FOUNDATION ENGINEERING I

CEng 3204

CHAPTER THREE

Design of Shallow Foundations

General Principles of Foundation Design

- The usual approach to a normal foundation engineering problem is:

1. To prepare a plan of the base of the structure showing the various columns, load-bearing walls with estimated loads, including dead load, live load, moments and torques coming into the foundation units.
2. To study the tentative allowable bearing pressures allocated for the various strata below the ground level, as given by the soil investigation report.
3. To determine the required foundation depth. This may be the minimum depth based on soil strength or structural requirement considerations.
4. To compute the dimensions of the foundation based on the given loading and allowable bearing pressure.
5. To estimate the total and differential settlements of the structure.
    - If these are excessive the bearing pressure will have to be reduced or the foundation taken to a deeper and less compressible stratum or the structure will have to be founded on piles or other special measures taken

Loads on Foundation

- A foundation may be subjected to two or more of the following loads:

a. **Dead load:**
   - Weight of structure
     - All material permanently attached to structure
     - Static earth pressure acting permanently against the structure below ground surface.
     - Water pressure acting laterally against basement walls and vertically against slab.

b. **Live load:** temporary loads expected to be superimposed on the structure during its useful life.

c. **Wind load:-** lateral load coming from the action of wind and depends on the size, shape and dynamic properties of the structure.

   Local building codes provide magnitude of design wind pressure.

d. **Earth-quake load**:- lateral load coming from earth- quake motion.

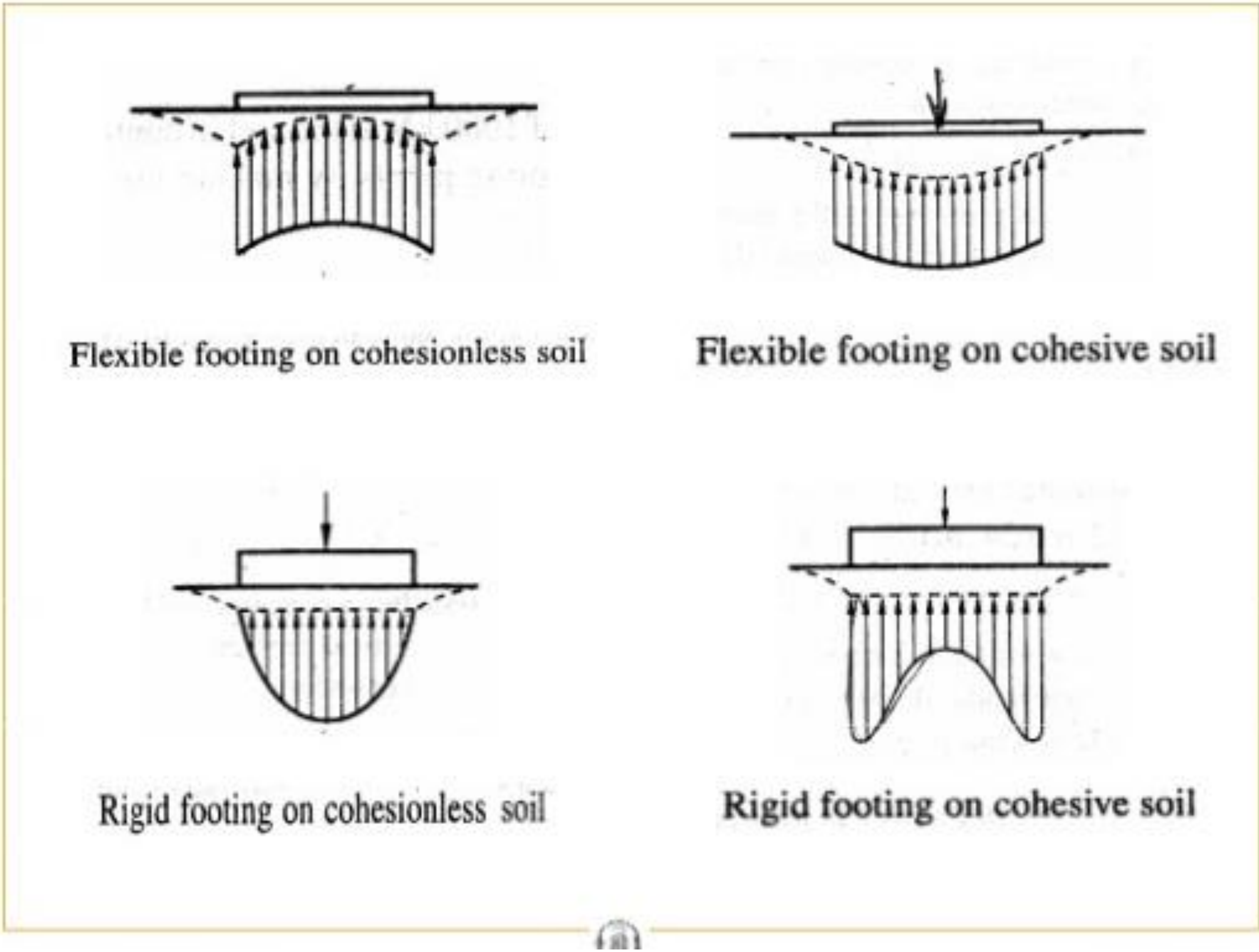
   -The total lateral force (base shear) at the base of a structure is evaluated in accordance with local building code.

e. **Dynamic load:-** load coming from a vibrating object (machinery).
   - In such case, separate foundation should be provided. The impact effect of such loads should be considered in design.

Pressure Distribution Beneath Foundation

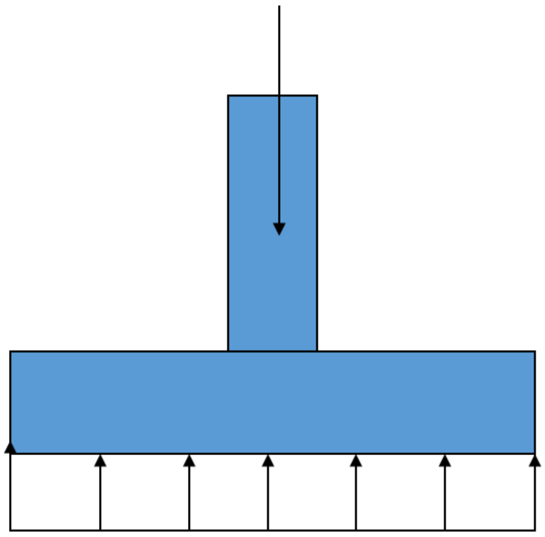
- The stability of a structure is majorly dependent on soil-foundation interaction.
- Even though they are of different physical nature, they both must be act together to get required stability. So, It is important to know about the contact pressure developed between soil and foundation and its distribution in different conditions.
- The pattern of the distribution varies according to the stiffness of the foundation and rigidity of the soil.

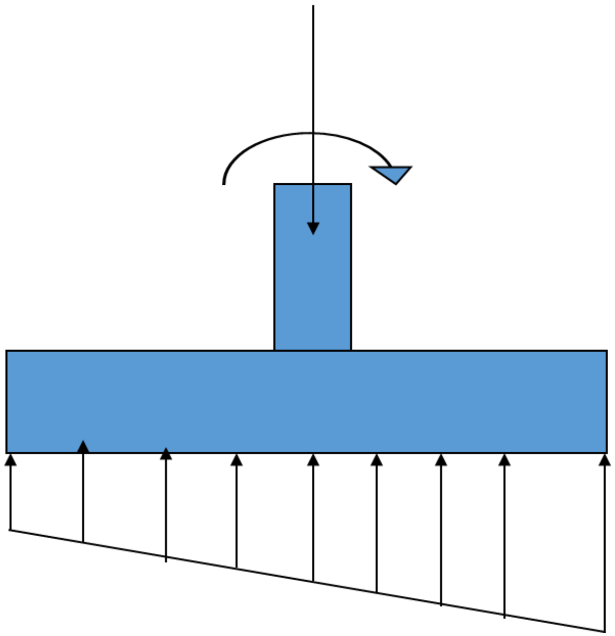
Pressure Distribution Beneath Foundation



Pressure Distribution Beneath Foundation

- For design purpose, the contact pressure is assumed to be uniform for all types of footings and all types of soils under symmetric loading.



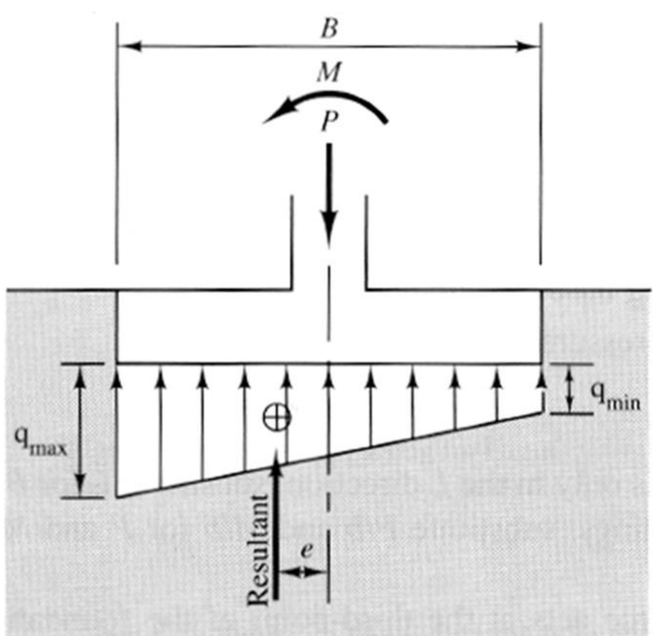


$q_{u,min}$ =

Pressure Distribution Beneath Foundation

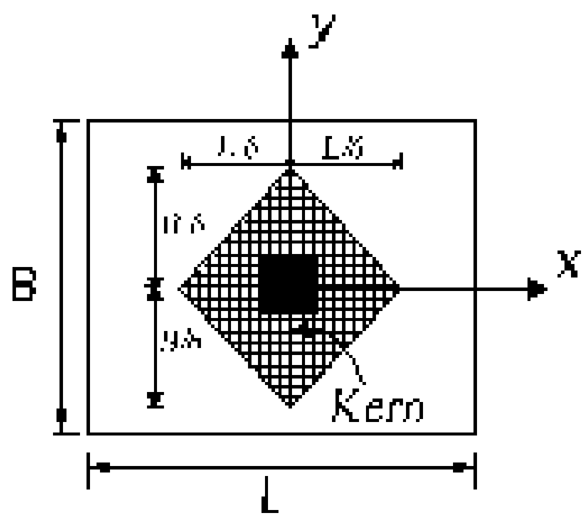
- Approximate contact pressure under a given symmetrical foundation can be determined by flexural formula.
- The considered load lies within the kern of the footing

[i.e. $e_y < B/6$ and $e_x < L/6$].



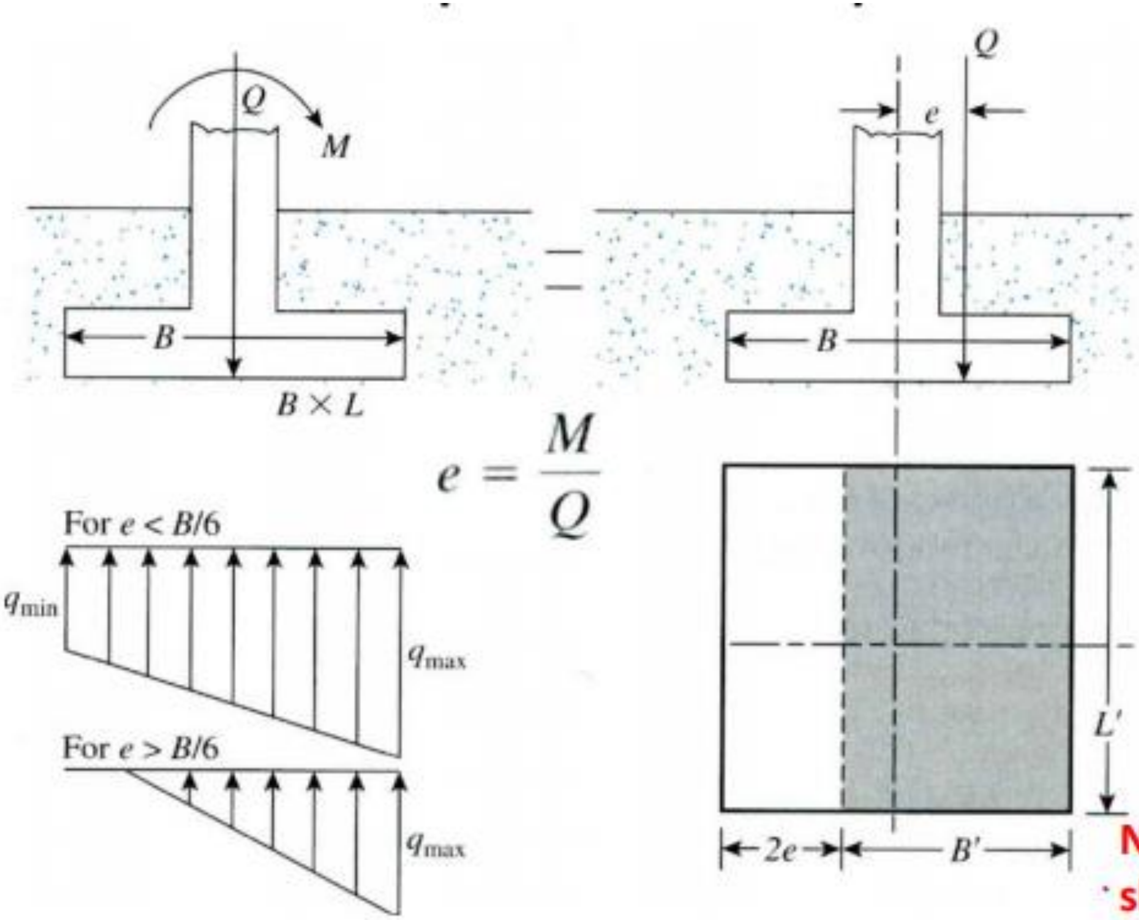
(a) $e < B/6$

$$\sigma(x, y) = \frac{P}{A} \pm \frac{M_x y}{I_x} \pm \frac{M_y x}{I_y}$$



Pressure Distribution Beneath Foundation

- **One-way eccentricity**



For e < B/6

$$q_{max} = \frac{Q}{BL}\left(1 + \frac{6e}{B}\right)$$

$$q_{min} = \frac{Q}{BL}\left(1 - \frac{6e}{B}\right)$$

For e > B/6

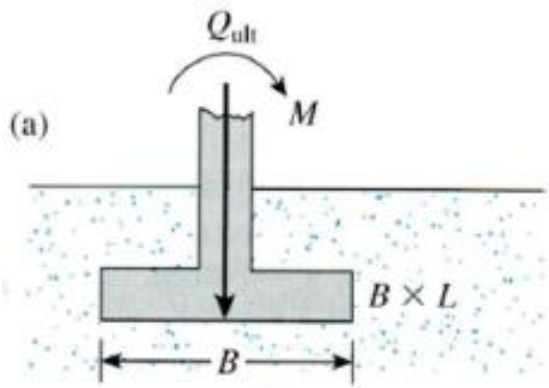
$$q_{max} = \frac{4Q}{3L(B - 2e)}$$

$q_{min} = 0$

Note that B′ is used to compute shape factors in general bearing capacity equation.

Pressure Distribution Beneath Foundation

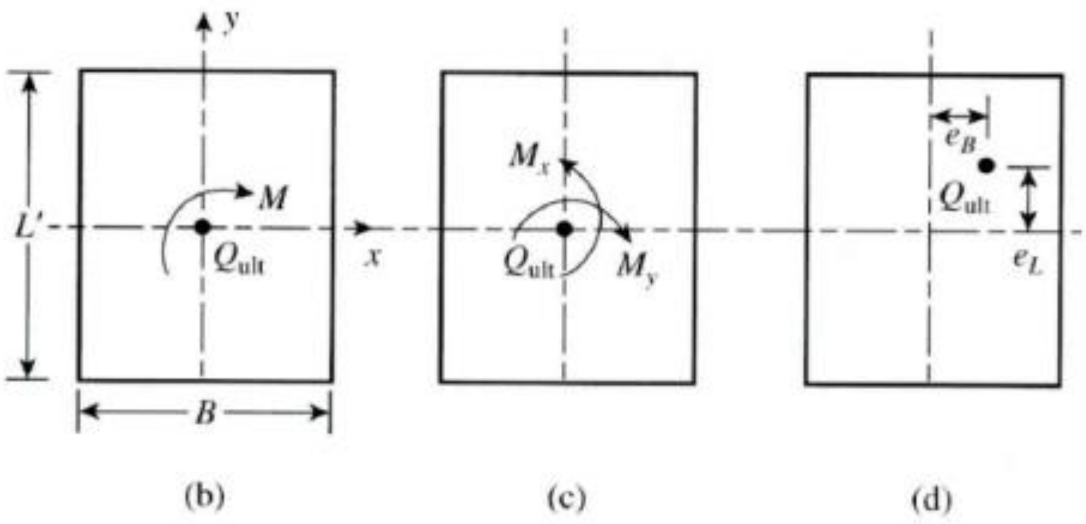
- **Two-way eccentricity**



$$e_B = \frac{M_y}{Q_{ult}}$$

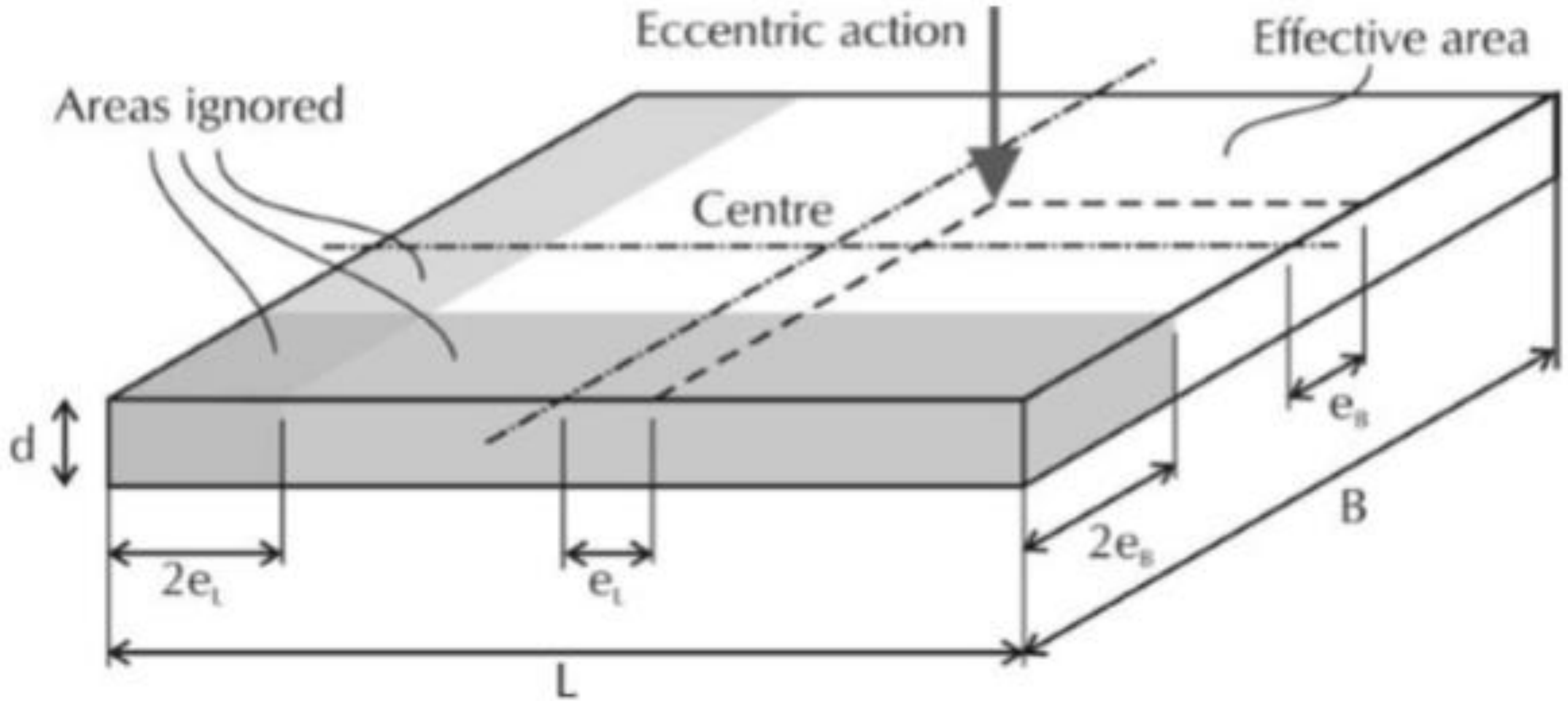
$$e_L = \frac{M_x}{Q_{ult}}$$

$$A' = \text{effective area} = B'L'$$



In order to evaluate effective width and length the following cases should be considered.

Pressure Distribution Beneath Foundation



Pressure Distribution Beneath Foundation

- **Two-way eccentricity**

Case I. $e_L/L \geq \frac{1}{6}$ and $e_B/B \geq \frac{1}{6}$. The effective area Figure 3.20, or

$$A' = \tfrac{1}{2}B_1 L_1$$

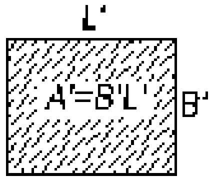
where

$$B_1 = B\left(1.5 - \frac{3e_B}{B}\right)$$

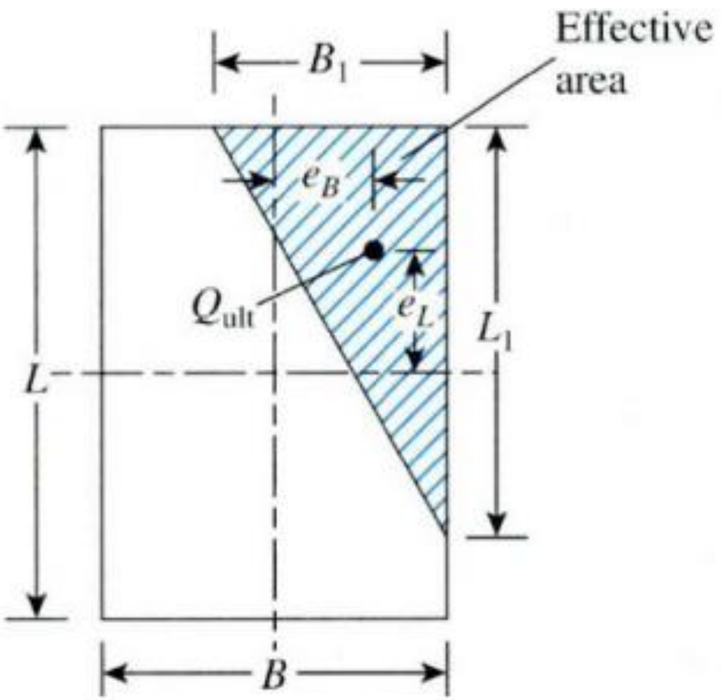
and

$$L_1 = L\left(1.5 - \frac{3e_L}{L}\right)$$

The effective length L' is the larger of the two dimensions



$$B' = \frac{A'}{L'}$$



Pressure Distribution Beneath Foundation

- **Two-way eccentricity**

Case II. $e_L/L < 0.5$ and $0 < e_B/B < \frac{1}{6}$. The effective area Figure 3.21a, is

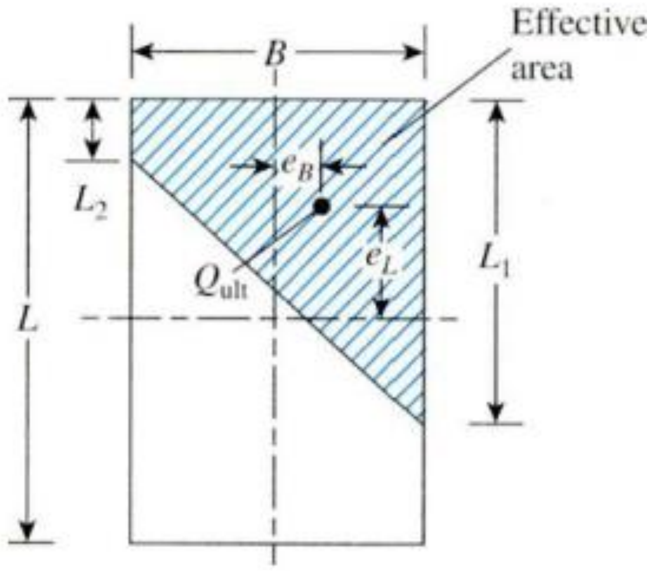
$$A' = \tfrac{1}{2}(L_1 + L_2)B$$

The magnitudes of L_1 and L_2 can be determined from Figure 3.2

$$B' = \frac{A'}{L_1 \text{ or } L_2 \quad \text{(whichever is larger)}}$$

The effective length is

$$L' = L_1 \text{ or } L_2 \quad \text{(whichever is larger)}$$



Pressure Distribution Beneath Foundation

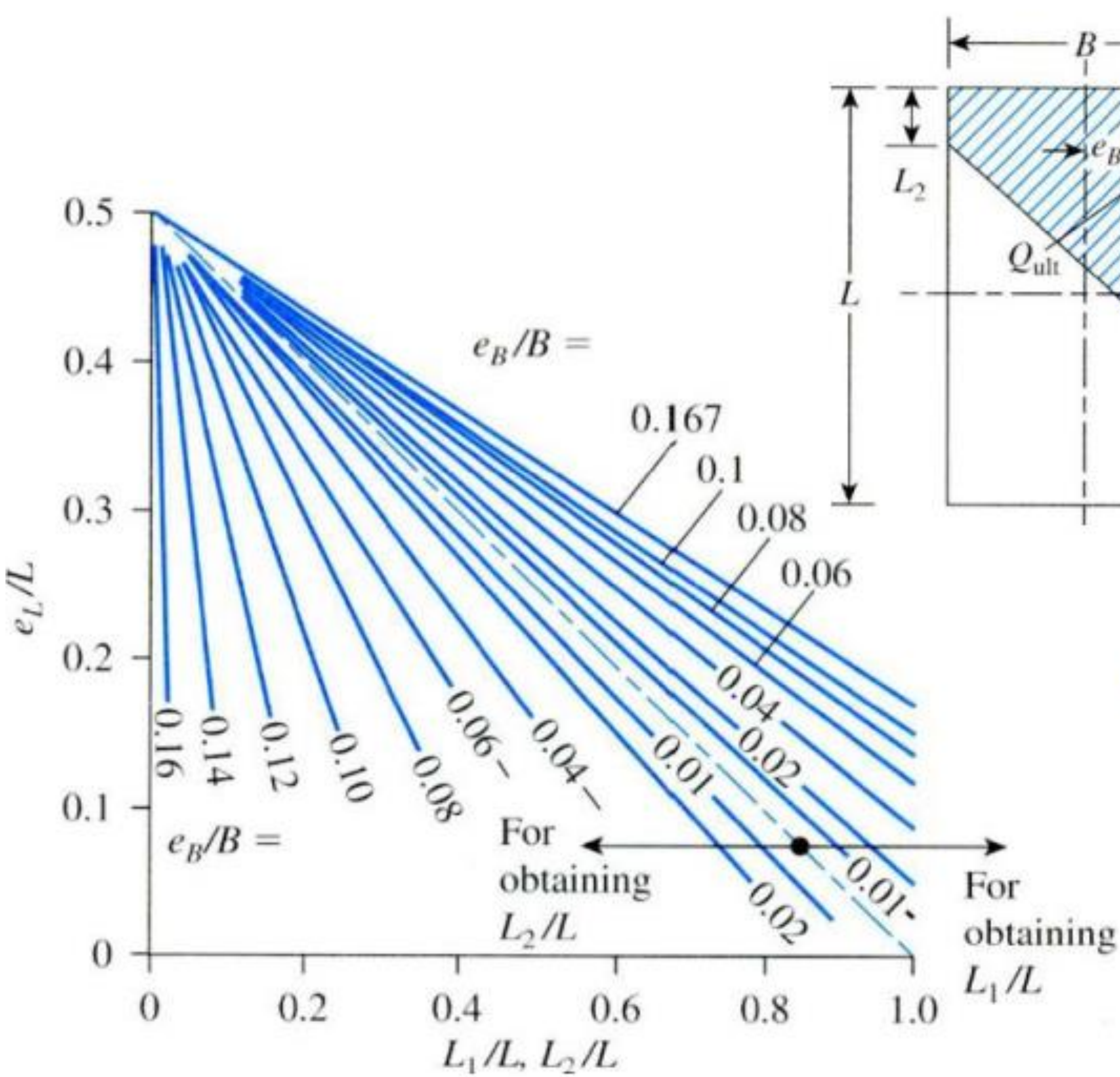


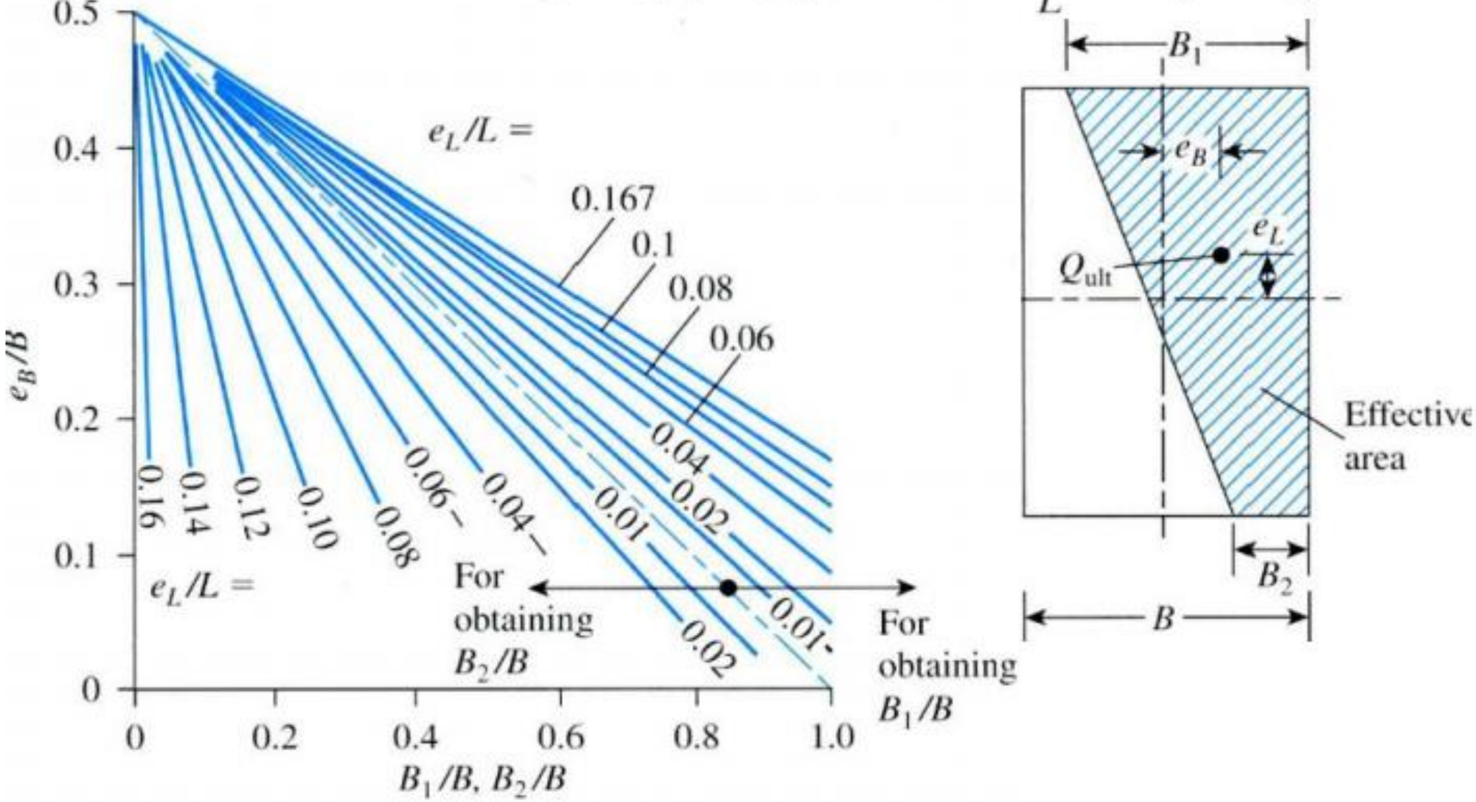
Figure 3.21 Effective area for the case of $e_L/L < 0.5$ and $0 < e_B/B < \frac{1}{6}$ (After Highter and Anders, 1985) (Highter, W. H. and Anders, J. C. (1985). "Dimensioning Footings Subjected to Eccentric Loads," *Journal of Geotechnical Engineering*, American Society of Civil Engineers, Vol. 111, No. GT5, pp. 659–665. With permission from ASCE.)

Pressure Distribution Beneath Foundation

- **Two-way eccentricity**

Case III. $e_L/L < \frac{1}{6}$ and $0 < e_B/B < 0.5$. The effective area,

$$A' = \frac{1}{2}(B_1 + B_2)L \qquad B' = \frac{A'}{L} \qquad L' = L$$

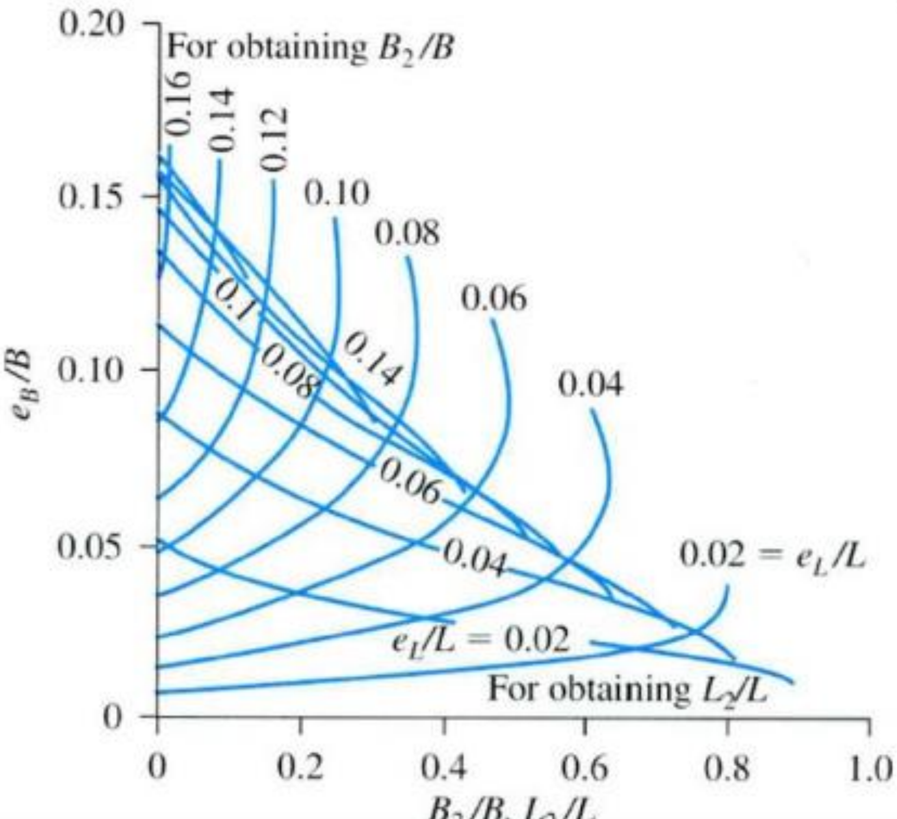


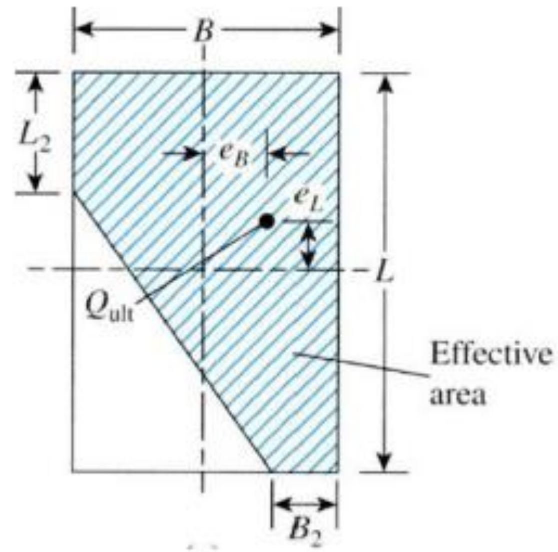
Pressure Distribution Beneath Foundation

- **Two-way eccentricity**

Case IV. $e_L/L < \frac{1}{6}$ and $e_B/B < \frac{1}{6}$.

$$A' = L_2B + \tfrac{1}{2}(B + B_2)(L - L_2) \qquad B' = \frac{A'}{L} \qquad L' = L$$





Pressure Distribution Beneath Foundation

Effective Area Method (Meyerhoff, 1953)

In 1953, Meyerhof proposed a theory that is generally referred to as the *effective area method*.

The following is a step-by-step procedure for determining the ultimate load that the soil can support and the factor of safety against bearing capacity failure:

Step 1. Determine the effective dimensions of the foundation (Figure 3.13b):

$$B' = \text{effective width} = B - 2e$$
$$L' = \text{effective length} = L$$

Note that if the eccentricity were in the direction of the length of the foundation, the value of L' would be equal to $L - 2e$. The value of B' would equal B. The smaller of the two dimensions (i.e., L' and B') is the effective width of the foundation.

Step 2. Use Eq. (3.19) for the ultimate bearing capacity:

$$q'_u = c'N_cF_{cs}F_{cd}F_{ci} + qN_qF_{qs}F_{qd}F_{qi} + \tfrac{1}{2}\gamma B'N_\gamma F_{\gamma s}F_{\gamma d}F_{\gamma i} \qquad (3.40)$$

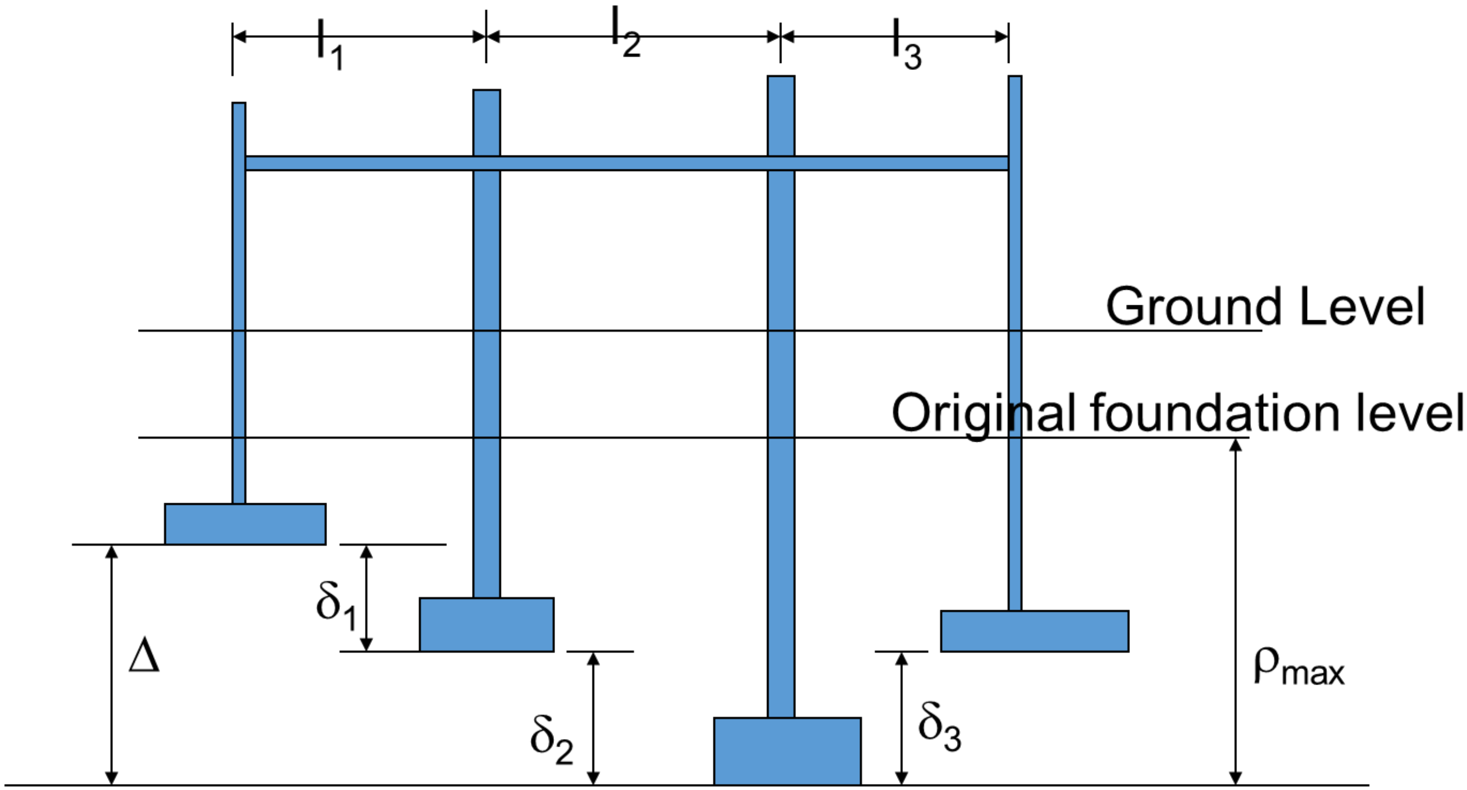
To evaluate F_{cs}, F_{qs}, and $F_{\gamma s}$, use the relationships given in Table 3.4 with *effective length* and *effective width* dimensions instead of L and B, respectively. To determine F_{cd}, F_{qd}, and $F_{\gamma d}$, use the relationships given in Table 3.4. However, do not replace B with B'.

Step 3. The total ultimate load that the foundation can sustain is

$$Q_{ult} = q'_u \overbrace{(B')(L')}^{A'} \qquad (3.41)$$

where A' = effective area.

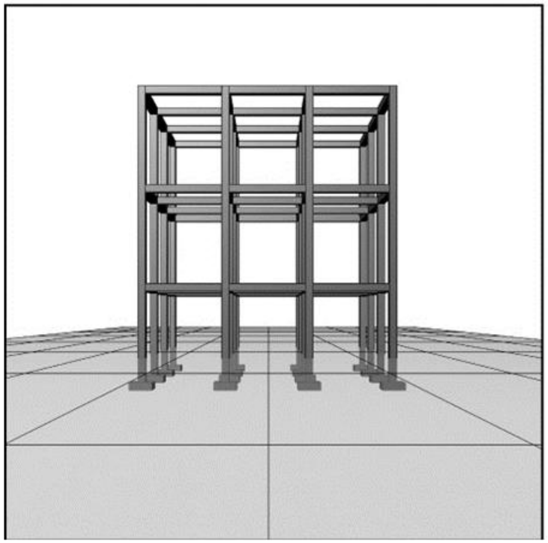
Settlement of Foundations



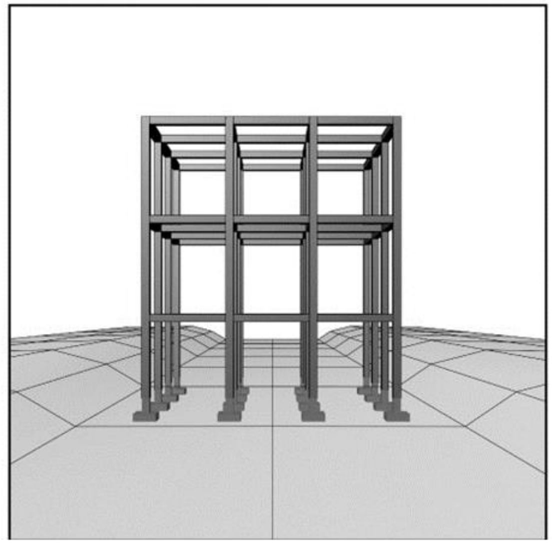
$\delta_1, \delta_2, \delta_3$ = Differential sett., Δ = Greatest differential sett.

ρ_{max} = maximum total sett., l_1, l_2, l_3 = Bay width, δ/l = angular distortion

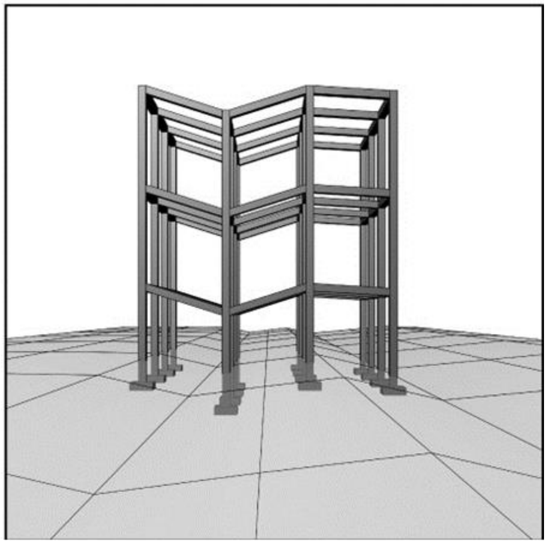
Settlement of Foundations



NO SETTLEMENT *



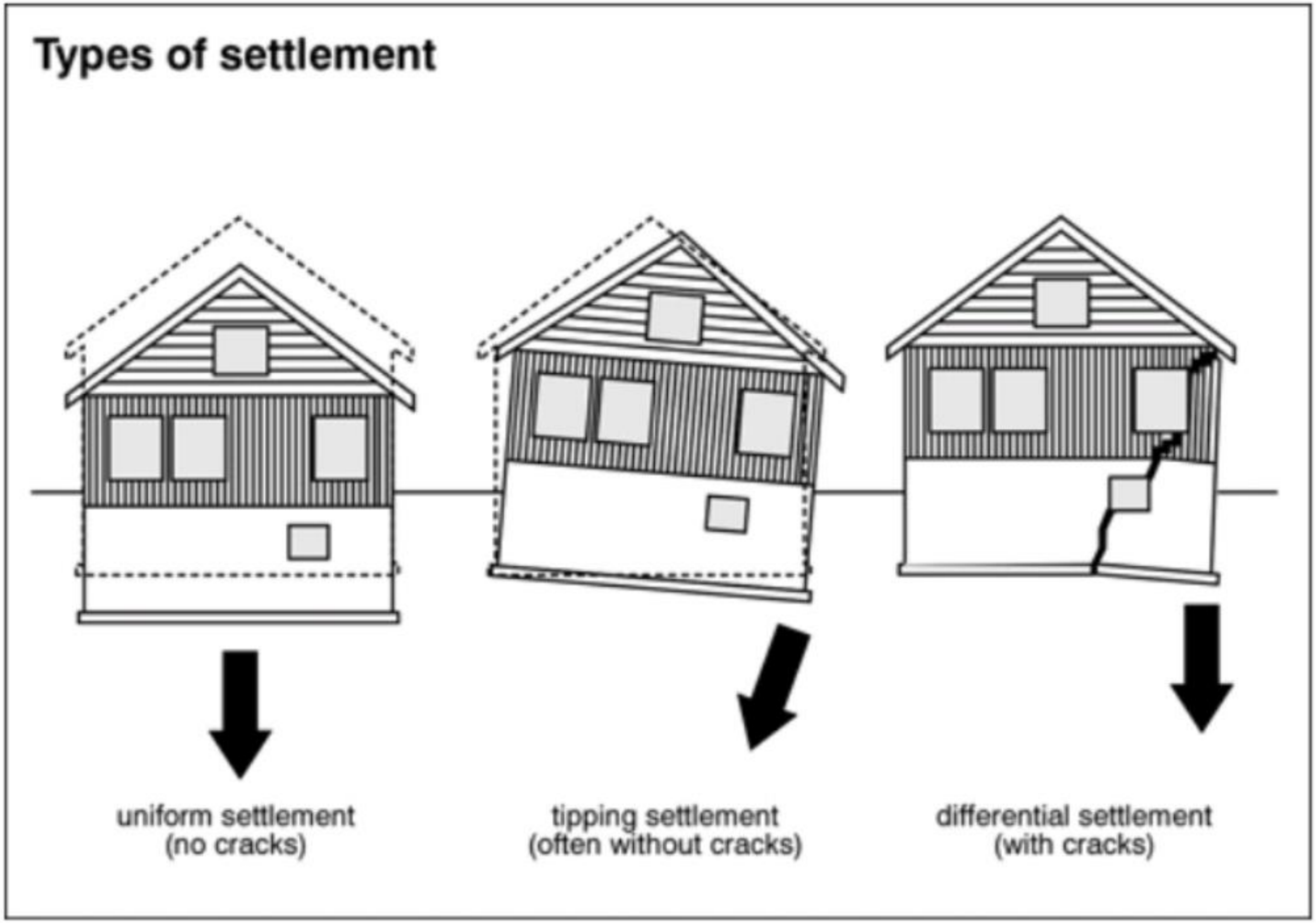
TOTAL SETTLEMENT *



DIFFERENTIAL SETTLEMENT

Uniform settlement is usually of little consequence in a building, but differential settlement can cause severe structural damage

Settlement of Foundations



Settlement of Foundations

1. **Recommendation by Skempton and MacDonald**

   i. Settlements on sand

a) Isolated footings: $\delta/l = \rho_{max}/600$, $\rho_{max} \leq 5.08cm$

b) Raft foundations: $\delta/l = \rho_{max}/750$, $\rho_{max} \leq 6.35cm$

   ii. Settlements on clay

a) Isolated footings: $\delta/l = \rho_{max}/1000$, $\rho_{max} \leq 8.38$ cm

b) Raft foundation: $\delta/l = \rho_{max}/1250$, $\rho_{max} \leq 10.8cm$

Settlement of Foundations

2. **Recommendation by Bowles**

Types of soil	Type of foundations	
	Isolated	Rafts
Sand	3.8cm	3.8-6.4cm
clay	6.4cm	6.4cm-10.2cm

Settlement of Foundations

2. **Recommendation by Euro code 7 (ES EN 1997-1:2015)**

Movement			Maximum movement to avoid limit state	
			Serviceability	Ultimate
Settlement		s	50 mm*	-
Relative rotation	sagging	β	1/2000–1/300†	1/150
	hogging		1/4000–1/600‡	1/300

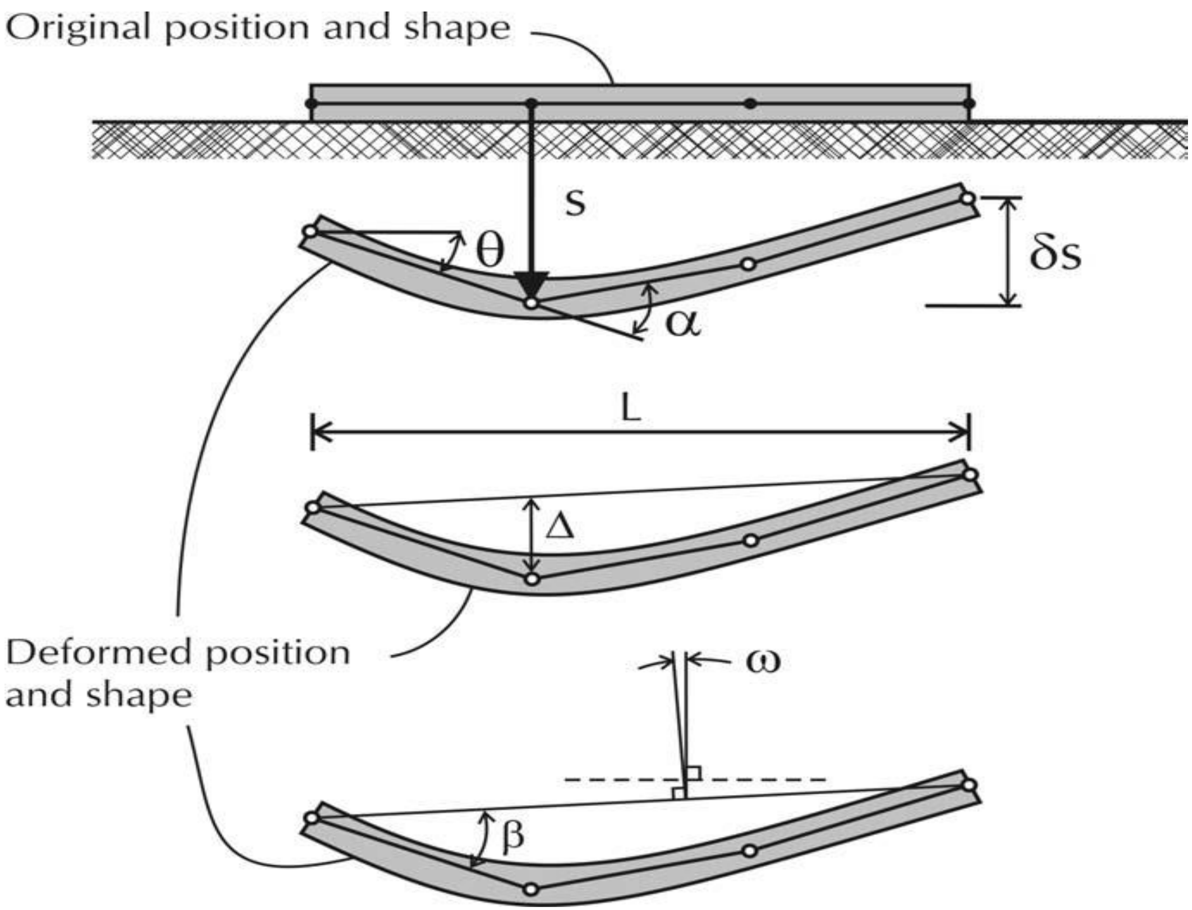
*Larger values may be acceptable if relative rotations and tilt are tolerable

†1/500 is acceptable for many structures

‡1/1000 is acceptable for many structures

Settlement of Foundations

2. **Recommendation of Euro code 7 (ES EN 1997-1:2015)**



Spread Foundation (ES EN 1997-1:2015)

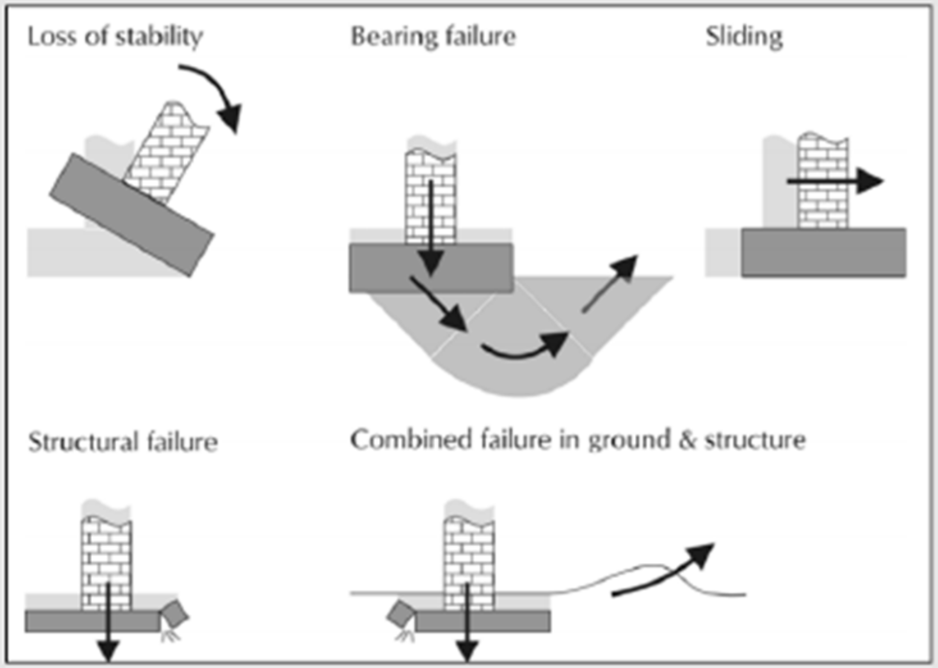
- **General**
  - Provisions apply to spread foundations including pads, strips and rafts.
  - One criteria for a safe design is that the structure should not become unfit for use.
  - The structure should not reach a limit state during its design life.
  - Achieved by designing the structure to ensure that it does not reach two important limit states.

1. **Ultimate Limit State (ULS):** concerned with the safety of the people and of the structure. This requires the whole structure or its elements should not collapse, overturn or buckle when subjected to the design loads.
2. **Serviceability Limit State (SLS):** concerned with comfort of occupants and appearance of the structure.

Spread Foundation (ES EN 1997-1:2015)

- Limit States

- loss of overall stability
- bearing resistance failure
- failure by sliding
- combined failure in the ground and in the structure
- structural failure due to foundation movement
- excessive settlements
- excessive heave due to swelling,frost and other causes
- unacceptable vibrations



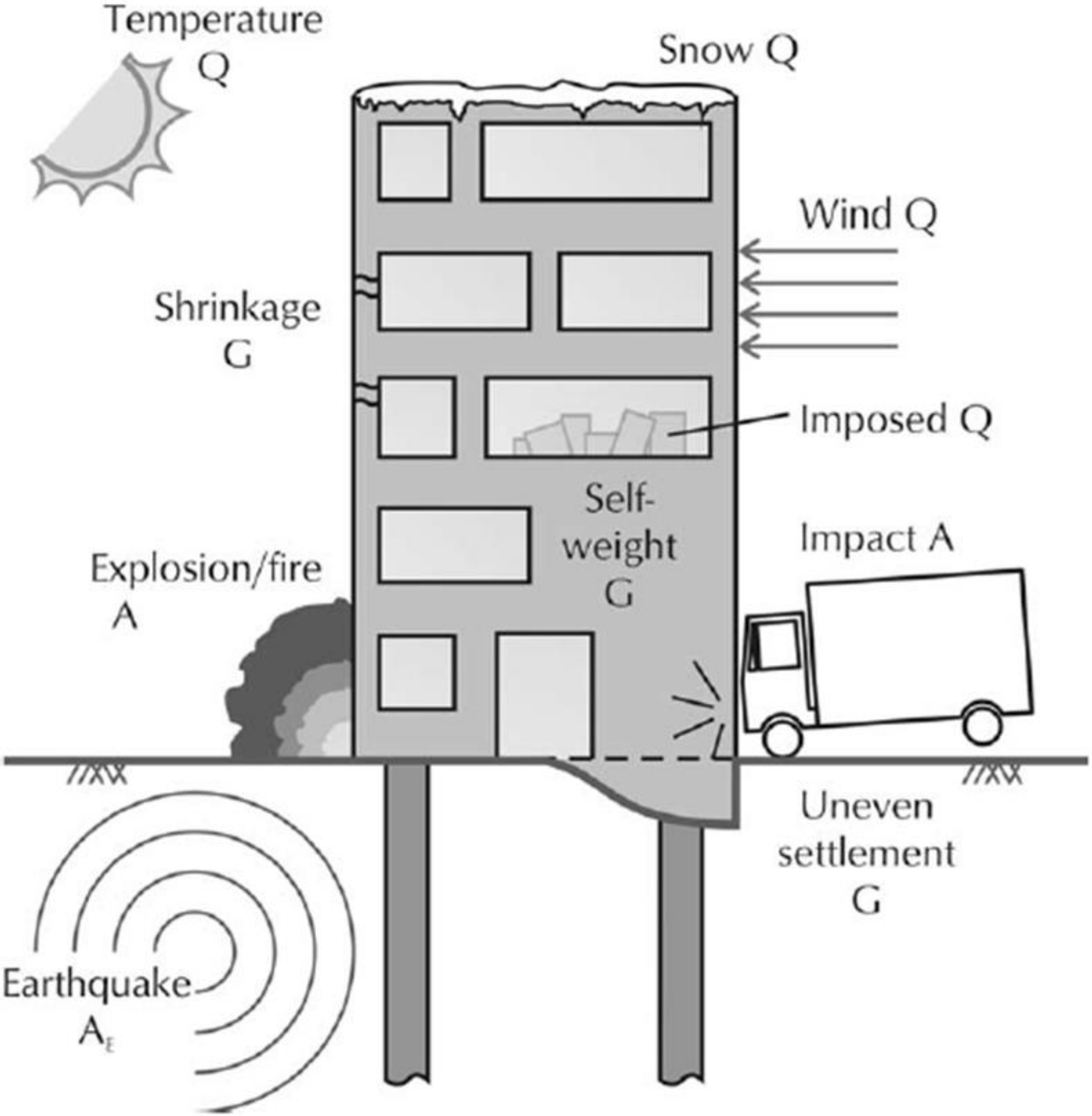
Some of above are **ultimate limit states** and some are **serviceability limit states** – both need to be considered

Spread Foundation (ES EN 1997-1:2015)

- Design situation and actions

Design situations shall be selected in accordance with 2.2.
(the actions, their combinations and load cases; overall stability; the disposition and classification of the various soils and elements of construction; dipping bedding planes; underground structures; interbedded hard and soft strata; faults, joints and fissures; possible instability of rock blocks; solution cavities; the environment within which the design is set..... earthquakes, subsidence, interference with existing constructions).

Actions include (weight of soil and water; earth pressures; free water pressure, wave pressure; seepage forces; dead and imposed loads from structures; surcharges; mooring forces; removal of load and excavation of ground; traffic loads....)


Temperature Q
Snow Q
Wind Q
Shrinkage G
Imposed Q
Self-weight G
Impact A
Explosion/fire A
Uneven settlement G
Earthquake A_E

Spread Foundation (ES EN 1997-1:2015)

- Actions, characteristic and design value of actions

Actions (loads) can be classified as

- Permanent actions (G): These are fixed values such as the self-weight of the structure and the weight of finishes, ceilings, services and partitions.
- Variable actions (Q): These are imposed loads due to people, furniture, and equipment etc. on floors, wind actions on the whole structure including roofs and snow loads on roofs.
- Accidental actions (A): These are loads due to crashing of vehicles against the building, bomb blasts and other forces.

1. **The characteristic permanent action G_k** is given by a single value as its value does not vary significantly during the lifetime of the structure.

2. **The characteristic variable action Q_k** is represented as follows.

- Combination value $\psi_0 Q_k$ is used for irreversible ultimate limit states.
- Frequent value $\psi_1 Q_k$ is used for reversible limit states.
- Quasi-permanent value $\psi_2 Q_k$ is used for calculating long term effects such as deflection due to creep and other aspects related to the appearance of the structure.

Note that combination factor ψ is a device for reducing the design value of variable loads when they act in combination.

Spread Foundation (ES EN 1997-1:2015)

The design value of an action is a product of the representative value and a load factor $\gamma_{F,\,i}$. Thus for permanent actions, design value is $\gamma_{F,i}\,G_k$. For variable actions, design value is $\gamma_{F,\,i}\,\psi_i\,Q_k$, where i = 0, 1, or 2 depending on whether it is a combination value, a frequent value or a quasi-permanent value. The value of $\gamma_{F,\,i}$ can be different for different Q_k and different from that for G_k.

The partial safety factor $\gamma_{F,\,i}$ takes account of

a. Possible increases in load
b. Inaccurate assessment of the effects of loads
c. Unforeseen stress distributions in members
d. Importance of the limit state being considered

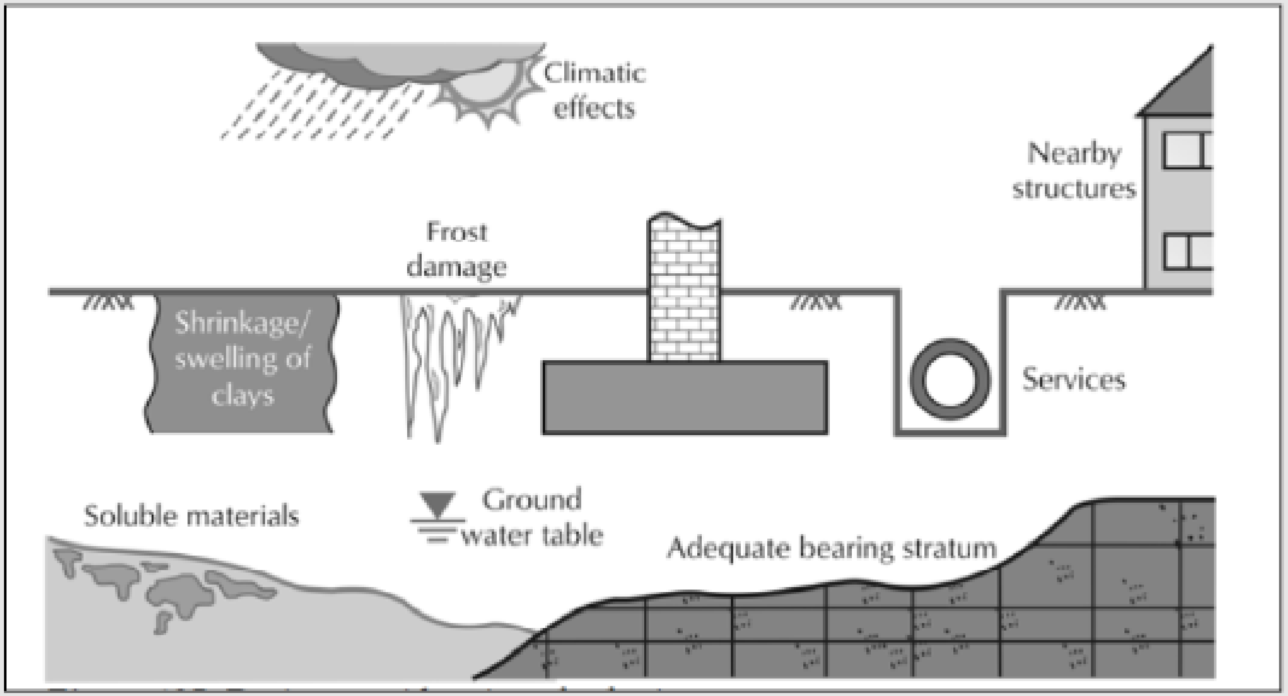
Spread Foundation (ES EN 1997-1:2015)

Imposed load on buildings				
Category	Description	Ψ_1	Ψ_2	Ψ_3
A	Domestic, residential areas	0.7	0.5	0.3
B	Office areas	0.7	0.5	0.3
C	Congregation areas	0.7	0.7	0.6
D	Shopping areas	0.7	0.7	0.6
E	Storage areas	1.0	0.9	0.8
F	Traffic area, Vehicle weight $\leq$ 30 kN	0.7	0.7	0.6
G	Traffic area, 30 kN $<$ Vehicle weight $\leq$ 160 kN	0.7	0.5	0.3
H	Roofs	0	0	0
Snow loads for sites at an altitude $>$ 1000 m		0.7	0.5	0.2
Snow loads for sites at an altitude $\leq$ 1000 m		0.5	0.2	0
Wind loads on buildings		0.6	0.2	0

Spread Foundation (ES EN 1997-1:2015)

- Design and construction considerations

A number of things that must be considered when choosing the depth of a spread foundation.



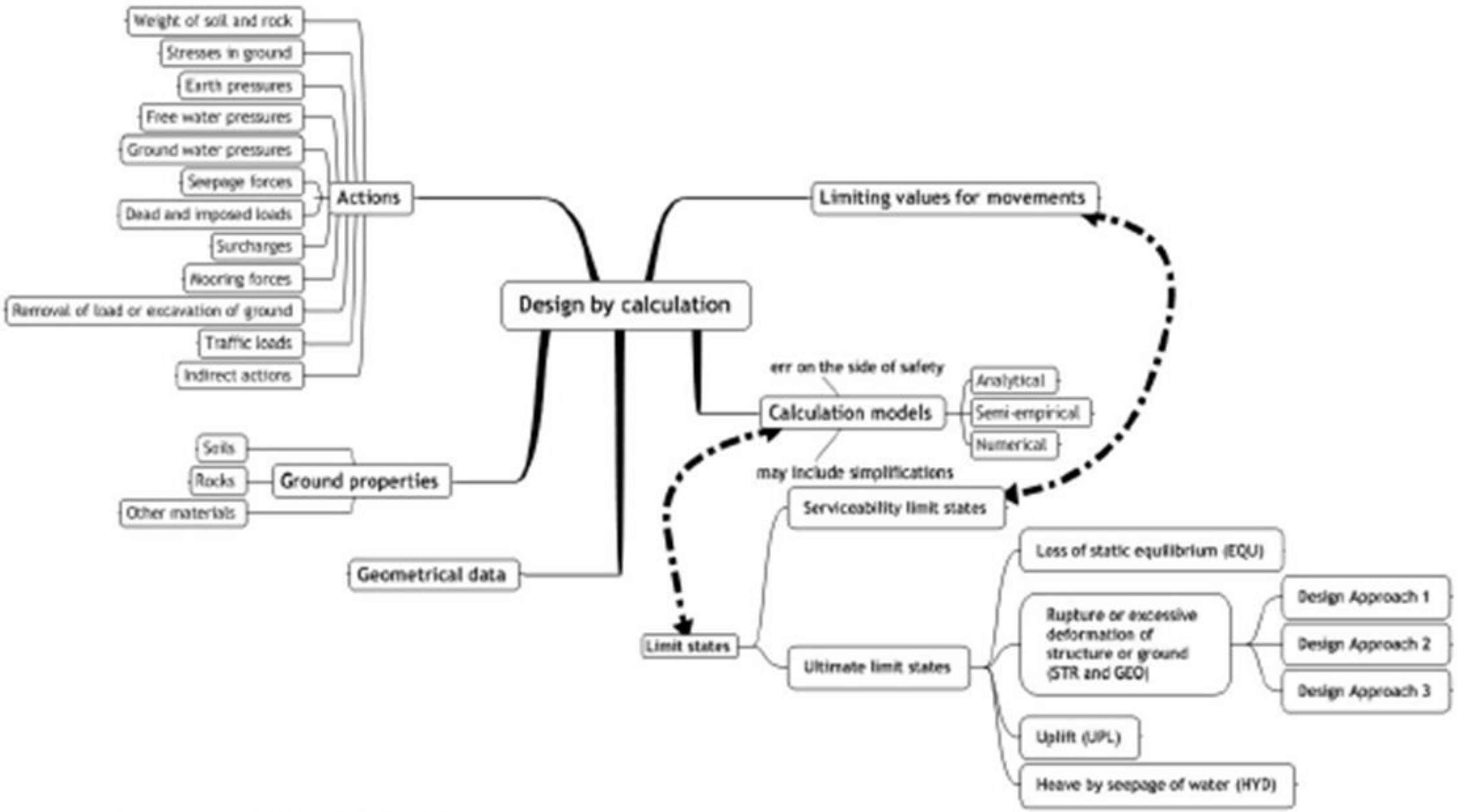


Figure 3.6. Overview of design by calculation

Spread Foundation (ES EN 1997-1:2015)

- In addition to fulfilling the performance requirements, the design foundation width shall take account of practical considerations such as economic excavation, setting out tolerances, working space requirements and dimensions of the wall or column supported by the foundation.

One of the following design methods shall be used for shallow foundations:

Method	Description	Constraints
Direct	Carry out separate analyses for each limit state, both ultimate (ULS) and serviceability (SLS)	(ULS) Model envisaged failure mechanism
		(SLS) Use a serviceability calculation
Indirect	Use comparable experience with results of field & laboratory measurements & observations	Choose SLS loads to satisfy requirements of all limit states
Prescriptive	Use conventional & conservative design rules and specify control of construction	Use presumed bearing resistance

Spread Foundation (ES EN 1997-1:2015)

ULS

Limit state design implies the application of partial factors to actions (or effect of actions) to obtain E_d and to geotechnical parameters or resistances to obtain R_d.

$$E_d \leq R_d$$

E_d design value of the effect of actions

R_d design value of the resistance to an action

SLS

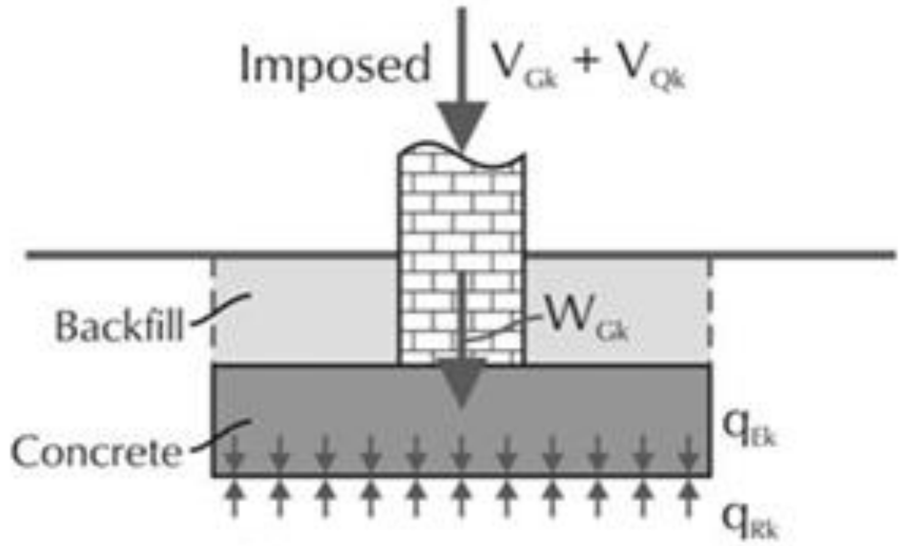
check for $E_d \leq C_d$

C_d is the limiting design value of the effect of an action

Spread Foundation (ES EN 1997-1:2015)

$$q_{Ed} \le q_{Rd}$$

where q_{Ed} is the design bearing pressure on the ground (an action effect), and q_{Rd} is the corresponding design resistance.



Spread Foundation (ES EN 1997-1:2015)

Representation of the design action

$$E_d = \sum_{j\geq 1} \gamma_{Gj} \times G_{kj} + \gamma_{Q1} \times Q_{k1} + \sum_{i>1} \gamma_{Qi} \times \psi_{0i} \times Q_{ki}$$

G_{kj}:	characteristic permanent loads
Q_{ki}:	characteristic variable loads
ψ_{0i} :	factors for combination value of variable loads
γ_{Gj} :	partial factors for permanent loads
γ_{Qi} :	partial factors for variable loads

Spread Foundation (ES EN 1997-1:2015)

- Ultimate limit state

Overall stability

Overall stability (ULS) check has to be performed for foundations on sloping ground, natural slopes or embankments and for foundations near excavations, retaining walls or buried structures, canals etc.

With DA-1 and DA-3 the stability check is carried out by using (almost) the same partial factors. DA-2 is slightly more conservative if ϕ'_k is not too great.

Table A.14 - Partial resistance factors (γ_R) for slopes and overall stability

Resistance	Symbol	Set		
		R1	***R2***	***R3***
Earth resistance	$\gamma_{R,e}$	1,0	1,1	1,0

Spread Foundation (ES EN 1997-1:2015)

Direct Method

1.ULS verifications with the three possible Design Approaches

- DA1 - Combination 1 **A1+ M1+R1**
  - Combination 2 **A2+ M2+R1**
- DA2 **A1+ M1+R2**
- DA3 **(A1 o A2)*+ M2+R3**

  *(A1 for structural actions and A2 for geotechnical actions)

– Undrained Conditions

– Drained Conditions

2. SLS check the performance of the foundation

Spread Foundation (ES EN 1997-1:2015)

Partial factors on actions (γ_F) or the effects of actions (γ_E)				
Action		Symbol	Set	
			A1	**A2**
Permanent	Unfavourable	γ_G	1.35	1.0
	Favourable		1.0	1.0
Variable	Unfavourable	γ_Q	1.5	1.3
	Favourable		0	0

Partial factors for soil parameters (γ_M)			
Soil parameter	Symbol	Value	
		M1	**M2**
Shearing resistance	$\gamma_{\varphi'}$ [1]	1.0	1.25
Effective cohesion	$\gamma_{c'}$	1.0	1.25
Undrained strength	γ_{cu}	1.0	1.4
Unconfined strength	γ_{qu}	1.0	1.4
Weight density	γ_γ	1.0	1.0
[1] This factor is applied to tan φ'			

Partial resistance factors for spread foundations (γ_R)				
Resistance	Symbol	Set		
		R1	**R2**	**R3**
Bearing	γ_{Rv}	1.0	1.4	1.0
Sliding	γ_{Rh}	1.0	1.1	1.0

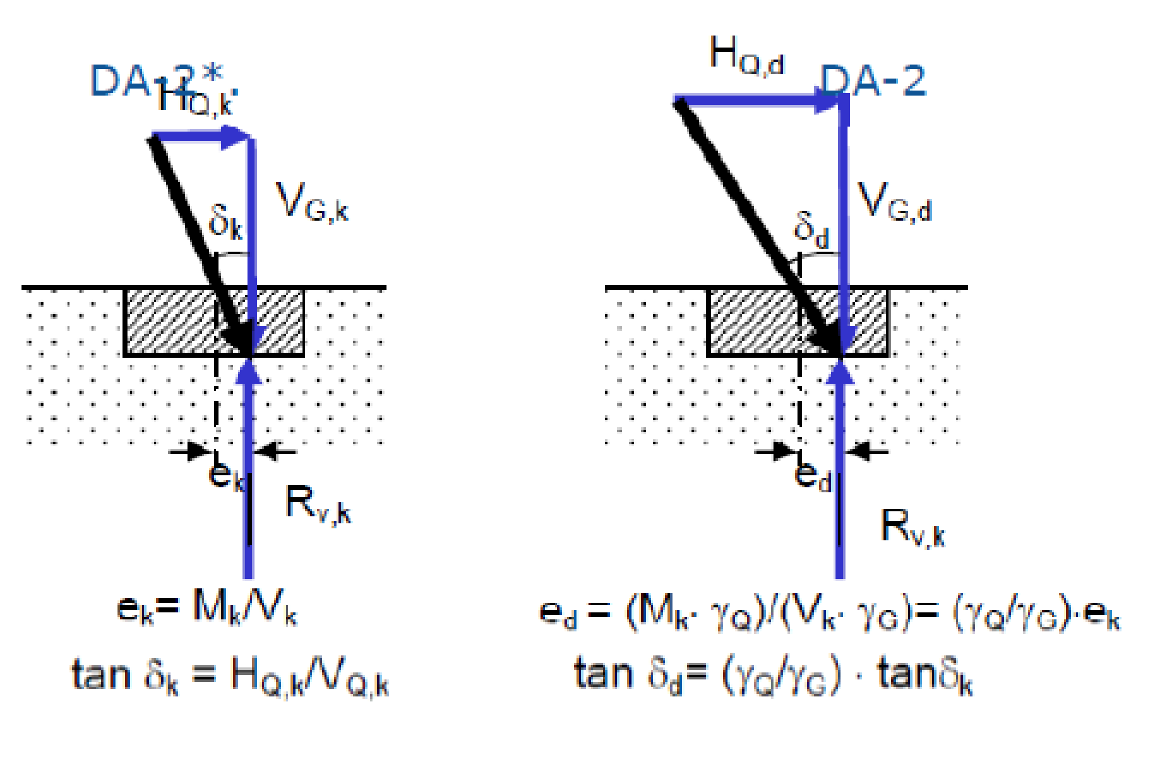
Spread Foundation (ES EN 1997-1:2015)

There are two ways of performing verifications according to Design Approach 2, either by applying them to the actions (at the source) or by applying them to the effect of the actions.

In the design approach referred to as **DA-2**, the partial factors are applied to the characteristic actions right at the start of the calculation and design values are then used.

In the design approach referred to as **DA-2***, the entire calculation is performed with characteristic values and the partial factors are introduced only at the end when the ultimate limit state condition is checked.

Spread Foundation (ES EN 1997-1:2015)



Determination of the ground bearing resistance in design procedures DA-2 and DA-2*. Design approach DA 2* gives the most economic (or less conservative) design.

Spread Foundation (ES EN 1997-1:2015)

Bearing resistance

V_d	design value of V
R_d	design value of the resistance to an action

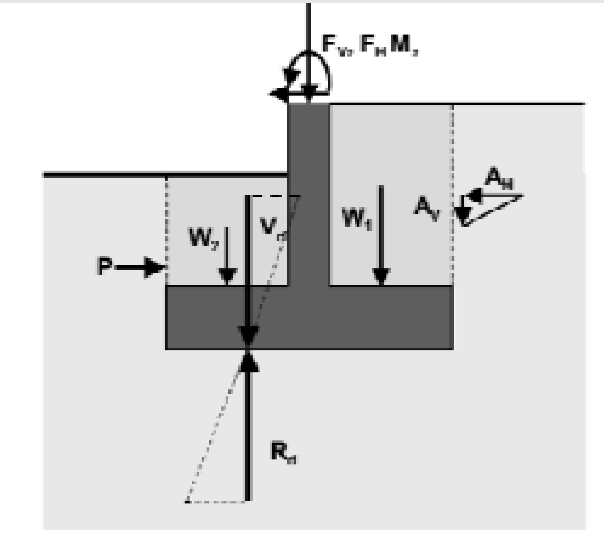
$$V_d \leq R_d$$

V_d should include the self-weight of the foundation and any backfill on it. This equation is a re-statement of the inequality: $E_d \leq R_d$

Design action V_d

- **Variable vertical load**
- **Permanent vertical load**

a) Supported permanent load
b) Weight of foundation
c) Weight of the backfill
d) Loads from water pressures
e) Uplift



Spread Foundation (ES EN 1997-1:2015)

$R/A' = c'N_c b_c s_c i_c + q'N_q b_q s_q i_q + 1/2\gamma' B' N_\gamma b_g s_g i_\gamma$ *DRAINED CONDITIONS*

$R/A' = (2+\pi) c_u s_c i_c + q$ *UNDRAINED CONDITIONS*

with the dimensionless factors for

- the bearing resistance:

$N_q = e^{\pi \times \tan\varphi'} \tan^2(45° + \varphi'/2)$

$N_c = (N_q - 1)\cot\varphi'$

$N_\gamma = 2(N_q - 1)\tan\varphi'$

- the inclination of the foundation base: b_c, b_q, b_γ
- the shape of foundation: s_c, s_q, s_γ
- the inclination of the load: i_c, i_q, i_γ

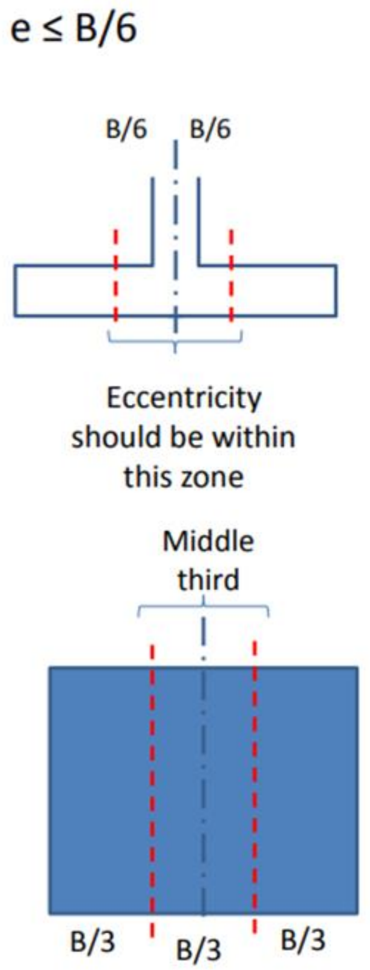
A′ = effective foundation area (reduced area with load acting at its centre)

Spread Foundation (ES EN 1997-1:2015)

The eccentricity of the action from the centre of the footing should be kept within the following limits (known as the foundation's 'middle-third') to avoid the loss of the contact between footing and ground:

$$e_B \leq B/6 \quad e_L \leq L/6$$

where B and L are the footing's breadth and length respectively and e_B and e_L are eccentricities in the direction of B and L.



Spread Foundation (ES EN 1997-1:2015)

$$R/A' = c'N_c b_c s_c i_c + q'N_q b_q s_q i_q + 1/2\gamma' B' N_\gamma b_g s_g i_\gamma$$ *DRAINED CONDITIONS*

$i_q = (1 - 0.70 \times H / (V + A' \times c' \times \cot\phi'))^m$

$m = m_B = [2+(B'/L')]/[1+(B'/L')]$

$m = m_L = [2+(L'/B')]/[1+(L'/B')]$

$m = m_\theta = m_L \cos^2\theta + m_B \sin^2\theta$

$i_c = (i_q \times N_q - 1) / (N_q - 1)$

$i_\gamma = (1 - H / (V + A' \times c' \times \cot\phi'))^3$

$s_q = 1 + (B' / L') \times \text{sen}\phi'$ (rectangular shape)

$s_q = 1 + \text{sen}\phi'$ (square or circular shape)

$s_c = (s_q \times N_q - 1) / (N_q - 1)$

$s_\gamma = 1 - 0.30 \times (B' / L')$ (rectangular shape)

$s_\gamma = 0.70$ (square or circular shape)

$b_c = b_q - (1-b_q) / (N_c \tan\phi')$

$b_q = b_\gamma = (1-\alpha \tan\phi')^2$

Spread Foundation (ES EN 1997-1:2015)

$$R/A' = (2+\pi)c_u\, b_c s_c i_c + q$$

UNDRAINED CONDITIONS

$b_c = 1 - 2\alpha/(\pi+2)$
α is the inclination of the foundation base to the horizontal

$s_c = 1 + 0.2\ (B'/L')$ (rectangular shape)
$s_c = 1.2$ (square or circular shape)

$i_c = 0.5(1+\sqrt{(1-H/(A'c_u))})$

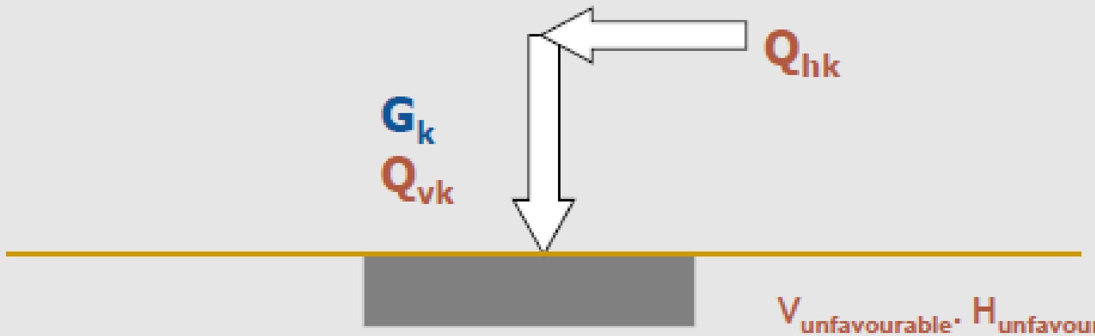
Spread Foundation (ES EN 1997-1:2015)

Considerations

For drained conditions water pressures must be included as actions. How to apply the partial factors to the weight of a submerged structure? Since the water pressure acts to reduce the value of V_d, it may be considered as favorable, while the total weight is unfavourable. Physically however, the soil has to sustain the submerged weight.

For the design of structural members, water pressure may be unfavorable.

Spread Foundation (ES EN 1997-1:2015)



$V_{unfavourable}$, $H_{unfavourable}$

$V_d = \gamma_G G_k + \gamma_{Qv} \psi_0 Q_{vk}$ $H_d = \gamma_Q Q_{hk}$

$\gamma_G = 1.35$, $\gamma_{Qv} = 1.5$, $\gamma_{Qh} = 1.5$

$V_{unfavourable}$, $H_{unfavourable}$

$V_d = \gamma_G G_k + \gamma_{Qv} Q_{vk}$ $H_d = \gamma_{Qh} \psi_0 Q_{hk}$

$\gamma_G = 1.35$, $\gamma_{Qv} = 1.5$, $\gamma_{Qh} = 1.5$

$V_{favourable}$, $H_{unfavourable}$

$V_d = \gamma_G G_k + \gamma_{Qv} Q_{vk}$ $H_d = \gamma_{Qh} Q_{hk}$

$\gamma_G = 1.00$, $\gamma_{Qv} = 0.0$, $\gamma_{Qh} = 1.5$

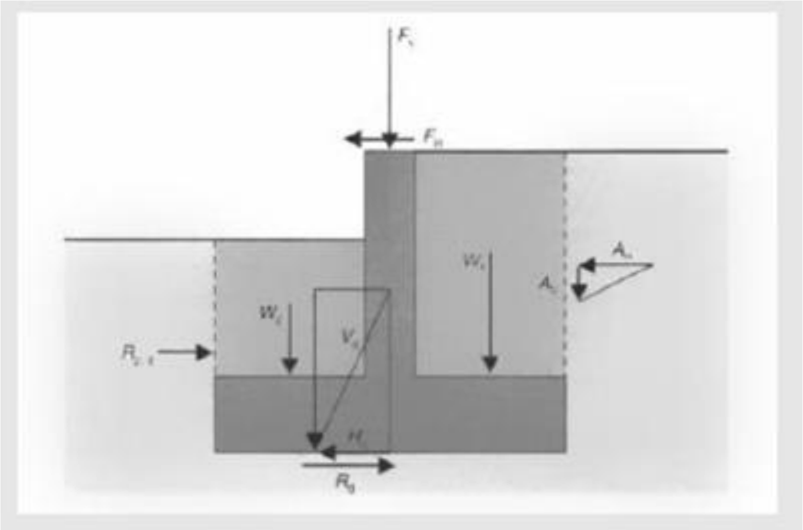
As the eccentricity influence the effective base dimension it could be necessary to analyze different load combinations, by considering the permanent vertical load both favourable and unfavourable and by changing the principal variable load.

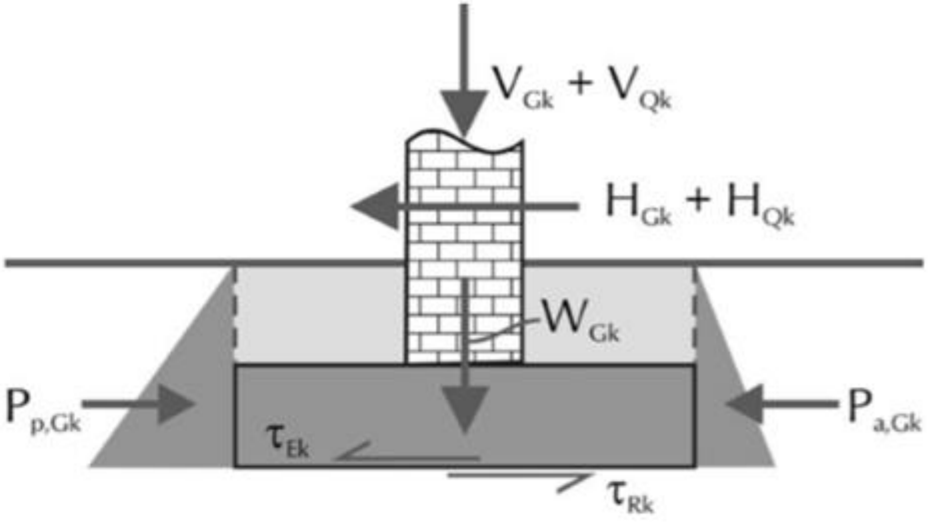
Spread Foundation (ES EN 1997-1:2015)

Sliding resistance

$$H_d \leq R_d + R_{p.d}$$

$$\tau_{Ed} \leq \tau_{Rd}$$





where τ_{Ed} is the design shear stress acting across the base of the footing (an action effect) and τ_{Rd} is the design resistance to that shear stress.

Spread Foundation (ES EN 1997-1:2015)

For drained conditions the design shear resistance, R_d, shall be calculated either by factoring the ground properties or the ground resistance as follows;

$$R_d = V'_d \tan \delta_d \text{ or } R_d = (V'_d \tan \delta_k) / \gamma_{Rh}$$

Normally it is assumed that the soil at the interface with concrete is disturbed. So the design friction angle δ_d may be assumed equal to the design value of the effective critical state angle of shearing resistance, $\phi'_{cv,d}$, for cast-in-situ concrete foundations and equal to 2/3 $\phi'_{cv,d}$ for smooth precast foundations.

Any effective cohesion c' should be neglected.

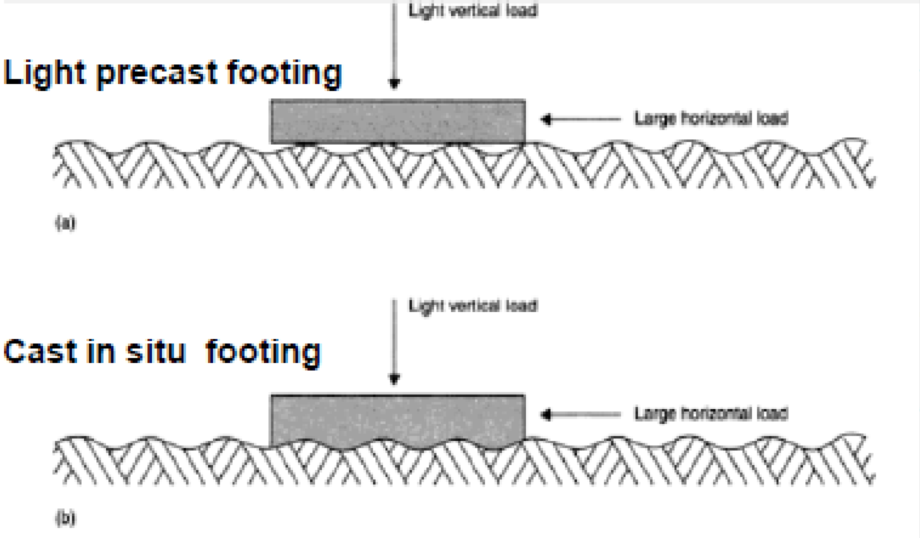
For undrained conditions, the design shearing resistance, *Rd*, shall be calculated either by factoring the ground properties or the ground resistance as follows:

$$R_d = A_c c_{u,d} \quad \text{or} \quad R_d = (A_c c_{u,k})/\gamma_{Rh}$$

Spread Foundation (ES EN 1997-1:2015)

Considerations

The maximum available sliding resistance is likely to be mobilized with relatively little movement (and may reduce as large movements take place). Hence it could be difficult to mobilize the maximum value of both R_d and $R_{p,d}$. Considering also the remoulding effects of excavation, erosion and shrinkage the passive resistance should be neglected.



In undrained conditions. in some circumstances the vertical load is insufficient to produce full contact between soil and foundation: the design resistance should be limited (0.4 V_d).

Spread Foundation (ES EN 1997-1:2015)

- Serviceability limit state

With direct methods, settlement calculations are required to check SLS

$$E_d \leq C_d$$

For soft clays settlement calculations shall always be carried out.

For spread foundations on stiff and firm clays in Geotechnical Categories 2 and 3. calculations of vertical displacement should usually be undertaken.

The following three components of settlement have to be considered:

•s_0: immediate settlement; for fully-saturated soil due to shear deformation at constant volume and for partially-saturated soil due to both shear deformation and volume reduction;

•s_1: settlement caused by consolidation;

•s_2: settlement caused by creep.

In verifications of serviceability limit states:

- Partial factors are normally taken as 1

WORKED EXAMPLES

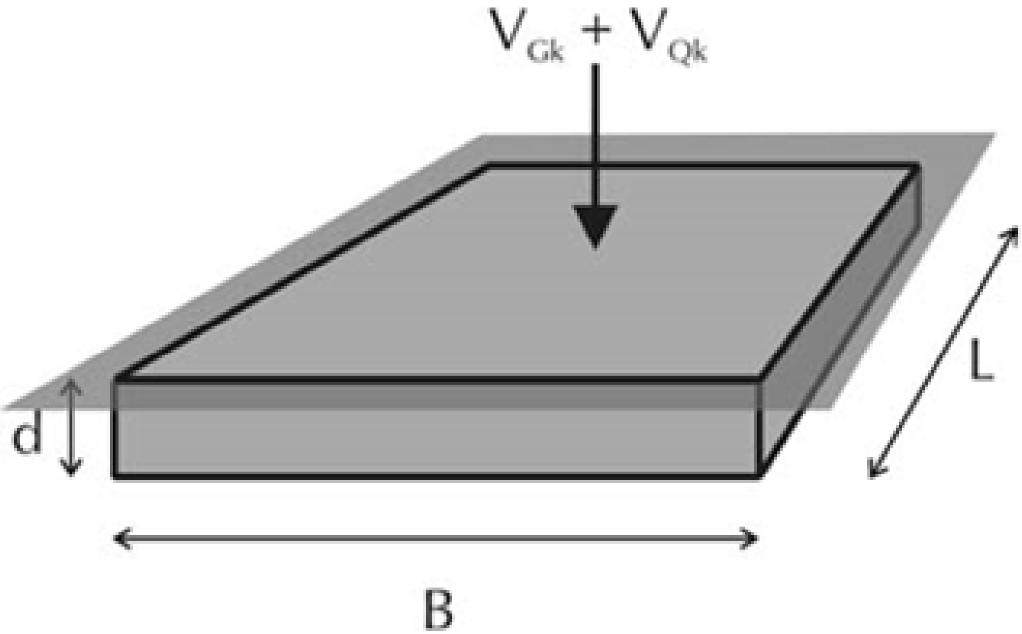
Verification of Strength and Serviceability(Limit State)

Worked Examples

1. **Pad footing on dry sand**

Example 1 considers the design of a simple rectangular spread footing on dry sand, as shown in **Figure** It adopts the calculation method given in Annex D of EN 1997-1.

In this example it is assumed that ground surface is at the top of the footing, i.e. the base of the footing is 0.5m below ground level.



. Pad footing on dry sand

Worked Examples

Design situation

Consider a rectangular pad footing of length $L = 2.5m$, breadth $B = 1.5m$, and depth $d = 0.5m$, which is required to carry an imposed permanent action $V_{Gk} = 800kN$ and an imposed variable action $V_{Qk} = 450kN$, both of which are applied at the centre of the foundation. The footing is founded on dry sand ❶ with characteristic angle of shearing resistance $\varphi_k = 35°$, effective cohesion $c'_k = 0kPa$, and weight density $\gamma_k = 18\frac{kN}{m^3}$. The weight density of the reinforced concrete is $\gamma_{ck} = 25\frac{kN}{m^3}$ (as per EN 1991-1-1 Table A.1).

Worked Examples

<u>Design Approach 1</u>

Actions and effects

Characteristic self-weight of footing is $W_{Gk} = \gamma_{ck} \times L \times B \times d = 46.9\,kN$

Partial factors from Sets $\begin{pmatrix} A1 \\ A2 \end{pmatrix}$: $\gamma_G = \begin{pmatrix} 1.35 \\ 1 \end{pmatrix}$ and $\gamma_Q = \begin{pmatrix} 1.5 \\ 1.3 \end{pmatrix}$

Design vertical action: $V_d = \gamma_G \times \left(W_{Gk} + V_{Gk}\right) + \gamma_Q \times V_{Qk} = \begin{pmatrix} 1818.3 \\ 1431.9 \end{pmatrix} kN$

Area of base: $A_b = L \times B = 3.75\,m^2$

Design bearing pressure: $q_{Ed} = \dfrac{V_d}{A_b} = \begin{pmatrix} 484.9 \\ 381.8 \end{pmatrix} kPa$

Worked Examples

Material properties and resistance

Partial factors from Sets $\begin{pmatrix} M1 \\ M2 \end{pmatrix}$: $\gamma_\varphi = \begin{pmatrix} 1 \\ 1.25 \end{pmatrix}$ and $\gamma_c = \begin{pmatrix} 1 \\ 1.25 \end{pmatrix}$

Design angle of shearing resistance is $\varphi_d = \tan^{-1}\left(\frac{\tan(\varphi_k)}{\gamma_\varphi}\right) = \begin{pmatrix} 35 \\ 29.3 \end{pmatrix}°$

Design cohesion is $c'_d = \frac{c'_k}{\gamma_c} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ kPa

Worked Examples

Bearing capacity factors

For overburden: $$N_q = \overrightarrow{\left[e^{(\pi \times \tan(\varphi_d))} \times \left(\tan\left(45° + \frac{\varphi_d}{2}\right)\right)^2\right]} = \begin{pmatrix} 33.3 \\ 16.9 \end{pmatrix}$$

For cohesion: $$N_c = \overrightarrow{\left[(N_q - 1) \times \cot(\varphi_d)\right]} = \begin{pmatrix} 46.1 \\ 28.4 \end{pmatrix}$$

For self-weight: $$N_\gamma = \overrightarrow{\left[2(N_q - 1) \times \tan(\varphi_d)\right]} = \begin{pmatrix} 45.2 \\ 17.8 \end{pmatrix}$$ ❷

Shape factors

For overburden: $$s_q = \overrightarrow{\left[1 + \left(\frac{B}{L}\right) \times \sin(\varphi_d)\right]} = \begin{pmatrix} 1.34 \\ 1.29 \end{pmatrix}$$

For cohesion: $$s_c = \overrightarrow{\frac{(s_q \times N_q - 1)}{N_q - 1}} = \begin{pmatrix} 1.35 \\ 1.31 \end{pmatrix}$$

For self-weight: $$s_\gamma = 1 - 0.3 \times \left(\frac{B}{L}\right) = 0.82$$ ❸

Worked Examples

Bearing resistance

Overburden at foundation base is $\sigma'_{vk,b} = \gamma_k \times d = 9$ kPa

Partial factors from Set $\begin{pmatrix} R1 \\ R1 \end{pmatrix}$: $\gamma_{Rv} = \begin{pmatrix} 1.0 \\ 1.0 \end{pmatrix}$

From overburden $q_{ult_1} = \overrightarrow{\left(N_q \times s_q \times \sigma'_{vk,b}\right)} = \begin{pmatrix} 402.8 \\ 196.9 \end{pmatrix}$ kPa

From cohesion $q_{ult_2} = \overrightarrow{\left(N_c \times s_c \times c'_d\right)} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ kPa

From self-weight $q_{ult_3} = \overrightarrow{\left(N_\gamma \times s_\gamma \times \gamma_k \times \frac{B}{2}\right)} = \begin{pmatrix} 500.7 \\ 197.5 \end{pmatrix}$ kPa

Total resistance $q_{ult} = \sum_{i=1}^{3} \overrightarrow{q_{ult_i}} = \begin{pmatrix} 903.5 \\ 394.4 \end{pmatrix}$ kPa

Design resistance is $q_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = \begin{pmatrix} 903.5 \\ 394.4 \end{pmatrix}$ kPa

Worked Examples

Verification of bearing resistance

Utilization factor $\Lambda_{GEO,1} = \frac{q_{Ed}}{q_{Rd}} = \left(\frac{54}{97}\right)\%$ ❹

Design is unacceptable if utilization factor is > 100%

❹ For Design Approach 1, DA1-2 is critical with a utilization factor of 97% implying that the requirements of the code are only just met.

Worked Examples

<u>Design Approach 2</u>

<u>*Actions and effects*</u>

Partial factors from Set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$

Design action is $V_d = \gamma_G \times \left(W_{Gk} + V_{Gk}\right) + \gamma_Q \times V_{Qk} = 1818.3\,\text{kN}$

Design bearing pressure is $q_{Ed} = \dfrac{V_d}{A_b} = 484.9\,\text{kPa}$

<u>*Material properties and resistance*</u>

Partial factors from Set M1: $\gamma_\varphi = 1.0$ and $\gamma_c = 1.0$

Design angle of shearing resistance is $\varphi_d = \tan^{-1}\left(\dfrac{\tan\left(\varphi_k\right)}{\gamma_\varphi}\right) = 35°$

Design cohesion is $c'_d = \dfrac{c'_k}{\gamma_c} = 0\,\text{kPa}$

Worked Examples

Bearing capacity factors

For overburden: $N_q = e^{(\pi \times \tan(\varphi_d))} \left(\tan\left(45° + \frac{\varphi_d}{2} \right) \right)^2 = 33.3$

For cohesion: $N_c = (N_q - 1) \times \cot(\varphi_d) = 46.1$

For self-weight: $N_\gamma = 2(N_q - 1) \times \tan(\varphi_d) = 45.2$

Shape factors

For overburden: $s_q = 1 + \left(\frac{B}{L} \right) \times \sin(\varphi_d) = 1.34$

For cohesion: $s_c = \frac{s_q \times N_q - 1}{N_q - 1} = 1.35$

For self-weight: $s_\gamma = 1 - 0.3 \times \left(\frac{B}{L} \right) = 0.82$

Worked Examples

Bearing resistance

Partial factor from Set R2: $\gamma_{Rv} = 1.4$ ❺

From overburden $q_{ult_1} = N_q \times s_q \times \sigma'_{vk,b} = 402.8\,\text{kPa}$

From cohesion $q_{ult_2} = N_c \times s_c \times c'_d = 0\,\text{kPa}$

From self-weight $q_{ult_3} = N_\gamma \times s_\gamma \times \gamma_k \times \frac{B}{2} = 500.7\,\text{kPa}$

Total resistance $q_{ult} = \sum q_{ult} = 903.5\,\text{kPa}$

Design resistance is $q_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = 645.3\,\text{kPa}$

Worked Examples

Verification of bearing resistance

Utilization factor $\Lambda_{GEO,2} = \dfrac{q_{Ed}}{q_{Rd}} = 75\,\%$ ❻

Design is unacceptable if utilization factor is > 100%

❻ The calculated utilization factor is 75% which would indicate that according to DA2 the footing is potentially over-designed.

Worked Examples

Design Approach 3

Actions and effects

Partial factors on structural actions, Set A1: $\gamma_G = 1.35$ and $\gamma_Q = 1.5$

Design vertical action $V_d = \gamma_G \times (W_{Gk} + V_{Gk}) + \gamma_Q \times V_{Qk} = 1818.3\ kN$

Design bearing pressure $q_{Ed} = \frac{V_d}{A_b} = 484.9\ kPa$

Material properties and resistance

Partial factors from Set M1: $\gamma_\varphi = 1.25$ and $\gamma_c = 1.25$ ❼

Design angle of shearing resistance is $\varphi_d = \tan^{-1}\left(\frac{\tan(\varphi_k)}{\gamma_\varphi}\right) = 29.3°$

Design cohesion is $c'_d = \frac{c'_k}{\gamma_c} = 0\ kPa$

Worked Examples

Bearing capacity factors

For overburden: $N_q = e^{(\pi \times \tan(\varphi_d))} \times \left(\tan\left(45° + \frac{\varphi_d}{2}\right)\right)^2 = 16.9$

For cohesion: $N_c = (N_q - 1) \times \cot(\varphi_d) = 28.4$

For self-weight: $N_\gamma = 2(N_q - 1) \times \tan(\varphi_d) = 17.8$

Shape factors

For overburden: $s_q = 1 + \left(\frac{B}{L}\right) \times \sin(\varphi_d) = 1.29$

For cohesion: $s_c = \frac{s_q \times N_q - 1}{N_q - 1} = 1.31$

For self-weight: $s_\gamma = 1 - 0.3 \times \left(\frac{B}{L}\right) = 0.82$

Worked Examples

Bearing resistance

Partial factor from Set R2: $\gamma_{Rv} = 1$

From overburden $q_{ult_1} = N_q \times s_q \times \sigma'_{vk,b} = 196.9\,kPa$

From cohesion $q_{ult_2} = N_c \times s_c \times c'_d = 0\,kPa$

From self-weight $q_{ult_3} = N_\gamma \times s_\gamma \times \gamma_k \times \frac{B}{2} = 197.5\,kPa$

Total resistance $q_{ult} = \sum q_{ult} = 394.4\,kPa$

Design resistance $q_{Rd} = \frac{q_{ult}}{\gamma_{Rv}} = 394.4\,kPa$

Worked Examples

Verification of bearing resistance

Utilization factor $\Lambda_{GEO,3} = \frac{q_{Ed}}{q_{Rd}} = 123\,\%$ ❽

Design is unacceptable if utilization factor is > 100%

❽ The resultant utilization factor is 123% thus the DA3 calculation suggests the design is unsafe and re-design would be required.

Worked Examples

2. Eccentric pad footing on dry sand

Example 2 considers the design of a pad footing on dry sand, in which the imposed vertical load from the superstructure is eccentric to the centre of the foundation, as shown in **Figure**

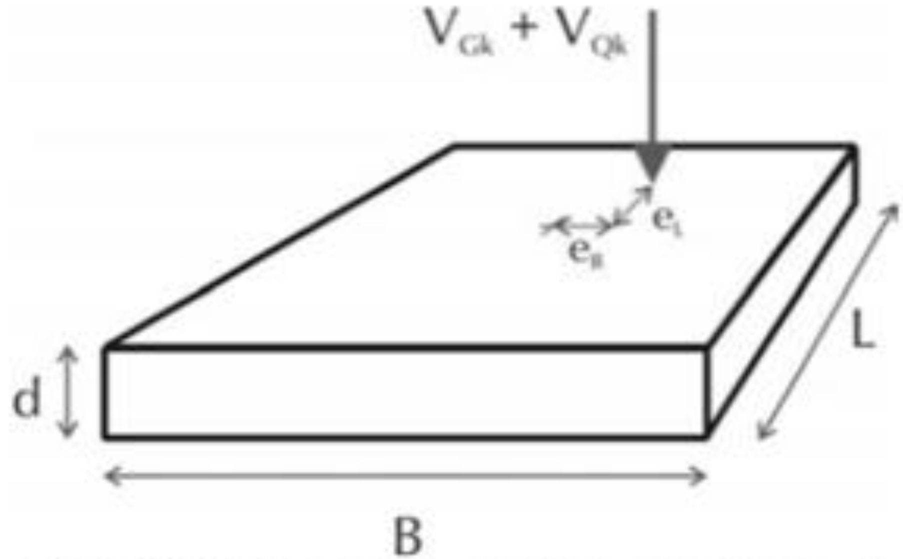


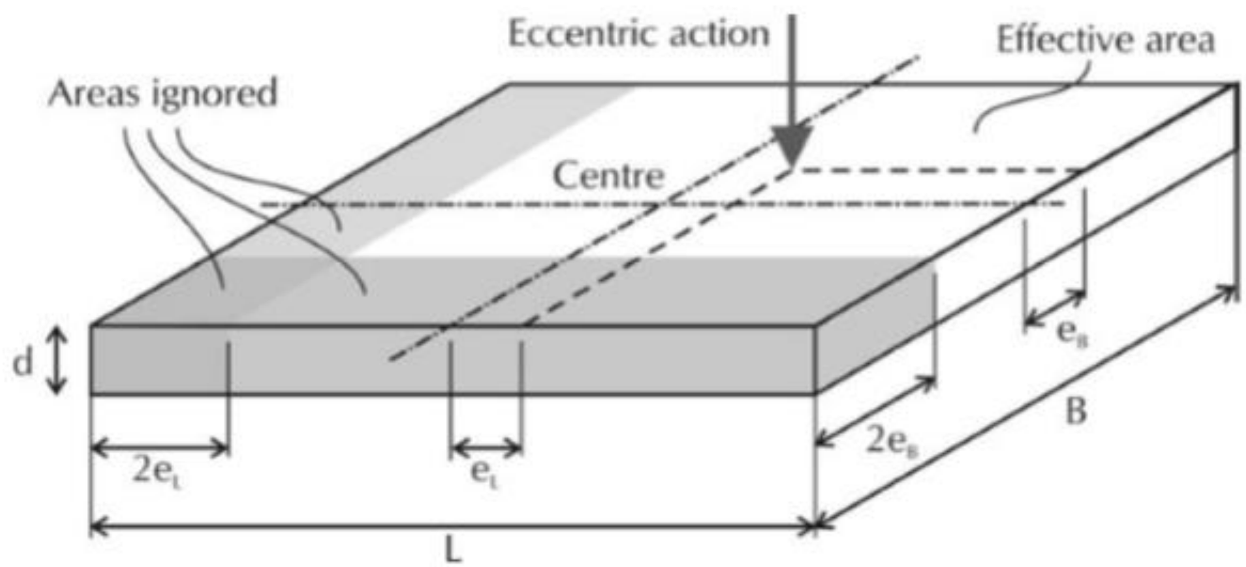
Figure Eccentric pad footing on dry sand

Because the load is eccentric, the foundation's design is based on its effective area. The foundation's self weight (which acts through the centre of the footing) helps to reduce the eccentricity of the total load. Eccentric loads should be avoided whenever possible since they make the footing inefficient.

Worked Examples

<u>*Design situation*</u>

Owing to an error on site, the pad footing from the previous design example is out-of-position on plan, such that the imposed actions act at distances $e_B = 75mm$ and $e_L = 100mm$ from the centre of the footing.



Worked Examples

Design Approach 1

Geometry

Eccentricity of total vertical action:

$$e'_B = \frac{\left(\gamma_G V_{Gk} + \gamma_Q V_{Qk}\right) \times e_B}{\gamma_G \times \left(W_{Gk} + V_{Gk}\right) + \gamma_Q V_{Qk}} = \begin{pmatrix} 72.4 \\ 72.5 \end{pmatrix} \text{mm} \quad ❶$$

Load is within middle-third of base if $e'_B \leq \dfrac{B}{6} = 250\,\text{mm}$

Effective breadth is $B' = B - 2e'_B = \begin{pmatrix} 1.36 \\ 1.35 \end{pmatrix} \text{m}$ ❷

Worked Examples

Eccentricity of total vertical action:

$$e'_L = \frac{(\gamma_G V_{Gk} + \gamma_Q V_{Qk}) \times e_L}{\gamma_G \times (W_{Gk} + V_{Gk}) + \gamma_Q V_{Qk}} = \begin{pmatrix} 96.5 \\ 96.7 \end{pmatrix} mm$$

Load is within middle-third of base if $e'_L \le \frac{L}{6} = 417\,mm$

Effective length is $L' = L - 2e'_L = \begin{pmatrix} 2.31 \\ 2.31 \end{pmatrix} m$ ❷

Effective area of base is therefore $A'_b = \overrightarrow{(L' \times B')} = \begin{pmatrix} 3.13 \\ 3.13 \end{pmatrix} m^2$

Continue…….