CE-632 Foundation Analysis and Design

Shallow Foundations



SUMMARY of Terminology

Gross Loading Intensity

Total pressure at the level of foundation including the weight of superstructure, foundation, and the soil above foundation.

$$q_{g} = \frac{Q_{\text{superstructure}} + Q_{\text{Foundation}} + Q_{\text{soil}}}{A_{\text{Foundation}}}$$

Net Loading Intensity

Pressure at the level of foundation causing actual settlement due to stress increase. This includes the weight of superstructure and foundation only.

$$q_n = q_g - \gamma D_f$$

Ultimate Bearing capacity:

Maximum gross intensity of loading that the soil can support against shear failure is called ultimate bearing capacity.

$$q_u$$
 from

Bearing capacity calculation

Net Ultimate Bearing Capacity:

Maximum net intensity of loading that the soil can support at the level of foundation.

$$q_{nu} = q_u - \gamma D_f$$



SUMMARY of Terminology

Net Safe Bearing capacity:

Maximum net intensity of loading that the soil can safely support without the risk of shear failure.

$$q_{ns} = \frac{q_{nu}}{FOS}$$

Gross Safe Bearing capacity:

Maximum gross intensity of loading that the soil can safely support without the risk of shear failure.

$$q_{gs} = q_{ns} + \gamma D_f$$

Safe Bearing Pressure:

Maximum net intensity of loading that can be allowed on the soil without settlement exceeding the permissible limit.

 $q_{\rho s}$ from settlement analysis

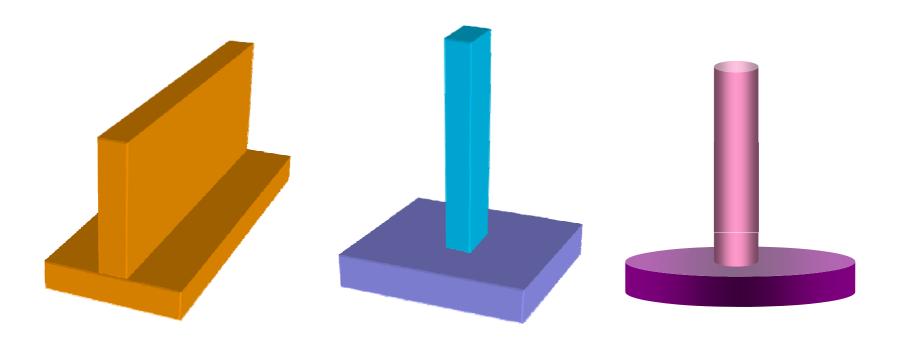
Allowable Bearing Pressure:

Maximum net intensity of loading that can be allowed on the soil with no possibility of shear failure or settlement exceeding the permissible limit. q_{a-net} Minimum of bearing capacity and settlement analysis



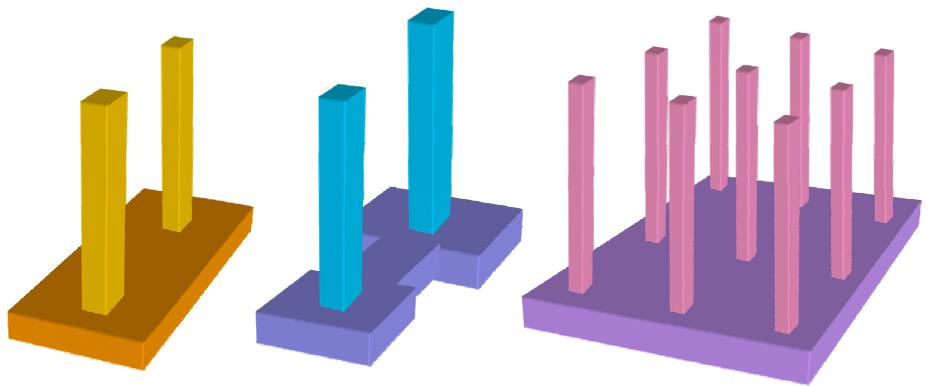
Common Types of Footing

- Strip footing
- Spread Footing





- Combined Footing
- Raft or Mat footing





General Requirements of Foundation

Location and Depth of Foundation

Bearing Capacity of Foundation

DONE

Settlement of Foundation

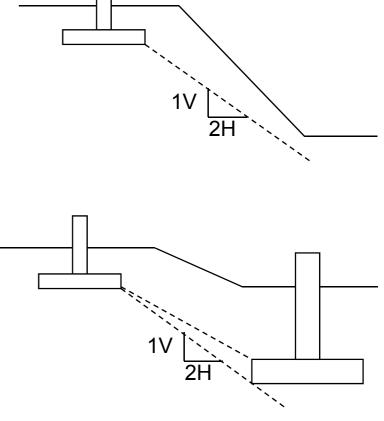
DONE



- The following considerations are necessary for deciding the location and depth of foundation
 - > As per IS:1904-1986, minimum depth of foundation shall be 0.50 m.
 - Foundation shall be placed below the zone of
 - The frost heave
 - Excessive volume change due to moisture variation (usually exists within 1.5 to 3.5 m depth of soil from the top surface)
 - Topsoil or organic material
 - Peat and Muck
 - Unconsolidated material such as waste dump
 - Foundations adjacent to flowing water (flood water, rivers, etc.) shall be protected against scouring. The following steps to be taken for design in such conditions
 - Determine foundation type
 - Estimate probable depth of scour, effects, etc.
 - Estimate cost of foundation for normal and various scour conditions
 - > Determine the scour versus risk, and revise the design accordingly



- ➤ IS:1904-1986 recommendations for foundations adjacent to slopes and existing structures
 - When the ground surface slopes downward adjacent to footing, the sloping surface should not cut the line of distribution of the load (2H:1V).
 - In granular soils, the line joining the lower adjacent edges of upper and lower footings shall not have a slope steeper than 2H:1V.
 - In clayey soil, the line joining the lower adjacent edge of the upper footing and the upper adjacent edge of the lower footing should not be steeper than 2H:1V.





- Other recommendations for footing adjacent to existing structures
 - Minimum horizontal distance between the foundations shall not be less than the width of larger footing to avoid damage to existing structure
 - If the distance is limited, the principal of 2H:1V distribution should be used so as to minimize the influence to old structure
 - Proper care is needed during excavation phase of foundation construction beyond merely depending on the 2H:1V criteria for old foundations. Excavation may cause settlement to old foundation due to lateral bulging in the excavation and/or shear failure due to reduction in overburden stress in the surrounding of old foundation



- Footings on surface rock or sloping rock faces
 - > For the locations with shallow rock beds, the foundation can be laid on the rock surface after chipping the top surface.
 - ▶ If the rock bed has some slope, it may be advisable to provide dowel bars of minimum 16 mm diameter and 225 mm embedment into the rock at 1 m spacing.
- A raised water table may cause damage to the foundation by
 - Floating the structure
 - Reducing the effective stress beneath the foundation

Water logging around the building may also cause wet basements. In such cases, proper drainage system around the foundation may be required so that water does not accumulate.



Loads on Foundation

- Permanent Load: This is actual service load/sustained loads of a structure which give rise stresses and deformations in the soil below the foundation causing its settlement.
- **Transient Load:** This momentary or sudden load imparted to a structure due to wind or seismic vibrations. Due to its transitory nature, the stresses in the soil below the foundation carried by such loads are allowed certain percentage increase over the allowable safe values.

- Dead Load: It includes the weight of the column/wall, footings, foundations, the overlaying fill but excludes the weight of the displaced soil
- Live Load: This is taken as per the specifications of IS:875 (pt-2) 1987.

Loads for Proportioning and Design of Foundation IS:1904 - 1986

- Following combinations shall be used
 - Dead load + Live load
 - Dead Load + Live load + Wind/Seismic load
- For cohesive soils only 50% of actual live load is considered for design (Due to settlement being time dependent)
- For wind/seismic load < 25% of Dead + Live load</p>
 - Wind/seismic load is neglected and first combination is used to compare with safe bearing load to satisfy allowable bearing pressure
- For wind/seismic load ≥ 25% of Dead + Live load
 - ➤ It becomes necessary to ensure that pressure due to second combination of load does not exceed the safe bearing capacity by more than 25%. When seismic forces are considered, the safe bearing capacity shall be increased as specified in IS: 1893 (Part-1)-2002 (see next slide). In non-cohesive soils, analysis for liquefaction and settlement under earthquake shall also be made.

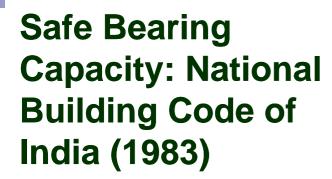
Table 1 Percentage of Permissible Increase in Allowable Bearing Pressure or Resistance of Soils

 $(\ Clause\ 6.3.5.2\)$

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Sl No.	Foundation	Type of Soil Mainly Constituting the Foundation				
		Soil: Well graded gravel and sand gravel		soil other than SP ¹⁾		
(1)	(2)	(3)	(4)	(5)		
i)	Piles passing through any soil but resting on soil type I	50	50	50		
ii)	Piles not covered under item i	_	25	25		
iii)	Raft foundations	50	50	50		
iv)	Combined isolated RCC footing with tie beams	50	25	25		
v)	Isolated RCC footing without tie beams, or unreinforced strip foundations	50	25	_		
vi)	Well foundations	50	25	25		

Safe Bearing Capacity: National Building Code of India (1983)

Rocks and Cohesionless soils			Rocks and Cohesionless soils				
		Description	Safe Bearings capacity (kN/m²)			Description	Safe Bearings capacity (kN/m²)
(a)	Roci	ks		(b)	Coh	esionless soils	
	1.	Rocks (hard) without lamination and defects, for example, granite, trap and diorite	1	penetration when excavated b		and offering resistance to penetration when excavated by	
	2.	Laminated rocks, for example sand stone and line stone in sound condition		6.	tools (See Note 1) Coarse sand, compact and dry	440	
	3.	Residual deposits of shattered and broken bedrock and hard shale, cemented material					245
					7.	Medium sand, compact and dry	245
	4.	Soft rock	440		8.	Find sand, silt (dry lumps easily pulverised by fingers)	150
					9.	Loose gravel or sand gravel mixture: Loose coarse to medium sand, dry	1
					10.	Fine sand, loose and dry	100



Cohesive soils						
71		Description	Safe Bearings capacity			
	· .		(kN/m^2)			
(c)	Coh	esive soils	-			
	1.	Soft shale, hard or stiff clay in deep bed, dry	440			
-	2.	Medium clay readily indented with a thumb nail	245			
	3.	Moist clay and sand clay mixture which can be indented with strong thumb pressure	150			
-	4.	Soft clay indented with moderate thumb pressure	100			
; ;	5.	Very soft clay which can be penetrated several centimetre, with the thumb	50			
	6.	Black cotton soils or other shrinkable or expansive clay in dry condition (50 percent saturation.	·			



Other considerations for Shallow Foundation Design

- For economical design, it is preferred to have square footing for vertical loads and rectangular footing for the columns carrying moment
- Allowable bearing pressure should not be very high in comparison to the net loading intensity leading to an uneconomical design.
- It is preferred to use SPT or Plate load test for cohesion less soils and undrained shear strength test for cohesive soils.
- In case of lateral loads or moments, the foundation should also be checked to be safe against sliding and overturning. The FOS shall not be less than 1.75 against sliding and 2.0 against overturning. When wind/seismic loads are considered the FOS is taken as 1.5 for both the cases.
- Wall foundation width shall not be less than [wall thickness + 30 cm].
- Unreinforced foundation should have angular spread of load from the supported column with the following criteria
 - 2V:1H for masonry foundation
 - > 3V:2H for lime concrete
 - > 1V:1H for cement concrete foundation

The bottom most layer should have a thickness of atleast 150 mm.



Combined Footings

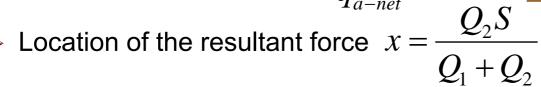
- Combined footing is preferred when
 - The columns are spaced too closely that if isolated footing is provided the soil beneath may have a part of common influence zone.
 - The bearing capacity of soil is such that isolated footing design will require extent of the column foundation to go beyond the property line.
- Types of combined footings
 - Rectangular combined footing
 - Trapezoidal combined footing
 - Strap beam combined footing

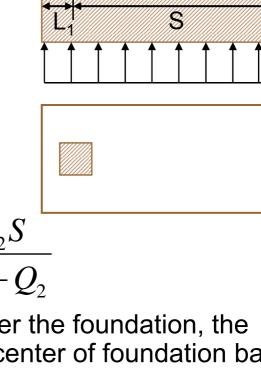


Rectangular Combined Footing

- If two or more columns are carrying almost equal loads, rectangular combined footing is provided
- Proportioning of foundation will involve the following steps
 - \rightarrow Area of foundation $A = \frac{Q_1 + Q_2}{Q_1 + Q_2}$

$$A = \frac{Q_1 + Q_2}{q_{a_1 \text{ nat}}}$$





X

 Q_1+Q_2

> For uniform distribution of pressure under the foundation, the resultant load should pass through the center of foundation base.

Length of foundation,
$$L = 2(L_1 + S)$$

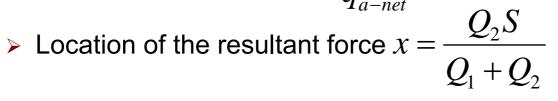
Offset on the other side,
$$L_2 = L - S - L_1 > 0$$

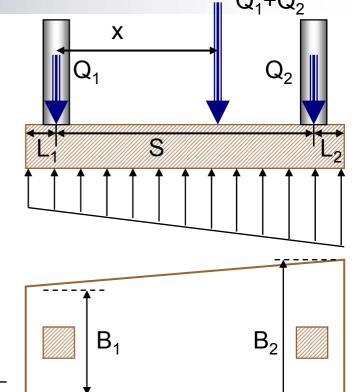
ightharpoonup The width of foundation, B=A/L

Trapezoidal Combined Footing

- If one of the columns is carrying much larger load than the other one, trapezoidal combined footing is provided
- Proportioning of foundation will involve the following steps if L, and L₁ are known







For uniform distribution of pressure under the foundation, the resultant load should pass through the center of foundation base. This gives the relationship,

snip,

$$x + L_1 = \left(\frac{B_1 + 2B_2}{B_1 + B_2}\right) \frac{L}{3}$$

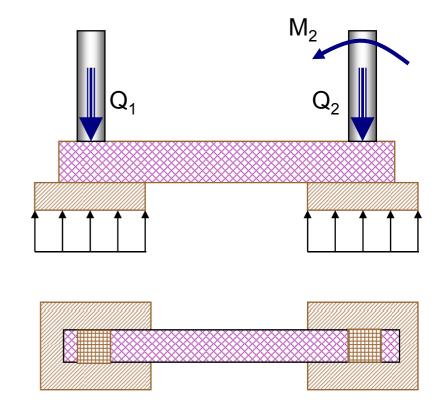
> Area of the footing, $\frac{B_1 + B_2}{2}L = A$

Solution of these two equations gives B₁ and B₂



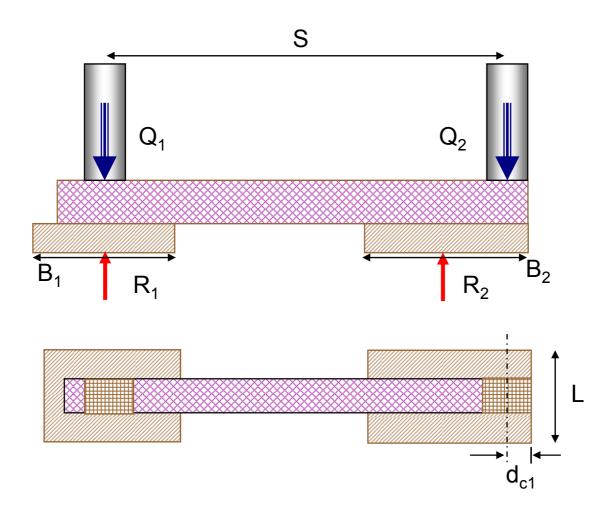
Strap Combined Footing

- Strap footing is used to connect an eccentrically loaded column footing to an interior column so that the moment can be transferred through the beam and have uniform stress distribution beneath both the foundations.
- This type of footing is preferred over the rectangular or trapezoidal footing if distance between the columns is relatively large.
- Some design considerations:
 - > Strap must be rigid: $I_{strap}/I_{footing} > 2$.
 - Footings should be proportioned to have approximately equal soil pressure in order to avoid differential settlement
 - > Strap beam should not have contact with soil to avoid soil reaction to it.





Example: Strap Footing





Raft or Mat Foundations

- Where is it needed?
 - Structures like chimneys, silos, cooling towers, buildings with basements where continuous water proofing is needed
 - For foundations where differential settlement can be a major concern
 - For soft soils strata or site with pockets of weak soil
 - In situations where individual footings may touch or overlap each other.



Types of Raft Foundation

- Plane Slab Rafts: For fairly small and uniform spacing of columns and when the supporting soil is not too compressible.
- Beam and Slab: For large column spacing and unequal column loads.
- Slab with Column Pedestals: For columns with heavy loads which may require large shear strength or flexural strength of slab.
- Cellular Rafts: For compensated foundations to avoid differential settlements in weak soils.
- **Piled Rafts:** For heavy structures on soft soils in order to share the loads with piles.
- Strip Rafts or Grid Rafts: For economical design where a complete slab may be avoided.



General Considerations for Raft Foundation

- The depth of foundation shall not be less than 1.0 m.
- Punching shear failure for raft foundation on cohesionless soils is not an option so it shall not be considered for analysis. The design is mostly governed by settlement criteria.
- For raft foundations on cohesive soils, stability against deep seated failure shall be analyzed. The effect of long term settlement due to consolidation shall also be considered.
- The uplift due to sub-soil water shall be considered in design. The construction below water table shall be checked for floatation
- Foundations subjected to heavy vibratory loading should preferably be isolated



Rigidity of Soil-Structure System

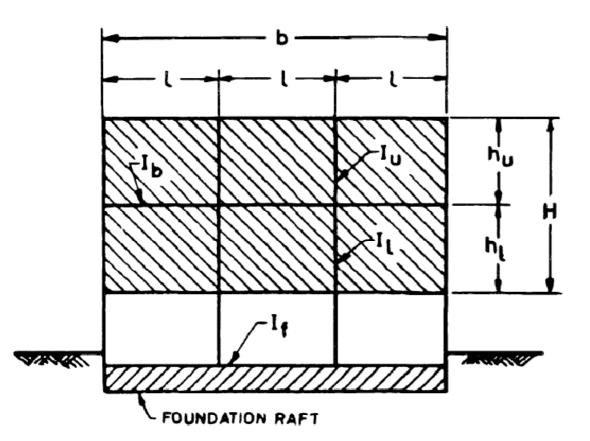
- Performance of raft depends on the relative rigidity of its three components
 - Super structure
 - > Raft
 - > Soil
- Distribution of contact pressures depends on the relative rigidity of the foundation with respect to soil
- It is important that the rigidity of superstructure also matches with the rigidity of foundation
 - Rigid Superstructure with Rigid Foundation: Does not allow differential settlement so it is good
 - Rigid Superstructure with Flexible Foundation: Large deformations in the foundation which is not suitable for superstructure
 - Flexible Superstructure with Rigid Foundation: It may acceptable but not necessary
 - Flexible Superstructure with Flexible Foundation: This is also good



Flexural Rigidity of Structure, El

$$EI = \frac{E_{l}I_{l}b^{2}}{2H^{2}} + \sum E_{2}I_{b} \left[1 + \frac{\left(I'_{u} + I'_{l}\right)b^{2}}{\left(I'_{b} + I'_{u} + I'_{f}\right)l^{2}} \right]$$

→Terms on next slide



- The summation is to be done over all the floors, including foundation beam of raft.
- For top layer I_u' becomes zero.
- For foundation beams I_f' replaces I_b' and I_l becomes zero



 E_l = modulus of elasticity of the infilling material (wall material) in kg/cm²,

= moment of inertia of the infilling in cm⁴,

= length or breadth of the structure in the direction of bending,

H = total height of the infilling in cm,

 E_2 = modulus of elasticity of frame material in kg/cm²,

 I_b = moment of inertia of the beam in cm⁴,

$$I'_u = \frac{I_u}{h_u},$$

l = spacing of the columns in cm,

 $I'_l \,=\, \frac{I_l}{h_1},$ h_u = length of the upper column in cm,

 h_l = length of the lower column in cm,

 $I'_b = \frac{I_b}{I},$ = moment of inertia of the upper column in cm⁴,

= moment of inertia of the lower column in cm⁴, and $I'_f = \frac{I_f}{I}$ = moment of inertia of the foundation beam or raft in cm⁴.



Relative Stiffness of Structure and Foundation Soil

Relative Stiffness Factor:

For the whole structure
$$K = \frac{EI}{E_s b^3 a}$$
 For circular rafts $K = \frac{E}{12 E_s} \left(\frac{d}{2 R}\right)^3$

For rectangular rafts or beams
$$K = \frac{E}{12E_s} \left(\frac{d}{b}\right)^3$$

EI = flexural rigidity of the structure over the length (a) in kg/cm²,

 E_s = modulus of compressibility of the foundation soil in kg/cm²,

b = length of the section in the bending axis in cm,

a = length perpendicular to the section under investigation in cm,

d = thickness of the raft or beam in cm, and

R = radius of the raft in cm.

- For K > 0.5, the foundation may be considered as rigid with the ratio of differential to total settlement (δ) being equal to zero.
- For K = 0, ratio δ may be taken as 0.1, and for K < 0.5, it can be taken as 0.35 for square and 0.5 for long mat foundations.



Characteristic Length and Critical Column Spacing

 The characteristic coefficient λ, as used in classical solution of beams on elastic foundation, can be obtained as

$$\lambda = \sqrt[4]{\frac{kB}{4E_cI}} \qquad \longrightarrow \qquad \text{Characteristic Length Parameter, } L_e = \frac{1}{\lambda}$$

where

 $k = \text{modulus of subgrade reaction in kg/cm}^3$ for footing width B in cm

B = width of raft in cm

 E_c = modulus of elasticity of concrete in kgf/cm²

I = moment of inertia of the raft in cm⁴



Characteristic Length and Critical Column Spacing

 Rigidity of foundation can be defined by the spacing between columns, L

$$L < 1.75 \times L_e \Rightarrow$$
 Foundations may be treated as short beam, hence rigid $L > (3\pi/2) \times L_e \Rightarrow$ Foundations may be treated as long beam, hence flexible $1.75 \times L_e < L < (3\pi/2) \times L_e \Rightarrow$ Foundations may be treated as finite beam with intermediate rigidity

Hetenyi's (1946) recommendations

$$\begin{array}{ll} L<0.8\times L_e \Rightarrow & \text{Rigid Foundation} \\ L>3\times L_e \Rightarrow & \text{Flexible Foundation} \\ 0.8\times L_e < L>3\times L_e \Rightarrow & \text{Intermediate Flexibility of Foundation} \\ \end{array}$$



Determination of Modulus of Elasticity from Plate Load Test

$$E_s = qB \frac{1 - v^2}{s} I_f$$

q = intensity of contact pressure

 $\nu = Posson's ratio$

B = Plate width

 I_f = Influence factor

s = settlement

Elastic Modulus of granular soil below foundation considering scale effects:

$$E_{sf} = E_{sP} \frac{B_f}{B_P} \left(\frac{B_f + B_p}{2B_f} \right)^2$$

Modulus of Subgrade Reaction from Plate Load Test

SOIL CHARACTERISTIC		*Modulus of Subgrade Reaction (k) in kg/cm^3		
Relative Density	Standard Penetration Test Value (N)	For Dry or Moist State	For Submerged State	
(1)	(2)	(3)	(4)	
Loose	< 10	1.5	0.9	
Medium	10 to 30	1.5 to 4.7	0.9 to 2.9	
Dense	30 and Over	4.7 to 18.0	2.9 to 10.8	

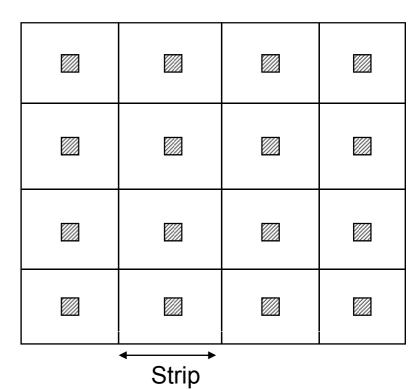
^{*}The above values apply to a square plate 30×30 cm or beams 30 cm wide.

Soil Cha	ARACTERISTIC	*Modulus of Subgrade Reaction ($K_{ m s}$) in kg/cm 3
Consistency	Unconfined Compressive Strength, kg/cm ²	
(1)	(2)	(3)
Stiff	1 to 2	2.7
Very stiff	2 to 4	2.7 to 5.4
Hard	4 and over	5.4 to 10.8

*The values apply to a square plate 30×30 cm. The above values are based on the assumption that the average loading intensity does not exceed half the ultimate bearing capacity.

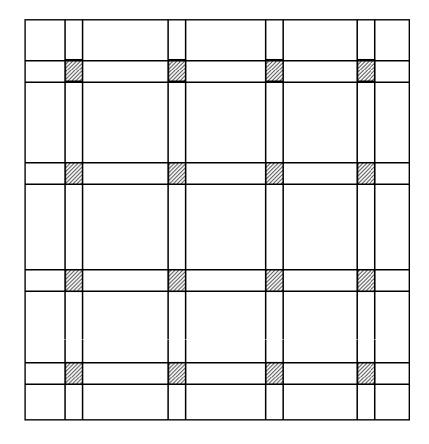


- Assumptions
 - Foundation is rigid relative to soil and compressible layer is relatively shallow.
 - ➤ The contact pressure is planar such that centroid of the contact pressure coincides with the line of action of resultant force.
- The above conditions are satisfied if
 - Relative stiffness factor > 0.5
 - Spacing between the columns is less than 1.75xL_e
- Types of Analysis
 - Flat Slab Analysis: Flat plate with regular layout of vertical loads can be analyzed assuming beam with the width of distance between mid-span width when ground settlement due to structural loads are not large.





- Types of Analysis (Continued...)
 - Equivalent Frame Analysis: If adjacent loads or column spacing exceed 20% of their higher value, the perpendicular beams as defined above may be treated as part of a frame structure and the analysis is performed for this equivalent frame.
 - Beam and Slab Analysis: For the raft with added perpendicular beams to increase rigidity of foundation, an elemental analysis may be performed by cutting it into pieces as beams and slabs. Slab is designed as two way slab and beam as T-beam.





- Types of Analysis (Continued...)
 - ➤ Deep Cellular Raft: This involves raft slab with beams and structural walls. Cross walls act as beam between the columns with net loading from soil pressure minus the self weight of wall and slab section beneath. A simple elemental analysis may be performed as in the previous case. An arbitrary value of ±wL²/10 for positive and negative moment can give reasonable results.



Pressure distribution:

$$q = \frac{Q}{A'} \pm \frac{Qe'_y}{I_x} y \pm \frac{Qe'_x}{I_y} x$$

Q = total vertical load on the raft,

A' = total area of the raft,

 e'_x , e'_y , I'_x , I'_y = eccentricities and moments of inertia about the principal axes through the centroid of the section, and

x, y = co-ordinates of any given point on the raft with respect to the x and y axes passing through the centroid of the area of the raft.

 I_x , I_y = moment of inertia of the area of the raft respectively about the x and y axes through the centroid,

 $I_{xy} = \int xy dA$ for the whole area about x and y axes through the centroid, and

 e_x , e_y = eccentricities in the x and y directions of the load from the centroid.

$$I_x = I_x - \frac{I_{xy}^2}{I_y} \,,$$

$$I_y = I_y - \frac{I_{xy}^2}{I_x} \,,$$

$$e'_{x} = e_{x} - \frac{I_{xy}}{I_{x}} e_{y},$$

$$e'_{y} = e_{y} - \frac{I_{xy}}{I_{y}} e_{x}$$

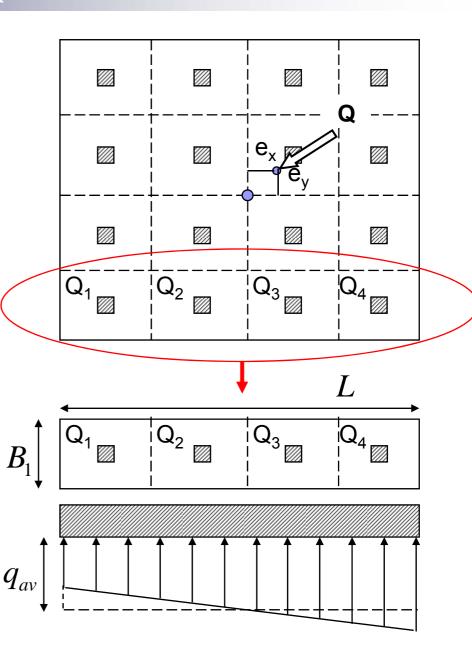
Modification Factor for Column Loads and Soil Reaction:

The total soil reaction = $q_{av}.B_1.L$

Total load from columns =

$$Q_1 + Q_2 + Q_3 + Q_4$$

Total load from columns is slightly different than the total soil reaction due to the fact that no consideration has been given to the shear between adjacent strips. Therefore column loads and soil reaction need to adjusted.





Modification Factor for Column Loads and Soil Reaction:

Average Load =
$$\frac{q_{av}.B_1.L + (Q_1 + Q_2 + Q_3 + Q_4)}{2}$$

Modified Soil Reaction
$$(q_{av})_{\text{modified}} = q_{av} \left(\frac{\text{Average Load}}{q_{av}.B_1.L} \right)$$

Column load modification factor
$$F = \frac{\text{Average Load}}{Q_1 + Q_2 + Q_3 + Q_4}$$

Modified Column Loads:
$$(Q_i)_m = FQ_i$$



Raft Foundation: Rigid Beam Analysis - Example

