Foundations

The foundation of a structure is in direct contact with the ground and transmits the load of the structure to the ground. Foundations may be characterised as **shallow** (pad, strip or raft) or **deep** (piles, piers or caissons). When designing foundations, two principal criteria must be satisfied:

Bearing capacity
There must be an adequate factor of safety against collapse (plastic yielding in the soil and catastrophic settlement or rotation of the structure).

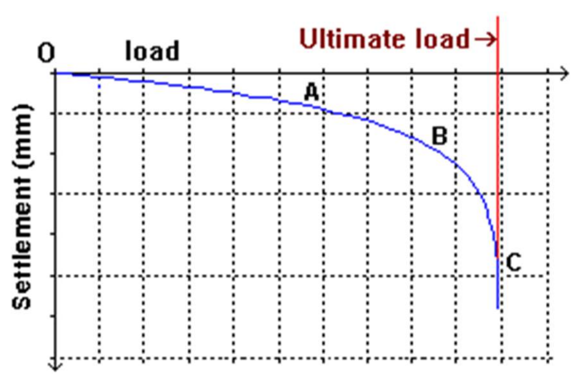
Settlement
Settlements at working loads must not cause damage, nor adversely affect the serviceability of the structure.

There are other considerations that may be relevant to specific soils, foundation types and surface conditions.

Foundations

Load-settlement behaviour

The application of a load on a foundation causes some settlement. The three main stages of the load-settlement curve are:



Relatively elastic vertical compression
(O-A) The load-settlement curve is almost straight.
Local shear failure
(B) Local yielding causes some upward and outward movement of the soil and results in slight surface heave.
General shear failure

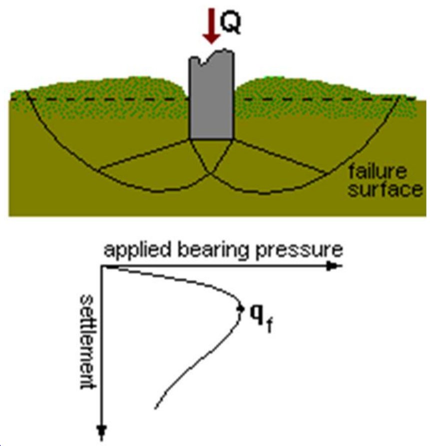
(C) Large settlements are produced as plastic yielding is fully developed within the soil.

Bearing capacity failure can occur in three different modes: general shear failure, local shear failure, or punching shear failure. Local or punching shear are characterised by relatively large settlements and the ultimate bearing capacity is not clearly defined. In these cases settlement is the major factor in the foundation design.

Load-settlement behaviour

General shear failure

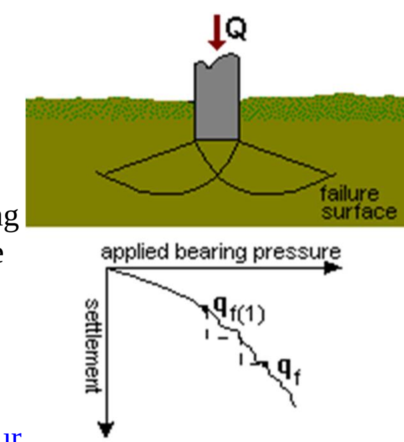
When a load (Q) is gradually applied on a foundation, settlement occurs which is almost elastic to begin with. At the ultimate load, **general shear failure** occurs when a plastic yield surface develops under the footing, extending outward and upward to the ground surface, and catastrophic settlement and/or rotation of the foundation occurs. The load per unit area at this point is called the **ultimate bearing capacity** (q_f) of the foundation.



Load-settlement behaviour

Local shear failure

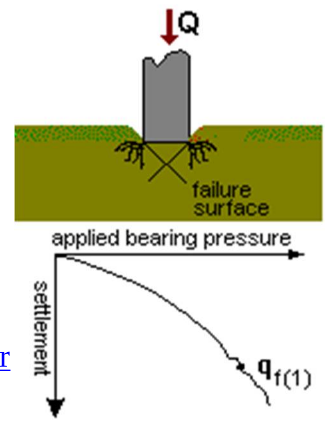
In moderately compressible soils, and soils of medium relative density, significant vertical settlement may take place due to **local shear failure**, i.e. yielding close to the lower edges of the footing. The yield surfaces often do not reach the surface. Several yield developments may occur accompanied by settlement in a series of jerks. The bearing pressure at which the first yield takes place is referred to as the **first-failure pressure** **($q_{f(1)}$)** - the term first-failure load ($Q_{f(1)}$) is also used.



Load-settlement behaviour

Punching shear failure

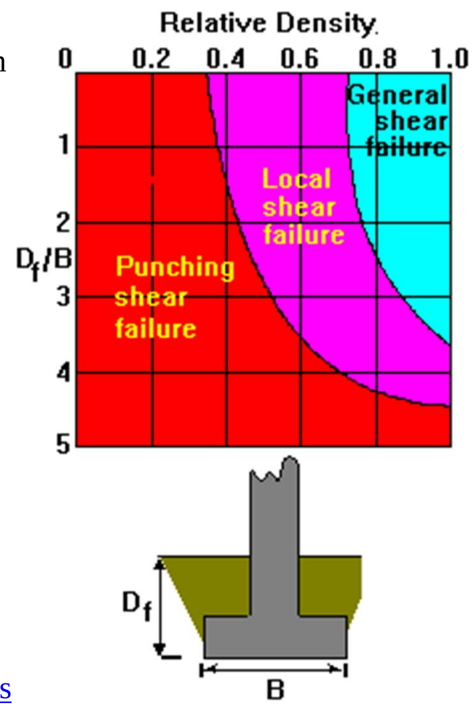
In weak compressible soils, and soils of low relative density, considerable vertical settlement may take place with the yield surfaces restricted to vertical planes immediately adjacent to the sides of the foundation; the ground surface may be dragged down. After the first yield has occured the load-settlement curve will steepen slightly, but remain fairly flat. This is referred to as a **punching shear failure.**



Load-settlement behaviour

Factors affecting modes of failure

According to experimental results from foundations resting on sands (Vesic, 1973), the mode of failure likely to occur in any situation depends on the size of the foundation and the relative density of the soil.



Other factors might be:

permeability: relating to drained/undrained behaviour
compressibility: similar to RD
shape: e.g. strips can only rotate one way
interaction between adjacent foundations and other structures
relative stiffnesses of soil and footing/structure
incidence and relative magnitude of horizontal loadings or moments
presence of stiffer or weaker underlying layers.

Foundations

Settlement

- Total and differential settlement criteria
- Imposed stress distribution below foundations
- Settlements on clays and silty clays
- Settlements on sands and gravels

The are **three** components making up the final settlement quantity:

Immediate settlement (ρ_i)
· elastic deformation with no change in water content
· occurs rapidly during the application of load

· quite small quantity in dense sands/gravels and stiff/hard clays

Consolidation settlement (ρ_c)

· decrease in voids volume as porewater is squeezed out of the soil
· occurs slowly according to the permeability
· only significant in clays and silts

Secondary settlement or creep (ρ_a)

· due to gradual changes in the particulate structure of the soil
· occurs very slowly, long after consolidation is completed
· most significant in soft organic soils and peats

Thus, **final settlement,** $\rho = \rho_i + r_c + r_a$

Reliable predictions of settlement require a thorough assessment of ground conditions, including measurements of soil properties. Extensive ground investigations and statistically-reliable testing programmes can be expensive and time-consuming, and thus not economically viable for the routine design of shallow foundations.

Settlement

Total and differential settlement criteria

- Definitions of quantities
- Cracking and ease of repair

The principal undesirable effects of settlement in buildings are cracking due to angular distortion; tilting due to differential settlement and excessive downward displacement. The settlement of foundations must be limited to satisfy three main sets of criteria:

Cracking or tilting that affects visual appearance

· cracking damage can be related to the ease of repair
· a vertical tilt (w) of > 1/250 is unpleasantly noticeable
· horizontal dveviation of >1/100 and deflection/span ratos are also noticeable

Cracking or other damage that adversely affects serviceability

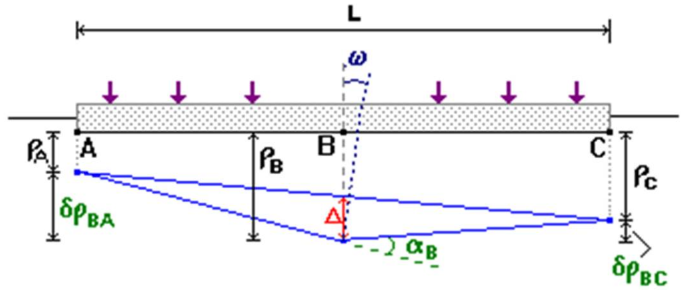
· cracking of wall and floor components can affect serviceability and be costly to repair
· differential displacements may affect the functionality of lifts, conveyors, cranes, internal traffic movement, aligment of drains, etc.

Damage that affects structural integrity or stability

· Angular distortion (Δ/L) in the foundation produces consequential distortion and increases in stresses in the structure above
· Structural damage is unlikely to occur if Δ/L is < 1/150
· Values of Δ/L > 1/1000 can cause cracking and overstressing.

Total and differential settlement criteria

Definitions of quantities



The following definitions and quantities have been suggested by Burland and Wroth (1975):
Settlement (ρ or s): the downward displacement of a point in a foundation
Differential settlement (δρ) the displacment of one point with respect to another
e.g $\delta\rho_{BA}$ = displacement of B with respect to A = $\rho_B - \rho_A$
Angular strain (α): the change in slope from horizontal at a point
Tilt angle (ω): the vertical angle of displacement of a unit of structure
Relative deflection (Δ): maximum displacement between two points relative to a straight line drawn between them
Angular distortion (Δ/L): the ratio of the relative deflection between two points and the horizontal distance between them
Sagging occurs when the relative deflection is downward, i.e. Δ is +ve
Hogging occurs when the relative deflection is upward, i.e. Δ is -ve

---

Total and differential settlement criteria

Cracking and ease of repair

Jennings and Kerrich (1962) proposed a classification of damage due to the cracking based on the ease of repair.

degree of damage	type of damage	crack width (mm)
0 negligible	Barely visible or none	< 0.1
1 very slight	Fine cracks repairable by normal decoration	1-5
2 slight	Cracks easily filled, may be visible externally. Doors & windows stick slightly	>5
3 moderate	Cracks need raking out & filled by a mason Doors & windows sticking Services fractured; water	5-15 (more than 3)

	ingress	
4 severe	Breaking out & replacing of masonry; floors sloping; walls leaning/bulging; doors & windows not functioning; floor beams displaced; services disrupted, serious water ingress	15-25 (depends on number)
5 very severe	Rebuilding or major repair required; beams lose bearing; walls require shoring; danger of instability or collapse.	>25 (depends on number)

Settlements on clay

Imposed stress distribution below foundations

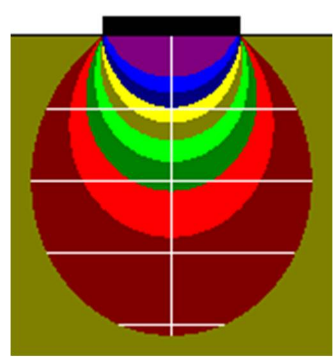
- Boussinesq's solution
- Circular foundation
- Strip foundation
- Rectangular foundation
- Approximate methods

The distribution of stresses in the ground under a foundation due to applied loading is not uniform. Changes in vertical stress decrease with both depth and horizontal distance from the load; but can be predicted with reasonable accuracy using elasticity theory (and sometimes simpler approximate methods).

Imposed stress distribution below foundations

Boussinesq's solution

According to Boussinesq (1885), the vertical stress $\Delta\sigma_v$ in the ground due to a point load Q is



$$\Delta\sigma_v = \frac{3Q}{2\pi z^2} \cdot I_P$$

$$I_P = \frac{1}{[1 + (r/z)^2]^{5/2}}$$

where z is the depth below the load and r is the horizontal distance from the load.

Simple solutions are available for stresses below strip footings, below the centre of circular footings and below a **corner** of a rectangular footing. The latter can be used to calculate the stress at any point by dividing the rectangle into two or more rectangles and summing the stresses due to each part. For example, to find the stress under the centre of a (B x L) rectangular base, find the stress under the corner of a (1/2B x 1/2L) rectangle, then multiply by 4.

[Imposed stress distribution below foundations]

Stress below a circular foundation

The vertical stress at a depth **z** below the **centre** of circular base of radius **R** is
$\Delta\sigma_v = q\ .I_c$
where q is the bearing pressure and

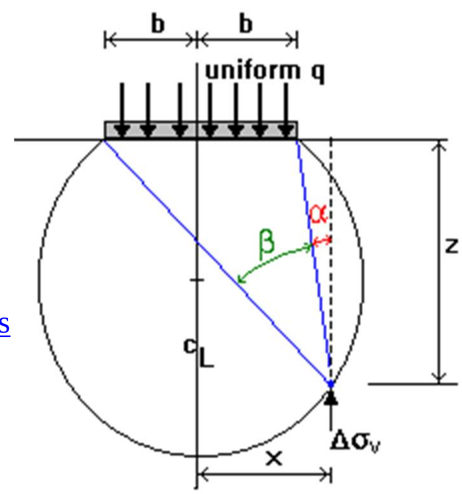
$$I_c = 1 - \frac{1}{[1 + (R/z)^2]^{3/2}}$$

The stress value below the centre is a maximum for a given depth. The expressions for stresses off-centre are much more complex. Over deep soil layers, the average value will be between 0.85 and 0.6 of the centre-line value according to the stiffness of the footing.

[Imposed stress distribution below foundations]

Stress below a strip foundation

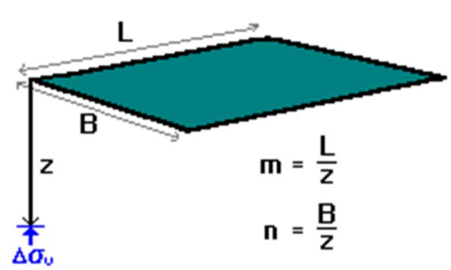
The vertical stress at a depth **z** below a uniformly loaded strip footing of width **B=2b** is
$\Delta\sigma_v = q\ .I_s$
where q is the bearing pressure and
$I_s = [\beta + \sin\beta.\cos(\ \beta + 2\ \alpha)\ ] / \pi$



[Imposed stress distribution below foundations]

Stress below a rectangular foundation

The vertical stress at a depth **z** below the corner of a rectangular subject to uniform pressure is



$\Delta\sigma_v = q.\ I_R$
where q is the bearing pressure and

$$I_R = \frac{1}{4\pi}\left[\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+m^2n^2+1}\left(\frac{m^2+n^2+2}{m^2+n^2+1}\right) + \tan^{-1}\left(\frac{2mn\sqrt{m^2+n^2+1}}{m^2+n^2+m^2n^2+1}\right)\right]$$

Imposed stress distribution below foundations

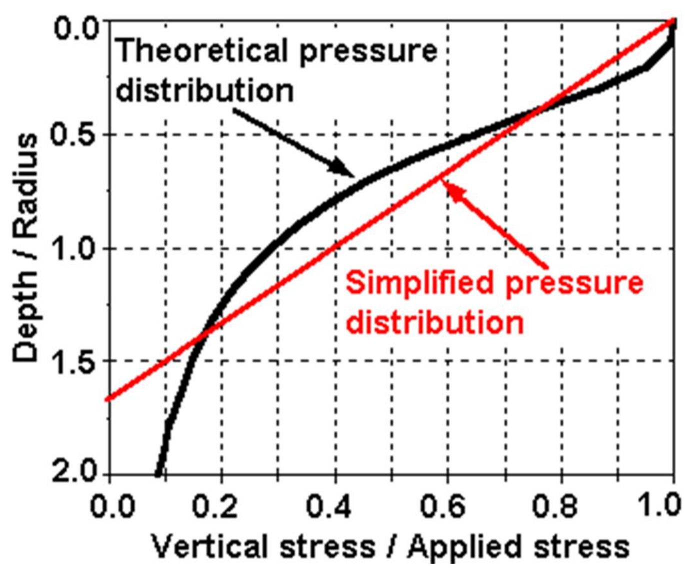
Approximate methods

For settlement calculations (but not necessarily for other geotechnical problems), sufficient accuracy is usually obtained by assuming a simplified pressure distributuion. The two methods given below are in common use.

Tomlinson's method
Tomlinson suggests using an approximate pressure distribution
for small foundations on stiff clay:

Settlement, ρ = (1.5 B) x (0.55 q_n) x m_v

where
B is the breadth of the foundation
q_n is the net bearing pressure



2 : 1 distribution method
The vertical stress on horizontal planes is assumed to remain uniform, but decrease linearly with depth below the foundation, thus:

For a strip footing: $\Delta\sigma_z = \dfrac{q_n B}{B + z}$

For a rectangular footing: $\Delta\sigma_z = \dfrac{q_n BL}{(B + z)(L + z)}$

where: q_n = applied net bearing pressure
B = breadth,

L = length
z = depth from underside of footing

Settlement

Settlements on clays and silty clays

- Calculation of immediate settlement
- Calculation of consolidation settlement

Settlements are time-dependent and may take several years to complete. The soil properties are obtained principally from laboratory tests. Relative proportions of final settlement that occur as immediate and consolidation settlement vary according to the stress history and state of the soil.

Soft normally consolidated clays and silts
ρ_i » 0.1r_{oed}
where ρ_{oed} = consolidation settlement from oedometer m_v
The final settlement (excluding creep),
$\rho = \rho\iota + \rho_{oed} = 1.1\ r_{oed}$

Stiff overconsolidated clays
Both immediate and consolidation settlement are incorporated in the oedometer-measured modulus.
Thus, final settlement, $\rho = \rho_{oed}$
Proportions:
ρ_i » $0.5\rho_{oed}$ - $0.6\rho_{oed}$
ρ_c » $0.5\rho_{oed}$ - $0.4\rho_{oed}$

Settlements on clays and silty clays

Calculating immediate settlement

- Typical values of Poisson's ratio
- Typical values of undrained stiffness
- Typical values of influence factor

The net immediate settlement is assumed to be due entirely to elastic volume change upon loading.

The following expression is based on elastic theory.

Immediate settlement $\rho_i = \frac{q_n B(1 - \nu^2)}{E_u} I_p$

where q_n = net bearing pressure
B = breadth of foundation
ν = Poisson's ratio
E_u = undrained stiffness modulus
I_p = influence factor

Calculating immediate settlement

Typical values of Poisson's ratio

Soil	Poisson's ratio (ν)
Undrained saturated clays/silts	$\nu_u = 0.5$
Stiff sandy or silty clays	$\nu' = 0.2 - 0.4$
Medium to loose sands	$\nu' = 0.4$
Dense sands	$\nu' = 0.2 - 0.45$

Calculating immediate settlement

Typical values of undrained stiffness

It is general practice to obtain values for E_u from undrained laboratory tests. However, other empirical relationships can also be used:

From oedometer test results
The drained stiffness modulus,
$E' = 1/m_v$
and then
$E_u = 1.5E'/(1 + \nu')$
where ν' = drained value of Poisson's ratio.

From undrained shear strength
In soils, stiffness moduli are strain-dependent. The strains associated with normal foundations at working loads are generally less than 0.1%. Some empirical relationships have been noted, for example, for London clay,
E_u / s_u = 150 to 500

Calculating immediate settlement

Typical values of influence factor

Influence factors I_p for vertical displacement due to elastic compression of a layer of semi-infinite thickness

Shape	Flexible			Rigid
	Centre	Corner	Average	
Circle	1.00	0.64	0.85	0.79
Rectangle				
L/B = 1.0	1.122	0.561	0.946	0.82
L/B = 1.5	1.358	0.679	1.148	1.06
L/B = 2.0	1.532	0.766	1.300	1.20
L/B = 3.0	1.783	0.892	1.527	1.42
L/B = 4.0	1.964	0.982	1.694	1.58
L/B = 5.0	2.105	1.052	1.826	1.70
L/B = 10.0	2.540	1.270	2.246	2.10
L/B = 100.0	4.010	2.005	3.693	3.47

Settlements on clays and silty clays

Calculating consolidation settlement

- Typical values of volume compressibility

The oedometer settlement of a soil layer can be calculated from:
$\rho_{oed} = m_v.\Delta\sigma'.H_L$
where
m_v = coefficient of volume compressibilty measured in an oedometer test
$\Delta\sigma'$ = the average change in vertical effective stress in the layer
H_L = thickness of the layer

In layered deposits, the sum of layer-settlements should be take down to a depth where
$\Delta\sigma' < 0.1q_n$

Oedometer test results tend to overestimate the actual settlement; the following correction factors should be applied:

$\rho_c = \mu_g . \rho_{oed}$

where μ_g = a factor suggested by Skempton and Bjerrum (1957)

Type of clay	**m_g**
Very sensitive; soft alluvial, estuarine and marine clays	1.0-1.2
Normally consolidated clay	0.7-1.0
Overconsolidated clays, e.g. London Clay, Weald, Kimmeridge, Oxford and Lias clays.	0.5-0.7
Heavily overconsolidated clays, e.g. Keuper Marl, glacial till	0.2-0.5

Calculating consolidation settlement

Typical values of volume compressibility

The values given below should be taken as guideline figures only, for preliminary design and first estimates; values based on reliable tests should be used in final design calculations.

Type of soil	**Degree of commpressibility**	**mv (m^2/MN)**
Heavilly overconsolidated clays	Very low compressibilty	< 0.05
Overconsolidated clays	Low compressibilty	0.05 - 0.1
Weathered overconsolidated clays	Medium compressibilty	0.1 - 0.3
Normally consolidated clays	High compressibilty	0.3 - 1.5
Organic alluvial clays and silts; peats	Very high compressibilty	> 1.5

Settlement

Settlements on sands and gravels

Settlements on sands and gravels take place almost immediately. Obtaining undisturbed samples for laboratory testing is difficult. The soil properties are estimated from *in situ* test results.

Standard penetration test
Relationships have been suggested between N-values and the settlement; one exmaple is that of Burland and Burbidge (1985), a simplified version of which is:
Immediate settlement,

$$\rho_i = 1.7 q_n' B^{0.7} N^{1.4}$$

where q_n' = net effective bearing pressure
B = breadth of foundation
N = average SPT N-value in the layer below of thickness B

Cone penetration test
For overconsolidated sands, estimates of E´ may be made from the measured cone resistance (q_c):
When $q_c < 50$ MN/m², E' - $5q_c$
When $q_c >= 50$ MN/m², E' - 250 MN/m²

Pressuremeter tests
The shear modulus G is obtained from pressuremeter results.
Then, $E' = 2G(1 + \nu')$

Foundations

Foundation design

Design is an iterative process. Designers use their experience to estimate the dimensions, then check whether the design is safe. If it is not safe, or the check indicated that it may be possible to make economies, then they modify the dimensions and repeat the calculations. For example:

Use **presumed bearing values** to obtain a first estimate of the size.

Calculate the **ultimate bearing capacity** (q_f) at which collapse will occur.

Obtain the **allowable bearing pressure** from

$$q_a = \frac{q_f - q_0}{F} + q_0$$

Divide the design load by this allowable pressure to obtain a **required area**.

Select appropriate **dimensions**.

Calculate the likely **settlement** for this size of foundation.

Check that the predicted settlement due to this allowable bearing pressure is likely to be acceptable.