CVE 409: FOUNDATION ENGINEERING

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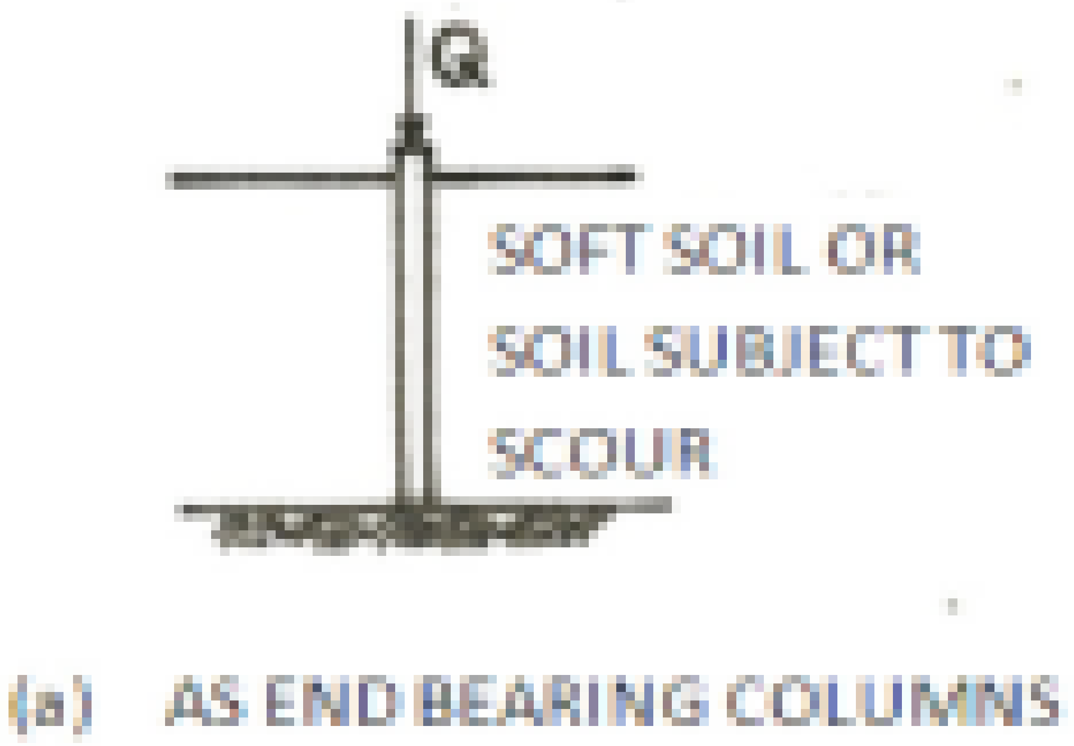
- **Chapter 10**
- **PILE FOUNDATIONS**
- **10.1 Introduction**
- **Shallow foundations are normally used where the soil from the ground surface to the significant depth possesses adequate bearing capacity for safely transmitting the load of the superstructure to the subsoil. However, where the soil immediately below a footing is loose or soft, and/or is likely to be eroded as in the case of bridge substructure, the load of the superstructure has to be transmitted to firm strata at deeper depths through piles or other types of deep foundations e.g. piers and caissons.**

- **A pile is a relatively small diameter shaft driven or installed into the ground through suitable means. These may be subjected to vertical loads, horizontal loads or a combination of vertical and horizontal loads. The piles are usually driven in groups to provide foundations for structures. Generally, piers and caissons are larger in diameter than piles, and are installed by an excavation technique. They are normally used to carry very heavy loads e.g. in bridges.**

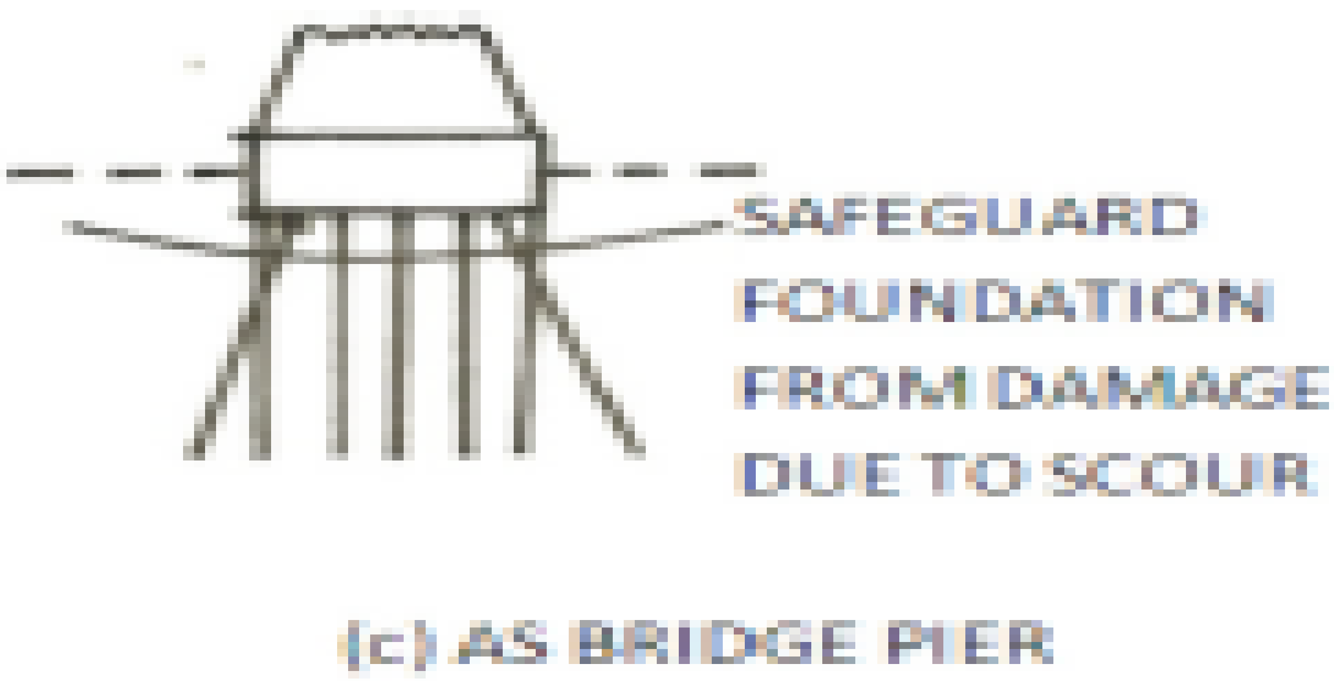
- **Design of pile foundations requires consideration of the basic uses of piles, geology of the site, boring results, pile types, driving equipment in conjunction with a proper dynamic formula, pile capacity using a static formula, driving of test piles and performance of load tests, and bearing capacity of the soil below the piles.**
- **10.2 Uses of Piles**
- **Piles are used in many ways. Details of the various uses are given in Fig.10.1. Fender piles and Dolphins protect water front structures against impacts from ships or other floating objects. Batter piles resist large horizontal and inclined forces.**



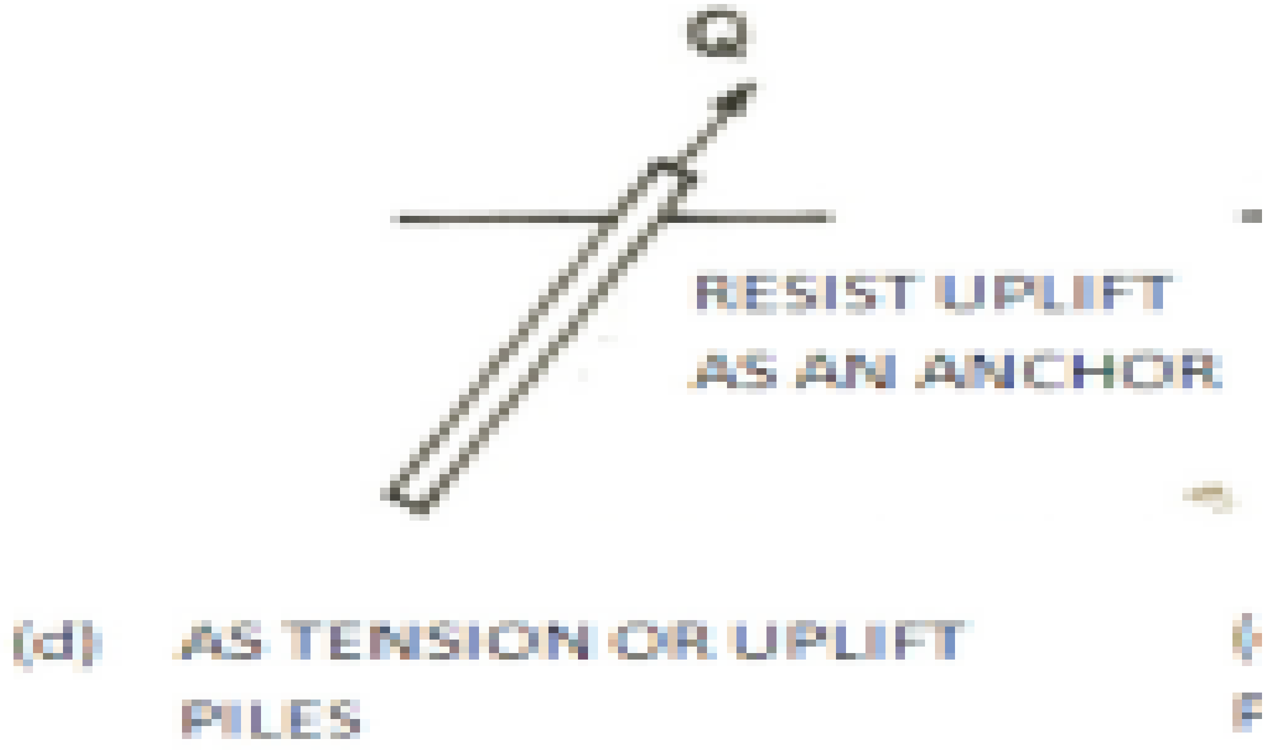
(a) As END BEARING COLUMNS

(b) AS FRICTION PILES

(b) AS FRICTION PILES

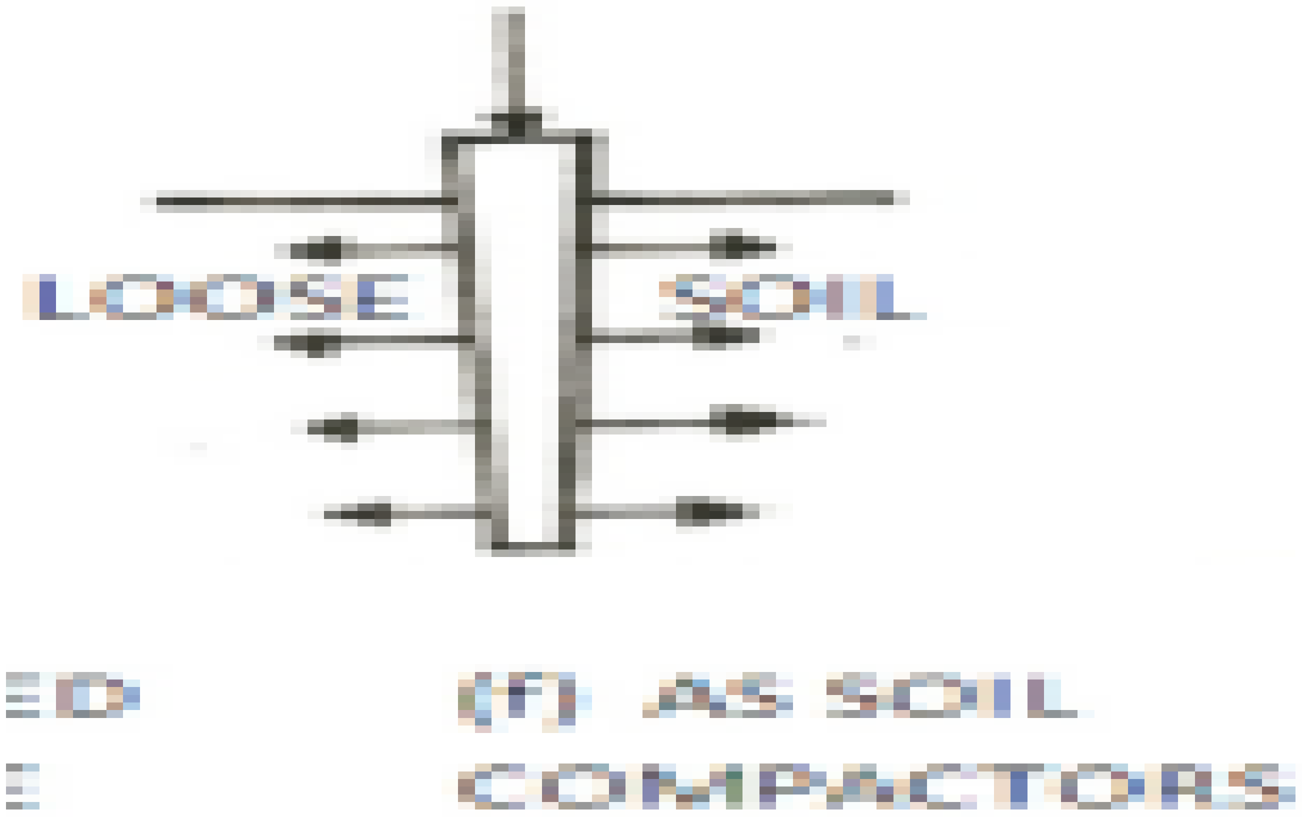


(c) AS BRIDGE PIER



(d) AS TENSION OR UPLIFT PILES

(e) RESIST LOADS APPLIED PERPENDICULAR TO PILE



(f) AS SOIL COMPACTORS

(g) AS ANCHOR PILES (RETAINING WALLS)

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(h) AS STABILIZERS OF BANKS

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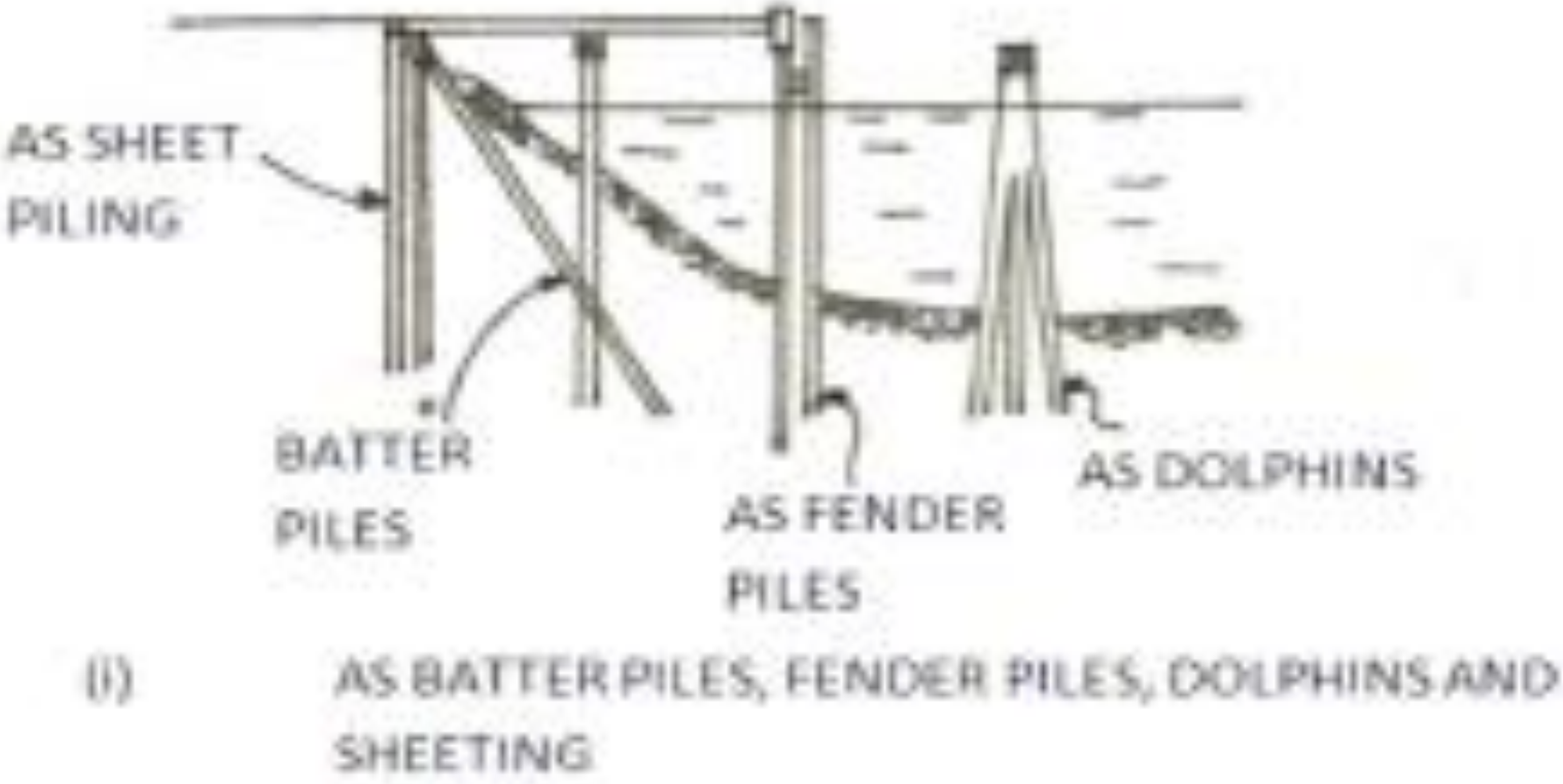


(i) AS BATTER PILES, FENDER PILES, DOLPHINS AND SHEETING

- **Unless piles are effective in one of these ways, they should not be used. It has been a common belief that piles should be driven when in doubt, and that at least they would do no harm. Actually, they may be of no value or be harmful. For instance, with a thick bed of fairly firm clay over a deep bed of soft clay, soil studies might show the firm clay to have enough carrying value as a distributing mat over the soft clay, whereas piles might destroy this advantage of spreading the load and thus decreasing the unit pressure on the soft clay, thereby increasing settlements.**

10.3 General Characteristics of Piles

A brief summary of the general characteristics of piles including the type, usual maximum length, usual maximum design load, advantages and disadvantages is presented in *Table 10.1*.

Table 10:1: General Characteristics of Piles.

Type of Pile	Usual Max. Length (metres)	Usual Max. Design load tonnes per pile	Advantages	Disadvantages
Timber	18.0	25 – 30	1. Low initial cost per metre 2. Easy to handle 3. Readily available	1. Small bearing capacity 2. Difficult to splice 3. Prone to damage by hard driving 4. Vulnerable to decay unless treated when piles are intermittently submerged
Precast Concrete (Presressed)*	24.0 60.0*	80 200*	1. High Load Capacities 2. Corrosion resistance can be attained. 3. Hard driving possible	1. Difficult to handle unless prestressed. 2. High initial cost 3. Prestressed difficult to splice
Cast-in-Place Concrete "Cased" "Uncased"	24.0 18.0	80 60 – 75	1. Easy to alter pile length 2. Damage due to trans-port or handling or driving can be elimi-nated	1. Necking may occur for uncased ones
H-Pile Steel	30.0	100	1. High capacity 2. Easy to splice 3. Small displacement 4. Able to penetrate through light obstru-ctions.	1. Vulnerable to corrosion. 2. Less effective as friction or compa-ction pile.

*Note: Usual maximum length and maximum load for various piles (design value). Greater lengths and higher loads are not uncommon.

10.4. Static Formulas for Bearing Capacity of a Single Pile

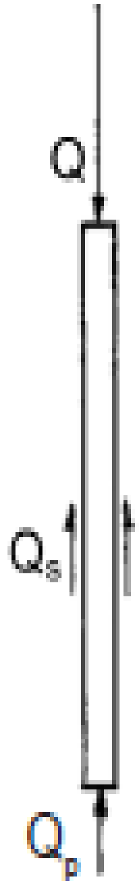


Fig. 10.2: Pile Capacity

- $Q_{ult} = Q_p + Q_S$……………………………………………(10.1)
- where Q_{ult} is the ultimate bearing capacity of the pile
- Q_p= point resistance and Q_s = skin resistance or shaft resistance. If Q_p>>Q_s, we have *Point Bearing Piles*; If Q_p is relatively insignificant, we have *Friction Piles*
- $Q_p = A_P \left(cN_C + \frac{\gamma B}{2} N_\gamma + \gamma D N_q \right) - General \ldots \ldots (10.2)$
- $Q_P = \pi R^2 (1.3cN_C + \gamma D N_q + 0.6\gamma R N_\gamma)$ – for round Piles…………………………………………….(10.3)
- $Q_S = 2\pi R L f_S$ - for round or cylindrical piles………….(10.4)

- **where for equation 10.2 and 10.3,**
- **B = footing width;**
- **R = radius of pile tip;**
- **c = cohesion of soil;**
- **D = total penetration of pile from ground surface to pile tip;**
- **γ = unit weight of soil the supporting stratum, use buoyant**
- **weight for the portion below ground water;**

- **N_c,N_q,N_γ = bearing capacity factors, depending on the Φ value of the soil (see Fig. 10.3); and for equation 10.4,**
- **R = average radius of pile**
- **L = total length of embedment of pile**
- **f_s = unit skin friction or unit shaft resistance.**

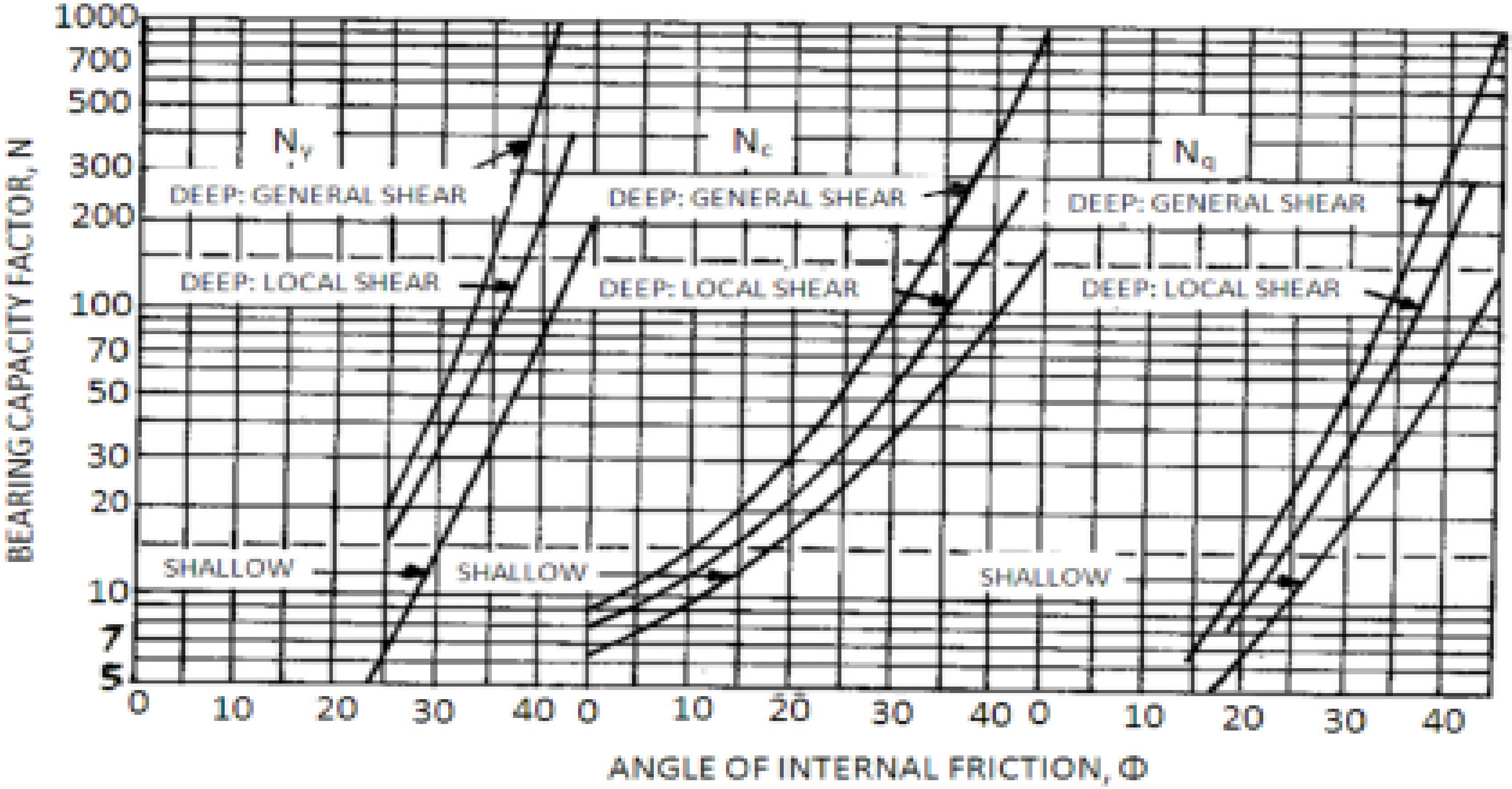


Fig. 10.3: Bearing Capacity Factors for Shallow and Deep Square or Cylindrical Foundations (Adapted from Meyerhof, 1959 and Berezantezev, 1961)

- **Equation 10.4 also gives *Pull-Out Capacity* of the pile.**
- ***Cohesive Soils***
- **For cohesive soils,**
- $f_S = c_a \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.\ldots\ldots\ldots\ldots\ldots (\mathbf{10.5})$
- **Where c_a is the adhesion.**
- **These values can be taken from the data in Table 10.2 or the adhesion factors in Fig. 10.4 can be utilized.**

Table 10.2: Ultimate Values of Skin Friction (Adhesion) on Piles Embedded in Cohesive Soils

Material of Pile	Cohesion $c = q_u/2$ (kN/m²)	Adhesion c_a (kN/m²)
Concrete and timber	0 36 72 144 Or greater	0 33.5 48 62
Steel	0 36 72 144 Or greater	0 33.5 48 58

For granular soils, see *Figure 10.5*.

- $\sigma'_h = K\sigma'_v = K\gamma' y$ (at any depth 'y'
  $\text{the friction} \quad f_S = \sigma'_h \tan\delta = K\gamma' y \tan\delta$
- where δ is the angle of friction between soil and pile. The average friction along the entire length L of the pile is
- $f_S = {}^1/_2\, K.\, \gamma'.\, L \tan\delta$……………………………….(10.6)
- where K = coefficient of lateral earth pressure. Typical values of K, and δ are given in Table 10.3 and Table 10.4 respectively:

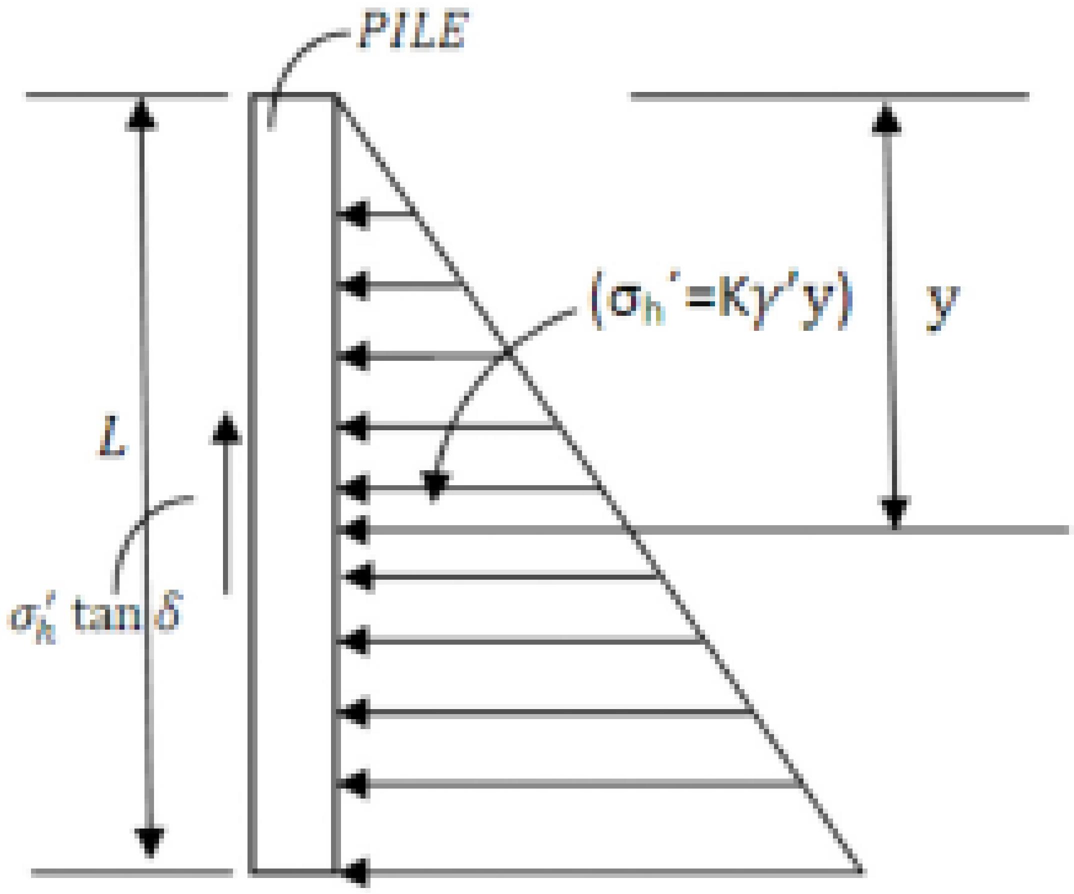


Fig. 10.5: Lateral Pressure on a Pile

Table 10.4: Coefficient of Friction, Cohesionless Soils against Pile (& Similar Structures)

Material	Coefficient of friction (tan δ)	δ
Wood	0.4	22°
Rough concrete, cast against soil	tan φ	φ
Smooth, formed concrete	0.3 – 0.4	17
Clean Steel	0.2	11
Rusty Steel	0.4	22
Corrugated metal	tan φ	φ

- **10.5 Negative Skin Friction**
- **Negative skin friction can occur when:**
- **(i) bearing piles have been driven into a fill which has recently been placed.**
- **(ii) fill is placed around piles after driving of the piles**
- **(iii) bearing piles are driven through a soft soil causing a sufficient amount of structural disturbance to introduce consolidation and lead to subsidence of the soil which is larger than the settlement which the piles undergo when they are loaded (This condition is worse with sensitive clays.)**

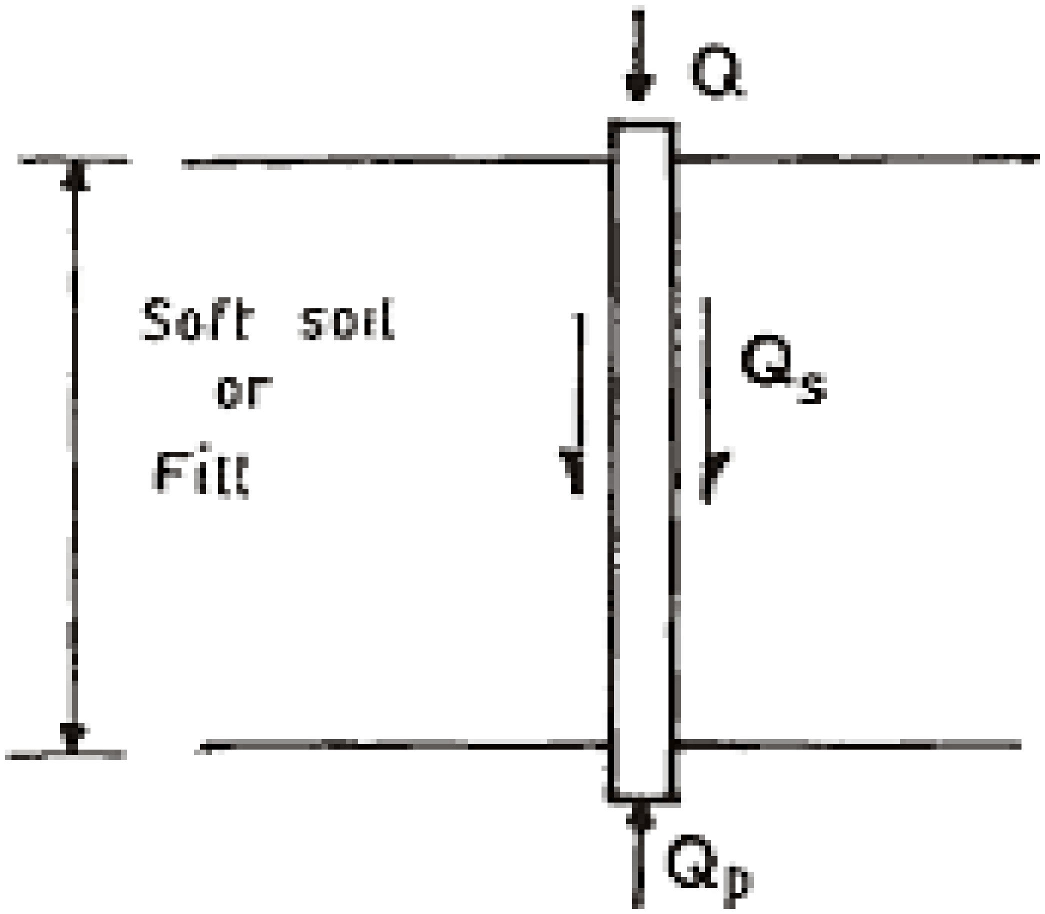


Fig. 10.6: Negative Skin Friction in Pile

- **More specifically, this condition occurs in any case in which the soil subsides relative to the piles, and the piles must support the soil instead of the soil supporting the pile and its load, as in friction pile foundation. Only about 25mm of relative displacement is required to mobilize fully the skin friction. Equations 10.7 and 10.8 are utilized in determining the bearing capacity of a pile subjected to negative skin friction.**

- $\mathbf{Q = Q_p - Q_S \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10.7)}$
- **where** $\mathbf{Q_S = 2\pi R c_a L \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (10.8)}$

- **10.6 Pile Groups (Cluster)**
- **Building codes do not permit the use of less than three piles to support a major column and less than two piles to support a foundation wall unless the loads fall concentrically to the centroid of the piles. Consequently, piles are seldom installed singularly, but instead, they are always in groups or clusters. The bearing capacity and settlement of pile groups are the end results needed for the design of the foundation. Fig.10.7 shows that the total stress distribution below a pile cluster may be several times greater than that under a single individual pile. Consequently, much higher settlement will occur under a pile cluster. Fig. 10.8 shows approximate stress distribution at 60°to the horizontal.**

(a) SINGLE STRESS (b) OVERLAPPING STRESS

Fig. 10.7: Vertical Stress at the Level of Pile Tips

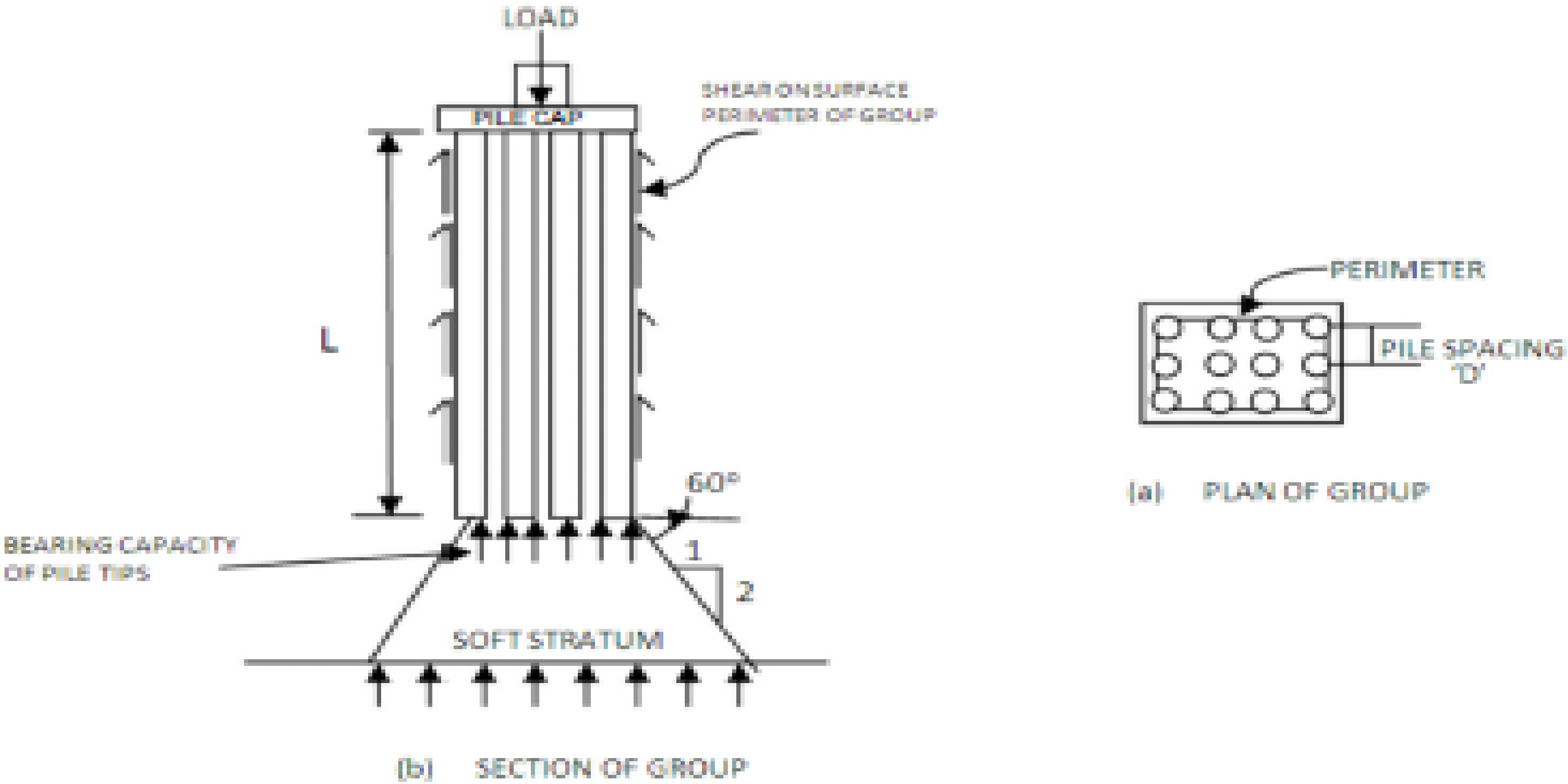


Figure 10.8 Distribution of Pressure beneath Point Bearing Piles

The pile spacing in *Table 10.5* is used to keep the cost of the pile cap to a minimum. Larger spacing increases the cost of the footings without materially benefitting the foundation.

Table 10.5: Recommended Minimum Pile Spacing for Economic Pile Cap

Function of Pile	Minimum Pile Spacing Centre to Centre of piles
Point-bearing piles in hard stratum	2 to 2½ x butt diameter or 75cm
Point-bearing piles on hard bedrock	2 x butt diameter or 60 cm
Friction Pile	3 to 5 butt diameter or 1.07m

- ***10.6.1*** **Bearing Capacity of Piles in Groups**
- $$(\mathbf{Q_g})_{\mathbf{ult}} = \mathbf{sLp} + \mathbf{q_{ult}A} - \boldsymbol{\gamma}\mathbf{LA} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (\mathbf{10.9})$$

where,

$(Q_g)_{ult}$ =ultimate bearing capacity of group (upper limit of pile group capacity, not exceeding the ultimate capacity of a single pile times the number of piles in the group).

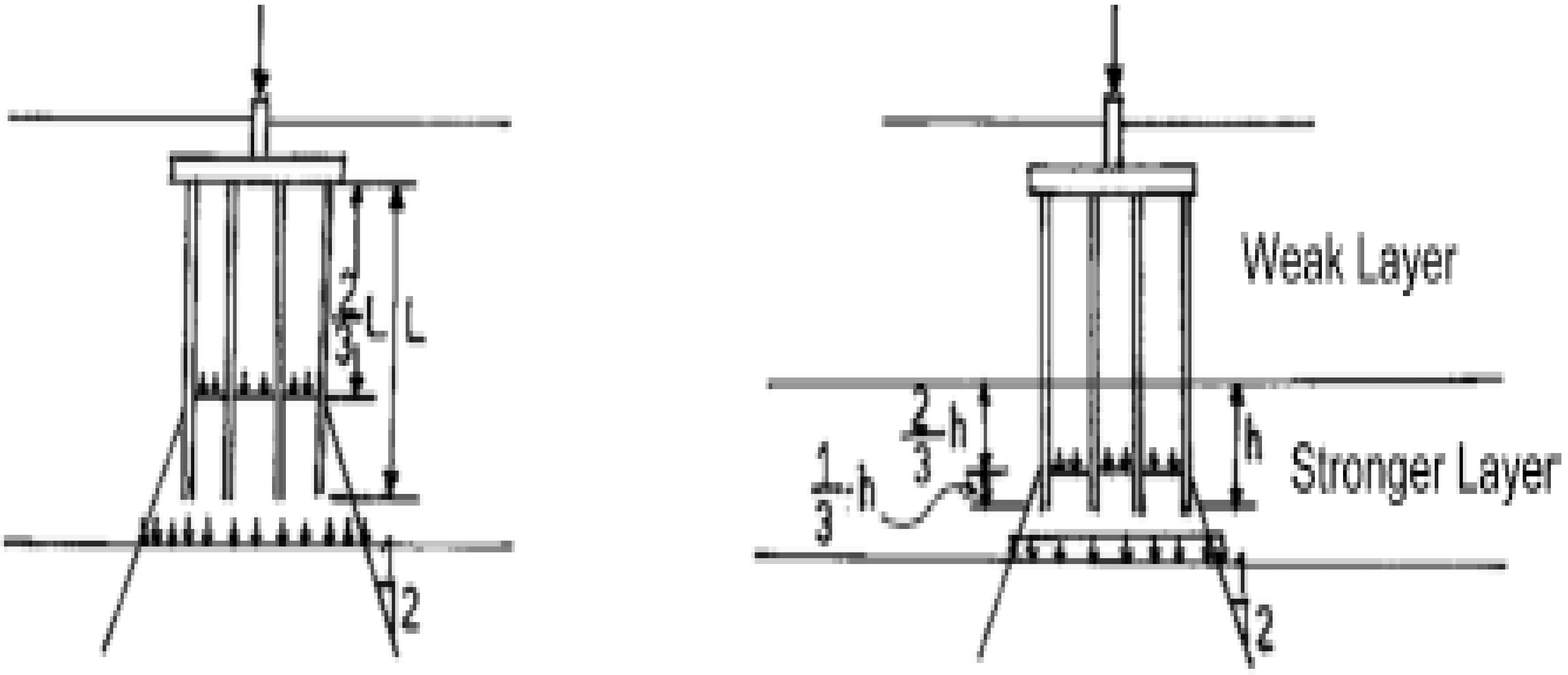
s =shear resistance of soil along the vertical surface of the block;

= ½ x unconfined compression strength for cohesive soils

= earth pressure at rest x tanϕ, for granular soils with angle of internal friction ϕ

- **L = length of pile embedment in soil**
- **P = perimeter of area enclosing all the piles in the group**
- **Q_{ult} = ultimate bearing capacity of soil at the level of pile tip (use equation 10.2 with the area A_p changed to A).**
- **A = area enclosing all the piles in the group**
- **γ = unit weight of soil within the block L x A.**

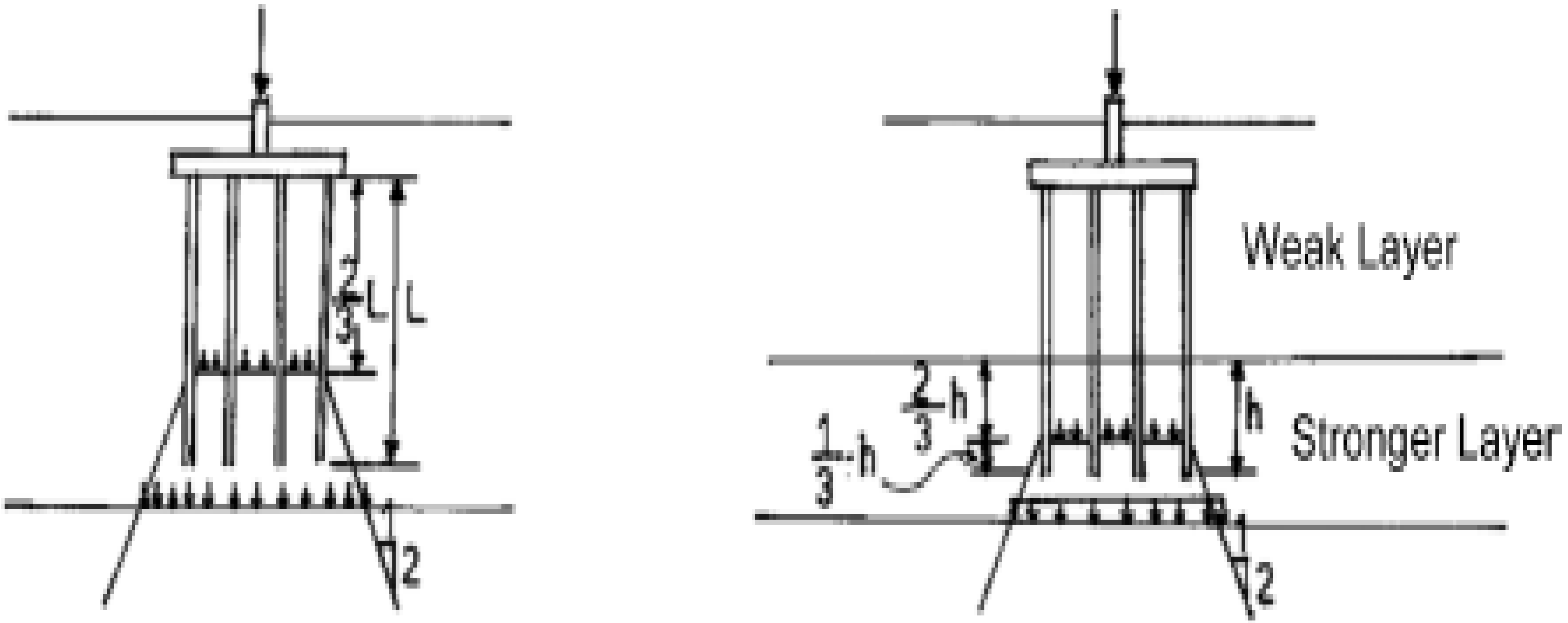
- **10.6.3 Settlement of Piles in Groups**
- **For computation of settlements, for point-bearing piles, the total load on the pile group is assumed to spread out at 2:1 slope from the pile tips (See Fig. 10.8). For friction piles, the load is assumed to spread out at 2:1 slope from a depth L/3 from the tip (See Fig. 10.10).**



L, h are the length of embediment of piles in the layer of soil offering skin friction to the piles

Fig. 10.10: Distribution of Pressures for Friction

10.10).



L, h are the Length of embedment of piles in the layer of soil offering skin friction to the piles.
Fig. 10.10: Distribution of Pressures for Friction

- **10.10 Foundation Selection**

Table 10.6 gives the procedures for foundation selection. It must be regarded as suggestions for guidance only. The foundation engineer must always be aware of the function and type of structure and must provide a foundation type that will not either overstress any underlying weaker substrata or result in excessive settlements, both overall and differential. In the case of highly irregular deposits, he may find it necessary to base the foundation type and design on the most unfavourable condition.

Table 10.6: Procedures for Foundation Selection

Subsoil Conditions	Foundation Possibilities	
	Light, Flexible Structure	Heavy, Rigid Structure
Deep compact stiff deposit	1. Shallow footing foundation	1. Shallow footing foundation 2. Shallow mat
Deep compressible strata	1. Shallow footing foundation on compacted granular zone 2. Shallow mat 3. Friction piles	1. Deep mat with possible rigid construction in basement 2. Long piles or caissons to by pass soft deposit 3. Friction piles
Soft or loose strata overlying firm strata	1. Bearing piles or piers 2. Shallow footing foundation on compacted granular zone or used in conjunction with site preloading 3. Shallow mat	1. Bearing piles or piers 2. Deep mat
Compact or stiff layer overlying soft deposit	1. Shallow footing foundation 2. Shallow mat	1. Deep mat (floating type) 2. Long piles or caissons to bypass soft deposit
Alternating soft and stiff layers	1. Shallow footing foundation 2. Shallow mat	1. Deep mat 2. Piles or caissons to underlying firm stratum to provide satisfactory foundation.

- **Example 10.1**
- **At a site the soil is firm clay, with an average undrained shearing strength 'c' of 48kN/m^2 to a depth of 12m and is underlain by very dense sandy gravel.**

- **Compare the allowable load on a 1.5m x 1.5m spread footing founded at a depth of 1.5m in the clay to the allowable load for 4 concrete piles each 300mm x 300mm square and 6.1m long and driven at 1.2m centres in a square pattern.**

- **Using the minimum calculated allowable load for both foundations (as determined in (a) above), calculate the settlement occurring in each foundation type, use C_c = 0.08, γ = 18.9 kN/m^3, e_o = 1.4. Assume a 2:1 stress distribution.**

(a) (i)q_{ult} (gross) = 1.3cNc + O.4γBNγ + γ$D_{f.}$.Nq

q_{ult} (net) = 1.3 cN_c+ 0.4γBNγ + γD_f (Nq- 1)

- **≈ 1.3 cN_c(for clay at a shallow depth)**

1.3 (48 kN/m^2) (9.0) = 561.60 kN/m^2

q_{allow}= q_{ult}/3 = 187.20 kN/m^2

Q_{allow}= A { q_{allow}} = (1.5 x 1.5) m^2x 187.20 kN/m^2

= 421.20kN

(ii) Computing the load per pile

$Q_{ult/pile} = Q_p + Q_s$

$Q_{ult(net)/pile} = A_p\{1.3cN_c + 0.4\gamma BN\gamma + \gamma D_f(Nq\text{-}l)\} + 4BLf_s$

$= A_p(l.3cN_c) + 4BLf_s$

$= (0.3 \text{ x } 0.3m^2)\ \{1.3(48\ kN/m^2)\ (9.0)\} + 4(0.03m)(6.1m)\ (48\ kN/m^3)$

$= (50.54 + 351.36)\ kN = 401.9\ kN$

$nQ_{ult} = 4 \text{ x } 401.9 = 1607.6kN\ nQ_{ult}$

$$\mathbf{nQ_{ult} = \frac{1607.6}{3}\ kN = 535.9kN}$$

(iii) Using group effect

$(Q_g)_{ult(net)} = q_{ult} A + sLp - \gamma LA$

$q_{ult}A = (1.5m \times 1.5m)\{1.3 \times 48\ kN/m^2 \times 9.0\} =$ 1263..6 kN

sLp = $(48kN/m^2))(6.1m)(4x\ 1.5m) = 1756.8\ kN$

$\gamma LA = (18.9\ kN/m^2)\ (6.1m)(1.5 \times 1.5m) = 259.40\ kN$

$(Q_g)_{ult(net)} = 1263.6 + 1756.8 - 259.40 = 2761\ kN$

$(Q_g)_{allow} = 2761/3 = 920.3\ kN$

∴ Individual pile governs and allowable load is 535.9 kN. Thus the allowable load for the spread footing is only about $\left(\frac{421.20}{535.9} \times\ 100\right)$ i.e. 7

of the allowable load for the pile foundation.

Generally, it is more accurate to divide the section into layers of about 3m thickness. However, only one layer is utilized in this analysis. Most of the settlements will occur in the clay layer.

***Spread Footing*:**

$\sigma'_o = \gamma' H = (18.9\ kN/m^3)(6.75m) = 127.59 kN/m^3$

$\Delta\sigma$ = Minimum calculated allowable load / $(6.75m)^2$

$$= \frac{421.20}{(6.75)^2} = 9.24\,\frac{kN}{m}$$

$$\rho = (10.5\mathrm{m})\left(\frac{0.08}{2.4}\right)\log\left(1 + \frac{9.24}{127.58}\right)$$

$$= 0.35\log(1.0721)$$

- **=0.35(0.304)m=0.0106m =10.6m**

Piling

σ'_o = γ'H = (18.9kN/m^3) (8.03m) = 151.77 kN/m^2

$$\Delta\sigma = \frac{421.20}{(5.47)^2} = 14.08\ kN/m^2$$

$$\rho = (7.93m)\left(\frac{0.08}{2.4}\right) log\left(1 + \frac{14.08}{151.77}\right)$$

$$= 0.264 log\ (1.093)$$

=0.264 (0.039) = 0.0102m = 10.2mm

Settlement of spread footing is 10.6mm while the settlement of the pile group is 10.2mm.

THANK YOU