

Foundations

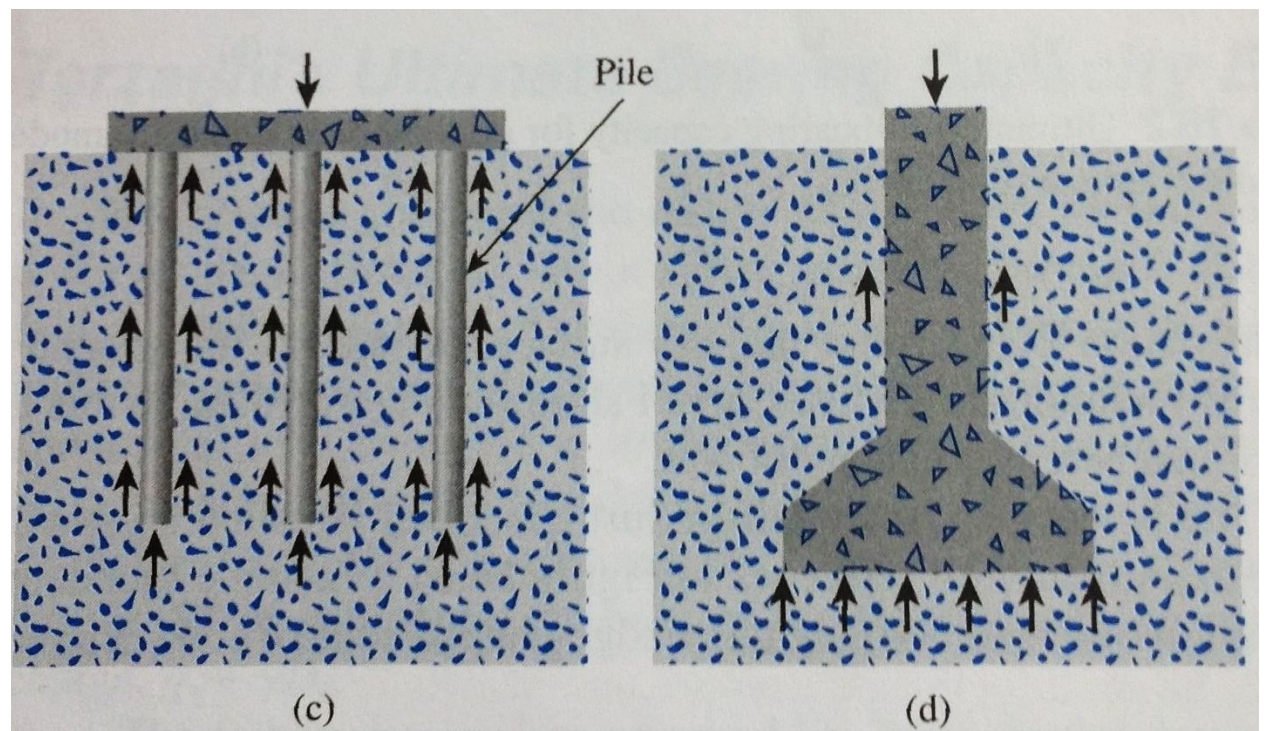
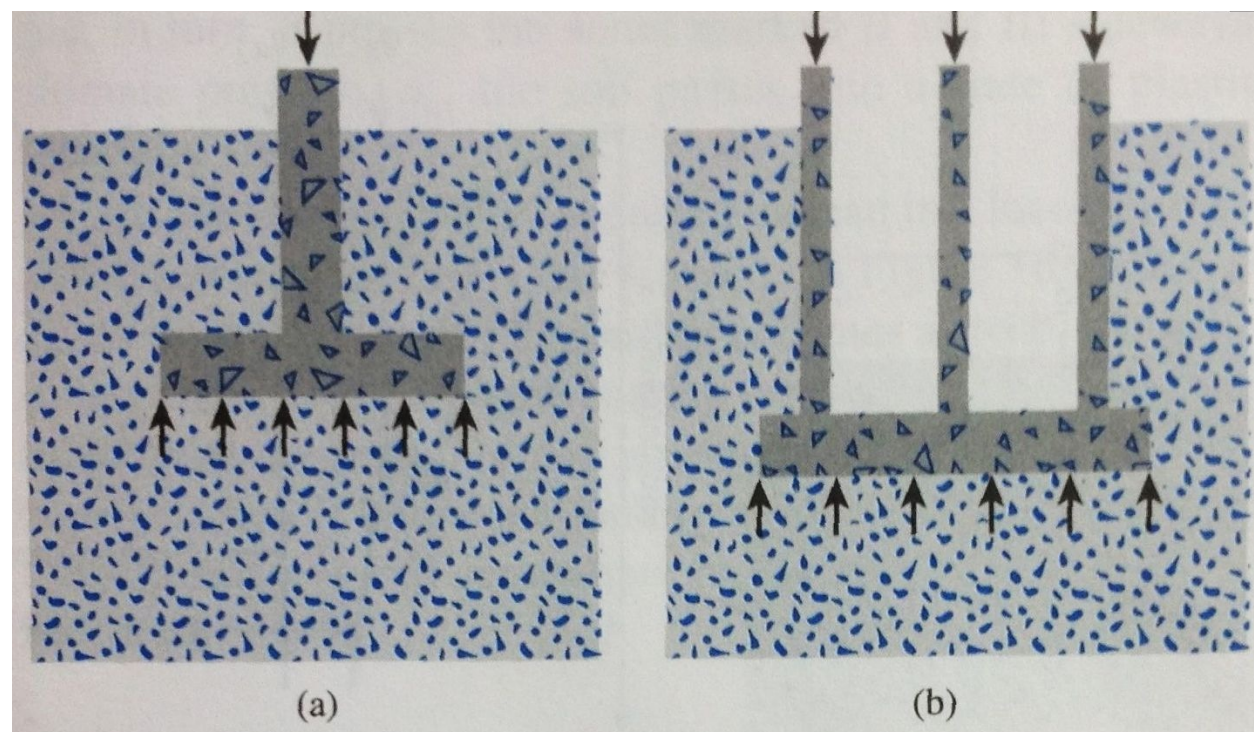
Text: Das, 2010. Chapter 16.

A properly designed foundation transfers the load through the soil without overstressing the soil, which can result in either excessive settlement or shear failure.

A wide range of different foundation types are in use:

- a) Spread footing
- b) Mat or raft foundation
- c) Pile foundation
- d) Drilled shaft foundation

In soils with low bearing capacity a simple spread footing is uneconomical: Mat foundations provide broad, shallow support to reduce soil stress. Piles and shafts use soil friction or bearing on deeper, stronger soil or rock layers. *Shallow foundations* are classified as having a depth to width ratio of less than 4, otherwise they are referred to as *deep foundations*.



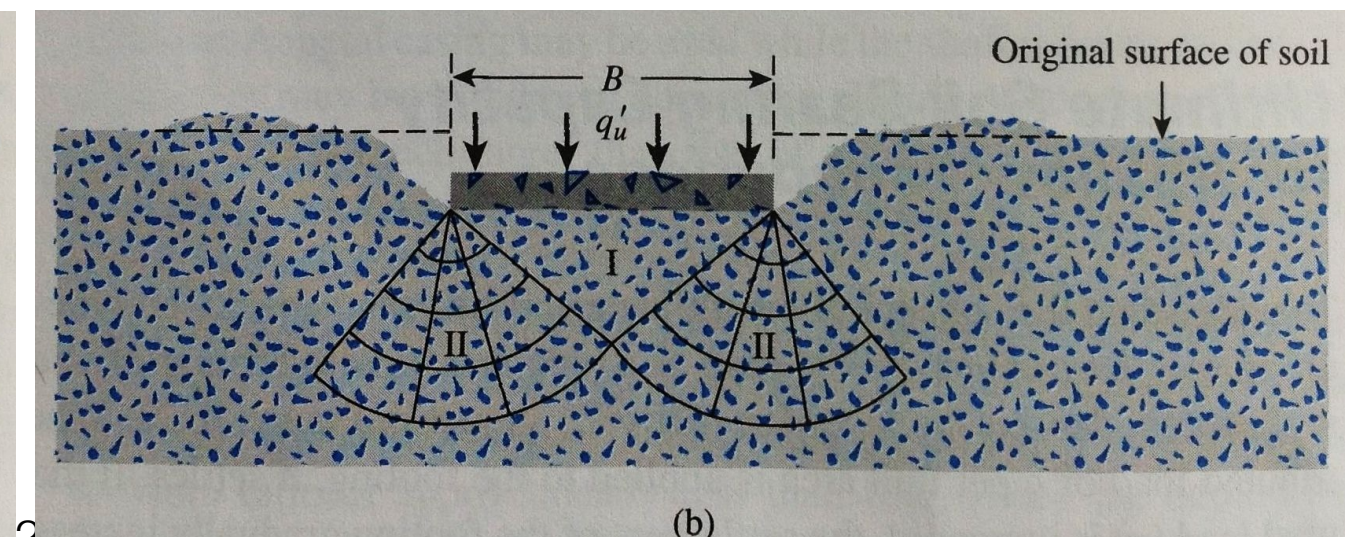
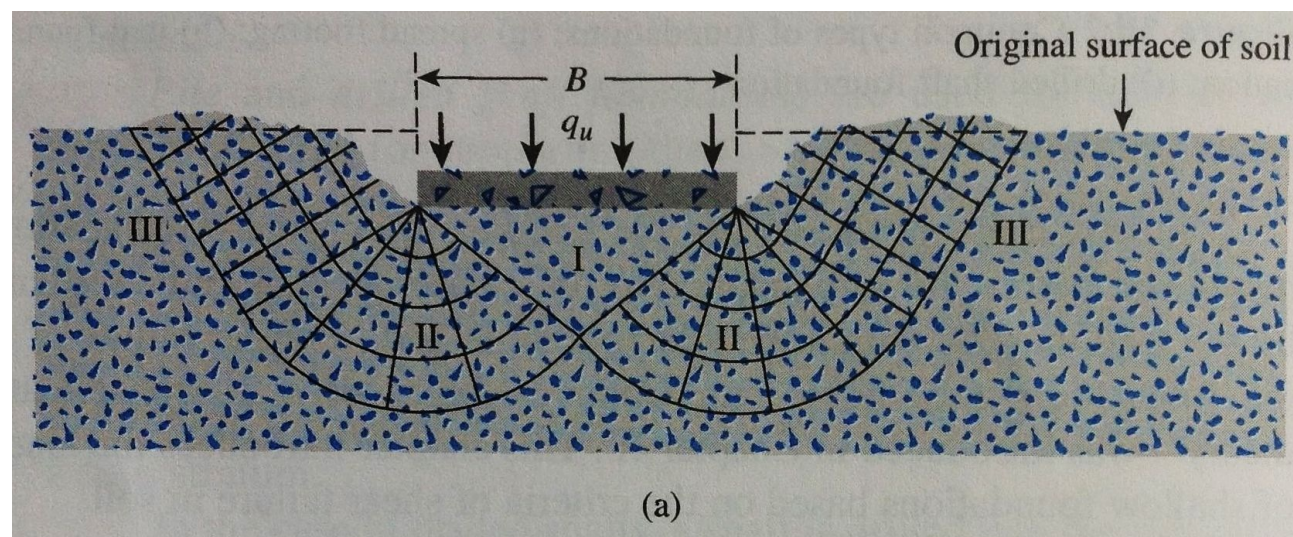
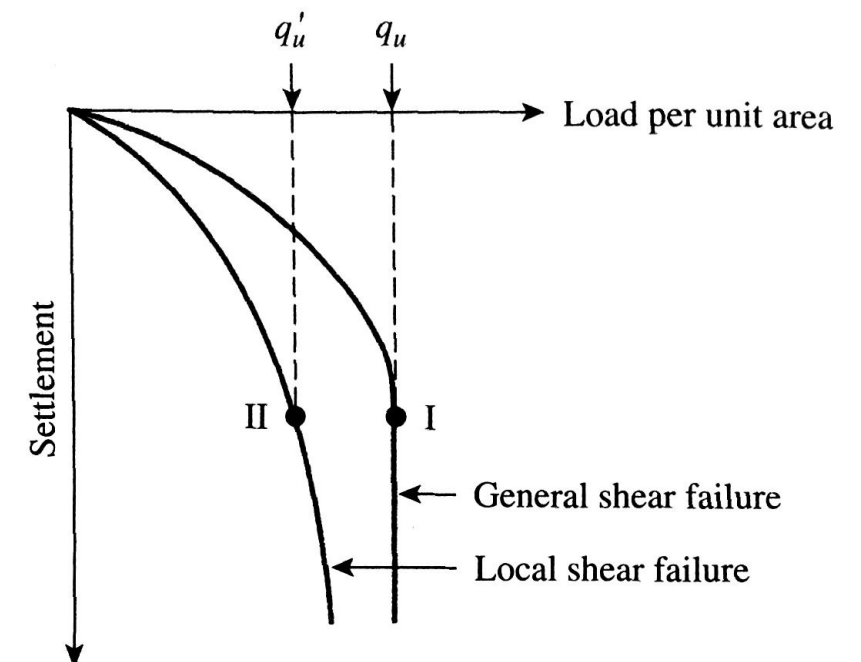
Ultimate Soil-Bearing Capacity: Shallow Foundations

When a uniformly distributed load q is applied to a footing, it settles elastically. As the load increases the settlement increases and becomes plastic.

When the value of $q = q_u$ (ultimate bearing capacity) is reached, the footing undergoes a large settlement with no increase in q .

At failure the soil on one or both sides of the foundation bulges and a slip surface develops. There are two types of failure:

- A. General slip failure: the slip surface extends to the ground surface and the foundation fails by a general movement of soil out of the way of the settling foundation.
- B. Local slip failure: the slip surface terminates at some depth in the soil and the foundation fails by "punching" shear; the soil compresses downwards and fails near the edge of the foundation but not at any distance from the edge.



Ultimate Soil-Bearing Capacity: Shallow Foundations

Soil bearing strength is determined by three main factors: the soil's density, its cohesion, and the effect of restraint by surcharge due to the foundation depth.

Additional factors are the shape of the footing, the type of failure (general or local), the drained or undrained condition of the soil and the presence or absence of water table.

The various factors are collected together in what is known as the *modified Terzaghi equation*:

$$q_u = k_c c' N_c + k_q q N_q + k_\gamma \gamma B N_\gamma$$

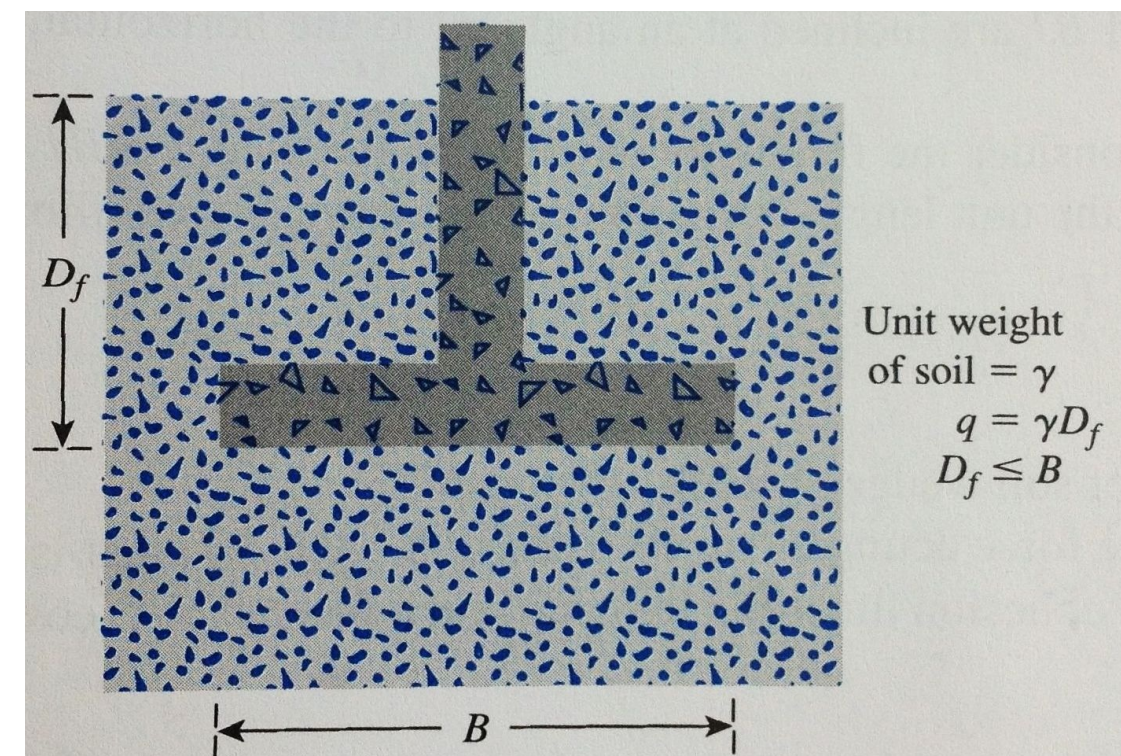
where the subscripts indicate components for cohesion (c), surcharge (q) and unit weight (γ). The 3 components use context-dependent multipliers (k) and empirical formulas (N).

The parameters of cohesion (c'), surcharge (q) and unit weight (γ) are as measured or designed. Generally $q = \gamma D_f$

B is the width or diameter of the footing. For shallow footings $D_f < B$

Depth and shape factors are also used but these are not essential. Eccentric loading of footings is beyond our scope and should be avoided.

The values of k and N are set out for the main design cases below:



Footing Shape and Failure Type

Multipliers/ footing types	k_c	k_q	k_γ
Rectangular or Strip footing	1	1	0.5
Square footing	1.3	1	0.4
Circular footing	1.3	1	0.3

Parameters/ failure types	c'	ϕ'
General failure	c' as measured	ϕ' as measured
Local failure	$\frac{2}{3}c'$	$\tan^{-1} \left(\frac{2}{3} \tan(\phi') \right)$

Drained/Undrained Condition

Factors/ Drainage	N_q	N_c	N_γ
Undrained	1	5.7	0
Drained	$e^{\pi \tan(\phi')} \tan^2 \left(45 + \frac{\phi'}{2} \right)$	$\frac{(N_q - 1)}{\tan(\phi')}$	$(N_q - 1) \tan(1.4\phi')$

The drained equations are the modern forms of Terzaghi's bearing capacity factors.
These can be read directly from Table 16.1 Das

The original forms of the equations can be evaluated as a check on your assumptions:

$$N_c = \frac{228 + 4.3\phi'}{40 - \phi'}$$

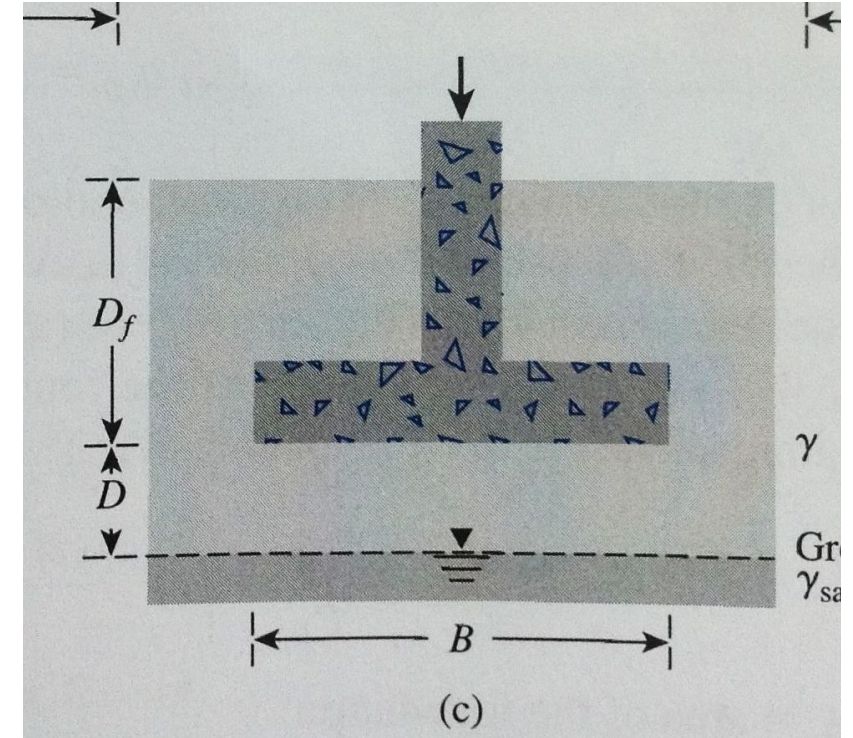
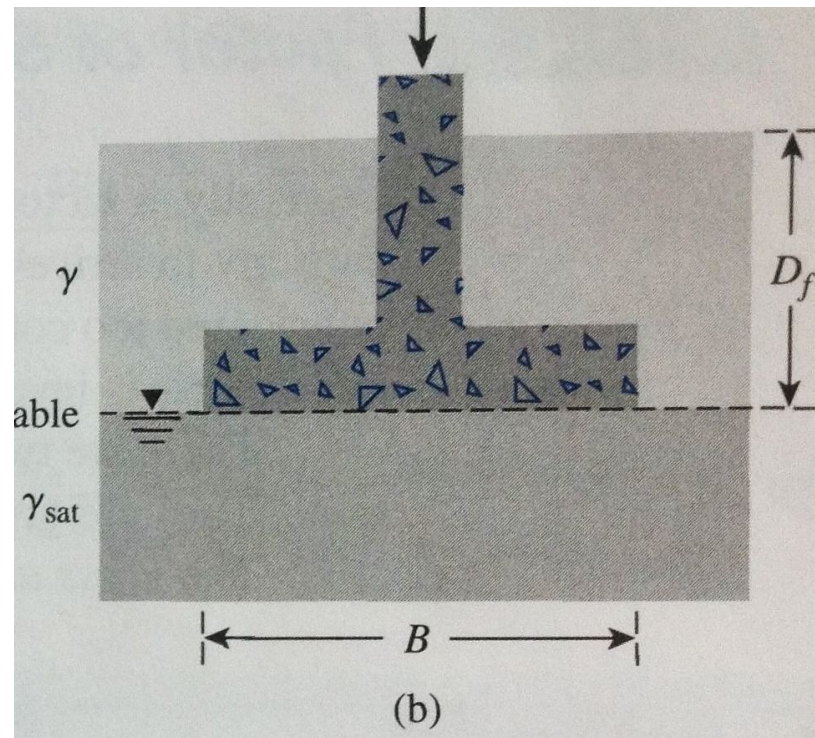
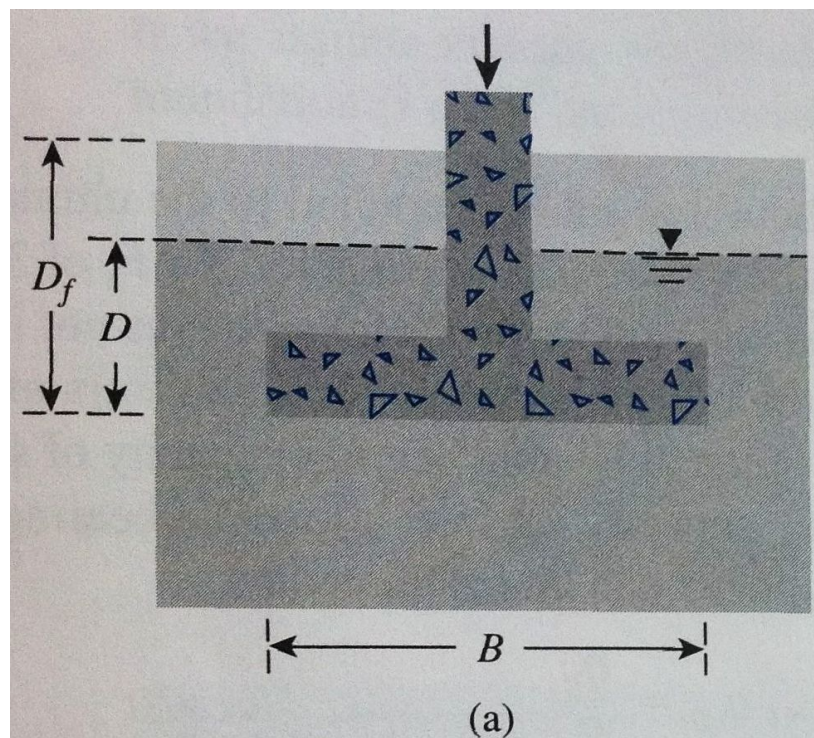
$$N_q = \frac{40 + 5\phi'}{40 - \phi'}$$

$$N_\gamma = \frac{6\phi'}{40 - \phi'}$$

Water Table

Water table case	Surcharge calculation q
a) above foundation	$\gamma(D_f - D) + \gamma' D$
b) at foundation	γD
c) below foundation	$\frac{1}{B} [\gamma D + \gamma'(B - D)] \quad (D \leq B)$
	$\gamma \quad (D > B)$

For cases a) and b) the bearing capacity equation uses effective unit weight as $k_v \gamma' B N_\gamma$. For case c) the bulk unit weight is used as $k_v \gamma B N_\gamma$



Bearing Capacity Safety Factors

Typically a safety factor F_s of about 3 or more is applied to the ultimate bearing capacity to arrive at the *allowable bearing capacity*.

This is not considered excessively conservative. A great deal of uncertainty remains in the measurement of shear strength parameters, the type and conditions of failure.

In addition it is common to subtract the pre-existing effective stress at the depth of the foundation before applying a safety factor. This reflects the effect of overconsolidation and allows for short- and long-term stress.

$$q_{all} = \frac{q_u - \gamma D_f}{F_s} \leq \frac{q_u - \gamma D_f}{3}$$

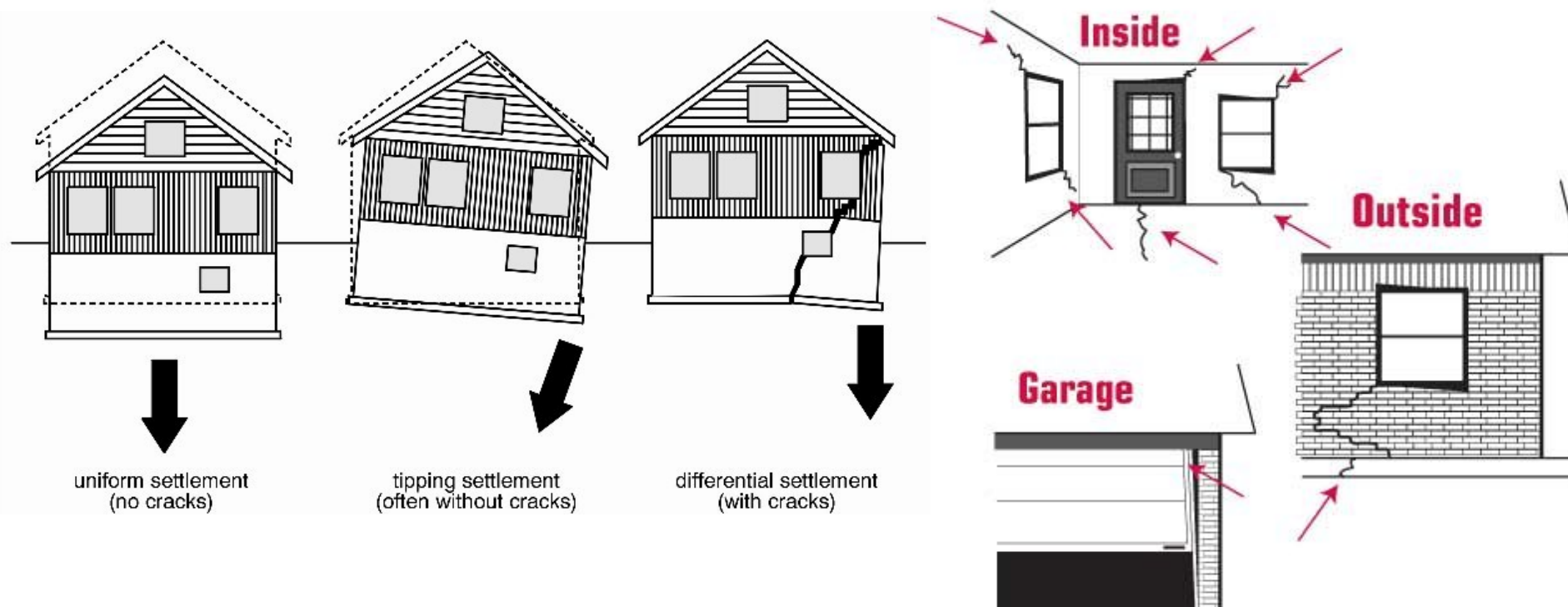


Plate-Load Test

In many cases conducting field load tests to determine soil bearing capacity is useful.

To conduct the test a pit of depth D_f is excavated on site at a typical location, at least four times the width of the bearing plate.

An incremental load is applied to the bearing plate and enough time is allowed between increments for settlement to occur.

A load-settlement graph is obtained. The point of ultimate failure may be a matter of judgment or selection as there is not necessarily a distinct threshold.

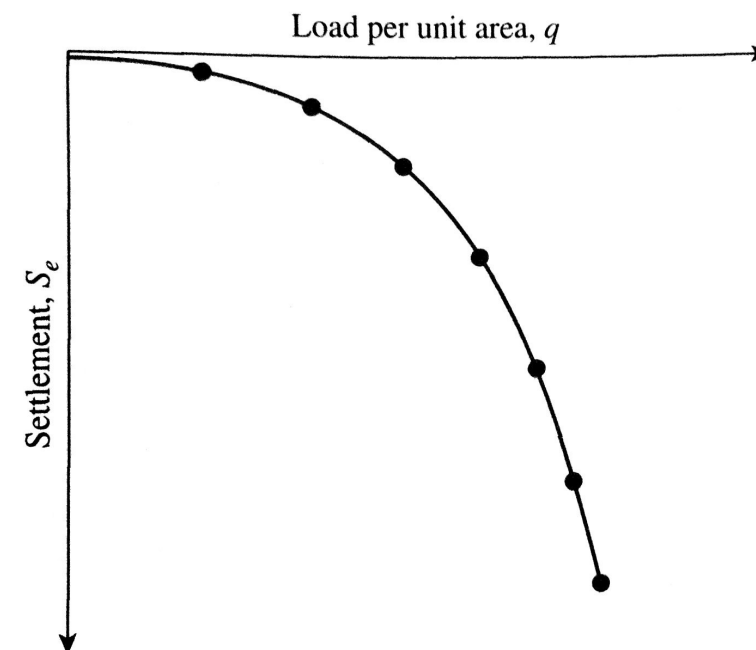
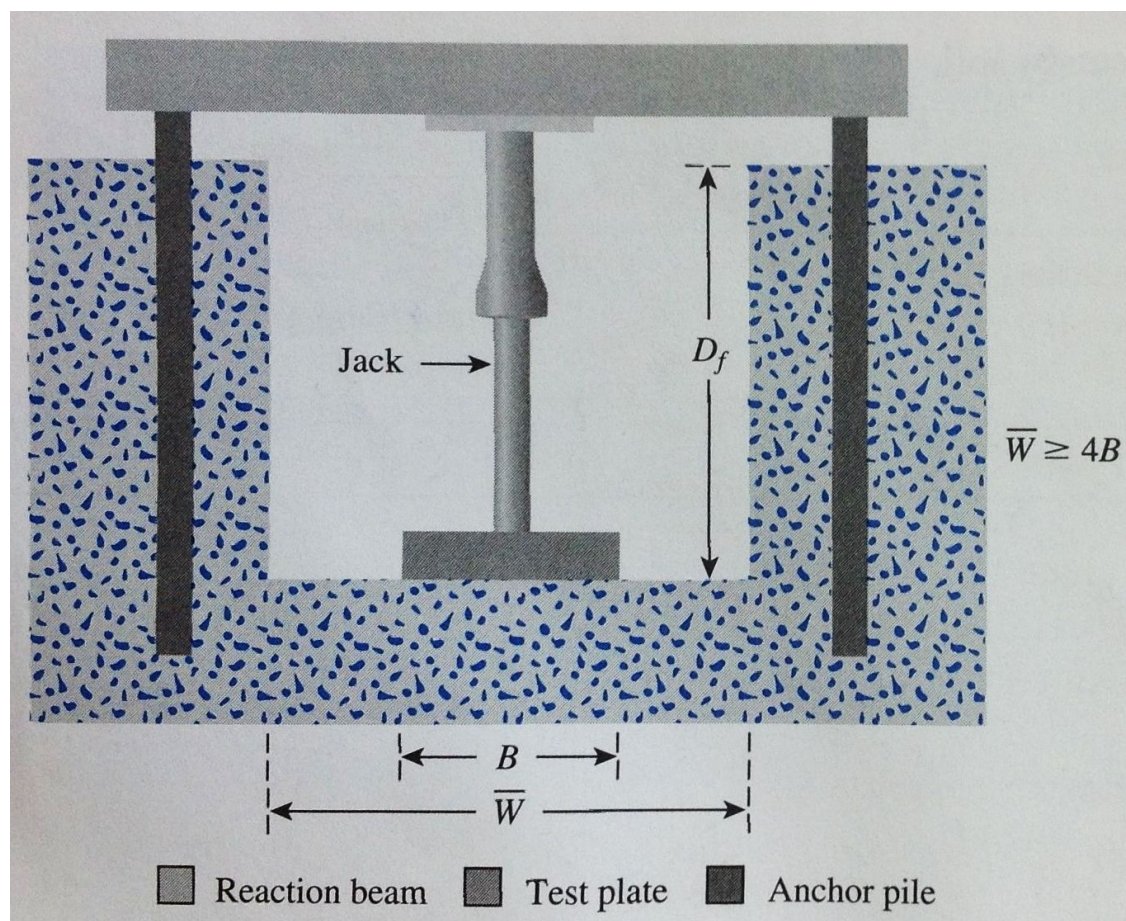


Plate-Load Test

The results depend on the type of soil:

Clay soil: $q_{u(footing)} = q_{u(plate)}$

$$S_{ettlement(footing)} = S_{ettlement(plate)} \frac{B_{footing}}{B_{plate}}$$

Sand soil: $q_{u(footing)} = q_{u(plate)} \frac{B_{footing}}{B_{plate}}$

$$S_{ettlement(footing)} = S_{ettlement(plate)} \left[\frac{2B_{footing}}{B_{footing} + B_{plate}} \right]^2$$



Pile Foundations

Smith, 1992 (Reading 13)

Pile foundations are a relatively expensive foundation and are generally only used when shallow foundations are not expected to perform satisfactorily, or special circumstances prevail.

The special circumstances usually cited for piling are:

- a) a weak soil overlying stronger soil
- b) very large loads in any principal direction
- c) expansive or collapsing soils
- d) specialised structures such as marine, bridge abutments etc.

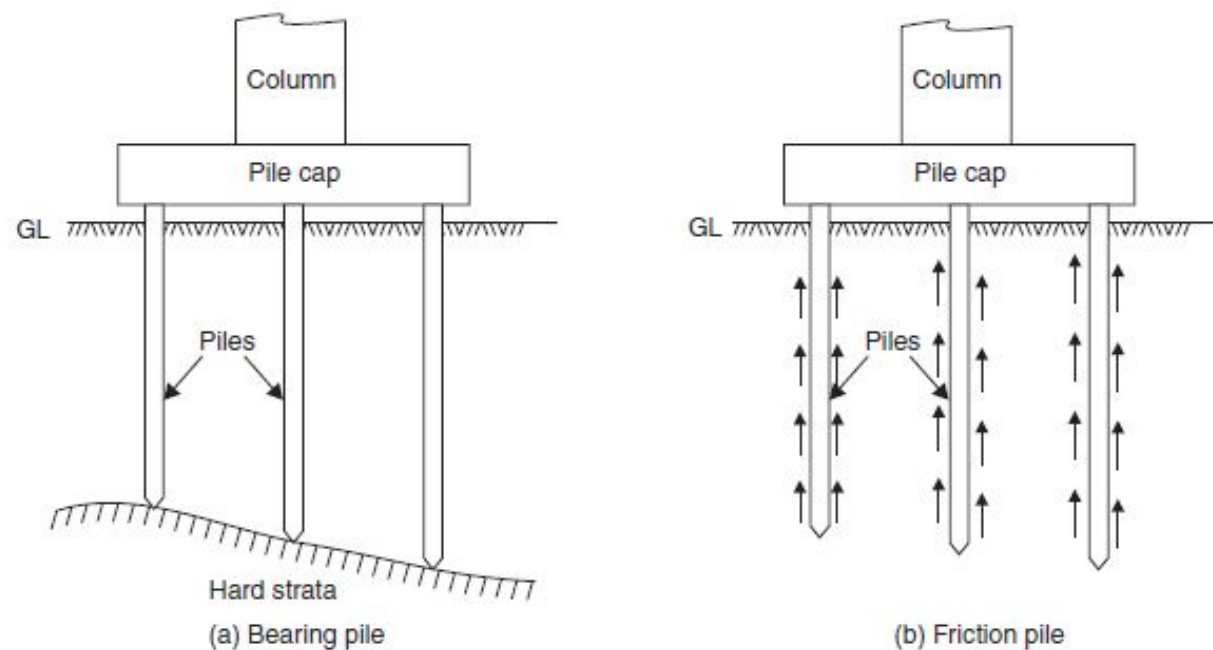
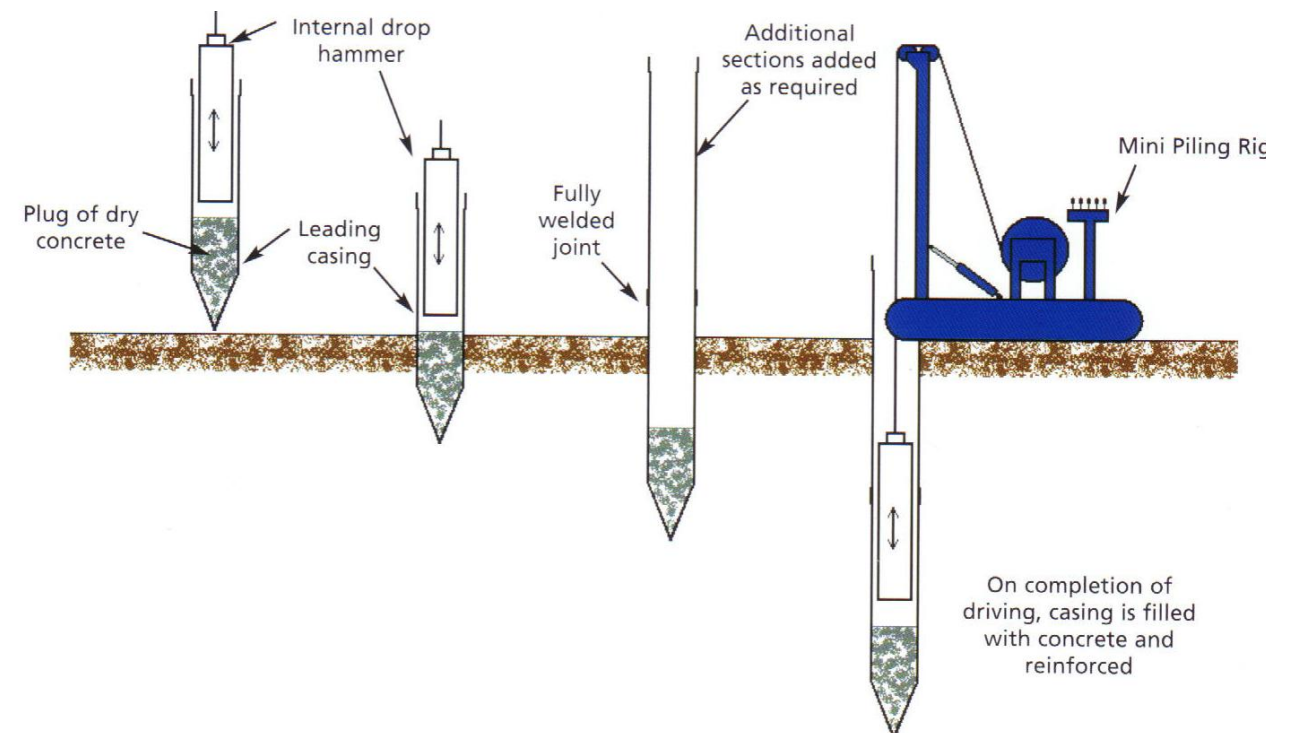


Fig. 7.9. Pile foundations

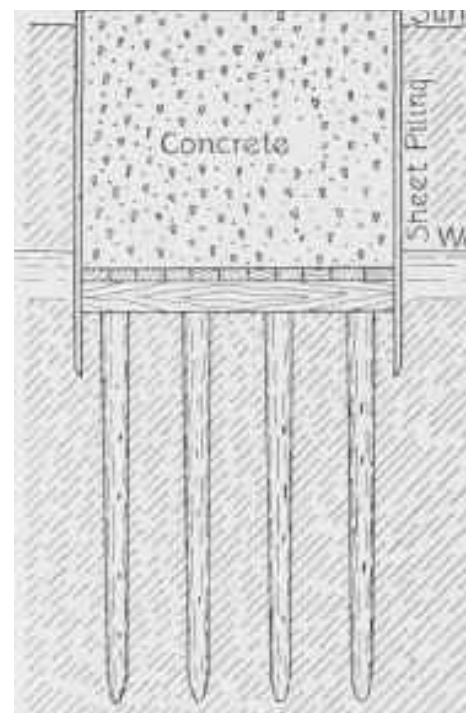
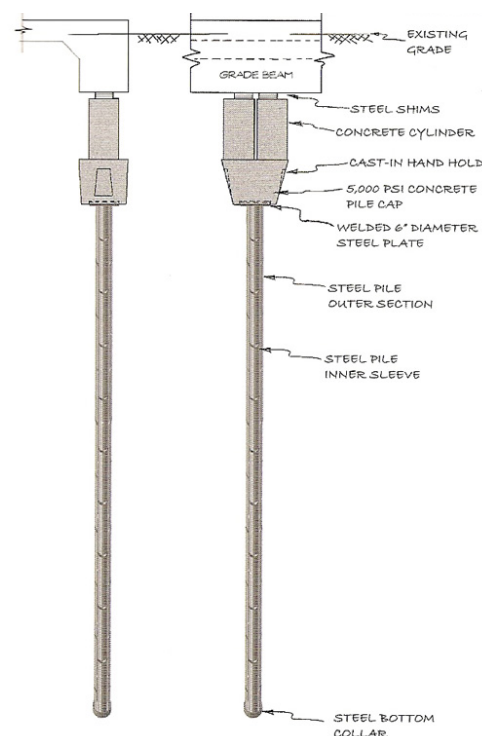


Types of Pile Foundations

Piles may be classified in a number of ways. Useful classifications are the construction material, load mechanism and construction method:

1. Material Types: Protected Steel, Reinforced Concrete or Treated Timber

- A. Steel, usually pipe or H section, or sheet pile for dewatering. Preferred for toughness and durability, especially with galvanic or cathodic protection.
- B. Reinforced or post-tensioned concrete, pre-cast or cast in-situ, often cast in a permanent steel casing. Cover is a very important aspect of durability of exposed uncased concrete
- C. Timber, particularly for low bearing loads eg domestic construction. Preservative treated, often with steel caps, shoes and bands to increase durability during installation driving.



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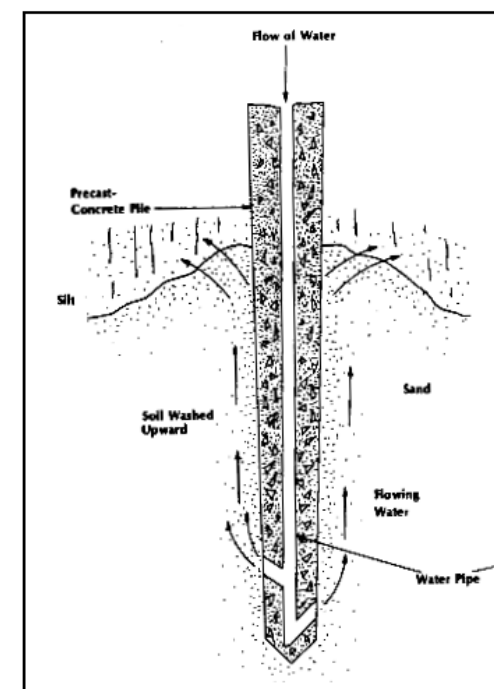


Figure 4-15 Precast concrete piles with internal setting pipes

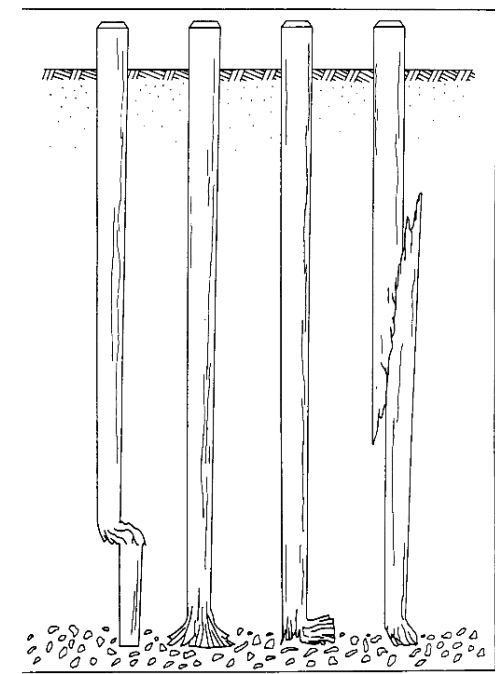


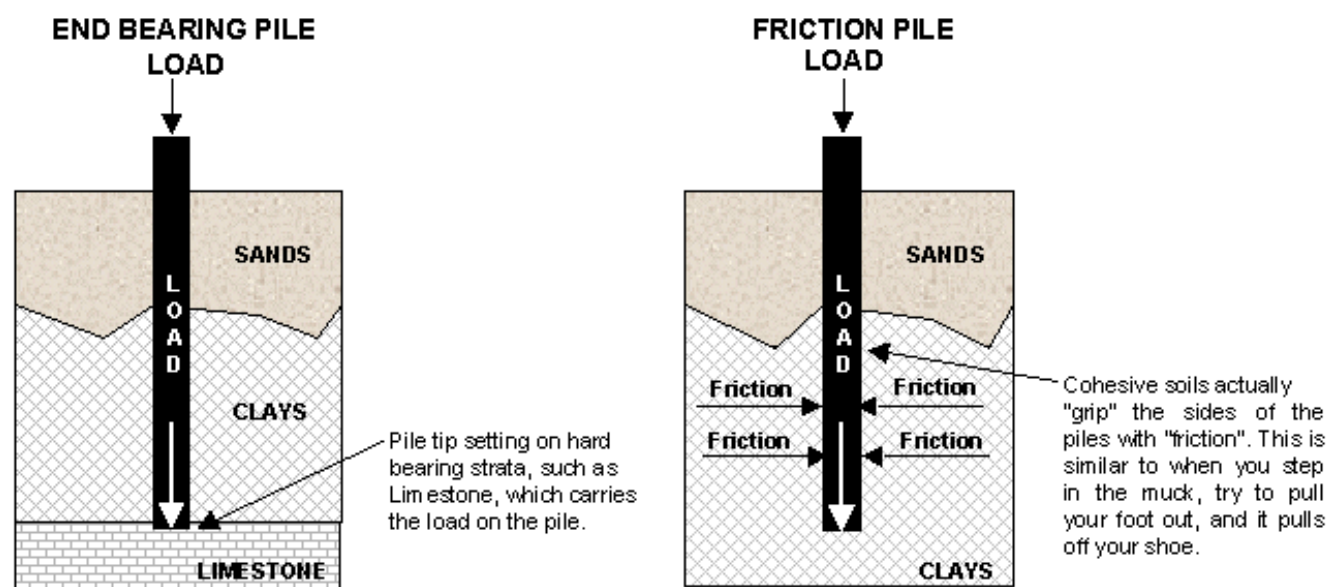
Figure 4-8 Types of damage to timber piles from overdriving

Types of Pile Foundations

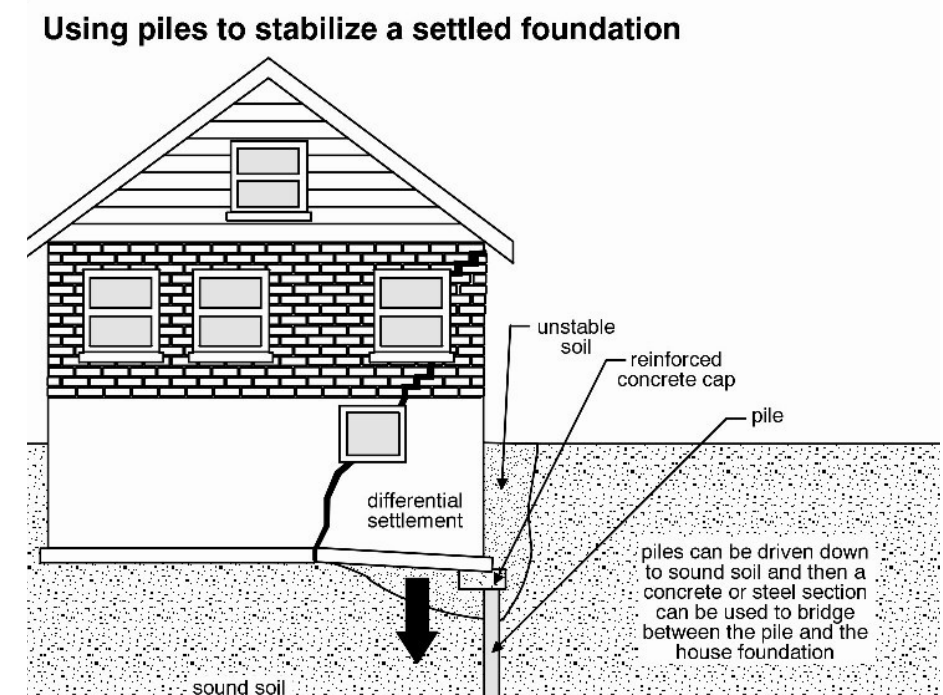
2. Load Carrying Mechanism: Friction-bearing or End-bearing

- A. Friction piles carry most of the load along the shaft of the pile, using contact adhesion and friction with lateral pressures due to displacement driving (nailing). Shaft adhesion is usually less than undrained cohesion, ie this is a fairly weak mechanism in clay.
- B. End-bearing piles carry most of the load at the base of the pile, ie they perform the role of a long, laterally braced column.

Piles may be used where significant uplift loads eg due to ocean currents occur. Uplift piles are always friction bearing.



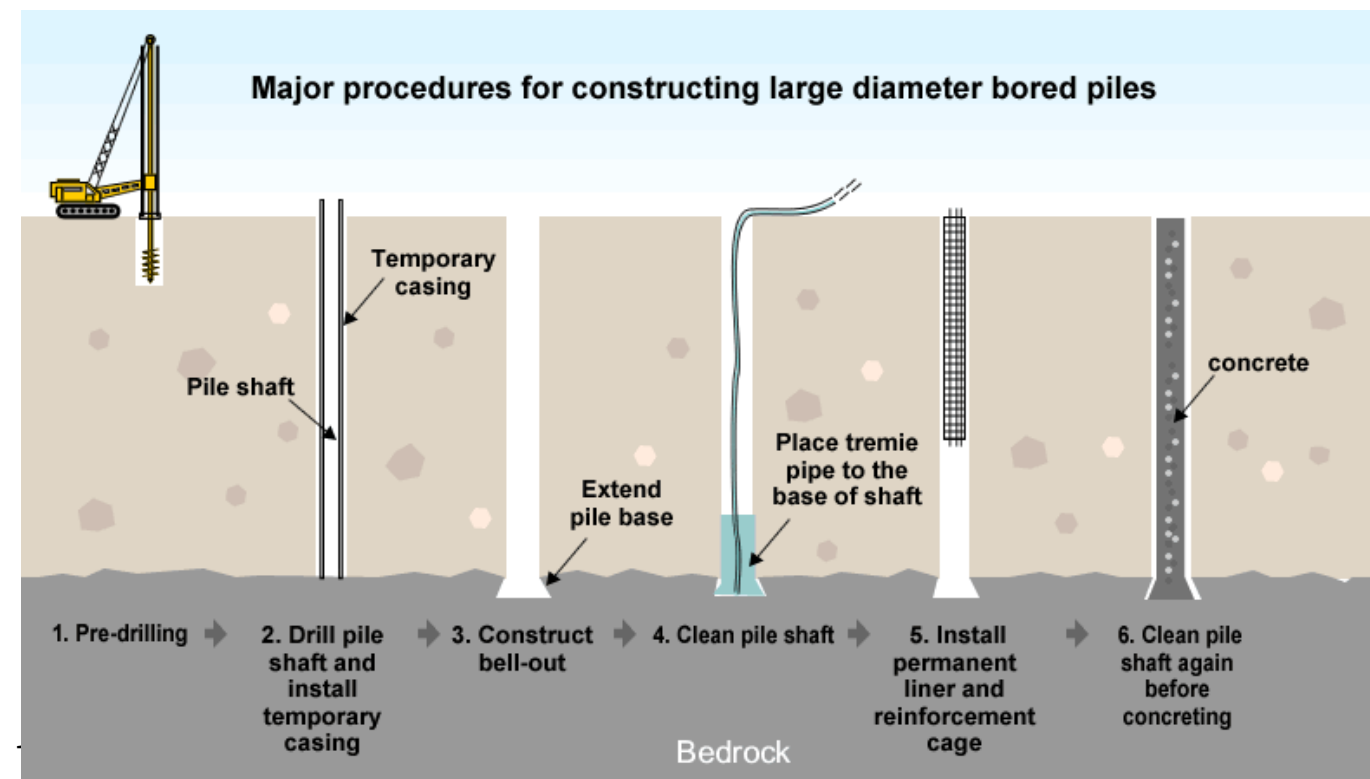
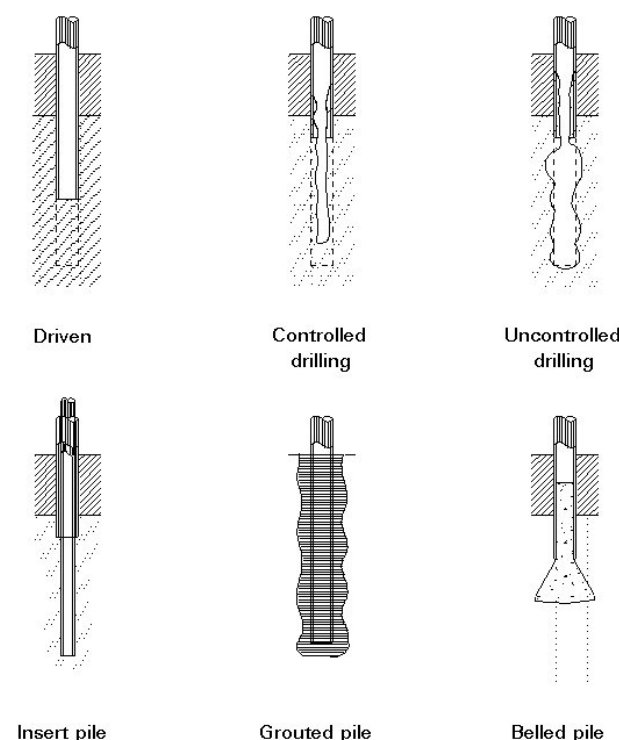
Common Pile Types



Types of Pile Foundations

3. Installation Methods: Driven or Bored

- A. Driven piles displace the soil laterally as the pile is inserted, producing a horizontal stress on the pile shaft. Soils are compacted and remoulded for 5 to 7 pile diameters, the higher range being for granular soils. This creates a larger effective friction between the pile and soil. In clay soils, excess pore water pressures due to remoulding dissipate slowly, leading to a gradual strength increase of driven piles in clay soils.
- B. Bored piles reduces horizontal stresses, so bored piles are typically weaker than similar driven piles. Density of soil around a bored pile decreases due to active lateral movement. Bored piles can be very large, and when so are referred to as *caissons*. Bored piles are typically designed for end-bearing rather than friction-bearing.



Pile Foundation Load Capacity

The ultimate load capacity of a pile (Q_u) is the sum of the shaft resistance (Q_{su}) and the base resistance (Q_{bu}) less the pile weight (W_p):

$$Q_u = Q_{su} + Q_{bu} - W_p$$

It is common practice to neglect the weight of the pile as this is usually quite small comparable to the design structural load.

The ultimate base resistance is taken directly from shallow foundation theory, modified for the depths and dimensions of a pile:

$$Q_{bu} = A_b(k_c^* c' N_c^* + k_q^* q N_q^* + k_\gamma^* \gamma B N_\gamma^*)$$

where A_b is the basal area of the pile. Starred * terms indicate deep as opposed to shallow foundations. Research is ongoing as to the form of these values.

The diameter B is small compared to other factors so the third term is often neglected.

Frictional resistance is estimated by integrating the variable shear stress along the length of a pile:

$$Q_{su} = C \int_0^L (K \sigma_v \tan(\delta) + c) dl$$

where C is the circumference, K is a lateral earth pressure coefficient and σ_v , δ and c are the drained or undrained strength parameters.

Pile Foundation Load Capacity

The ultimate load capacity of a pile does not increase indefinitely with length but reaches a limiting maximum value.

Surcharge restraint for example does not increase beyond a certain point.

Other mechanisms for limited pile bearing capacity are still the subject of research.

The limit is usually expressed as a critical depth z_c , which varies with soil density. The piling code AS2159 gives limits based on diameter. As a typical limit, the dimensionless ratio $z_c/B \sim 15$, ie strength does not increase beyond a depth of about 15 diameters.

When a pile is driven deeper than 20 diameters to reach end-bearing depth, it may be satisfactory to use "rule of thumb" values such as in the following table, or to develop site specific guidelines on the basis of strength developed by the first piles installed at a site.

<i>Relative density</i>	<i>Average unit skin friction (kN/m²)</i>
Less than 0.35 (loose)	10
0.35–0.65 (medium-dense)	10–25
0.65–0.85 (dense)	25–70
More than 0.85 (very dense)	70 to not more than 110

(Tomlinson, 1986)

Pile Foundation Load Capacity

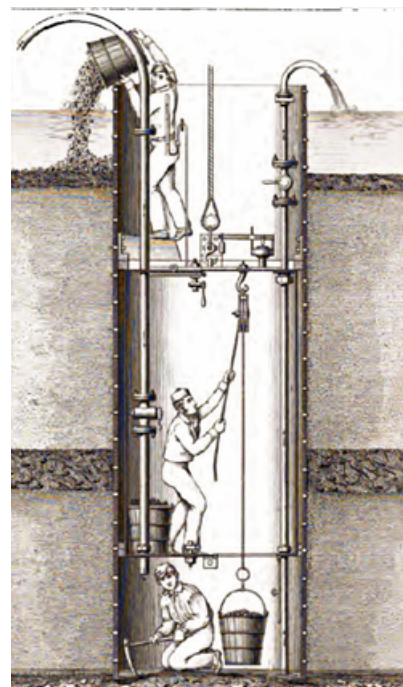
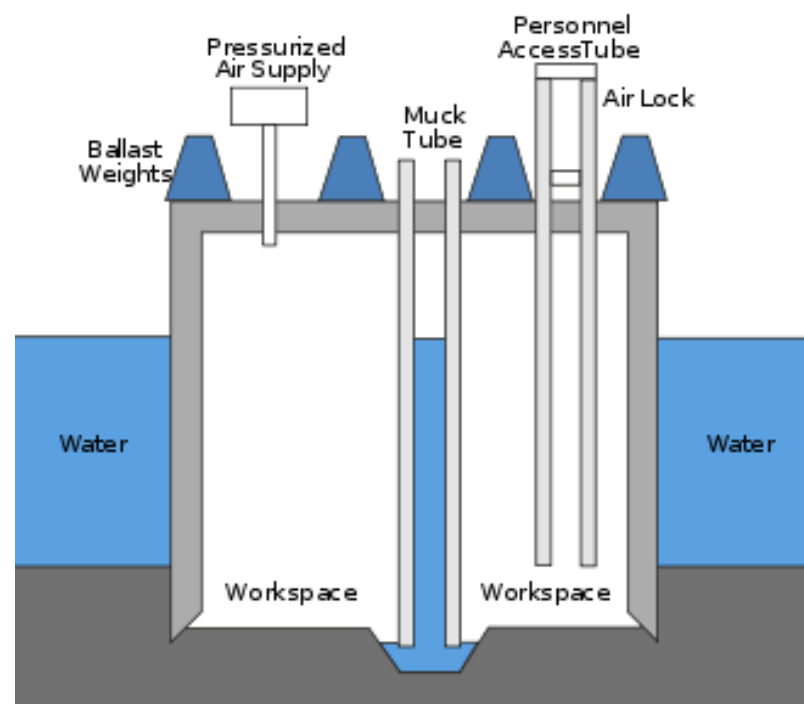
Granular soils tend to break down under pile driving stresses and can be greatly reduced in strength.

Rules of thumb cannot be used where there is any risk of major soil disruption during construction.

A slight inward taper (narrowing) on a pile can increase bearing capacity substantially. A taper of as little as 1 degree can increase strength 4-fold.

A useful rule of thumb that avoids questions of soil strength at depth is as articulated by Tomlinson (1986):

"the allowable working load on an isolated pile driven to virtual refusal (by normal driving equipment in a dense sand or gravel ... is given by the allowable load on the pile considered as a structural member rather than by consideration of failure of the supporting soil.



Pile driving remains a dangerous job under any conditions...

Readings

Chapter 16 Das

Smith, D.W. 1992. General Principles of Foundation Design (Reading 12)

Smith, D.W. 1992. Pile Foundations (Reading 13)

