Pile foundation I

Uses of piles

1. To carry vertical load

If all the (majority amount) loads are transferred to the pile tips

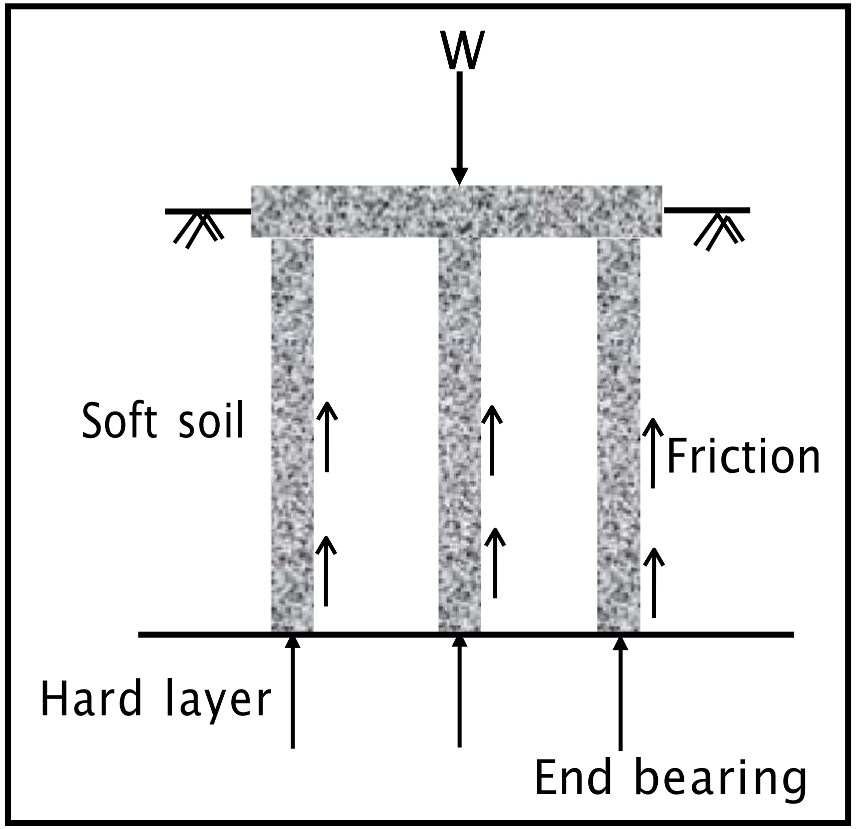
↓

End bearing pile

If all the (majority amount) loads are transferred to the soil along the length of pile

↓

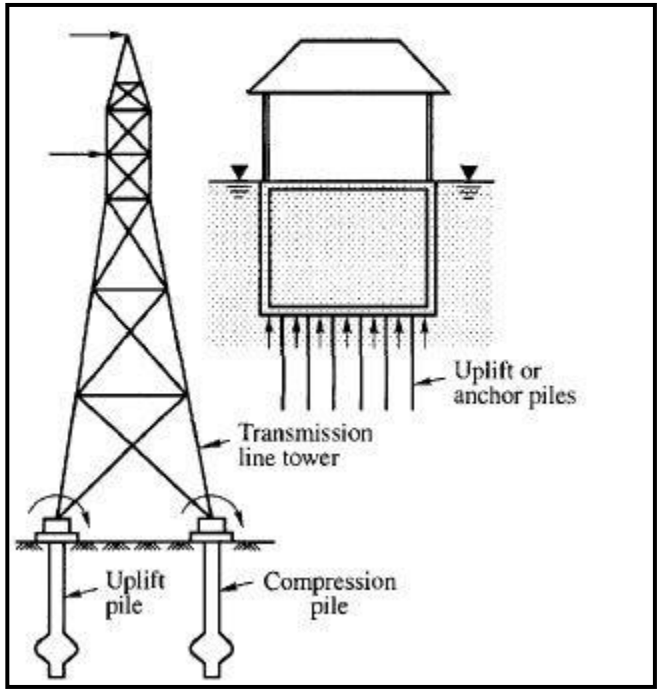
Friction pile



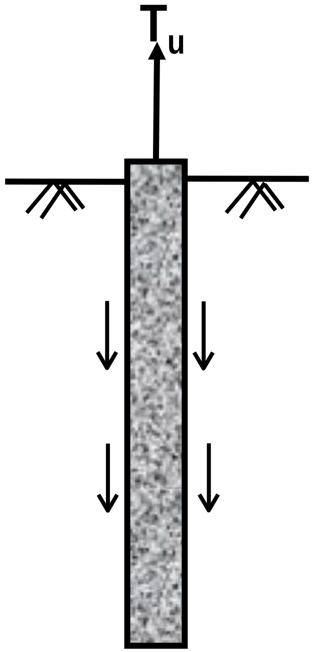
Compaction pile: *Short piles used for compacting loose sand.*

2. To resist uplift load

Tension pile or Uplift: Below some structures such as transmission tower, offshore platform which are subjected to tension.



Murthy (2001)



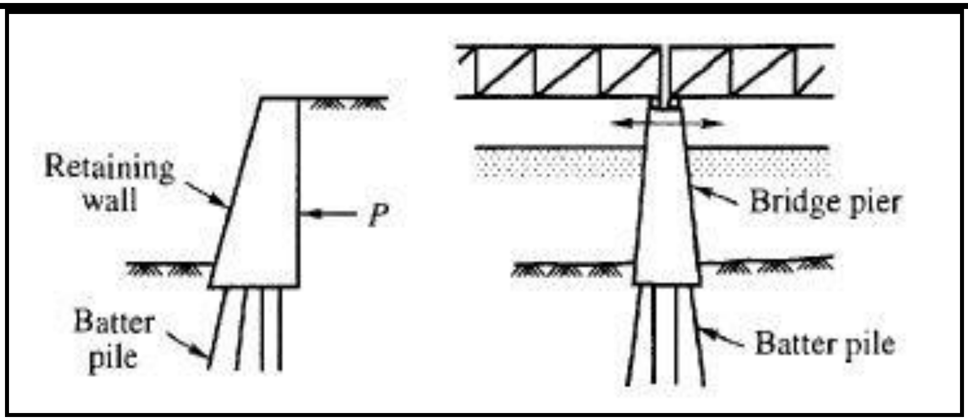
Tension Pile

3. To carry inclined and horizontal load (foundation for retaining wall, bridge, abutments and wharves)

Laterally loaded piles: Horizontal load acts perpendicular to the pile axis.

Batter piles: Driven at an angle

Carry large horizontal load



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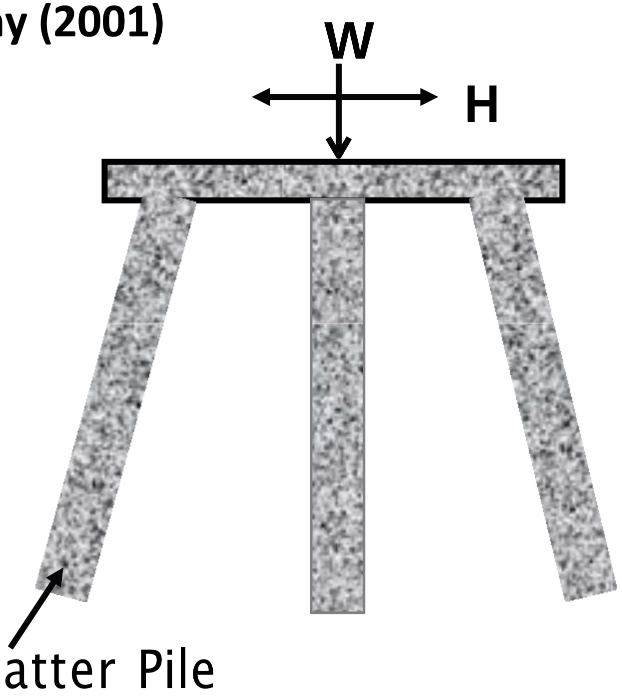
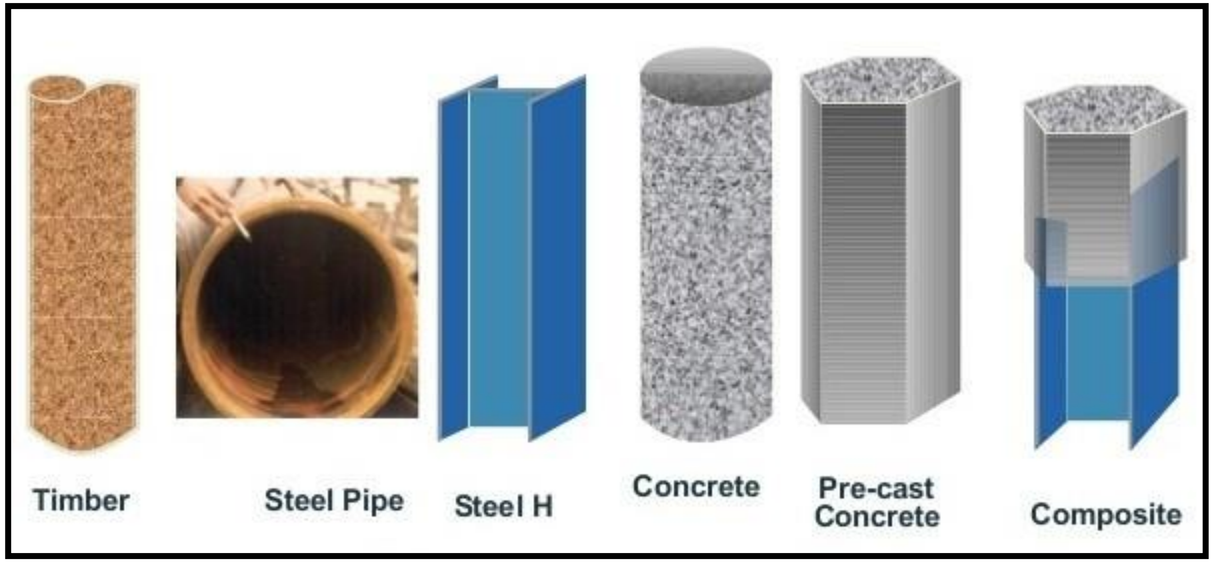


Types of pile

- **Material used**
  - Steel pile
  - Timber pile
  - Concrete pile
  - Composite pile
- **Cross-section**
  - Circular
  - Square
  - Hexagonal
  - I-section
  - H- section
  - Pipe
- **Shape**
  - Cylindrical
  - Tapered
  - Under-reamed
- **Mode of load transfer**
  - End bearing
  - Friction
  - Combined
- **Method of installation**
  - Driven
  - Bored
  - Jetted
- **Method of forming**
  - Pre-cast
  - Pre-stressed
  - Cast *in situ*
- **Based on displacement of soil**
  - Displacement piles
  - Non displacement piles

Based on material used :



https://www.slideshare.net/shivamsgandhi/pile-foundation

https://in.pinterest.com/pin/680043612452541560/

Concrete Pile

Steel Pile

http://www.86steelpipe.com/cs/gr-50-steel-pipe-piles.html

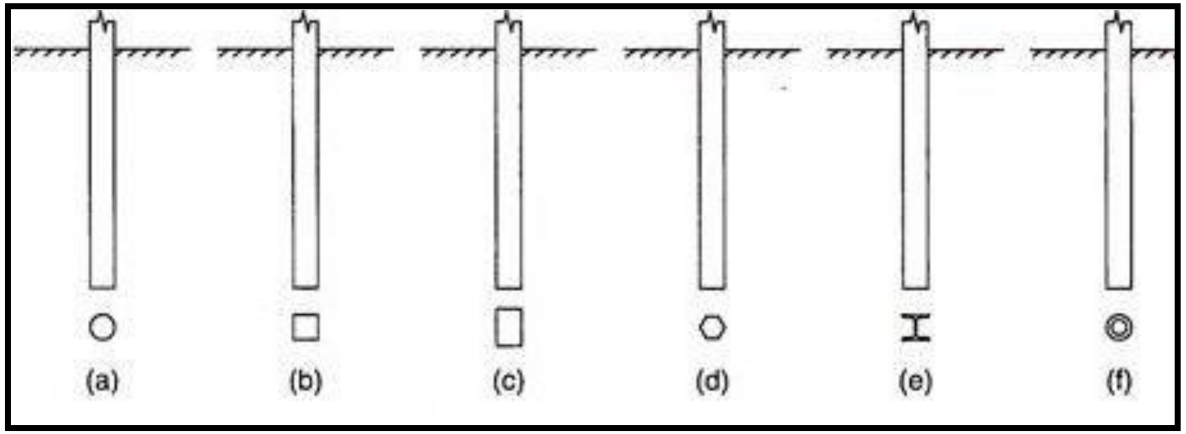
Timber Pile

Timber pile: suitable for light loads varies from 100 to 250 kN per pile. Suitable for soft cohesive soil.

Concrete Pile: all load condition. Most frequently used piles. Strong, durable.

Steel pile: Used to carry heavy load

Based on crosssection:



a) circular, **b)** square, **c)** rectangular, **d)** hexagonal, **e)** H- section, **f)** pipe

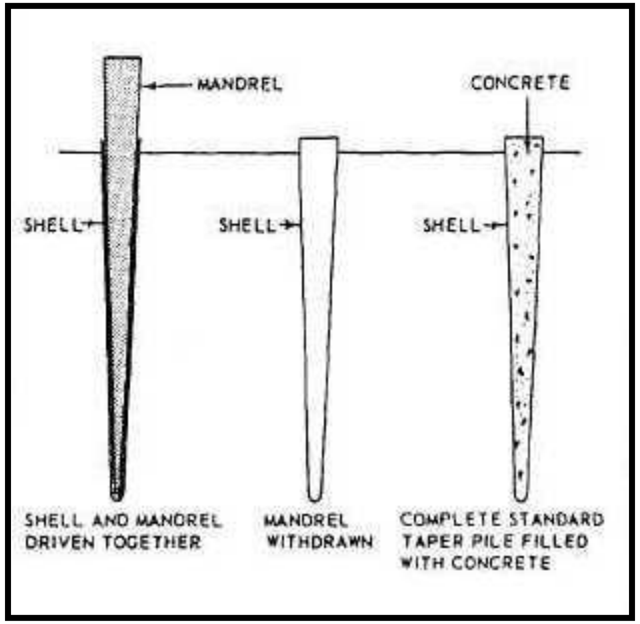
Rock or very dense sand – H pile and open ended pipe pile (least driving effort)

Under the vertical load, the type of pile cross section does not play a important role. However, under horizontal load, **square and H section pile perform well as compared to circular pile**

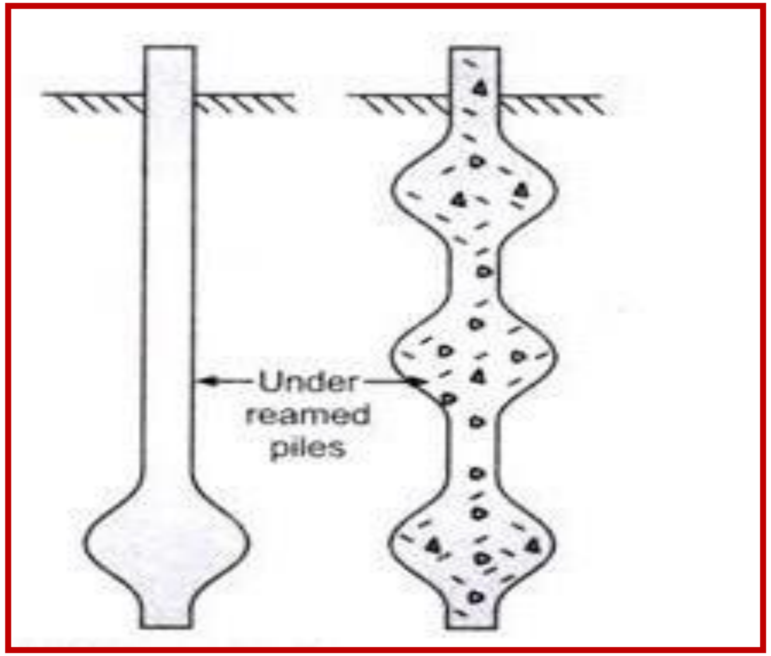
Pile foundation II

Based on Shape:

Cylindrical Pile



Tapered Pile



Underreamed Pile

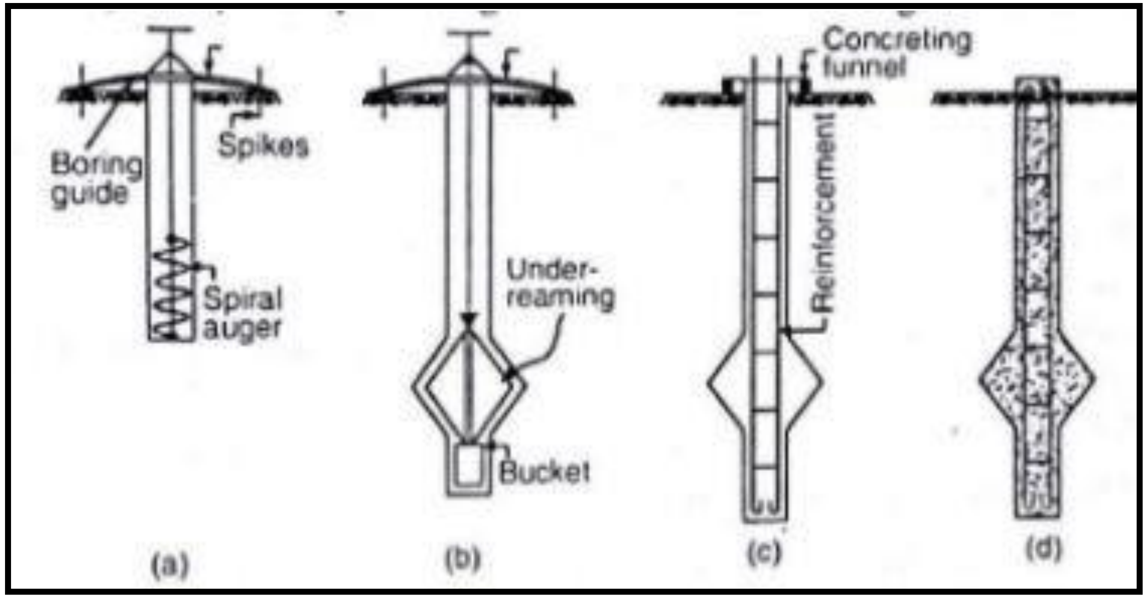
Cohesive soil under laid by a granular soil – **Cylindrical pile**

Loose to medium dense granular soil – **Tapered pile** (for efficient transfer of load along the length of pile.
efficient distribution of pile materials)

Expansive soil – **Under-reamed pile**

Under-reamed Pile:

- **150-200 mm** shaft diameter
- **3 to 4 m** long
- Underreamed portion is **2 to 3 times** the shaft dia.
- Used for **expansive soil**



Punmia (1973)

a) Boring by auger
b) Under-reaming by under-reamer
c) Placing reinforcement cage in position
d) Concreting of pile
e) Concreting of pile caps

Mode of load transfer:

End- bearing pile

- Act as column
- Transmit the load through a weak soil to a hard stratum
- The ultimate load carried by pile= load carried by the bottom end

Friction pile

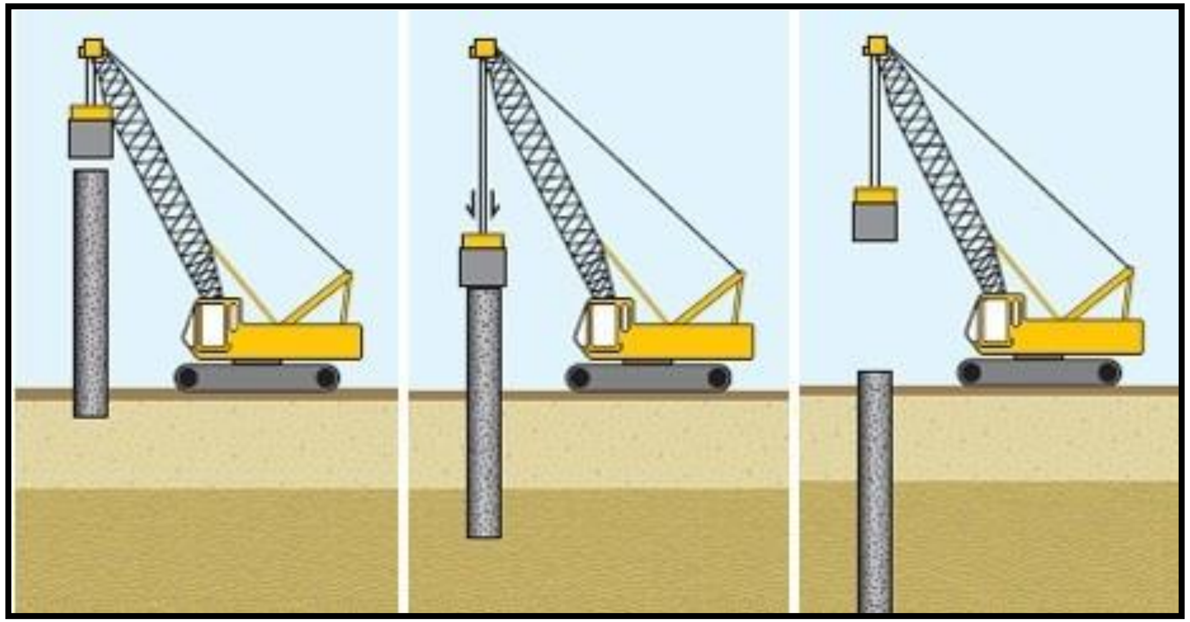
- Do not reach hard stratum
- Transfer the load through skin friction between embedded soil and pile
- The ultimate load carried by pile= load transferred by skin friction

Combined end- bearing and friction pile

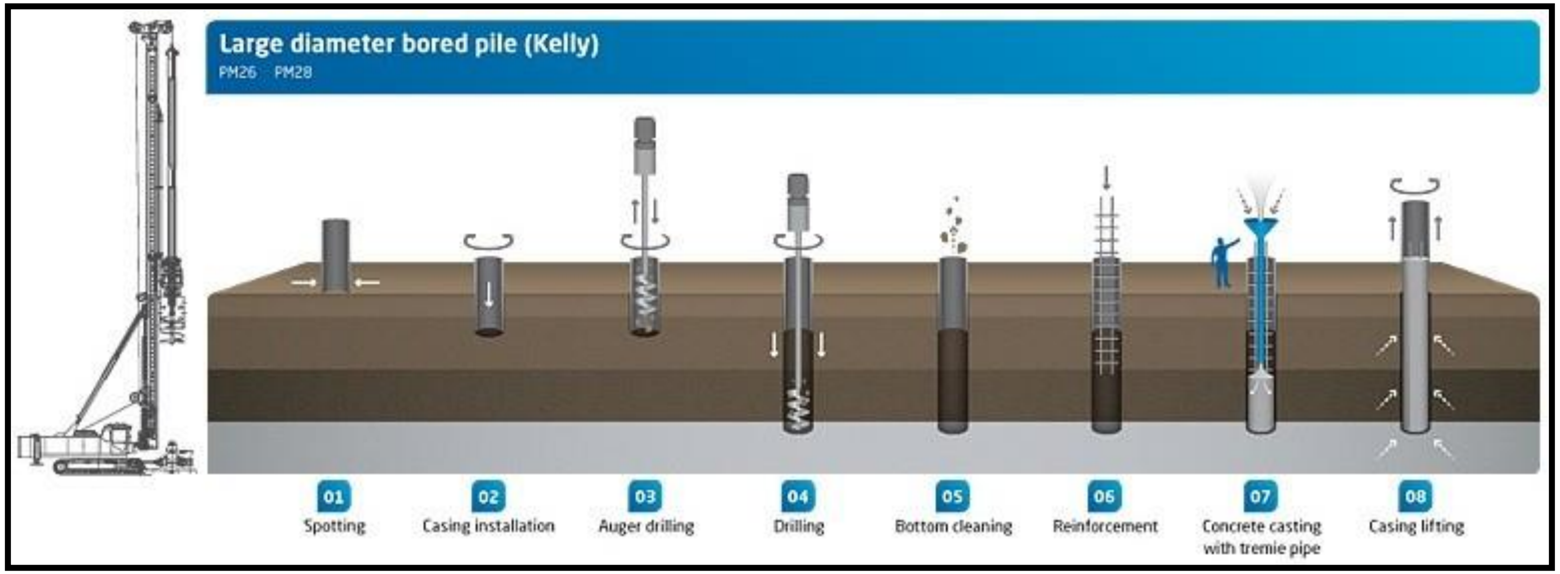
- The ultimate load carried by pile= load transferred by skin friction + load carried by the bottom end of pile

Method of installation

Driven Pile:



Bored Pile:


Large diameter bored pile (Kelly)
PM26 PM28
01
Spotting
02
Casing installation
03
Auger drilling
04
Drilling
05
Bottom cleaning
06
Reinforcement
07
Concrete casting with tremie pipe
08
Casing lifting

Driven Pile: loose granular soil (compact the soil, thus increase its shear resistance)

Bored pile: best suited to clay soil

Jetted pile: used if granular soil are in a very compact state

Method of forming

Precast concrete piles:

- Formed in a central casting yard to the specified length, cured and shipped to the construction sites.

or

If space is available, casting yard may be provided at the site

- **Length upto 20m and precast hollow pipe piles can go up to 60m**

- Shorter piles can carry load up to **600kN,** and capacity of longer pile can be as large as **2000KN (in some cases)**

Prestressed concrete piles:

Formed by tensioning high-strength steel (f_{ult} =1700 to 1860 MPa) prestress cables and casting the concrete pile about the cable

The prestress cables are cut, when the concrete hardens

Cast in situ pile

Formed by making a hole in the ground and filling it with concrete
If the hole is formed by drilling, then it is called **bored cast in situ**. If it is formed by driving a metallic shell or a casing into the ground, then it is called **driven cast in situ**.
If during concreting the casing is left in position, then it is termed as **cased pile.** If the casing is gradually withdrawn, then it is termed as **uncased pile**.

Precast and Prestressed pile: Use in marine structure.

Prestressed piles have large vertical load and bending moment capacity and are used in such installation

Cast in-situ Pile: Soil of poor drainage quality

Suited in places where vibrations are avoided to save the adjoining structures

Based on displacement of soil:

Displacement Piles : All driven piles are displacement piles as the soil is displaced laterally when the piles is installed.

Non-Displacement Piles : Bored piles are non- displacement piles

Advantages of precast concrete pile:

- Piles are cast in controlled environment
- The required number of piles can be cast in advance
- Loose granular soil is compacted
- The reinforcements remain in proper position.

Disadvantages of precast concrete pile:

- Addition reinforcements are required due handling and transportation
- Special equipments are required for handling and driving
- Piles can be damaged during handling and transportation
- If the soil is saturated, then pore water pressure is developed which reduces the shear strength of the soil.
- Length adjustment is difficult

Advantages of cast-in-situ concrete pile:

- The length of the shell or pile can be increased or decreased
- No additional reinforcement is required
- Additional pile can be installed quickly
- Little chance of damage due to handling and transportation

Disadvantages of cast-in-situ concrete pile:

- Proper quality control
- Loose granular soil is not compacted significantly
- A lot of storage space is required for materials

Bored cast-in-situ piles: Large diameter pile can be made. Installation can be made without appreciable noise or vibration. Boring may be loosen the granular soil. In uncased pile, concreting is difficult due to the presence of drilling mud. Bored piles are commonly cheaper. Length of the pile can be changed or varied depending the ground condition.

Driven cast-in-situ piles: Diameter of the pile can not be made too large. More noise and vibration . Granular soil is compacted . Drilling mud is not required. It is costlier (especially the cased one). Length adjustment is difficult.

(Ranjan and Rao, 1991) **Typical length and capacities of various piles:**

Pile Type	Pile length		Approximate design load (kN)	
	Usual range	Maximum	Usual range	Maximum
Timber	10-18	30	150-200	300
Driven precast concrete	10-15	30	300-600	900
Driven prestressed concrete	20-30	60	500-600	900
Cast insitu concrete (Drilled shell)	15-25	40	300-750	900
Concrete cast insitu bulb piles	15-25	45(large dia.)	600-3000	9000 (large dia.)
Steel Pile	20-40	Unlimited	300-1000 (small dia.)	2500-10000 (large dia.)
Composite Pile	20-40	60	300-900	2000

The information can be used only as a guide line during the initial planning and analysis stages

Pile foundation III

Pile load capacity in compression :

a) Static pile load formulae

b) Pile load tests

c) Pile driving formulae

d) Correlation with penetration test data

Static pile load formulae

The ultimate load capacity of the pile (Q_u)

$$Q_u = Q_{pu} + Q_f$$

Q_{pu} = Ultimate point load resistance of the pile
Q_f = Ultimate skin friction

$Q_{pu} >> Q_f$ → **point bearing pile or end bearing pile**

$Q_f >> Q_{pu}$ → **friction pile**

The ultimate point load can be expressed in the form: $Q_{pu} = q_{pu} A_b$

A_b = sectional area of the pile at its base

The ultimate skin friction can be written in the form : $Q_f = f_s A_s$

f_s = unit skin friction resistance

A_s = surface area of the pile in contact with soil

The ultimate load capacity (Q_u) can be written in the form

$$Q_u = q_{pu} A_b + f_s A_s$$

The general equation for **unit point bearing resistance (q_{pu})** for c–ϕ soil :

$$q_{pu} = cN_c + \sigma' N_q + 0.5\gamma B N_\gamma$$

where B = width or diameter of pile

σ’ = effective overburden pressure at the tip of the pile, equal to γL

N_c, N_q, N_γ = bearing capacity factor

c = unit cohesion

L = length of embedment of pile

γ = effective unit weight of soil

In a deep foundation **, $\sigma' N_q \gg 0.5\gamma B\ N_\gamma$** . Hence, the third term is usually neglected

$$q_{pu} = cN_c + \sigma' N_q$$

For a granular soil, c=c′=0 $q_{pu} = \sigma' N_q$

For a clay soil, c = c_u and ϕ_u = 0 $q_{pu} = c_{ub} N_c$

c_{ub} = undrained shear strength at the base of the pile

Piles in granular soils:

Driven Piles:

Tomlinson's / Berezantsev's Method

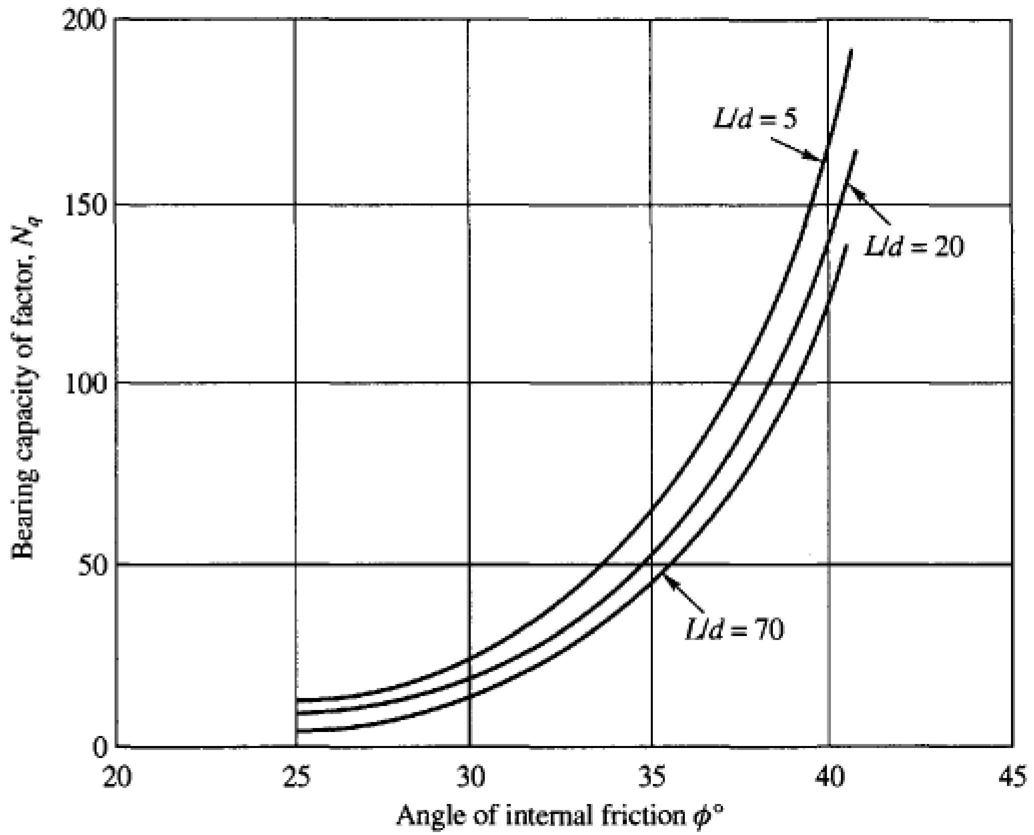
$$q_{pu} = \sigma' N_q$$

For a driven piles in sand $\phi_c = \dfrac{\phi + 40^\circ}{2}$

ϕ_c – *in situ* value of angle of shearing resistance

If $\phi > 40^\circ$, Pile driving shall have the effect of reducing the angle of shearing resistance of sand due to **dilatancy effect**

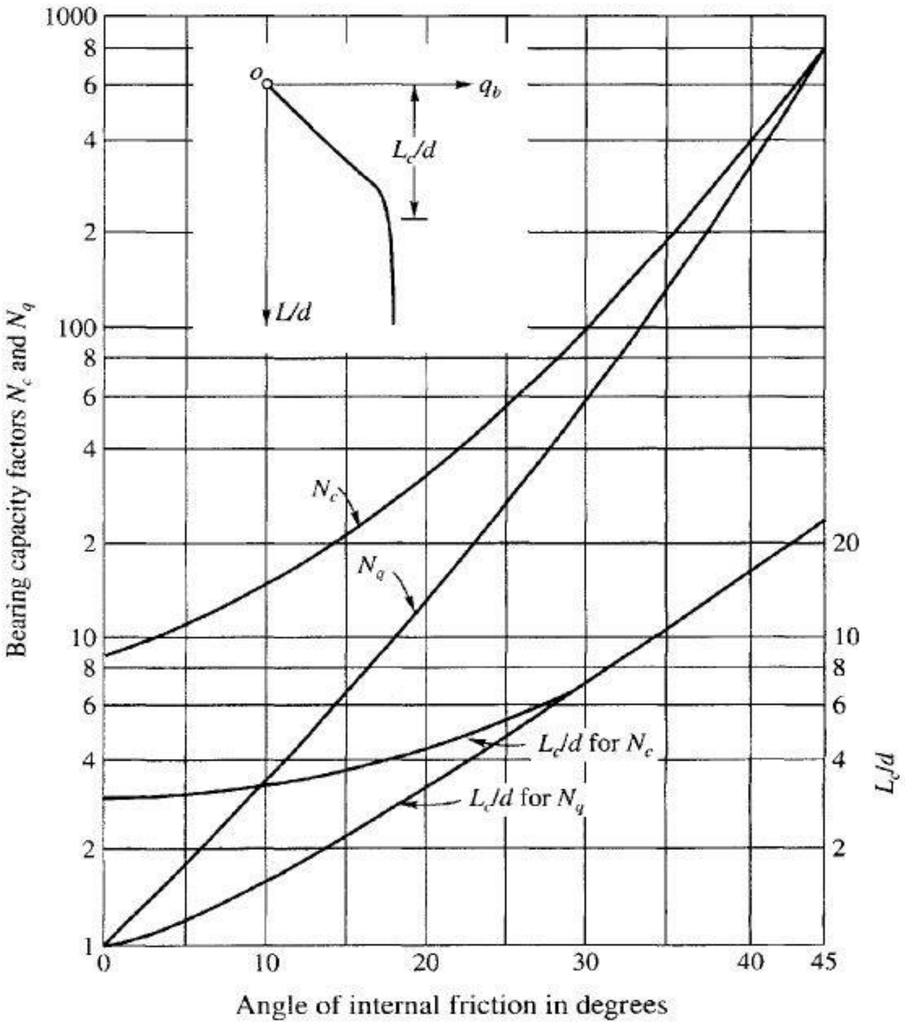
The maximum base or tip or point bearing resistance is limited to 11000 kN/ m^2



Berezantsev's Bearing Capacity factor

Murthy (2001)

Mayerhof (1976) Solution



Mayerhof (1976) bearing capacity factors

$$q_{pu} = \sigma' N_q$$

Limiting value for point end bearing

$$q_{pul} = 50 N_q \tan\phi \;\; kN/m^2 \quad \textit{for dense sand}$$

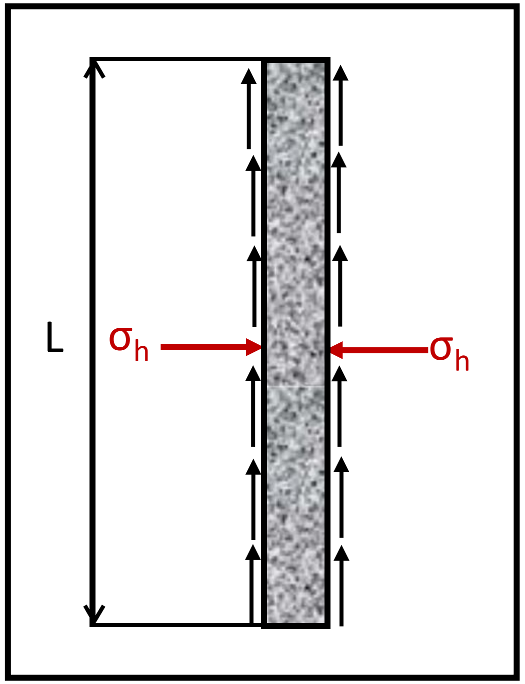
$$q_{pul} = 25 N_q \tan\phi \;\; kN/m^2 \quad \textit{for loose sand}$$

Murthy (2001)

Skin friction:

$$f_s = \sigma_h \tan(\delta)$$

$$f_s = K\sigma' \tan(\delta)$$



δ = angle of friction between the pile and the soil
K= the lateral earth pressure
σ_h = the soil pressure acting normal to the pile surface (horizontal)
σ' = the effective vertical overburden pressure

Ultimate Skin friction resistance (Q_f) :

$$Q_f = f_{s(av)} A_s$$

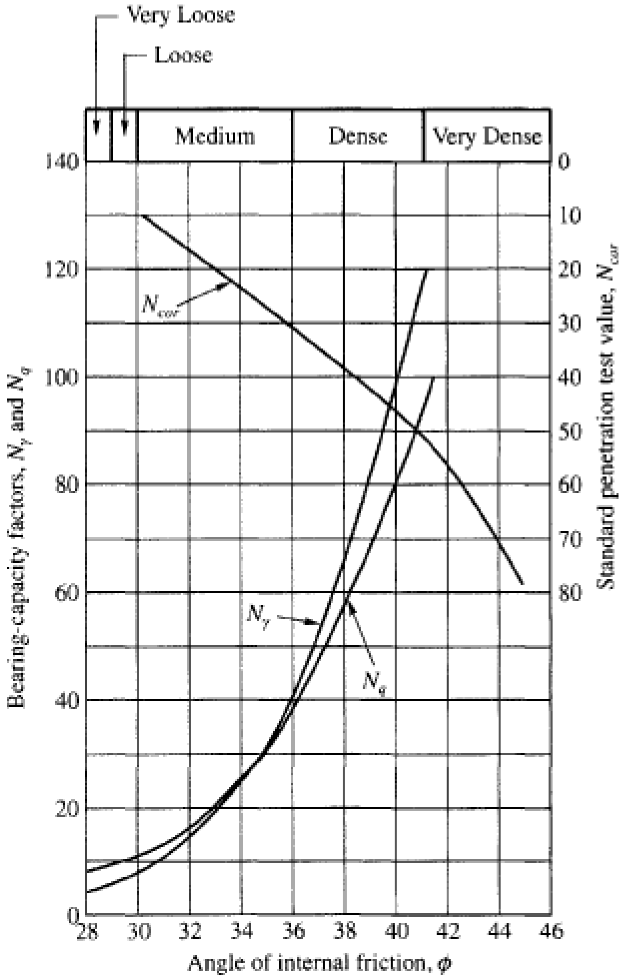
$$Q_f = K\sigma_{av}' \tan(\delta) A_s$$

σ'_{av} = average effective overburden pressure over the embedded length of the pile

Broms (1966) recommends the value of K and δ shown in Table for piles driven into sand

Pile material	δ	Values of K	
		Loose sand	Dense sand
Steel	20°	0.5	1
Concrete	0.75ϕ	1	2
Timber	0.67ϕ	1.5	4

Ranjan and Rao, 1991



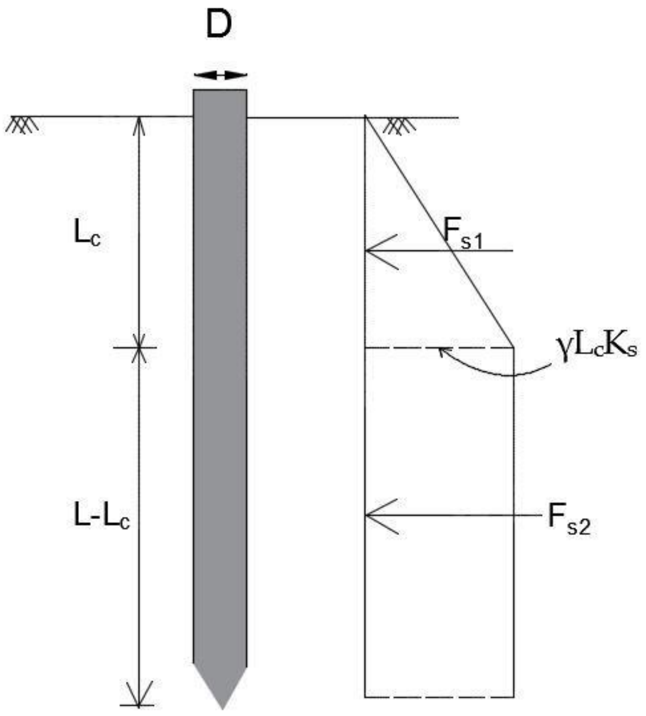
Murthy (2001)

Critical depth:

Depend on **ϕ' value and diameter of pile (D).**

Critical depth may vary from about 15D in loose to medium sand to 20D in dense sand.

Limiting value for skin Resistance in homogenous sand



The allowable load Q_a :

$$Q_a = \frac{Q_u}{F}$$

Q_u = ultimate load

F = factor of safety = 2.5

Note: The bored piles in sand have a point bearing or top resistance **(q_{pu}) is 1 / 2 to 1 / 3** of the value of the driven piles. In case of bored pile in sand, the lateral earth pressure coefficient can be calculated as: K = 1−sin ϕ. The value of **K varies from 0.3 to 0.75 (average value of 0.5).** The δ **value is equal to** ϕ for bored piles excavated in dry soil and a reduced value is considered if slurry has been used during excavation.

IS:2911(Part1): 2010

- Piles in granular soil

$$Q_u = A_p\left(\frac{1}{2}D\gamma\, N_\gamma + P_D N_q\right) + \sum_{i=1}^{n} K_i P_{Di} \tan\delta_i A_{si}$$

where A_p=c/s area of pile tip

D= diameter of pile

N_q and N_γ= bearing capacity factors depending on angle of internal friction

P_D= effective overburden pressure at pile tip

i= any layer between 1 to n layers in which pile is installed and it contributes to positive skin friction

K_i= coefficient of earth pressure applicable in i th layer of soil .It depends on the nature of soil strata, type of pile, spacing of pile and its method of construction.

For driven piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 2 may be used.

For bored piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 1.5 may be used.

P_{Di}= effective overburden pressure for i th layer
δ_i= angle of wall friction between soil and pile in i th layer **(may be taken as ϕ)**
A_{si}= surface area of pile shaft at i th layer

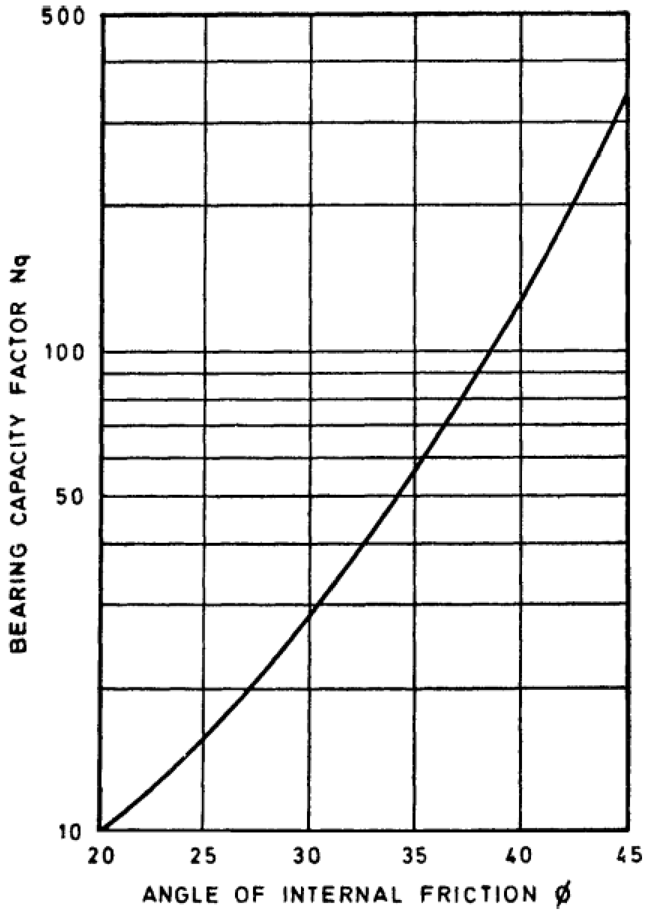
Note: As per IS Code [IS:2911(Part1/Sec 1):2010], for piles longer than 15 to 20 times the pile diameter, maximum effective overburden stress at pile tip should correspond to the pile length equal to 15 (if $\phi \leq 30°$) to 20 (if $\phi \geq 40°$) times of the diameter.

- N_{γ} factor can be taken for general shear failure according to IS 6403.
- N_q factor will depend on the nature of soil, type of pile, the L/D ratio and its method of construction. The values applicable for driven piles are given in this figure.

IS 6403:1981

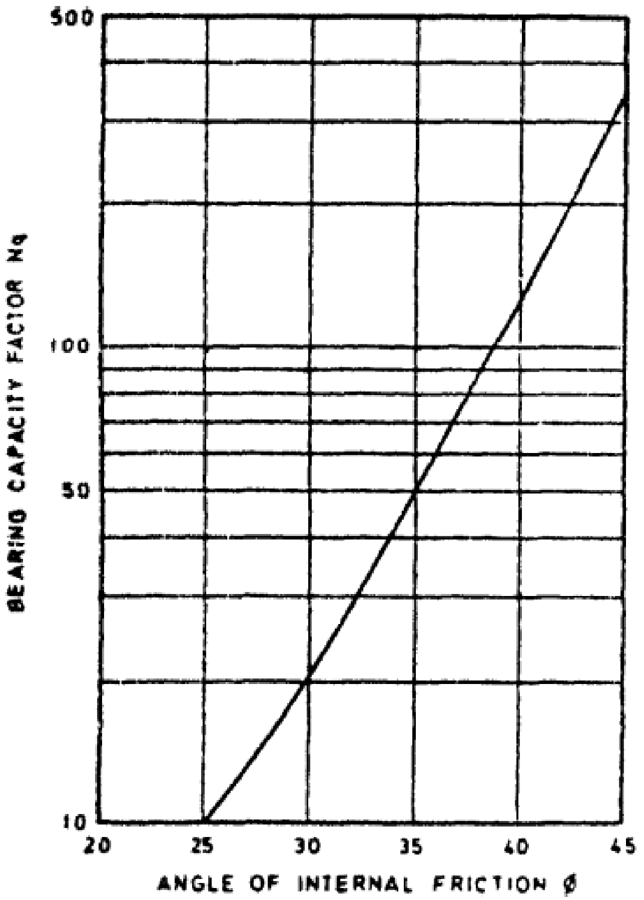
φ(in degree)	Nγ
0	0
5	0.45
10	1.22
15	2.65
20	5.39
25	10.88
30	22.40
35	48.03
40	109.41
45	271.76
50	762.89

IS:2911(Part1 / Sec 1): 2010



Driven precast and cast in situ concrete pile

IS:2911(Part I / Sec2): 2010



Bored precast and cast in situ concrete pile

Pile foundation IV

Example: (a) A 15m long, 300 mm diameter pile was driven in a uniform sand (ϕ'= 40°). The water table is at great depth. Average unit weight of soil is 19 kN/ m^3. Calculate the safe load capacity of the pile with F.O.S =2.5.

(b) Calculate the safe load capacity of the pile if water table is located at 2m below the ground level.

Piles in granular soils:

Driven Piles:
Tomlinson's / Berezantsev's Method

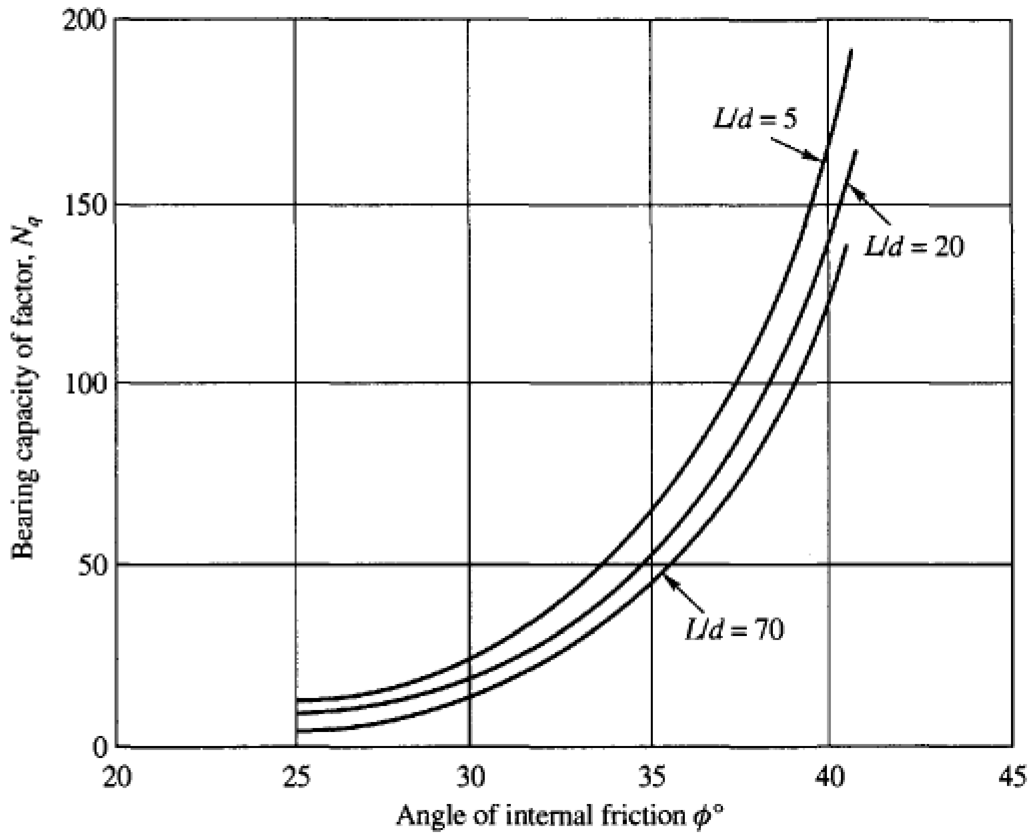
$$q_{pu} = \sigma' N_q$$

For a driven piles in sand $\phi_c = \dfrac{\phi + 40^\circ}{2}$

ϕ_c – *in situ* value of angle of shearing resistance

If $\phi > 40^\circ$, Pile driving shall have the effect of reducing the angle of shearing resistance of sand due to **dilatancy effect**

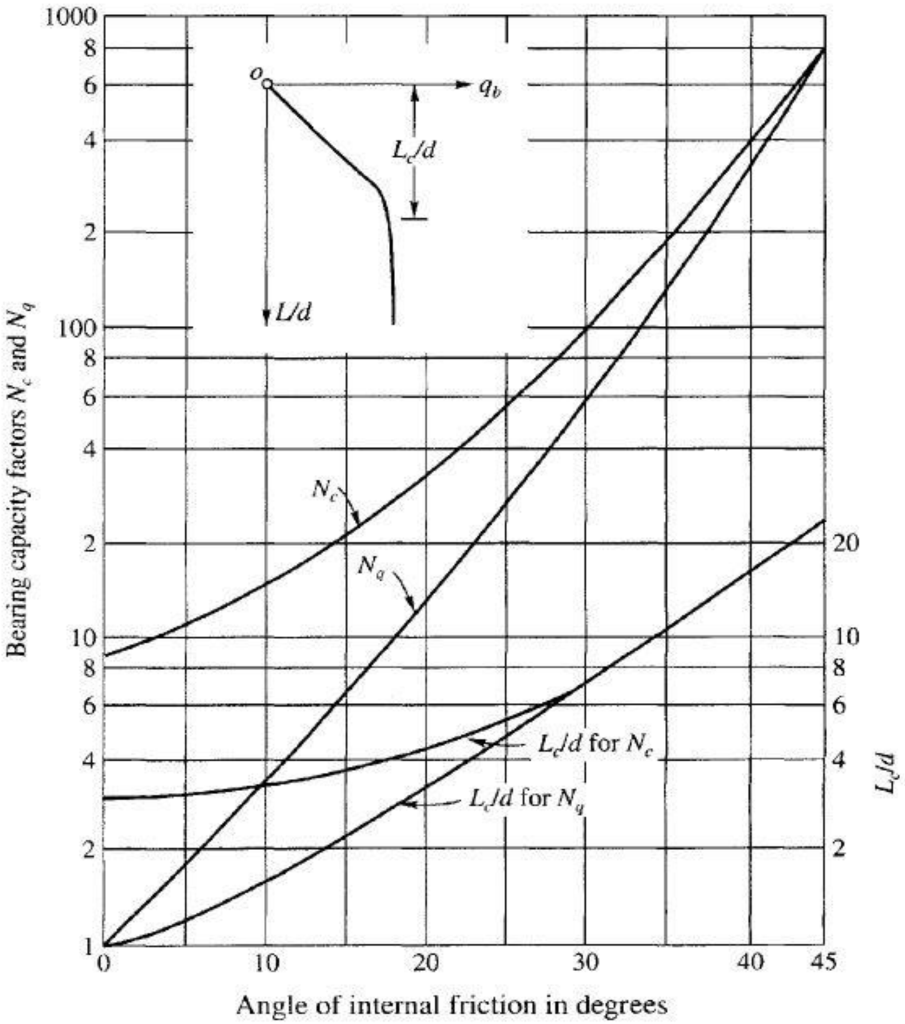
The maximum base or tip or point bearing resistance is limited to 11000 kN/ m²



Berezantsev's Bearing Capacity factor

Murthy (2001)

Mayerhof (1976) Solution



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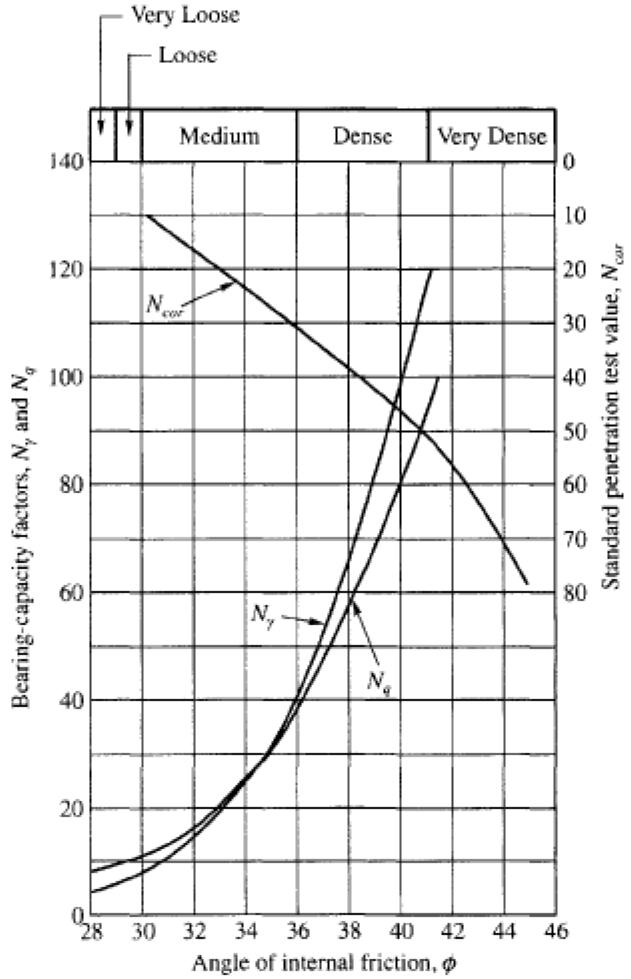

Murthy (2001)

IS:2911(Part1): 2010

- Piles in granular soil

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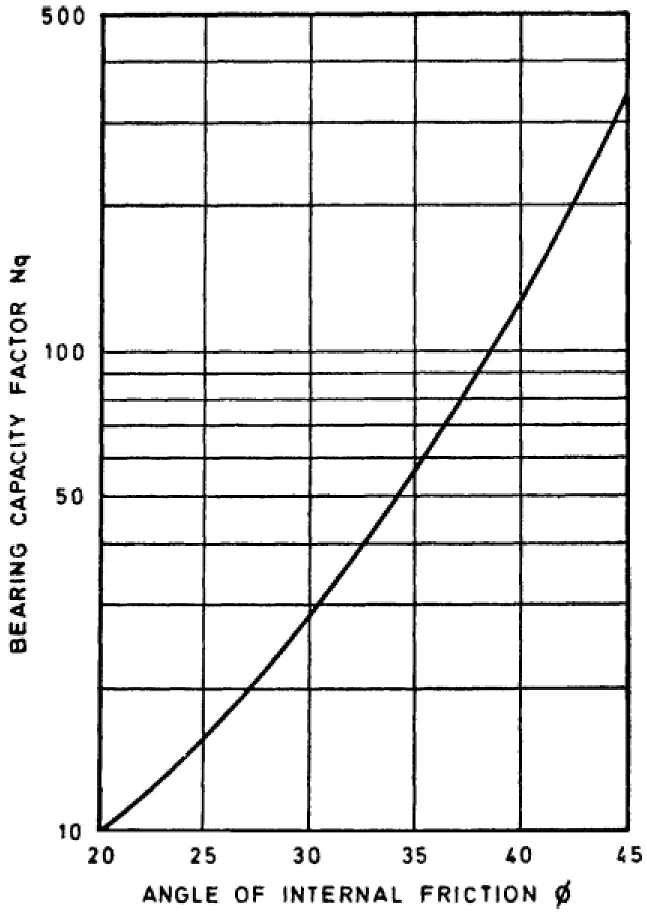
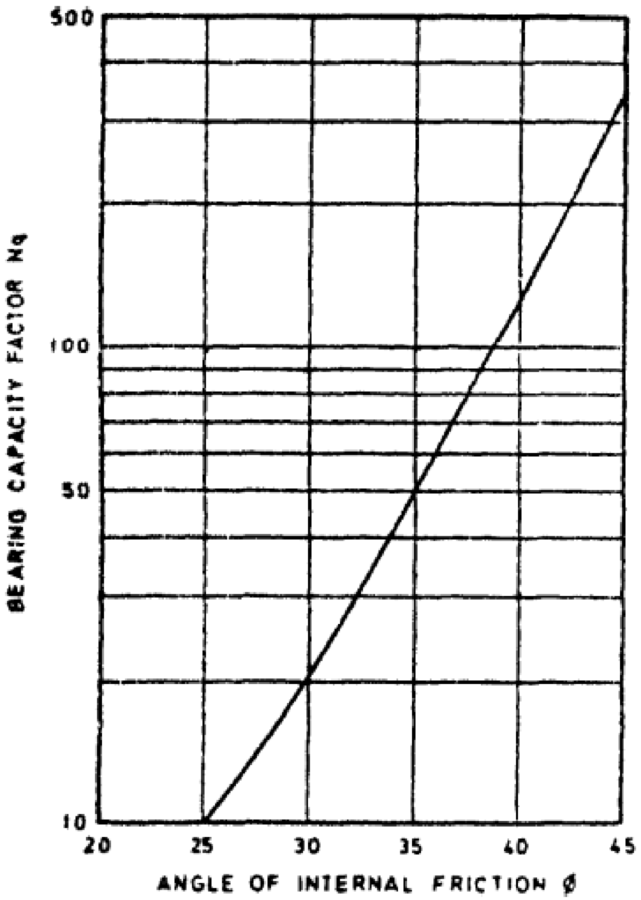


Driven precast and cast in situ concrete pile

IS:2911(Part I / Sec2): 2010



Bored precast and cast in situ concrete pile

Pile foundation V

Example: (a) A 15m long, 300 mm diameter pile was driven in a uniform sand ($\phi' = 40^\circ$). The water table is at great depth. Average unit weight of soil is 19 kN/ m^3. Calculate the safe load capacity of the pile with F.O.S =2.5.

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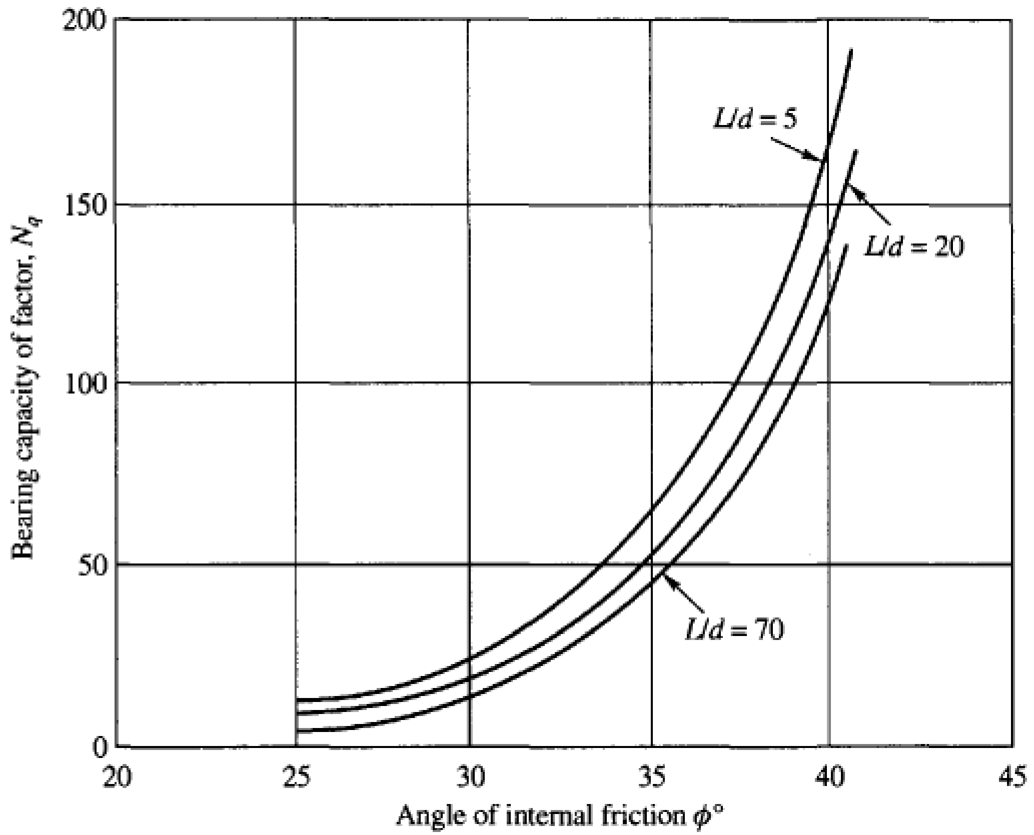
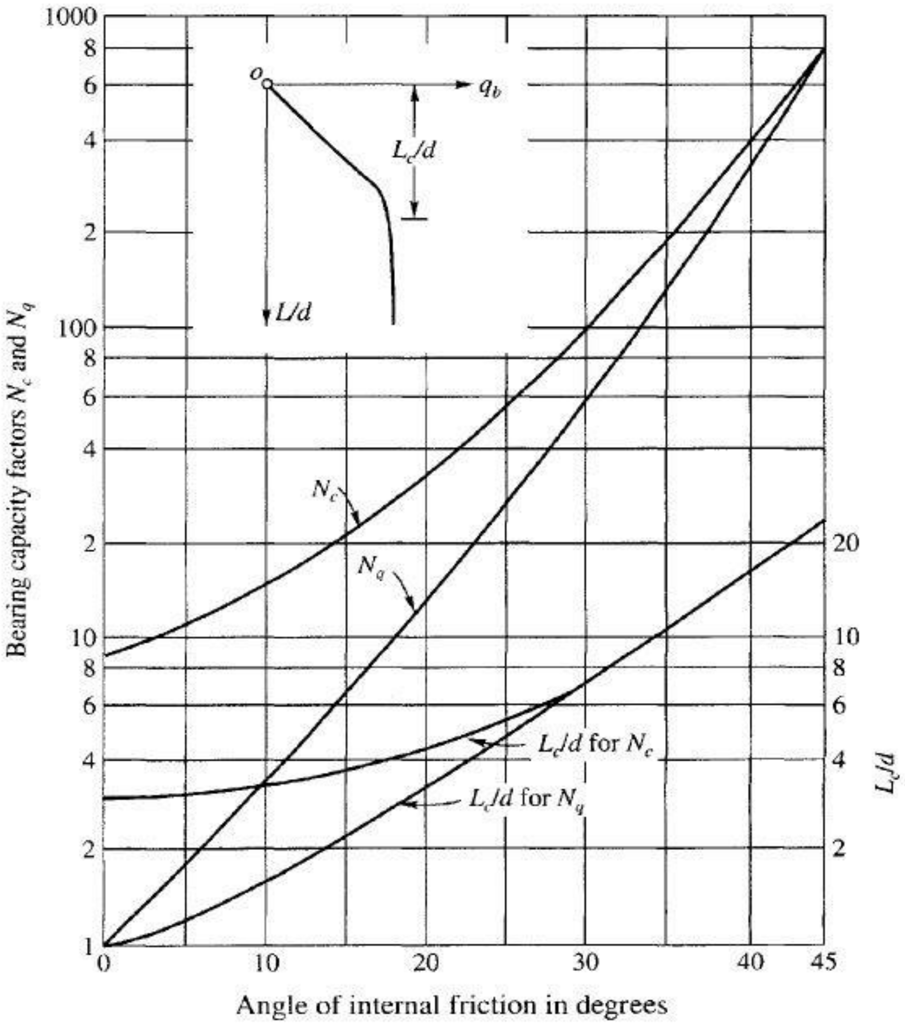
The maximum base or tip or point bearing resistance is limited to 11000 kN/m^2



Berezantsev's Bearing Capacity factor

Murthy (2001)



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Mayerhof (1976) Solution

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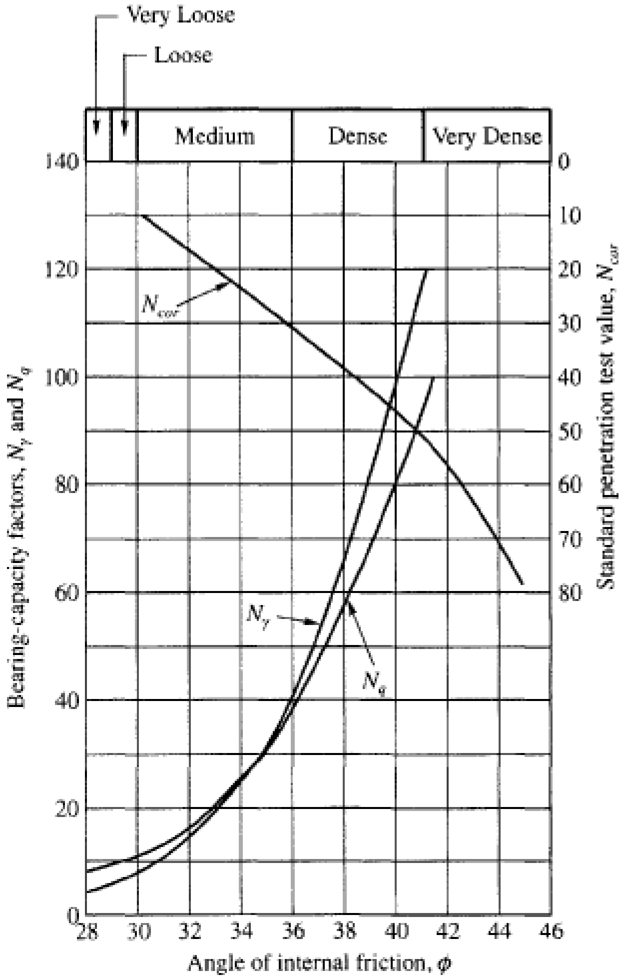
Pile material	δ	Values of K	
		Loose sand	Dense sand
Steel	20°	0.5	1
Concrete	0.75ϕ	1	2
Timber	0.67ϕ	1.5	4

Ranjan and Rao, 1991



Murthy (2001)

IS:2911(Part1): 2010

- Piles in granular soil

$$Q_u = A_p\left(\frac{1}{2}D\gamma\, N_\gamma + P_D N_q\right) + \sum_{i=1}^{n} K_i P_{Di} \tan\delta_i A_{si}$$

where A_p=c/s area of pile tip

D= diameter of pile

N_q and N_γ= bearing capacity factors depending on angle of internal friction

P_D= effective overburden pressure at pile tip

i= any layer between 1 to n layers in which pile is installed and it contributes to positive skin friction

K_i= coefficient of earth pressure applicable in i th layer of soil .It depends on the nature of soil strata, type of pile, spacing of pile and its method of construction.

For driven piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 2 may be used.

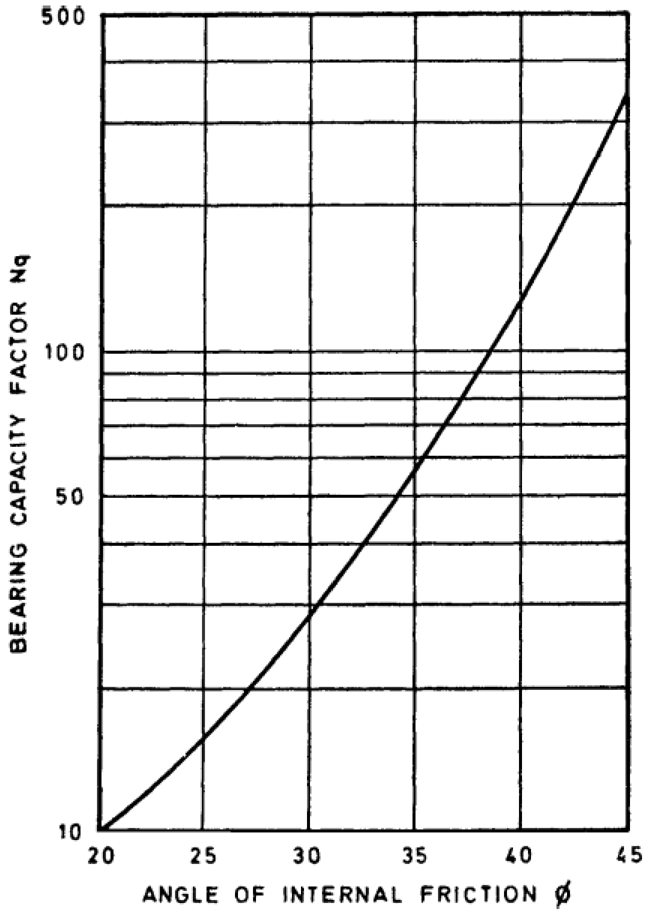
For bored piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 1.5 may be used.

- N_γ factor can be taken for general shear failure according to IS 6403.
- N_q factor will depend on the nature of soil, type of pile, the L/D ratio and its method of construction. The values applicable for driven piles are given in this figure.

IS 6403:1981

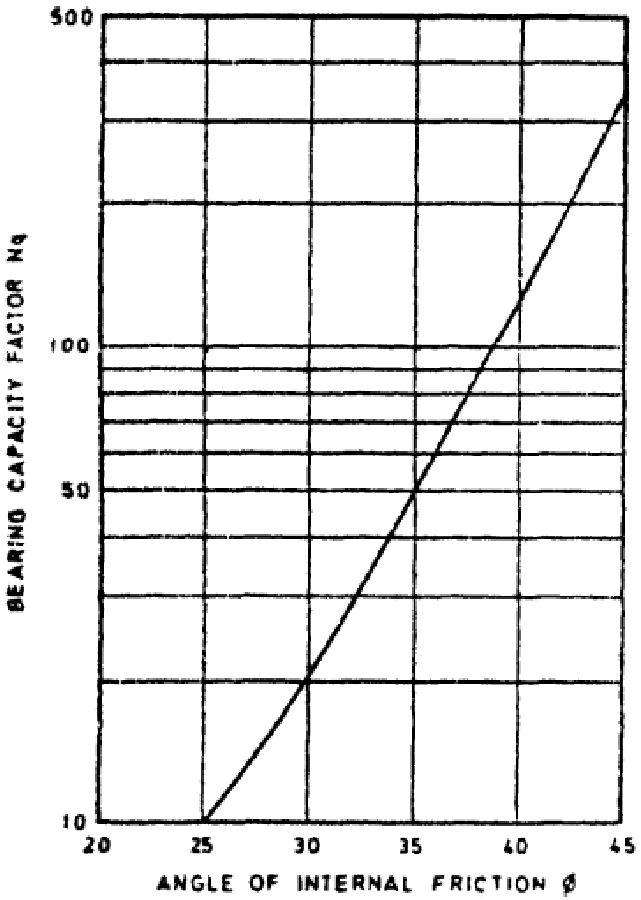
φ(in degree)	Nγ
0	0
5	0.45
10	1.22
15	2.65
20	5.39
25	10.88
30	22.40
35	48.03
40	109.41
45	271.76
50	762.89

IS:2911(Part1 / Sec 1): 2010



Driven precast and cast in situ concrete pile

IS:2911(Part I / Sec2): 2010



Bored precast and cast in situ concrete pile

Pile foundation VI

With and without considering critical length concept: Layered soil

Piles in granular soils:

Driven Piles:

Tomlinson's / Berezantsev's Method

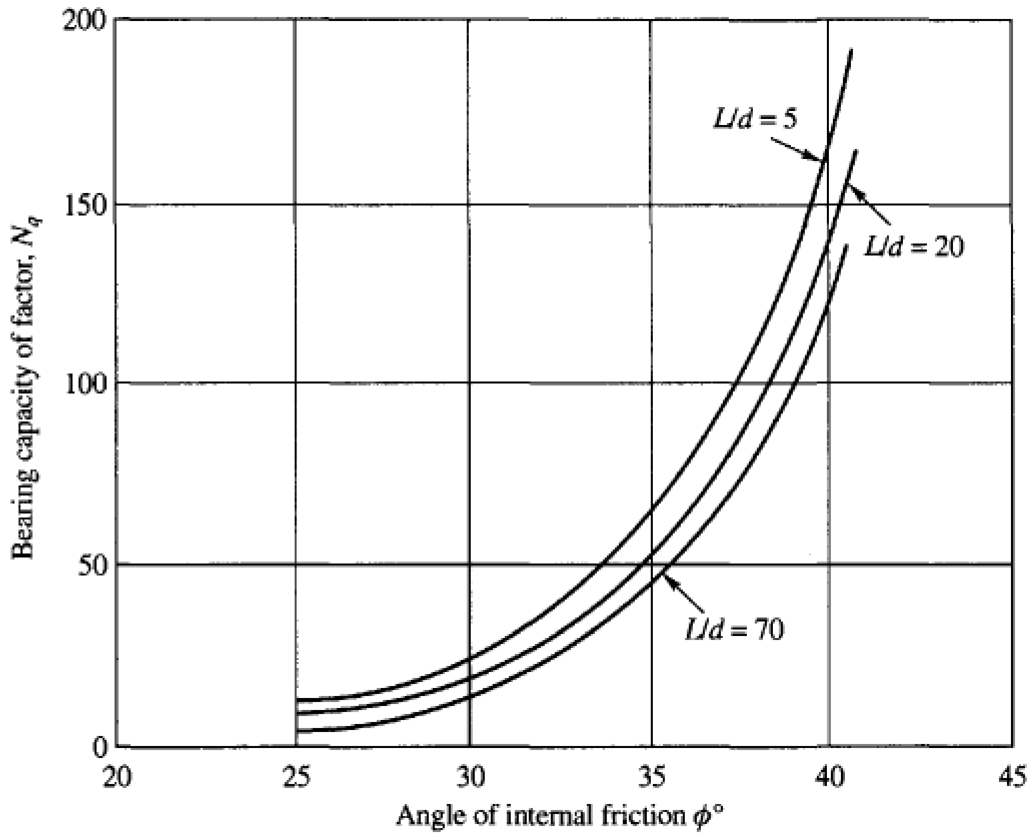
$$q_{pu} = \sigma' N_q$$

For a driven piles in sand $\phi_c = \frac{\phi + 40^\circ}{2}$

ϕ_c – *in situ* value of angle of shearing resistance

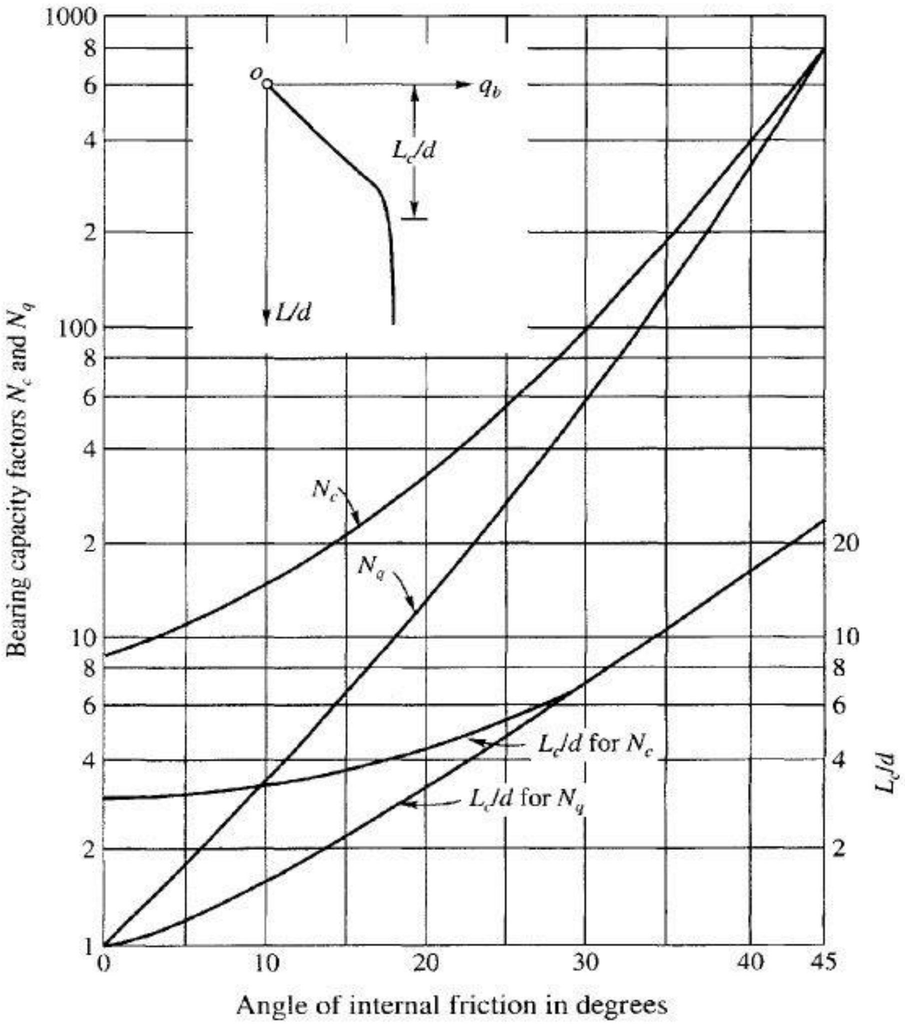
If $\phi > 40^\circ$, Pile driving shall have the effect of reducing the angle of she aring resistance of sand due to **dilatancy effect**

The maximum base or tip or point bearing resistance is limited to 11000 kN/m^2



Berezantsev's Bearing Capacity factor

Murthy (2001)



Mayerhof (1976) bearing capacity factors

Mayerhof (1976) Solution

$$q_{pu} = \sigma' N_q$$

Limiting value for point end bearing

$$q_{pul} = 50 N_q \tan\phi \;\; kN/m^2 \quad \textit{for dense sand}$$

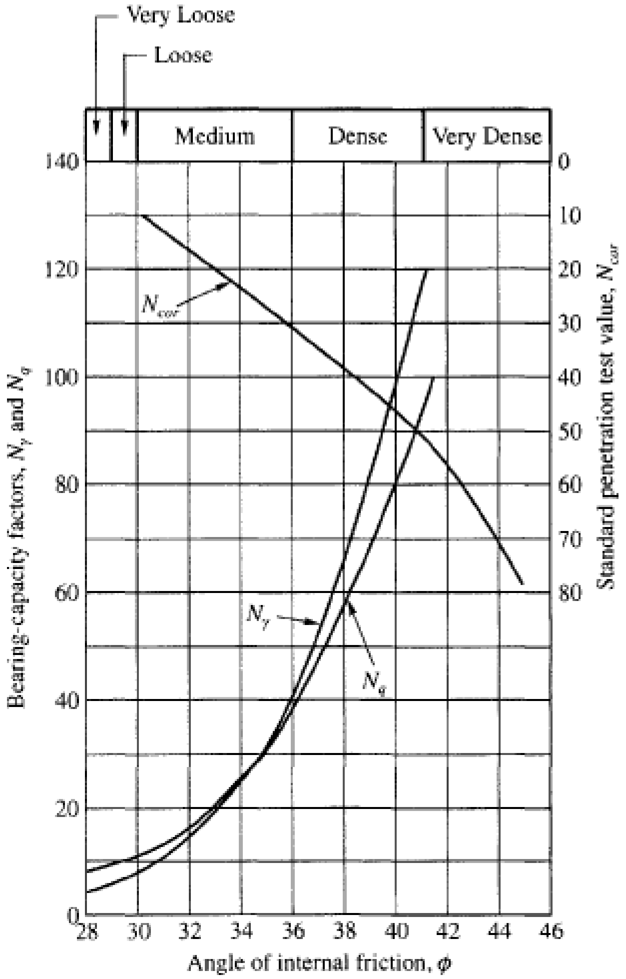
$$q_{pul} = 25 N_q \tan\phi \;\; kN/m^2 \quad \textit{for loose sand}$$

Murthy (2001)

Broms (1966) recommends the value of K and δ shown in Table for piles driven into sand

Pile material	δ	Values of K	
		Loose sand	Dense sand
Steel	20°	0.5	1
Concrete	0.75ϕ	1	2
Timber	0.67ϕ	1.5	4

Ranjan and Rao, 1991



Murthy (2001)

IS:2911(Part1): 2010

- Piles in granular soil

$$Q_u = A_p\left(\frac{1}{2}D\gamma\, N_\gamma + P_D N_q\right) + \sum_{i=1}^{n} K_i P_{Di} \tan\delta_i A_{si}$$

where A_p=c/s area of pile tip

D= diameter of pile

N_q and N_γ= bearing capacity factors depending on angle of internal friction

P_D= effective overburden pressure at pile tip

i= any layer between 1 to n layers in which pile is installed and it contributes to positive skin friction

K_i= coefficient of earth pressure applicable in i th layer of soil .It depends on the nature of soil strata, type of pile, spacing of pile and its method of construction.

For driven piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 2 may be used.

For bored piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 1.5 may be used.

- N_γ factor can be taken for general shear failure according to IS 6403.
- N_q factor will depend on the nature of soil, type of pile, the L/D ratio and its method of construction. The values applicable for driven piles are given in this figure.

IS 6403:1981

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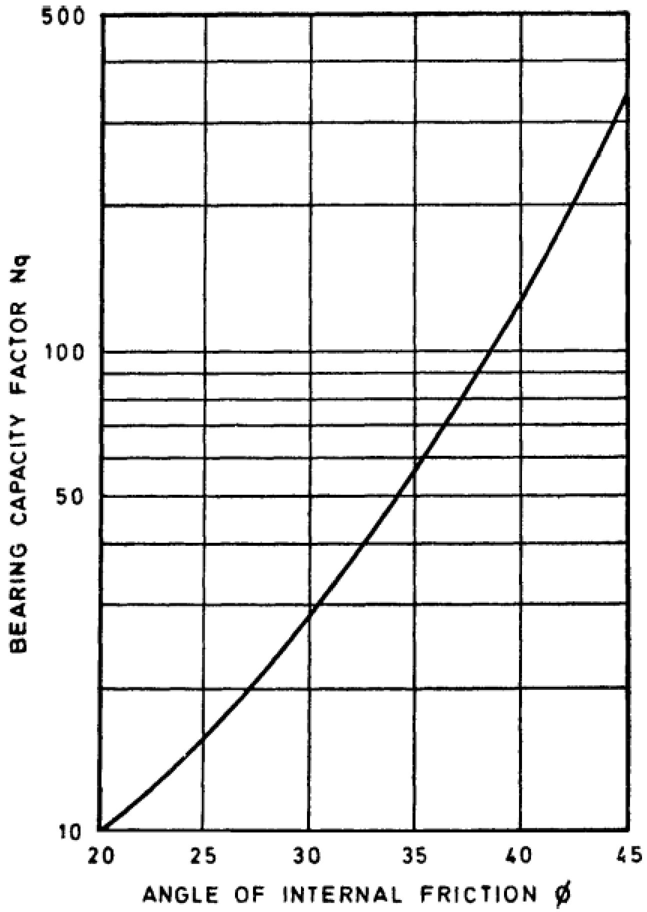
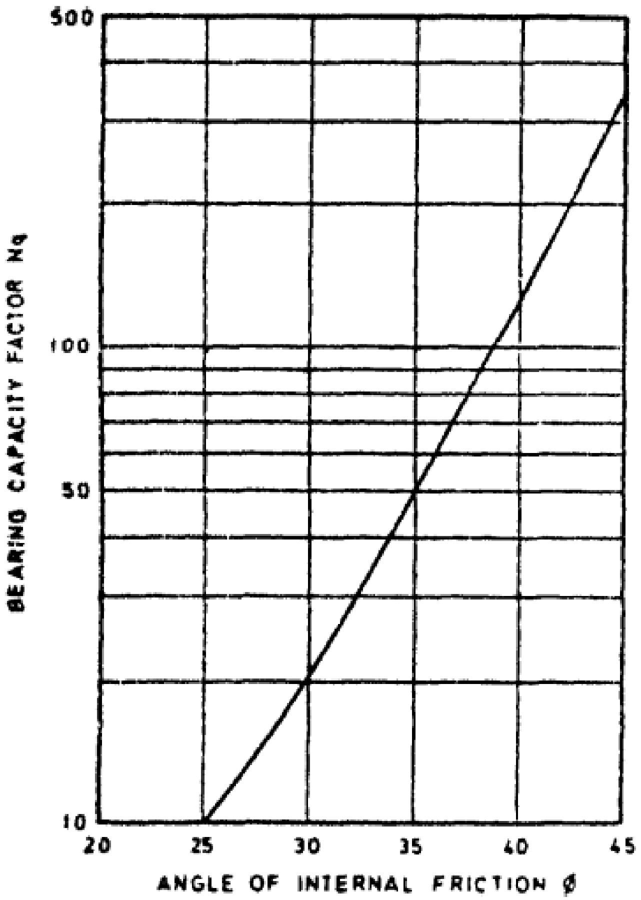
IS:2911(Part1 / Sec 1): 2010



Driven precast and cast in situ concrete pile

IS:2911(Part I / Sec2): 2010



Bored precast and cast in situ concrete pile

The ultimate load capacity of pile (Q_u):

$$Q_u = q_{pu} A_b + f_s A_s$$

In clays, $q_{pu} = c_u N_c$ and $f_s = c_a = \alpha c_u$

$$\boxed{Q_u = c_{ub} N_c A_b + \alpha c_u A_s}$$

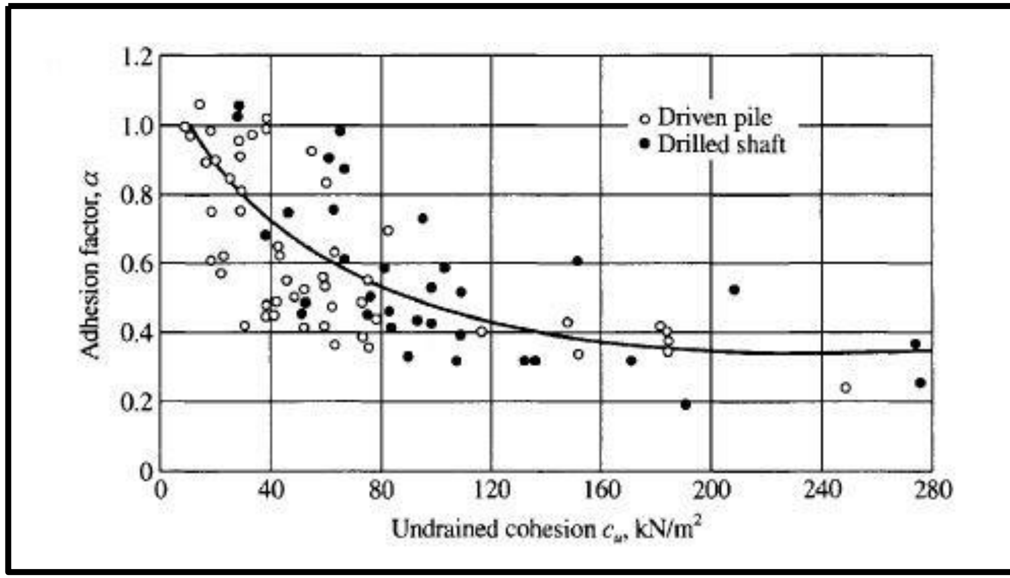
c_{ub} = undrained cohesion at the base of pile

N_c = bearing capacity factor for a deep foundation. **For circular and square piles N_c = 9** (proposed by Skempton). **Pile must go at least 5D inside the bearing stratum.**

α = adhesion factor

c_u = undrained cohesion in the embedded length of pile

c_u (kPa)	consistency
0 - 12.5	very soft
12.5–25	soft
25–50	medium
50–100	stiff
100–200	very stiff
>200	hard



Ranjan and Rao, 1991

Consistency	N value	α value	
		Bored piles	Driven cast *in situ* piles
Soft to very soft	<4	0.7	1.0
Medium	4-8	0.5	0.7
Stiff	8-15	0.4	0.4
Stiff to hard	>15	0.3	0.3

Pile foundation VII

IS:2911(Part1): 2010

- Piles in granular soil

$$Q_u = A_p\left(\frac{1}{2}D\gamma\, N_\gamma + P_D N_q\right) + \sum_{i=1}^{n} K_i P_{Di} \tan\delta_i A_{si}$$

where A_p=c/s area of pile tip

D= diameter of pile

N_q and N_γ= bearing capacity factors depending on angle of internal friction

P_D= effective overburden pressure at pile tip

i= any layer between 1 to n layers in which pile is installed and it contributes to positive skin friction

K_i= coefficient of earth pressure applicable in i th layer of soil .It depends on the nature of soil strata, type of pile, spacing of pile and its method of construction.

For driven piles in loose to dense sand (ϕ = 30° to 40°), K_i value in the range of 1 to 2 may be used.

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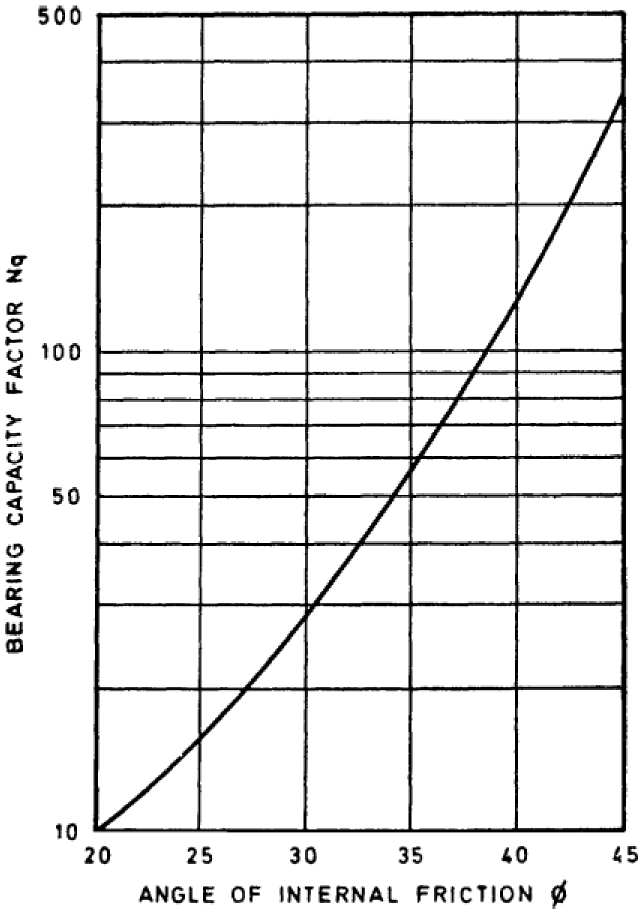
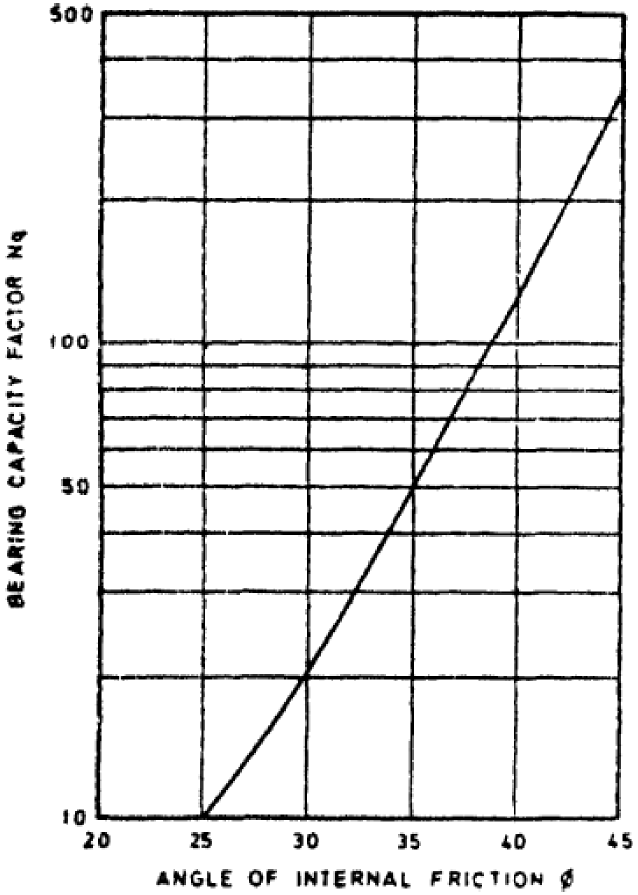
IS:2911(Part1 / Sec 1): 2010



Driven precast and cast in situ concrete pile

IS:2911(Part I / Sec2): 2010



Bored precast and cast in situ concrete pile

Piles in clay :

The ultimate load capacity of pile (Q_u):

$$Q_u = q_{pu} A_b + f_s A_s$$

In clays, $q_{pu} = c_u N_c$ and $f_s = c_a = \alpha c_u$

$$Q_u = c_{ub} N_c A_b + \alpha c_u A_s$$

c_{ub} = undrained cohesion at the base of pile

N_c = bearing capacity factor for a deep foundation. **For circular and square piles N_c = 9** (proposed by Skempton). **Pile must go at least 5D inside the bearing stratum.**

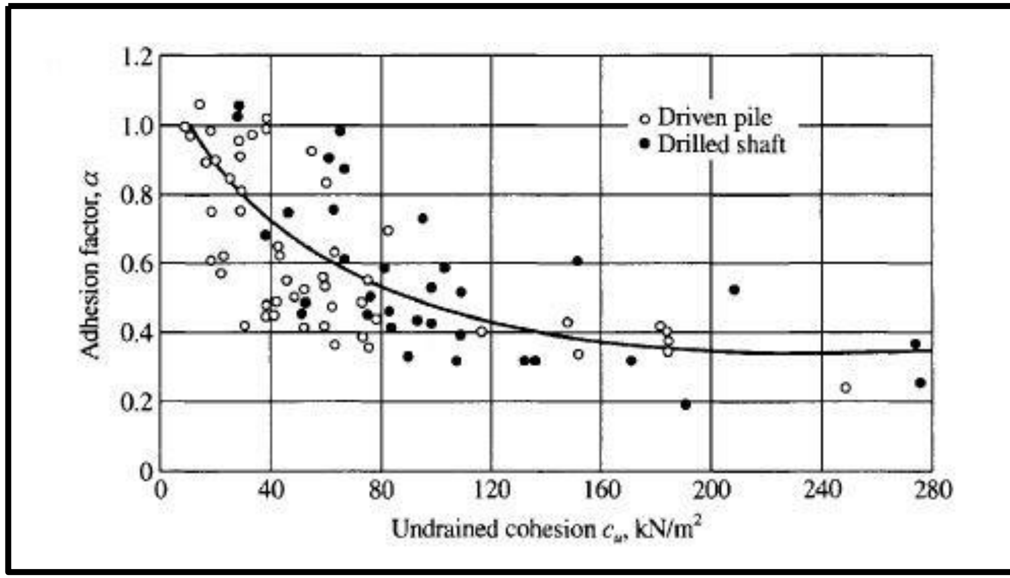
α = adhesion factor

c_u = undrained cohesion in the embedded length of pile

Values of reduction factor α

Murthy (2001)

c_u (kPa)	consistency
0 - 12.5	very soft
12.5–25	soft
25–50	medium
50–100	stiff
100–200	very stiff
>200	hard



Ranjan and Rao, 1991

Consistency	N value	α value	
		Bored piles	Driven cast *in situ* piles
Soft to very soft	<4	0.7	1.0
Medium	4-8	0.5	0.7
Stiff	8-15	0.4	0.4
Stiff to hard	>15	0.3	0.3

The allowable load Q_a :

$$Q_a = \frac{Q_u}{F}$$

Q_u = ultimate load

F = factor of safety = 2.5

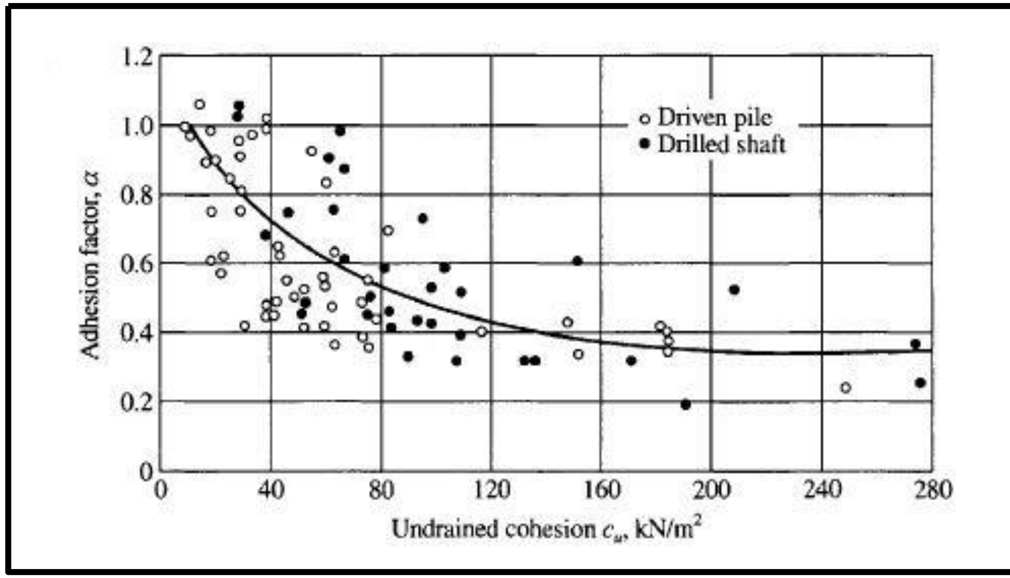
Example: A 15 m long pile with diameter 400mm was driven in a homogeneous clay with unconfined compressive strength of 100 kPa. Calculate the ultimate load Carrying capacity of the pile.

Example: Layered soil (only Clay)

Values of reduction factor α

Murthy (2001)

c_u (kPa)	consistency
0 - 12.5	very soft
12.5–25	soft
25–50	medium
50–100	stiff
100–200	very stiff
>200	hard



Ranjan and Rao, 1991

Consistency	N value	α value	
		Bored piles	Driven cast *in situ* piles
Soft to very soft	<4	0.7	1.0
Medium	4-8	0.5	0.7
Stiff	8-15	0.4	0.4
Stiff to hard	>15	0.3	0.3

- <u>Piles in cohesive soil</u> **[IS:2911(Part1): 2010]**

$$Q_u = A_p N_c c_p + \sum_{i=1}^{n} \alpha_i c_i A_{si}$$

where A_p = c/s area of pile tip

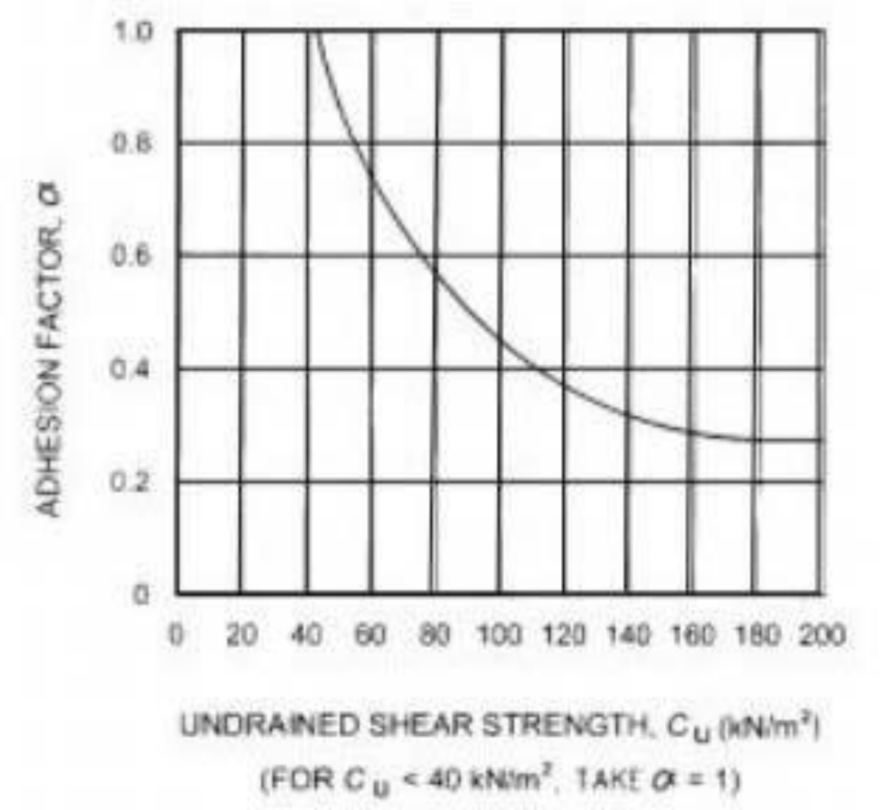
N_c = bearing capacity factor may be taken as **9**

c_p = average cohesion at pile tip

α_i = adhesion factor for i th layer

c_i = average cohesion at i th layer

A_{si} = surface area of pile shaft at i th layer

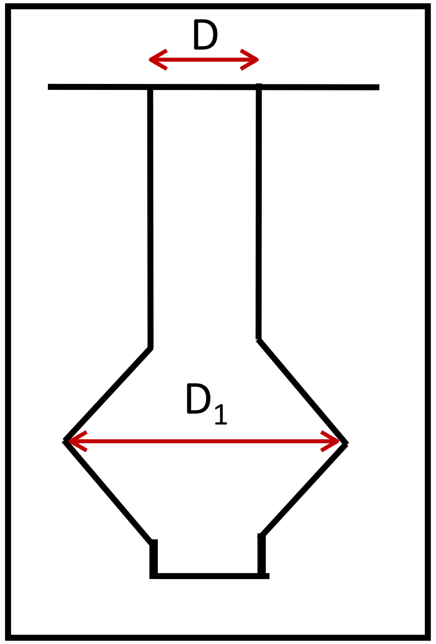


Pile foundation VIII

Example: Layered soil (Sand-Clay)

Load carrying capacity of under-reamed pile in Clay

$$Q_u = c_{ub} N_c A_b + \alpha c'_u A_s = (9c_{ub}) \frac{\pi}{4} D_1^2 + \alpha c'_u A_s$$



N_c = 9

α = adhesion factor

A_b = area of the enlarge base

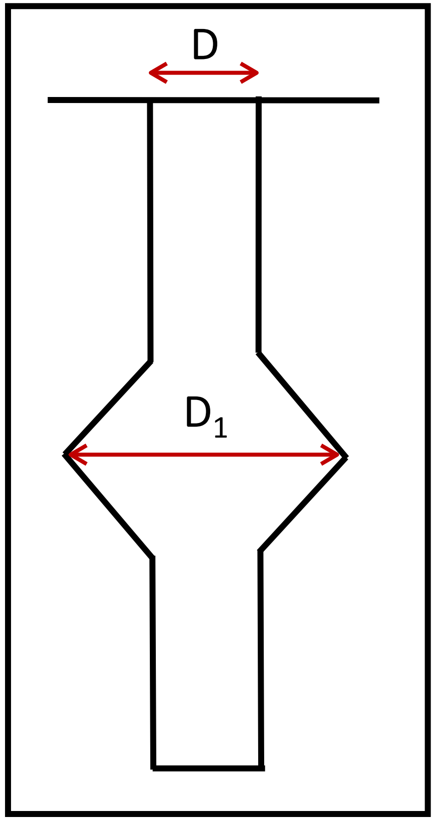
D_1 = diameter of the bulb

Note: When the bulb is slightly above the tip, A_b is equal to the area of the diameter of the bulb and the projected stem below the bulb is ignored.

If bulb is quite high :

<u>For single bulb</u>

$$Q_u = (9c_{ub})\frac{\pi}{4}D^2 + \frac{\pi}{4}\times 9c'_{ub}\times\left(D_1^2 - D^2\right) + \alpha c'_u A_s$$

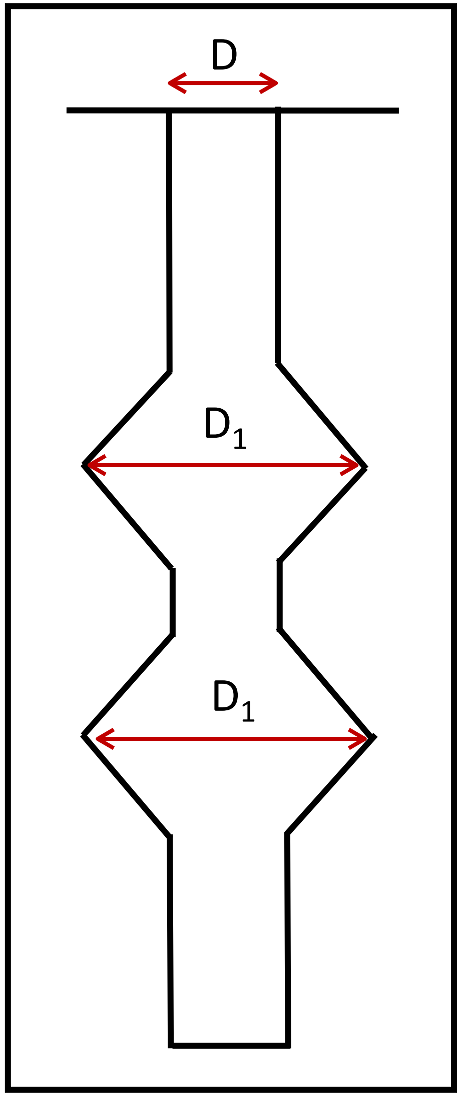


c_{ub} = unit cohesion at the tip
c'_{ub} = unit cohesion at the bulb level
c'_u = average cohesion on A_s
A'_s = surface area
= The length of the shaft equal to 2D above the bulb is usually neglected
(As the pile settles, there is possibility of formation of a small gap between the top of bulb)

Two or more bulbs

$$Q_u = (9c_{ub})\frac{\pi}{4}D^2 + \frac{\pi}{4}\times 9c'_{ub}\times\left(D_1^2 - D^2\right) + \alpha c'_u A_s + c''_u A_{sb}$$

c_{ub} = unit cohesion at the tip
c'_{ub} = unit cohesion at the bulb level
A_s = surface area of the shaft above the top bulb (ignoring 2B length)
A_{sb} = surface area of the cylinder circumscribing the bulbs between top and bottom bulbs
c'_u = average cohesion on A_s
c''_u = average cohesion on A_{sb}



Pile Load test

- It is the only direct method for determining the allowable load on piles.
- It is an in-situ test and the most reliable one also.
- It is very useful for cohesion less soil.
- However, for cohesive soil, data from pile load test should be used with caution because of pile driving disturbanc e, pore water pressure development, and inadequate time allowed for the consolidation settlement.

Types of load test

- Vertical load test (compression)
- Lateral load test
- Pull out test (Tension)

➢ It is carried out to esta blish load- settlement relationship under compression and determine the allowable load on pile.

➢These two tests are carried out when piles are required to resist the lateral loads or uplift loads .

Initial test

It is to be carried out on test piles to estimate the allowable load, or to predict the settlement at working load. It does not carry any load coming from superstructure .

Where there is no specific information about subsoil strata and no past experience, for a project involving more than 200 piles, there should be minimum two initial tests.

The **minimum** load on test piles should be twice the safe load or the load at which total settlement attains a value of 10% of pile diameter for single pile and 40 mm in group.

Routine test

It is carried out as a check on working pile to assess the displacement corresponding to working load.

The minimum no. of routines tests should be half percentage of the piles used. It may vary up to 2 percent or more depending upon the nature of soil strata and importance of structure.

A working pile is driven or cast in situ along with other piles to carry the load from superstructure . The load on such piles should be **up to** 1.5 times the safe load or the load at which the total settlement attains 12mm for single pile and 40 mm for group pile , whichever is earlier.

Pile load test

Types of Load test

Continuous loading

Continuous increment of load is applied on the pile head

Cyclic loading

Load is raised to a particular level and then dropped to zero, again increased to a higher level and reduced to zero.

Procedure: As per IS: 2911 part IV (1979)

Step 1

- The test shall be carried out by applying the load on a RCC cap over the pile.
- The load is applied in increment of 20 % of the safe load.

Step 2

- Settlements are recorded with at least three dial gauges.

Step 3

- Each stage of loading shall be maintaining till the rate of movement of pile top is not more than 0.1 mm /hr.

Pile foundation IX

The allowable load on a single pile shall be lesser of the following:

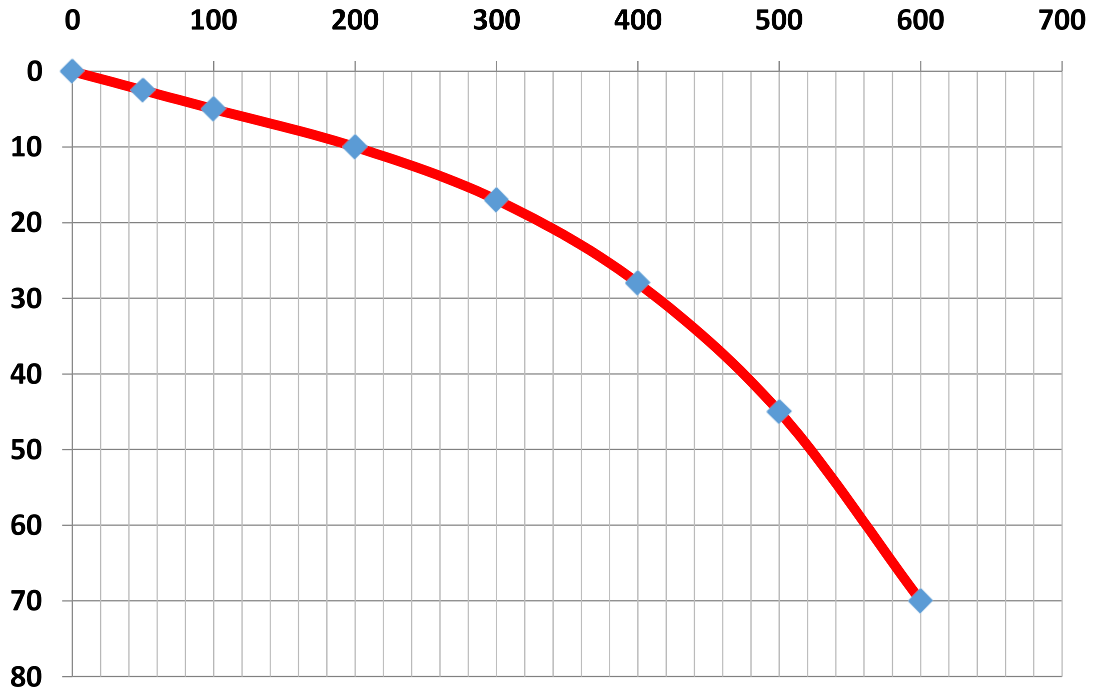
- 2/3rd of final load at which the total settlement attains a value of 12mm. If nothing is specified, then the permissible settlement =12mm. If any other permissible value is specified, then load shall correspond to actual permissible total settlement.
- 50% of final load at which the total settlement equals to 10% of the pile diameter in case of uniform diameter piles and 7.5% of bulb diameter in case of under reamed piles.

The allowable load on a group of piles shall be lesser of the following:

- Final load at which the total settlement attains a value of 25mm. The permissible settlement is 25mm.
- 2/3rd of the final load at which the total settlement attains a value of 40mm.

Example: The following data was obtained in a vertical pile load test on 300 mm diameter pile. Determine the allowable or safe load as per IS 2911 part IV (1979).

Load (kN)	Settlement (mm)
50	2.5
100	5.0
200	10.0
300	17
400	28
500	45
600	70



Vertical cyclic plate load test:

- It is carried out when it is required to separate the pile load into skin friction and point bearing on single piles of uniform diameter.
- It is limited to initial tests only.

Pile foundation IX

The allowable load on a single pile shall be lesser of the following:

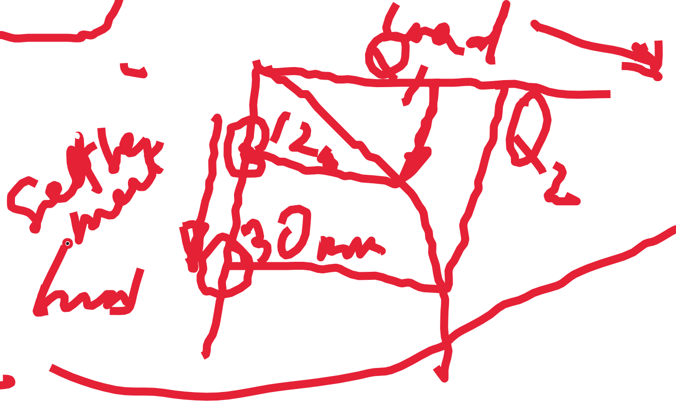
- 2/3rd of final load at which the total settlement attains a value of 12mm. If nothing is specified, then the permissible settlement =12mm. If any other permissible value is specified, then load shall correspond to actual permissible total settlement.
- 50% of final load at which the total settlement equals to 10% of the pile diameter in case of uniform diameter piles and 7.5% of bulb diameter in case of under reamed piles.

10% = 30mm

$Q_{allowable}$ = ?

① $Q_{all_1} = \frac{2}{3} \times Q_1$

② $Q_{all_2} = \frac{1}{2} Q_2$



Minimum of Q_{all_1} & Q_{all_2}

The allowable load on a group of piles shall be lesser of the following:

- Final load at which the total settlement attains a value of 25mm. The permissible settlement is 25mm.
- 2/3rd of the final load at which the total settlement attains a value of 40mm.

Example: The following data was obtained in a vertical pile load test on 300 mm diameter pile. Determine the allowable or safe load as per IS 2911 part IV (1979).

Load (kN)	Settlement (mm)
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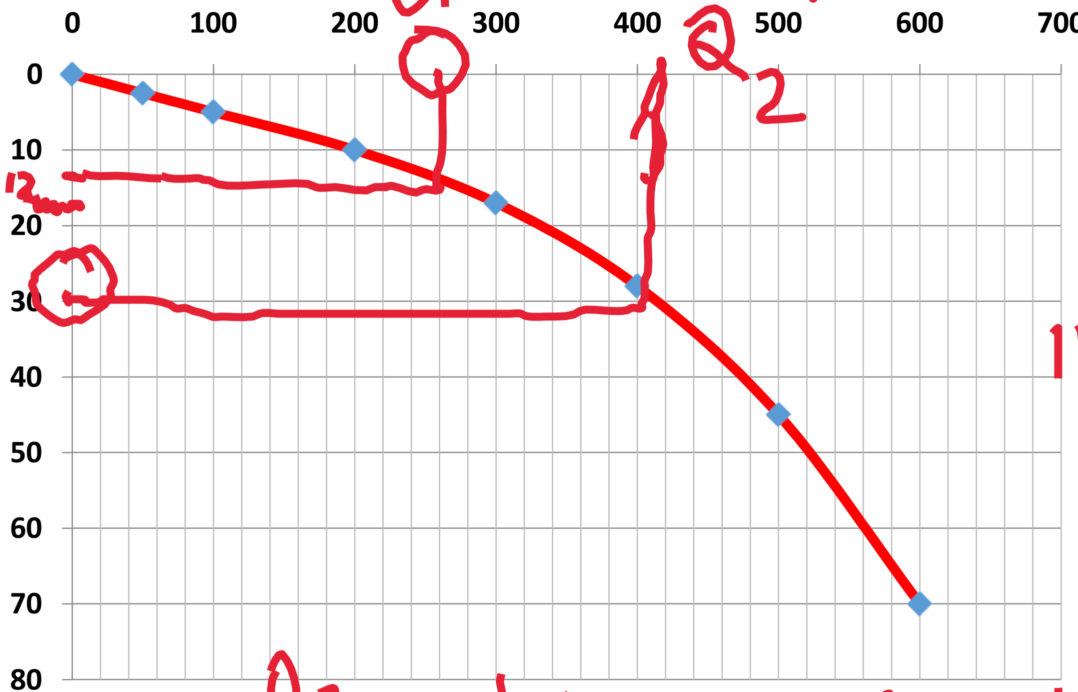

Vertical cyclic plate load test:

- It is carried out when it is required to separate the pile load into skin friction and point bearing on single piles of uniform diameter.
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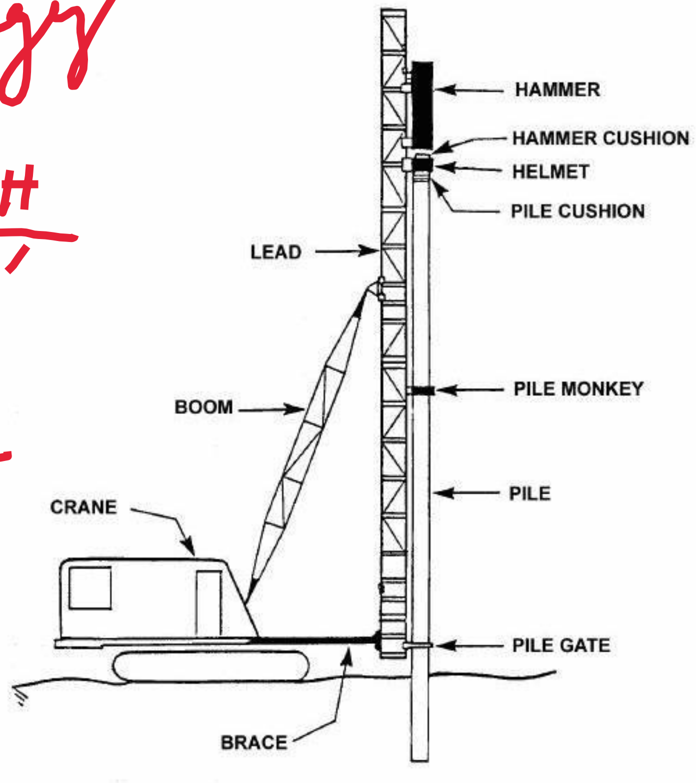
Pile foundation X

Dynamic Pile formula

- Engineering News Record Formula (ENR)

Energy input= Work done

$$Q_u S' = WH$$



From above formula, the allowable pile load is expressed as

$$Q_a = \frac{WH}{F(S+C)}$$

W= weight of the hammer falling through a height, H
S'= Theoretical set= S+C
S= real set per blow
C= empirical factor allowing reduction in theoretical set due to energy losses
F= factor of safety (usually taken as 6)

http://hammer.m88play.com/drop-hammer-pile-driver/

a) Drop hammer $Q_a = \dfrac{WH}{6(S+2.5)}$

b) Single acting steam hammers $Q_a = \dfrac{WH}{6(S+0.25)}$

c) Double acting steam hammers $Q_a = \dfrac{(W+ap)H}{6(S+0.25)}$

FS = F = 6

steam hammers

where W (weight of hammer) and Q_a are expressed in kg. H is the height of free fall of hammer in cm. a is the effective area of piston in cm^2 and p is the mean effective steam pressure in kg/cm^2. S is the final set in cm/blow, usually taken as average penetration for the last 5 blows of a drop hammer or 20 blows of a steam hammer.

Example: A 250 diameter pile was driven with a drop hammer of weight 2200 kg and having a free fall of 1.5m. The total penetration of the pile recorded in the last 5 blows was 30mm. Determine the safe pile load using ENR.

$W = 2200\ kg$, $H = 1.5\ m = 1.5 \times 10^2\ cm$

5 blows — 30 mm, $S = \frac{30}{5} = 6\ mm = 0.6\ cm$

$$Q_a = \frac{WH}{F(S+C)} = \frac{WH}{6(S+2.5)}$$

$$= \frac{2200 \times 1.5 \times 10^2}{6(0.6+2.5)} = 17742\ kg$$

$$= \frac{(17742 \times 9.81)\ N}{1000}$$

$$Q_a = 174\ kN$$

• Modified Hiley Formula

Actual Energy delivered= Energy used + Energy losses

$$Q_u = \frac{W h \eta_h \eta}{S + C/2} = \frac{W h \eta_h \eta}{S + \frac{1}{2}(C_1 + C_2 + C_3)}$$

where Q_u= ultimate driving resistance in tonnes. Safe load is estimated by dividing the ultimate resistance by a factor of safety 2.5.

W= weight of hammer in tonnes.

h= effective fall of hammer, in cm

η= efficiency of blow that represents the ratio of energy after impact to striking energy of ram.

η_h=hammer efficiency

S= final set or penetration per blow in cm.

C= total elastic compression= $C_1 + C_2 + C_3$

- When W> Pe and pile is driven into penetrable ground,

$$\eta = \frac{W + Pe^2}{W + P}$$

- When W< Pe and pile is driven into penetrable ground,

$$\eta = \frac{W + Pe^2}{W + P} - \left(\frac{W - Pe}{W + P}\right)^2$$

where P= weight of pile + anvil+ helmet +follower (if any) in tonnes

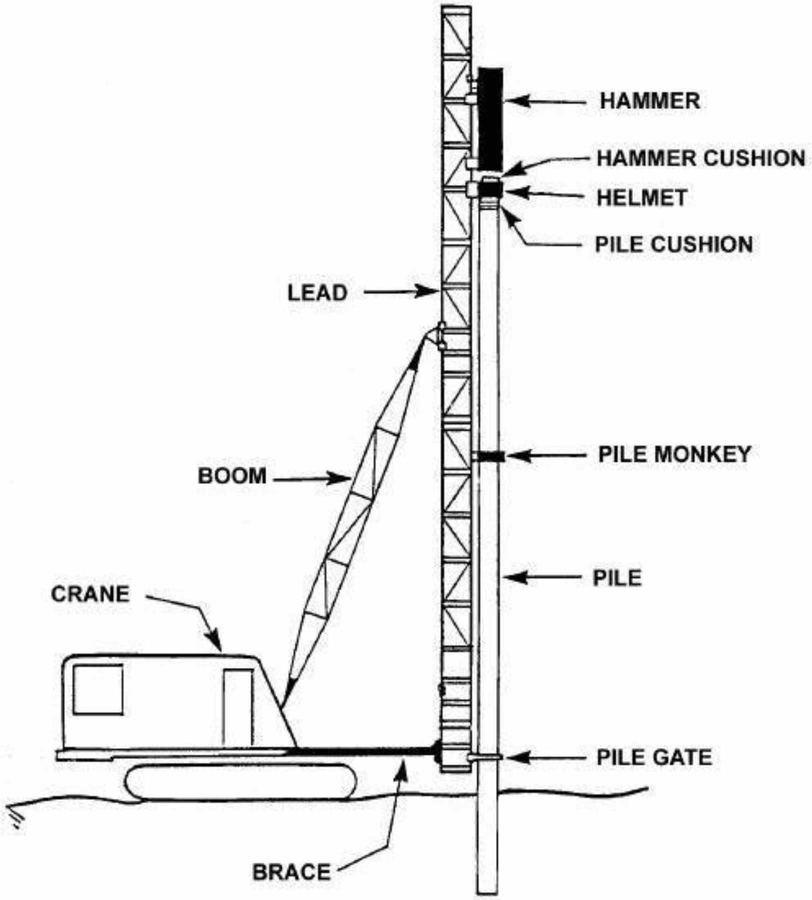
e= coefficient of restitution of material under impact and ranges from 0 to 1.

C_1	C_2	C_3
It is temporary elastic compression of dolly and packing.	It is temporary elastic compression of pile.	It is temporary compression of soil.
$= 1.77 \frac{Q_u}{A}$ *where the driving is with 2.5cm thick cushion only on head of pile* $= 9.05 \frac{Q_u}{A}$ *where the driving is with short dolly upto 60cm long, helmet and 7.5cm thick cushion*	$= 0.675 \frac{Q_u L}{A}$ *where L is length of pile in meter. A is area of pile in* cm^2.	$= 3.55 \frac{Q_u}{A}$ *where A is area of pile in* cm^2.

Pile-hammer efficiency

Hammer Type	η_h
Drop	1.00
Single acting	0.75–0.85
Double acting	0.85
Diesel	1.00

Murthy (2001)



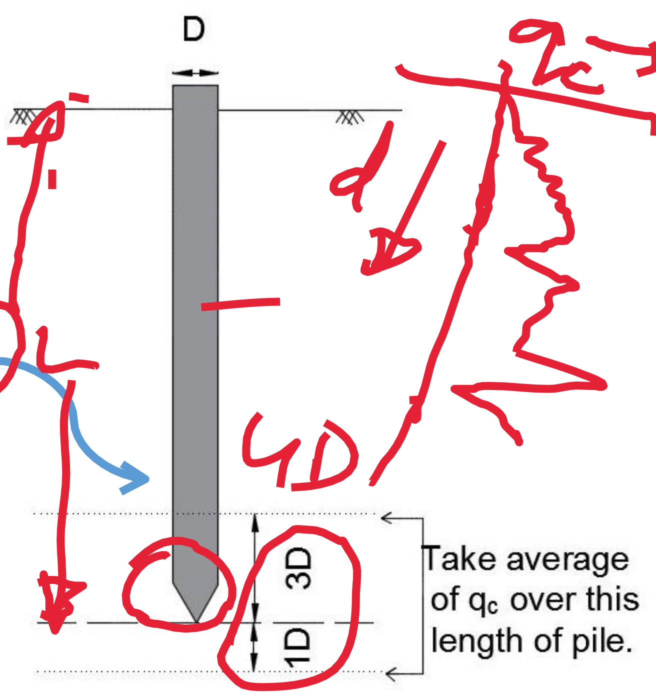
Pile foundation XI

Correlation with penetration test data

- Driven piles in sand

1. *Using Cone Penetration resistance*

- The unit point resistance of driven pile q_{pu} = static cone resistance q_c



- The skin friction resistance for driven piles can also be determined with help of cone penetration resistance using **Meyerhof(1956)** correlation:

For Displacement piles, $$f_s = \frac{q_c(av)}{2}\ kN/m^2$$ (limited to 100 kN/m²)

For H piles, $$f_s = \frac{q_c(av)}{4}\ kN/m^2$$ (limited to 50 kN/m²)

where $q_c(av)$ = average field value of cone penetration resistance in kg/cm² over pile length.

- Using of static cone penetration data

[IS:2911(Part1/Sec 1):2010]

For non homogeneous soil,

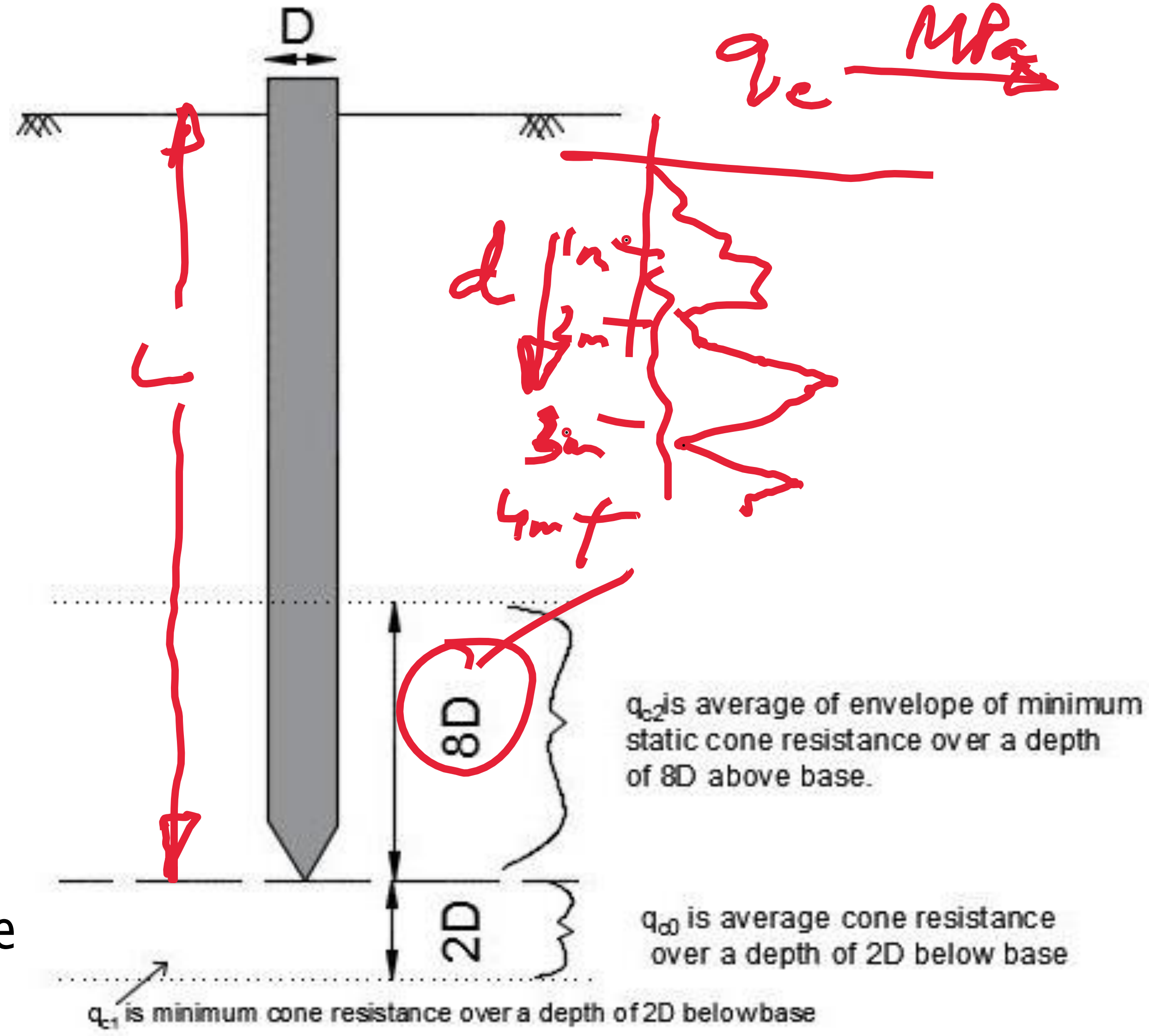
The ultimate point bearing capacity can be taken as

$$q_{pu} = \frac{\left(\frac{q_{c0} + q_{c1}}{2}\right) + q_{c2}}{2}$$

q_{c0} is the average cone resistance

q_{c1} is the minimum cone resistance

q_{c2} is the average of minimum cone resistance



Using of static cone penetration [IS:2911(Part1/Sec 1):2010]

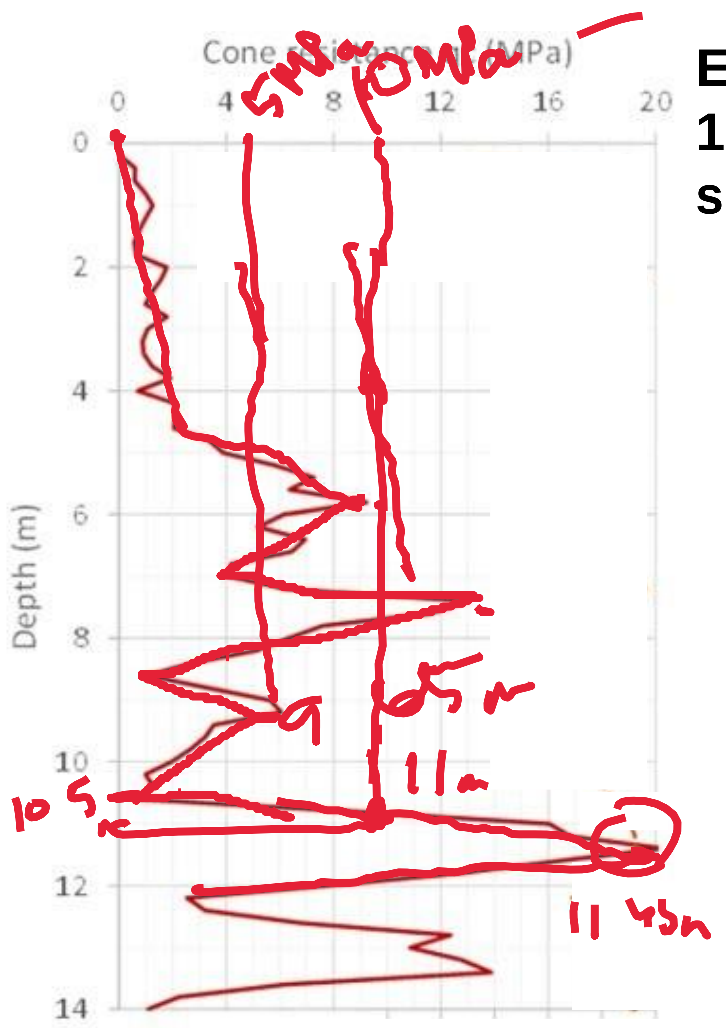
Side or skin friction (f_s) in kN/m^2

$$\frac{q_c}{25} < f_s < \frac{2q_c}{25} \quad \textit{for clay}$$

$$\frac{q_c}{100} < f_s < \frac{q_c}{25} \quad \textit{for silty clay and silty sand}$$

$$\frac{q_c}{100} < f_s < \frac{2q_c}{100} \quad \textit{for sand}$$

$$\frac{q_c}{100} \; f_s < \frac{q_c}{150} \quad \textit{for coarse sand and gravel}$$



Example: Determine the allowable load carrying capacity of a 11 m long and 450 mm diameter driven pile constructed in the sand with cone resistance (SCPT) profile as shown in the figure.

$Q_{pu} = q_{pu} \times A_b$

$= 6507 \times \frac{\pi}{4} \times 0.45^2$

$= 1034.4$ kN

$q_{pu} = \dfrac{\frac{500+500}{2} \times (10.5 - 9.65) + \ldots}{(0.45 + 1.35)}$

$= 6507$ kN/m²

$q_{pu} = q_c = 6507$ kN/m²

Pile foundation XII

2. Using N value:

- The unit penetration resistance of driven pile in sand including H pile can be determined as:

$$q_{pu} = 40N(L/D)\ kN/m^2$$

where N= standard penetration resistance observed in field without overburden correction
L= length of the pile
D= diameter of pile
For driven piles, q_{pu} is limited to 400 *N* kN/m².

- The skin friction resistance for driven pile in sand can be determined as:

For displacement piles: (Driven Piles) $$f_s = 2N_{av}\ kN/m^2$$ (limited to 100 kN/m²)

For H piles: $$f_s = N_{av}\ kN/m^2$$ (limited to 50 kN/m²)

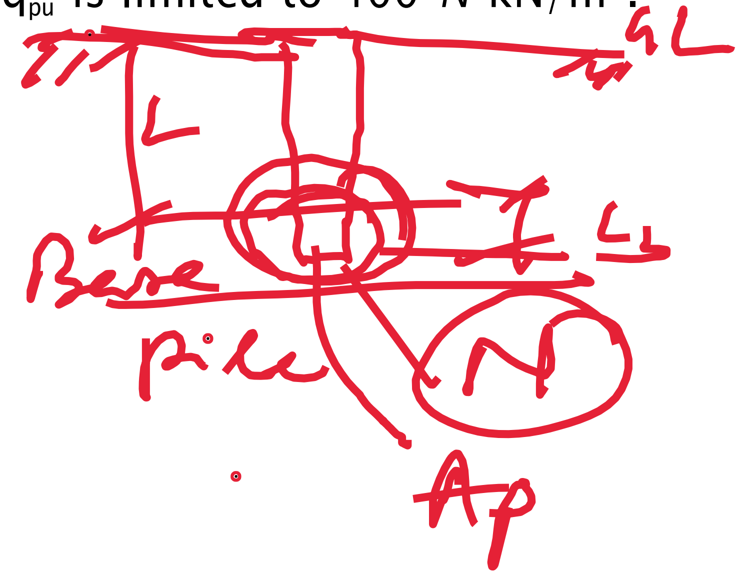
where N_{av}= average field value of N along pile length

- <u>Using of standard penetration data</u> **[IS:2911(Part1 /Sec 1):2010]**

➢ For saturated cohesionless soil, the ultimate load bearing capacity of pile in kN is given by

$$Qu = 40N \frac{L_b}{D} A_p + \frac{\overline{N} A_s}{0.5}$$

For driven piles, q_{pu} is limited to 400 N kN/m^2.



where N= average N value at tip

L_b=length of penetration in bearing strata , in m

d= diameter of pile in m

A_p= c/s area of pile tip in m^2

$\overline{N}$= average N value along pile shaft

A_s= surface area of shaft in m^2

➢ for non plastic silt or very fine sand,

$$Qu = 30N \frac{L_b}{D} A_p + \frac{\overline{N} A_s}{0.6}$$

- Bored and cast *in situ* piles in sand

$$q_{pu} = \frac{1}{3} q_{pu} \text{ of driven pile}$$

$$f_s = \frac{1}{2} f_s \text{ of driven pile}$$

- Driven and cast *in situ* piles in sand

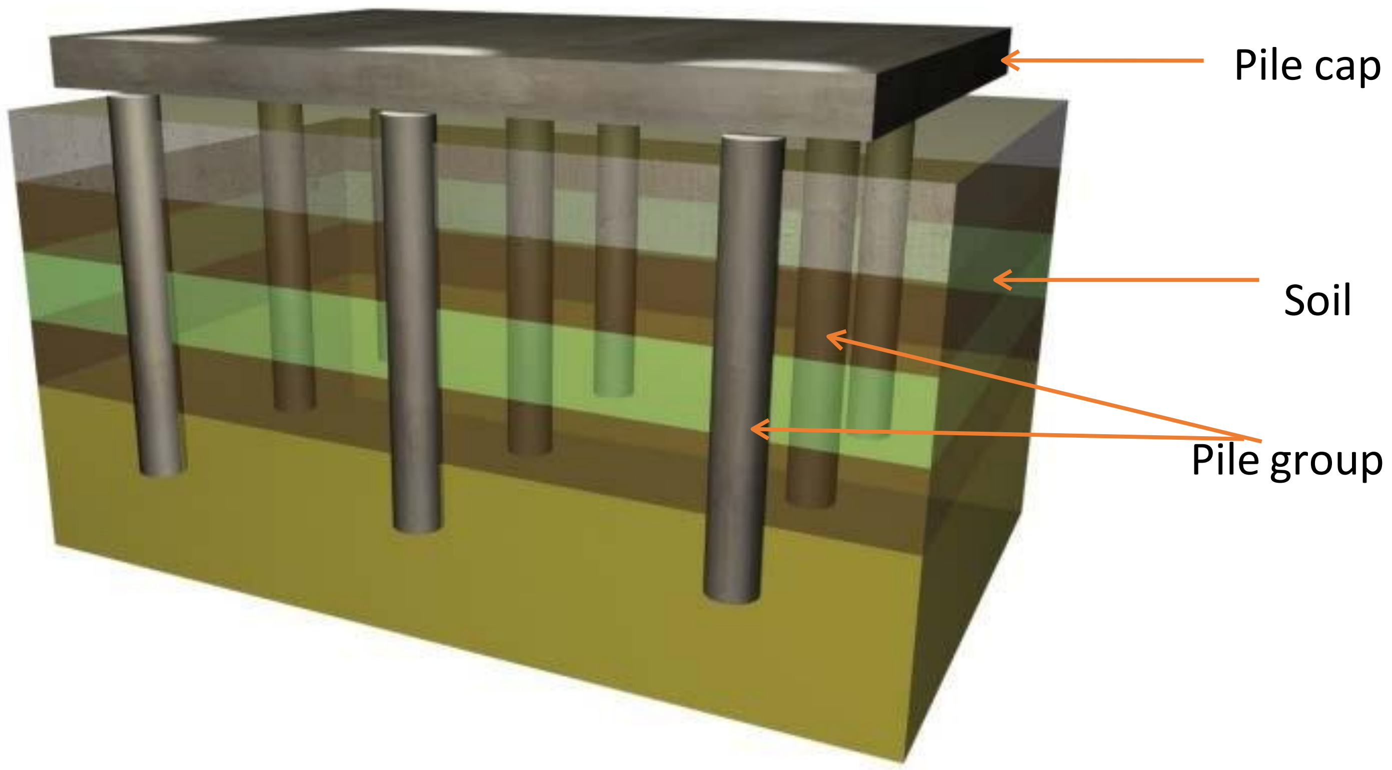
For cased pile: q_{pu} and f_s can be taken same as that of driven pile.

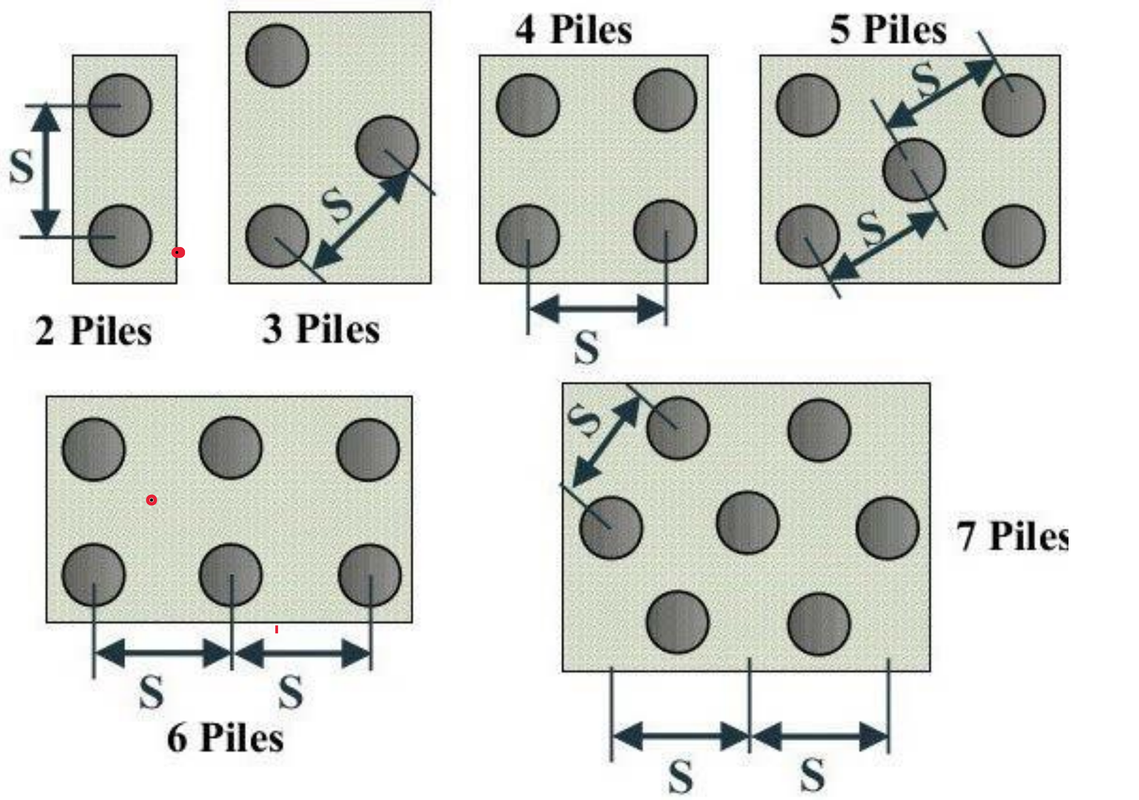
For uncased pile:

$f_s = f_s$ of driven pile (if proper compaction of concrete is done)

$f_s = f_s$ of bored cast *in situ* (if proper compaction of concrete is not done)

Group action of piles:





https://www.deltares.nl/en/software/module/d-pile-group-cap-layered-soil-interaction-3/

https://theconstructor.org/geotechnical/foundations/pile/page/2/

- Ultimate bearing capacity of pile group ≠ sum of all individual piles present in the group.
- Group efficiency,

$$\eta_g = \frac{Q_{ug}}{nQ_u}$$

where Q_{ug} = ultimate load bearing capacity of pile group

Q_u = ultimate load bearing capacity of single pile

n = no. of piles

✓ $\eta_g < 1$ for smaller spacing between piles

✓ $\eta_g > 1$ for driven piles in loose to medium soil

✓ $\eta_g = 1$ for larger spacing of piles

Pile group efficiency can be calculated using Converse- Labarre formula:

$$\eta_g = 1 - \left[\frac{m(n-1) + n(m-1)}{mn}\right]\frac{\theta}{90}$$

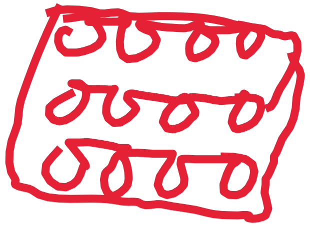
where m= no. of rows of piles

n= no. of piles in a row

$$\theta = \tan^{-1}\left(\frac{D}{S}\right)$$

D= Diameter of pile

S= Centre to centre spacing



m = 3

n = 4

Minimum pile spacing

Length of pile	Friction piles in sand	Friction piles in clay	Point bearing pile
< 12m	3D	4D	3D
12 to 24 m	4D	5D	4D
> 24m	5D	6D	5D

As per IS: 2911-I-1979

Bearing pile- 2 D

Friction pile- 3D

Loose sand or fill deposit -2D

2D to 3D

Pile group in clay

Pile may fail in one of the following way

- By block failure (when spacing is less than 2-3 times diameter of a pile)
- By individual pile failure (when piles are spaced wider)

- The ultimate load capacity of the pile group by block failure is given by:

$$Q_{ug} = c_{ub} N_c A_b + P_b L c_u$$

- c_{ub}: Undrained strength of clay at base of pile group
- N_c: Bearing capacity factor=9
- A_b: c/s area of block
- P_b: Perimeter of block
- L: Embedded length of pile
- c_u: Undrained strength of clay along length of block

- The ultimate load capacity of the pile group by individual pile failure is given by:

$$Q_{ug} = nQ_u$$

Example: Determine the spacing of a group of 16 piles with diameter of 300mm such that the efficiency of the pile group is 1. The piles were constructed in uniform clay soil with unconfined compressive strength of 50 kPa.

Solution

$\eta_g = 1$

$Q_{ug} = nQ_u$

① ~~Single pile failure~~

$= n \times Q_u$

$= 16 \times \alpha C_u A_s$

$= 16 \times 0.95 \times 25 \times \pi \times D \times L$

$\alpha = 0.95$

$P_b = 2(B+$

$= 100(3S + D) \times L$

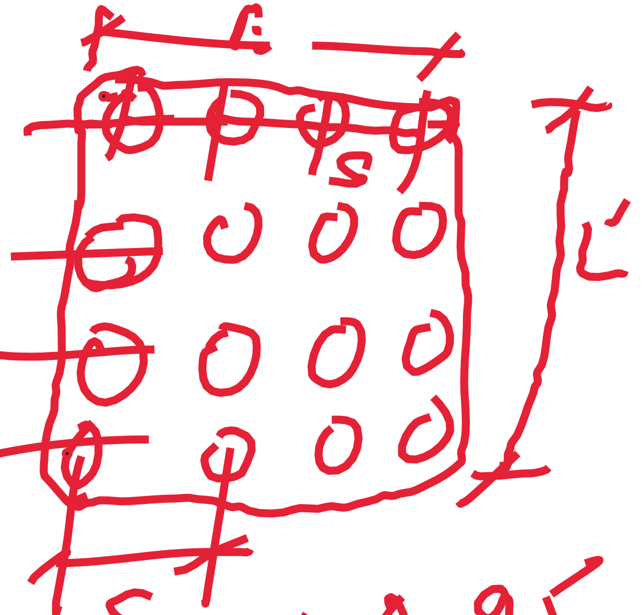
$100(3S + D)L = 16 \times 0.95 \times 25 \times \pi \times D \times L$

$\Rightarrow S = 1094\ mm$

$S = 2D$ or $3.5D$

$\frac{1094}{300} = 3.65$

$= 3.65\,S$

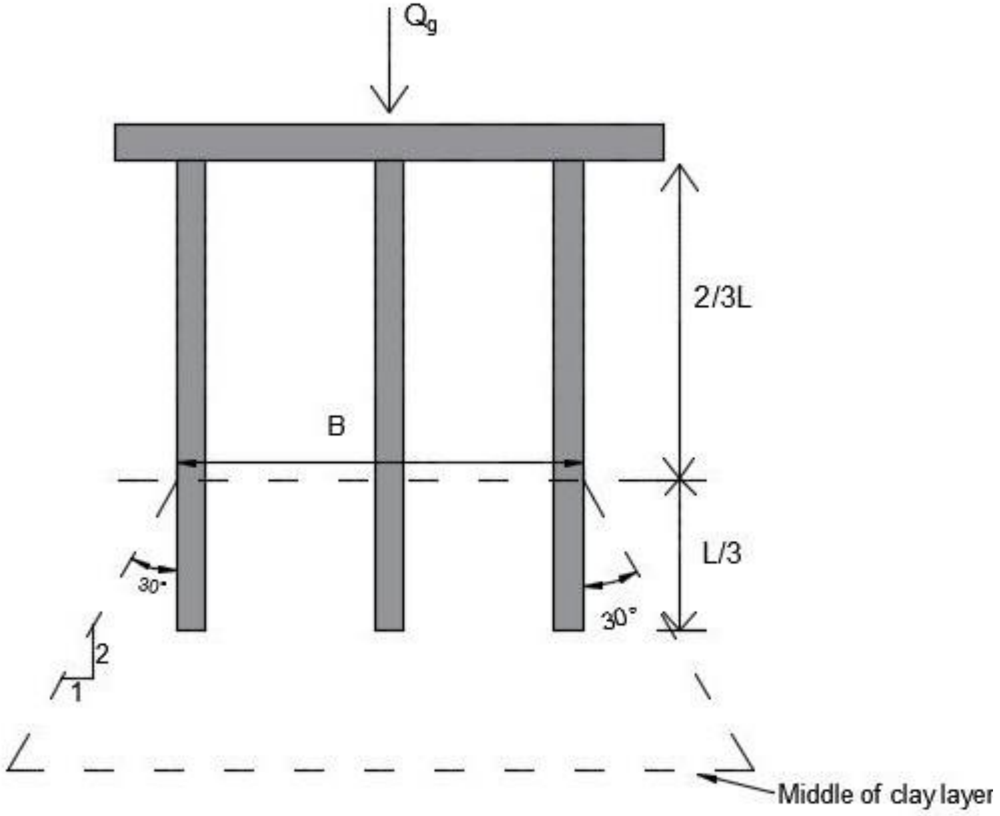


Settlement of a pile group

- <u>Pile group in clay</u>

1. For the displacement piles or friction piles in homogeneous clay

$$S_i = q_n B\left(\frac{1-\mu^2}{E}\right) I_f$$



where q_n= Net pressure on pile

μ= Poisson's ratio

E= young's Modulus

I_f= Influence factor

Consolidation settlement

$$S_c = \sum \frac{C_c}{1+e_0} H \log_{10}\left(\frac{p_0 + \Delta p}{p_0}\right)$$
$$or\ S_c = \sum m_v H \Delta p$$

Where p_0 = initial effective overburden pressure before applying foundation load

Δp= vertical stress at the centre of the layer due to application of load

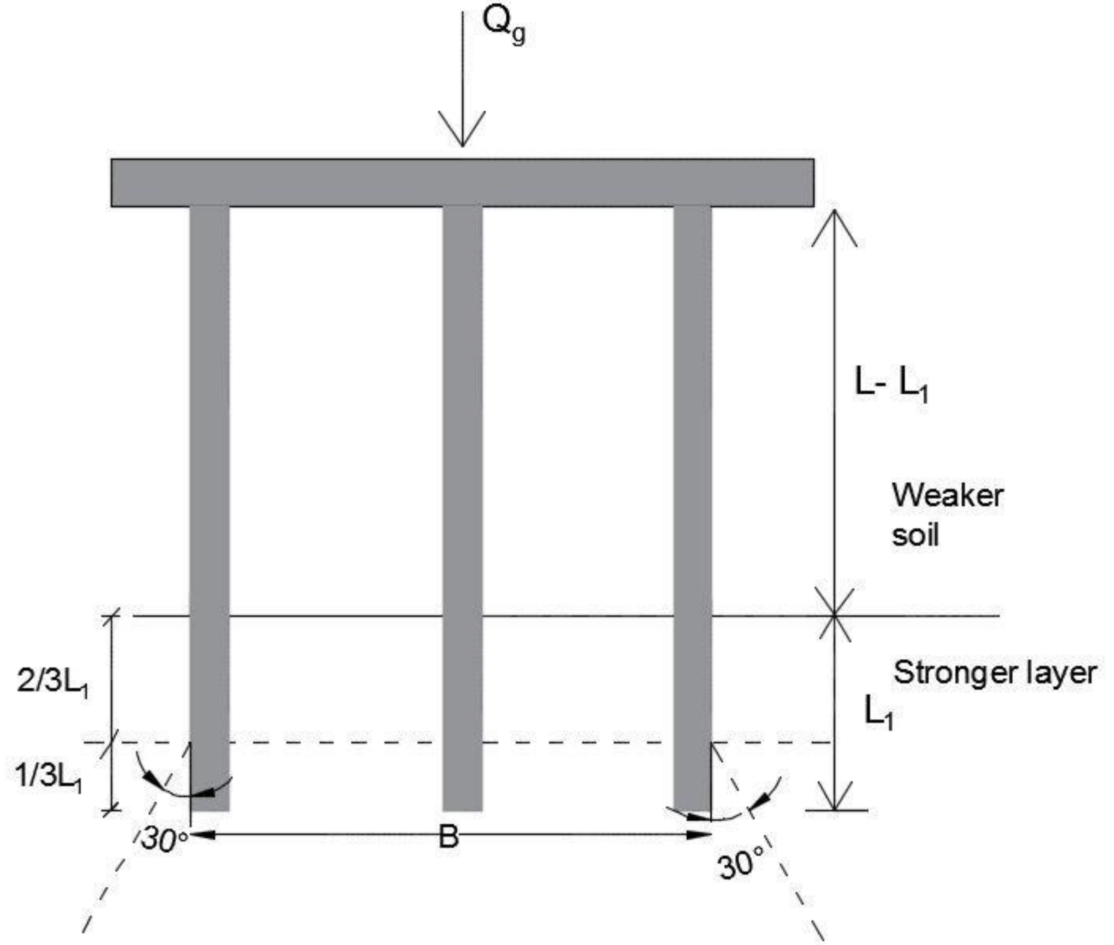
C_c= Compression index

e_0= initial void ratio

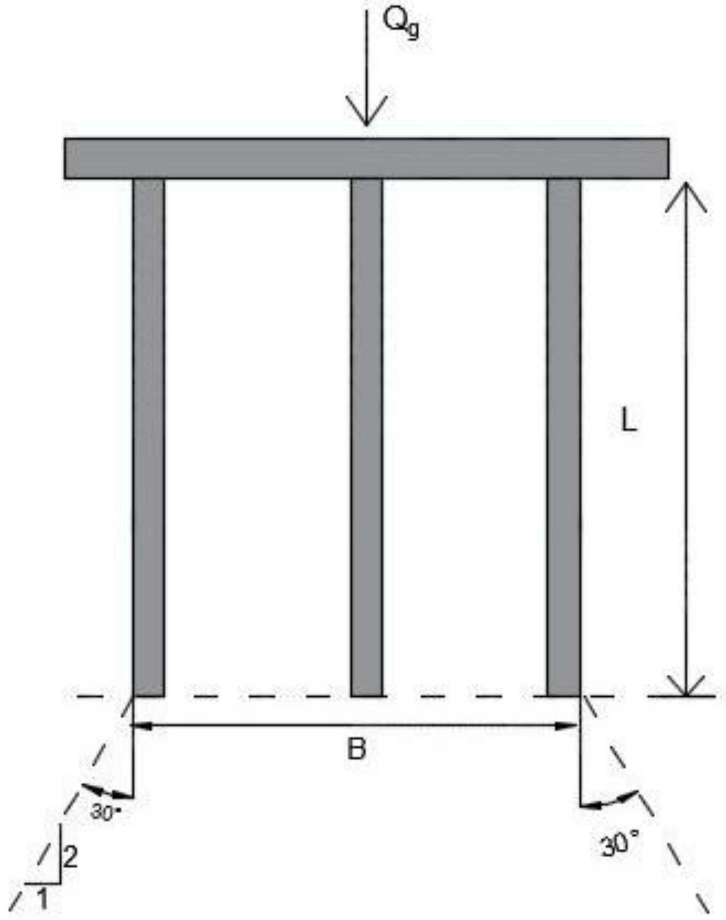
m_v= coefficient of volume compressibility

H= thickness of each layer

2. Piles driven into a firm or strong stratum through an overlying clay stratum.



3. For bored piles or end bearing piles bearing on firm stratum



Equivalent raft acts at the base of the pile.

•Pile group in sand

➢ Skempton (1953):

For same average load Q/pile acting in driven piles, the settlement ratio of group of pile to single pile can be obtained as:

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

where B= width of the pile group in 'meter'

S_g= settlement of pile group

S_i= settlement of single pile

➢ Meyerhof (1959):

It is for square pile groups driven in sand

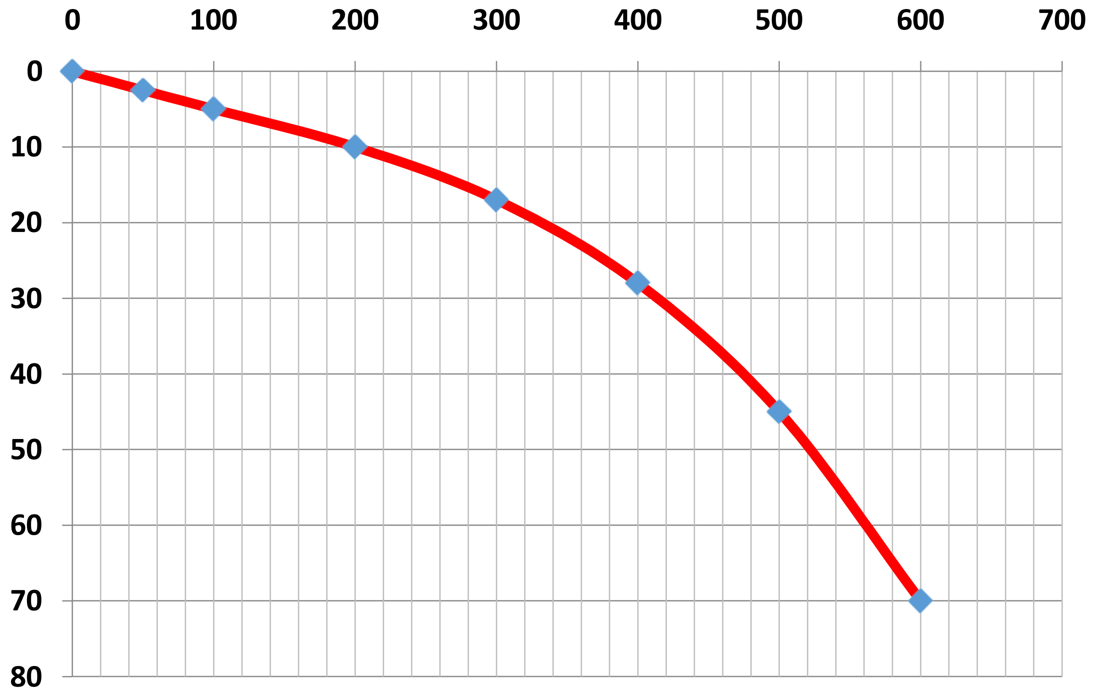
$$\frac{S_g}{S_i} = \frac{S(5 - S/3)}{\left(1 + \frac{1}{r}\right)^2}$$

where S= ratio of pile spacing to pile diameter

r= no. of rows in the pile group

Example: The following data was obtained in a vertical pile load test on 300 mm diameter pile. Determine the allowable or safe load as per IS 2911 part IV (1979).

Load (kN)	Settlement (mm)
50	2.5
100	5.0
200	10.0
300	17
400	28
500	45
600	70



Pile Foundation XIII

Example: Design a pile group consisting of RCC piles for a column of size 650mm × 650 mm carrying a load of 1500 kN (Total). The exploration data reveal that the sub-soil consists of deposit of clay extending to a greater depth. The other data of the deposit are: Compression index = 0.10, Initial void ratio = 0.9, Saturated unit weight = 20 kN/m^3, Unconfined compressive strength= 70kN/m^2. Proportion the pile group for the permissible settlement of 40 mm. Design the pile group by considering both bearing and settlement criteria. The water table is considered at the ground level. Use a factor of safety 2.5 against bearing and assume adhesion factor of 0.7.

2) Group or Block failure mode:

$Q_u = C_u N_c \times A_b + \alpha C_u A_s$

$= [35 \times 9 \times 2.4^2] + [1 \times 35 \times 2(2.4+2.4) \times 15]$

$= 68.54$ kN

$Q_{ug} = 4514$

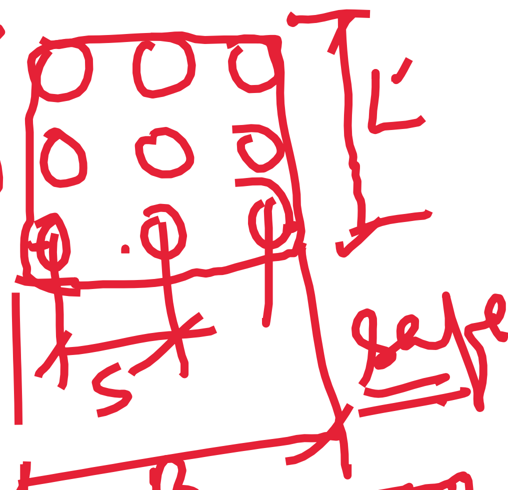
$A_b = L' \times B$

$= 2.4 \times 2.4$

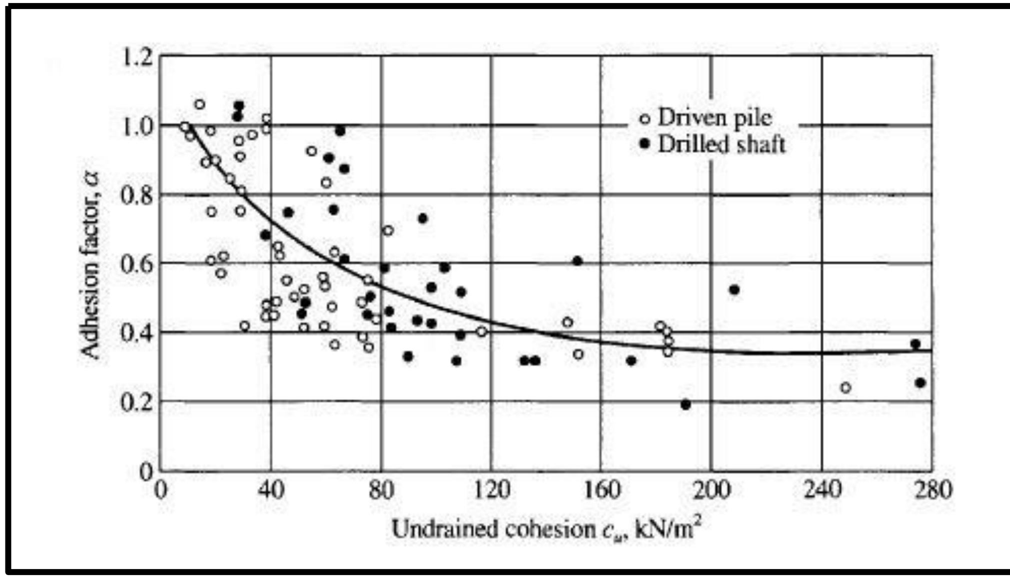
$A_s = P \times L$

$Q_s = \frac{4514}{2.5}$

$= 1804$ kN > 1500 kN



c_u (kPa)	consistency
0 - 12.5	very soft
12.5–25	soft
25–50	medium
50–100	stiff
100–200	very stiff
>200	hard



Ranjan and Rao, 1991

Consistency	N value	α value	
		Bored piles	Driven cast *in situ* piles
Soft to very soft	<4	0.7	1.0
Medium	4-8	0.5	0.7
Stiff	8-15	0.4	0.4
Stiff to hard	>15	0.3	0.3

Fox’s Correction Curves

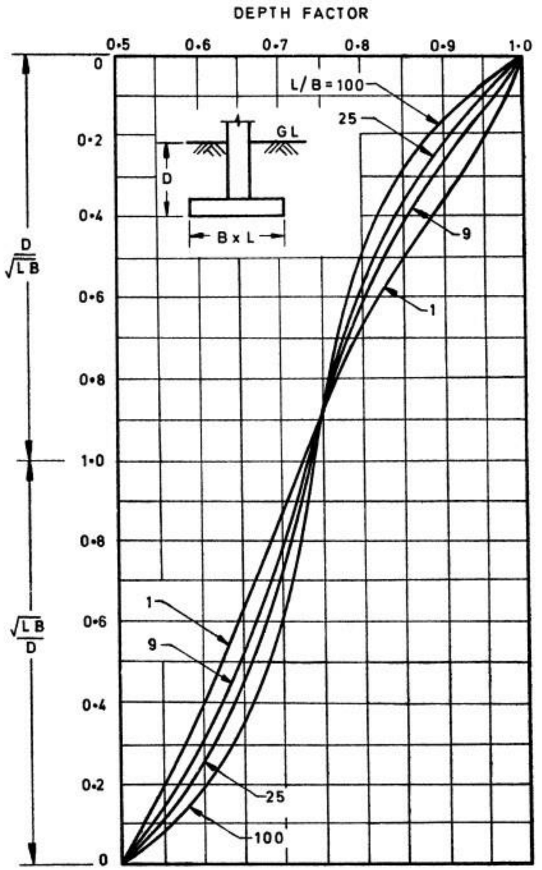
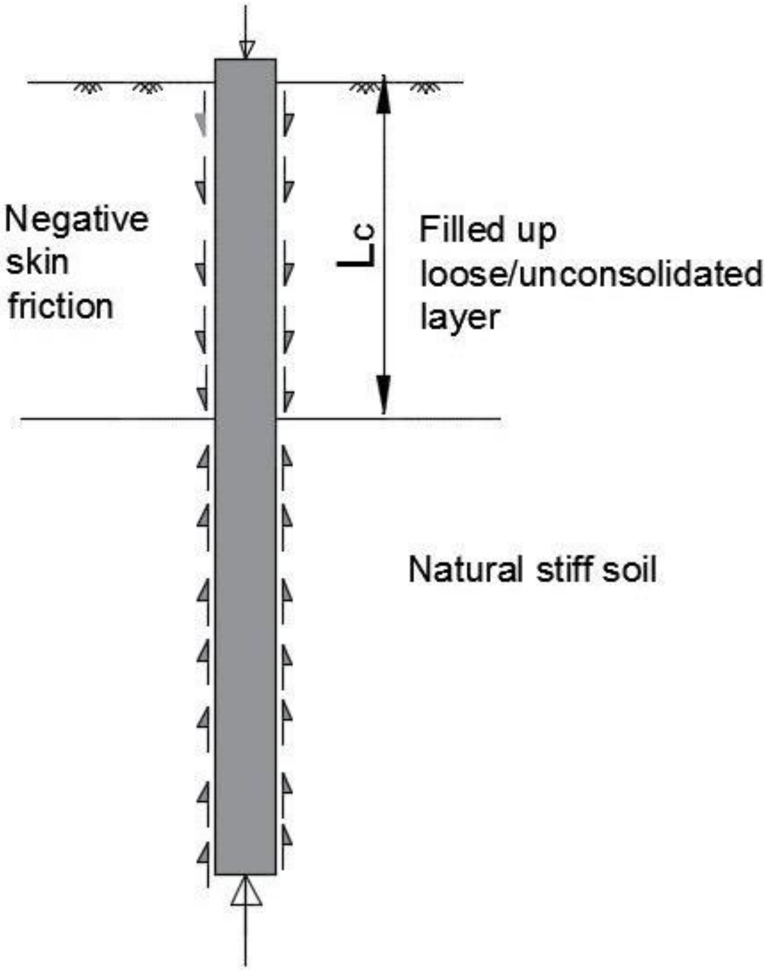


FIG. 12 FOX’S CORRECTION CURVES FOR SETTLEMENTS OF FLEXIBLE RECTANGULAR FOOTINGS OF $L \times B$ AT DEPTH D

Pile Foundation XIV

Negative skin friction:

Negative skin friction in single piles



The magnitude of negative skin friction, F_n for **a single pile** may be estimated as below:

Cohesive soils:

$$F_n = PL_c c_a$$

Where, P= perimeter of pile

L_c= Length of pile in compressible stratum

c_a= unit adhesion=αc_u

α= adhesion factor

c_u= undrained cohesion of compressible layer

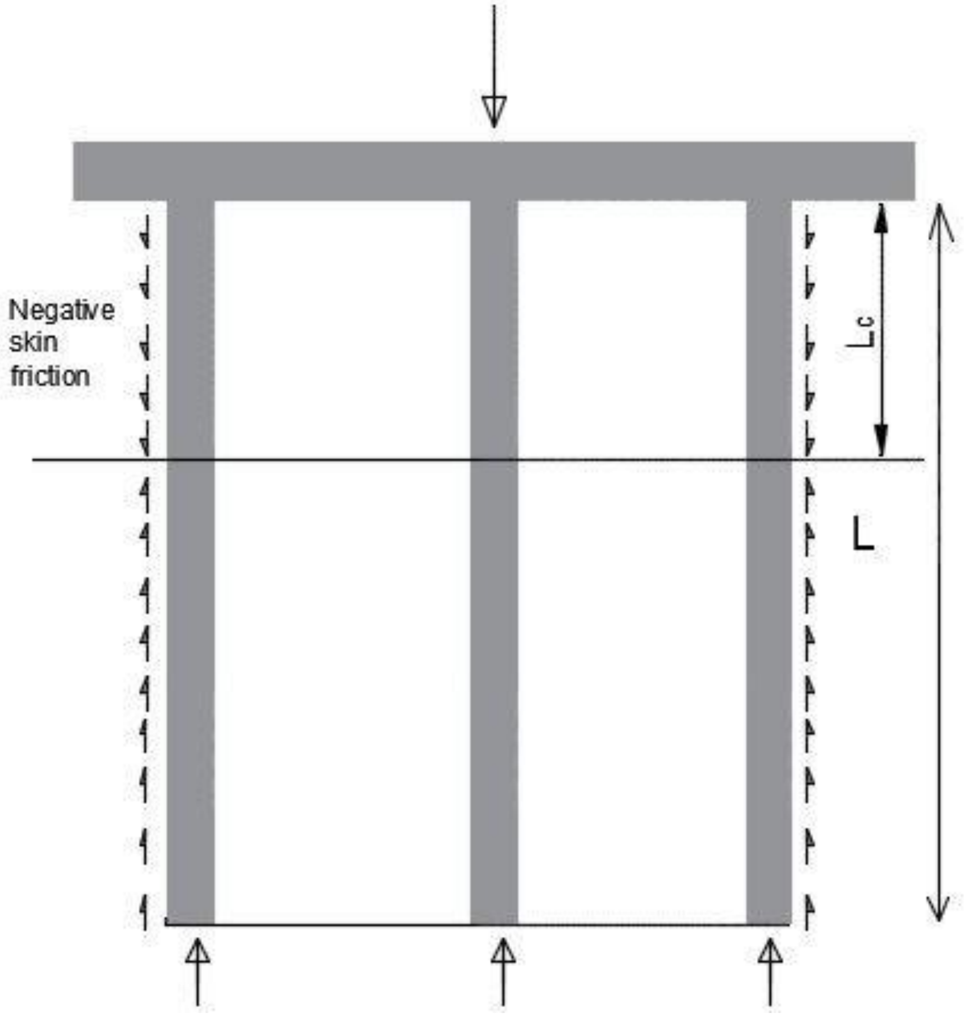
Cohesionless soils:

$$F_n = \frac{1}{2} P L_c{}^2 \gamma \, K \tan\delta$$

where K=lateral earth pressure coefficient

δ= angle of friction between pile and soil (1/2 ϕ to 2/3ϕ)

Negative skin friction in pile groups



The magnitude of negative skin friction, F_{ng} for **a pile group** passes through soft and unconsolidated soil may be estimated as below:

$$F_{ng} = nF_n$$

$$F_{ng} = c_u L_c P_g + \gamma L_c A_g$$

Higher of value from these two Equation is used in design

where n= number of piles in the group

P_g= perimeter of group

γ= unit weight of soil within pile group up to a depth of L_c

A_g= area of pile group within perimeter P_g

$$F.O.S = \frac{Ultimate\ load\ capacity\ of\ a\ single\ or\ a\ group\ of\ piles}{Working\ load\ +\ negative\ skin\ friction}$$

- <u>Using of static cone penetration data</u>

[IS:2911(Part1/Sec 1):2010]

For non homogeneous soil,

The ultimate point bearing capacity can be taken as

$$q_{pu} = \frac{\left(\frac{q_{c0} + q_{c1}}{2}\right) + q_{c2}}{2}$$

q_{c0} is the average cone resistance

q_{c1} is the minimum cone resistance

q_{c2} is the average of minimum cone resistance