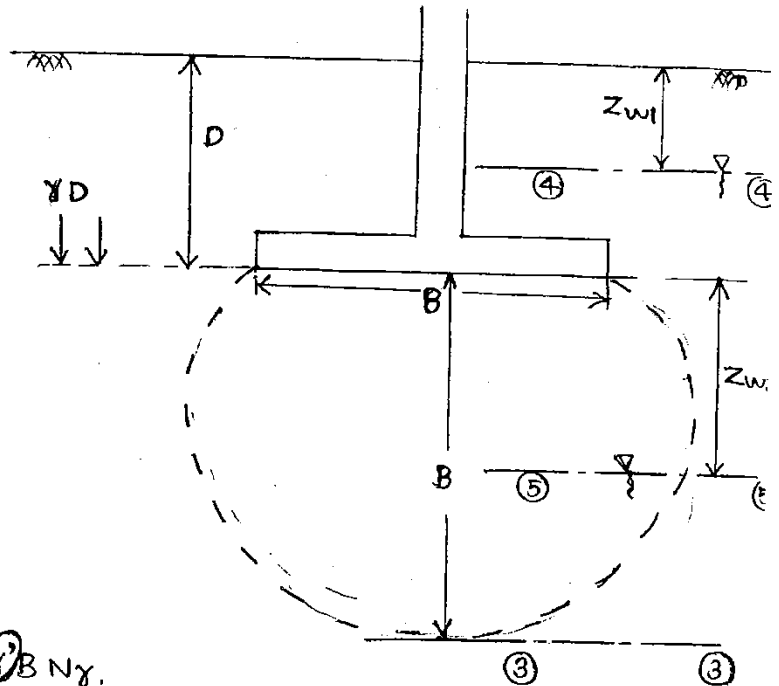
$$q_u = c'N_c + \gamma D N_q R_{w1} + 0.5 \gamma B N_\gamma R_{w2}$$

$R_{w1}$  &  $R_{w2} \rightarrow$  water table correction factors

$$R_{w1} = 0.5 \left( 1 + \frac{z_{w1}}{D} \right)$$

$$R_{w2} = 0.5 \left( 1 + \frac{z_{w2}}{B} \right)$$

$$0.5 \leq R_w \leq 1$$



If WT is at GL:

$$Z_{w1} = Z_{w2} = 0$$

$$R_{w1} = R_{w2} = 0.5$$

If WT at footing level: (77)

$$Z_{w1} = D ; R_{w1} = 1$$

$$Z_{w2} = 0 ; R_{w2} = 0.5$$

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If WT is below the footing:

$$R_{w1} = 1 \text{ (no correction reqd.)}$$

If WT is above footing:

$$Z_{w2} = 0$$

$$R_{w2} = 0.5$$

If WT is at a depth B below footing:

$$R_{w1} = R_{w2} = 1 \text{ (no correction reqd.)}$$

For cohesionless soils,

$$q_u = \gamma D N_q R_{w1} + 0.5 \gamma B N_\gamma R_{w2}$$

① If WT is at or above GL,  $R_{w1} = R_{w2} = 0.5$

$$q_u = \gamma D N_q (0.5) + (0.5 \gamma B N_\gamma) (0.5)$$

$R_{w1} \qquad R_{w2}$

$\therefore$  for cohesionless soils, bearing capacity reduces by 50% when WT raised to GL.

In case of cohesive soils, the effect of WT on the bearing capacity is negligible.

$$q_{nu} = 5.7 C \text{ (no '}\gamma\text{' included)}$$

→ Skempton's Theory:

- For cohesive soils only ( $\phi = 0$ )

$$q_{nu} = C N_c$$

- For strip footing:

$$N_c = 5 \left( 1 + 0.2 \frac{D}{B} \right)$$

$$5.14 \leq N_c \leq 7.50$$

- For rectangular footing:

$$N_c = 5 \left( 1 + 0.2 \frac{D}{B} \right) \left( 1 + 0.2 \frac{B}{L} \right)$$

$$6.2 \leq N_c \leq 9$$

## → Plate Load Test.

- to find BC and settlements.

\* Specifications:

Min. size of plate

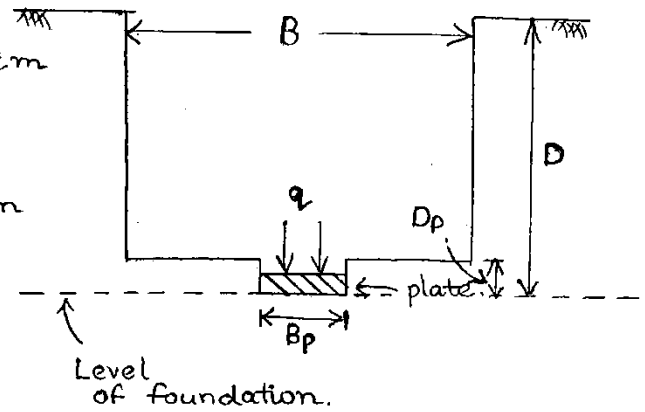
$$= 30 \text{ cm} \times 30 \text{ cm}$$

Max. size of plate

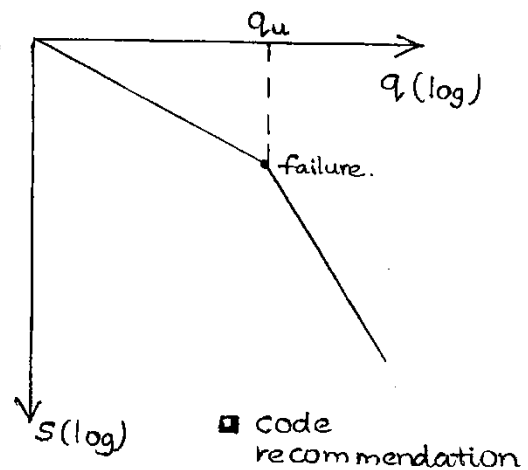
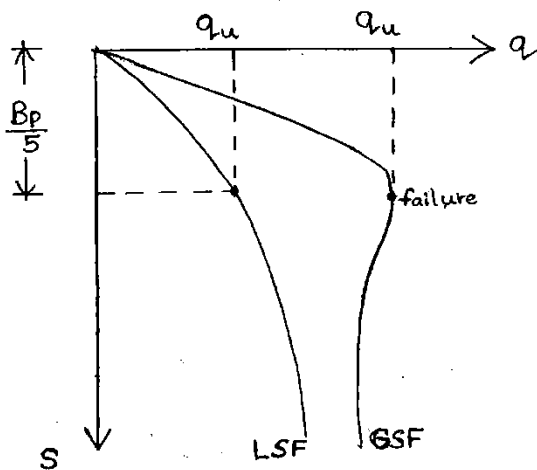
$$= 75 \text{ cm} \times 75 \text{ cm}$$

Min. thickness = 25 mm (1")

$$\frac{B}{B_p} = 5 \quad \& \quad \frac{D}{D_p} = 5$$



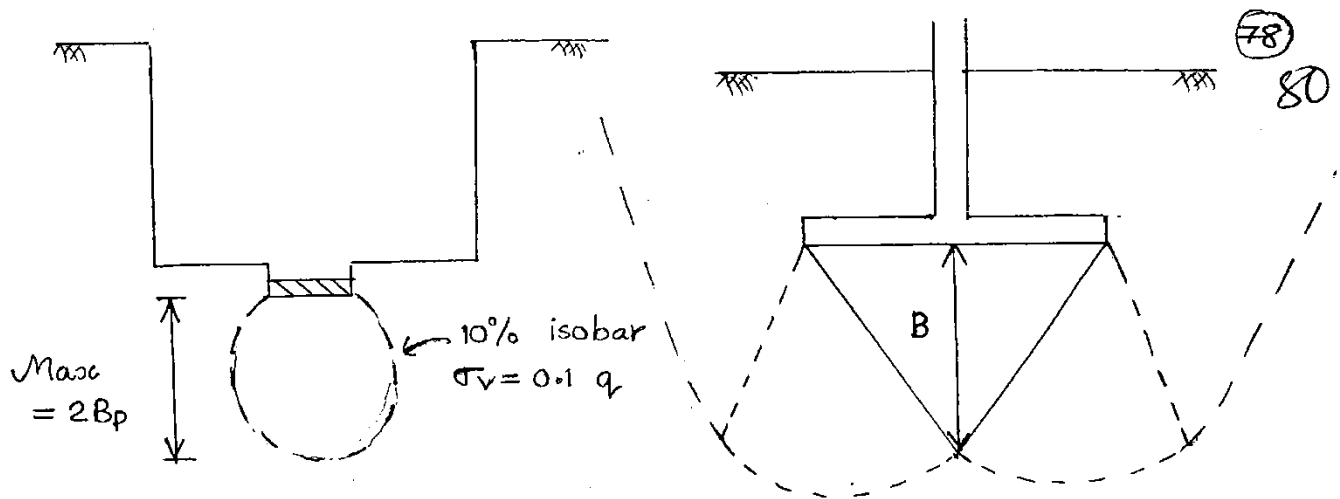
- Initially, a seating pressure of 7.5 kPa applied



$$\text{Safe bearing capacity, } q_s = \frac{q_u}{F}$$

\* Limitations of Plate Load test:

- (i) It is a short duration test. Hence not reliable for pure clays. (consolidation settlement occurs for pure clays)
- (ii) There is a width effect. ( $q_u$  depends on  $B$  in Terzaghi's theory & Skempton's theory)
- (iii) Depth effect. (max. depth of pressure bulb in plate load test =  $2B_p$ )



→ Corrections for Plate Load test Results:

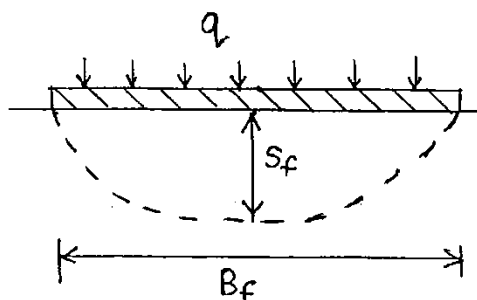
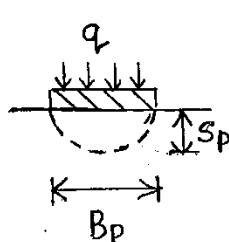
\* Correction for Settlements

(i) For clays

$$\frac{S_F}{S_p} = \frac{B_F}{B_p} \Rightarrow S \propto B$$

(ii) For sands.

$$\frac{S_F}{S_p} = \left[ \frac{B_F (B_p + 0.3)}{B_p (B_F + 0.3)} \right]^2 \quad B_F \text{ \& } B_p \text{ in metres}$$



□  $q$  is same in both plate & footing

\* Correction for Bearing Capacity

(i) For clays

$$q_f = q_p \quad (q_u \text{ independent of } B)$$

(ii) For sands

$$\frac{q_f}{q_p} = \frac{B_f}{B_p}$$

→ Meyerhof's Theory:

- For both shallow and deep foundations.

$$q_u = C N_c S_c d_c i_c + \gamma D N_q S_q d_q i_q + 0.5 \gamma B N_{\gamma} S_{\gamma} d_{\gamma} i_{\gamma}$$

$S \rightarrow$  shape factor

$D \rightarrow$  depth factor

$i \rightarrow$  load inclination factor.

\* For (DL + LL) → BC obtained by formulae can be used directly.

For DL + LL + WL  
DL + LL + EL } → above BC is increased by 25%

→ Loads for Settlement Calculation:

\* For sands: DL + LL + WL or EL

For clays: Permanent loads (DL + 50% LL)

→ Settlements

\* Uniform Settlement: equal settlement everywhere.

\* Differential Settlement: more detrimental to struct (additional moments are created)

Differential settlement  $\approx$  75% of total uniform settlement

\* Permissible limits:

	Isolated Foundations	Raft Foundations <span>↙ differential settlements.</span>
Sand & Hard clay	50 mm	75 mm
Plastic clay (settlement occurs slowly for plastic clay)	75 mm	100 mm

01.  $q_{ns} = \frac{1}{F} (C N_c) ; \text{ for clay.}$

Usually,  $F \approx 3$  &  $N_c = 5.7$  for clays.

$$q_{ns} = \frac{1}{3} (C \times 5.7) \approx 2C \Rightarrow \text{unconfined compressive strength.}$$

02.  $B = 3 \text{ m}, \gamma_{\text{sat}} = 20 \text{ kN/m}^3, \phi = 35^\circ, C = 0, N_q = 33, N_\gamma = 34.0$   
 $D = 2 \text{ m}, \gamma = 18 \text{ kN/m}^3$

(i). WT at GL

$$q_u = 1.3 C' N_c + \gamma' D N_q + 0.4 \gamma' B N_\gamma$$

$$= 0 + 10 \times 2 \times 33 + 0.4 \times 34 \times 3 \times 10 = \underline{\underline{1068 \text{ kPa}}}$$

(ii) WT at footing level

$$q_u = \gamma D N_q + 0.4 \gamma' B N_\gamma$$

$$= 18 \times 2 \times 33 + 0.4 \times 10 \times 3 \times 34 = \underline{\underline{1596 \text{ kPa}}}$$

(iii) at 1 m below footing

$$R_{w2} = 0.5 \left( 1 + \frac{1}{3} \right) = 0.666$$

$$q_u = 18 \times 2 \times 33 + 0.4 \times \overset{20}{18} \times 3 \times 34 \times 0.66 \quad \left\{ \text{use accurate method} \right\}$$

$$= \underline{\underline{1460 \text{ kPa}}}$$

(iv) at 1 m below GL.

$$\gamma_a = \frac{\gamma Z_{w1} + \gamma' (D - Z_{w1})}{D} = \frac{18 \times 1 + 10 \times (2 - 1)}{2} = 14$$

$$q_u = 14 \times 2 \times 33 + 0.4 \times 10 \times 3 \times 34 = \underline{\underline{1332 \text{ kPa}}}$$

03. Strip footing  $\rightarrow$  WT at footing.

$$q_{ns} = \frac{1}{F} (C N_c + \gamma D (N_q - 1) + 0.5 \gamma' B N_\gamma)$$

For short term condition: use  $C_u$  &  $\phi_u$

For long term condition: use  $C'$  &  $\phi'$

a) Short term:

$$q_{ns} = \frac{1}{2} (80 \times 6 + 16 \times 1(1-1) + 0) \\ = \underline{\underline{240 \text{ kPa}}}$$

b) Long term:

$$q_{ns} = \frac{1}{2} (0 \times 37.2 + \frac{16}{2.5} \times 1(22.5-1) + 0.5 \times 10 \times 2 \times 19.7) \\ = \underline{\underline{270.5}}$$

4. For clays:

$$q_s = \frac{1}{F} (C N_c) + \gamma D$$

$$N_c = 5.7 \text{ for rough base (Terzaghi)} \\ = 5.14 \text{ for smooth base (Prandtl)}$$

$$C = \frac{1}{2} \times q_u = 10 \text{ t/m}^2.$$

$$q_s = \frac{1}{2} (10 \times 5.14) + 2 \times 1 = \underline{\underline{27.7 \text{ t/m}^2}}$$

5. For design purpose, the condition to be satisfied:

$$q_n \leq q_{na} \quad \rightarrow \text{smaller of } q_{ns} \text{ \& } q_{np}$$

Since  $q_{np}$  is not given,  $q_{na} = q_{ns}$ .

$$\therefore q_n \leq q_{ns}$$

$$q_n = \frac{Q}{A} = \frac{1000}{B^2} \text{ kN/m}^2$$

$$q_{ns} = \frac{1}{F} (1.3 C N_c + \gamma D (N_q - 1) + 0.4 \gamma B N_\gamma) \\ = \frac{1}{2.5} (0.4 \times 19 \times B \times 42).$$

$$\Rightarrow \frac{1000}{B^2} = (0.4 \times 19 \times B \times 42) \times \frac{1}{2.5}$$

$$\Rightarrow B = 1.98 \text{ m} \approx \underline{\underline{2 \text{ m}}}$$

Since  $q_{np}$  not given,

$$q_n \leq q_{ms}$$

$$\text{or } q \leq q_s$$

$$q = \frac{300}{B \times 1} \text{ kN/m}^2$$

$$q_n = q - \gamma D = \frac{300}{B} - 18 \times 1$$

$$q_{ms} = \frac{1}{F} (C N_c) = \frac{1}{3} (60 \times 5.7) = 114$$

$$\frac{300}{B} - 18 = 114$$

$$\therefore B = \underline{\underline{2.27 \text{ m}}}$$

\* For cohesionless soil  $\rightarrow$  use  $\phi$  to decide GSF & LSF

For cohesive soil.  $\rightarrow$  use  $C$  to decide GSF & LSF

For  $c-\phi$  soil  $\rightarrow$  use strain to decide GSF & LSF

007. Elastic settlement,  $S_i = \frac{q_n}{E_s} B (1-\mu^2) I.$

$$\boxed{S_i \propto q_n}$$

$$\therefore \frac{S_2}{S_1} = \frac{q_2}{q_1}$$

$$\frac{10}{25} = \frac{q_2}{7.2 / 0.3^2}$$

$$\Rightarrow q_2 = \underline{\underline{32 \text{ t/m}^2}}$$

008.  $q_n = q - \gamma D.$

$$0 = 150 - 20 D$$

$$\Rightarrow D = \underline{\underline{7.5 \text{ m}}}$$

9.  $B_p = 0.3 \text{ m}$ ,  $B_F = 1.5 \text{ m}$

$q_p = 6 \text{ t/m}^2$ ,  $q_f = ?$

For sands,

$$\frac{q_f}{q_p} = \frac{B_F}{B_p}$$

$$\frac{q_f}{6} = \frac{1.5}{0.3} \Rightarrow q_f = 30 \text{ t/m}^2$$

Load = area  $\times q_f = 1.5^2 \times 30 = \underline{\underline{67.5 \text{ tons}}}$

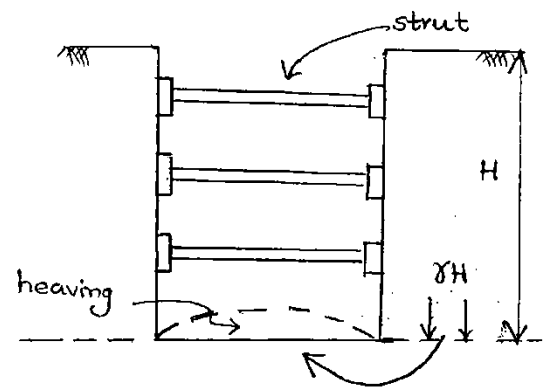
→ Braced Excavations - Heave Failure of Bottom

Factor of safety against heave

failure,  $F = \frac{CN_c}{\gamma H}$

$N_c = 5.7$  (Terzaghi).

$= 5 \left( 1 + 0.2 \frac{D}{B} \right)$ ; Skempton's theory



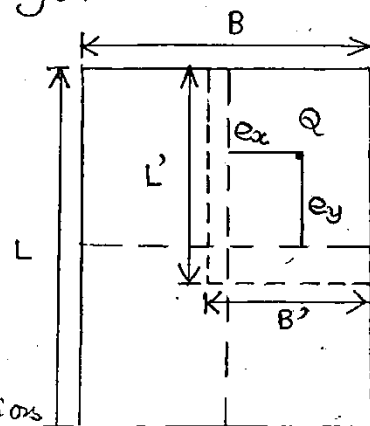
10.  $N_c = 5 \left( 1 + 0.2 \times \frac{5}{2.5} \right) = \underline{\underline{7}} \quad (D = H)$

FOS =  $\frac{CN_c}{\gamma H} = \frac{20 \times 7}{20 \times 5} = \underline{\underline{1.4}}$

Bearing Capacity of Eccentric Footings:

For eccentric footings, modified dimensions (reduced) are to be taken to calculate the bearing capacity. The reduced dimensions are taken in such a manner that the load acting point should become the CG of modified dimensions.

$$B' = 2 \left( \frac{B}{2} - e_x \right) \quad \& \quad L' = 2 \left( \frac{L}{2} - e_y \right)$$



Accordingly the modified dimensions  $B'$ ,  $L'$ ,  $A'$  are shown below: 83

$$B' = B - 2e_x$$

$$L' = L - 2e_y$$

$$A' = B' L'$$

$$\therefore q_u = \left(1 + 0.3 \frac{B'}{L'}\right) C N_c + \gamma D N_q + 0.5 \gamma B' N_\gamma \left(1 + 0.2 \frac{B'}{L'}\right)$$

$$\text{Safe load capacity, } Q_{\text{safe}} = A' q_s$$

# PILE FOUNDATIONS

- Deep Foundation.
- Punching shear failure occurs

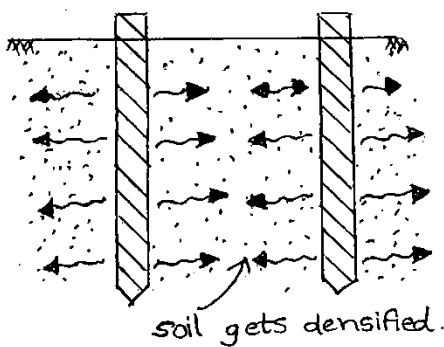
→ Necessity of Pile foundation:

- if loads are heavy, and soil is poor.
- in expansive soils (like black cotton soil)
- to transfer loads onto a hard stratum.
- to resist uplift loads, horizontal loads etc.
- to reduce settlements.

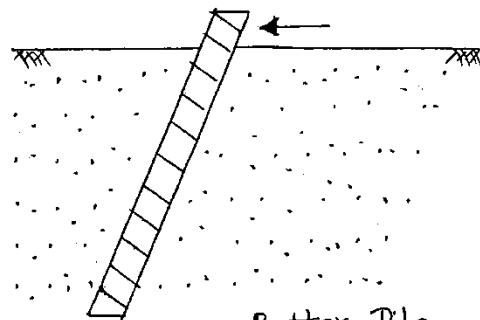
→ Classification of Piles:

\* Based on Function (or purpose).

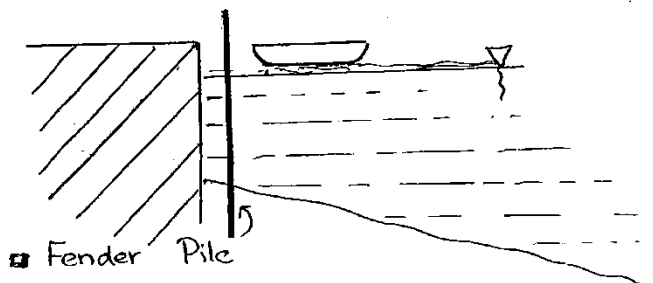
- compaction pile.: to compact the soil (loose & medium sand,
- tension pile: to resist uplift loads.
- batter pile.: inclined pile to resist lateral load.
- anchor pile: to anchor the structure
- Fender or dolphin pile.: for protection of water front structures



■ Compaction pile.



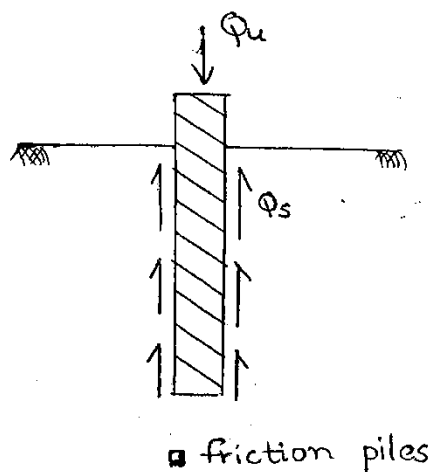
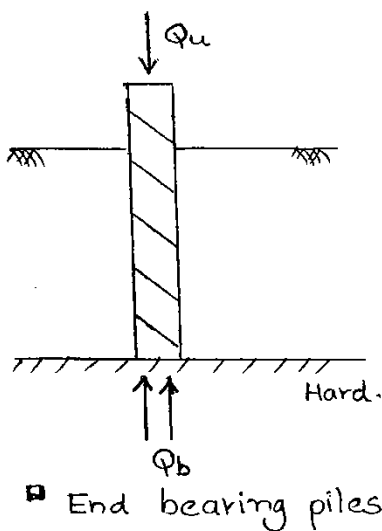
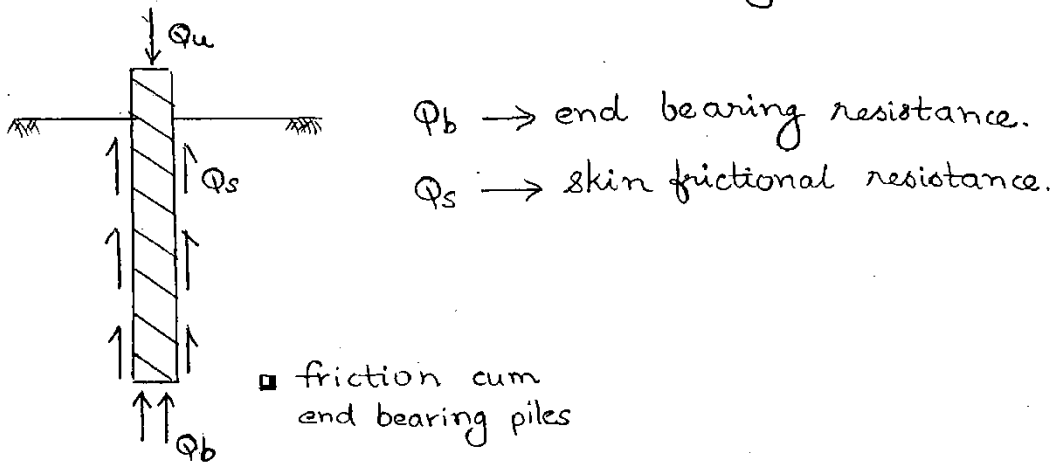
■ Batter Pile.



■ Fender Pile

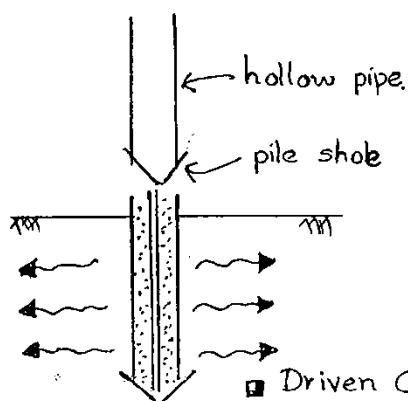
### \* Based on Load Transfer.

- Friction Pile : generally in clays.
- End bearing Pile : pile resting on hard stratum
- Friction cum end bearing pile : generally in sands



### \* Based on Construction

- Precast driven pile : in loose sand & medium dense sand
- Driven cast-in-situ pile.: in loose sand & "
- Bored cast-in-situ pile.: in clays.



- Hollow pipe is driven into soil
- Pile is casted in site using steel rft. & concrete in the hollow pipe.
- Hollow pipe is removed using cranes immediately after casting the piles.

→ Pile driving Equipment:

- Simple drop hammer
- Single acting steam hammer.
- Double acting steam hammer
- Diesel hammer
- vibratory driving system: least noise. (no hammers used in loose soils).

→ Load Carrying Capacity of Pile:

1. Static Formulae
2. Dynamic Formulae.
3. Pile load tests.
4. N-Value method (N-SPT value)

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\* Static Formulae:

$$Q_u = Q_b + Q_s$$

$$= A_b f_b + A_s f_s$$

$A_b$  → area of pile at pile base  
( $= \pi/4 d^2$ )

$f_b$  → bearing capacity of soil at pile base level.

$A_s$  → <sup>skin.</sup> surface area of pile. ( $= \pi d l$ )

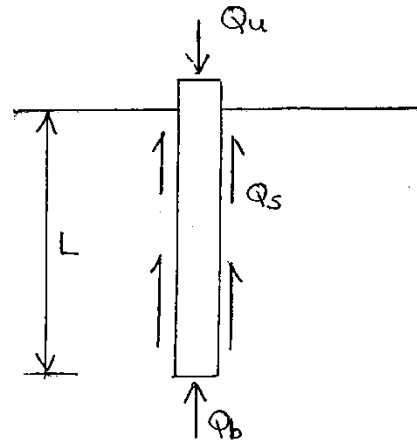
$f_s$  → shear resistance of soil, surrounding the pile shaft

a) For clays: ( $\phi = 0$ )

$$f_b = C N_c$$

$C$  : cohesion at pile base level.

$$N_c = 9 \quad (\text{for } \phi = 0)$$



$$f_s = \alpha C_2$$

$$S = c + \sigma \tan \phi$$

$$S = c + 0.$$

$C_2$  : cohesion of soil along the pile shaft.

$\alpha$  : shear mobilisation factor (or) adhesion factor

$\alpha = 1$  ; for soft clay

$\alpha < 1$  ; for stiff clay.

$\therefore$

$$Q_u = A_b C_1 N_c + A_s \alpha C_2$$

$$Q_{safe} = \frac{Q_u}{F}$$

29th Sept,  
MONDAY

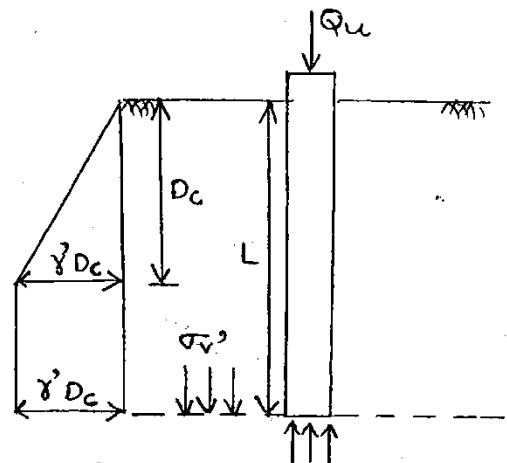
b) Single Pile in Sand ( $c=0$ )

$$Q_u = A_b f_b + A_s f_s$$

To find  $f_b$ :

$$f_b = \sigma_v' N_q$$

$\sigma_v'$  = effective vertical stress at pile base level.



$D_c \rightarrow$  critical depth : depth upto which  $\sigma_v'$  increases and then remains a constant.

$D_c = 10d$  to  $20d$  ; depending on soil type

$$\therefore f_b = \sigma_v' N_q$$

$$\Rightarrow \begin{cases} \sigma_v' = \gamma' D_c & ; \text{ if } L \geq D_c \\ \sigma_v' = \gamma' L & ; \text{ if } L < D_c \end{cases}$$

To find  $f_s$ :

$$f_s = k \cdot \sigma_a' \cdot \tan \delta$$

$\sigma_a'$   $\rightarrow$  average effective vertical stress along the pile shaft.

$k \rightarrow$  coefficient of lateral earth pressure.

'K' is found out from field in-situ test for pile. (8)

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$K = 1 \text{ to } 3$ ; depending on soil type.

$\delta \rightarrow$  angle of friction b/w pile and soil

$\delta = \phi$ ; as per BIS

For Clay:

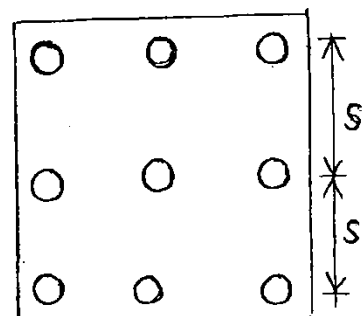
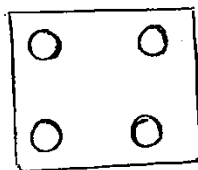
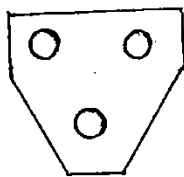
$$Q_u = A_b C_1 N_c + A_s \cdot \alpha C_2$$

For Sand:

$$Q_u = A_b \sigma_v' N_q + A_s K \cdot \sigma_a' \tan \delta$$

### $\rightarrow$ Group Piles

- under a column, a min. of 3 piles shall be used.



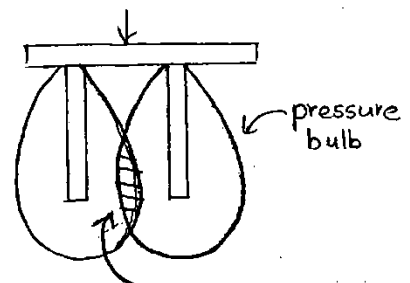
$S \rightarrow$  min spacing b/w c/c of piles.

$S = 3d$  ; for friction piles.

$= 2.5d$  ; for end bearing piles.

- Benefits of group piling are:

- Increases reliability.
- eccentricity is avoided.



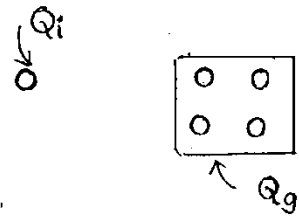
- Min spacing is recommended to avoid "stress overlap"  
(Due to stress overlap, settlement increases)

\* Pile Group Efficiency,  $\eta_g = \frac{Q_g}{n \cdot Q_i} \times 100$

$Q_g \rightarrow$  total group capacity.

$n \rightarrow$  no. of piles in the group.

$Q_i \rightarrow$  capacity of single, in isolation.



$\eta_g$  is the ratio of average capacity of a single pile in a group action to the single capacity of a pile in isolation. (OR) is the ratio of total capacity of a group pile to the sum of capacities of individual piles in isolation.

$\eta_g > 100\%$  ; for loose & medium dense sands

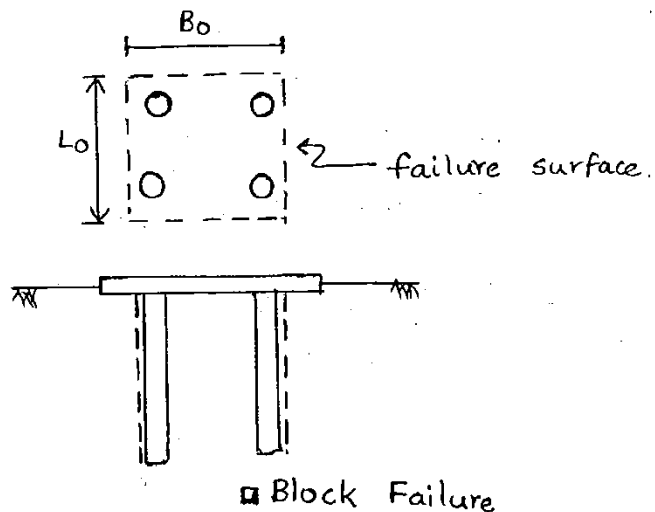
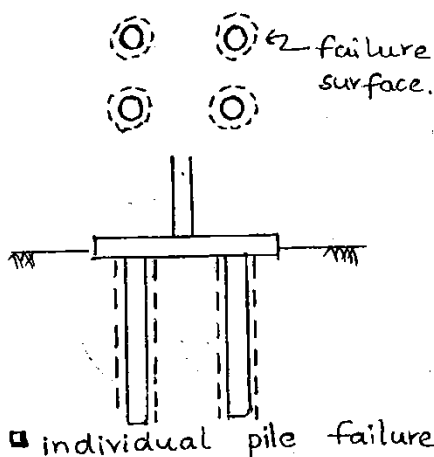
$\eta_g < 100\%$  ; for dense sand & clays

Loose and medium dense sands gets compacted upon group piling and  $\therefore \eta_g > 100\%$ .

\* Modes of failure of Pile Group:

(i) Individual Pile Failure.

(ii) Block Failure.



\* Pile Group Capacity based on Individual Failure mode

$$Q_{gi} = n Q_i$$

$$= n (A_b C_1 N_c + A_s \alpha C_2) \rightarrow \text{for clay}$$

$$= n (A_b \sigma'_v N_q + A_s K \cdot \sigma'_a \tan \phi) \rightarrow \text{for sand}$$

\* Pile Group Capacity based on Block Failure mode:

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$$Q_{gb} = A_B \cdot C_1 N_c + A_s C_2 \rightarrow \text{for clay}$$

$$= A_B \cdot \sigma'_v N_q + A_s K \cdot \sigma'_a \tan \phi \rightarrow \text{for sand}$$

$A_B \rightarrow$  area of block  $= B_o \cdot L_o$

$A_s \rightarrow$  perimeter of block  $\times L = 2(B_o + L_o) \cdot L$

$\alpha$  is adhesion factor.

$\alpha = 1$  for block failure because contact is b/w soil & soil.

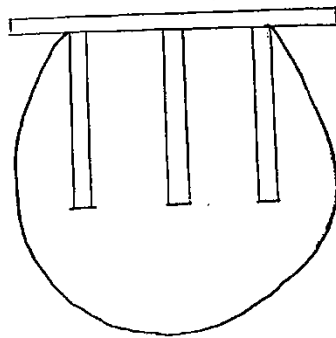
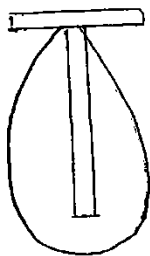
$\alpha < 1$  for individual pile as contact is b/w soil & pile.

$\therefore$  Pile group capacity,  $Q_g = \text{Smaller of } Q_{gi} \text{ \& } Q_{gb}$

$$\text{Safe capacity, } = \frac{Q_g}{F}$$

NOTE:

Settlement of a group pile is always more than that of a single pile. (due to larger size of pressure bulb)



larger pressure bulb  
 $\Rightarrow$  more soil gets compressed, and  
 $\therefore$  more settlement.

$\rightarrow$  Empirical Formulae to find  $n_g$ :

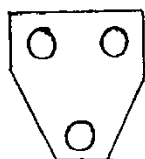
1. Feld's Rule.

In this rule, for every nearby pile,  $\frac{1}{16}$ th capacity is reduced. (for all types of soil)



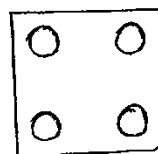
$$n_g = 1 - \frac{1}{16}$$

$$= \frac{15}{16} //$$



$$n_g = 1 - 2 \times \frac{1}{16}$$

$$= \frac{14}{16} //$$



$$n_g = 1 - 3 \times \frac{1}{16}$$

$$= \frac{13}{16} //$$

## 2. Converse - Lebarre Formula.

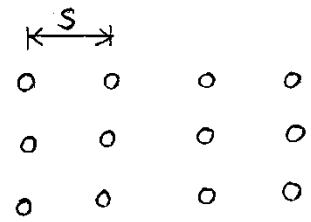
$$\eta_g = 1 - \frac{\theta^\circ}{90} \left( \frac{m(n-1) + n(m-1)}{m \cdot n} \right)$$

$$\theta^\circ = \tan^{-1} \left( \frac{d}{s} \right)$$

$m$  = no: of rows of piles.

$n$  = no: of piles in each row.

$d \rightarrow$  diameter of pile ;  $s \rightarrow$  spacing b/w piles



## $\rightarrow$ Dynamic Formulae:

### 1. Engineering News Formula

$S \rightarrow$  set value or settlement per blow.

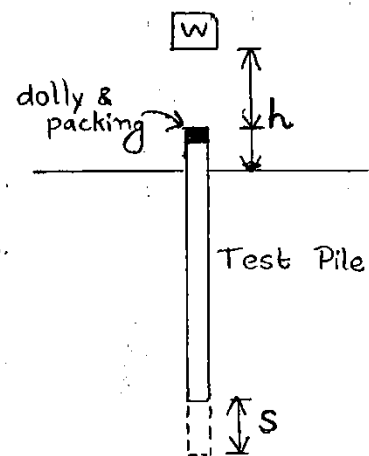
$$Q_{\text{safe}} = \frac{Wh\eta_h}{F(s+c)}$$

$C \rightarrow$  a constant

$C = 2.54 \text{ cm}$  for drop hammer

$= 0.254 \text{ cm}$  for steam hammer

$F \rightarrow$  factor of safety (min. of 6)



### 2. Hiley's Formula.

$$Q_{\text{safe}} = \frac{Wh\eta_h \cdot \eta_b}{F(s + C/2)}$$

$\eta_h \rightarrow$  efficiency of hammer

$\eta_b \rightarrow$  efficiency of blow.

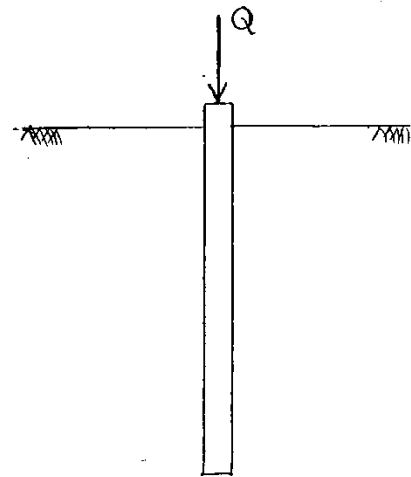
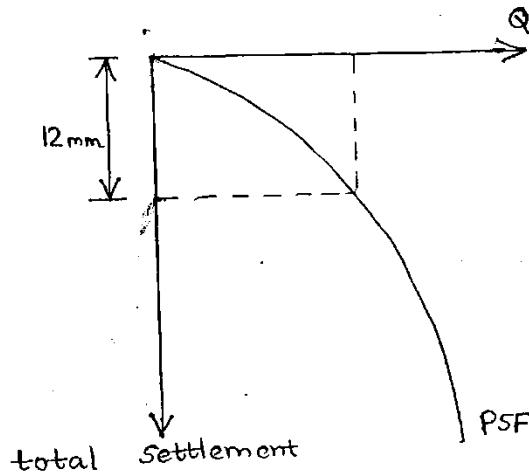
$C \rightarrow$  total <sup>temporary</sup> elastic compression of soil, pile & packing.

$$C = C_1 + C_2 + C_3$$

As this test is based on 'short term loading', it is suitable only for sand and not for clays.

(83)  
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### → Pile Load Test

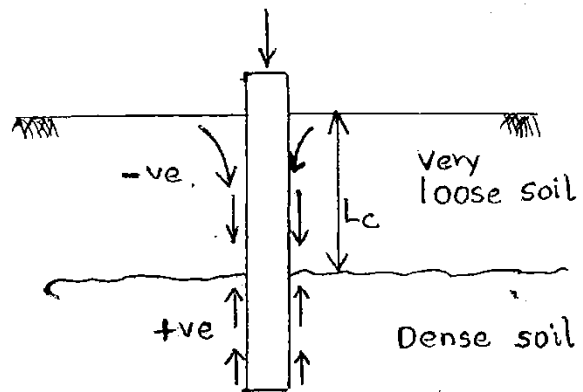


Safe load is taken as the smaller of the following:

- (i)  $\frac{2}{3}$  of load corresponding to a <sup>total</sup> settlement of 12 mm.
- (ii)  $\frac{2}{3}$  of load corresponding to a net settlement of 6 mm.
- (iii)  $\frac{1}{2}$  of load corresponding to a total settlement of 10% d.

### → Negative Skin Friction:

When loose soil compacts, it drags the pile along with it. Negative skin friction occurs when settlement of loose soil due to compaction is more than the settlement of pile due to external loading.



\* Negative Skin Friction occurs in the case of:

(i) Recently filled up soil.

(ii) Very loose sand.

(iii) Soft clay.

(iv) Due to lowering of WT ( $\sigma' \uparrow$  and settlement increases)

(v) Pile driving operations nearby.

\* Negative Skin Friction can be reduced by:

(i) Keeping the surface of pile smooth in areas of loose sand.

(ii) Providing a sleeve to the pile and isolating it from surrounding loose sand.

\* To calculate negative skin friction:

(i) In Clays:-

$$Q_{nf} = \pi d L_c \alpha C. \quad (\text{usually } \alpha = 1)$$

(ii) In Sands:-

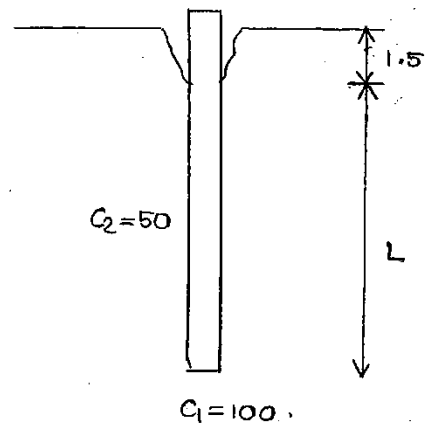
$$Q_{nf} = \pi d L_c k \cdot \sigma'_a \tan \delta$$

1<sup>st</sup> Oct,  
WEDNESDAY. → R

$$1. \quad Q_u = A_b C_1 N_c + A_s \alpha \cdot C_2$$

$$= \frac{\pi}{4} \times 0.3^2 \times 100 \times 9 + \pi \times 0.3 \times 5 \times 0.3 \times 50$$

$$= \underline{\underline{134 \text{ kN}}}$$



$$2. \quad Q_{safe} = \frac{1}{F} (A_b C_1 N_c + A_s \alpha C_2)$$

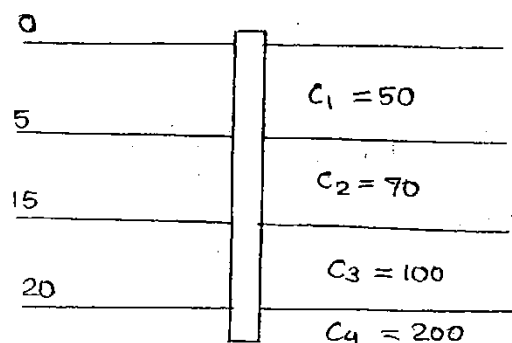
$$400 = \frac{1}{2.5} \left( 0.45^2 \times 100 \times 9 + 4 \times 0.45 \times L \times 0.75 \times 100 \right)$$

$$\Rightarrow \underline{\underline{L = 6.05 \text{ m}}}$$

$$3. \quad Q_{safe} = \frac{1}{F} (A_b C_1 N_c + A_s \alpha C_2)$$

$$= \frac{1}{2.5} \left( \frac{\pi}{4} \times 0.5^2 \times 200 \times 9 + \pi \times 0.5 \times 0.4 (50 \times 5 + 70 \times 5 + 100 \times 5 + 200 \times 5) \right)$$

$$= \underline{\underline{669.16 \text{ kN}}}$$



904.

1





1





05.

9



D

Q

b2

0

$$Q_{gi} = Q_{gb}$$

$$n (\pi d L \alpha c) = 4 \times B_o \times L \times C$$

$$16 (\pi \times d \times L \times 0.6 C) = 4 (3s + d) L C$$

$$\Rightarrow s = \underline{\underline{2.18d}}$$

07. Safe capacity of single isolated pile,

$$Q_i = \frac{1}{F} \left( \frac{\pi}{4} d^2 \times C_1 N_c + \pi d L \alpha C_2 \right)$$

$$= \frac{1}{2.5} \left( \frac{\pi}{4} \times 0.3^2 \times 150 \times 9 + \pi \times 0.3 \times 10 \times 0.57 \times 100 \right)$$

$$\text{For } \eta_g = 1,$$

$$= \underline{\underline{253.05 \text{ kN}}}$$

$$Q_g = n Q_i$$

$$\text{or } n = \frac{Q_g}{Q_i} = \frac{5000}{253.05} = 19.75 \text{ no.s} \approx \underline{\underline{20}}$$

09. Rated energy,  $W_h = 3500 \text{ kNcm}$ .

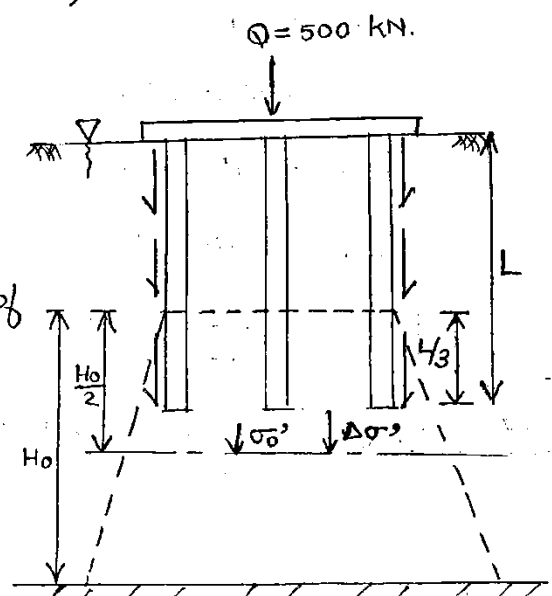
$$Q_{\text{safe}} = \frac{W_h \eta_h \eta_b}{F (s + C/2)}$$

$$s = \frac{25.4}{6} = 4.23 \text{ mm} = \underline{\underline{0.423 \text{ cm}}}$$

$$\therefore Q_{\text{safe}} = \frac{3500 \times 0.8 \times 0.476}{4 (0.423 + 1.8/2)} = \underline{\underline{251 \text{ kN}}}$$

08. The given pile group is assumed to be friction pile group and the total load is assumed to be acting at lower  $\frac{1}{3}$ rd of length of pile for settlement calculations

$$S_f = H_o \cdot \frac{C_c}{1+e_o} \log_{10} \left( \frac{\sigma'_o + \Delta \sigma'}{\sigma'_o} \right)$$



$$H_0 = 3.667 \text{ m}$$

$$\sigma_0' = \left( 3.33 + \frac{3.667}{2} \right) \gamma = 51.63$$

$$\Delta \sigma^2 = \frac{Q}{(B_0 + z)^2} \quad ; \quad B_0 = 2.5 + d$$

$$z = \frac{H_0}{2}$$

$$= \frac{500}{(1.2 + 1.8335)^2} = 54.335 \text{ kN/m}^2$$

$$S_f = 3.667 \times \frac{0.027}{(1 + 1.05)} \times \log_{10} \left( \frac{51.63 + 54.335}{51.63} \right) = \underline{\underline{15.08 \text{ mm}}}$$

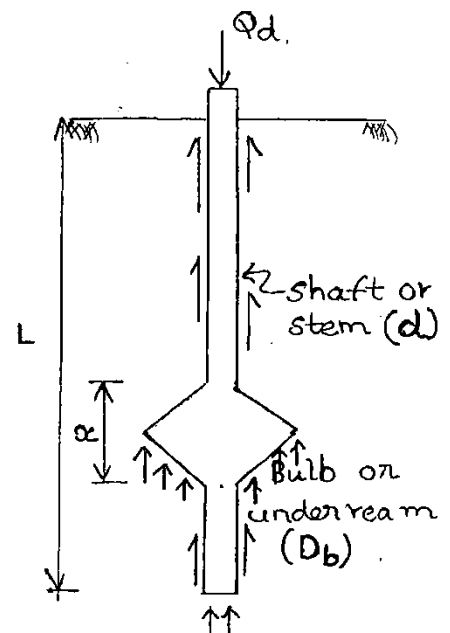
→ Under-reamed Piles.

- The bulb provides anchorage against uplift caused by expansive soils.
- Generally used in B.C soil.
- Bulb diameter,  $D_b \approx 2.5 d$ .
- Bored cast-in-situ piles.

Ultimate downward load carrying capacity,  $Q_d = \frac{\pi}{4} d^2 C_1 N_c +$

$$\frac{\pi}{4} (D_b^2 - d^2) C_2 N_c +$$

$$\pi d (L - x) \alpha C_a$$

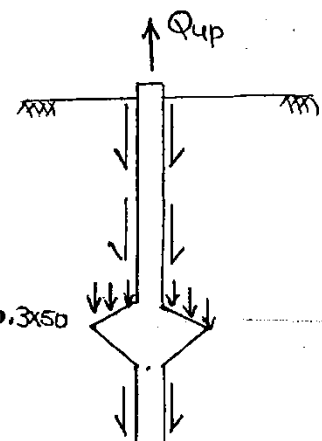


$C_a \rightarrow$  avg. cohesion along pile length.

Ultimate uplift resisting capacity,

$$Q_{up} = \frac{\pi}{4} (D_b^2 - d^2) C_2 N_c +$$

$$\pi d (L - x) \alpha C_a + \text{self weight.}$$



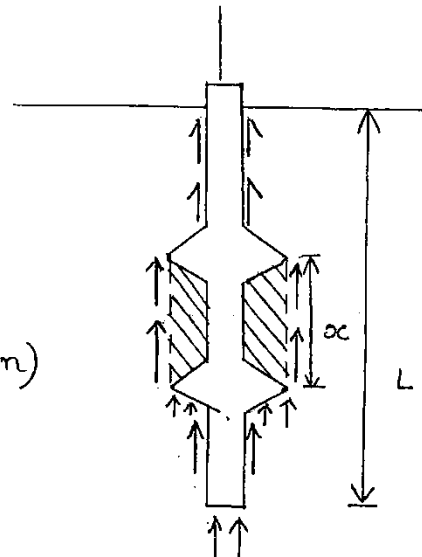
$$Q = \frac{\pi}{4} (0.75^2 - 0.35^2) \cdot 50 \times 9 + \pi \times 0.35 (8 - 0.4) \times 0.3 \times 50$$

$$+ 20$$

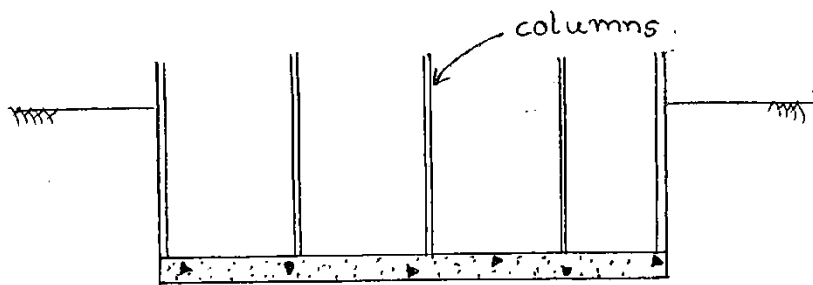
$$= \underline{\underline{300.8 \text{ kN}}}$$

### \* Double Under-reamed Pile.

$$Q_d = \frac{\pi}{4} d^2 C_1 N_c + \frac{\pi}{4} (D_b^2 - d^2) C_2 N_c + \pi d (L - \alpha) \alpha C_a + \pi D_b \cdot \alpha \cdot C_a$$



→ Raft Foundations: (Mat Foundation)  
 - common footing for all columns.



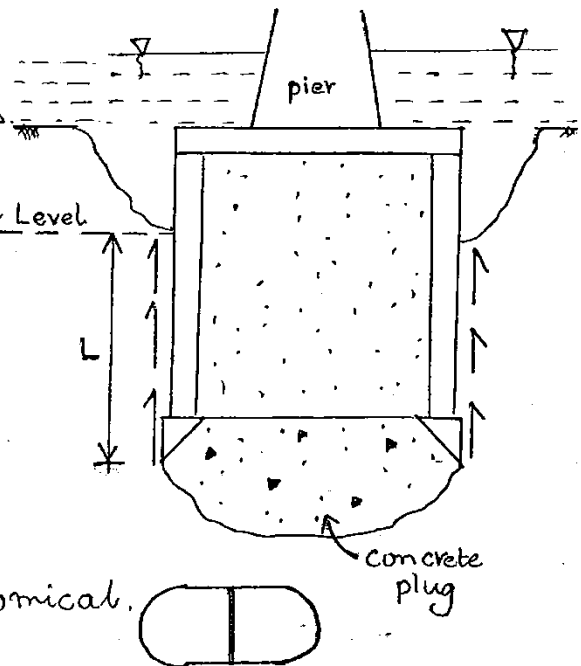
- shallow foundation
- to avoid differential settlement.
- also used in poor soils if loads are heavy.

→ Well Foundation:

- used for bridges across rivers.

Mass Scour level is depth at which mass erosion occurs.

Depth of the well foundation below the mass scour level is the 'Grip Length'



- double D shape is most economical.

- As per IS code of practice, the allowable tilt & shift are 1 in 60 & 1% of depth of sunk.

## 18. SOIL EXPLORATION

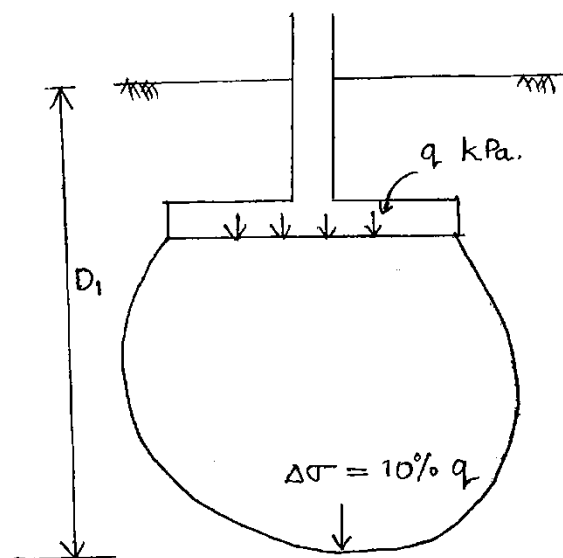
### → Soil Investigation

\* For small sites → 1 hole at centre.

For areas upto 0.4 ha  
with important buildings } 5 holes → 1 @ centre  
→ 4 @ corners

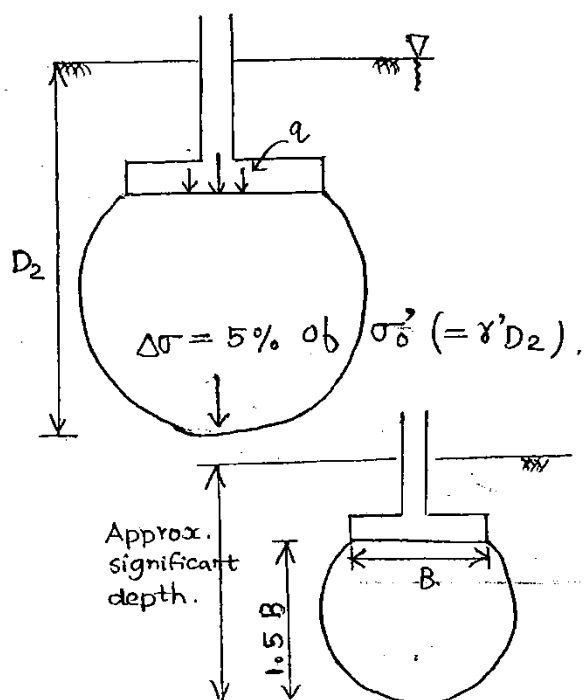
\* The min. depth of exploration is equal to 'significant depth'.

Significant depth is the depth at which increase in stress is equal to 10% of intensity of load applied, ( $= D_1$ ).



It can also be explained as the depth ( $D_2$ ) at which increase in stress is equal to 5% of overburden pressure at that point.

Significant depth = Higher of  $D_1$  &  $D_2$



\* Approximately significant depth =  $1.5 B$  to  $2 B$ , below the footing. As per IS code, its  $\approx 1.5 B$ .

## \* Methods of Exploration:

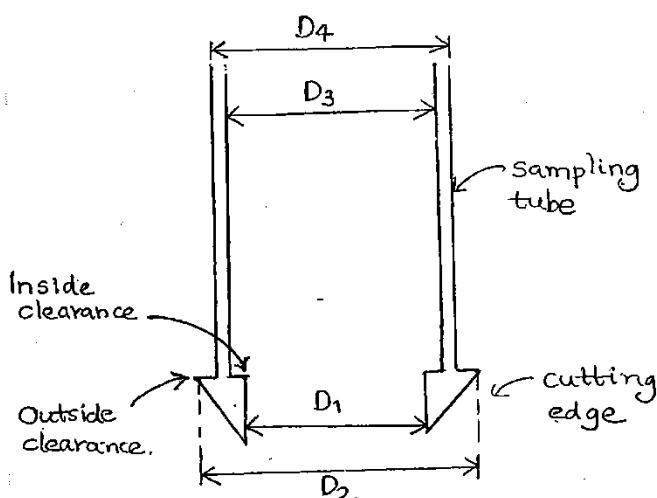
- (i) Open trial pits  $\rightarrow$  upto 3m depth
- (ii) Auger boring - suitable for clays & shallow depths (6m) for highways, railways etc.
- (iii) Wash boring - for deep holes, not suitable for hard stratum, can be used even below WT
- (iv) Rotary drilling - for any soil, including rock.
- (v) Percussion boring - for hard strata & rocks
- (vi) Core drilling - to obtain rock samples.

## \* Sampler :-

An equipment to collect soil sample.

### -Types of Samplers:

- (i) Thin walled Sampler - used to collect undisturbed samples. (engineering properties)
- (ii) Thick walled Sampler - used to collect disturbed samples (index properties)



$$\text{* Area ratio, } Ar = \frac{D_2^2 - D_1^2}{D_1^2} \times 100$$

• To obtain undisturbed sample,  $Ar \leq 10\%$

$$* \text{ Inside clearance, } = \frac{D_3 - D_1}{D_1} \times 100$$

(87)

92

◉ To obtain undisturbed sample, it should be 0.5 to 3%

$$* \text{ Outside clearance } = \frac{D_2 - D_4}{D_4} \times 100$$

◉ It shall be 0 to 2%

### → Standard Penetration Test (SPT)

- an insitu test.
- best suited to cohesionless soils.
- conducted by using split spoon sampler.

\* SPT value or N-value of soil:

- It is the no: of blows to cause a penetration of 30 cm.

$$- N \text{ value} = n_2 + n_3$$

(at field)

- The more the N-value, the more the strength of soil.

- Weight of hammer,  $w = 65 \text{ kg}$

- Height of fall,  $h = 75 \text{ cm}$

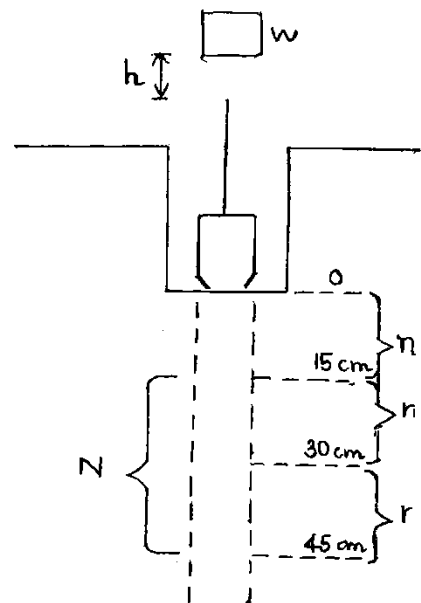
\* Corrections for N-value.

(i) Overburden Pressure Correction

- to report N-value at a std overburden pressure.

(96 kN/m<sup>2</sup>  $\approx$  100 kN/m<sup>2</sup>)

- If  $N_F$  is N-value measured at field, the corrected value  $N'$  for overburden pressure.



Peck, Hansen & Thornburn (by IS code also) :-

$$\odot N' = N_F * 0.77 \log_{10} \left( \frac{1905}{\sigma'_0} \right) \quad \text{for } \sigma'_0 \geq 24 \text{ kN/m}^2$$

where  $\sigma'_0 \rightarrow$  effective overburden pressure at the depth.  
(in  $\text{kN/m}^2$ ).

Correction factor,  $\frac{N'}{N_F}$  shall be b/w 0.45 & 2.

$$\odot N' = N_F * \left( \frac{350}{\sigma'_0 + 70} \right); \text{ by Gibbs \& Holtz}$$

(ii) Dilatancy Correction.

- It is required only if the soil is fine sand or silt and is present below the WT.

- If  $N' > 15$ ;

$$\text{Corrected value, } N'' = 15 + \left( \frac{N' - 15}{2} \right)$$

- If  $N' \leq 15$ ;

Corrected value,  $N'' = N'$  (no correction required)

→ Cone Penetration Test (CPT)

- insitu test for cohesionless soil.

- types :

(i) Static

(ii) Dynamic

→ Pressuremeter Test

- to measure in-situ stress-strain curve of soil.

→ Geophysical Methods

(i) Seismic Refraction method. - for civil engg. investigation

(ii) Seismic Reflection method. - for petroleum investigation

## → Soil Stabilisation Methods:

- (i) Mechanical Stabilisation.
- (ii) Cement Stabilisation.
- (iii) Lime stabilisation.
- (iv) Chemical stabilisation.

## → Ground Improvement Techniques:

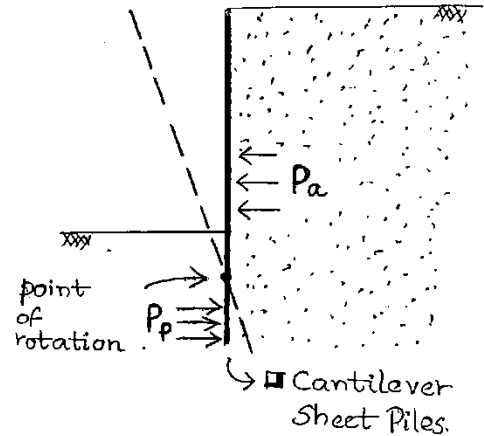
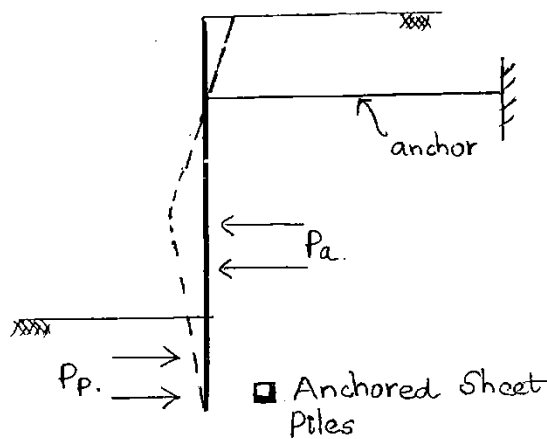
- (i) Electro osmosis.
- (ii) Vibro floatation method.
- (iii) Terraprobe method.
- (iv) Lime piles.
- (v) Stone columns.
- (vi) Geotextiles.

# SOIL EXPLORATION

## 19 SHEET PILES

- used to retain soil.

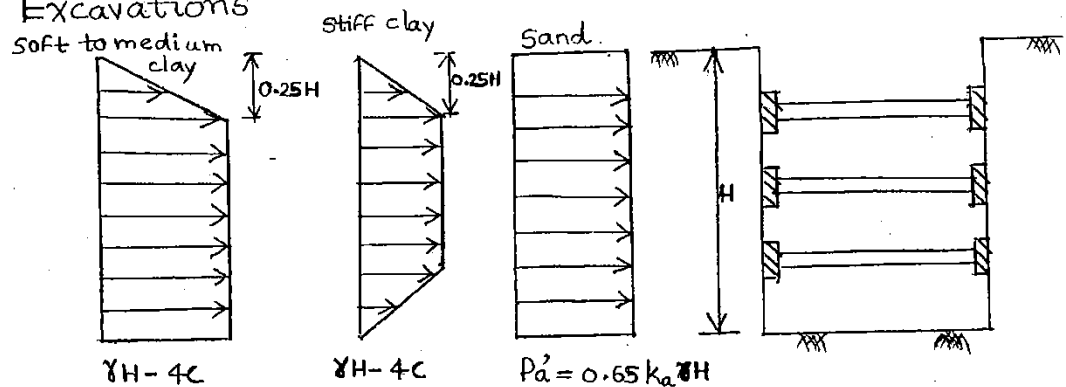
- Point of rotation for a cantilever sheet pile is just above the bottom point. (used for heights up to (5m))



→ Types of Anchored Sheet Piles

- (i) Free Earth Support Type: if depth of penetration shall be
- (ii) Fixed Earth Support Type: depth of penetration deep

→ Braced Excavations



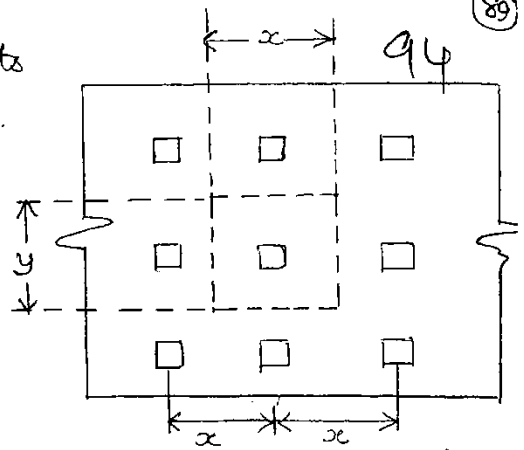
$x \rightarrow$  c/c horizontal spacing of struts

$y \rightarrow$  c/c vertical spacing of struts.

Max. compressive force induced in the struts,

$$P = \text{Influencing area} \times \text{pressure.}$$

$$= x \cdot y \cdot p_a'$$



- Q. A vertical trench 3m wide & 6.5m deep is proposed in a cohesionless deposit ( $\phi = 36^\circ$  &  $c = 0$ ). Assuming first row of struts to be placed at 0.5m below ground surface and spacing b/w the struts as 1.5m in the vertical direction and 3m spacing in the horizontal direction, calculate max strut compressive load. Take  $\gamma = 20 \text{ kN/m}^3$

$$p_a' = 0.65 k_a \gamma H$$

$$= 0.65 \left( \frac{1 - \sin 36}{1 + \sin 36} \right) 20 \times 6.5 = 21.94 \text{ kN/m}^2$$

$$\text{Max strut compressive load} = x y p_a'$$

$$= 3 \times 1.5 \times 21.94$$

$$= \underline{\underline{98.72 \text{ kN}}}$$