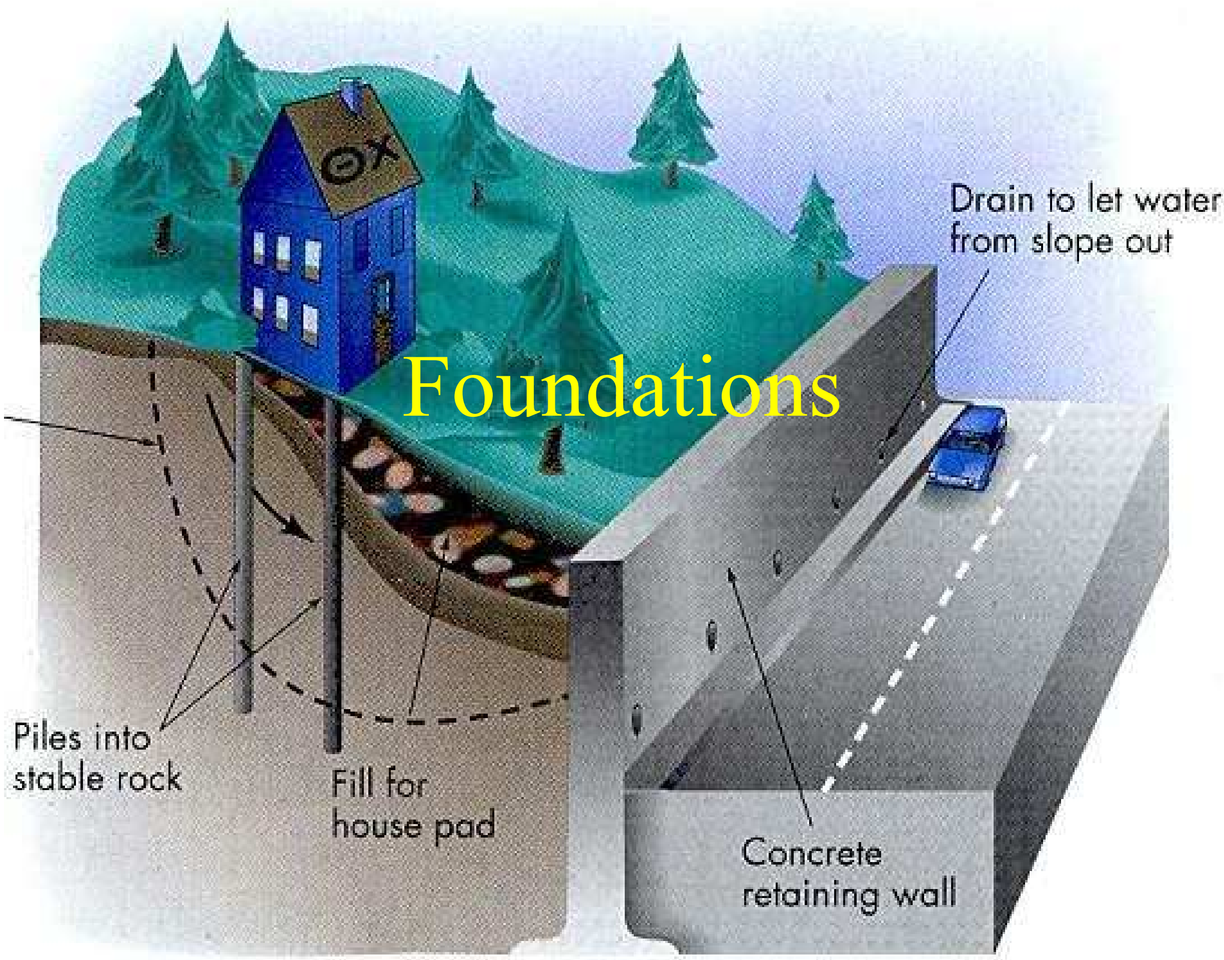
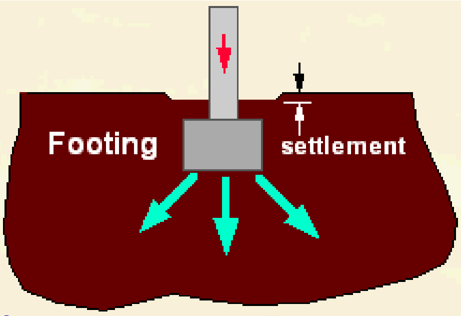
Foundations



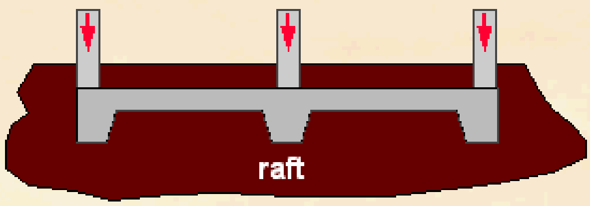
Function of foundation

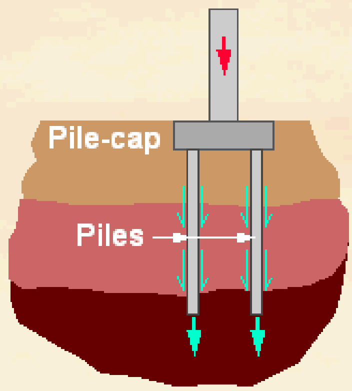
- The substructure or foundation is the part of a structure that is usually placed below the surface of the ground to transmit the load from the superstructure to the underlying soil or rock.



- If soil of sufficient bearing capacity lies immediately below the structure then the load can be spread by footings, as shown above.

Footings range from isolated pads supporting individual columns, through strips supporting walls or closely spaced columns, to a raft footing supporting the whole structure.





- However, if the soil has insufficient bearing capacity then it is necessary to use deep foundations, such as piles, to transmit the load to deeper, firmer strata.

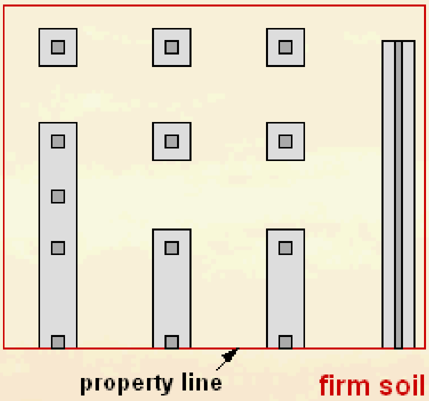
Types of foudations

This is a plan of a 3 storey building showing the columns and wall at ground level. It will illustrate the use of each type of footing. The soil has good bearing capacity.

- The simplest and most economical type is an isolated pad footing positioned under each column .....

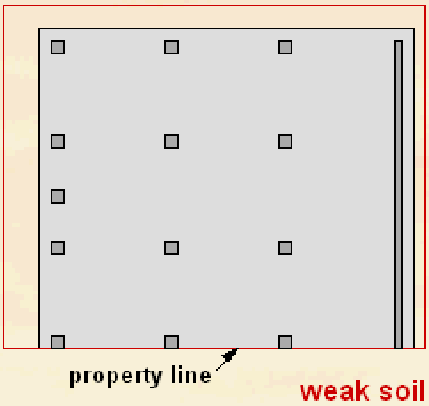
  But they cannot be used under external columns if property rights are infringed, and it is not good practice to have the column on the edge of an isolated pad .....
- so a combined footing is used .....
- a strip footing is used under a wall .....

  and can also be used under columns where the pads nearly or completely merge .....

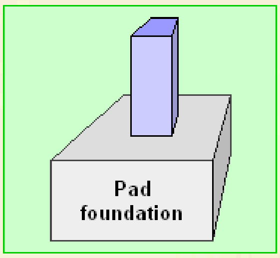


If the loads are now increased significantly, or the same building is to be supported by much weaker soil, then the area of the pad footings would be excessive.

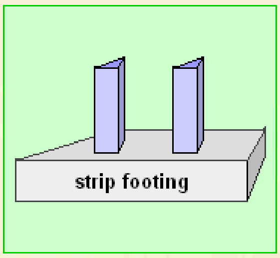
- Strip footings in both directions may be sufficient to spread the load and reduce bearing pressures to acceptable levels.
- If not, a raft foundation may give suitable bearing pressures.
- If the bearing pressures are still excessive, a deep basement at a firmer soil level, or piled foundations must be used.



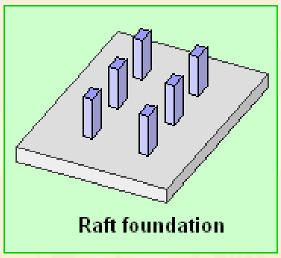
Use of different foundations



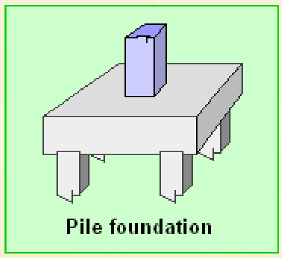
Where suitable bearing strata are at a shallow depth, mass concrete pad footings can be used. It is also the most economical choice for the ground conditions. The depth of the pad allows dispersion of the load without the need for reinforcement.



Strip footings are used if individual pad footings would be too closely spaced. Strip footings can also be used on weak ground to reduce the bearing pressure.



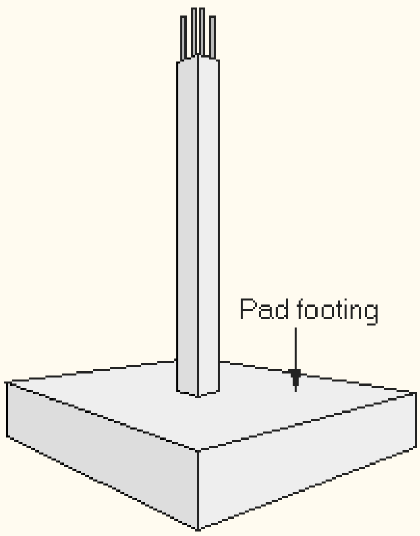
Where the ground conditions are poor and the depth to a strong bearing strata is excessive, raft foundations are used to distribute the load over a large area.



Piles are used where the bearing strata at the foundation level are too weak to support the superstructure.
Piles find support at a deeper, firmer level where the load is dispersed.

Pad footing

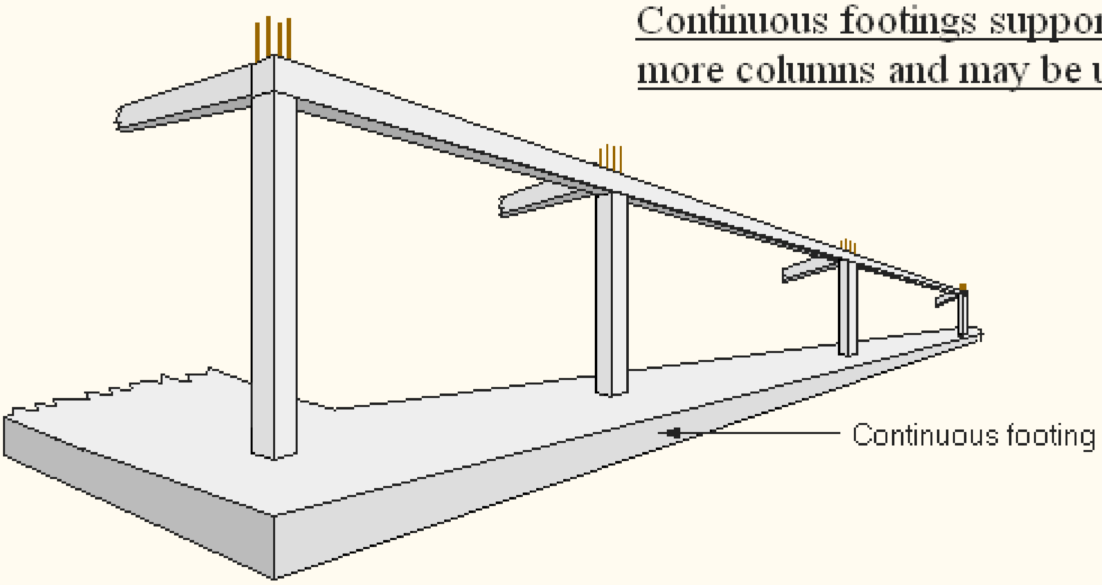
The purpose of a foundation is to transmit loads from the structure to the ground making sure that any settlement, either immediately after construction or during the intended life of the structure, is uniform and acceptably small.



Where there is a good uniform bearing stratum at a relatively shallow depth, columns may be supported on independant pad foundations, (provided of course that the columns are spaced sufficiently far apart for adjacent pads not to overlap).

A good bearing stratum is one where the bearing capacity is adequate to support the foundation safely and economically.

Continuous footings

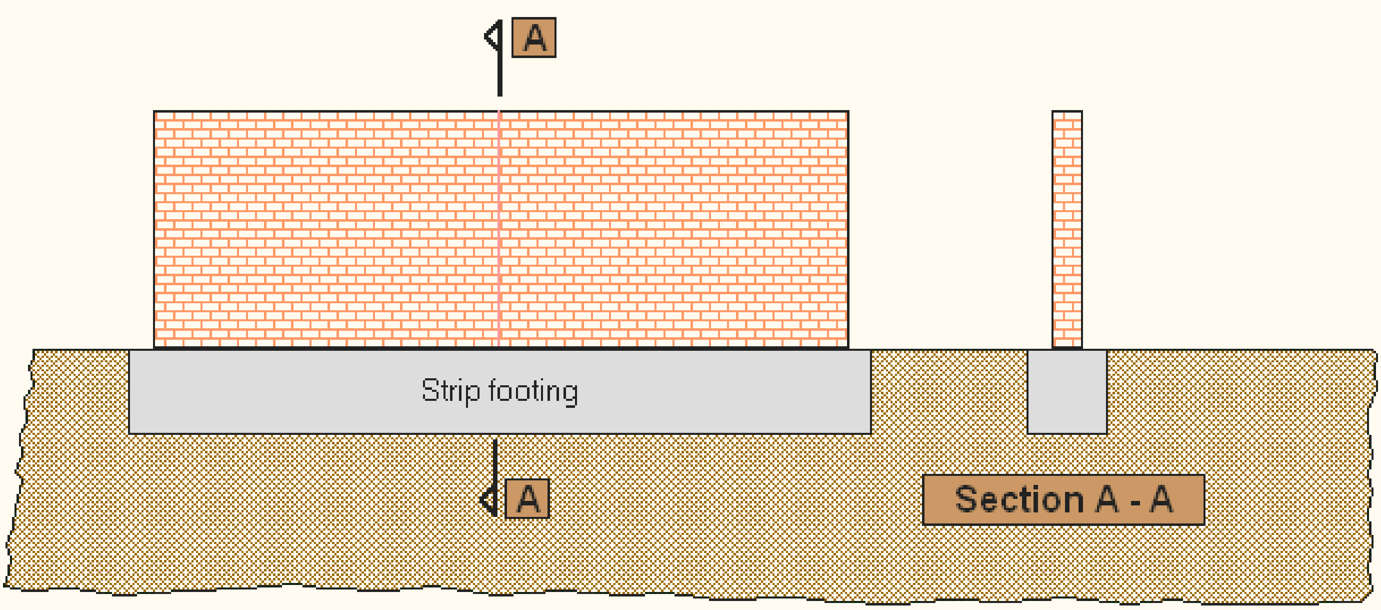


Continuous footings support two or more columns and may be used if :-

- close spacing of columns would lead to the overlap of individual pad footings
- the bearing capacity of the soil is variable
- differential settlement needs to be avoided

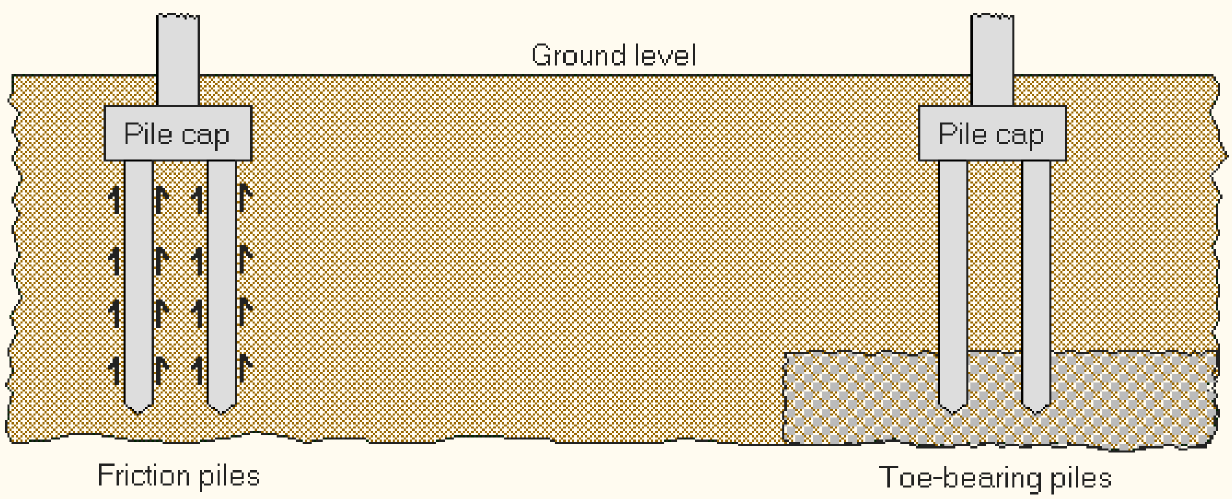
Strip footings

Strip footings are continuous foundations carrying continuous loads, (for example walls constructed from brickwork, blockwork or reinforced concrete).



Piled foundation

Where the cost of excavation to a good bearing stratum would be prohibitive, or where the stratum is not continuous, piled foundations may be used.



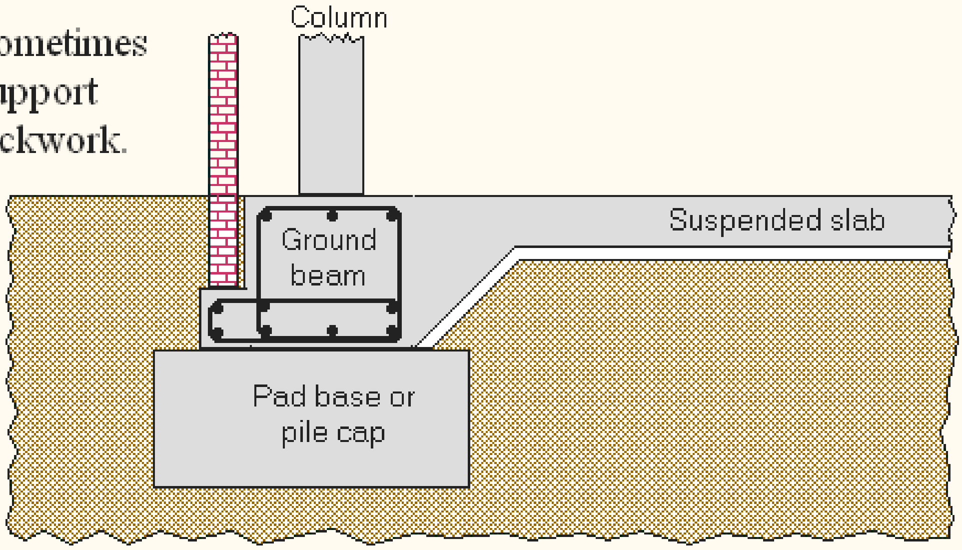
Piles can either rely on friction along their length

or, on end support from a good bearing stratum at some depth below ground level

Beam foundation

When the upper layer of ground has such a low bearing pressure that it is incapable of sustaining the loads imposed on ground-floor slabs, the slabs are suspended and supported on ground beams.

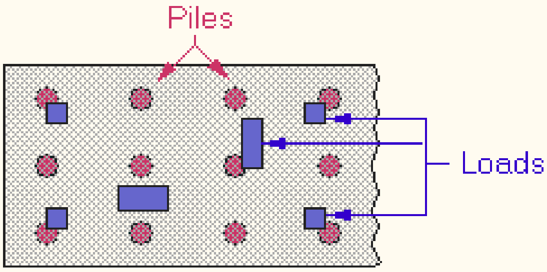
Ground beams sometimes include nibs to support brickwork or blockwork.



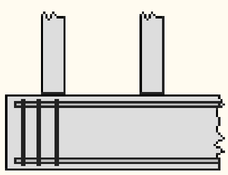
The beams are supported at column positions on pad foundations or pile caps.

Rafts

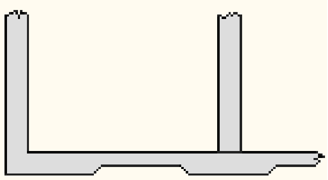
There are a number of different forms of raft foundation but the common purpose is to spread a system of loads over a large area, thus giving a low linearly-imposed load on to the ground below.



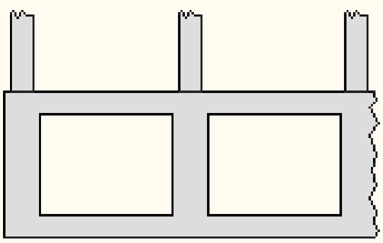
Plan view of piled raft



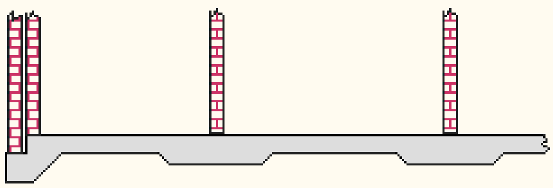
Section thro' stiff raft



Section thro' flexible raft



Section thro' cellular raft



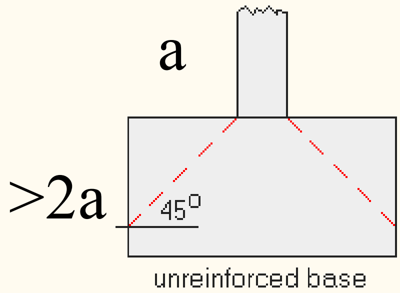
Section thro' light raft

Basic rules

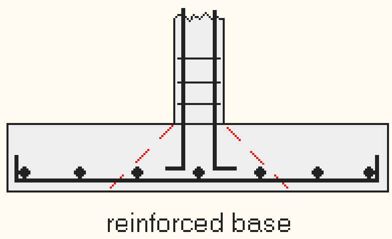
- The Code specifies minimum concrete covers as follows :-

for concrete cast directly against the earth	75mm
for concrete cast against prepared ground (e.g. blinding)	40mm

- If loads are small, or allowable ground pressures high, unreinforced pad footings are permitted (provided the depth is such that a line at 45 degrees from the edge of the column intersects the vertical face of the footing).



- For reinforced pad footings the width is generally greater than the 45^{o} load spread (as shown opposite).



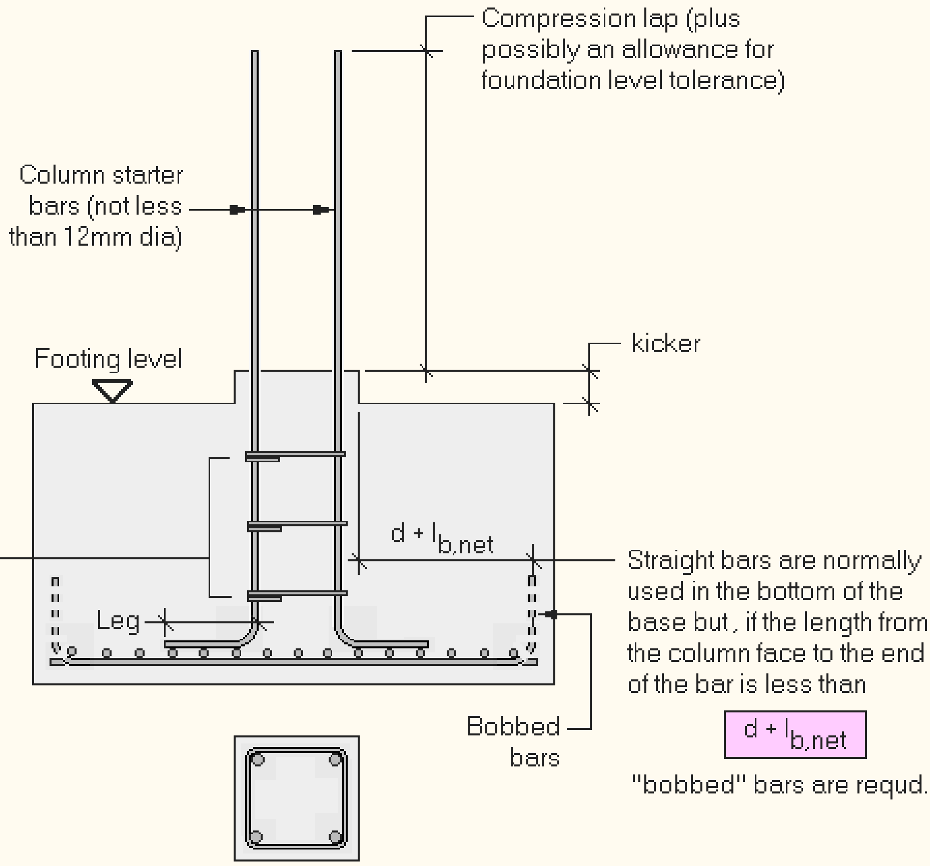
Footing

Simple pad footings usually have reinforcement only in the bottom but, depending on the loading situation, may also have top and shear reinforcement.

Most pad footings are used to support one or more columns and therefore usually include column starter bars, (not less than 12mm). Minimum leg length is 10ϕ but, for practical fixing reasons, is unlikely to be less than 300mm.

The starter bars should be linked with transverse reinforcement, the spacing of which must not exceed the lesser of the following three distances :-

- 12 times minimum dia of starter bars
- the least dimension of the column
- 300mm



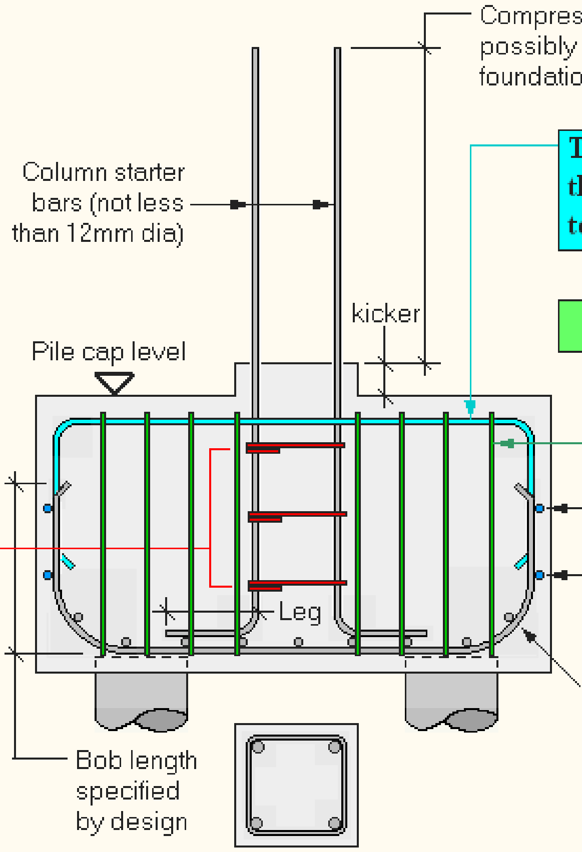
Piles cap

The main bottom bars are bent at both ends and usually rest on top of the piles. The *bottom cover* must allow for the rough and uneven surface at the top of the piles.

Most pile caps are used to support one or more columns and therefore usually include column starter bars, (not less than 12mm). Minimum leg length is 10ϕ but, for practical fixing reasons, is unlikely to be less than 300mm.

The starter bars should be linked with transverse reinforcement, the spacing of which must not exceed the lesser of the following three distances :-

- 12 times minimum dia of starter bars
- the least dimension of the column
- 300mm



The forces and moments on the pile cap may be such that top reinforcement is required.

Also, shear reinforcement.

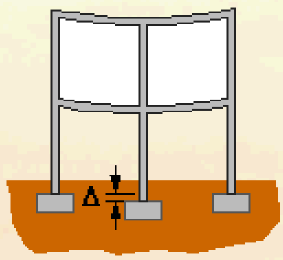
The vertical legs of the bobbed bars are confined by at least two layers of lacer bars.

The design will often specify large radius bends on these bars, (in which case the corner bars should be shifted accordingly).

Settlement

The two essential requirements in the design of foundations are -

- that the total settlement of the structure be limited to a relatively small amount, and
- that differential settlement of the various parts of the structure be kept to a minimum.



Restricting differential settlement, Δ is more important than limiting uniform overall settlement, because it is far more likely to cause structural damage due to the additional moments and forces that it applies to the structure.

The actual amount of distortion that a structure can undergo without damage is clearly dependent on the strength and rigidity of the structure.

The effects of settlement on the structure and its occupants dictate the limits of settlement to be used in the design of the foundations, thus -

Usual appearance. A *tilt rotation or a deflection ratio* greater than 1/250 is likely to be noticed by, and may cause concern to, the occupants.

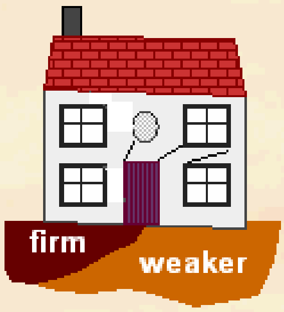
Serviceability. Cracking of load bearing walls or partitions is unsightly and remedial action may be required. Cracking of external walls can result in a loss of weather-tightness and thermal / sound insulation. The effect of settlement on underground services and machinery must also be considered.

Limiting deflections

Limiting values of distortion and deflection of structures have been proposed by numerous researchers. These recommendations are based upon experience and should be regarded as rules of thumb.

- Terzaghi and Peck suggested a maximum settlement of 25mm for ordinary structures with isolated foundations and 50mm for raft foundations. The 25mm is based on the assumption that the corresponding differential settlement between adjacent columns is unlikely to be more than 20mm, close to the limit that ordinary structures can tolerate without damage.
- For a limiting angle of distortion of 1/500, Skempton and MacDonald suggested a maximum settlement of 40mm for isolated foundations and up to 65mm for raft foundations.

The designer must either design the foundations to limit the total settlement in accordance with these empirical rules, or carry out a rigorous analysis of the soil-structure interaction.



The total settlement and the differential settlement, which caused the cracks in this house, can be reduced by providing one of the following -

- a rigid raft foundation.
- a deep basement.
- piled foundations.

In a framed structure another method would be to design the superstructure such that the columns could be re-levelled by inserting flat-jacks.

Bearing capacity

The ultimate bearing capacity of the soil, q_{ult} is the maximum bearing pressure that the soil can withstand. Values are established from principles of soil mechanics on the basis of load tests and other experimental determinations.

The allowable bearing capacity or pressure, q_a under service loads is generally based on a safety factor of 3 against exceeding the ultimate bearing capacity of the soil and to keep settlements within acceptable limits.

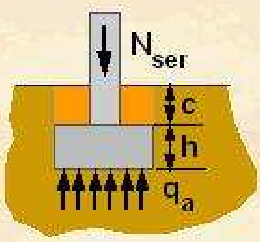
$$q_a = q_{ult} / 3$$

For initial design suitable presumed values of allowable bearing pressure are used.

Since the allowable bearing pressure acts at the base of the footing, the applied loads must also be calculated at this level. Thus, the weight of the footing and any load on top of the footing not included in the column load (e.g. the fill, any water pressure, a ground floor slab) must be added.

Footing sizes are determined for service loads.

For example, consider this pad footing of minimum plan area A.



For equilibrium of vertical forces - $N_{ser} + A\,c\,\rho_{fill} + A\,h\,\rho_c = A\,q_a$

ρ_{fill} is the density of the backfill

ρ_c is the density of the concrete

Hence
$$A = \frac{N_{ser}}{q_a - c\,\rho_{fill} - h\,\rho_c}$$

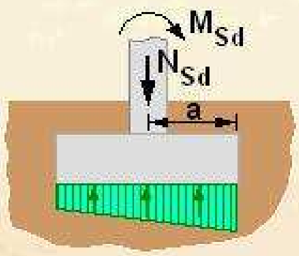
Footings are designed for ultimate loads.

The ultimate loads are balanced by a fictitious bearing pressure, q_u which is calculated solely for strength design ($q_u = \gamma_u\, q_a$; where $\gamma_u > 1$).

Stability

Foundations and retaining walls must be designed at the ultimate limit state to resist both overturning and sliding . The principles are described here for isolated pad footings. Retaining walls are covered fully in a later topic.

Overturning

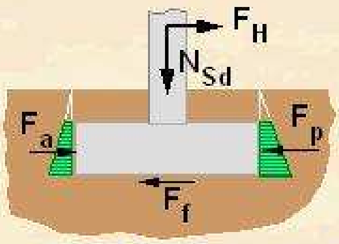


To prevent overturning the restoring moment due to the vertical load must be greater than the overturning moment, thus -

$$N_{Sd}\, a > M_{Sd}$$

Under this loading condition the bearing pressure is not uniform, and on compressible soils this can result in the footing 'tilting' if the pressure under one side is significantly larger than the pressure under the opposite side.

Sliding



To prevent the footing from sliding the resistance of the footing on the soil must exceed the applied horizontal load, thus -

$$F_f + F_p - F_a > F_H$$

where, F_f is the frictional resistance under the base ($= N_{Sd} \tan\delta$)
δ is the friction angle between concrete and soil
F_p is the passive resistance due to horizontal movement
F_a is the active pressure due to horizontal movement

Note: because F_p and F_a are dependent on the allowable horizontal movement of the footing, which is often uncertain, it is good practice to ignore F_p and F_a , thus $F_f > F_H$.

Exposure conditions

Soil and groundwater can contain chemicals which are actively harmful to concrete, the most aggressive of which are sulphates (SO_3). The concentration of sulphates in the soil is found from the soil investigation report.

Sulphate attack can usually be offset by using sulphate resisting cements - but even this will not alleviate the problem unless sufficient care is taken in placing the concrete, by vibrating and curing, or by incorporating protective barriers.

The nominal concrete cover to the reinforcement is dependent on the *exposure conditions*. The values are specified in the table, together with the required minimum quality of concrete.

In addition, the concrete cover should not be less than 40mm if cast on blinding, nor 75mm if cast directly on the soil.

Where there is a high concentration of sulphates, larger concrete covers may be specified.

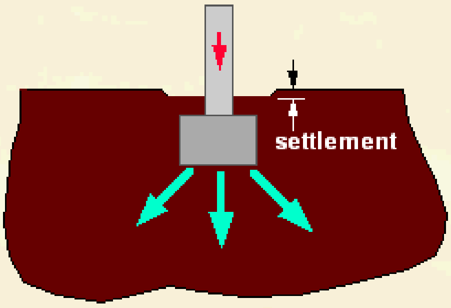
Cover to reinforcement and concrete quality for durability

Exposure class	Nominal cover (mm)				
1	20	20	20	20	20
2a	—	35	35	30	30
2b	—	—	35	30	30
3	—	—	40	35	35
4a	—	—	40	35	35
4b	—	—	40	35	35
5a	—	—	35	30	30
5b	—	—	—	30	30
5c	—	—	—	—	45
Maximum ratio free water/cement	0.65	0.60	0.55	0.50	0.45
Minimum cement content (kg/m^3)	260	280	300	300	300
Lowest concrete strength class	C25/30	C30/37	C35/45	C40/50	C45/55

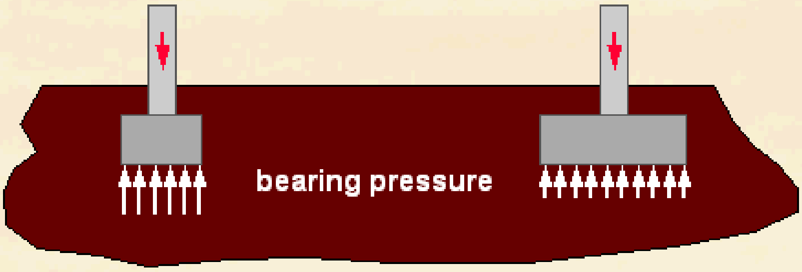
Protective barrier to prevent direct contact with aggressive media should be provided : 280 kg/m for exposure classes 2b and 5a.

Foundation

- The substructure or foundation is the part of a structure that is usually placed below the surface of the ground to transmit the load from the superstructure to the underlying soil or rock.



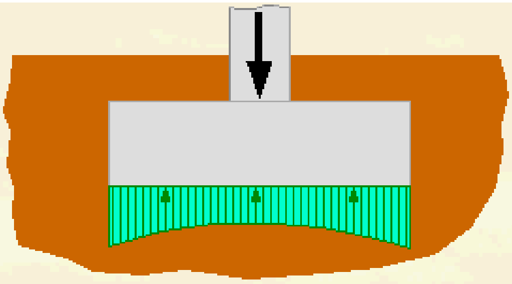
- All soils compress noticeably when loaded and cause the supported structure to settle.
- To limit settlement it is necessary to -
  - transmit the load of the structure to a soil stratum of sufficient strength, and
  - spread the load over a sufficiently large area of that stratum to minimise the bearing pressure.



Preasure distribution

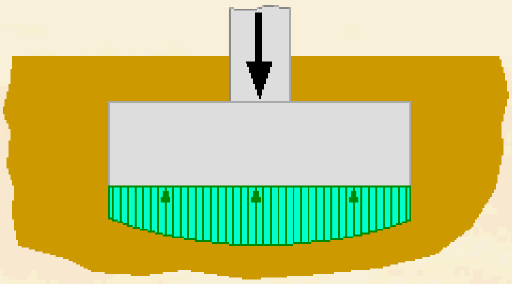
Soils are divided into two groups - cohesive (sticky - clays) and cohesionless (granular - gravels).

For a concentrically loaded pad footing the bearing pressure distribution for a cohesive soil is -

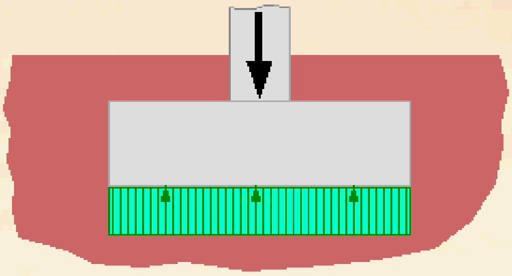


The pressures are higher near the edge because the load produces a shear resistance around the perimeter which adds to the upward pressure.

For a cohesionless soil the pressures are higher at the centre because the individual grains of soil at the perimeter can shift very slightly outwards to where the soil stresses are less.



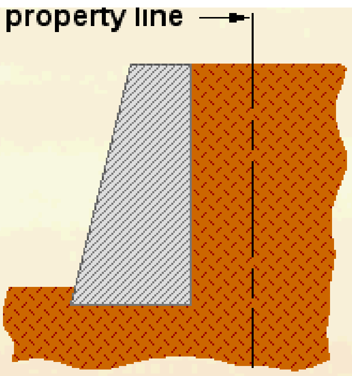
For design purposes, provided the load is symmetrical with respect to the bearing area, it is usual to disregard these variations and assume a uniform bearing pressure because -



- the actual numerical pressure distribution is uncertain and varies between similar soils,
- the effect on the magnitude of bending moments and shear forces in the footing is relatively small.

Retaining walls

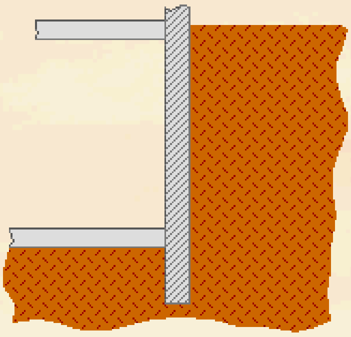
The function of a retaining wall is to hold back large quantities of earth or other loose material where conditions do not allow the material to assume its natural slope.



Such conditions occur when the width of the excavation or embankment is restricted because of ownership, use of the structure, or cost.

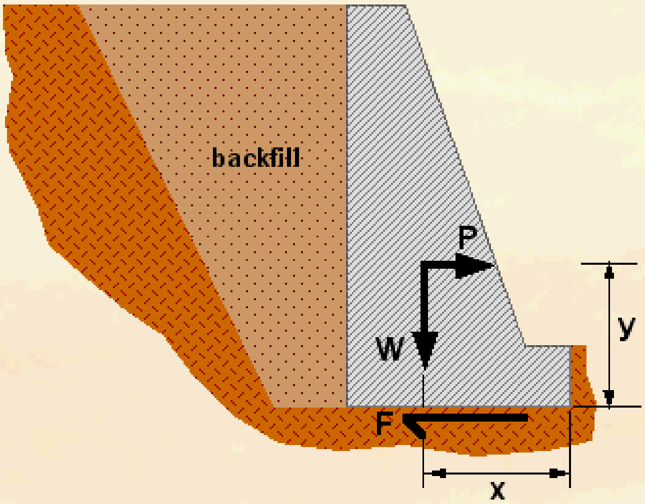
There are two basic types of retaining walls -

- Free-standing walls, of which there are several different forms, one of which, a gravity wall, is shown above.
- Embedment walls, which form part of a structure, such as a basement wall.



Verification of stability

Free-standing walls must provide their own stability against overturning and sliding.



Overturning

$$\gamma_{min} W x > \gamma_{max} P y$$

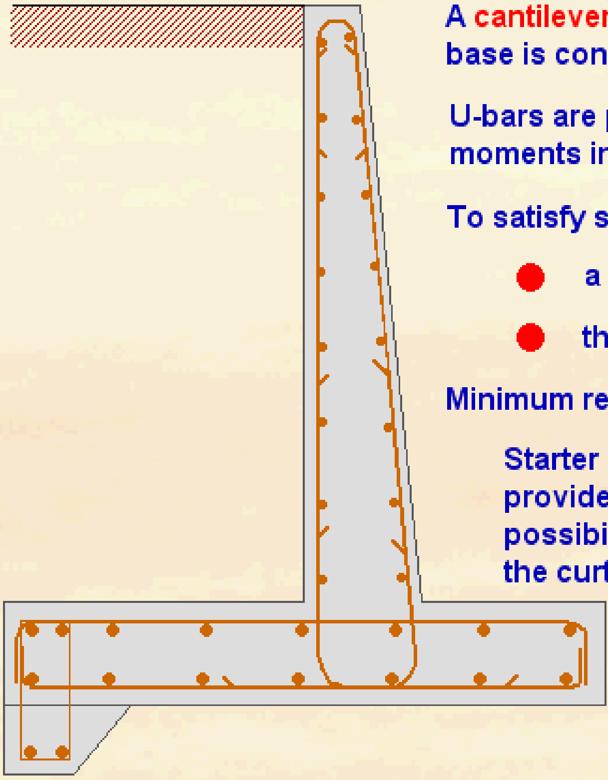
Sliding

$$\gamma_{min} F > \gamma_{max} P$$

This is achieved in different ways and gives rise to various types of wall -

- gravity
- cantilever
- counterfort

Reinforced concrete walls



A cantilever wall is not constructed in a single pour. First of all the base is constructed, including the key if present.

U-bars are provided top and bottom to satisfy the cantilever moments in the heel and the toe. The key is detailed as a nib.

To satisfy serviceability requirements of crack control -

- a *minimum* area of reinforcement must be provided,
- the *spacing* or the bar size should be limited.

Minimum reinforcement is provided along the base slab.

Starter bars are provided for the stem. Different length bars are provided alternately to distribute the laps and thus avoid the possibility of the concrete splitting. The longer bar is normally the curtailed bar for the reducing cantilever moment.

Minimum reinforcement is provided on the front face of the stem.

When the base has hardened sufficiently the stem is constructed.

A counterfort wall is constructed in a similar way, except that the counterfort and stem are constructed together.

Shanghai collapse

Shanghai collapse

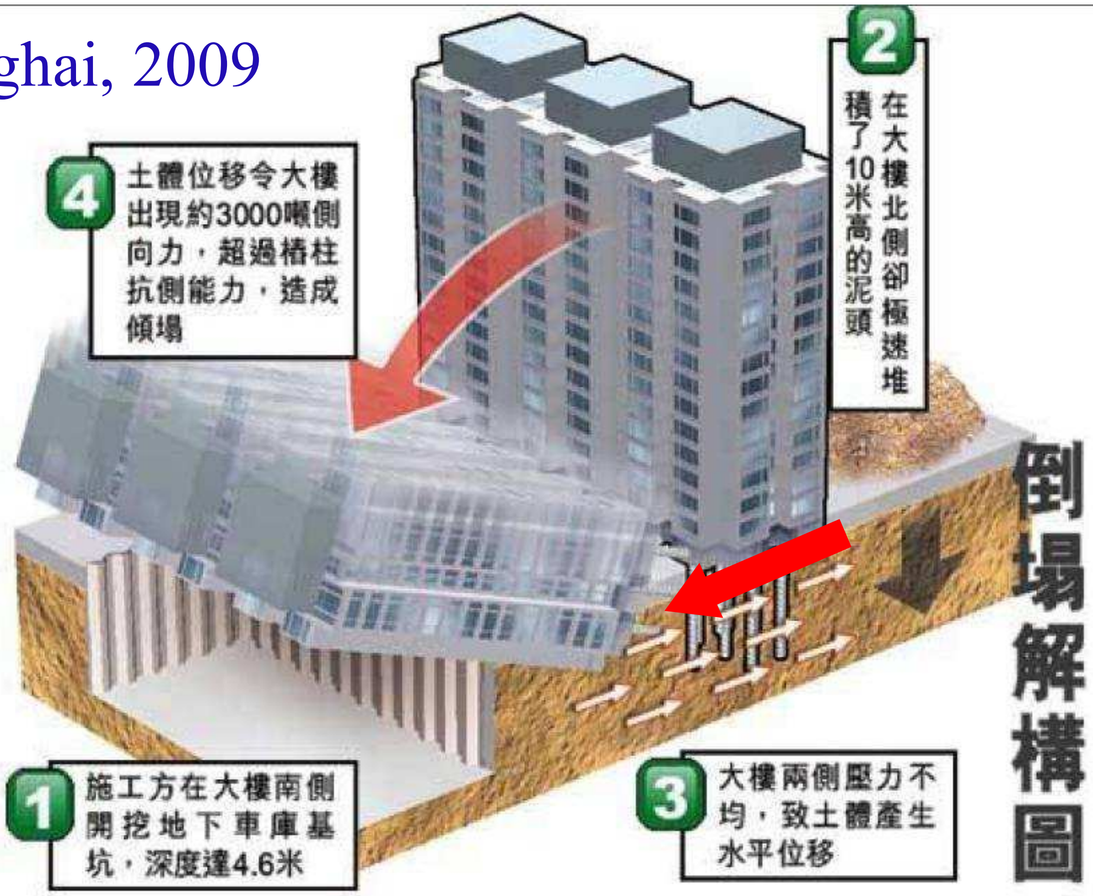
Main point

- the function of a foundation - to transfer load from the superstructure to the ground and to support the applied load.
- the types of foundations - pad and strip footings, rafts, and piles.
- the effect of total and differential settlement on a foundation - suggested limits of rotation (tilt) and deflection ratio.
- the ultimate bearing capacity of soil, the allowable bearing pressure for design and presumed values for different soils. The distribution of bearing pressure in cohesive and cohesionless soils.
- stability against overturning and sliding.
- the use of each foundation type.

Exam questions

- The functions of foundation
- Different foundations and their use
- Basic rules for pad footings (unreinforced, reinforced, concrete cover)
- Piled foundation
- Pressure distribution (in cohesive cohensionless soil, design assumption)
- Limiting distortion and deflections of isolated and raft foundations
- Cracking of walls due to foundation settlement

Shanghai, 2009



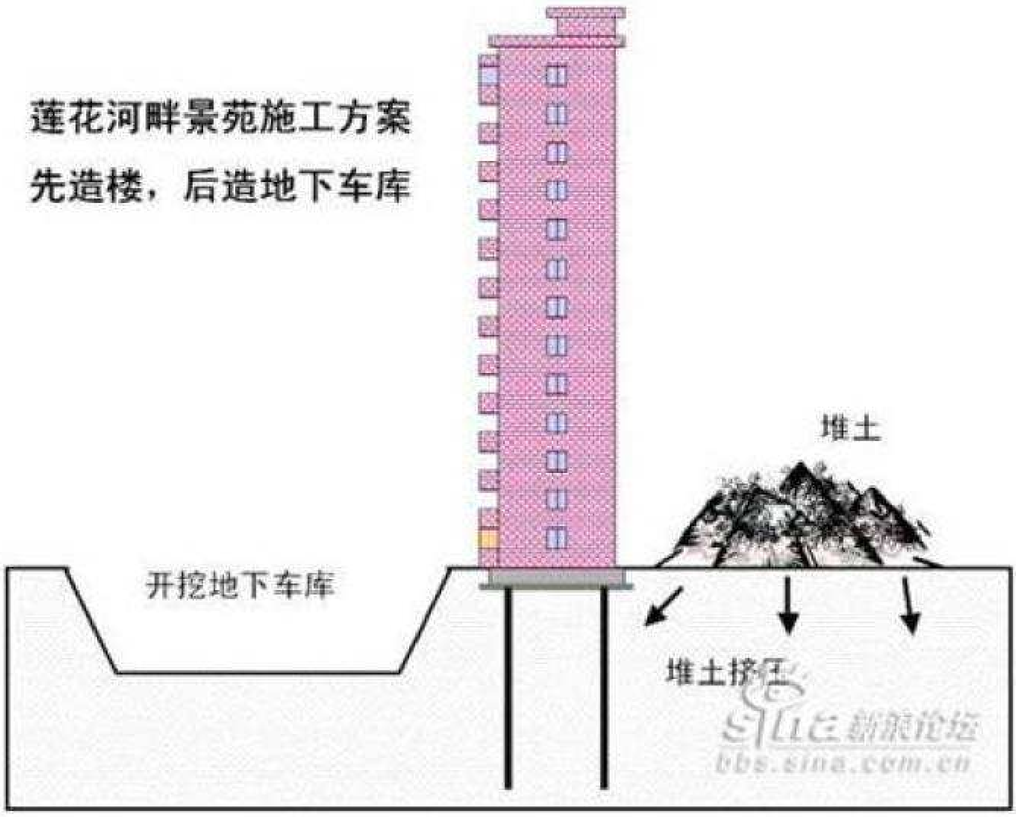
(1) An underground garage was being dug on the south side, to a depth of 4.6 meters
(2) The excavated dirt was being piled up on the north side, to a height of 10 meters
(3) The building experienced uneven lateral pressure from south and north
(4) This resulted in a lateral pressure of 3,000 tonnes, which was greater than why the pilings could tolerate. Thus the building toppled over in the southerly direction.

Building collapse in Shanghai, 2009

Building Collapsed In Shanghai (06/27/2009) **(Daqi)**
At around 5:30am on June 27, an unoccupied building still under construction at Lianhuanan Road in the Minhang district of Shanghai city toppled over. One worker was killed.

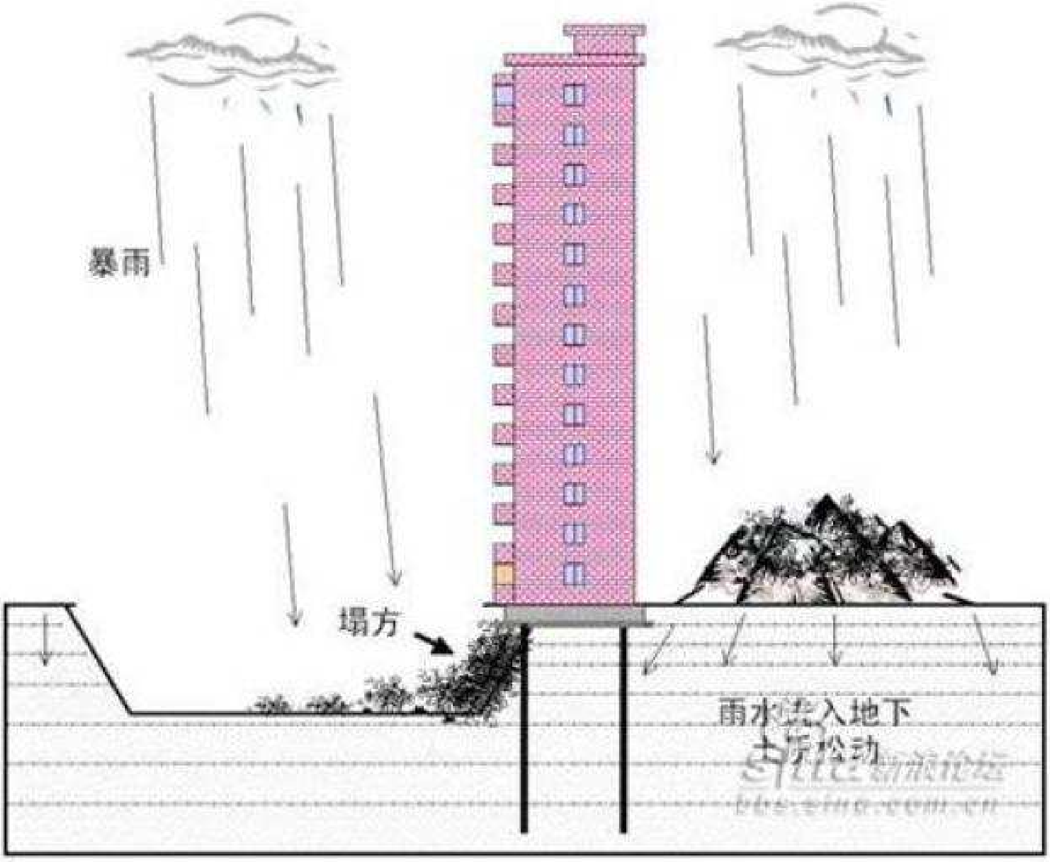
First, the apartment building was constructed

Building collapse in Shanghai, 2009



Then the plan called for an underground garage to be dug out.
The excavated soil was piled up on the other side of the building.

Building collapse in Shanghai, 2009



Heavy rains resulted in water seeping into the ground.

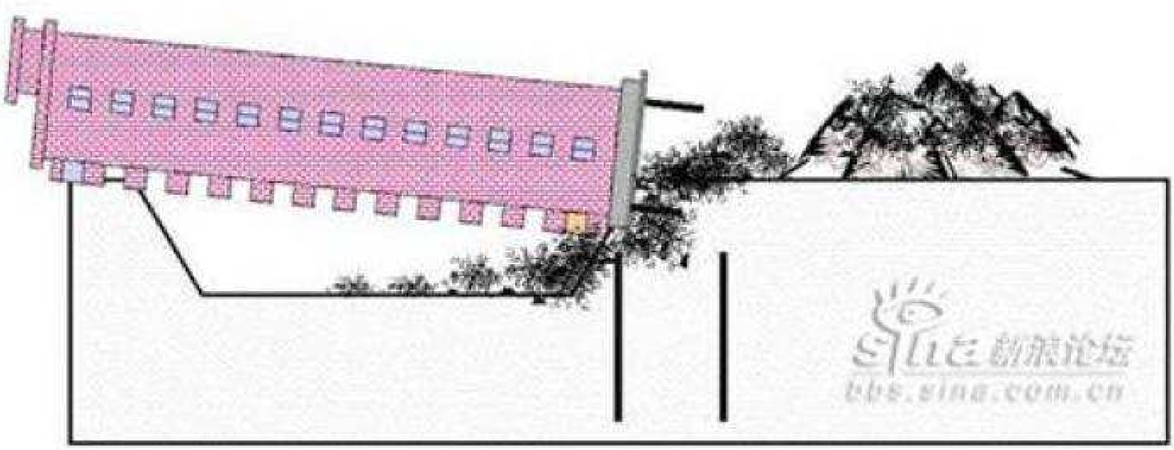
due to the uneven lateral pressures.

Building collapse in Shanghai, 2009

The building began to tilt.

Building collapse in Shanghai, 2009

创造世界房屋倒塌奇迹



And thus came the eighth wonder of the world.