ADVANCE FOUNDATION DESIGN

UNIT- 3

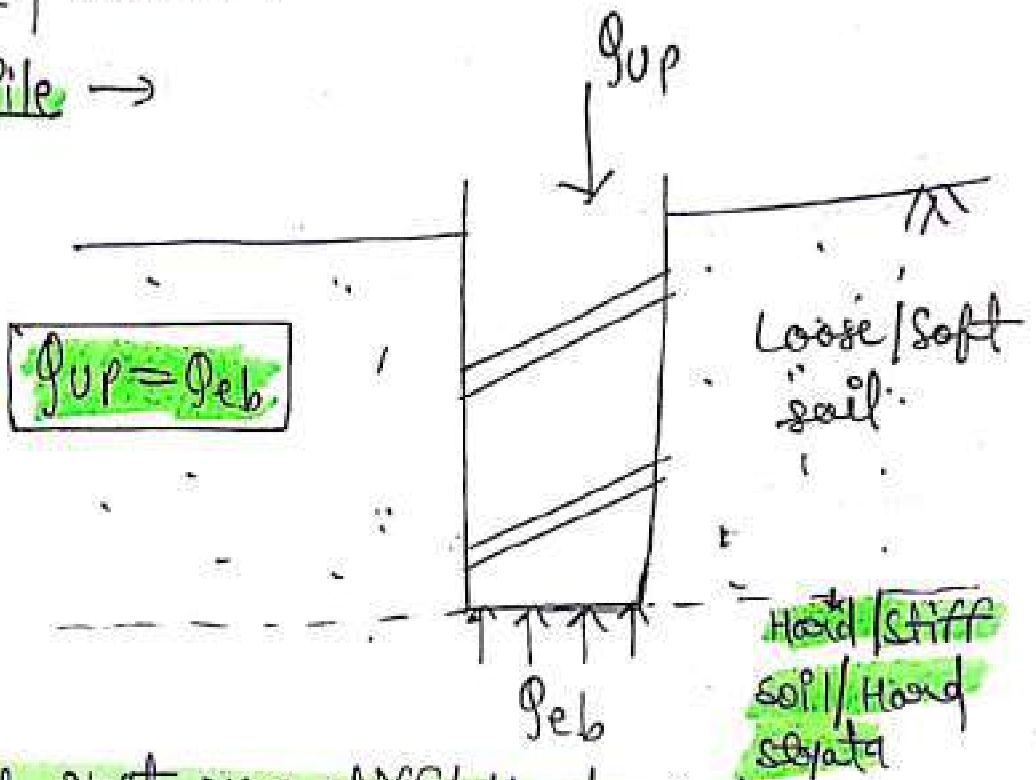
PILE FOUNDATION

Topics Covered: Classification of piles, load carrying capacity of single pile in clay, silt & sand. Method of determination of pile load capacity by dynamic & static methods, Pile load test (Field Method) IS Code Guidelines, Under-Reamed pile, negative skin friction, Group action of piles, group efficiency

Types of Pile →

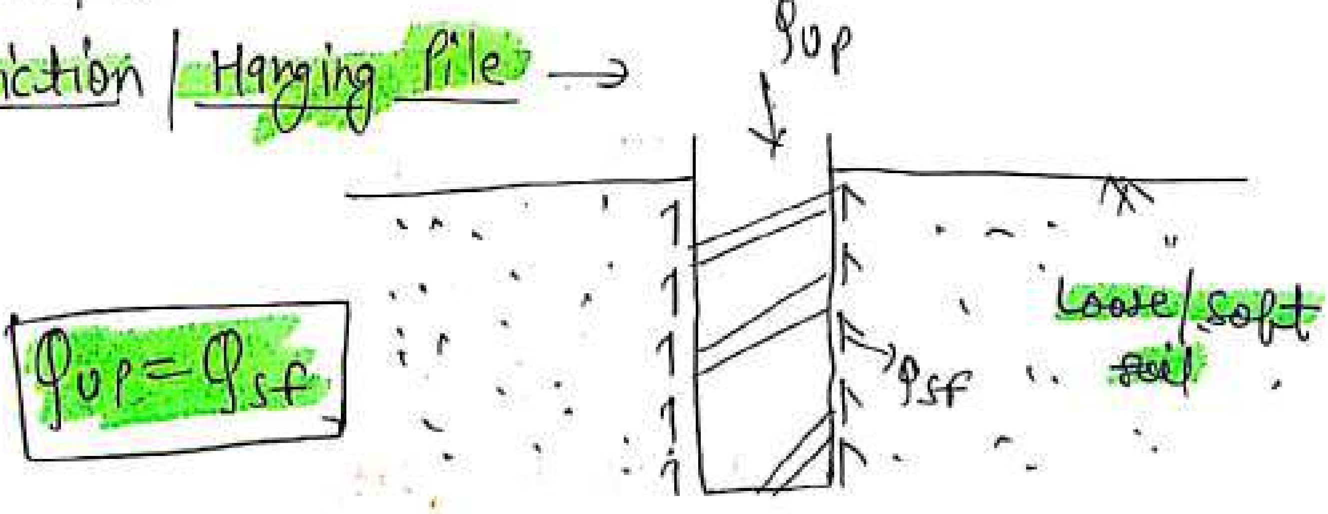
1) Based on load action →

a) End Bearing Pile →



* End bearing piles rest over stiff/Hard strata.
* The load carrying capacity is due to end bearing resistance or point resistance.
* The length of such piles depends upon position of stiff strata.

b) Friction/Hanging Pile →



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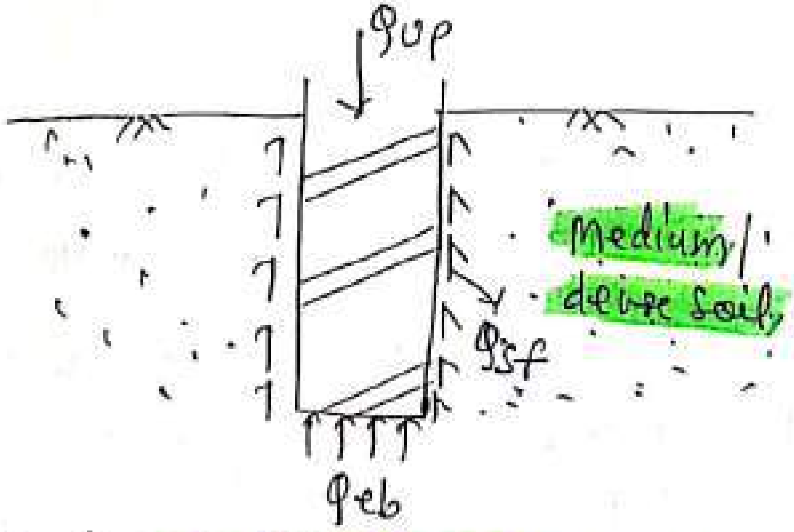
* Such piles are driven in soft clay or loose sand extending to great depth.
* The load carrying capacity is due to skin friction action
* Length of friction pile may be 10m to 20m.

(C) End bearing and friction pile →

$$q_{up} = q_{eb} + q_{sf}$$



* If, piles are driven in medium to stiff soil then, load carrying capacity is due to combined effect of end bearing action and skin friction action.

② Type of piles based on there method of installation →

(a) Driven / displacement pile →

* These piles are driven through hammering action.
* Such piles are essentially pre cast piles made of wood / metal.

* In driven piles, end bearing resistance & skin friction resistance both are efficiently developed.

(b). Bored Pile →

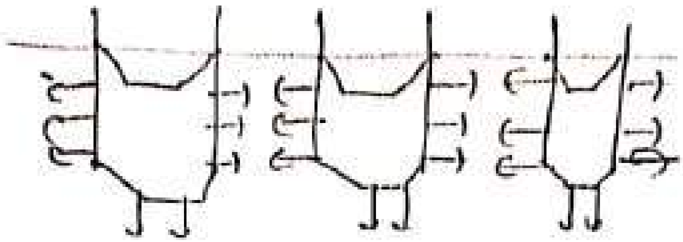
* Bored pile may be pre cast or cast insitu. (concrete piles).
* These piles are less efficient than, driven piles.

Note →
* Piles which displace the soil and cause disturbance while driving are called displacement piles whereas if, it does not displaced or does not disturb the adjacent soil are called non-displacement piles such piles are also called H- Piles.

③. Types of Pile Based on Their function →

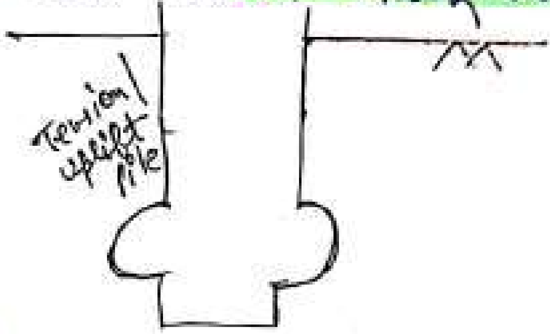
(i). Compaction Pile →

* These are driven in loose sand in order to increase its density and bearing capacity.
* Such piles are provided in those areas which are prone to liquifaction such as near the sea or rivers.



(b) Tension / Uplift type Pile →

* Used to anchor the structure subjected to uplift pressure caused by swelling of soil such as in black soil.

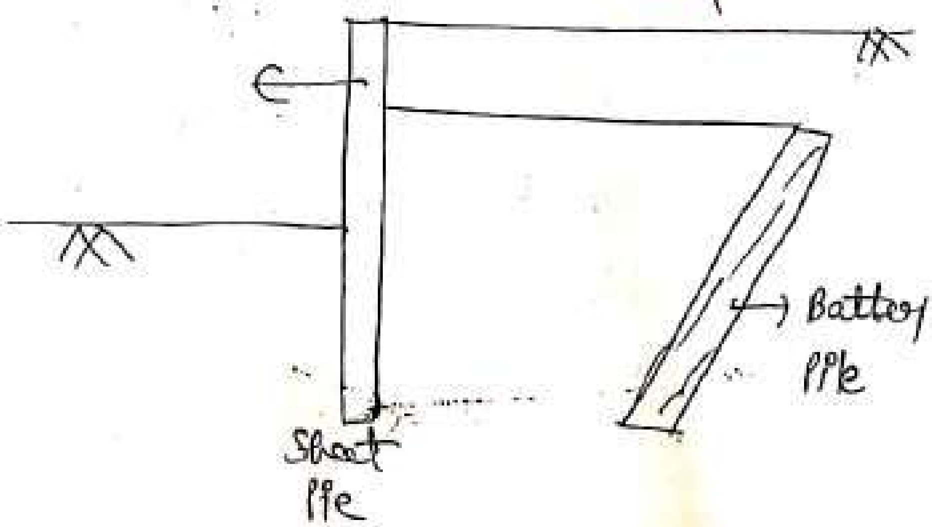


(c) Fender Pile →

* Fender pile used to anchor the structure subjected to tidal wave, caused by seismic activities or ships.
* These piles are used in water front structures.

(d) Batter Piles →

* These piles are driven in inclined direction to prevent horizontal thrust / inclined forces.



(e) Sheet Pile →
* Sheet Pile used to retain earth mass & also used below the hydraulic structure to minimize piping failure

④ Types of Pile Based on their material Used →

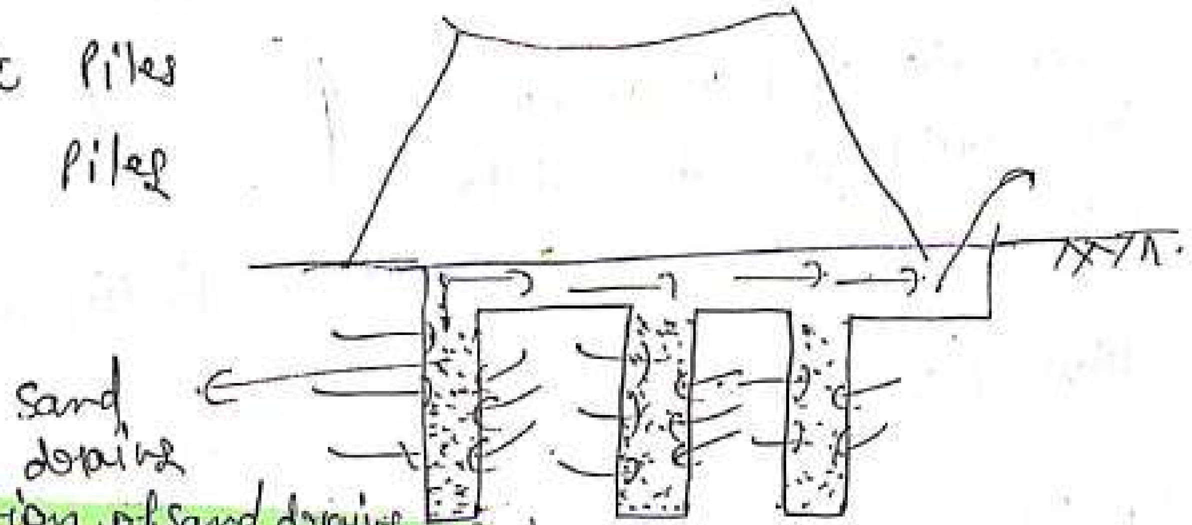
(a) Wooden / Timber Pile → (Ebony wood / Bamboo).
(These consume more carbon).

(b) Steel Pile.

(c) Cast iron Piles

(d) Concrete Piles

(e) Sand Piles



Main function of sand drains are →
* increasing the rate of consolidation.

Ultimate Load carrying Capacity of Pile → (Q_{up}) (in kN)

* It is the total load which can be applied on the pile without shear failure.

* ... the sum of end bearing resistance

Allowable or Safe Load on Piles → (Q_{ap} / Q_{safe})

* It is maxm safe load which can be allowed on the pile without risk of shear failure.

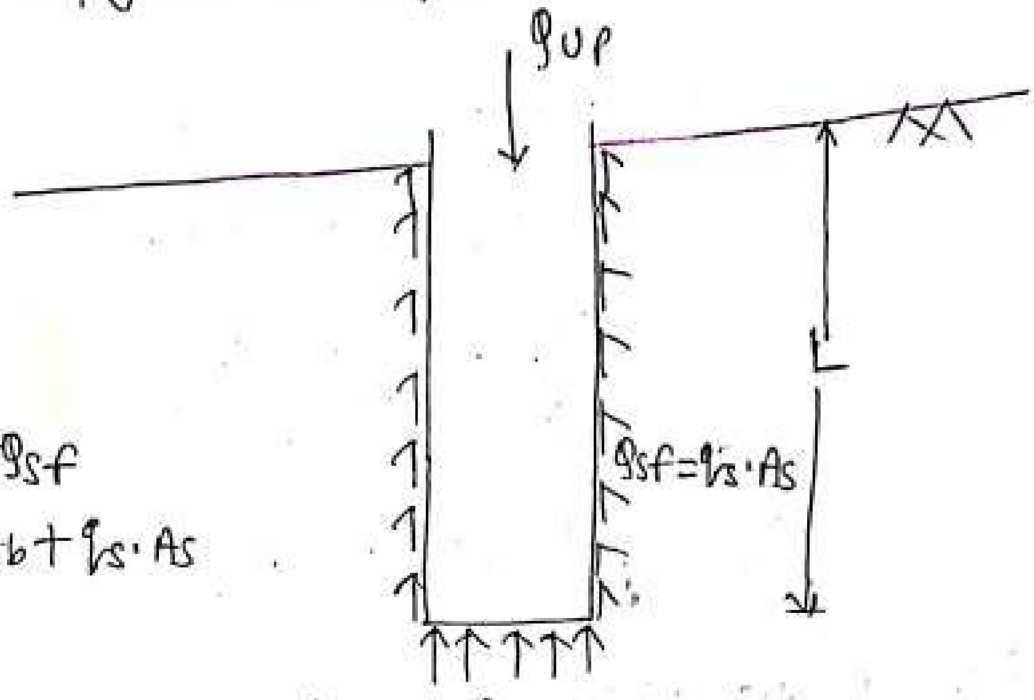
$$Q_{ap}/Q_{safe} = \frac{Q_{up}}{F} = \frac{Q_{eb}+Q_{sf}}{F}$$

Generally → FOS = (2.5 to 3)

Methods for determination of Pile load Capacity

1) Static/ Analytical Method
2) Dynamic Method → "Suitable for dense sand"
3) Field Method
   a) Pile Load Test
   b) ~~Cycling~~ Cyclic Pile load test → [This method gives end bearing resistance and skin friction resistance separately.]
   c) Standard Penetration Test
   d) Cone Penetration Test.

I) Static/ Analytical Method →



$q_{eb} = q_b \cdot A_b$

$$q_{up} = q_{eb} + q_{sf}$$

$$q_{up} = q_b \cdot A_b + q_s \cdot A_s$$

	Circular	Square
A_b (Base Area)	$\frac{\pi}{4} D^2$	B^2
A_s (Skin surface Area)	$\pi D L$	$4 B L$

Case 1st: **For clay**

q_b = End bearing resistance
= Ultimate bearing ~~resistance~~ capacity at base.

As per Meyerhof →

$$q_b = 9c$$

c → Unit cohesion at the base of Pile.

q_s = Side resistance.
= unit cohesion. (for clay).

$$q_s = \alpha \bar{c}$$

$\bar{c}$ = avg. cohesion along the length of pile
α = adhesion factor in b/w pile & soil
α = (0.6 to 0.9) for soft clay.
α = (0.4 to 0.6) for medium clay.
α = (0.2 to 0.4) for stiff clay.

Ultimate load carrying capacity of pile in clay →

$$Q_{up} = q_b A_b + q_s A_s$$

$$Q_{up} = 9c A_b + \alpha \bar{c} A_s \quad ***$$

Note →

* For very long pile (L ≥ 25 meter) the above method for estimating the skin friction is very conservative.

For such piles, unit skin friction also depends upon the effective overburden pressure. The avg. unit friction can be represented as →

$$q_s = \lambda(\bar{\sigma}_v + 2\bar{c})$$

where, λ = friction capacity factor
$\bar{\sigma}_v$ = Mean effective stress for the embedded length.

$$\therefore Q_{up} = 9c A_b + \lambda(\bar{\sigma}_v + 2\bar{c}) A_s$$

Case 2nd → **For Sand** →

As per Meyerhof →

$$q_0 = \cancel{cN_c}^{0} + \gamma D_f N_q + 0.5 B \gamma N_\gamma$$

$$\gamma D_f N_q >> 0.5 B \gamma N_\gamma$$

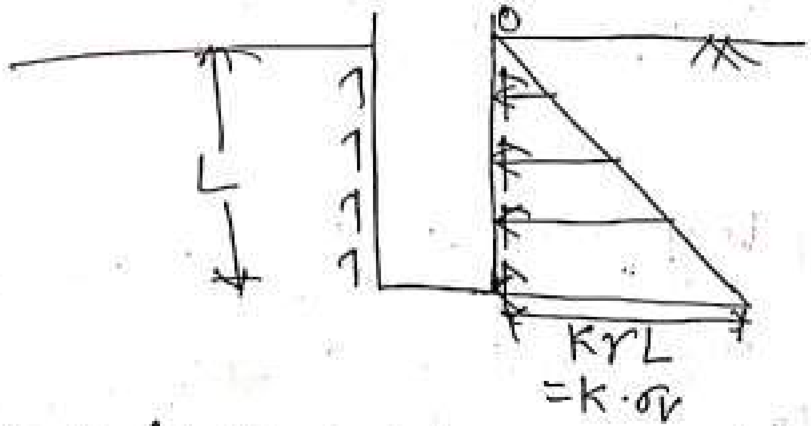
$$q_u = \gamma D_f N_q = \gamma L N_q$$

q_b = End bearing resistance
= Ultimate bearing capacity at base

$$\boxed{q_b = \gamma L N_q}$$

N_q → Meyerhof bearing capacity factor.

q_s = Skin friction resistance



$q_s = \mu$ (avg. Earth pressure)

$$= \mu\left(\frac{0 + K\sigma_v}{2}\right) = \frac{\mu K \gamma L}{2}$$

$$q_s = \left(\frac{0 + K\gamma L}{2}\right) \tan\delta$$

$K \rightarrow$ Earth pressure coefficient
$L \rightarrow$ Length of Pile
$\delta \rightarrow$ friction angle b/w pile & ~~earth~~ soil.

$$q = K \bar{\sigma}_v \tan\delta$$

Ultimate Load capacity for sand →

$$Q_{up} = q_b A_b + q_s A_s$$

~~= (γL A~~

$$Q_{up} = (\gamma L N_q) A_b + \left(\frac{1}{2} K \gamma L \tan\delta\right) A_s$$ **

② Dynamic Method →

* This analysis is based on the assumption that the dynamic resistance to drive the pile is equal to the ultimate load capacity using static method.

* In this method kinetic energy / potential energy of hammer is equated to the work done by the pile.

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Ultimate load carrying capacity of pile →

$$Q_{up} = \frac{WH}{S+C} \text{ (in kN)}$$

{for drop Hammer or single acting steam Hammer}.

$$Q_{up} = \frac{(W+a\,p)H}{(S+C)}$$

{Double Acting steam Hammer}.

Safe load carrying capacity of pile →

$$Q_{safe} / Q_{ap} = \frac{Q_{up}}{F} = \frac{Q_{up}}{6}$$

$$F.O.S. = 6^{*}$$

Where; W = weight of Hammer in kN

H = Height of free fall of hammer in cm

S = Set, penetration of pile per blow of hammer (cm). Set is taken as average value of last 5 blows for drop hammer

** $\begin{cases} C = 2.5\,cm & \text{for Drop Hammer} \\ C = 0.25\,cm & \text{for Steam Hammer (SASH; DASH)} \end{cases}$

p = Steam pressure in $\frac{KN}{m^2}$ applied on area of piston/ Hammer (a).

Safe load for drop Hammer →

$$Q_{safe} = \frac{WH}{6(S+2.5)}$$

$$Q_{safe} = \frac{WH}{6(S+2.5)} \quad \{\text{in KN}\}.$$

(W in KN, H in cm, S in cm)

(b) Hiley's formula →

*

$$Q_{up} = \eta_h \cdot \eta_b \left(\frac{WH}{S + \frac{C}{2}} \right)$$

Safe load carrying capacity of soil →

$$Q_{safe} / Q_{ap} = \frac{Q_{up}}{F} = \frac{Q_{up}}{3}$$, **F.O.S. = 3** *

where; W = weight of Hammer in KN,
H = Height of free fall of Hammer in cm
S = Set in cm
C = Elastic constant which accounts for elastic compression of pile and (soil/pile cap)

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Soil & Pile cap.

η_h = efficiency of hammer

$\eta_h \to 1$ (for drop hammer)

$\eta_h = (0.75 - 0.85)$ (for SASH)

$\eta_h = (0.7 - 0.8)$ (for DASH)

η_b = efficiency of hammer blow. It accounts for energy loss during impact. It is defined as the ratio of energy of hammer after impact to the energy of hammer before the impact.

$$\eta_b = \frac{W + e^2 P}{W + P} \quad \{W > eP\}$$

$$\eta_b = \frac{W + e^2 P}{W + P} - \left(\frac{W - eP}{W + P}\right)^2 \quad \{W \leq eP\}$$

Where;
W = weight of hammer
P = Weight of Pile
e = coefficient of restitution b/w pile & hammer.

Field Method →

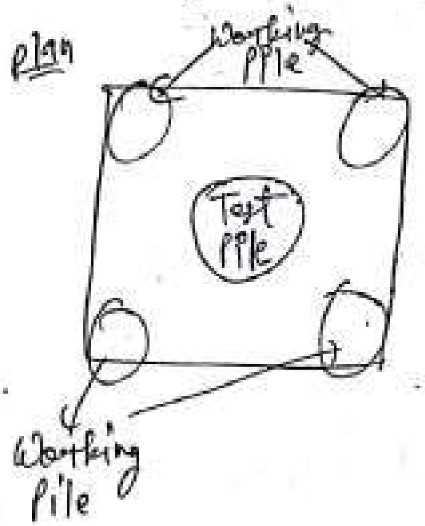
(9) Pile load Test →

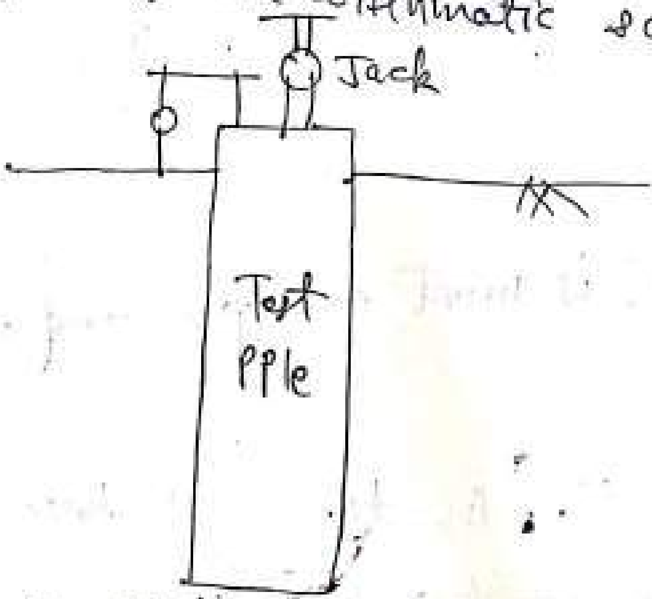
* It is a field ~~test~~ and suitable for dense sand because in clays remoulding whereas in loose saturated sand liquifaction may occure.

* The load on ~~test~~ pile is applied through jacking mechanism and settlement of pile is recorded.

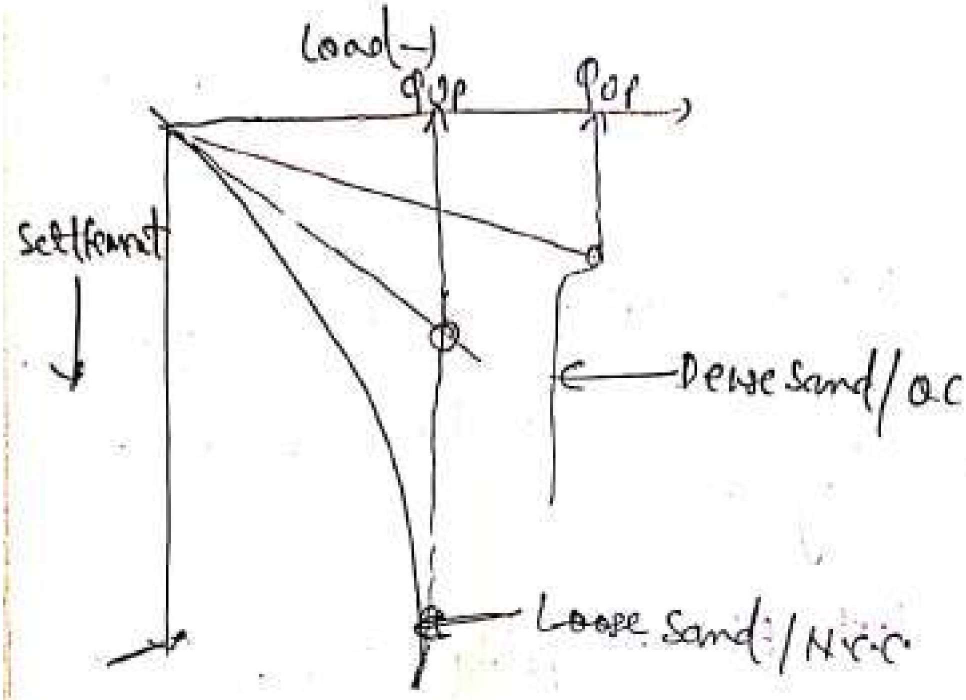
* Load settlement curve is plotted in which shear failure is represented by either progressive settlement or by sudden settlement at faster rate.

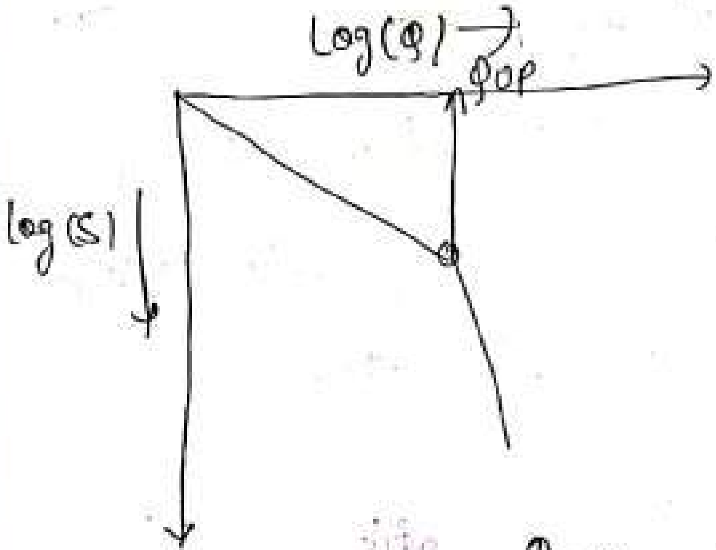
* The curve may plotted on arithmatic scale or log-log scale.





if this test is fail then, this test is called destractive test i.e., (waste)





$$q_{safe} = \frac{q_{up}}{F}$$ {Generally, F.O.S. = 2.5 to 3}

* This method is most accurate and recommended by IS code.
* The loaded pile in this test becomes waste. Hence, it is a destructive test.
* This test can also be used to find the allowable load on the pile / pile load capacity using settlement criteria.

IS code Guidelines →

1) The allowable load on pile may be taken as 50% of ultimate load at which total settlement of pile is 10% of its dia.

or

2) The allowable load on pile may be taken as $\frac{2}{3}$rd of ultimate load at which total settlement is 12 mm.

or

3) Allowable load on pile may be taken as $\frac{2}{3}$rd of ultimate load at which net ~~elastic~~ plastic settlement is 6 mm.

Standard Penetration Test →

Let 'N' is SPT number at the base of pile.

$\bar{N}$ = Average SPT number along the side of pile

As per Meyerhof, Ultimate bearing capacity for driven/ displacement pile is given as →

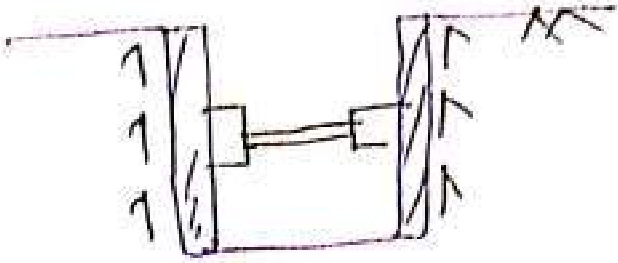
$$Q_{up} = q_b A_b + q_s A_s$$

$$\boxed{Q_{up} = 400 N A_b + 2 \bar{N} A_s} \text{ (in kN).}$$

{A_b & A_s is m^2}.

for Non-Displacement Pile (H-Piles) →

$$q_{up} = q_{eb} + \frac{q_{sf}}{2}$$



$$q_{up} = 400 N A_b + \bar{N} A_s$$

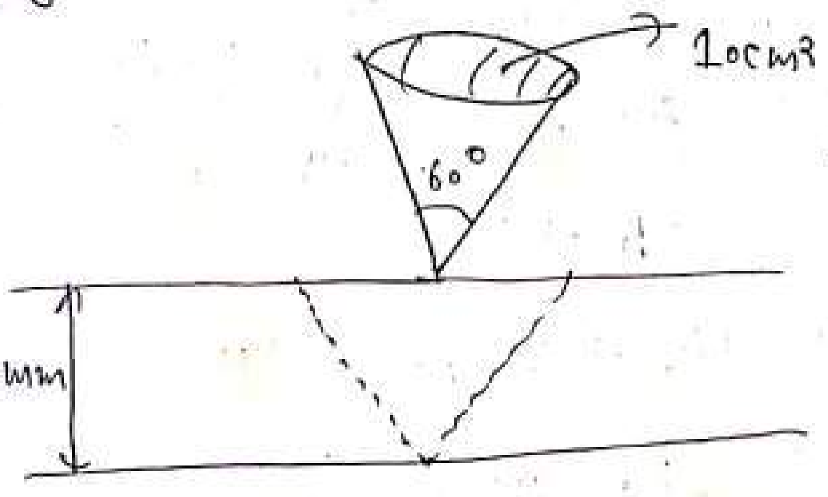
for Bored Pile →

$$(q_{up})_{Bored} = \frac{1}{3} (q_{up})_{driven}$$

$$q_{up} = \frac{1}{3}(400 N A_b + 2 \bar{N} A_s)$$

(d). Static/Dutch cone Penetration Test →

* The vertex angle of cone is 60°. The cone is penetrated into the soil for 100mm and when penetration is 100mm, the cone resistance of the soil is determined in $\frac{kg}{cm^2}$; which is called static cone penetration resistance.



q_c (kg/cm²)

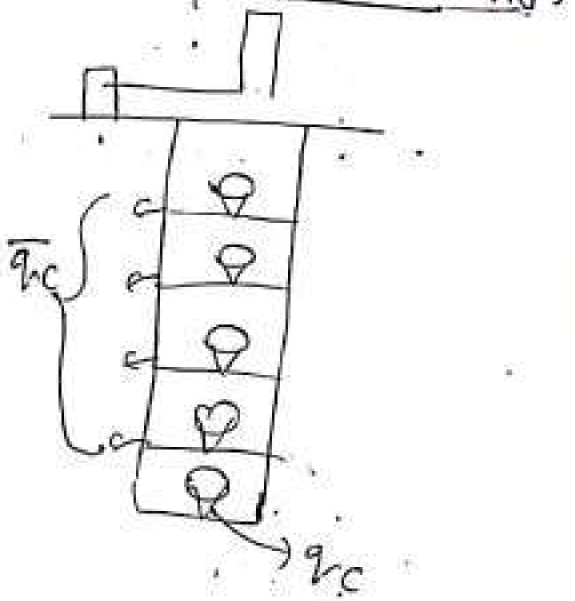
* Let q_c is static cone penetration resistance of the soil at the base of pile in $\frac{kg}{cm^2}$.

* Let $\bar{q}_c$ is average static cone resistance of the soil over the depth of pile then;

Ultimate load carrying capacity for driven/displacement pile →

$$Q_{up} = q_b A_b + q_s A_s$$

$$Q_{up} = q_c A_b + \frac{\bar{q}_c}{2} A_s \quad \text{(in kN)}$$



A_b & A_s in m^2.

q_c & $\bar{q}_c$ → kg/cm^2.

For Non-displacement Pile (H-Piles) →

$$Q_{up} = Q_{eb} + \frac{Q_{sf}}{2}$$

$$Q_{up} = q_c A_b + \frac{\bar{q}_c}{4} A_s$$

For Bored Pile →

$$(Q_{up})_{Bored} = \frac{1}{3} (Q_{up})_{driven}$$

$$Q_{up} = \frac{1}{3} \left(q_c A_b + \frac{\bar{q}_c}{2} A_s \right)$$

imp for interview or mcq/objective

Under Reamed Piles →

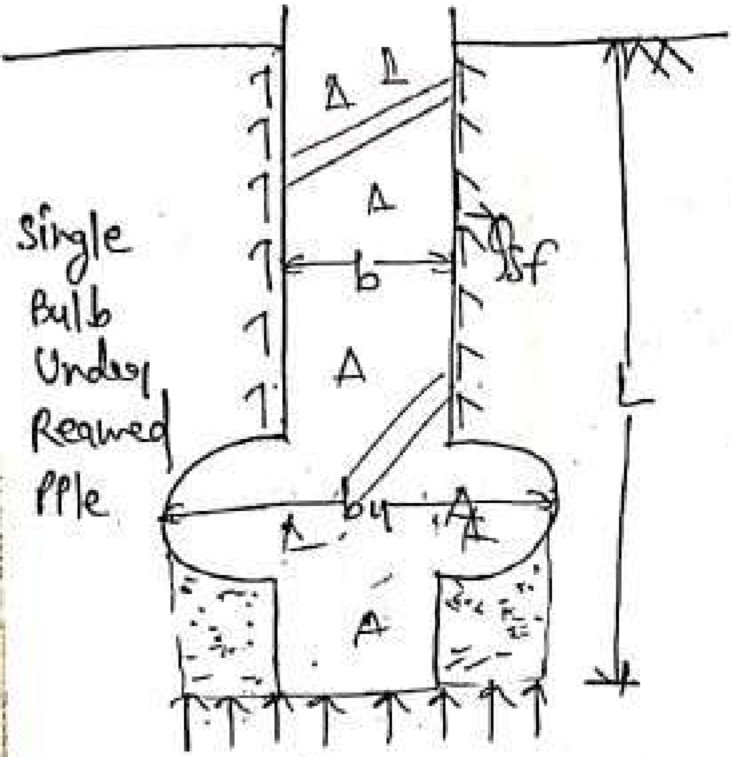


Fig a

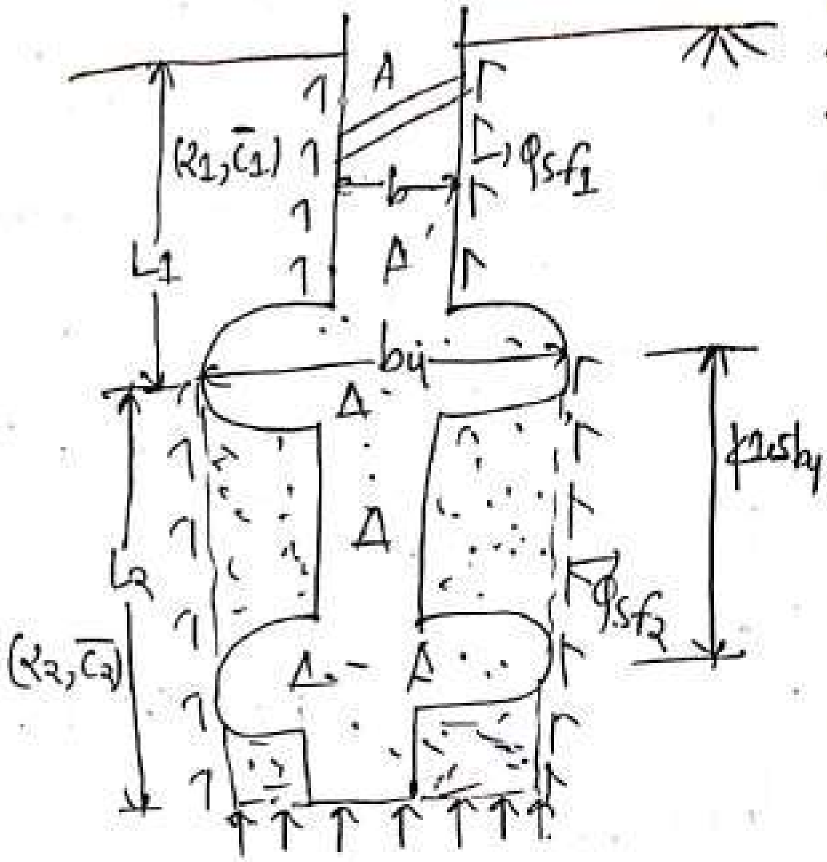
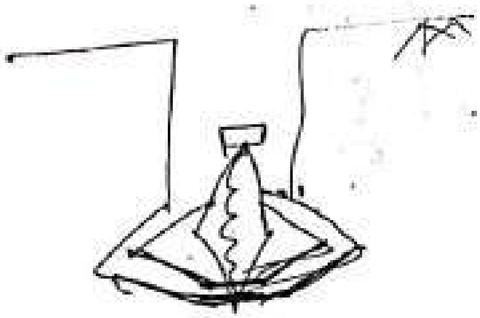


Fig b



$$\frac{b_u}{b} = 2 \text{ to } 3$$

* Under reamed piles are used in expansive soils (high swelling and shrinkage) to prevent uplift pressure caused by swelling such as in Black soil.

* Under reamed pile can not be driven therefore, these are essentially cast in situ bored piles.

* The depth at which the bulb should be placed should be in stable zone, it means there should be no fluctuations in the water content.
* Due to bulb base resistance increases because the compacted soil below the bulb acts as part of the pile.
* The bulb dia should be (2 to 3) times of shaft dia.
* In multi bulb under reamed pile, skin surface resistance also increases and minimum spacing (center to center) should be 1.5 times of bulb dia.

→ Ultimate Load carrying capacity for single bulb under reamed pile →

$$Q_{up} = q_b A_b + q_s A_s$$

$$Q_{up} = 9c\left(\frac{\pi}{4} b_4^2\right) + \alpha \bar{c}\,(\pi b L)$$

→ Ultimate Load capacity for Multi-bulb U-R piles,

$$Q_{up} = Q_{eb} + Q_{sf_1} + Q_{sf_2}$$

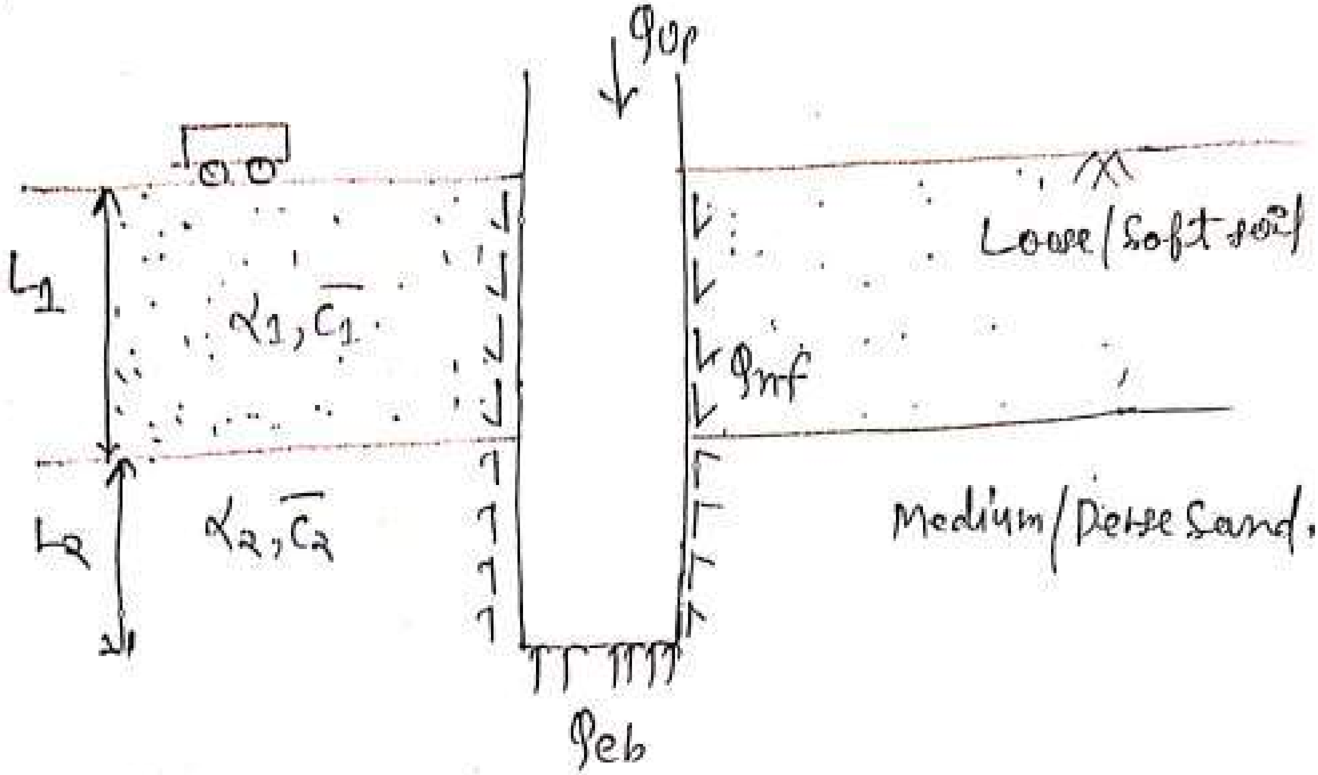
$$Q_{up} = 9c\left(\frac{\pi}{4} b_4^2\right) + \alpha_1 \bar{C}_1 (\pi b L_1) + \alpha_2 \bar{C}_2 (\pi b_4 L_2)$$

$\alpha_2 = 1$; ∵ Cohesion in b/w soils soil.

b_4 = bulb dia

b = Shaft dia.

Negative Skin friction →



* It is the phenomenon in which soil surrounding to the pile settles more than the settlement of pile; This conditions ... soil surrounding to the pile is loose/soft.

Ultimate load carrying capacity →

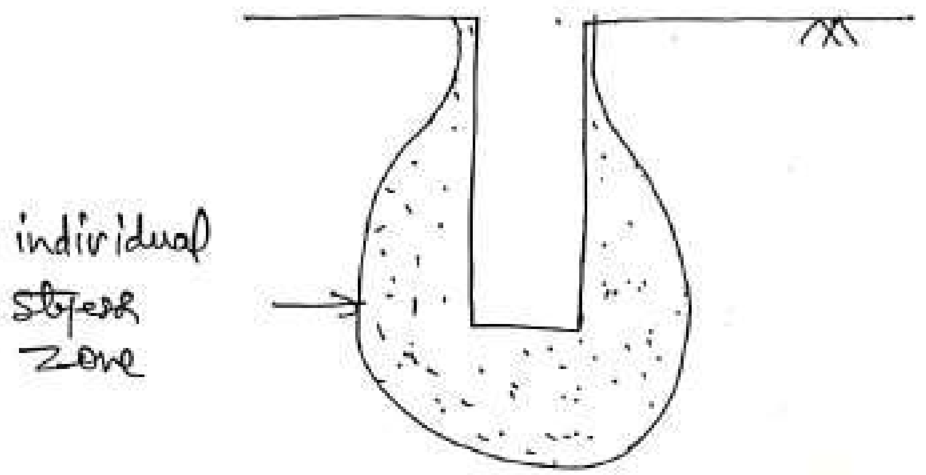
$$Q_{up} = Q_{eb} + Q_{sf} - Q_{nf}$$

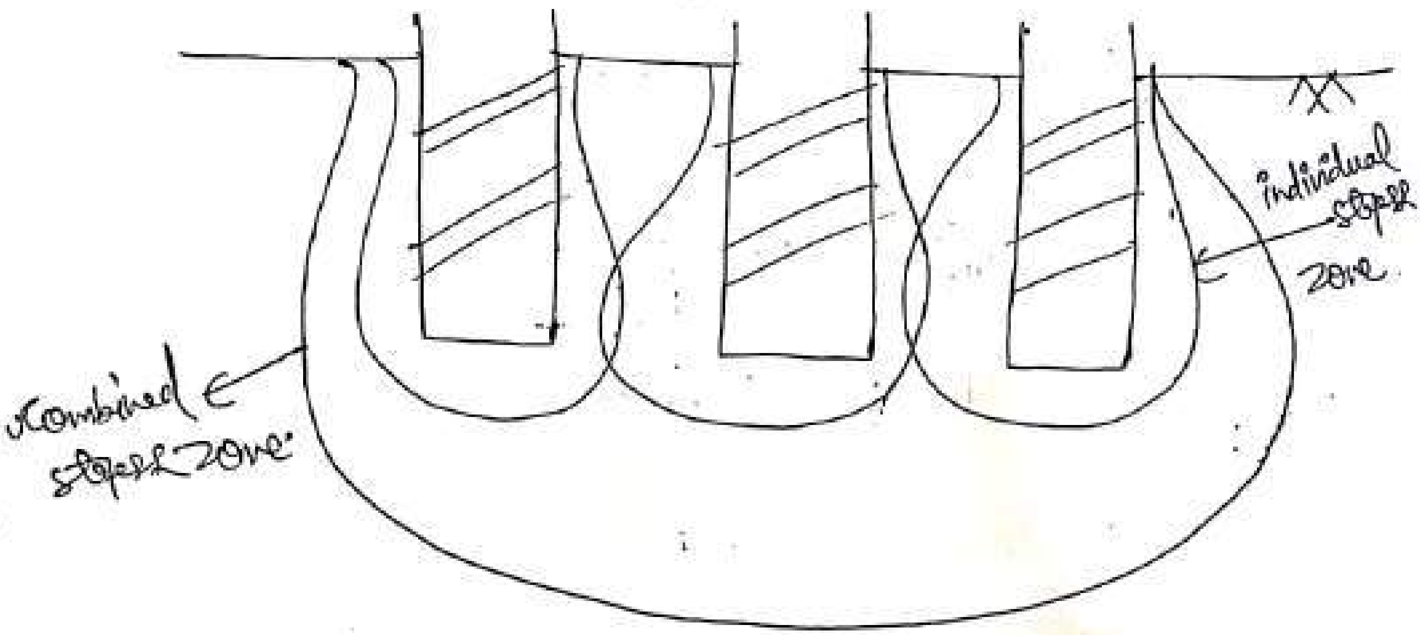
Q_{nf} → Negative skin-friction.

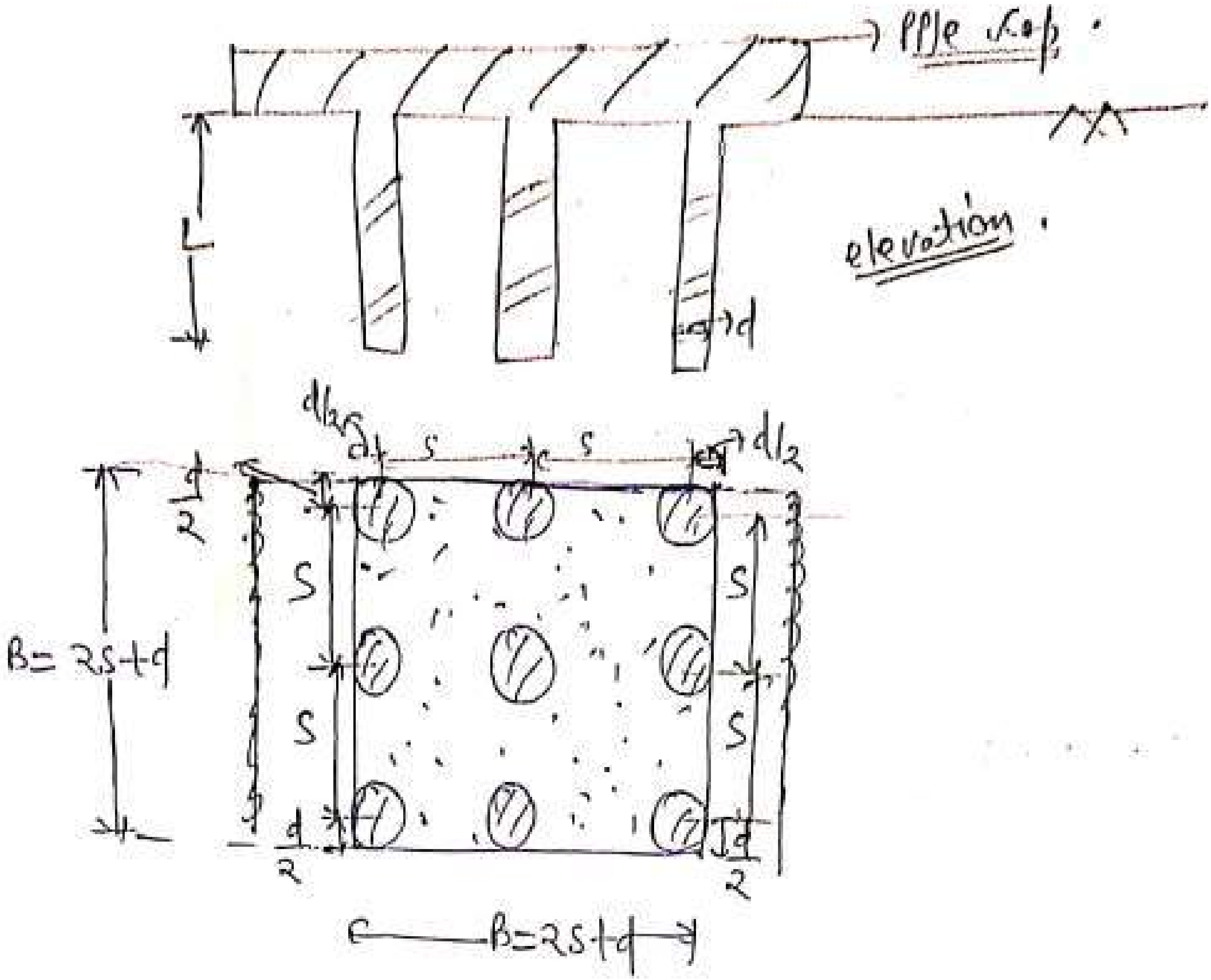
$$Q_{nf} = \alpha_1 \bar{C_1} \ (\pi d L_1) \quad \{\text{in clay}\}$$

$$Q_{nf} = \frac{1}{2} K \gamma L_1 \tan\delta \ (\pi d L_1) \ \{\text{in sand}\}$$

<u>Group Action of Piles</u> →







Size of pile Group →

- 2×2 $B = s + d$
- 3×3 $B = 2s + d$
- 4×4 $B = 3s + d$
- 5×5 $B = 4s + d$
- m×m $B = (m-1)s + d$

$A_b = B^2$ → Base Area

$A_s = 4BL$ → Surface Area

* If, Applied load is large and more no. of piles are used; either piles will act individually or in the group depending upon spacing in b/w the piles.

* If, c/c spacing is (2.5d to 4d) then, soil may get compacted b/w piles and entire wedge of size (B×B) may act as a single ~~pip~~ pile. Such a action is called group action.

* In group action, base area and surface area both will increases.

* In group action, the depth of stress zone extends to great depth then, in individual action. Therefore, settlement due to consolidation in group action will

* for friction action → (3d to 4d)

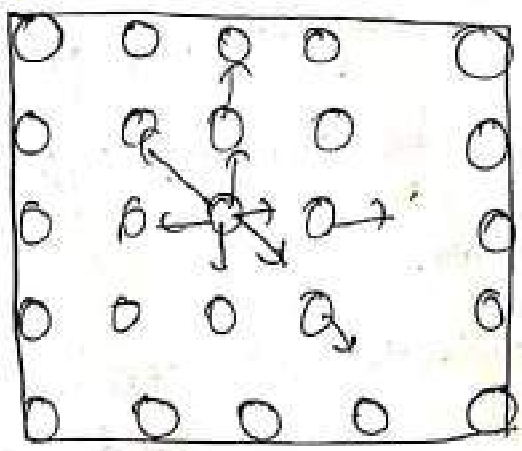
where, d → dia of shaft.

* If, spacing is governed as mentioned above then, usually load carrying capacity of pile group (Q_{ug}) is greater than sum of load carrying capacity of all the piles (nQ_u) in case of sand.

* However in case of clay, it depends upon properties of soil and spacing.

* If, piles are to be driven, pile driving mechanism should start from center and proceed outward it means central pile should be driven 1st and proceed radially outwards.

In this process, resistance in pile driving is less. Hence, cheaper.



Q11. Determination of ultimate load carrying capacity of Pile Group →

$$\alpha = 1$$

For →

$$Q_{ug} = Q_{eb} + Q_{sf}$$

$$= q_b A_b + q_s A_s$$

$\{ A_b = B^2, \; A_s = 4BL \}$

For clay →

$$Q_{ug} = 9C(B^2) + \bar{C}(4BL)$$

$\{$ Here, $\alpha = 1 \}$.

$\alpha = 1$; ∵ cohesion is in b/w soil & soil.

For Sand →

$$Q_{ug} = \gamma L N_q (B^2) + \frac{1}{2} K \gamma L (\tan\phi) \cdot (4BL)$$

Q.3, Group Efficiency → (η_g).

It is defined as the ratio of ultimate load carrying capacity of the pile group to the ultimate load carrying capacity of all the piles under individual action.

$$\eta_g = \frac{Q_{ug}}{n\,Q_{up}}$$

* If, $\eta_g \geq 1$ then; $Q_{safe} = \frac{n \cdot Q_{up}}{F}$

⇒ for Design, η_g should be ≥ 1.

Q.50 Group settlement Relation :- It is defined as the ratio of settlement of pile group to the settlement of individual pile.

$$GSR = \frac{S_g}{S_i}$$

{Always greater than 1}

* It is always greater than 1 and may be as high as 16.

SETTLEMENT OF PILE GROUP –

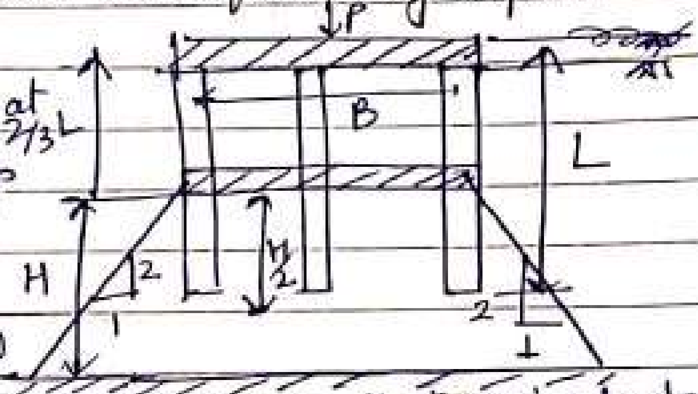
It is generally greater than settlement of individual pile for same loading (same load per pile) this is because the zone of influence of group of pile is generally more.

SETTLEMENT OF PILE GROUP IN CLAY

We use an empiral approach for settlement of pile groups in clay

CASE 1 – when pile is embedded in uniform clay deposit

~~settlement~~ In this case an equivalent raft is assumed at a depth of 2/3 L from the top where L is the embedded length of pile, and the loading on the pile cap (P) is assume to have been transfered on that equivalent raft.



The calcution of the settlement is done in a similar manner as done in consolidation settlement.

The approach discuss above is used for displacement pile. Some time it is used for Bored pile also but to a less degree of accuracy.

$$\Delta H = \frac{C_c}{1+e_0} \log\left(\frac{\bar{\sigma}_0 + \Delta\bar{\sigma}}{\bar{\sigma}_0}\right) \times H$$

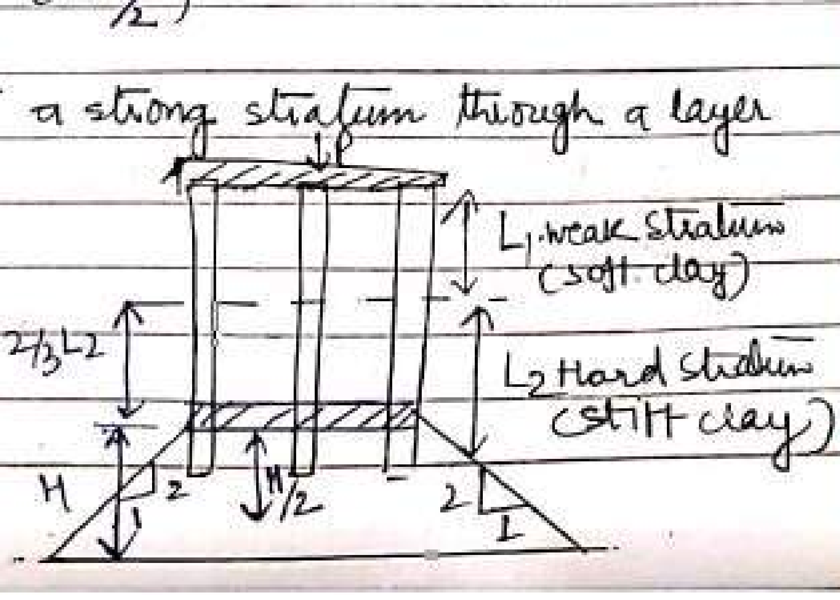
$$\bar{\sigma}_0 = \gamma_t \left(\tfrac{2}{3}L + \tfrac{H}{2}\right)$$

$$\Delta\bar{\sigma} = \frac{P}{\left(B + \frac{H}{2}\right)^2}$$

CASE 2: Pile are driven into a strong stratum through a layer of weak stratum

$$\left(\frac{\bar{\sigma}_0 + \Delta\bar{\sigma}}{\bar{\sigma}_0}\right) \times H$$

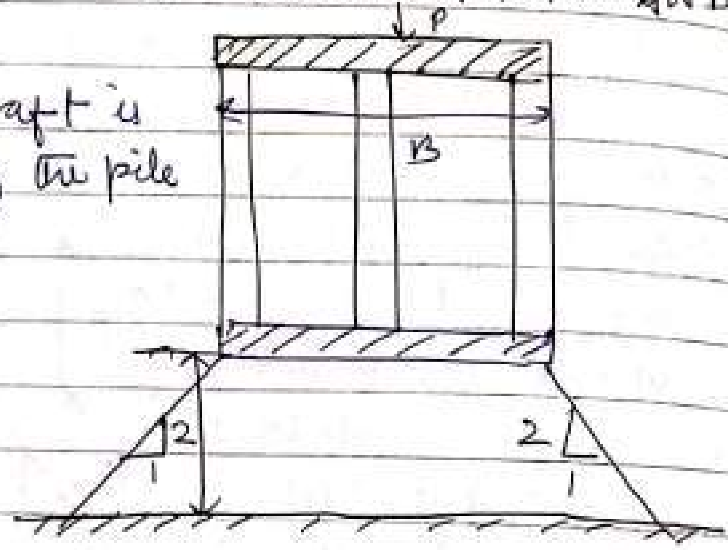
$$\left(\tfrac{2}{3}L + \tfrac{H}{2}\right)$$



In this case equivalent raft is located at a depth of $2/3 L_2$ below the top level of strong stratum where L_2 is the depth of embedded of pile in the strong stratum.

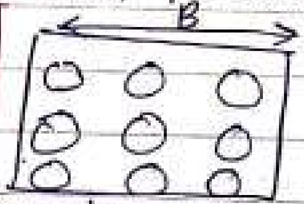
CASE 3: IN CASE OF END BEARING PILE RESTING ON STRONG STRATUM AND IN BORED PILE.

In this case equivalent raft is considered at the tip of the pile



- SETTLEMENT OF PILE GROUP IN SAND.

$$\frac{S_g}{S_i} = \left(\frac{4B + 2.7}{B + 3.6}\right)^2$$



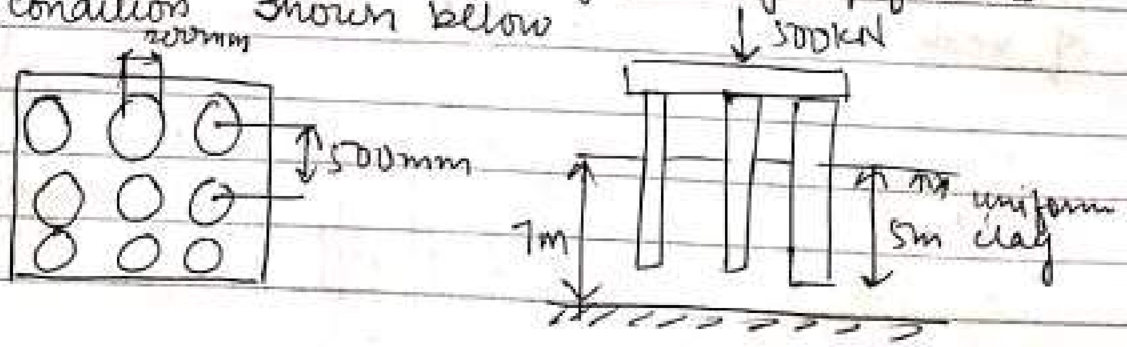
$S_g \rightarrow$ settlement of pile group

$B \rightarrow$ width in 'm'.

$S_i \rightarrow$ settlement of individual pile at the same load per pile as used in (S_g). It is calculate from pile load test.

load carrying capacity can be calculated from strength criteria and settlement criteria and minm value is adopted.

Ques: calculated settlement of pile group for the condition shown below

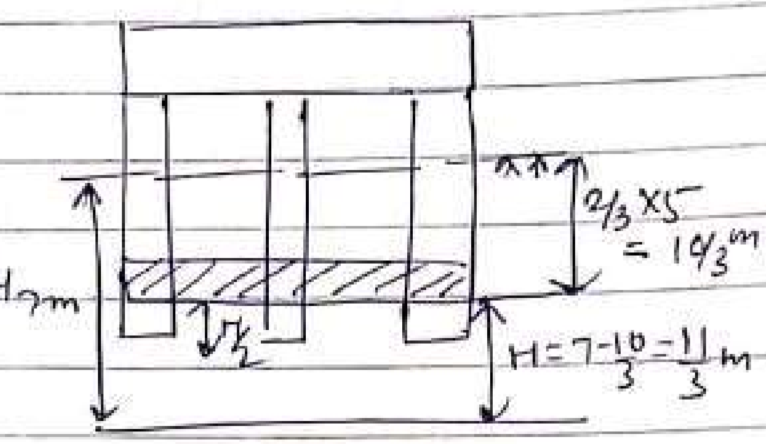


The soil may be assume to be NC, $\gamma_w = 10\,kN/m^3$.

Submerged soil.

$\gamma_{sat} = 20\,kN/m^3$ $\quad w_p = 25.25\%$, $e = 1.05$.

$W_L = 40\%$



$C_c = 0.009\,(w_L - 10)$.

$C_c = 0.009\,(40 - 10)$

$C_c = 0.27$

$$\Delta H = \frac{C_c}{1+e_0} \log\left(\frac{\bar{\sigma}_0 + \Delta\bar{\sigma}}{\bar{\sigma}_0}\right) \times H$$

$$\bar{\sigma}_0 = \gamma_{sub}\left(\frac{10}{3} + \frac{11}{3} \times \frac{1}{2}\right).$$

$$\bar{\sigma}_0 = (20-10)\left(\frac{10}{3} + 11/6\right) = 51.6\,kN/m^2$$

$$\Delta\bar{\sigma} = \frac{P}{(B + H/2)^2} = \frac{500}{\left(1.2 + \frac{11}{6}\right)^2} = 54.34\,kN/m^2.$$

$$\Delta H = \frac{0.27}{1+1.05} \times \log\left(\frac{54.34 + 57.6}{57.6}\right) \times \frac{11}{3} \times 10^3\,mm.$$

$$\boxed{\Delta H = 150.78\,mm}$$

Illustrative Example 25.3. *A 30 cm diameter concrete pile is driven into a homogeneous consolidated clay deposit (c_u = 40 kN/m², α = 0.7). If the embedded length is 10 m, estimate the safe load (F.S. = 2.5).*

Solution. From Eq. 25.15, $Q_u = c N_c A_p + \alpha \bar{c} A_s$

Taking $N_c = 9.0$,

$$Q_u = (40 \times 9.0)\,\pi/4 \times (0.3)^2 + 0.7 \times 40\,(\pi \times 0.3) \times 10 = 289.2 \text{ kN}$$

$$Q_a = \frac{Q_u}{2.5} = \frac{289.2}{2.5} = 115.7 \text{ kN}$$

Q. A concrete pile, 40 cm diameter is driven 25 m into a soft clay (c_u = 25 kN/m², γ = 19 kN/m²). Determine the allowable load. (FOS = 2.25); λ = 0.16, Water Table is at ground surface.

Soln: For $L \geq 25\,m$

$$q_s = \lambda(\bar{\sigma}_v + 2\tau)$$

$$= 0.16\left[\frac{1}{2} \times 25 \times \underset{\gamma - \gamma_w}{(19-10)} + 2 \times 25\right)$$

$$= \underline{\underline{26\ kN/m^2}}$$

$$Q_{up} = 9C\,A_b + q_s A_s$$

$$= 9 \times 25 \times \frac{\pi}{4}(0.4)^2 + 26 \times \underset{\pi D L}{(\pi \times 0.4) \times 25}$$

$$= 28.3 + 814.4$$

$$Q_{up} = 844.7\ kN$$

$$Q_u = 844.7 / 2.5 = \underline{\underline{337.9\ kN}}$$