UTHM
Universiti Tun Hussein Onn Malaysia

FKAAS
FAKULTI KEJURUTERAAN AWAM DAN ALAM SEKITAR

Semester 2 2017/2018

DESIGN OF REINFORCED CONCRETE FOOTINGS

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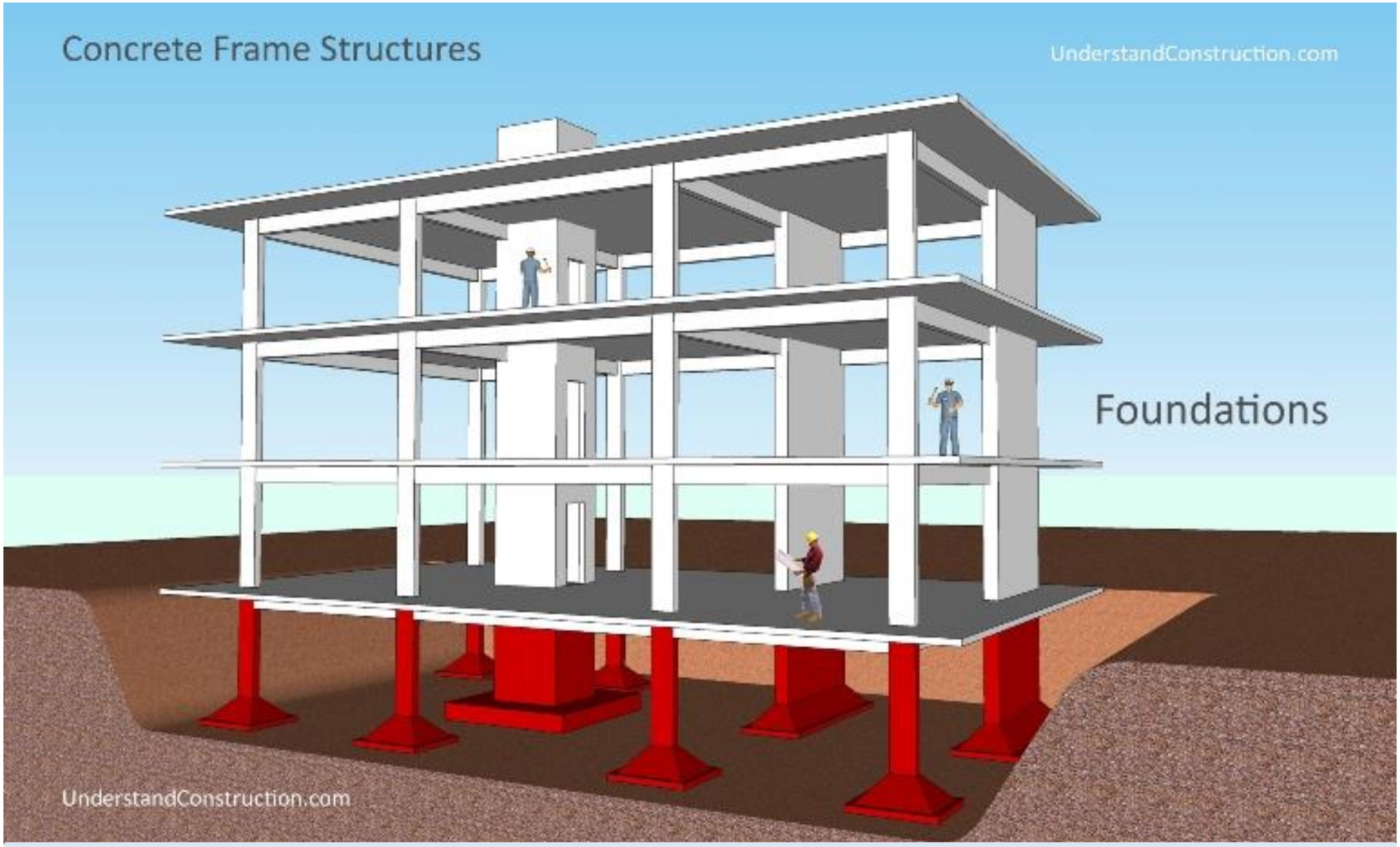
Introduction



From Soil Investigations To Foundation Design

Introduction

- Foundation is the part of a structure which transmits the loads from the structure to the underlying soil or rock.
- It is usually placed below the surface of the ground. All soils compress noticeably when loaded and caused the supported structure to settle.
- Two essential requirements in the design of foundation are:
  1. The total settlement of the structures shall be limited to a tolerably small amount
  2. The differential settlement of various parts the structure shall be eliminated as nearly as possible
- Requirement in EC2:
  - Design is similar as slab
  - Shear checking for vertical shear at 1.0d, punching shear at 2.0d and punching shear at column perimeter.

Introduction





Introduction

The Lotus Riverside, Shanghai, June 2009: Foundation design, geotechnical or construction failure?

Introduction

It is perhaps the ultimate example of foundation failure - a 100% loss of the structure. What happened?

The broken concrete pilings jutting out from the base. Concrete foundation pilings breaking?

Classification of Foundation

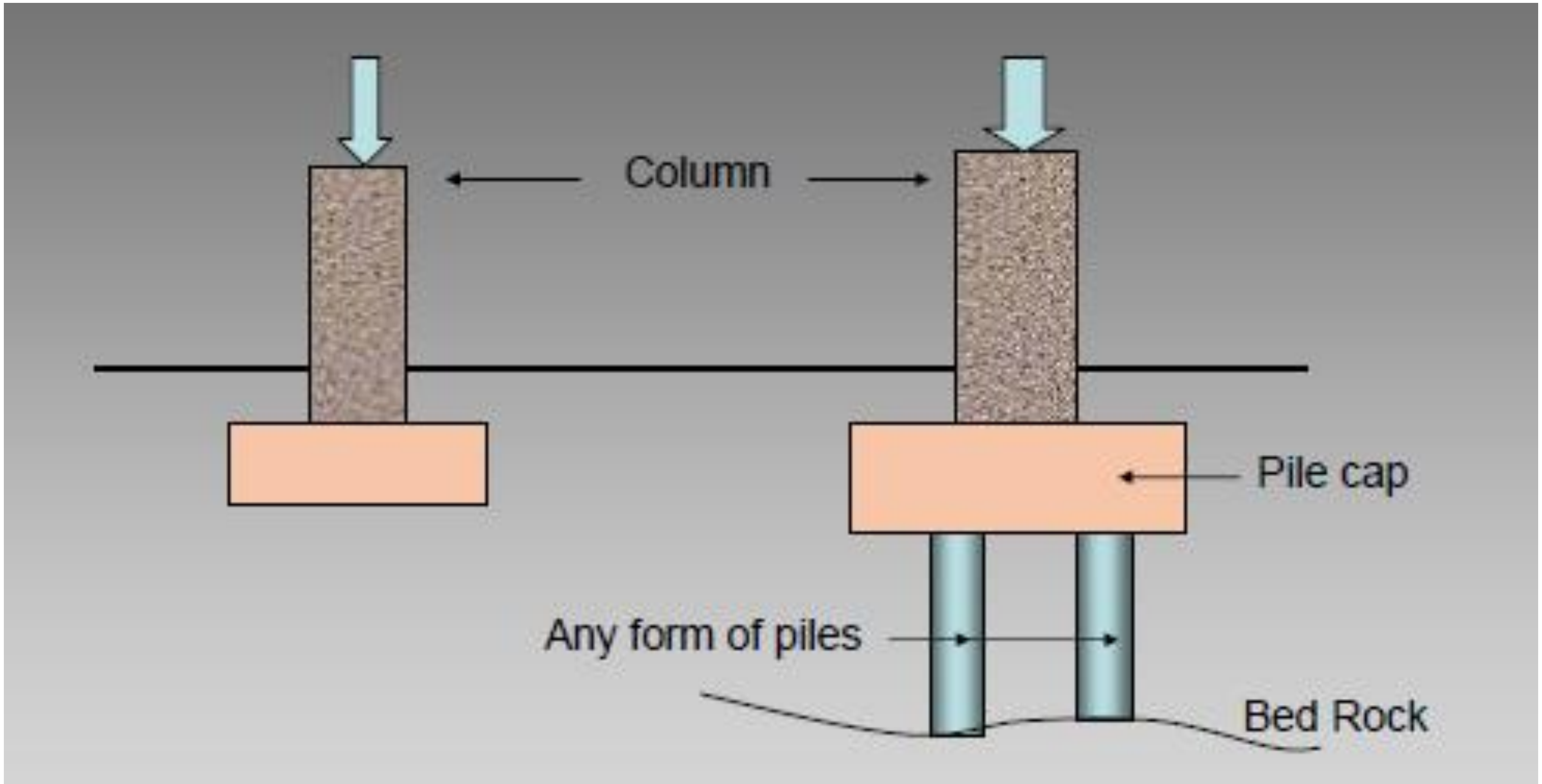
- Classification of reinforced concrete foundation:

Simple/Shallow	Deep
- Isolated or pad footing - Combined footing - Raft foundation - Strip footing - Strap footing	- Pile foundation

- Factor of selection: (i) the soil properties and conditions, (ii) the type of structure and loading, (iii) the permissible amount of differential settlement.

- The choice is usually made from experience but comparative designs are often necessary to determine the most economical

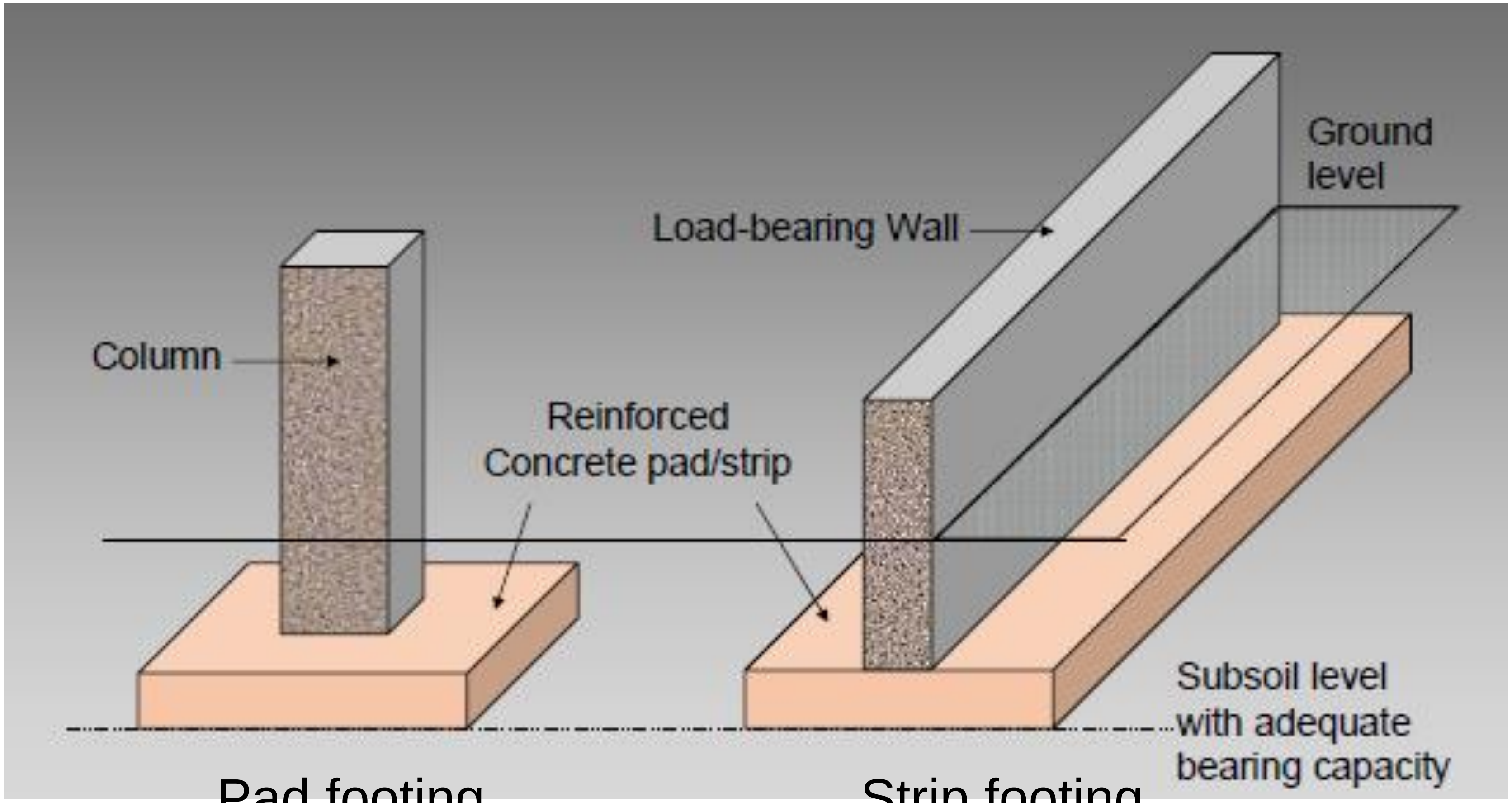
Classification of Foundation



Pad footing
Shallow foundation

Pile footing
Deep foundation

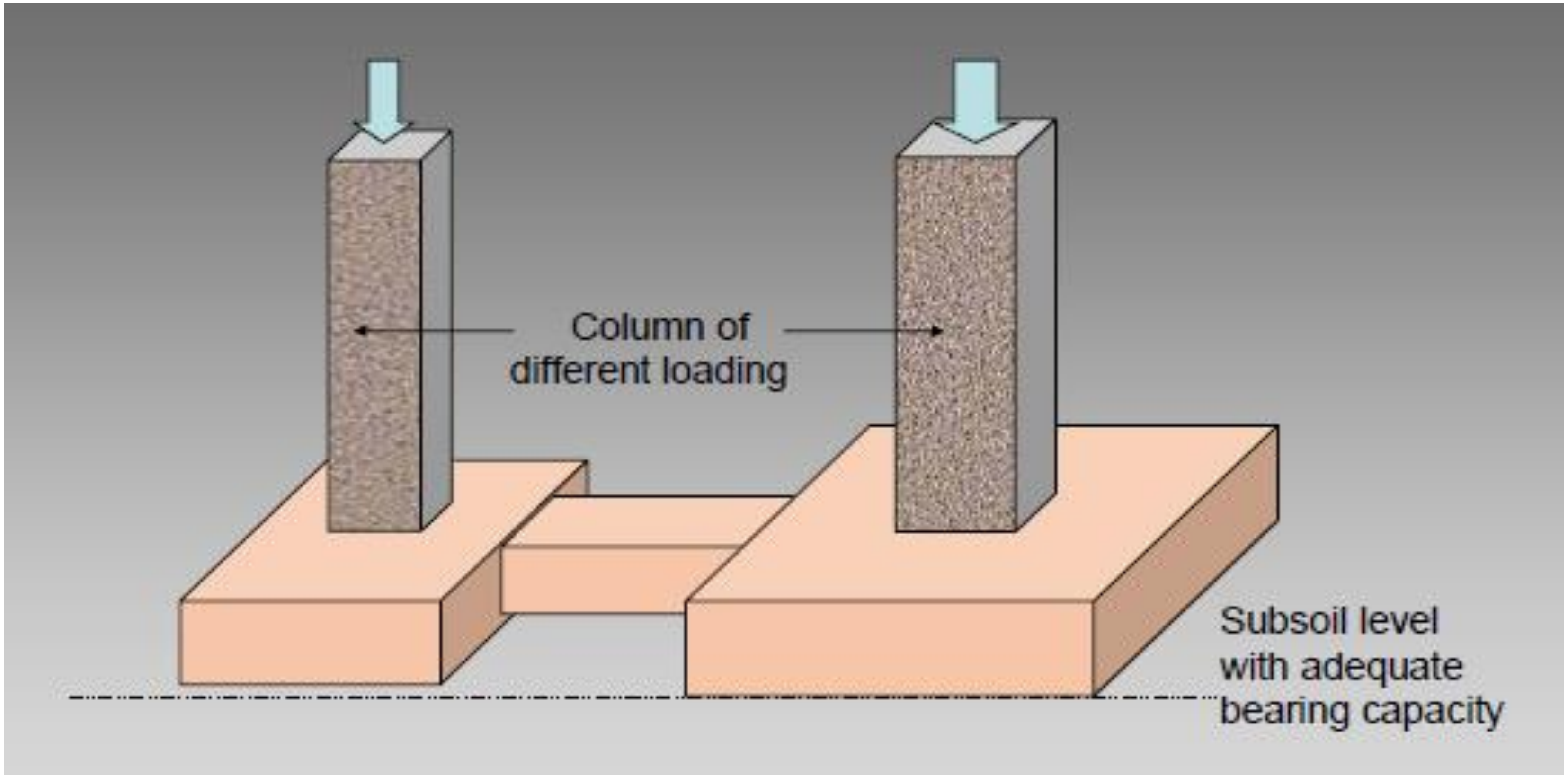
Classification of Foundation



Pad footing

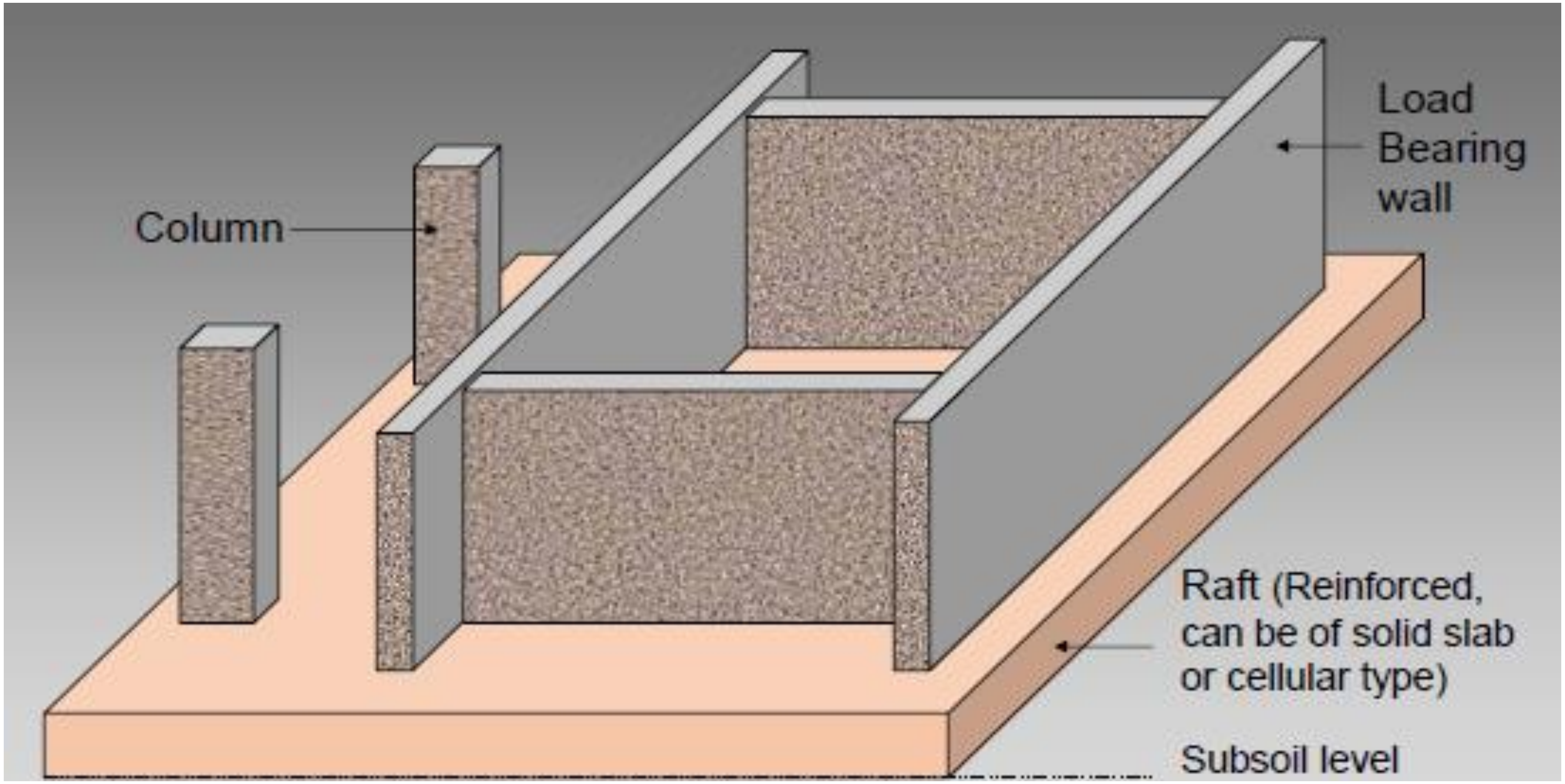
Strip footing

Classification of Foundation



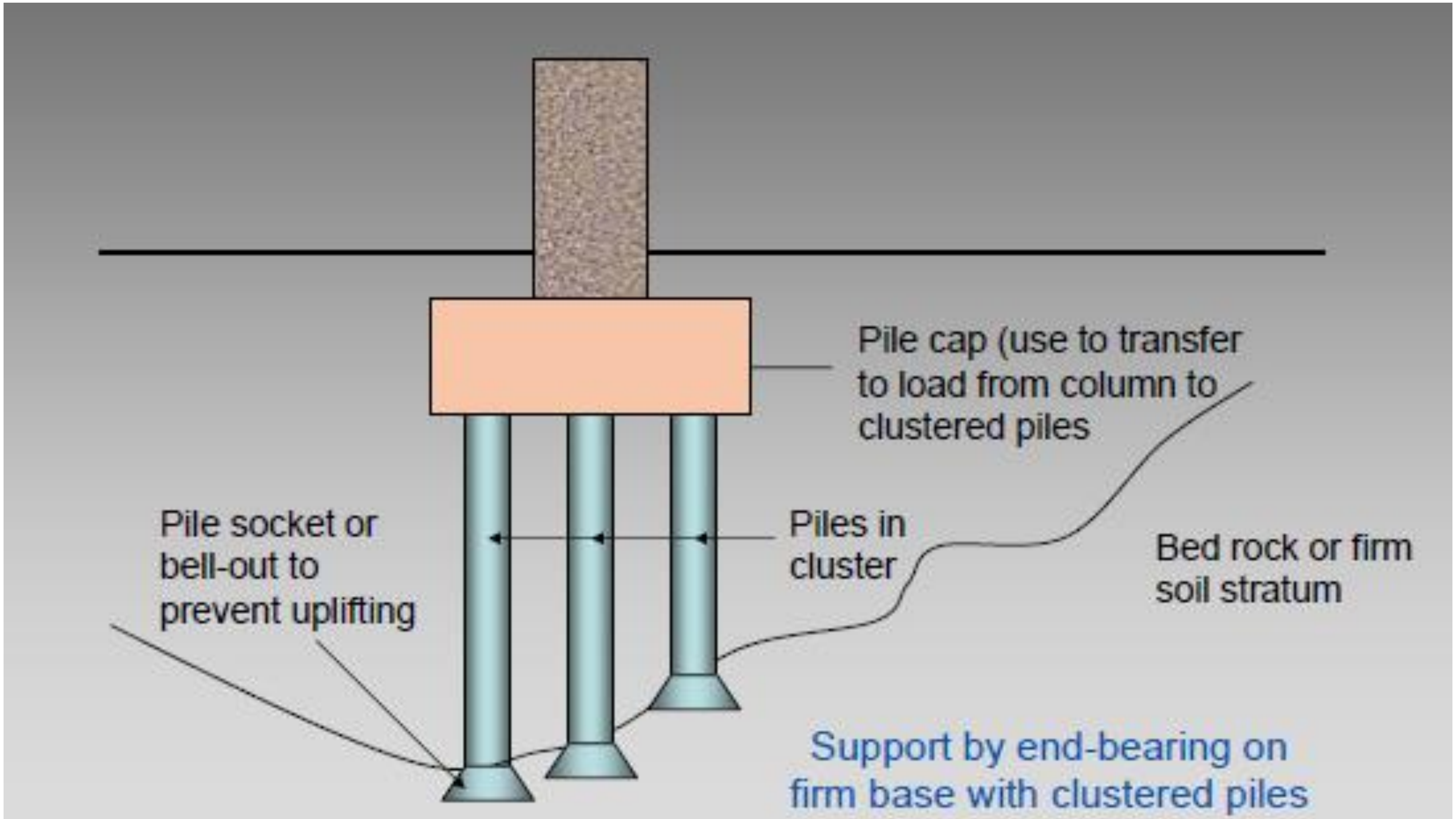
Strap footing

Classification of Foundation



Raft footing

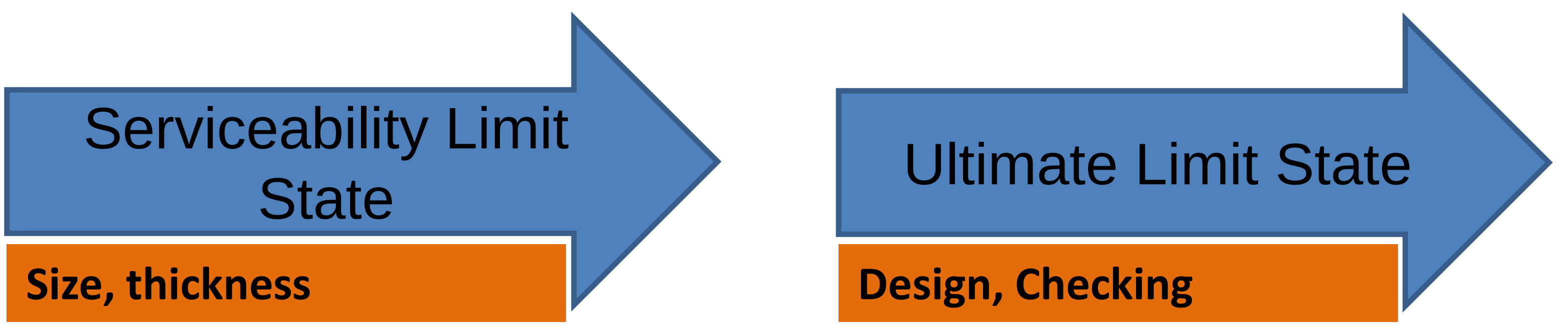
Classification of Foundation



Pile foundation

Design Consideration

- The major design considerations in the structural design of a footing relate to flexure, shear, bearing and bond.
- In these aspects, the design procedures are similar to those for beams and two way slabs supported on columns.
- Deflection control is not a consideration in the design of footing which are buried underground (and hence no visible).
- However, control of cracking and protection of reinforcement by adequate cover are important serviceability considerations, particularly in aggressive environments.
- Limit the crack width to 0.3 mm in a majority of footings.



Thickness and Size

- Thickness and size of footing:
  - The area at the base of the footing is determined from the safe bearing capacity of the soil.

$$Area = \frac{G_k + Q_k + W}{\text{Soil bearing capacity}}$$

  - The thickness of footing is generally based on consideration of shear (predominate) and flexure, which are critical near the column location. The minimum effective depth of pad:

$$d = \frac{N_{Ed}}{v_{Rd\max} u_o}$$

Thickness based on shear criteria, where:

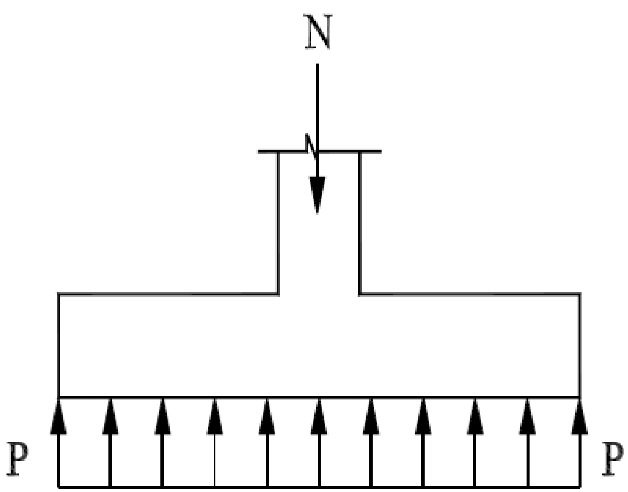
N_{Ed}=Ultimate vertical load=$1.35G_k+1.5Q_k$

$v_{Rdmax}=0.5vf_{cd}=0.5[06(1-f_{ck}/250)](f_{ck}/1.5)$

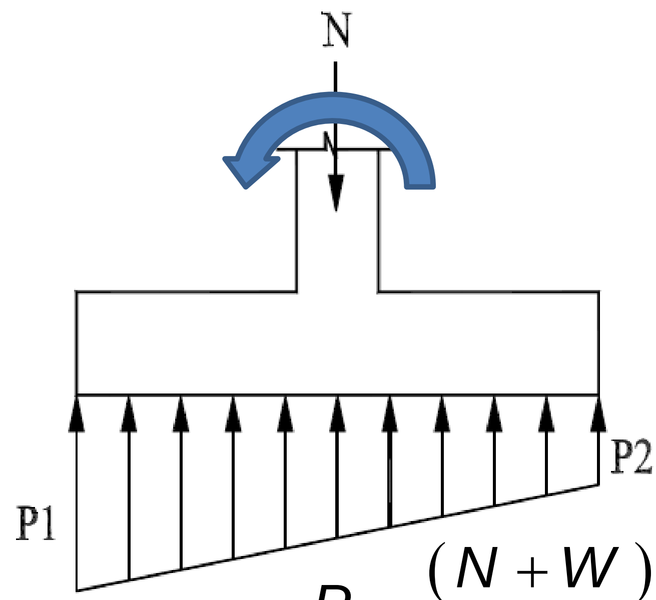
u_o=Column perimeter

Soil Pressure

- The distribution of soil pressure under a footing is a function of the type of soil and relative rigidity of the soil and the footing.
- For design purposes, it is customary to assume the soil pressures are linearly distributed, such that the resultant vertical soil force is collinear with the resultant downward force.
- For pad footing:



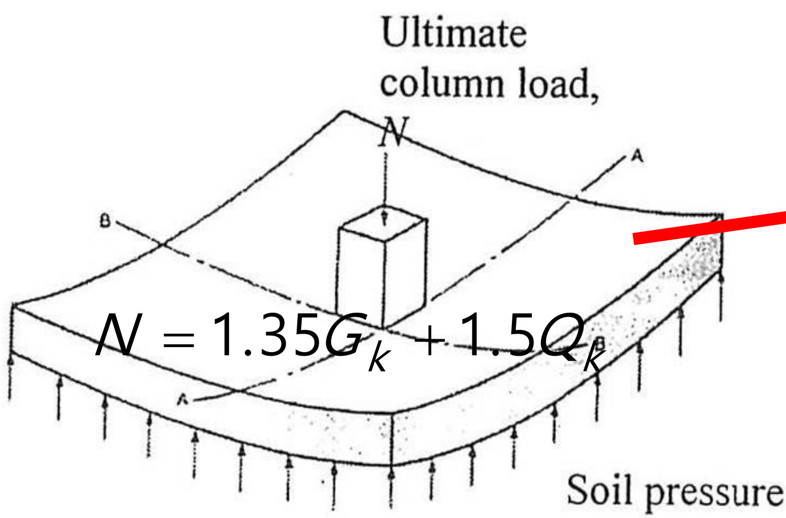
$$P = \frac{N_{Ed}}{A}$$



$$P = \frac{(N + W)}{A} \pm M\frac{y}{I}$$

Flexural Design

- The footing base slab bends upward into a saucer-like shape on account of the soil pressure underneath it.
- The critical section for bending is at the face of the column.
- The moment is taken on a section passing completely across the footing and is due to the ultimate loads on one side of the section. The moment and shear forces should be assessed using STR combination 1:

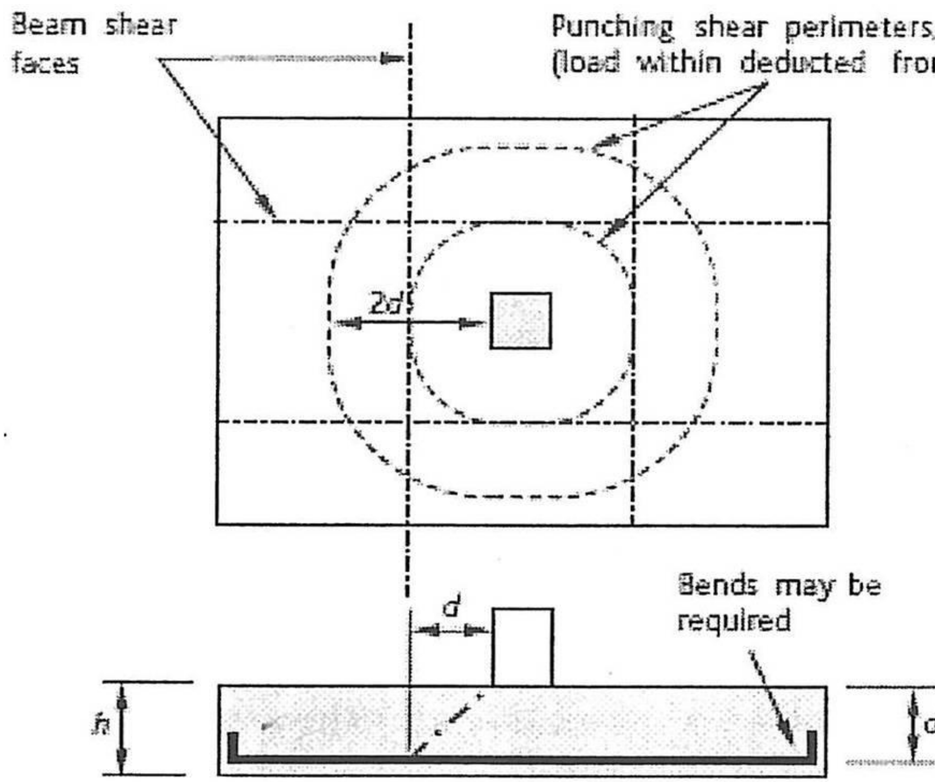


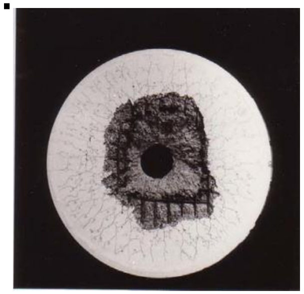
$$N = 1.35G_k + 1.5Q_k$$

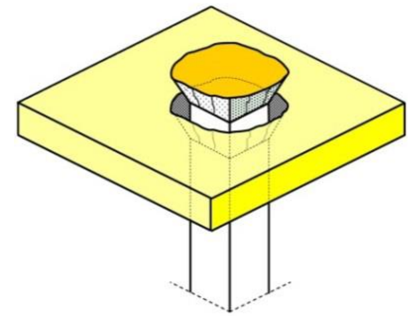
Flexural crack forming near the column-to-spread footing

Shear Resistance

- Footing may fail in shear as beam shear or punching shear at the location shown in the figure below:







Location of critical shear section and perimeter

Shear Resistance

Vertical shear	Punching shear
The critical section for vertical shear is at a distance *d* from the face of the column. The vertical shear force is the sum of the loads acting outside the section. If $V_{Ed} < V_{Rd,c}$ → no shear reinforced is required. V_{Ed} = the design shear force $V_{Rd,c}$ =the concrete shear resistance	The critical section for punching shear is at the perimeter *2d* from the face of column. The punching shear force is the sum of the loads outside the critical perimeter. The shear stress is $v_{Ed} = V_{Ed}/ud$ where *u* is the critical perimeter. If $v_{Ed} < v_{Rd,c}$ → no shear reinforced is required. The maximum punching shear at the column face must not exceed the maximum shear resistance V_{Rdmax}.

Shear Resistance

- Punching shear resistance can be significantly reduced in the presence of a coexisting bending moment, M_{Ed}, transmitted to the foundation.
- To allow for the adverse effect of the moment, which gives rise to a non-uniform distribution of shear around the control perimeter Cl.6.4.3(3) of EC2 gives the design shear stress to be used in punching shear.

$$v_{Ed} = \beta \frac{V_{Ed}}{u_i d}$$

where;

$$\beta = 1 + k \frac{M_{Ed}}{V_{Ed}} \frac{u_1}{w_1}$$

Factor used to include the effect of eccentric loads and bending moments

k = coefficient dependent on the ratio between the column dimension (c_1 and c_2).

Shear Resistance

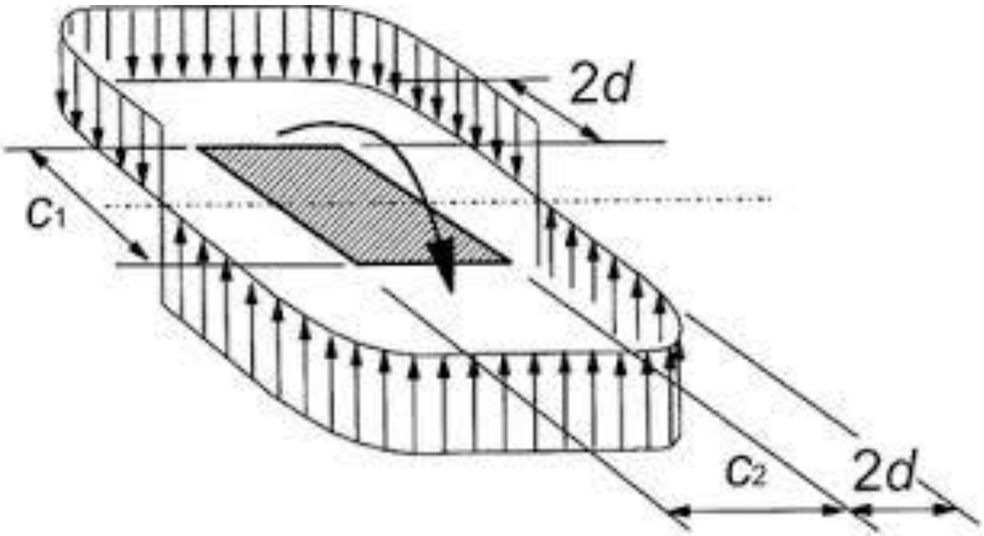
c_1/c_2	≤0.5	1.0	2.0	≥ 3.0
k	0.45	0.60	0.70	0.80

u_1= the length of basic control perimeter

w_1= function of the basic control perimeter corresponds to the distribution of shear

$w_1 = 0.5c_1^2 + c_1c_2 + 4c_2d + 16d^2 + 2\pi dc_1$

Shear distribution due to an unbalanced moment



Shear Resistance

- Vertical shear at 1.0d from column face is based on shear resistance, $V_{Rd,c} > V_{ed}$

$$V_{Rd,c} = [0.12k(100\rho_1 f_{ck})^{1/3}]bd \geq [0.035k^{3/2} f_{ck}^{\ 1/2}]bd$$

$$V_{\min} = [0.35k^{3/2} f^{1/2}]bd$$

- Punching shear at 2.0d from column face based on punching stress:

$$v_{Rd,c} = \frac{V_{\min}}{ud} > v_{Ed} = \frac{V_{Ed,punching}}{ud}$$

- Punching shear at column perimeter is based on maximum shear resistance

$$V_{Rd,\max} = 0.5ud\left[0.6\left(1 - \frac{f_{ck}}{250}\right)\right]\frac{f_{ck}}{1.5} > N_{Ed}$$

Crack Control

- Use similar rules as for beam in Cl.9.3 of EC2 and Cl.7.3, Table 7.2N and 7.3N
- Steel stress for limiting crack width, w_{max}=0.3mm

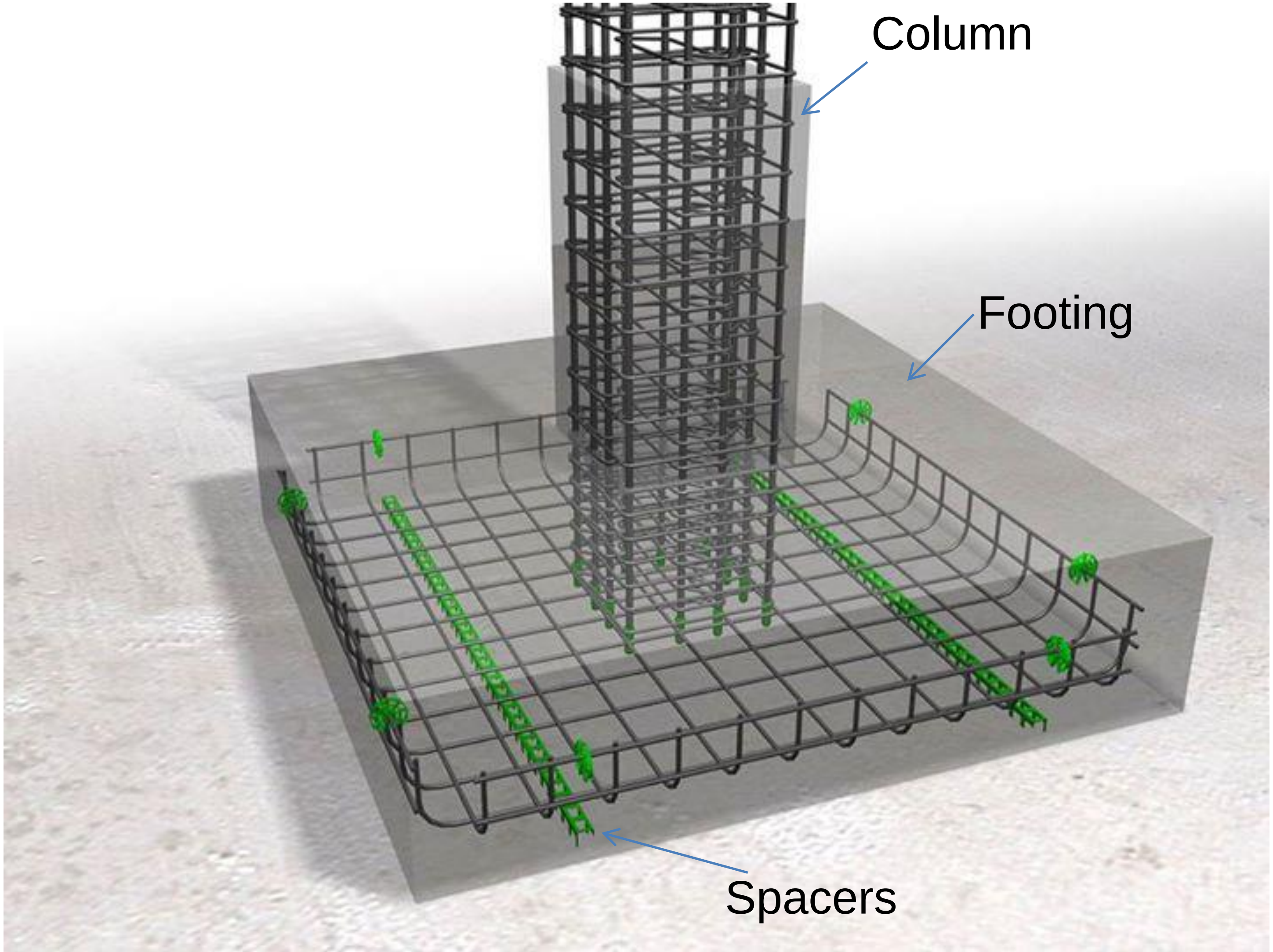
$$f_s = \frac{f_{yk}}{1.15}\left[\frac{G_k + 0.3Q_k}{1.35G_k + 1.5Q_k}\right]\frac{1}{\delta}$$

or

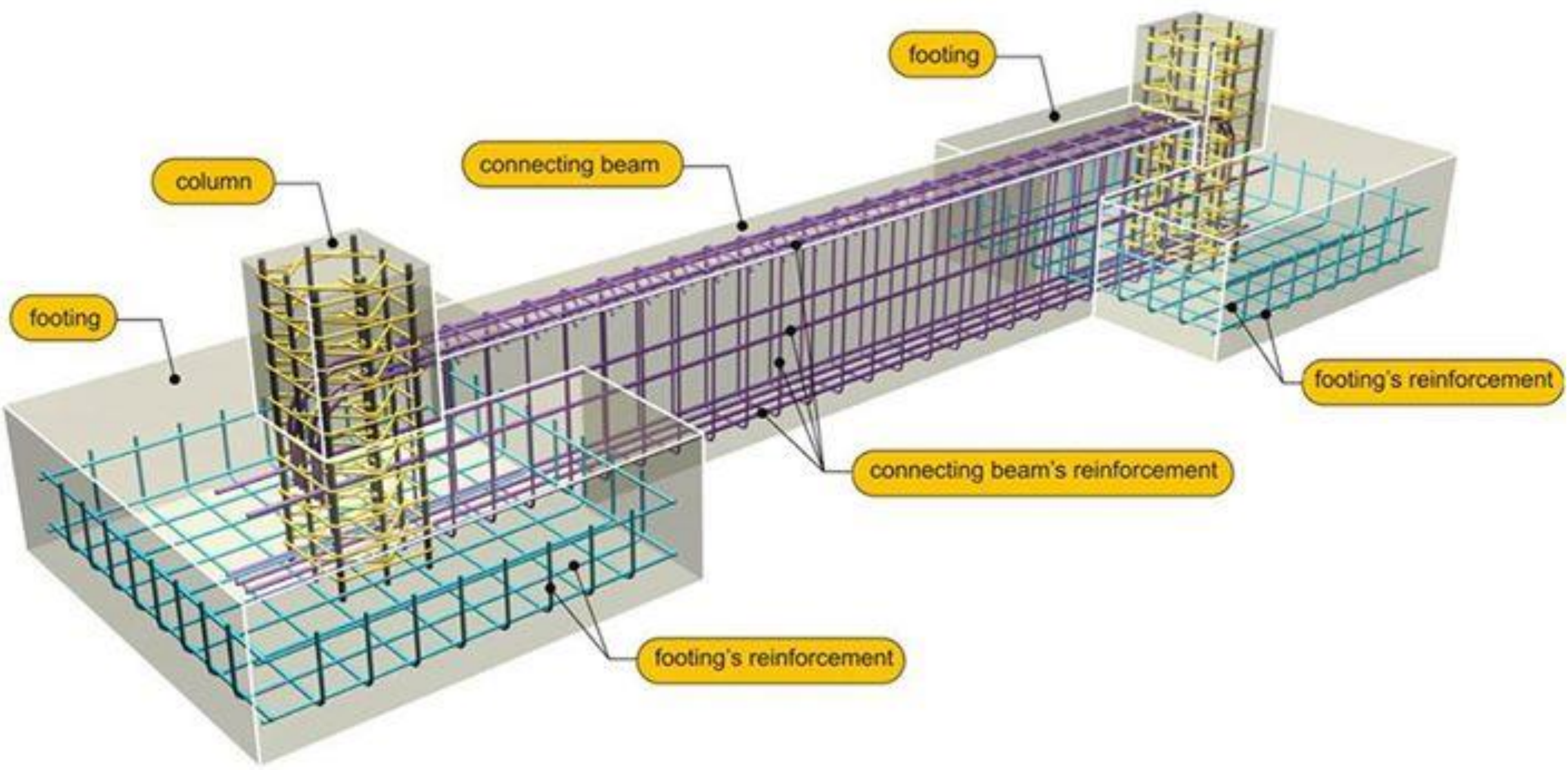
$$f_s = 435\left[\frac{G_k + 0.3Q_k}{1.35G_k + 1.5Q_k}\right]\left(\frac{A_{sreq}}{A_{sprov}}\right)$$

- For detailing requirement, maximum allowable spacing is 250mm

Detailing



Detailing


footing
connecting beam
column
footing
footing's reinforcement
connecting beam's reinforcement
footing's reinforcement

Example 4.1:

Pad footing under axial

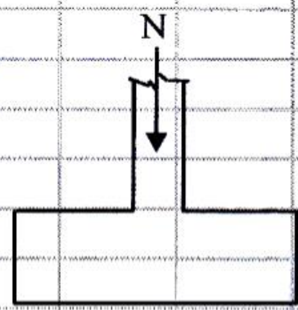
Example 4.1

A rectangular pad foundation is required to support a single column transferring an axial service load which consist of 600kN permanent load and 450kN variable load. Using the data provided, determine the suitable size of the footing and design the required reinforcement.

Design data:

f_{ck}	= 25 N/mm2
f_{yk}	= 500N/mm2
Soil bearing capacity	= 200N/mm2
Column dimension	= 300mm x 300mm
Design life	= 50 years
Exposure class	= XC2

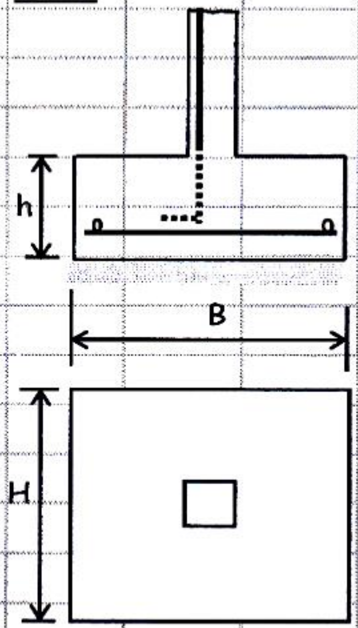
Example 4.1



Ref.	Calculations				Output
	SPECIFICATION				
		Axial Force, N			
		Permanent, G_k	=		600 kN
		Variable, Q_k	=		450 kN
		Design life		50 Years	(Table 2.1 EN 1990)
		Exposure classes	=		XC2
		Materials :			
		Concrete, f_{ck}	=		25 N/mm^2
		Reinforcement, f_{yk}	=		500 N/mm^2
	Column size :	Unit weight of concrete	=		25 kN/m^3
	300 x 300 mm	Soil bearing capacity	=		200 kN/m^2
		Assumed: ϕ_{bar}			16 mm
	DURABILITY & BOND REQUIREMENTS				
Table 4.2	Min. cover with regard to bond, $c_{min,b}$		=	16 mm	
Table 4.4N	Min. cover with regard to durability, $c_{min,dur}$		=	25 mm	
4.4.1.3	Allowance in design for deviation, Δc_{dev}		=	10 mm	
4.4.1.1(2)	Nominal cover,				Use:
	$c_{nom} = c_{min} + \Delta c_{dev}$ =	25 + 10	=	35 mm	c_{nom} = 35 mm

Example 4.1

SIZE



Service load, N = 1050.0 kN

Assume footing selfweight 10% of service load, W = 105.0 kN

Area of footing required,

= (N + W)/Soil bearing capacity

= (1050 + 105) / 200

= 5.78 m^2

Try square footing,

B x H x h	=	2.5 x 2.5 x 0.45m		
Area =	6.25	>	5.78	Ok !
Selfweight =	6.25	x 0.45	x 25	
=	70 kN	<	105kN	Ok !

ANALYSIS

Ultimate axial force,

$N_{Ed} = 1.35G_k + 1.5Q_k$

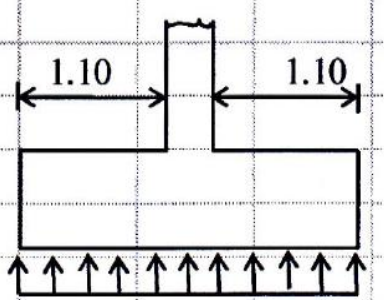
$= (1.35 \times 600) + (1.5 \times 450) = 1485$ kN

Example 4.1

Soil pressure at ulimate load,

$P = N_{Ed}/A$ = 1485 / 6.25 = 238 kN/m^2

Soil pressure per m length, w = 238 x 2.5 = 594 kN/m



Maximum momet at column face,

$M = wl^2/2$

= 594 x 1.10^2 / 2

= 359 kNm

6.1 **MAIN REINFORCEMENT**

Effective depth,

$d_{eff} = h - c_{nom} - 1.5\phi_{bar}$

= 450 - 35 - (1.5 x 16) = 391 mm

Bending, Moment, M = 359.4 kNm

$K = M / bd^2 f_{ck}$

= 359.4 x 10^6 / (2500 x 391^2 x 25)

= 0.038 < K_{bal} = 0.167

Compression reinforcement is not required

Example 4.1

$z = d\,[\,0.5 + \sqrt{(0.25 - K/1.134)}\,] = 0.97\,d \le 0.95d$

$A_s = M / 0.87 f_{yk} z$

$= 359 \times 10^6 / (0.87 \times 500 \times 0.95 \times 391)$

$= 2224\ mm^2$

Main bar :

9.2.1.1 Minimum and maximum reinforcement area,

13 H16

$(2614\ mm^2)$

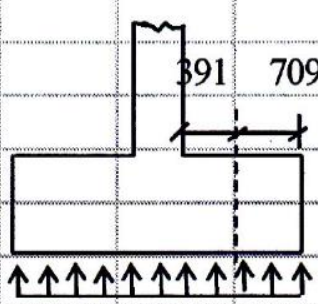
$A_{s,min} = 0.26(f_{ctm}/f_{yk})\,bd = 0.26 \times (2.56 / 500) \times bd$

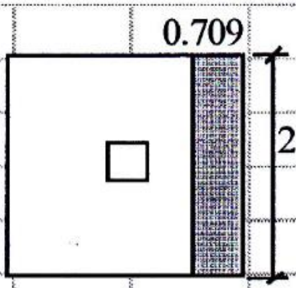
$= 0.0013\,bd = 0.0013 \times 2500 \times 391 = 1304\ mm^2$

$A_{s,max} = 0.04A_c = 0.04\ 2500 \times 450 = 45000\ mm^2$

SHEAR

(i). Vertical Shear : Critical at 1.0*d* from column face.





594 kN/m

Design shear force,

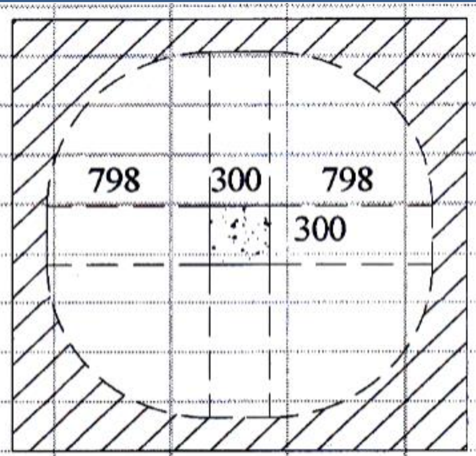
$V_{Ed} = 594 \times 0.709$

$= 421\ kN$

Example 4.1

Ref.	Calculations	Output
6.2.2	Design shear resistance,	
	$V_{Rd,c} = [\,0.12\,k\,(100\rho_1 f_{ck})^{1/3}\,]\,bd$	
	$k = 1 + (200/d)^{1/2} \leq 2.0$	
	$= 1 + (200 / 391)^{1/2} = 1.72 \leq 2.0$	
	$\rho_1 = A_{sl}/bd \leq 0.02$	
	$= 2614 / (2500 \text{ x } 391) = 0.0067 \leq 0.02$	
	$V_{Rd,c} = 0.12 \text{ x } 1.72 \text{ x } (100 \text{ x } 0.0067 \text{ x } 25)^{1/3} \text{ x } 2500 \text{ x } 391$	
	$= 514411$ N $=$ 514 kN	
	$V_{min} = [\,0.035k^{3/2} f_{ck}^{1/2}\,]\,bd$	
	$= 0.035 \text{ x } 1.72^{3/2} \text{ x } 25^{1/2} \text{ x } 2500 \text{ x } 391$	
	$= 384261$ N $=$ 384 kN	
	So, $V_{Rd,c} = 514.4$ kN $> V_{Ed}$	Ok !
6.4	(ii). Punching shear at perimeter $2d$ from column face	
	Average d = 450 - 35 - 16 = 399 mm	
	$2d$ = 2x399 = 798 mm	

Example 4.1



Control perimeter,

u = (4 x 300) + (2 x π x 798)
= 6215 mm

Area within perimeter

A = $(0.30)^2$ + (4 x 0.30 x 0.798) + (π x 0.798^2)
= 3.05 m^2

Punching shear force,

V_{Ed} = 238 (2.5^2 - 3.05) = 761 kN

Punching shear stress,

v_{Ed} = V_{Ed} / ud
= 761 x 10^3 / (6215 x 399) = 0.31 N/mm^2

Shear resistance,

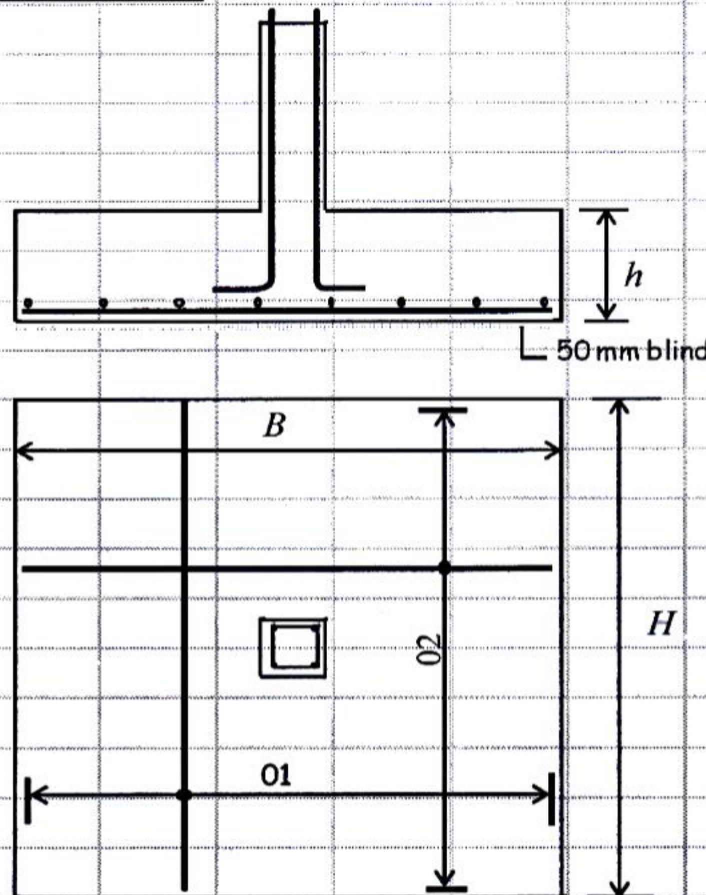
$v_{Rd,c}$ = 384 x 10^3 / (2500 x 399)
= 0.39 N/mm^2 > v_{Ed} Ok !

Example 4.1

	(iii). Maximum punching shear at column perimeter.	
	Maximum shear resistance,	
	$V_{Rd,max} = 0.5ud\ [0.6(1 - f_{ck}/250)]\ f_{ck}/1.5$	
	$= 0.5(4 \times 300) \times 399\ [0.6(1 - 25/250)]\ (25/1.5)$	
	$= 2155$ kN $>$ $V_{Ed,max} = 1485$ kN	Ok !
	CRACKING	
7.3.3	$h = 450$ mm > 200 mm	Need spesific measure !
	Steel stress under the action of quasi-permanent loading	
	$f_s = [(G_k + 0.3Q_k)/(1.35G_k + 1.5Q_k)](A_{s,req}/A_{s,prov})(f_{yk}/1.15)$	
	$G_k + 0.3Q_k = 600 + (0.30 \times 450) = 735$ kN	
	$(1.35G_k + 1.5Q_k) = 1485$ kN	
	$f_s = (735/1485)\ (2224/2614)\ (500/1.15)$	
	$= 0.49 \times 0.85 \times 435$	
	$= 183$ N/mm^2	
Table 7.3N	For design crack width = 0.3 mm	
	Max. allowable bar spacing = 250 mm	
	Max. bar spacing $= [2500 - 2(43) - 16] / 12$	
	$= 200$ mm $<$ 250 mm	Ok !

Example 4.1

DETAILING



Dimension:			
	B =	2500	mm
	H =	2500	mm
	h =	450	mm
Cover, C_{nom} =		35	mm
Reinforcement:			
01 :	13H	16	equally space
02 :	13H	16	equally space

Example 4.2:

Pad footing under axial + uniaxial-moment

Example 4.2

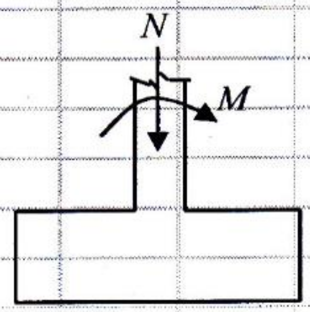
Design a rectangular pad footing of uniform thickness for a reinforced concrete column of size 300mm x 300mm and carrying axial load of 1500kN and ultimate bending moment of 50kNm.

Design data:

f_{ck}	=25 N/mm2
f_{yk}	=500N/mm2
Soil bearing capacity	= 200N/mm2
Column dimension	= 300mm x 300mm
Nominal cover	= 40mm

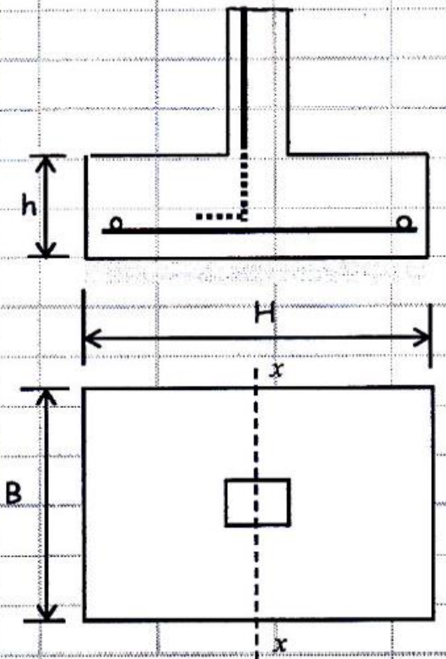
*Use a factor of 1.40 to change the design load to service load.

Example 4.2

Ref.	Calculations	Output
	SPECIFICATION	
		
	Ultimate action:	
	Axial, N =	1500 kN
	Moment, M =	50 kNm
	Design life 50 Years	(Table 2.1 EN 1990)
	Exposure classes =	XC2
	Materials :	
	Concrete, f_{ck} =	25 N/mm^2
	Column size : / Reinforcement, f_{yk} =	500 N/mm^2
	250 x 350 mm / Unit weight of RC =	25 kN/m^3
	Assumed ϕ_{bar} = 16 mm / Soil bearing capacity =	150 kN/m^2
	DURABILITY & BOND REQUIREMENTS	
Table 4.2	Min. conc. cover regard to bond, $c_{min,b}$ = 16 mm	
Table 4.4N	Min. conc. cover regard to durability, $c_{min,dur}$ = 25 mm	
4.4.1.3	Allowance in design for deviation, Δc_{dev} = 10 mm	
4.4.1.1(2)	Nominal cover,	Use:
	$c_{nom} = c_{min} + \Delta c_{dev}$ = 25 + 10 = 35 mm	c_{nom} = 35 mm

Example 4.2

SIZE



Service actions:

Axial, N = 1500 /1.40

= 1071 kN

Moment, M = 50 /1.40

= 36 kNm

Assumed selfweight of footing 10% of service load.

Area of footing required,

= 1.1N / Bearing capacity

= 1.1 x 1071 / 150

= 7.86 m^2

Try size : B x H x h

2.50 x 3.50 x 0.65 m

A = 8.75 m^2

$I_{xx} = BH^3/12 =$ 8.9323 m^4

y = $H/2$ = 1.75 m

Selfweight ,

= 25 x 8.75 x 0.65

= 142 kN

Max. soil pressure,

$P = (N+W)/A + My/I$

= (142 +1071) / 8.75

+ 36 x 1.75 / 8.93

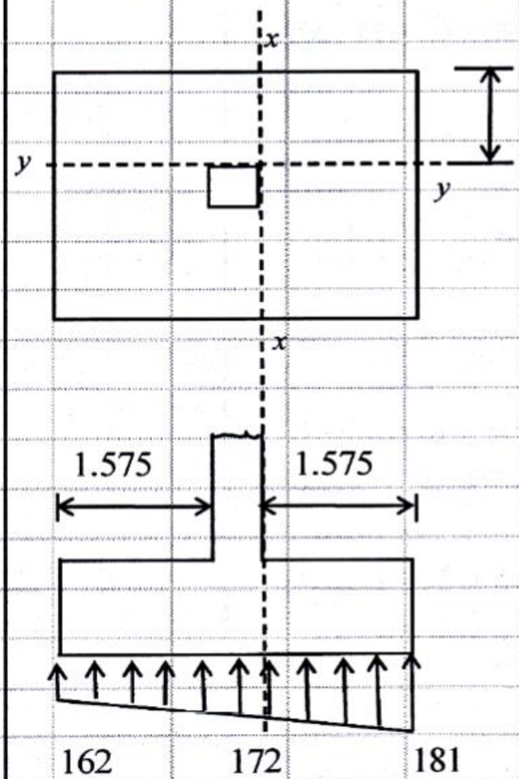
= 146 kN/m^2

< 150 kN/m^2

Size Ok!

Example 4.2

ANALYSIS



Ultimate soil pressure,

$P = N/A \pm My/I$

$= (1500 / 8.75) + (50 \times 1.75 / 8.93)$

$= 171 \pm 9.8$

$P_{max} = 181$ kN/m^2

$P_{min} = 162$ kN/m^2

Bending moment at column face,

$M_{xx} = (172 \times 1.575^2 / 2) + [(181 - 172) 1.575^2 \times 2/3]$

$= 228$ kNm/m $\times 2.50 = 571$ kNm

$M_{yy} = (171 \times 1.125^2 / 2)$

$= 108$ kNm/m $\times 3.50 = 380$ kNm

Example 4.2

6.1	**MAIN REINFORCEMENT**	
	Effective depth,	
	$d_{xeff} = h - c_{nom} - 0.5\phi_{bar}$ = 650 - 35 - 0.5x16 = 607 mm	
	$d_{yeff} = h - c_{nom} - 1.5\phi_{bar}$ = 650 - 35 - 1.5x16 = 591 mm	
	Longitudinal bar	
	Bending Moment, M = 571 kNm	
	$K = M / bd^2 f_{ck}$	
	= 571 x 10^6 / (2500 x 607^2 x 25)	
	= 0.025 < K_{bal} = 0.167	
	Compression reinforcement is not required	
	$z = d\,[0.5 + \sqrt{0.25 - K/1.134)}\,]$ = 0.98 d ≤ 0.95d	
	$A_s = M / 0.87 f_{yk} z$	
	= 571 x 10^6 / (0.87 x 500 x 0.95 x 607)	Use: 15 H16
	= 2277 mm^2	(3016 mm^2)

Example 4.2

Ref.	Calculations	Output
9.2.1.1	Minimum and maximum reinforcement area,	
	$A_{s,min} = 0.26(f_{ctm}/f_{yk})\,bd$ = 0.26 x (2.56 / 500) x bd	
	= 0.0013 bd = 0.0013 x2500 x 607 = 1973 mm^2	
	$A_{s,max} = 0.04A_c$ = 0.04 x 2500 x 650 = 65000 mm^2	
	Transverse bar	
	Bending Moment, M = 380 kNm	
	$K = M / bd^2 f_{ck}$	
	= 380 x 10^6 / (3500 x 591^2 x 25)	
	= 0.012 < K_{bal} = 0.167	
	Compression reinforcement is not required	
	$z = d\,[\,0.5 + \sqrt{0.25 - K/1.134}\,] = 0.99\,d \leq 0.95d$	
	$A_s = M / 0.87 f_{yk} z$	
	= 380 x 10^6 / (0.87 x 500 x 0.95 x 591)	Use: 25 H12
	= 1555 mm^2	(2828 mm^2)
9.2.1.1	Minimum and maximum reinforcement area,	
	$A_{s,min} = 0.26(f_{ctm}/f_{yk})\,bd$ = 0.26 x (2.56 / 500) x bd	
	= 0.0013 bd = 0.0013 x3500 x 591 = 2759 mm^2	
	$A_{s,max} = 0.04A_c$ = 0.04 x 3500 x 650 = 91000 mm^2	

Example 4.2

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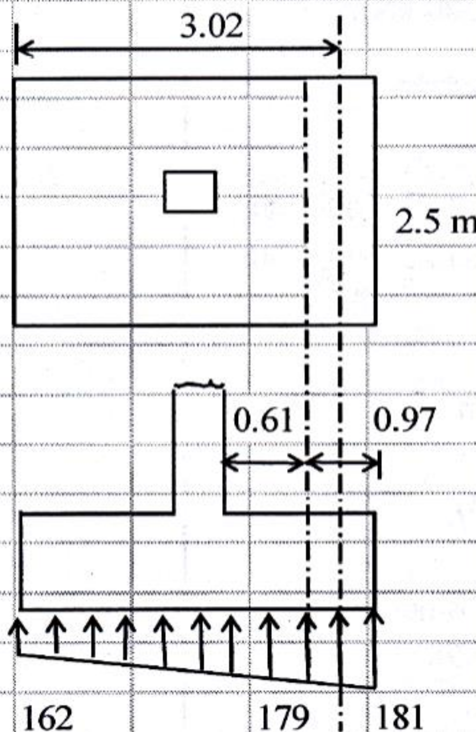
SHEAR

(i). Vertical shear : at 1.0d from column face



Average pressure at crtical section

= 162+ (3.02/ 3.50) x (19.6)

= 179 kN/m^2

Vertical shear force

V_{Ed} = 179 x 0.97 x 2.5

= 432 kN

Example 4.2

Ref.	Calculations	Output
	v_{Ed} = 1.08 (466 x 10^3 / 8728 x 607)	
	= 0.10 N/mm^2	
	Shear resistance,	
	$v_{Rd,c}$ = 524 x 10^3 / (8728 x 599)	
	= 0.10 N/mm^2 > v_{Ed}	Ok !
	(iii). Maximum Punching Shear at column perimeter.	
	Punching shear force at column perimeter	
	V_{Ed} = 1500 kN	
	Column perimeter u_o = (350 + 250) x 2 = 1200 mm	
6.4.3(2)	Punching shear stress,	
	$v_{Ed} = \beta (V_{Ed} / u_o d)$	
	where $\beta = 1 + k \, (M_{Ed}/V_{Ed})(u_o/W_1)$	
	$W_1 = (0.5c_1^2) + c_1 c_2$	
Table 6.1	= (0.50 x 350^2) + (350 x 250)	
	= 0.15 x 10^6	
	= 1 + [0.65 x (50 x 10^6 / 1500 x 10^3)	
	x (1200 / 0.15 x10^6)]	
	β = 1.17	
	v_{Ed} 1.17 1500 x 10^3 / 1200 x 599)	
	= 2.45 N/mm^2	

Example 4.2

	Maximum shear resistance,	
	$V_{Rd,max}$ = 0.5 [0.6(1 - f_{ck}/250)] f_{ck}/1.5	
	= 0.5 [0.6 (1 - 25 / 250)] (25/1.5)	
	= 4.50 N/mm² > v_{Ed}	Ok !
	CRACKING	
7.3.3	h = 650 mm > 200 mm	
	Assume steel stress under quasi permanent loading ,	
	= 0.6 (f_{yk}/1.15)($A_{s,req}$/$A_{s,prov}$)	
	= 0.6 (500 / 1.15) (2277 / 3016)	
	= 197 N/mm²	
Table 7.3N	For design crack width = 0.3 mm	
	Max. allowable bar spacing = 250 mm	
	Max. bar spacing 1 = 2500 - 2(43) - 16] / 14	
	= 171 mm < 250 mm	Ok !
	Max. bar spacing 2 = 3500 - 2(41) - 12] / 24	
	= 142 mm < 250 mm	Ok !

Example 4.2

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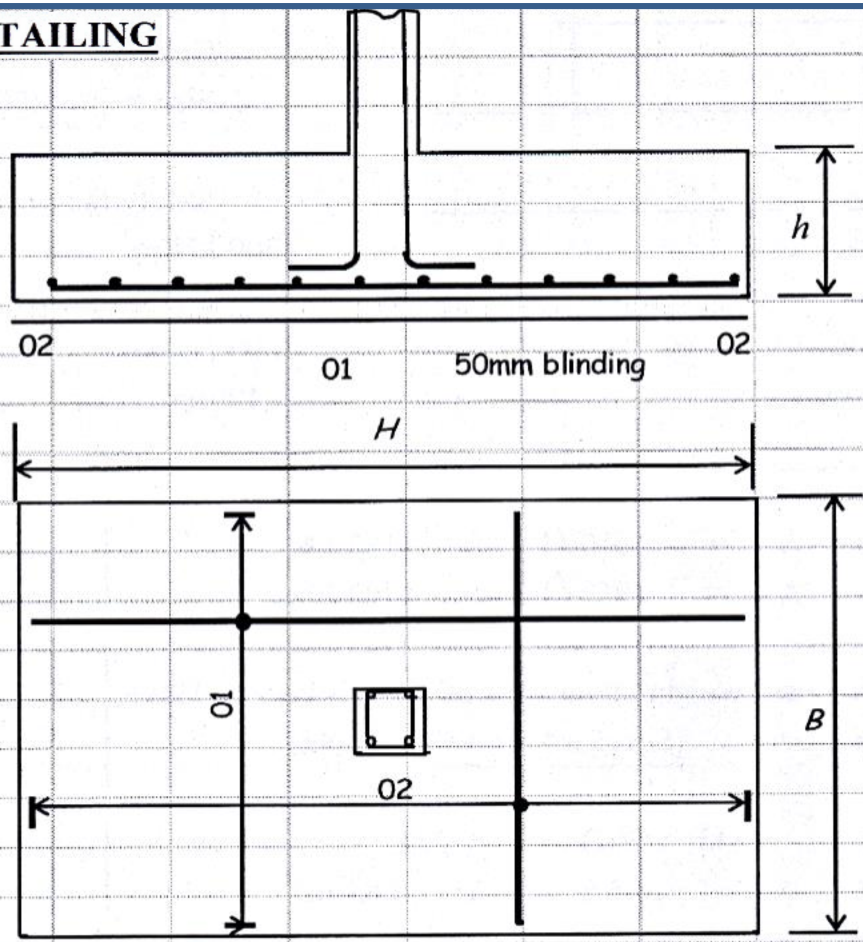
DETAILING



Dimension:	$B \times H \times h$ =	2500	x 3500	x 650	mm
Cover, c_{nom}	= 35 mm				
Reinforcement:	Bar mark 01:	15H	16 @	172	mm
	Bar mark 02:	25H	12 @	142	mm