Fundamentals of Foundations Design and Construction

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Introduction

- ✓ A foundation is that part of a structure which transmits loads directly to the underlying soil.

- ✓ A foundation is supposed to serve its purpose soil in such a way that the soil is not overly stressed and that excessive settlements of the structure are not caused

- ✓ The key factors dictating the type of foundation are:
  1. Nature of foundation soil
  2. Magnitude and nature of loading acting on the foundation

Types of foundation

Foundations

Shallow

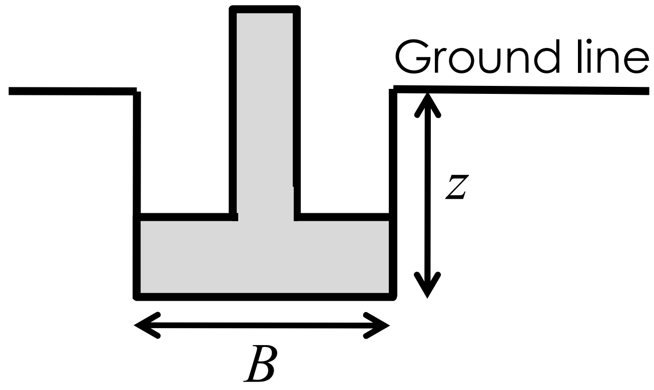
$$\frac{z}{B} < 1$$

- Strip footings
- Pad footings
- Rafts
- Grillages

Deep

$$\frac{z}{B} >> 1$$

- Piles
- Piers
- Shafts
- etc

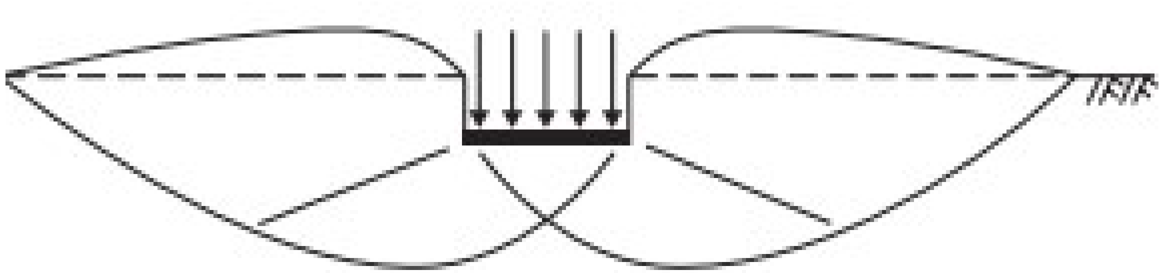


z = excavation depth
B = foundation width (or diameter)

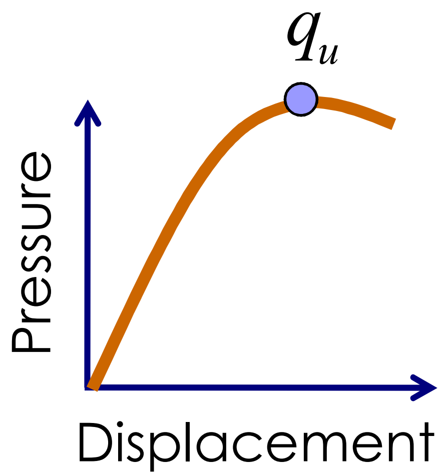
Steps involved in foundation design

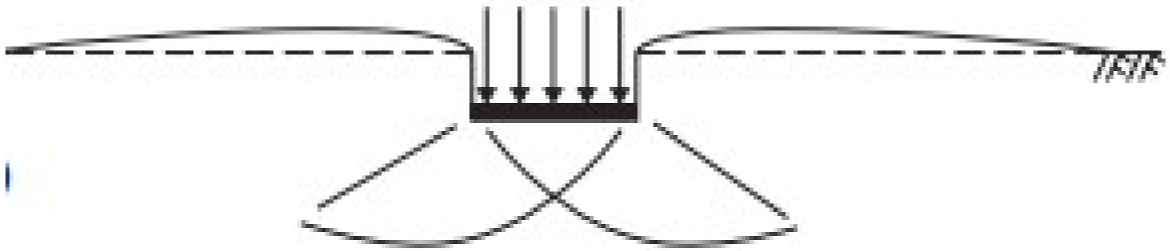
1. Do a sub-surface investigation to determine the soil strength and deformation parameters and obtain information regarding ground water condition
2. Select the type of foundation based on the information obtained in step 1
3. Estimate the bearing capacity of the supporting soil based n the info obtained in step 1
4. Do a structural design of the selected foundation based on the estimated bearing capacity and other relevant parameters obtained from step 1

Failure modes in shallow foundations

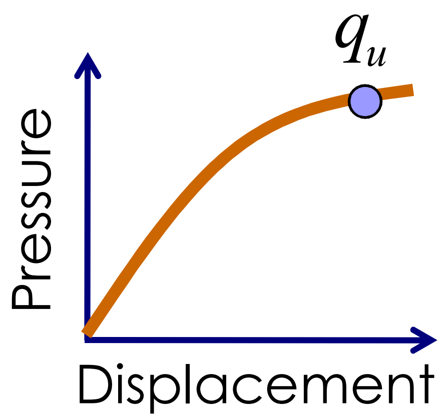


I. General shear failure

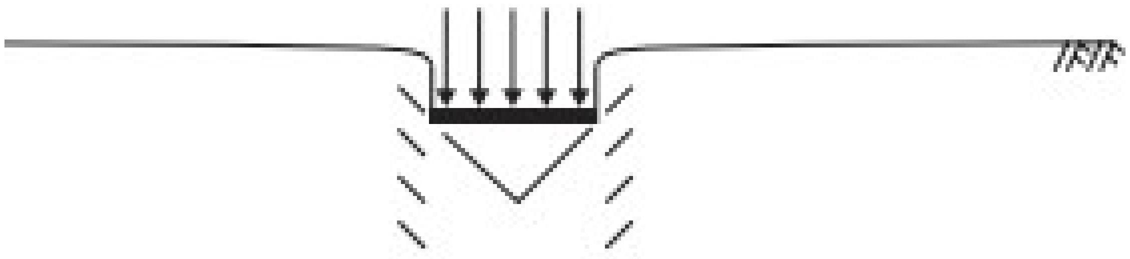


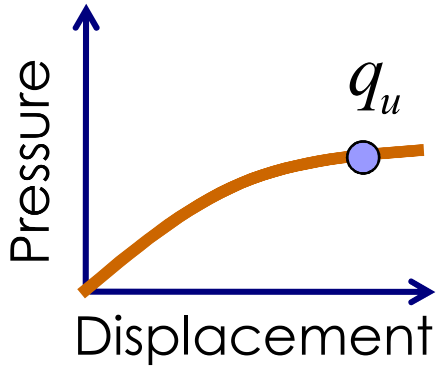


II. Local shear failure

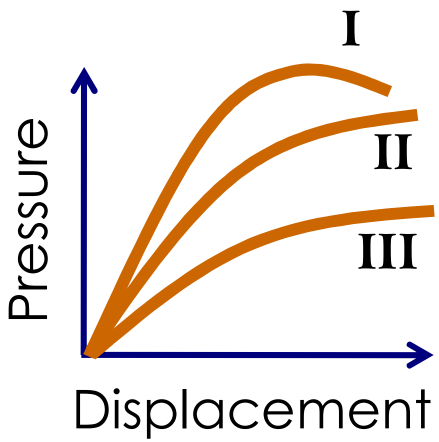


Failure modes in shallow foundations





III. Punching shear failure



I Dense sand/stiff clay

II Medium dense sand/ medium clay

III Loose sand/ soft clay

Bearing capacity definitions

<u>Ultimate bearing capacity</u>

Maximum pressure which a foundation can withstand without the occurrence of shear failure of the foundation soil.

<u>Safe bearing capacity</u>

Ultimate bearing capacity divided by the factor of safety. The factor of safety should be applied to the net ultimate bearing capacity and the surcharge pressure due to depth of the foundation should then be added to get the safe bearing capacity.

Bearing capacity Estimation

Terzhagi's Equations

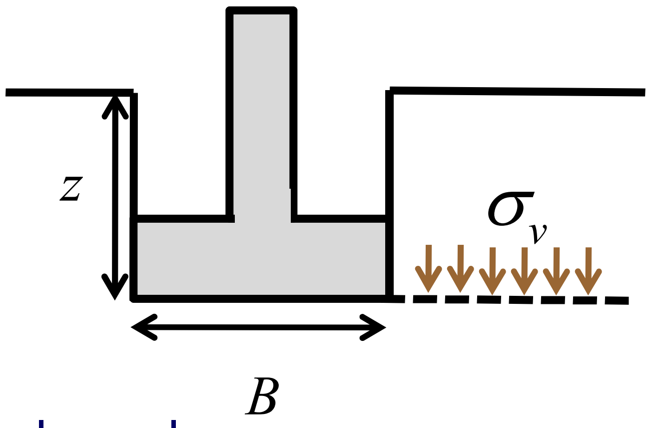
- Strip footings
$$q_u = cN_c + \sigma_v N_q + 0.5\gamma B N_\gamma$$

- Square footings
$$q_u = 1.3cN_c + \sigma_v N_q + 0.4\gamma B N_\gamma$$

- Circular footings
$$q_u = 1.3cN_c + \sigma_v N_q + 0.3\gamma B N_\gamma$$

- Rectangular footings
$$q_u = \left(1 + 0.3\frac{B}{L}\right)cN_c + \sigma_v N_q + 0.5\left(1 - 0.2\frac{B}{L}\right)\gamma B N_\gamma$$

Bearing capacity Estimation



$q_u =$ Ultimate bearing pressure

$c =$ Soil cohesion

$\gamma =$ Unit weight of soil

$\sigma_v =$ Vertical stress at foundation level

For a uniform dry soil, $\sigma_v = \gamma z$

$B =$ Foundation width/diameter

$N_c, N_q, N_\gamma =$ Bearing capacity Factors

→ depend on the angle of internal friction, ϕ

Bearing capacity factors

Table 1

ϕ' (deg)	N_c	N_q	N_γ
0	5.14	1.00	0
1	5.38	1.09	0.002
2	5.63	1.20	0.010
3	5.90	1.31	0.023
4	6.19	1.43	0.042
5	6.49	1.57	0.070
6	6.81	1.72	0.106
7	7.16	1.88	0.152
8	7.53	2.06	0.209
9	7.92	2.25	0.280
10	8.35	2.47	0.367
11	8.80	2.71	0.471
12	9.28	2.97	0.596
13	9.81	3.26	0.744
14	10.37	3.59	0.921
15	10.98	3.94	1.129
16	11.63	4.34	1.375
17	12.34	4.77	1.664
18	13.10	5.26	2.009
19	13.93	5.80	2.403
20	14.83	6.40	2.871
21	15.82	7.07	3.421
22	16.88	7.82	4.066
23	18.05	8.66	4.824
24	19.32	9.60	5.716
25	20.72	10.66	6.765

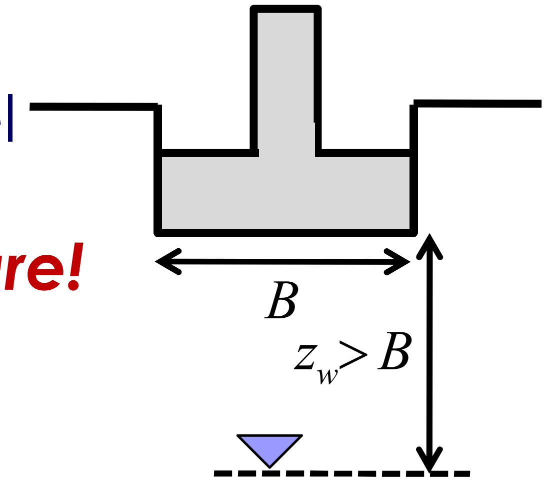
Bearing capacity factors

ϕ' (deg)	N_c	N_q	N_γ
26	22.25	11.85	8.002
27	23.94	13.20	9.463
28	25.80	14.72	11.190
29	27.86	16.44	13.236
30	30.14	18.40	15.668
31	32.67	20.63	18.564
32	35.49	23.18	22.022
33	38.64	26.09	26.166
34	42.16	29.44	31.145
35	46.12	33.30	37.152
36	50.59	37.75	44.426
37	55.63	42.92	53.270
38	61.35	48.93	64.073
39	67.87	55.96	77.332
40	75.31	64.20	93.690
41	83.86	73.90	113.985
42	93.71	85.38	139.316
43	105.11	99.02	171.141
44	118.37	115.31	211.406
45	133.88	134.88	262.739
46	152.10	158.51	328.728
47	173.64	187.21	414.322
48	199.26	222.31	526.444
49	229.93	265.51	674.908
50	266.89	319.07	873.843

Effect of ground water

Condition No.1 :

Water level far below foundation level



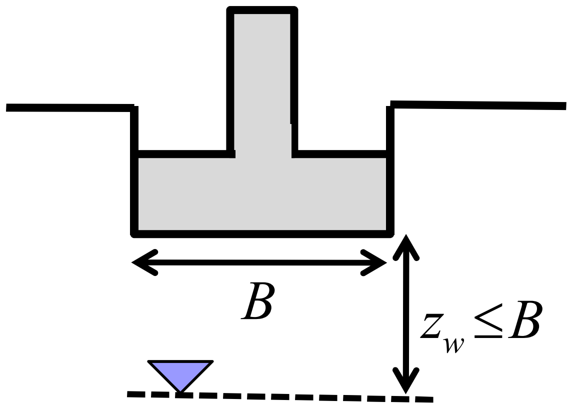
Use the Terzhagi's equations as they are!

Condition No.2 :

Water table at a depth ≤ B below foundation Level

$$q_u = cN_c + \sigma_v N_q + 0.5\underline{\gamma'} B N_\gamma$$

$$\gamma' = \gamma - \gamma_w; \quad \gamma_w = 9.81 kNm^{-3}$$

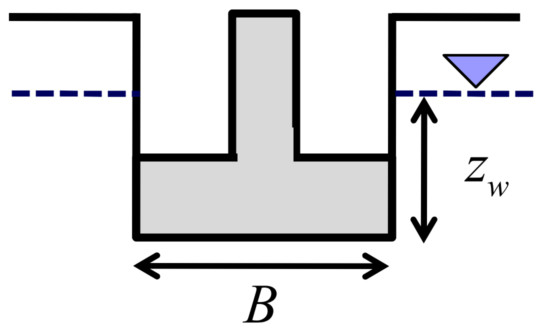


Effect of ground water

Based on condition No.2 B.C. modification, purely cohesive soils are unaffected, while the third term is reduced by half in the case of non-cohesive soils

Condition No.3 :

Water table above foundation level



$$q_u = cN_c + \underline{\sigma'_v} N_q + 0.5\underline{\gamma'} B N_\gamma$$

$$\sigma'_v = \sigma_v - \gamma_w z_w$$

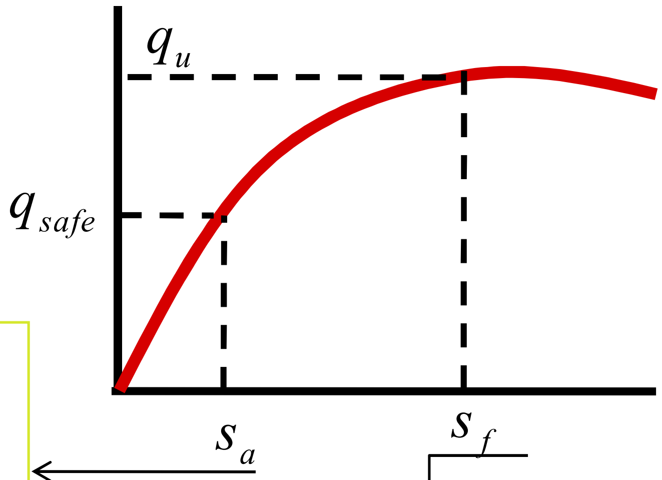
Under this condition the bearing capacity of non cohesive soils reduces by half

Safe bearing capacity

$$q_{safe} = \frac{q_{u,Net}}{F_S} + \sigma_v \quad \text{Where} \quad q_{u,Net} = q_u - \sigma_v$$

F_S = safety factor

Values of F typically range from 2.5 to 5



s_f = Foundation displacement corresponding to ultimate bearing pressure

s_a = Tolerable foundation settlement

F

- *Checks foundation collapse*
- *Takes into account uncertainty of soil strength*
- *Controls settlement*

Examples of BC calculations (strip footings)

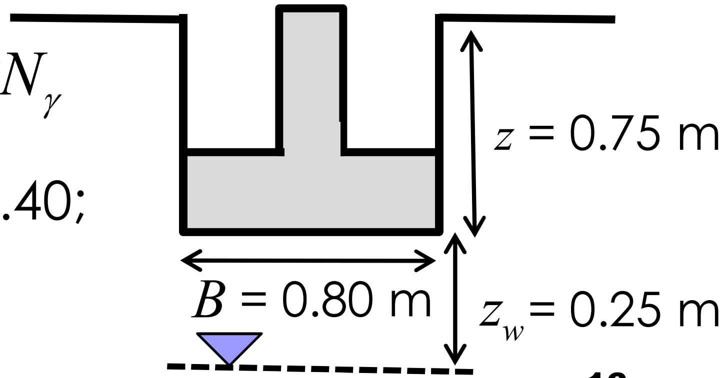
No. G1

A strip footing of width 0.80 m is founded at a depth of 0.75 m below the ground level in a granular soil (c=0; φ = 30^0; γ = 17 kN/m^3 ; γ_{sat}= 19.5 kNm^3). The water table is at a depth of 1.0 m below the ground surface. Determine the safe bearing capacity of the strip using Terzaghi's method. Take Fs to be 3.0.

Solution:

For strip footings: $q_u = cN_c + \sigma_v N_q + 0.5\gamma B N_\gamma$

c = 0; φ =30^0 → N_c = 30.14; N_q = 18.40; N_γ = 15.668



Examples of BC calculations (strip footings)

Since z_w is less than B the BC equation is modified as:

$$q_u = cN_c + \sigma_v N_q + 0.5\gamma' B N_\gamma$$

$\sigma_V = \gamma z$ = 17 * 0.75 = **12.75 kN/m²**

$\gamma' = \gamma_{sat} - \gamma_w$ = 19.5 – 9.81 = **9.69 kN/m³**

q_U = 0+ 12.75 * 18.4 + 0.5 * 9.69 * 0.8 * 15.668

= **295.329 kN/m²**

$q_{U,\,Net} = q_U - \sigma_V$ =295.329 – 12.75 = **282.58 kN/m²**

$q_{safe} = q_{U,\,Net}/F + \sigma_V$ = 282.58/3 + 12.75 = **106.94 kN/m²**

Examples of BC calculations (square footings)

No. G2

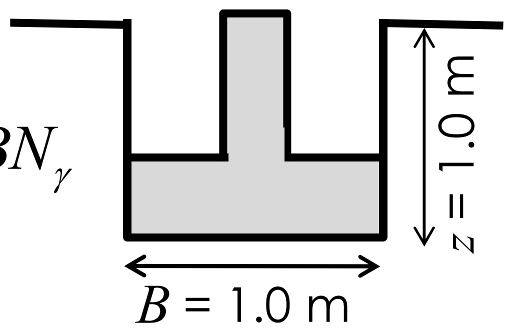
A square footing of width 1.0 m is founded at a depth of 1.0 m below the ground level in a lateritic soil (c=8.0 kPa; φ =28^0; γ = 18 kN/m^3). The water table is far below the foundation level. Determine the safe bearing capacity of the strip using Terzaghi's method. Take Fs to be 3.0. Repeat the exercise foundation with as 1.25 m and 1.5 m.

Solution:

For square footings: $q_u = 1.3cN_c + \sigma_v N_q + 0.4\gamma BN_\gamma$

c = 0; φ =28^0 → N_c = 25.80; N_q = 14.72;

N_γ = 11.19



Examples of BC calculations (square footing)

Since z_w is far greater than B, the BC equation is unmodified .

$\sigma_v = \gamma z = 18 * 1.0 =$ **18.00 kN/m²**

$q_U = 1.3 * 8.0 * 25.8 + 18 * 14.72 + 0.4 * 18.0 * 1.0 * 11.19$

$=$ **613.85 kN/m²**

$q_{U,\ Net} = q_U - \sigma_v = 613.85 - 18 =$ **595.85 kN/m²**

$q_{safe} = q_{U,\ Net} / F + \sigma_v = 595.85/3.0 + 18 =$ **216.62 kN/m²**

For B=1.25 m:

$q_U = 1.3 * 8.0 * 25.8 + + 18 * 14.72 + 0.4 * 18.0 * 1.25 * 11.19$

$=$ **633.99 kN/m²**

$q_{U,\ Net} = q_U - \sigma_v = 633.99 - 18 =$ **615.99 kN/m²**

Examples of BC calculations (square footing)

$q_{safe} = q_{U,\ Net} / F + \sigma_V = 615.99/3.0 + 18 =$ **223.33 kN/m²**

For B=1.5 m:

$q_U = 1.3 * 8.0 * 25.8 + 18 * 14.72 + 0.4 * 18.0 * 1.5 * 11.19$

$=$ **654.13 kN/m²**

$q_{U,\ Net} = q_U - \sigma_V = 654.13 - 18 =$ **636.13 kN/m²**

$q_{safe} = q_{U,\ Net} / F + \sigma_V = 636.13/3.0 + 18 =$ **230.04 kN/m²**

For B=1.75 m square footing: $q_{safe} =$ ***236.76 kN/m²***

For B=2.0 m square footing: $q_{safe} =$ ***243.47 kN/m²***

For granular (and c- φ) soils, Bearing Capacity is a function of foundation with B

Examples of BC calculations (rectangular footing)

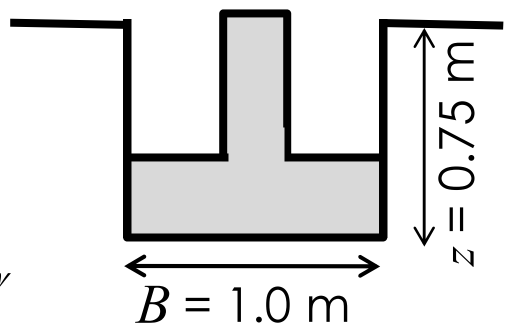
No. G3

A rectangular footing of in-plan dimensions 1.0 m by 2.0 m is founded at a depth of 0.75 m below the ground level in a layer of clay (c = 30 kPa; φ = 0^0; γ = 19 kN/m^3). The water table is 6.0 m below the ground level. Determine the safe bearing capacity of the strip using Terzaghi's method. Take Fs to be 3.5.

Solution:

For rectangular footings:

$$q_u = \left(1 + 0.3\frac{B}{L}\right)cN_c + \sigma_v N_q + 0.5\left(1 - 0.2\frac{B}{L}\right)\gamma B N_\gamma$$



Examples of BC calculations (rectangular footing)

$c = 30$ kPa; $\varphi = 0^0$ → $N_c = 5.14$; $N_q = 1.00$; $N_\gamma = 0.0$

Since z_w is far greater than B, the original BC equation is used without modification.

$\sigma_v = \gamma z = 19 * 0.75 =$ **14.25 kN/m²**

$q_u = (1+0.3*1.0/2.0) * 45 * 5.14 + 14.25 * 1.0 + 0$

$=$ **280.245 kN/m²**

$q_{u, Net} = q_u - \sigma_v = 280.245 - 14.25 =$ **266.0 kN/m²**

$q_{safe} = q_{u, Net} / F + \sigma_v = 266.00/3.5 + 14.25 =$ **129.65 kN/m²**

Structural design of pad foundations

Design steps

1. Select in-plan foundations such that the foundation pressure due to design load is not greater than S.B.C.

2. Assume a suitable value for thickness (h) and effective depth (d) and check that the shear force (V_{max}) at column face is less than $0.5\eta f_c ud/1.5$ where $\eta = 0.6(1 - f_c/250)$

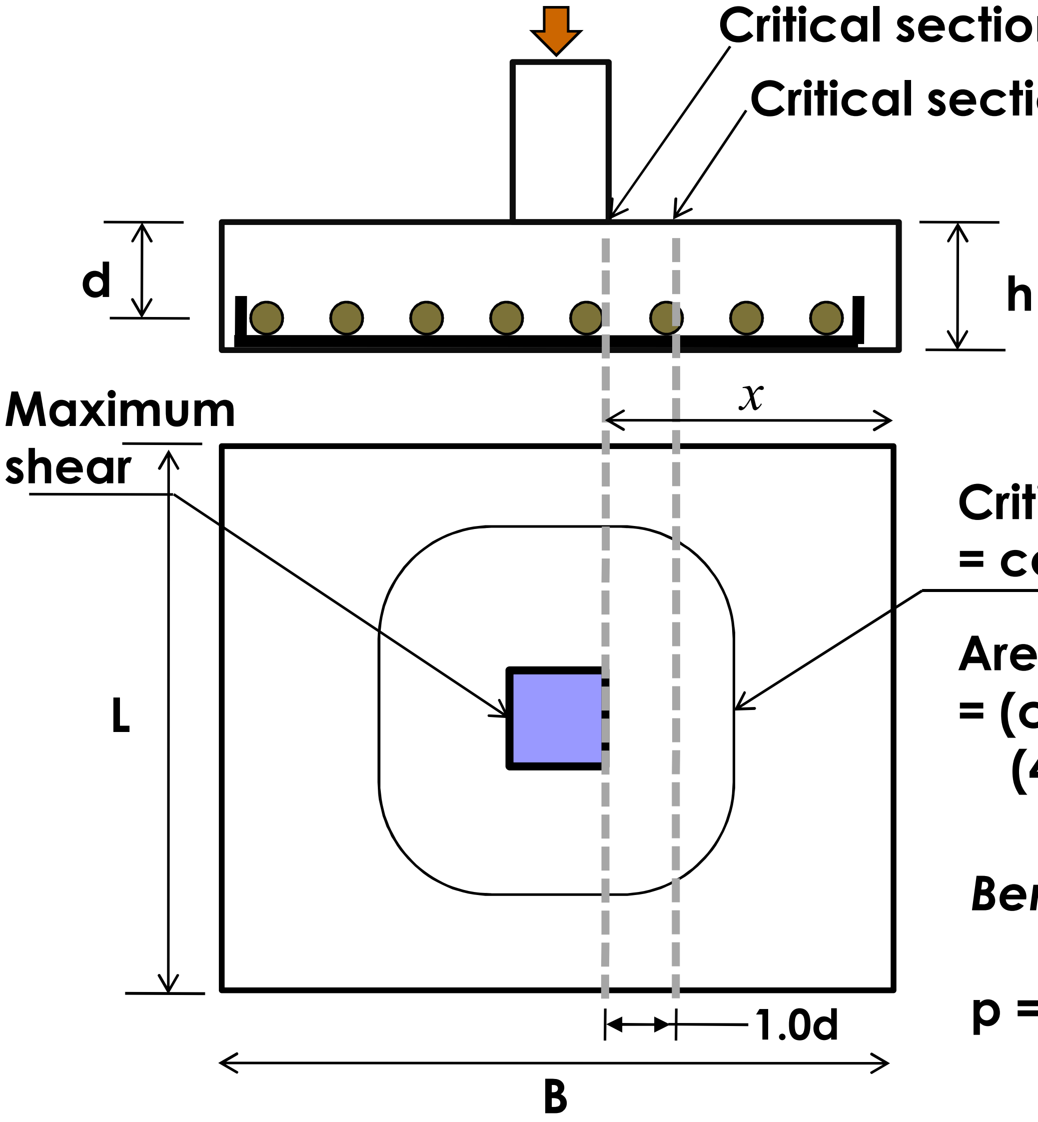
3. Carry out preliminary check for punching shear

4. Compute B. moment and determine suitable reinforcement

5. Make a final check against punching shear

6. Check shear force at critical sections

Structural design of pad foundations



f_c = xtic strength of conc.

u = column perimeter

Critical shear perimeter
= column perimeter +4πd

Area within shear perimeter
= (column with + 4d)^2 –
(4 – π) (2.0 d)^2

$$\textit{Bending Moment} = \frac{pLx^2}{2}$$

p = foundation pressure

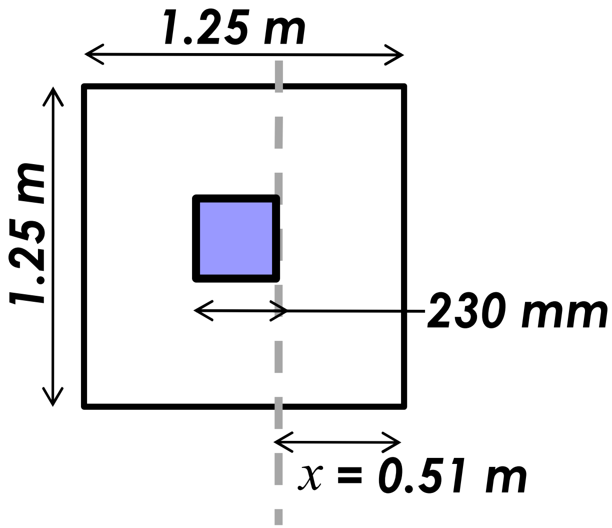
Structural design Examples

No. S1

Suppose a square footing in Example G2 supports a 230 mm square column and is subject to 100 kN design load from the super-structure. Carry out a structural design of the footing.

Solution:

Step 1. Assume 1.25 m X 1.25 m X 350 mm as footing dimensions.



q_{safe} = **132.45 kPa** (from example G2)

Self-weight of footing = $1.4 * 24 * 1.25^2 * 0.35$

= 18.375 kN

Total weight = 100 +18.375 +17 = 135.375 kN

Foundation pressure = $135.375/1.25^2$

= **86.64 kPa** (> q_{safe})

Structural design Examples

Step 2. Footing thickness, h = 350 mm;

For 12mm diameter reinforcement bars and 40 mm thick concrete cover, d = 350 – 50 – 6 = 294 mm

$\eta = 0.6\left(1 - f_c / 250\right)$ = 0.6 * (1- 25/250) = 0.54

u = 4 * 230 = 920 mm

At the column face, the maximum shear, $V_{\max} = 0.5\eta f_c ud / 1.5$

= 0.5 * 0.54 * 25 * 920 * 294 *10^{-3}/1.5 = 1217.16 kN (> 135. 38 kN)

Step 3. Preliminary check against punching shear

Critical perimeter = 4 * 230 +4 * π * 294 = 4614.51 mm

Area within perimeter = $(230 + 4 * 294)^2 - (4 - \pi)(2 * 294)^2$

= 1.680×10^6 mm^2

Since 1.680 m is greater than the area of footing (=1.25*1.25), the Punching shear force = **0**

Structural design Examples

Step 4. Bending moment @ critical section = **86.64 * 1.25 * 0.51^2/2**

= 14.084 kNm

$$k = \frac{M}{bd_2 f_{cu}}$$ = 14.084 * 10^6/(25*1250 *294^2) = 0.0066

$$z = d\left(0.5 + \sqrt{0.25 - k/0.9}\right)$$ = 292* (0.5+$[0.25\text{-}k/0.9]^{0.5}$) = 292.29;

$$A_s = \frac{M}{0.87 f_y z}$$ = 14.084 * 10^6/(0.87*450 *292.29) = 123.08 mm^2

Min. reinforcement = **0.15 bd/100** = 0.15*294*1250 = 551.25 mm^2

Provide Y12 @ 225 c/c [*565.48 mm²*]

Step 5. Final punching shear check:

The punching shear perimeter is outside the footing is greater than the footing perimeter, therefore, the foundation is safe from punching shear failure.

Structural design Examples

Step 6. Shear check @ critical section (1.0d from column face):

Design shear force = pLx_s = **86.64 * 1.25 * (0.51-0.294)**

= 23.39 kN

$$\frac{100A_{s\,provided}}{bd} = 565.48/(294*1250) = 0.1538$$

From Table 1, v_c = 0.36 N/mm^2.

Shear resistance of concrete $V_R = v_c .bd$ = 0.36 * 1250 * 294

= 132. 3 kN (>23.39 kN)

Therefore no shear reinforcement is required.

Structural design Examples

Table 2

$\frac{100A_s}{bd}$	Design conc. shear stress vc (N/mm^2) for values of fcu = 25 N/mm^2								
	Effective depth, d (mm)								
	100	125	150	200	300	400	600	1200	2000
<= 0.15	0.47	0.45	0.43	0.4	0.36	0.33	0.3	0.25	0.22
0.25	0.56	0.53	0.51	0.47	0.43	0.4	0.36	0.3	0.27
0.50	0.71	0.67	0.64	0.6	0.54	0.5	0.45	0.38	0.33
0.75	0.81	0.77	0.73	0.68	0.62	0.57	0.52	0.38	0.38
1.00	0.89	0.84	0.81	0.75	0.68	0.63	0.57	0.48	0.42
1.50	1.02	0.97	0.92	0.86	0.78	0.72	0.65	0.55	0.48
2.00	1.12	1.06	1.02	0.95	0.85	0.79	0.72	0.6	0.53
≥ 3.0	1.29	1.22	1.16	1.08	0.98	0.91	0.82	0.69	0.61

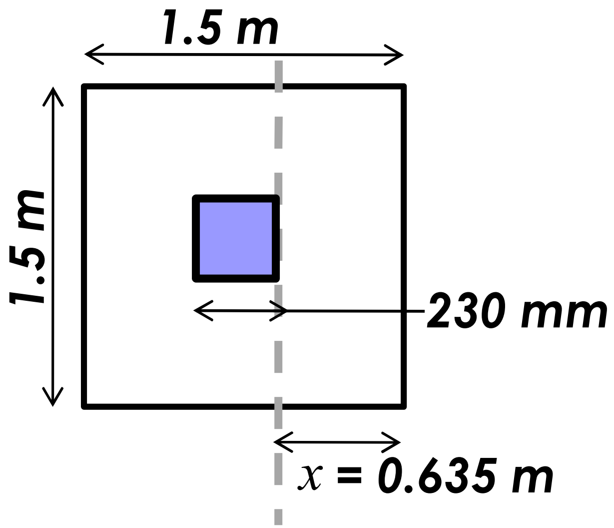
Structural design Examples

No. S2

Suppose a square footing in Example G2 supports a 230 mm square column and is subject to 250 kN design load and 92 kNm moment from the super-structure. Carry out a structural design of the footing. [f_c = 25 N/mm^2; f_y = 450 N/mm^2]

Solution:

Step 1. Assume 1.5 m X 1.5 m X 350 mm as footing dimensions.



q_{safe} = **230.04 kPa** (from example G2)

Self-weight of footing = 1.4*24*1.5^2*0.35

= 26.46 kN

Total weight = 250 +26.46 +17 = 294.46 kN

eccentricity, e = Moment/Total weight

= 92/294.46 = 0.312 m

Structural design Examples

B' = B – 2e = 1.5 – 2* 0.312 = 0.876 m

Foundation pressure = 294.46/(1.5*0.876) =224.32 kN (< qsafe)

Step 2. Footing thickness, h = 350 mm;

For 12mm diameter reinforcement bars and 50 mm thick concrete cover, d = 294 mm; u = 4 * 230 = 920 mm; $\eta = 0.54$

At the column face, the maximum shear,

$V_{max} = 0.5 \eta f_c u d / 1.5$ = 1217.16 kN (> 294.46 kN)

Step 3. Preliminary check against punching shear

Critical perimeter = 4 * 230 +4 * π * 294 = 4614.51 mm

Area within perimeter = $(230 + 4 * 294)^2 - (4 - \pi)(2*294)^2$

$= 1.680 \times 10^6\ mm^2$

Structural design Examples

Punching shear force = 224.32* $(1.5^2 - 1.68)$ = 127.86 kN

Punching shear stress = Punching shear force /(perimeter *d)

= 127.86*1000/(4614.51*294) =0.094 N/mm^2

The ultimate shear stress is far < than concrete resistance see Table 1.

Step 4. Bending moment @ critical section = **224.32 * 1.5 * 0.635^2/2**

= 67.84 kNm

$$k = \frac{M}{bd_2 f_{cu}}$$ = 67.84 * $10^6/(25*1500*294^2)$ = 0.02093

$$z = d\left(0.5 + \sqrt{0.25 - k/0.9}\right)$$ = 294* $(0.5+[0.25-k/0.9]^{0.5})$ = 287 mm

$$A_s = \frac{M}{0.87 f_y z}$$ = 69.73 * 10^6/(0.87*450 *287) = 603.78 mm^2

Min. reinforcement = **0.15 bd/100** = 0.15*294*1500/100 = 661.5 mm^2

Provide 6Y12 @ 225 c/c [678.58 *mm²*]

Structural design Examples

Step 5. Final punching shear check:

$$\frac{100A_{s\,provided}}{bd} =$$ 100*678.58/(294*1500) = 0.1538.

From Table 2, v_c = 0.36 N/mm²;

Punching shear resistance = $$\frac{vc}{punching\ perimeter \times d} = \frac{0.36 * 4614.51 * 294}{1000}$$

= 488. 4 kN (> 127.86 kN)

Step 6. Shear check @ critical section (1.0d from column face):

Design shear force = = **224.32 * 1.5 * (0.635-0.294)**

= 114.74 kN

Shear resistance of concrete $V_R = v_c\,.bd$ = 0.36 * 1500 * 294/100

= 158. 76 kN (>114.74 kN)

Therefore no shear reinforcement is required.

Structural design Examples

Step 4. Bending moment @ critical section = **86.64 * 1.25 * 0.51^2/2**

= 14.084 kNm

$$k = \frac{M}{bd_2 f_{cu}}$$ = 14.084 * 10^6/(25*1250 *294^2) = 0.0066

$$z = d\left(0.5 + \sqrt{0.25 - k/0.9}\right)$$ = 292* (0.5+$[0.25\text{-}k/0.9]^{0.5}$) = 292.29;

$$A_s = \frac{M}{0.87 f_y z}$$ = 14.084 * 10^6/(0.87*450 *292.29) = 123.08 mm^2

Min. reinforcement = **0.15 bd/100** = 0.15*294*1250 = 551.25 mm^2

Provide Y12 @ 225 c/c [*565.48 mm²*]

Step 5. Final punching shear check:

$$\frac{100A_{s\,provided}}{bd} =$$ 565.48/(294*1250) = 0.1538 (<2.0)

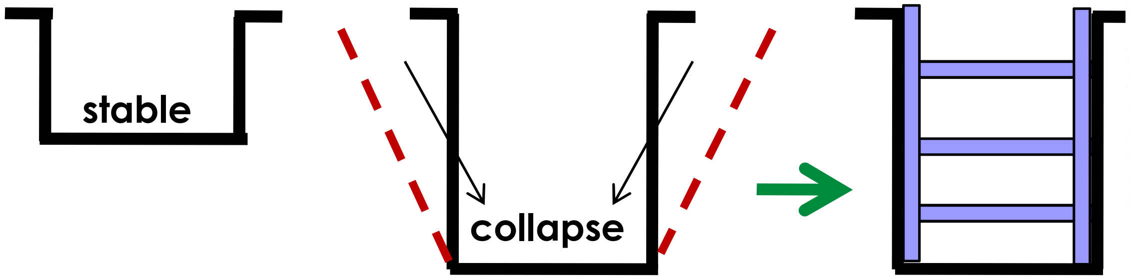
from Table 1, vc = 0.36 N/mm^2

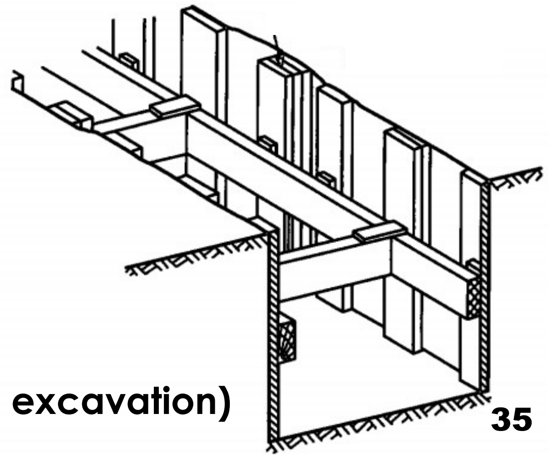
Foundation construction

Factors to consider

Depth of foundation

- Footing shall be deep enough to be below
  1. Zones of high volume change due to moisture fluctuations
  2. Topsoil or organic material
  3. Unconsolidated material such as abandoned (or closed) garbage dumps and similar filled-in areas.
- Generally, the deeper footing goes the greater the bearing capacity However, the cost of deep excavation is huge due to stability issues to address





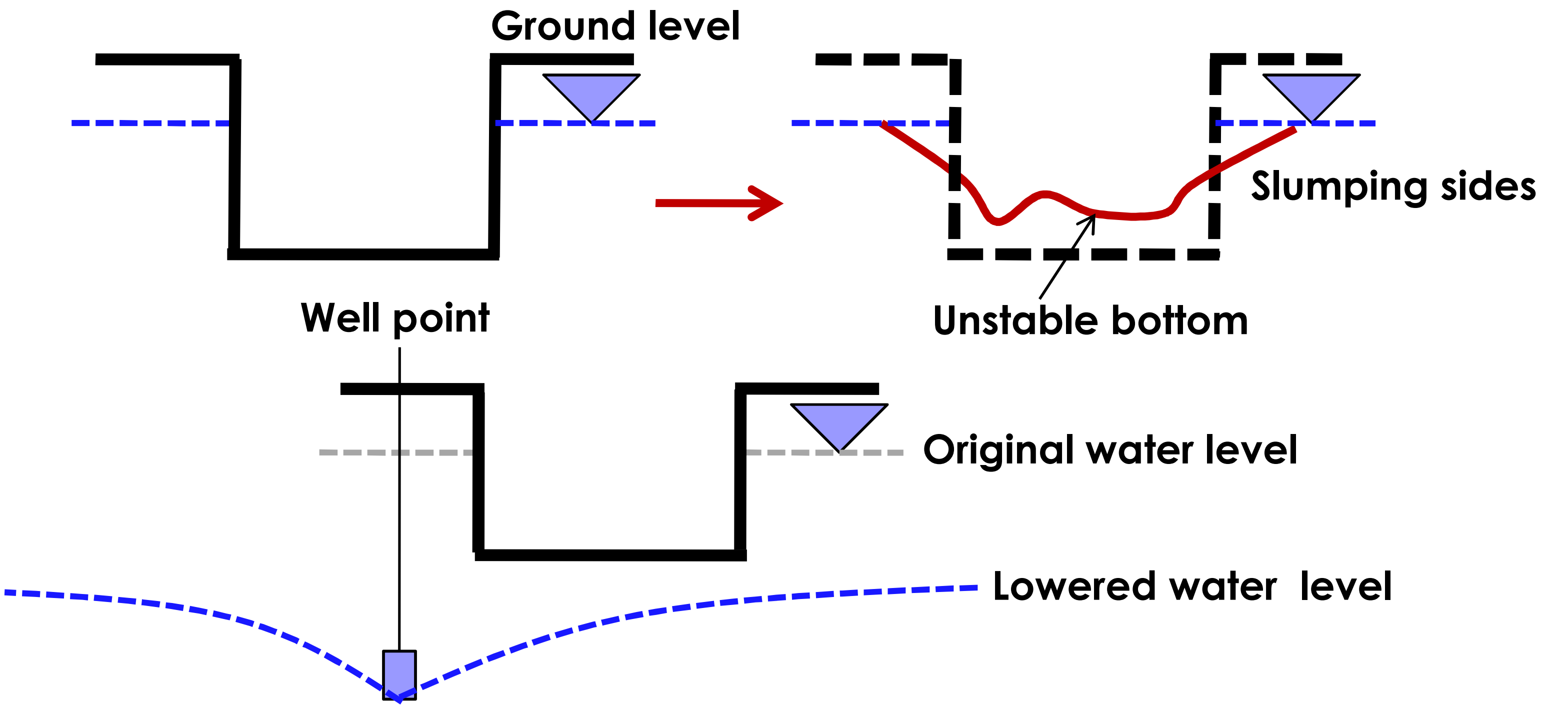
Remedy (strutted excavation)

Foundation construction

Factors to consider

Ground water level

- Excavation below the water table is troublesome as the sides slump and and the base becomes unstable
- The only way to be able to excavate without trouble is by arranging for dewatering



Foundation construction

Factors to consider

Nature of foundation soil

- A competent foundation material does not require any treatment prior to foundation placement
- weak/problem materials require some ground improvement to enable them to adequately perform under the foundation loading

***Collapsible soils* (such as loess)**

Compaction (excavate and replace)

Stabilization + compaction

Resort to other types of foundations such as pile

Expansive soils

Stabilization (using lime, cement, etc)

Stabilization + compaction

Resort to other types of foundations such as raft or pile

Many Thanks!