Pile foundation

Cases where pile foundation is used:-

1- When one or more upper soil layers are highly compressible and too weak to support the load transmitted by the superstructure, piles are used to transmit the load to underlying bedrock or a stronger soil layer, as shown in Fig.1a.

عندما تكون طبقة أو أكثر من طبقات التربة العلوية شديدة الهبوط وضعيفة جدًا بحيث لا تتحمل الحمل المنقول بواسطة البناء الثقيل، يتم استخدام الركائز لنقل الحمل إلى طبقة الصخور السفلية أو طبقة تربة أقوى.

2- When bedrock is not encountered at a reasonable depth below the ground surface, piles are used to transmit the structural load to the soil gradually. The resistance to the applied structural load is derived mainly from the frictional resistance developed at the soil–pile interface, Fig.1b.

عندما لا يتم العثور على الطبقة الصخرية على عمق معقول تحت سطح الأرض، يتم استخدام الركائز لنقل الحمل الإنشائي إلى التربة تدريجياً. تستمد الركيزة مقاومتها للاثقال بشكل أساسي من مقاومة الاحتكاك الناشئة بينها وبين التربة.

3- When subjected to horizontal forces, Fig.1c, pile foundations resist by bending, while still supporting the vertical load transmitted by the superstructure. This type of situation is generally encountered in the design and construction of earth-retaining structures and foundations of tall structures that are subjected to high wind or to earthquake forces.

عند تعرضها لقوى أفقية، فإن الركائز تقاوم الانحناء، مع الاستمرار في مقاومة الاثقال العمودية المنقولة اليها من المنشأ. يتم مواجهة هذه الحالات بشكل عام في تصميم وبناء الهياكل تحت الارض وأساسات الهياكل العالية التي تتعرض للرياح العاتية أو لقوى الزلازل.

4- In many cases, expansive and collapsible soils may be present at the site of a proposed structure. These soils may extend to a great depth below the ground surface. Expansive soils swell and shrink as their moisture content increases and decreases, and the pressure of the swelling can be considerable. If shallow foundations are used in such circumstances, the structure may suffer considerable damage. However, pile foundations may be considered as an alternative when piles are extended beyond the active zone, which is where swelling and shrinking occur. Fig.1d. Soils such as loess are collapsible in nature. When the moisture content of these soils increases, their structures may break down. A sudden decrease in the void ratio of soil induces large settlements of structures supported by shallow foundations.

في كثير من الحالات قد توجد تربة منتفخة وقابلة للانهيار في موقع البناء المقترح. وقد تمتد هذه التربة إلى عمق كبير تحت سطح الأرض. تنتفخ التربة وتنكمش مع زيادة ونقصان محتواها الرطوبي، ويمكن أن يكون الانتفاخ كبيرًا. إذا تم استخدام الأساسات الضحلة في مثل هذه الظروف، فقد يتعرض الهيكل لأضرار جسيمة. ومع ذلك، يمكن اعتبار الركائز كبديل لنقل الاثقال عبر طبقات التربة الضعيفة والقابل للانتفاخ والتقلص. التربة الضعيفة تكون قابلة للانهيارعندما يزيد محتواها الرطوبي بسبب النقصان الكبير في نسبة الفراغات.

5- The foundations of some structures, such as transmission towers, offshore platforms, and basement mats below the water table, are subjected to uplifting forces. Piles are sometimes used for these foundations to resist the uplifting force. Fig.1e.

تتعرض أساسات بعض المنشآت مثل أبراج النقل والمنصات البحرية والاسس الحصيرية الواقعة تحت منسوب الماء إلى القوى الرافعة. تُستخدم الركائز أحيانًا لهذه الأساسات لمقاومة قوة الرفع

6- Bridge abutments and piers are usually constructed over pile foundations to avoid the loss of bearing capacity that a shallow foundation might suffer because of soil erosion at the ground surface. Fig.1f.

عادة ما يتم إنشاء اعمدة واكتاف الجسور فوق أساسات الركائز لتجنب فقدان قوة التحمل التي قد تتعرض لها الأساس الضحلة بسبب انجراف التربة تحت الاسس بسبب تيارات الماء.

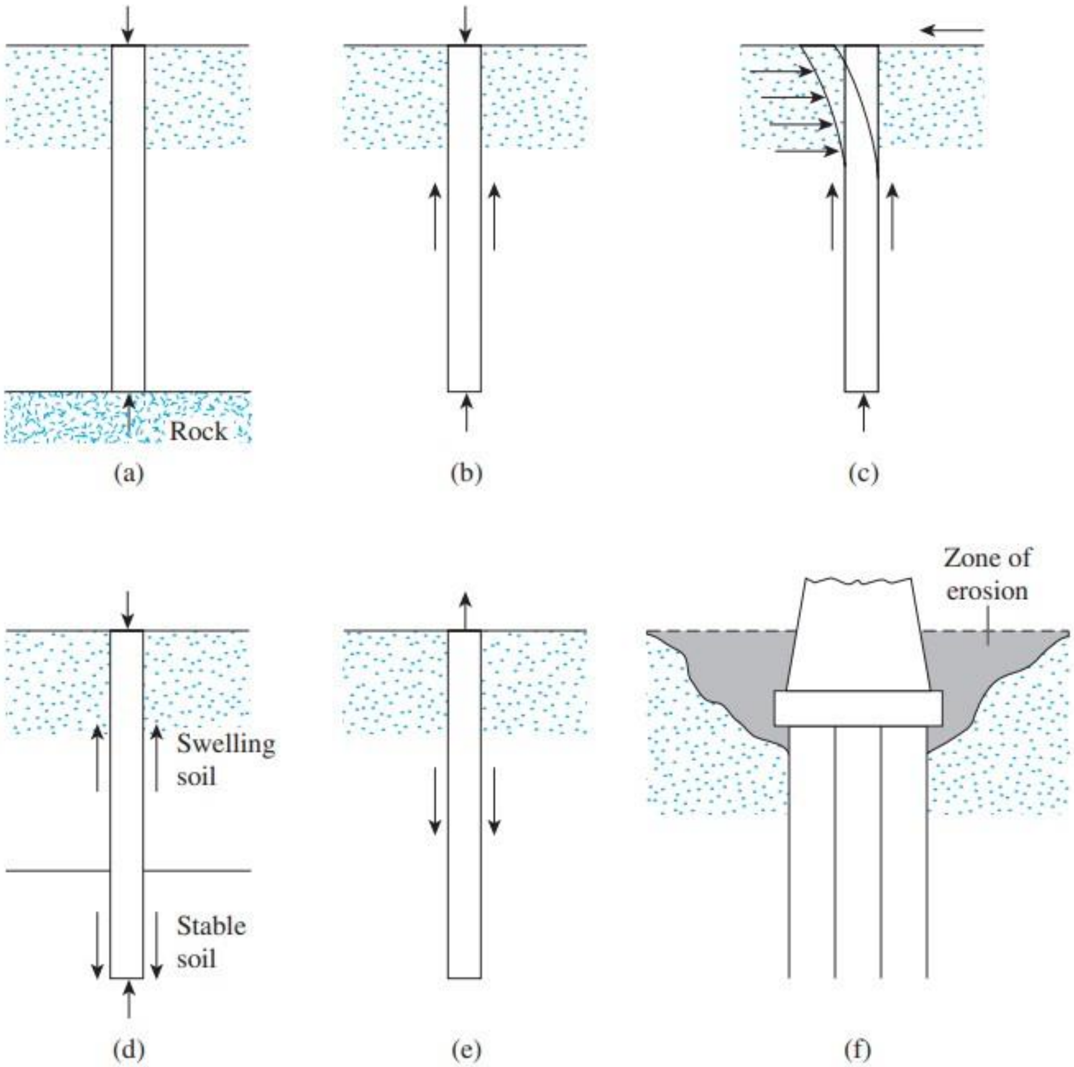
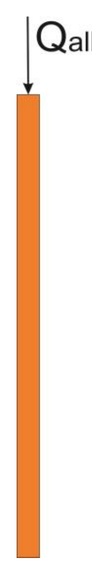


Fig.1 Conditions that require the use of pile foundations

Steel piles



The allowable structural capacity (Q_{all}) for steel piles is:-

$$Q_{all} = A_s f_s \quad , \quad f_S = (0.3 - 0.5) f_y \qquad \textbf{(1)}$$

A_s: ***Area of pile cross section*, can be determined by Eq.1**

f_S: ***Allowable steel stress,***

Following are some general facts about steel piles:

- **Usual length: 15 m to 60 m**
- **Usual load: 300 kN to 1200 kN**

Advantages:

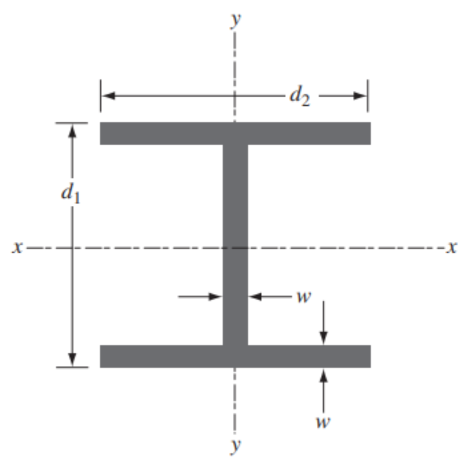
a. Easy to handle with respect to cutoff and extension to the desired length.
b. Can stand high driving stresses.
c. Can penetrate hard layers such as dense gravel and soft rock.
d. High load-carrying capacity.

Disadvantages:

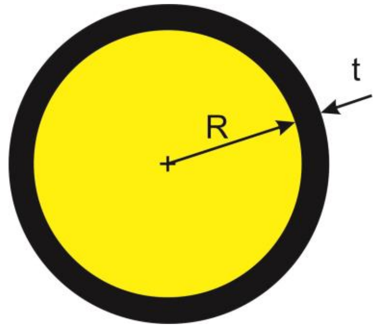
a. Relatively costly
b. High level of noise during pile driving .
c. Subject to corrosion.
d. H-piles may be damaged or deflected from the vertical during driving through hard layers or past major obstructions.

Table 1 Common H-Pile Sections

Designation, size (mm) × weight (kg/m)	Depth d_1 (mm)	Section area ($m^2 \times 10^{-3}$)	Flange and web thickness w (mm)	Flange width d_2 (mm)	Moment of inertia ($m^4 \times 10^{-6}$) I_{xx}	I_{yy}
HP 200 × 53	204	6.84	11.3	207	49.4	16.8
HP 250 × 85	254	10.8	14.4	260	123	42
× 62	246	8.0	10.6	256	87.5	24
HP 310 × 125	312	15.9	17.5	312	271	89
× 110	308	14.1	15.49	310	237	77.5
× 93	303	11.9	13.1	308	197	63.7
× 79	299	10.0	11.05	306	164	62.9
HP 330 × 149	334	19.0	19.45	335	370	123
× 129	329	16.5	16.9	333	314	104
× 109	324	13.9	14.5	330	263	86
× 89	319	11.3	11.7	328	210	69
HP 360 × 174	361	22.2	20.45	378	508	184
× 152	356	19.4	17.91	376	437	158
× 132	351	16.8	15.62	373	374	136
× 108	346	13.8	12.82	371	303	109



Pipe shape piles



$$A_S = \frac{\pi}{4}[(R+t)^2 - R^2]$$

$$A_S = \frac{\pi}{4}[(R^2 + 2Rt + t^2) \quad - R^2]$$

$$A_S = \frac{\pi}{4}(2Rt + t^2)$$

$$R = \frac{2A_S}{\pi t} - t/2 \qquad \textbf{(2)}$$

Example : Design a steel pile that extended to 30 m downward and undergoes a load of 1500KN.
1) H-shape. 2) Pipe-shape

$f_S = 0.3\, f_y = 0.3 * 420$ =126 n/mm2

$$A_S = \frac{Qall}{fs} = \frac{1500KN*1000}{126\ N/mm2} = 11{,}904.7mm2 = 0.0119m2 = 11.9 * 10^{-3}m$$

Use HP 310*93 from Table 1

2) Pipe shape

$R = \frac{2A_S}{\pi t} - t/2$ **, let t = 1cm**

$$R = \frac{2*119}{\pi*1} - \frac{1}{2} = 75cm$$

let t = 2cm

$$R = \frac{2*119}{\pi*2} - \frac{2}{2} = 37cm$$

Concrete pile

Concrete piles may be divided into two basic categories:

(a) Precast piles can be prepared by using ordinary reinforcement, and they can be square or octagonal in cross section, Fig.1.

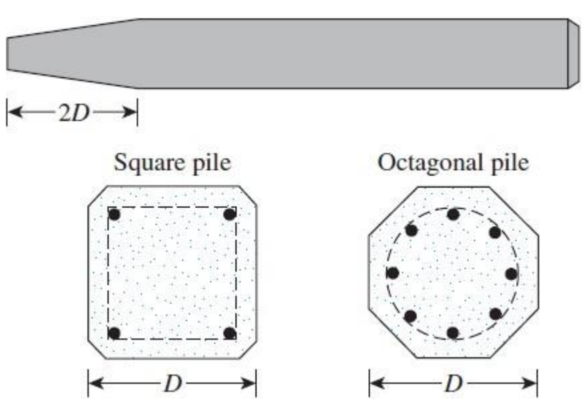


Fig.1 Precast piles with ordinary Reinforcement

(b) cast-in-situ piles:

Reinforcement is provided to enable the pile to resist the bending moment developed during pickup and transportation, the vertical load, and the bending moment caused by a lateral load. The piles are cast to desired lengths and cured before being transported to the work sites.

يمكن تقسيم الركائز الخرسانية إلى فئتين أساسيتين:

(أ) الركائز مسبقة الصب: يمكن تحضير الركائز مسبقة الصب باستخدام التسليح العادي، ويمكن أن تكون مربعة أو ثمانية المقطع.

(ب) ركائز الصب الموقعي.

يضاف حديد التسليح لتمكين الركيزة من مقاومة عزوم الانحناء الذي يحدث أثناء التحميل والنقل، والاثقال العمودية، ولحظة الانحناء الناتجة عن الحمل الجانبي. يتم صب الركائز بالأطوال المرغوبة ومعالجتها بالغمر بالماء الى عمر يزيد عن 28 يوم قبل نقلها إلى مواقع العمل.

Some general facts about concrete piles are as follows:

• Usual length: 10 m to 15 m
• Usual load: 300 kN to 3000 kN

• Advantages:

a. Can be subjected to hard driving
b. Corrosion resistant
c. Can be easily combined with a concrete superstructure

$$Q_{all} = A_s f_s + A_c f_c$$

where

A_s = area of cross section of steel
A_c = area of cross section of concrete
f_s = allowable stress of steel
f_c = allowable stress of concrete

Friction and End bearing

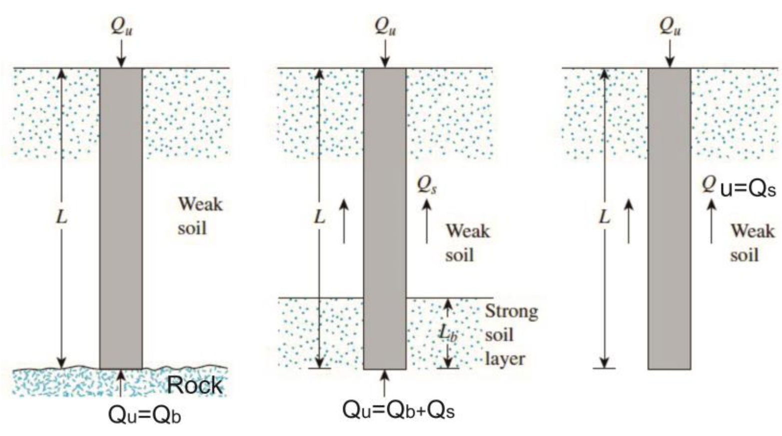


Fig.3 a) end bearing b) end bearing + friction c) friction pile

Estimation of Pile capacity

The ultimate load-carrying capacity Q_u of a pile is given by the equation:

$\boldsymbol{Q_u = Q_b + Q_s}$
$\boldsymbol{Q_b}$ **:** End bearing resistance
$\boldsymbol{Q_s}$ **:** Friction resistance

End bearing capacity

$$\boldsymbol{q_u = CN_C^* + qN_q^* + \gamma BN_\gamma^*} \qquad \textbf{(3)}$$

Since the width of pile equals the diameter B = D, Eq.3 becomes

$$q_u = q_b = CN_C^* + qN_q^* + \gamma DN_\gamma^* \qquad (4)$$

Because the width *D* of a pile is relatively small, the term $\boldsymbol{\gamma DN_\gamma^*}$ may be dropped from the right side of the preceding equation without introducing a serious error; thus, we have

$q_u = CN_C^* + qN_q^*$, so

$Q_b = A_b(CN_C^* + qN_q^*)$

Frictional Resistance, Qs

The frictional, or skin, resistance of a pile may be written as:-

$$Q_s = \sum P\Delta Lf \qquad (5)$$

P : Parameter of the pile section
f : Friction resistance between pile and soil
ΔL : Increment of pile length

Allowable Load, Q_{all}

After the total ultimate load-carrying capacity of a pile has been determined by summing the end bearing capacity and the frictional (or skin) resistance, a reasonable factor of safety should be used to obtain the total allowable load for each pile, or

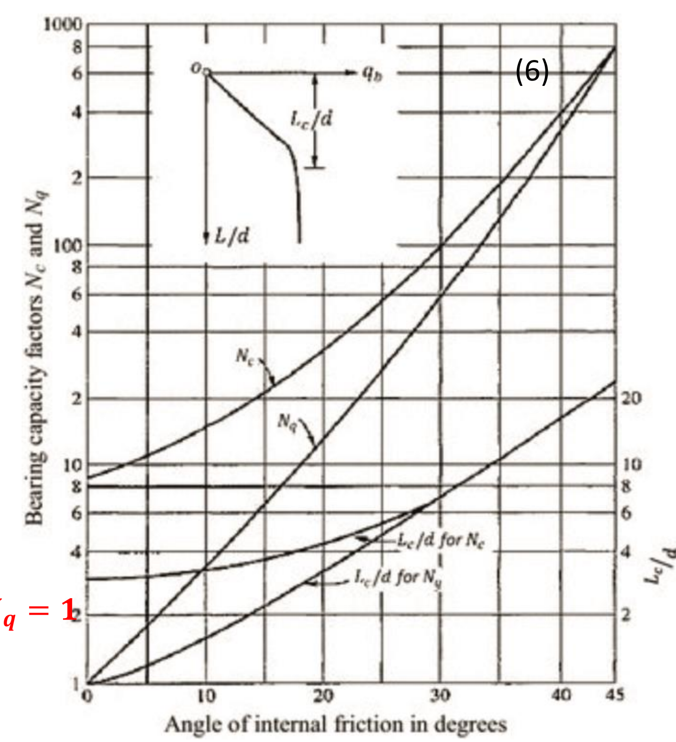
$$Q_{all} = \frac{Q_u}{F} \qquad (6)$$

F is the factor of safety

In sand $(\mathbf{C = 0})$

$Q_b = A_b q N_q^* \ \leq \ 0.5 P_{atm} N_q^* tan\emptyset A_b$

In Clay $(\boldsymbol{\emptyset = 0})$



Soil friction angle, ϕ (deg)	N_q^*
20	12.4
21	13.8
22	15.5
23	17.9
24	21.4
25	26.0
26	29.5
27	34.0
28	39.7
29	46.5
30	56.7
31	68.2
32	81.0
33	96.0
34	115.0
35	143.0
36	168.0
37	194.0
38	231.0
39	276.0
40	346.0
41	420.0
42	525.0
43	650.0
44	780.0
45	930.0

From the graph for $\boldsymbol{\emptyset = 0, N_C = 9, N_q = 1}$

$Q_b = A_b(CN_C^* + qN_q^*)$

$Q_b = A_b(9C + q)$

Example:

Consider a 15-m long concrete pile with a cross section of 0.45m*0.45m fully embedded in sand. For the sand, given: unit weight, 17 KN/m3; and soil friction angle, $\emptyset = 35$. Estimate the ultimate end bearing.

Ans:

$Q_b = A_b q N_q^* \leq A_b \; 0.5 P_{atm} N_q^* tan\emptyset$

$Q_b = A_b q N_q^* = 0.45 * 0.45 * 17 * 15m * 143 = 7{,}384 KN/m2$

$A_b 0.5 P_{atm} N_q^* tan\emptyset = 0.45 * 0.45 * 0.5 * 100KN/m2 * 143 * tan35 = 1014KN/m2$

Take $Q_b = 1014KN/m2$

Soil friction angle, ϕ (deg)	N_q^*
20	12.4
21	13.8
22	15.5
23	17.9
24	21.4
25	26.0
26	29.5
27	34.0
28	39.7
29	46.5
30	56.7
31	68.2
32	81.0
33	96.0
34	115.0
35	143.0
36	168.0
37	194.0
38	231.0
39	276.0
40	346.0
41	420.0
42	525.0
43	650.0
44	780.0
45	930.0

Example 11.2

Consider a pipe pile having an outside diameter of 406 mm.
The embedded length of the pile in layered saturated clay is 30 m.
The following are the details of the subsoil:

The groundwater table is located at a depth of 5 m below ground surface. Estimate Q_b by using Meyerhof's method.

Depth from ground surface (m)	Saturated unit weight, γ (kN/m^3)	c_u (kN/m^2)
0–5	18	30
5–10	18	30
10–30	19.6	100

Ans:

$Q_b = (9C + q)A_b$

$Q_{b=}$ (9*100+5*18+5*8+9.6*20)*$\frac{\pi}{4}(0.406)^2$ =158KN/m2

Q_b *in Sand by SPT*

$$\boldsymbol{q_b = 0.4 P_{atm} N \frac{L}{D} \quad \leq \quad 4 P_{atm} N}$$

Example:

Consider a concrete pile that is 0.305 m × 0.305 m in cross section in sand. The pile is 15.2 m long. The following are the variations of N_{60} with depth.

Depth below ground surface (m)	N_{60}
1.5	8
3.0	10
4.5	9
6.0	12
7.5	14
9.0	18
10.5	11
12.0	17
13.5	20
15.0	28
16.5	29
18.0	32
19.5	30
21.0	27

The tip of the pile is 15.2 m below the ground surface. For the pile, $D = 0.305m$. The average of 10*D* above and about 5*D* below the pile tip is:-

$$N = \frac{17+20+28+29}{4} = 23.5 \approx 24$$

$$\boldsymbol{Q_b = A_b q_b = A_b\left(0.4P_{atm}N\frac{L}{D}\right) = \frac{\pi*0.305^2}{4}(0.4*100KN/m2*24*\frac{15.2}{0.305}) = 3,495KN}$$

$$\boldsymbol{Q_b = A_b(4P_{atm}N) = \frac{\pi*0.305^2}{4}(4*100*24) = 701KN/m2}$$ **, so take it 701KN**

Q_S *in Sand*

The unit skin friction increases with depth more or less linearly to a depth of $\acute{L}$ and remains constant thereafter. The magnitude of
the critical depth may be 15 to 20 pile diameters. A conservative estimate would be

$\acute{L} \approx 15D$

For $z = 0 - \acute{L}$

$f = k\sigma tan\delta$

For $z = \acute{L} - L$

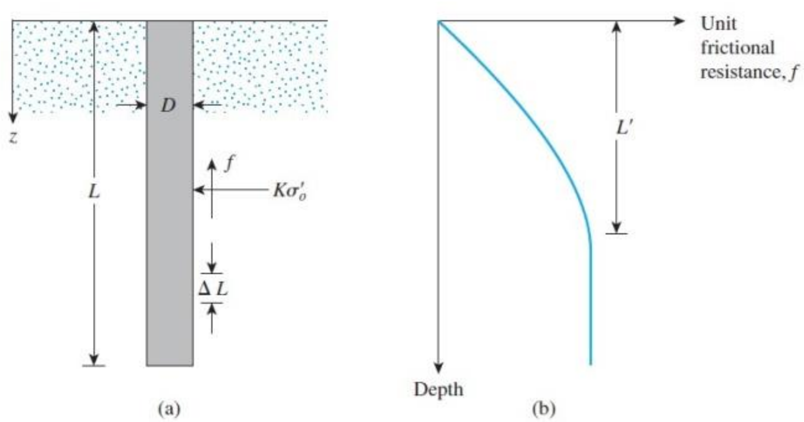
$f = f_{z=\acute{L}}$

$\delta = 0.8\emptyset$

$Q_s = K\sigma\tan(0.8\emptyset)PL$

H pile, K=1.65

Steel pile, K= 1.26



Precast pile , K = 1.5

Example:

Consider a 15-m long concrete pile with a cross section of 0.45m*0.45m fully embedded in sand. For the sand, given: unit weight, 17 KN/m3; and soil friction angle, $\emptyset = 35, K = 1.3$. Estimate Qs and Qu if F = 3.

$$\acute{L} \approx 15D = 15 * 0.45 = 6.75m$$
$$at\ z = 0,\ \ \sigma = 0\ and\ thus\ f_{z=0} = 0$$
$$at\ z = 6.75m, \sigma = 17 * 6.75 = 114.75$$
$$f = k\sigma tan\delta$$
$$f_{6.75} = 1.3 * 114.74 * \tan(0.8 * 35) = 79.3$$
$$f = \frac{0+79.3}{2} = 39.65$$
$$Qs_{0\ -6.75} = 39.65 * 0.45 * 4 * 6.75 = 481.7475KN$$
$$Qs_{6.75-15} = 79.3 * 4 * 0.45 * (15 - 6.75) = 1177.6KN$$
$$Q_s = 1659KN\ ,\ Q_b = 1014KN$$
$$Q_{all} = \frac{Q_u}{F} = \frac{Q_s+Q_b}{F} = \frac{1659+1014}{3} = 891KN$$

Skin friction in clay

The ultimate side resistance can thus be given as

$$\boldsymbol{Q_S = \sum \alpha CuP\Delta L}$$

$\boldsymbol{Cu}$ **: is the undrained cohesion**

$$\boldsymbol{\alpha = C(\frac{\sigma}{C_U})^{0.45}}$$

where

$\sigma = Average$ vertical effective stress

$C = 0.4 - 0.5$ for bored piles and > 0.5 for driven piles

Table 11.10 Variation of α (interpolated values based on Terzaghi, Peck and Mesri, 1996)

$\frac{c_u}{p_a}$	α
$\leq$ 0.1	1.00
0.2	0.92
0.3	0.82
0.4	0.74
0.6	0.62
0.8	0.54
1.0	0.48
1.2	0.42
1.4	0.40
1.6	0.38
1.8	0.36
2.0	0.35
2.4	0.34
2.8	0.34

Note: p_a = atmospheric pressure $\approx 100\ kN/m^2$

End bearing capacity of pile resting on rock

$$Q_{p(all)} = \frac{[q_{u(design)}(N_\phi + 1)]A_p}{FS}$$

$$\boldsymbol{N_\emptyset = tan^2(45 + \frac{\emptyset}{2})}$$

$\boldsymbol{q_u}$: ***Unconfined compression strength of rock***

$\emptyset$: **drained friction angle**

$$\boldsymbol{q_u design = \frac{q_u}{5}}$$

$$\boldsymbol{Q_{all} = \frac{[q_u design(N_\emptyset+1)]A_b}{F}}$$

Table 11.11 Typical Unconfined Compressive Strength of Rocks

Type of rock	q_u MN/m²
Sandstone	70–140
Limestone	105–210
Shale	35–70
Granite	140–210
Marble	60–70

Table 11.12 Typical Values of Angle of Friction ϕ' of Rocks

Type of rock	Angle of friction, ϕ' (deg)
Sandstone	27–45
Limestone	30–40
Shale	10–20
Granite	40–50

Let $q_u = 100\ Mpa = 100000\frac{KN}{m2}$ $for\ sand\ stone\ from\ table 11.11$**, and**

$\emptyset = 40\ frome\ table\ 11.12,\ \ , D = 0.3m$

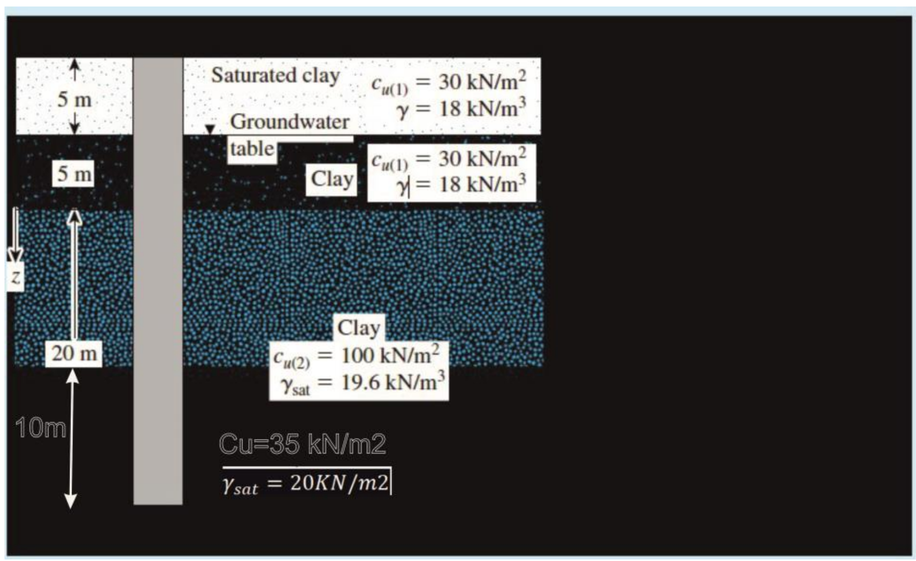
$$N_\emptyset = tan^2\left(45 + \frac{\emptyset}{2}\right) = 4.6\ ,$$

$$q_u design = \frac{q_u}{5} = \frac{100000KN/m2}{5} = 20000KN/m2$$

$$Q_{all} = \frac{[q_u design(N_\emptyset+1)]A_b}{Fs} = \frac{200000\ *\ (4.6+1)\ *\ \frac{\pi 0.3^2}{4}}{2} = 3958\ KN$$

Example:

Calculate pile capacity shown in the figure. The top 10 m of clay is normally consolidated. The pile diameter is D=0.406 m. The bottom layer is clay. F=3



$$Q_b = (9C_U + q)A_b$$

$$Q_b = (9 * 35 + 18 * 5 + 8 * 5 + 20 * 9.6 + 10 * 10)\frac{\pi 0.406^2}{4} = 737kN$$

$$Q_u = Q_s + Q_b$$

$$Q_u = 1885 + 737 = 2{,}622KN$$

$$Q_{all} = \frac{2622}{3} = 874\ KN$$

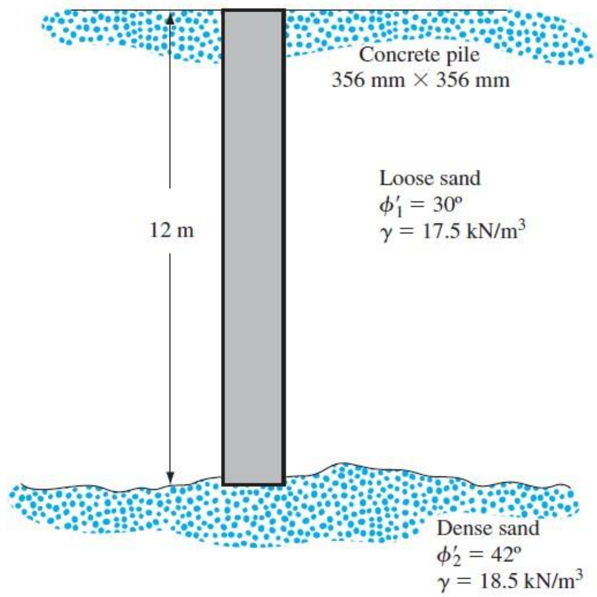
$$Q_s = \Sigma \alpha c_u p \Delta L$$

[*Note*: $p = \pi(0.406) = 1.275$m] Now the following table can be prepared.

Depth (m)	ΔL (m)	c_u (kN/m²)	α (Table 11.10)	$\alpha c_u p \Delta L$ (kN)
0–5	5	30	0.82	156.83
5–10	5	30	0.82	156.83
10–30	20	100	0.48	1224.0
30-40	10	35	0.78	348
				Qs=1885

Problems:

Problem1: A 12 m long concrete pile is shown in Fig.P1. Estimate the ultimate load Q_U. Use the allowable pile capacity Q_{all} if F = 4.



Problem2:

A driven closed-ended pile, circular in cross section, is shown in Fig.P4. Calculate the ultimate capacity Q_u. Estimate the allowable capacity, if F = 5, $\delta = 0.6\emptyset$

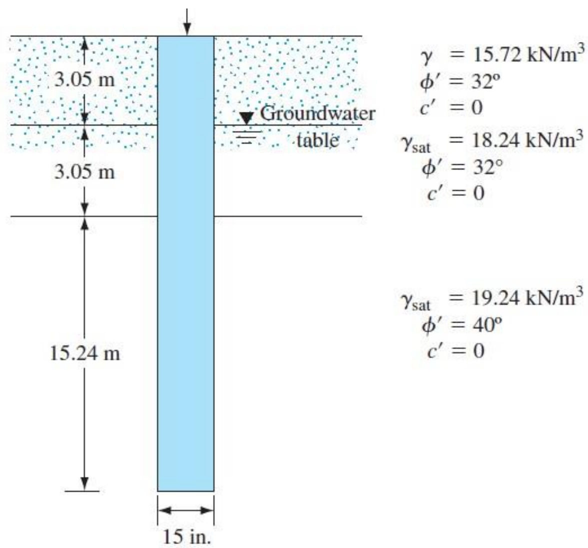


Fig.P4

Problem3

A concrete pile 406 mm * 406 mm in cross section is shown in Fig. P10. Calculate the ultimate skin friction resistance by using the α method

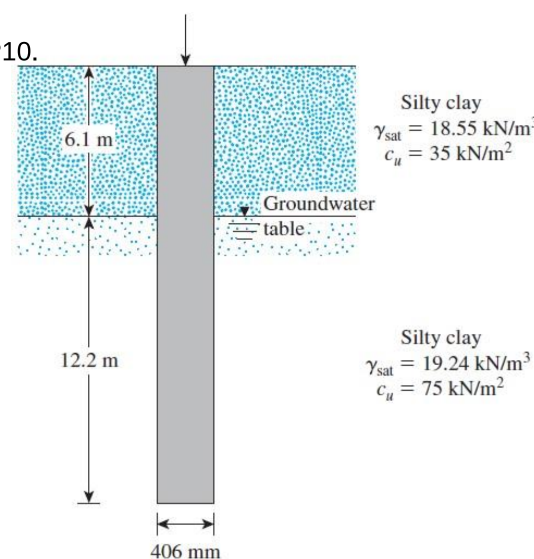


Fig.p10