FOUNDATION ENGINEERING I (CONTD…)

CEng 3204

CHAPTER THREE

Design of Shallow Foundations**: Strap and Mat/Raft Foundation**

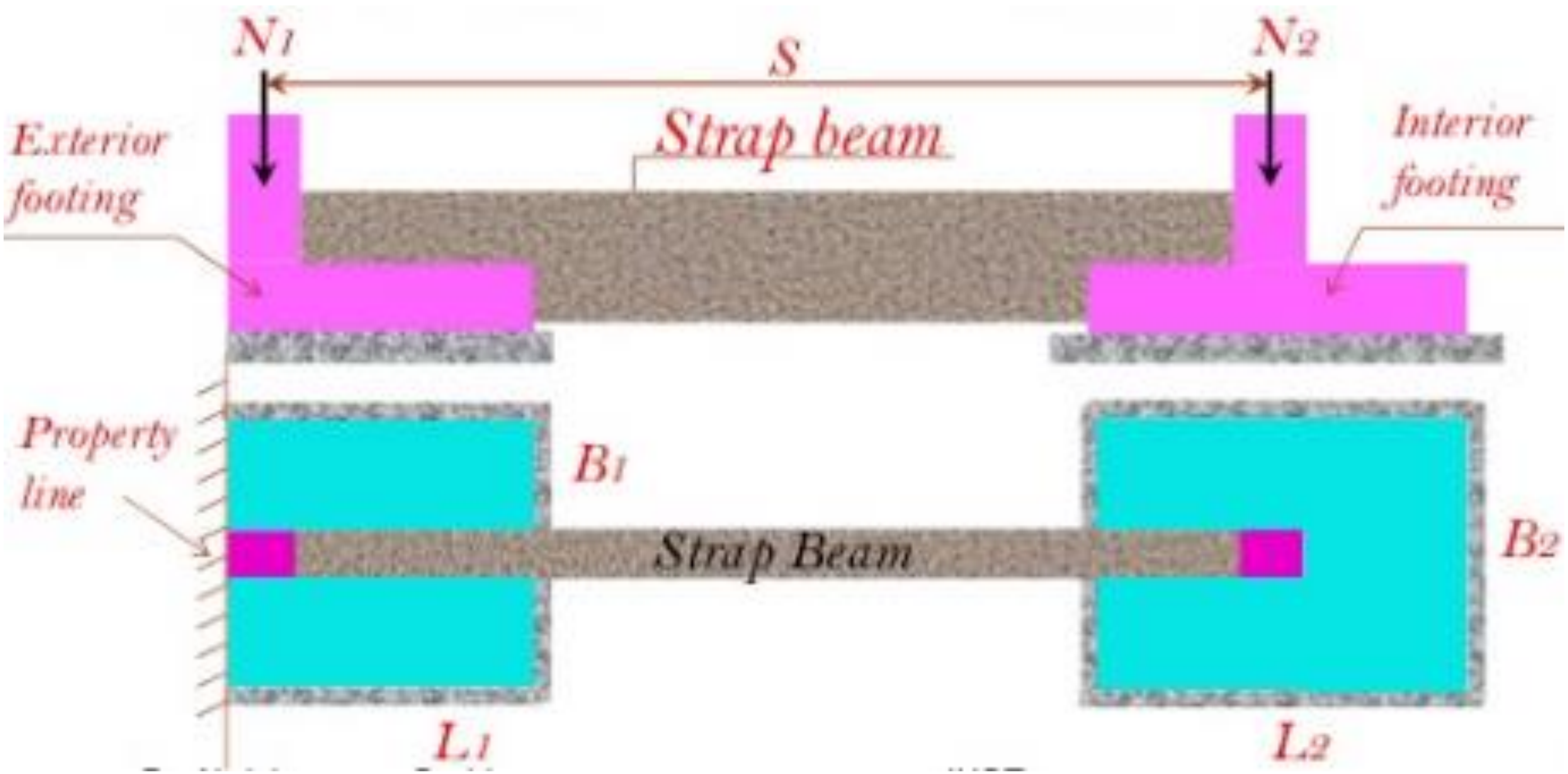
Strap Footing Design

- A strap footing may be used instead of a combined footing if the distance between columns is large and/or the allowable soil pressure is relatively large so that the additional footing area is not needed.

- A strap footing is used to connect an eccentrically loaded column footing to an interior column.

- The strap is used to transmit the moment caused from an eccentricity to the interior column footing so that a uniform soil pressure is generated beneath both footings.

Strap Footing Design

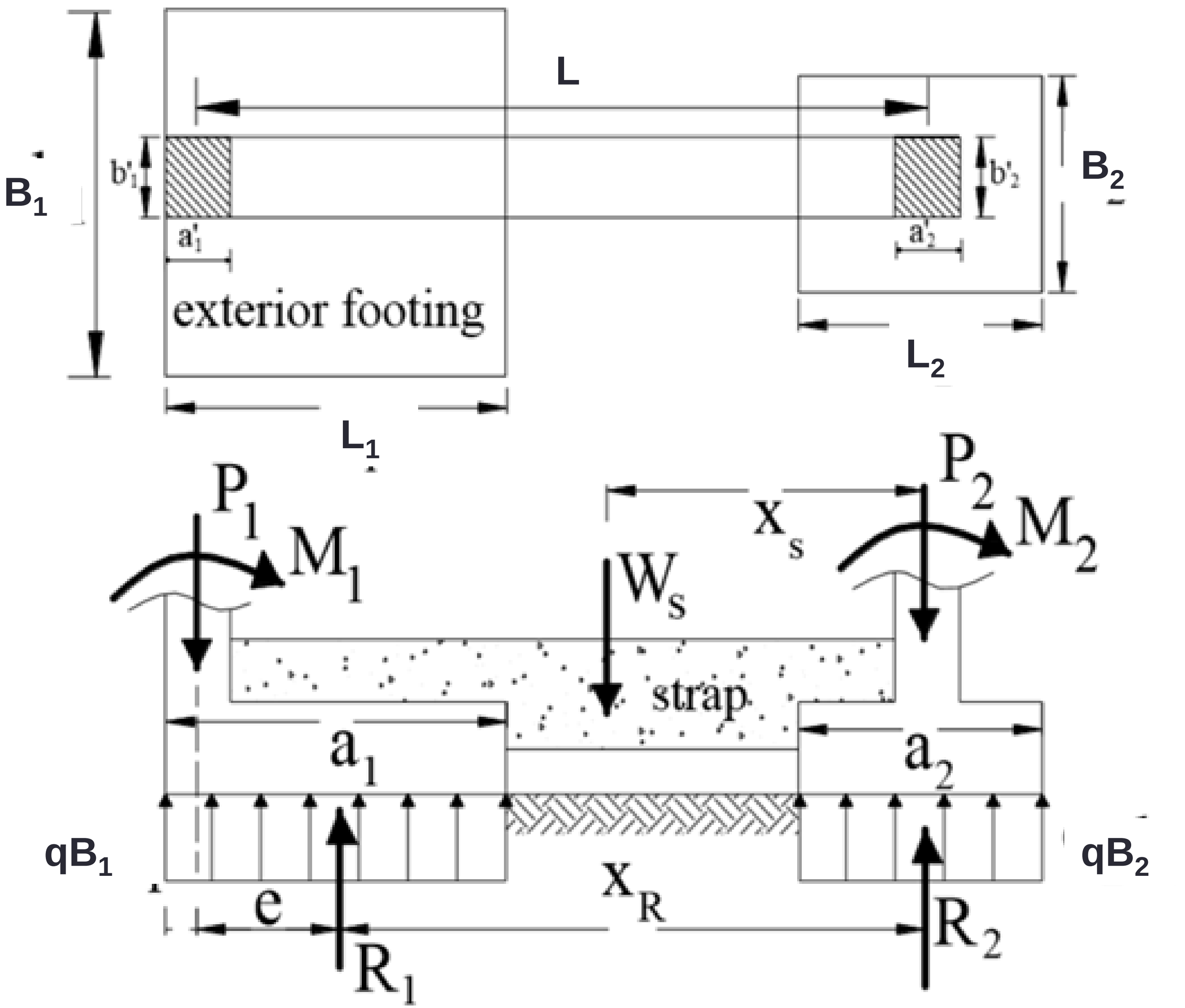


Strap Footing Design

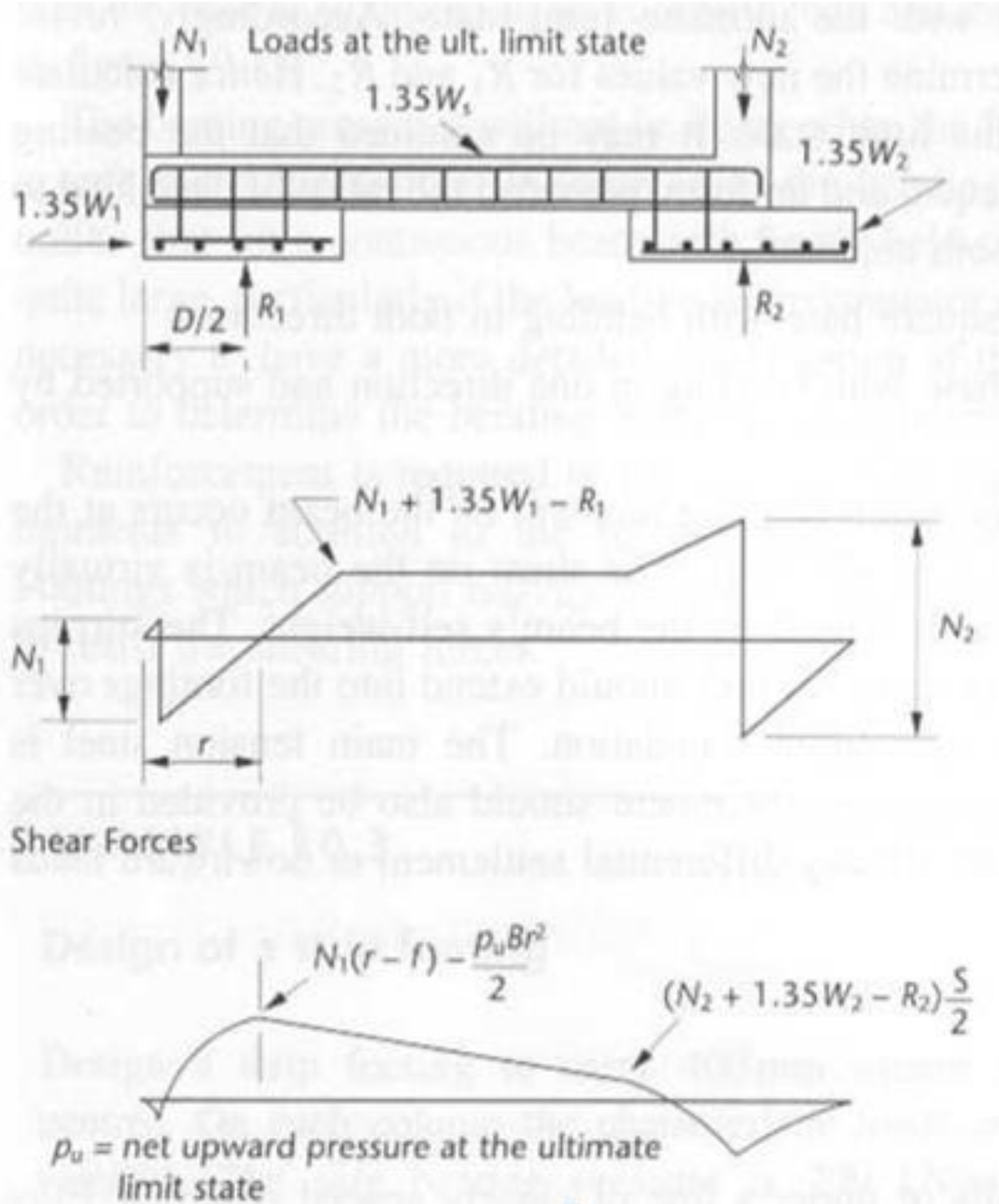
- Considerations for strap footing design;
  - Strap must be rigid.
  - The footing areas are proportioned in such a way to keep the pressure under the two footings uniform and equal and for the centroid of the combined footing areas to coincide with the resultant of the two column loads.
  - Strap should be out of contact with the soil so that there are no soil reaction.

Strap Footing Design: Procedures

1. Assume L_1 and establish the eccentricity, e of the soil reaction force R_1.
2. Determine the magnitude of the soil reaction, R_1 by taking moment about R_2.
3. Determine the magnitude of R_2 from $\Sigma F_y = 0$.
4. Compute the widths of the footings.
5. Check if the location of the resultant of the column forces coincide with the center of gravity of the two footings .
6. Apply the loading associated with ULS and evaluate the new values of the reaction. Calculate the bearing pressure for this limit state.
7. Draw the SFD and BMD
8. Design the inner footing as a square base with bending in both directions.
9. Design the outer footing as a base with bending in one direction and supported by the strap beam.
10. Design the strap beam.



L
B1
b'1
b'2
B2
a'1
a'2
exterior footing
L2
L1
P1
M1
P2
M2
xs
Ws
strap
a1
a2
qB1
qB2
xR
e
R1
R2

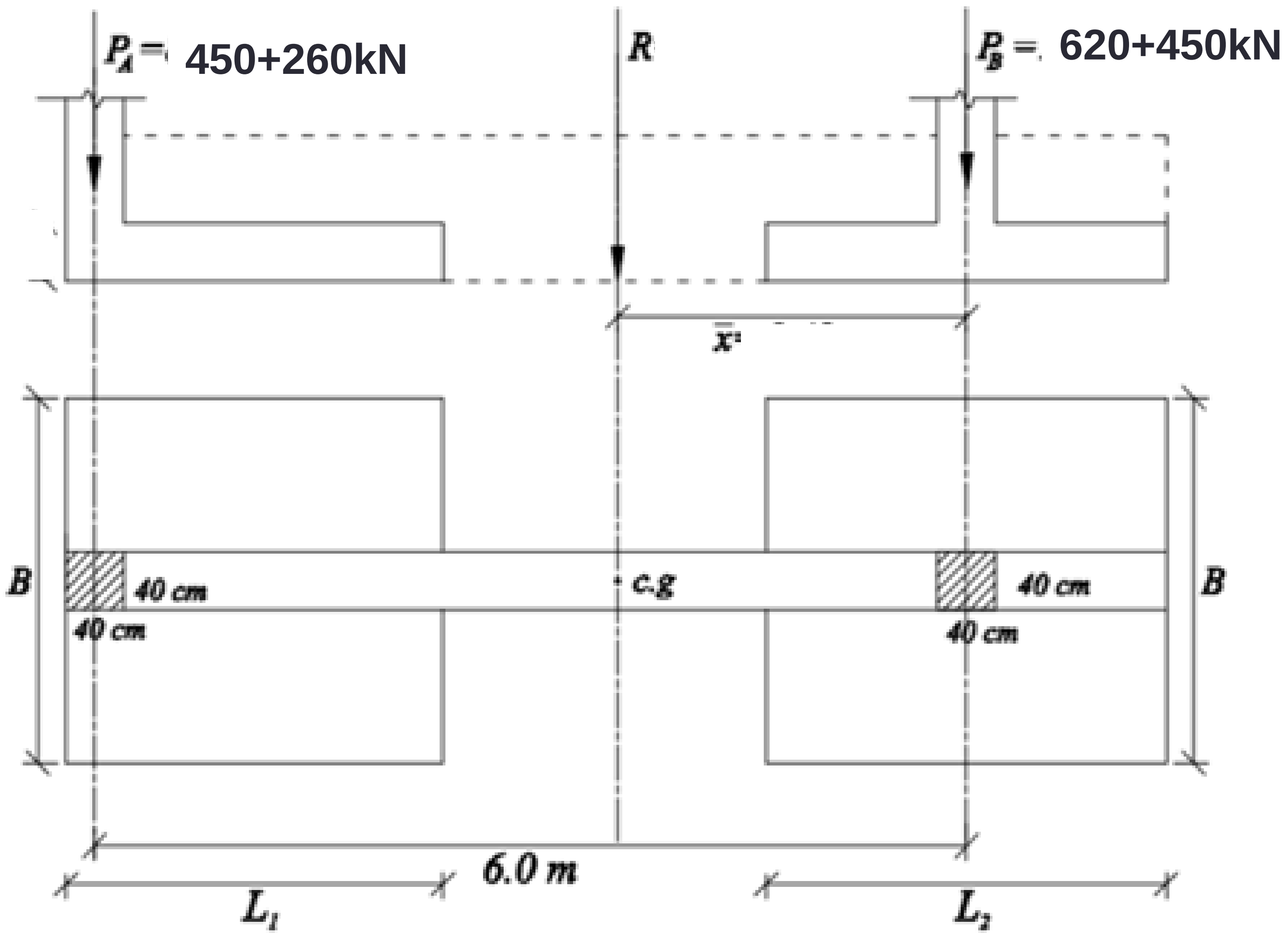


N1 Loads at the ult. limit state N2
1.35W1
1.35W2
1.35W1
R1
R2
D/2
N1 + 1.35W1 − R1
N1
N2
r
Shear Forces
N1(r − f) − puBr²/2
(N2 + 1.35W2 − R2)S/2
pu = net upward pressure at the ultimate limit state

Worked Example

Design a strap footing to support two column spaced at a distance of 6 m center-to-center. Column 1 is *40 cm X 40 cm* and carries *a dead load of 450kN* and *imposed load of 260kN*. Column 2 is also *40 cm X 40 cm* in cross section and carries a *dead load o 620kN* and *imposed load of 450kN.*

Use f_{yk} = 300MPa, f_{ck} = 20 Mpa. And the safe bearing pressure is100kPa.

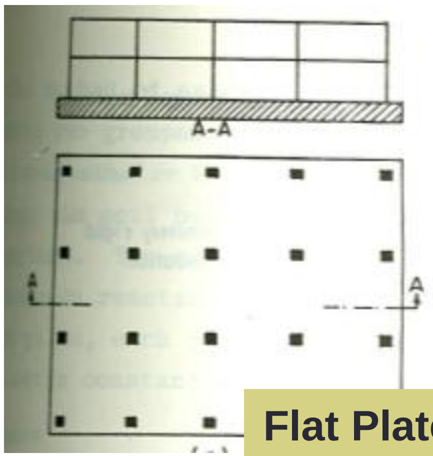

P_A = 450+260kN
R
P_B = 620+450kN
$\bar{x}$'
B
40 cm
40 cm
c.g
40 cm
40 cm
B
6.0 m
L_1
L_2

Design of Mat/Raft Foundation

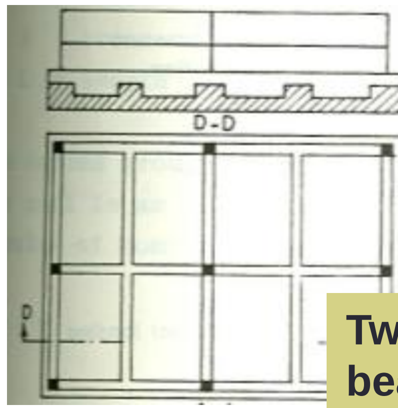
- A foundation system in which the entire building is placed on a large continuous footing.
- It is a large concrete slab supporting many columns.
- Raft foundation is generally suggested in the following situations;
  - When building loads are very heavy.
  - Whenever soil contains compressible lenses and it is difficult to define and asses the extent of each of the weak pockets or cavities thus the differential settlement.
  - Soil has a very low bearing capacity.
  - When structure and equipment to be supported are sensitive to differential settlement.

Design of Mat/Raft Foundation

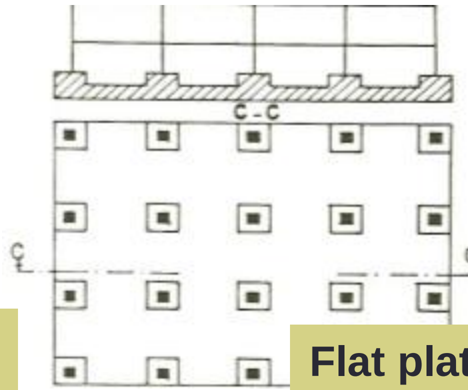
- Mat foundation have different forms.



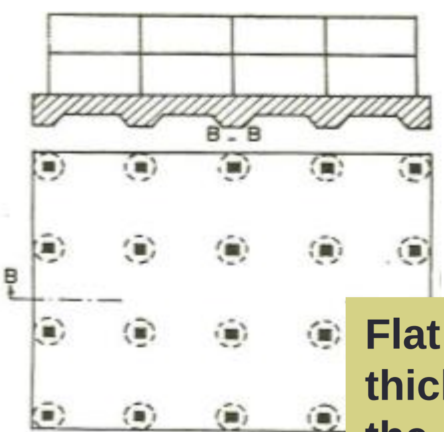
Flat Plate



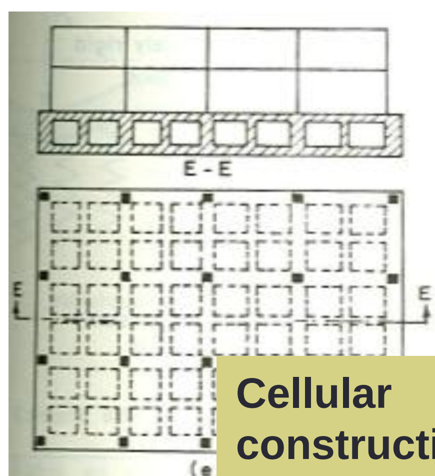
Two-way beam and ribbed slab



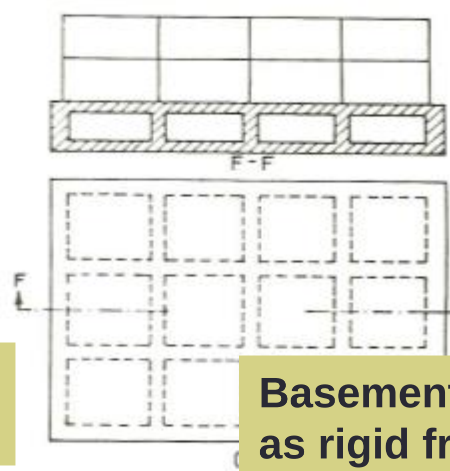
Flat plate with pedestals



Flat Plate thickened at the column



Cellular construction



Basement walls as rigid frames

Design of Mat/Raft Foundation

- Design Methods
  - Similar to a flat slab upside down. (loaded upward by the bearing pressure and downward by the concentrated column reactions.
  - Method of design depends on the assumption made regarding the distribution of bearing pressures.
  - Two design approaches are suggested.
    1. **Rigid foundation approach**
    2. **Flexible foundation approach.**

Design of Mat/Raft Foundation

1. Rigid foundation approach

- The mat is assumed to be infinitely rigid in comparison with the sub-soil.
- The mat is rigid enough to bridge over non-uniformities of the soil structure.
- A mat foundation can be designed by the conventional rigid method if it satisfies the following condition.

1. The spacing of columns in a strip of the mat is less than **1.75/λ** where **λ** is the characteristic coefficient is defined by Hetenyi M. (1946) as

$$\lambda = \sqrt{\frac{B\,k_s}{4\,EI}}$$

k_s : Coefficient of subgrade reaction

B: width of strip

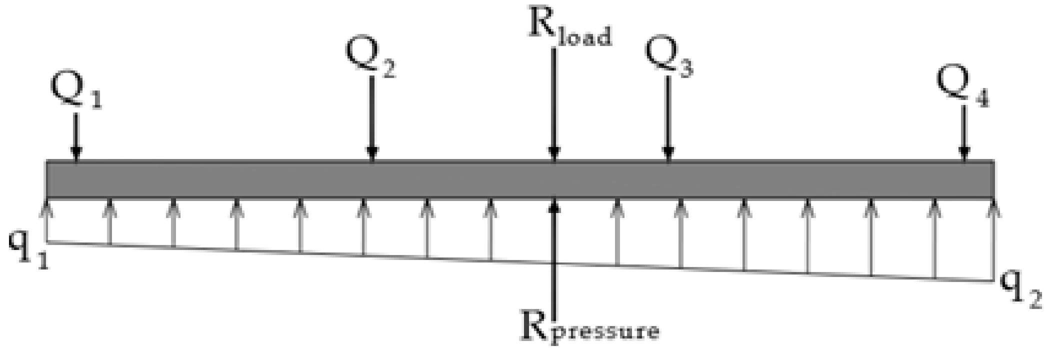
E: Modulus of elasticity of raft material

I: Moment of inertia of a strip of width B

2. Variation in column loads and spacing is not over 20%.

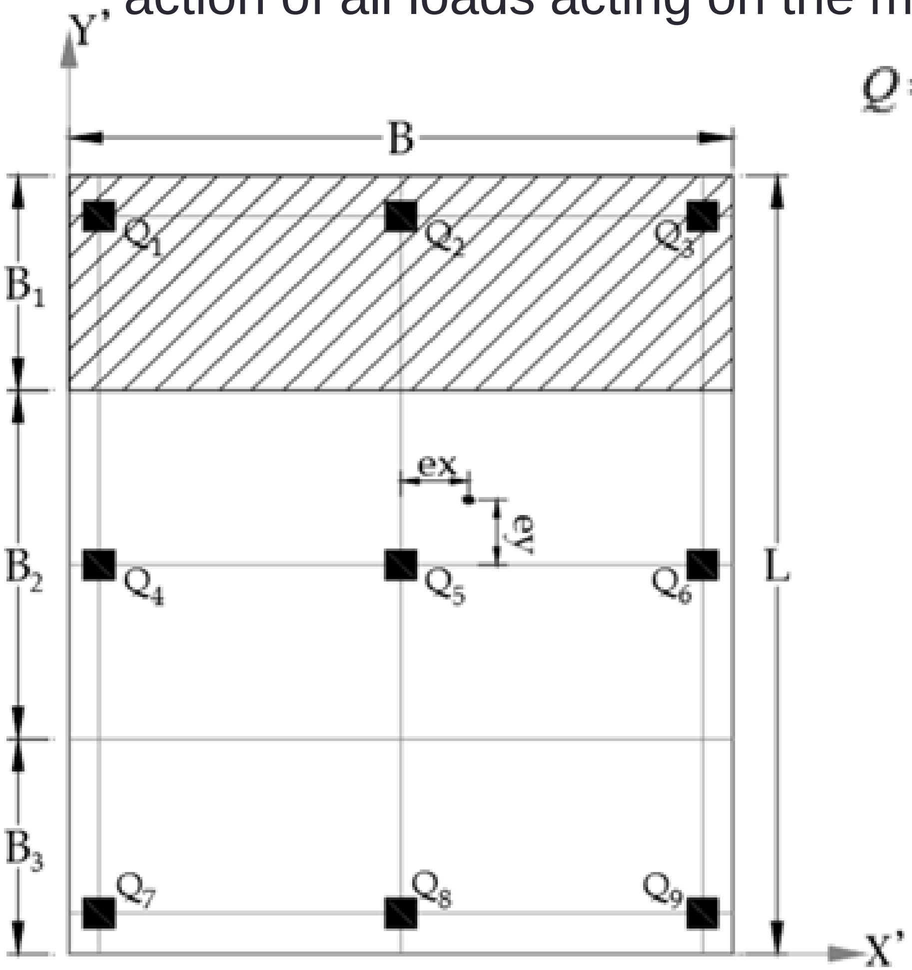
Design of Mat/Raft Foundation

- ***Pressure distribution*** is considered to be either ***uniform or varying linearly,*** such that the centroid of the soil pressure coincides with the line of action of the resultant force of all loads acting on the mat.



Design of Mat/Raft Foundation: Procedures

1. Compute the total column and wall load and determine the line of action of all loads acting on the mat.



$$Q = Q_1 + Q_2 + Q_3 + \ldots\ldots = \sum Q_i$$

Design of Mat/Raft Foundation: Procedures

2. Determine the allowable pressure distribution using flexural equation and check whether the pressure values are less than the allowable bearing pressure..

$$q = \frac{Q}{A} \pm \frac{M_x Y}{I_x} \pm \frac{M_y X}{I_y}$$

Where, A = B L =Base area of the mat foundation

I_x moment of inertia about x - axis = $BL^3/12$

I_y moment of inertia about x - axis = $LB^3/12$

M_x moment of the column loads about the x - axis = $\sum Q.e_y$

M_y moment of the column loads about the y - axis = $\sum Q.e_x$

$$x = \frac{(Q_1 x_1 + Q_2 x_2 + Q_3 x_3 + \ldots\ldots)}{\sum Q} \quad \Rightarrow e_x = x - \frac{B}{2}$$

$$y = \frac{(Q_1 y_1 + Q_2 y_2 + Q_3 y_3 + \ldots\ldots)}{\sum Q} \quad \Rightarrow e_y = y - \frac{L}{2}$$

Design of Mat/Raft Foundation: Procedures

3. Analyze the mat in one of the following approximate methods.

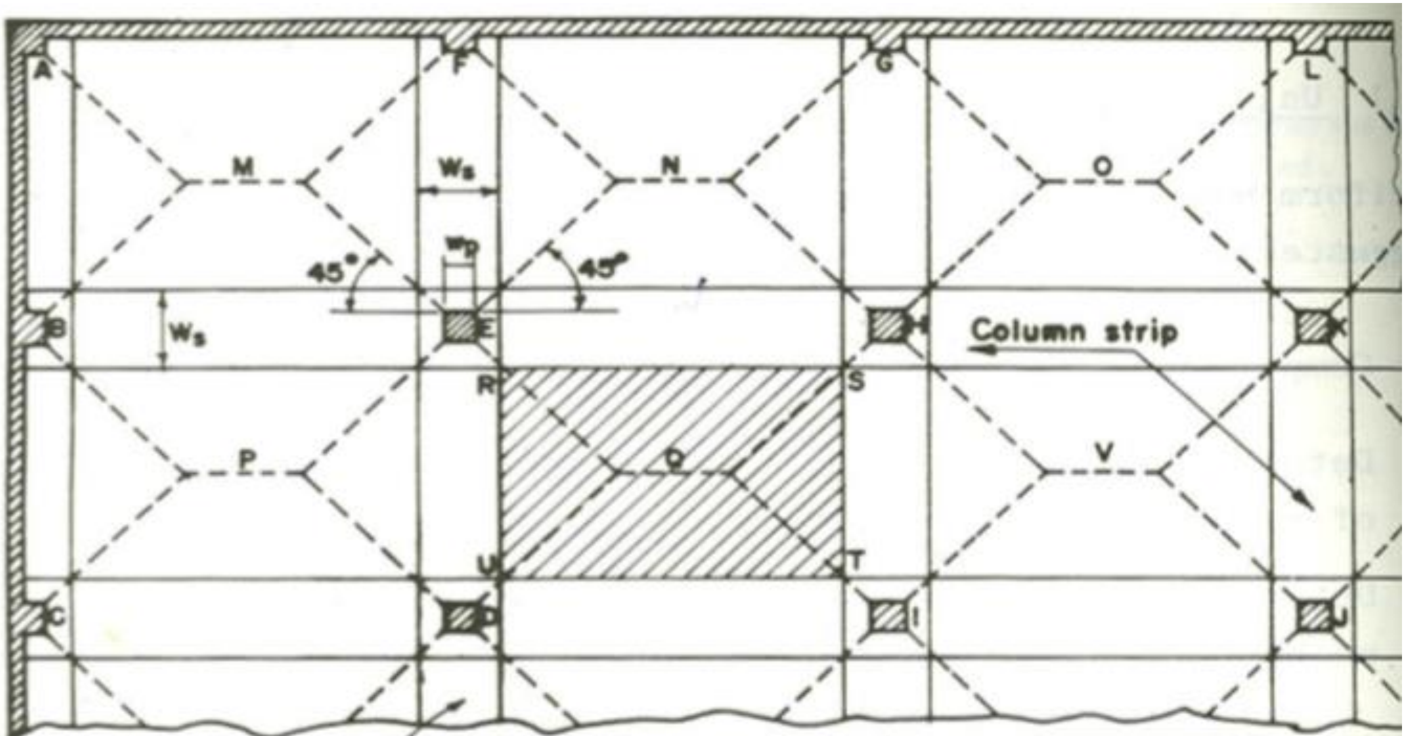
- **Method A: Inverted floor system**
- **Method B: Combined footing approach**

Design of Mat/Raft Foundation: Procedures

1. **Rigid foundation approach**

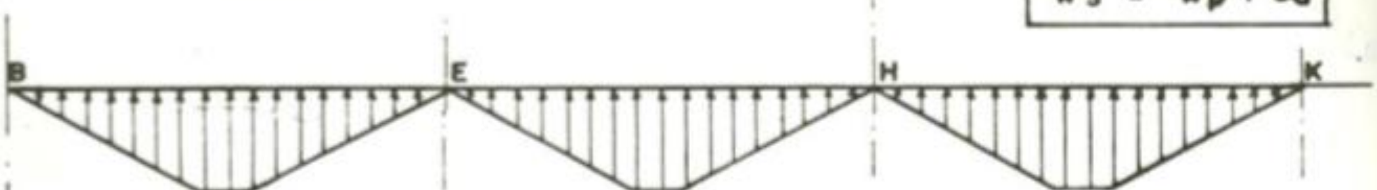
- **Method A: Inverted floor system**

- Convert the contact pressure to a uniform contact pressure distribution using engineering judgment.
- Take a system of column width with width Ws.
- Draw a 45^0 diagonal lines from the edges of columns.
- The central slabs are designed as two-way rectangular slabs with fixed edges supported by strips.
- The column strips are designed as a series of fixed-end beams with triangular loading.

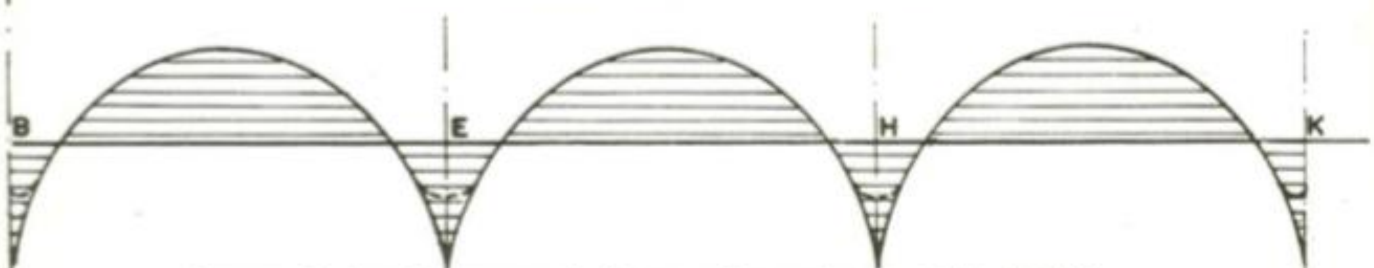


Assumed column strips.

$W_s = W_p + 3d$



Assumed upward loading for column strip BEHK



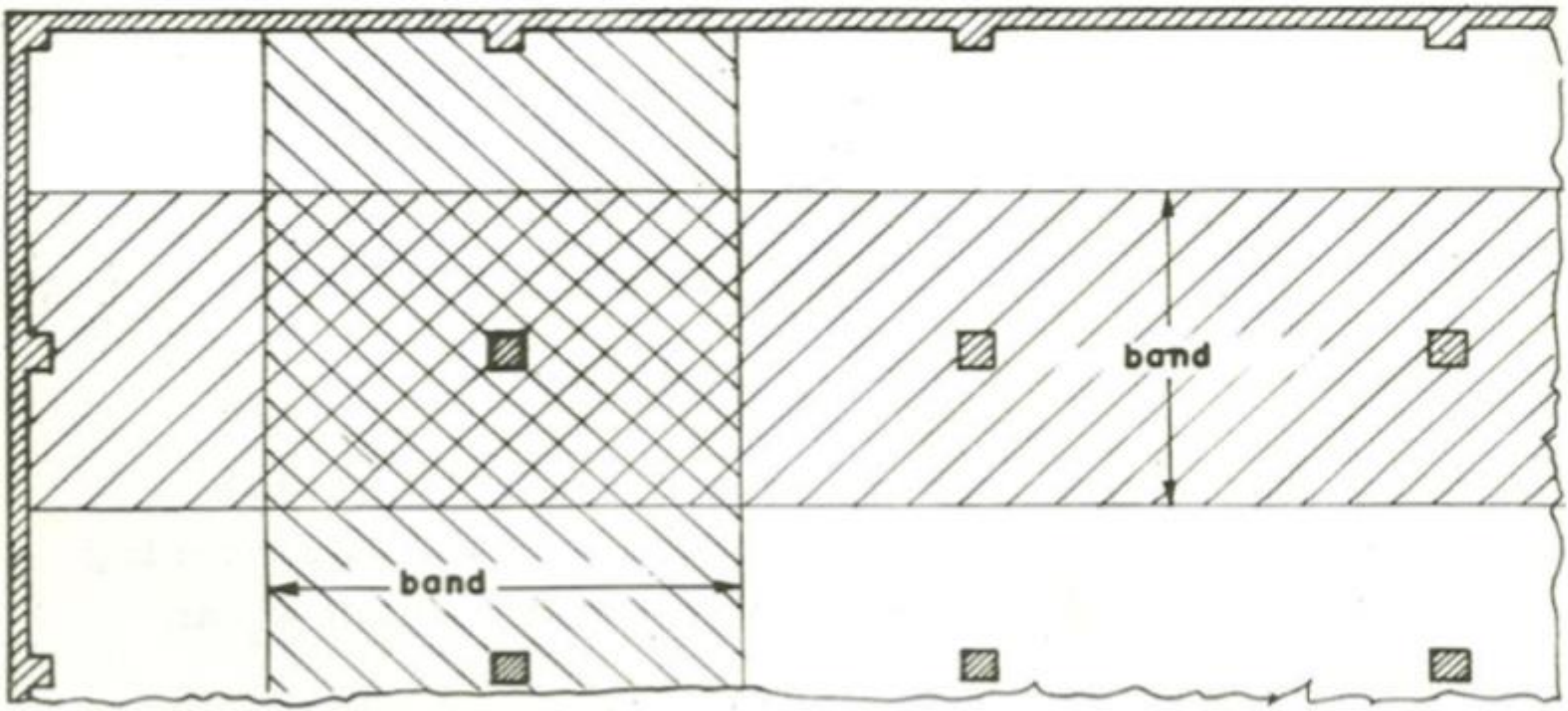
Assumed bending moment diagram for column strip BEHK

Design of Mat/Raft Foundation

1. **Rigid foundation approach**

- **Method B: Combined footing approach**

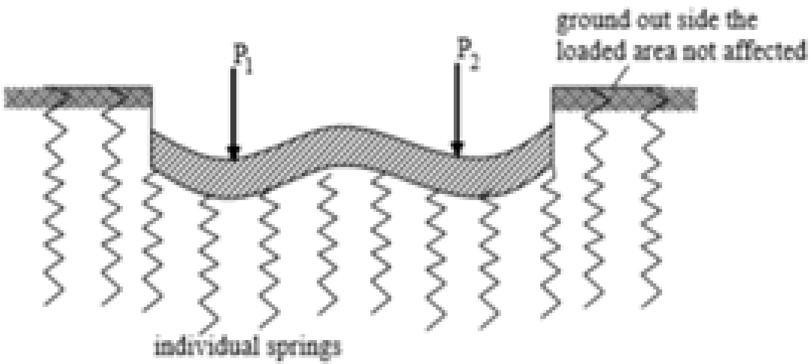
- Divide the slab into perpendicular bands.
- Each band is assumed to act as an independent beam subjected to known contact pressure and known loads.
- Determine the magnitude of the positive and negative moments using $M = \frac{w\,l^2}{10}$ for interior spans and $M = \frac{w\,l^2}{8}$ for exterior spans.
- Check vertical and punching shear.
- Provide the necessary reinforcements.


band
band

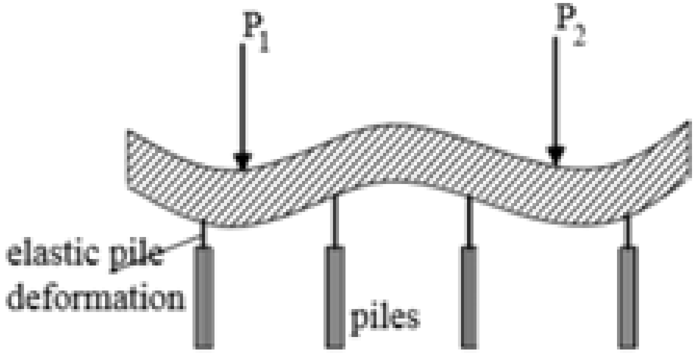
Design of Mat/Raft Foundation

2. Flexible foundation approach

- This method assumes that the soil behaves like an infinite number of individual springs each of which is not affected by the other.
- This method is also known as the **Winkler method.**
- The elastic constant of the springs is equal to the coefficient of sub-grade reaction k of the soil.



(a) Mat resting on Soil



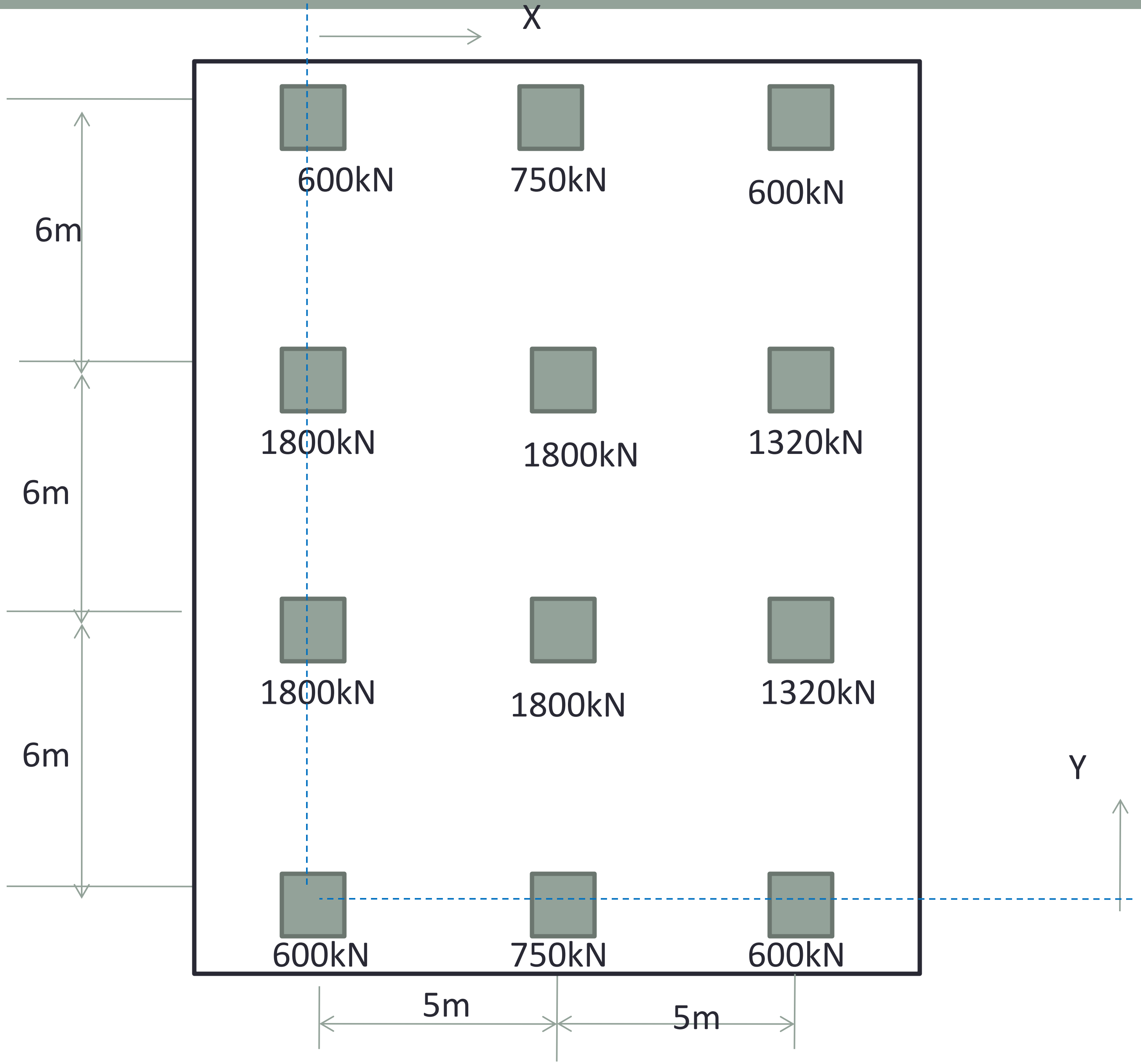
(b) Mat resting on Piles

Example

- A mat foundation is to be designed by the conventional method (rigid method) for the loadings shown in Fig. below.

  - All columns are 40X40cm
  - Ultimate soil bearing pressure , q_{ult} = 100kPa
  - f_{yk} = 300MPa$\Rightarrow$ f_{yd} = 300/1.15 = 260.87 Mpa
  - C25 $\Rightarrow f_{ck}$= 20MPa$\Rightarrow f_{ctk}$ = 1.5 MPa,

  f_{cd}=20/1.5=13.33MPa


X
600kN
750kN
600kN
6m
1800kN
1800kN
1320kN
6m
1800kN
1800kN
1320kN
6m
Y
600kN
750kN
600kN
5m
5m

Location of cg. of loads

$\sum P$ = (600 +750+ 600)*2 +(1800+1800+1320)*2 =13740kN

13740 $\bar{X}$ = (750 +1800+1800+750)*5 + (600 +1320+1320+600)* 10

$\bar{X}$ = 4.65m

e_x = 5-4.65 = 0.35

X' = 5 +0.35 = 5.35m

B_{min} = 2*(5.35 +0.20+0.15) =11.40m

13740 $\bar{Y}$ = (600 +750+600)*18 + (1800 +1800+1320)* 12 + (1800+1800+1320)* 6

Y = 9m

e_y = 6+ 6/2 -9 = 0

L_{min} = 2* (9+0.20+0.15) = 18.70m

Dimension of Mat 11.40m X 18.70m

Actual contact pressure

$\sigma = \Sigma P/(BL) = 13740/(11.40*18.70) = 64.45kPa < \sigma_{ult} = 100kPa$

- Thickness of the mat
  - Punching shear

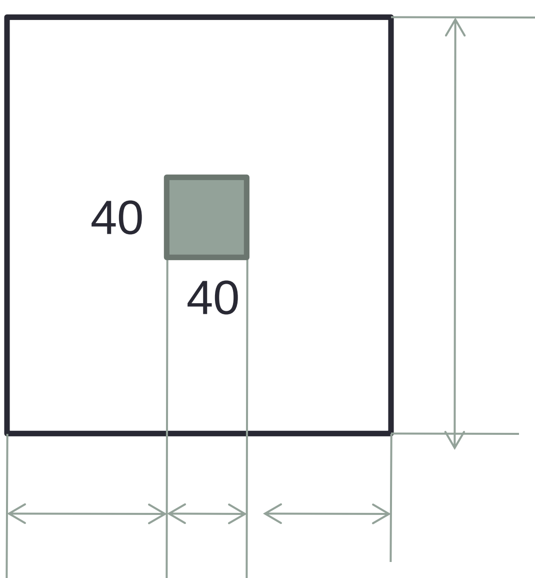
Punching shear under 1800kN load (Max Load)

Take d= 0.70m and $\rho = \rho_{min} = 0.50/f_{yk} = 0.50/300 = 0.0017$

1. Column perimeter= 2*(C1+C2) = 2(400+400) =1600mm

$V_{ed,red} = 1800 - \sigma*(0.4*0.4)$, $\sigma = 64.45kP$

$V_{ed,red} = 1800 - 64.45*(0.4*0.4) = 1789.7kN$



Shear stress around column perimeter,

$V_{ED} = 1789.7*1000/(1600*700) = 1.6MPa$

$V_{RD,max} = 0.3*(1-f_{ck}/250)*f_{cd} = 0.3*(1-20/250)*13.33 = 3.6MPa$

$> V_{ED}$ OK!

2. Check punching shear around the perimeters from d >a>2d from the face of the column

For a=d=700mm

$U=2*(C1+C2)+2\pi a = 2*(0.4+0.4)+2*\pi*0.7$

$= 4.72m$

$A= \pi a^2+2(C1+C2)a+(C1*C2)$

$= \pi*0.7*0.7+2(0.4+0.4)*0.7+(0.4*0.4)$

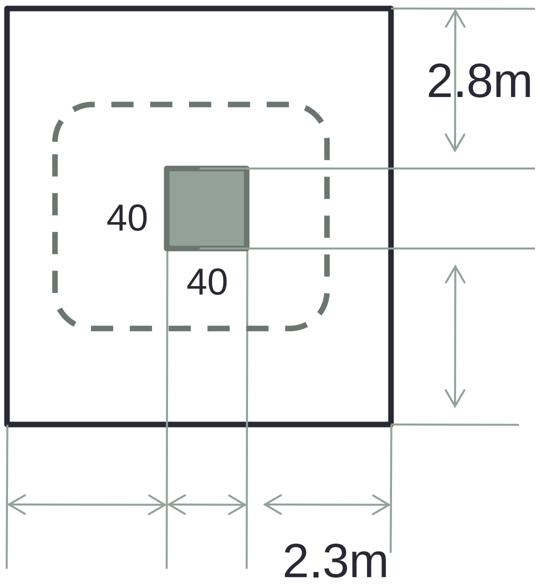
$=2.82m^2$

σ =64.45 Kpa, Column load=1800KN

$V_{ed,red}$=Column load-A* σ

=1800-(2.82*64.45)=1618.25KN

$v_{ed}=V_{ed,red}/u*d= 1618.25/(4.72*0.7) = 0.49MPa$



- Punching shear Resistance,

$$v_{Rd,c} = c_{Rd,c} * k * (100 * \rho * f_{ck})^{0.33}$$

$$c_{Rd,c} = 0.18/1.5 = 0.12,$$

$$k = 1 + sqrt(200/d) = 1 + sqrt(200/700) = 1.534$$

$$\rho = \rho_{min} = 0.50/f_{yk} = 0.5/300 = 0.0017$$

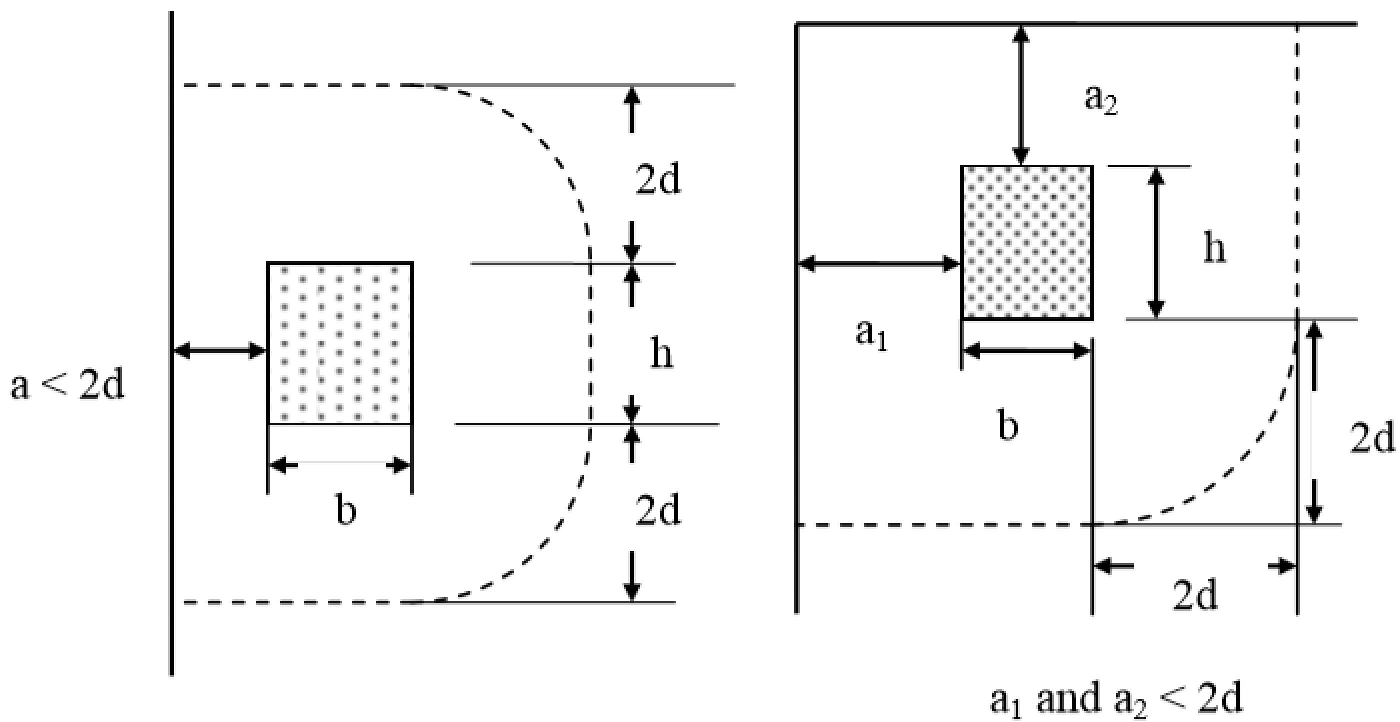
$$v_{Rd,c} = 0.12 * 1.534 * (100 * 0.0017 * f_{ck})^{0.33}$$

$$= 0.27 MPa$$

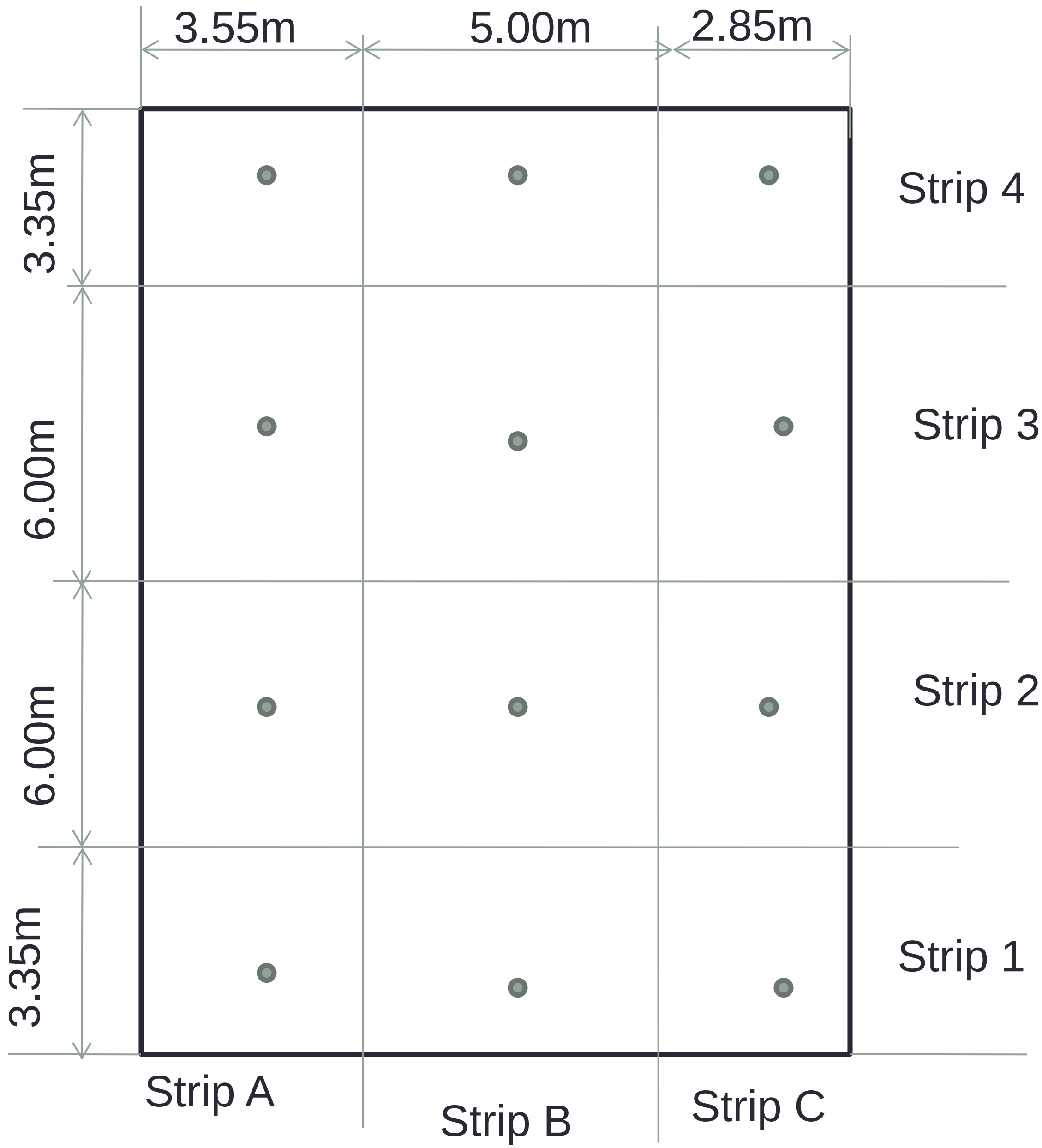
$$v_{rd} = v_{Rd,c} * 2d/a = 0.27 MPa * 2 * 0.7/0.7 = 0.55 Mpa$$

v_{rd}=0.55Mpa> v_{ed}=0.49MPa OK!

- Check the Punching Shear for the corner Column = 600KN
- Check Punching Shear for the edge column = 1320KN

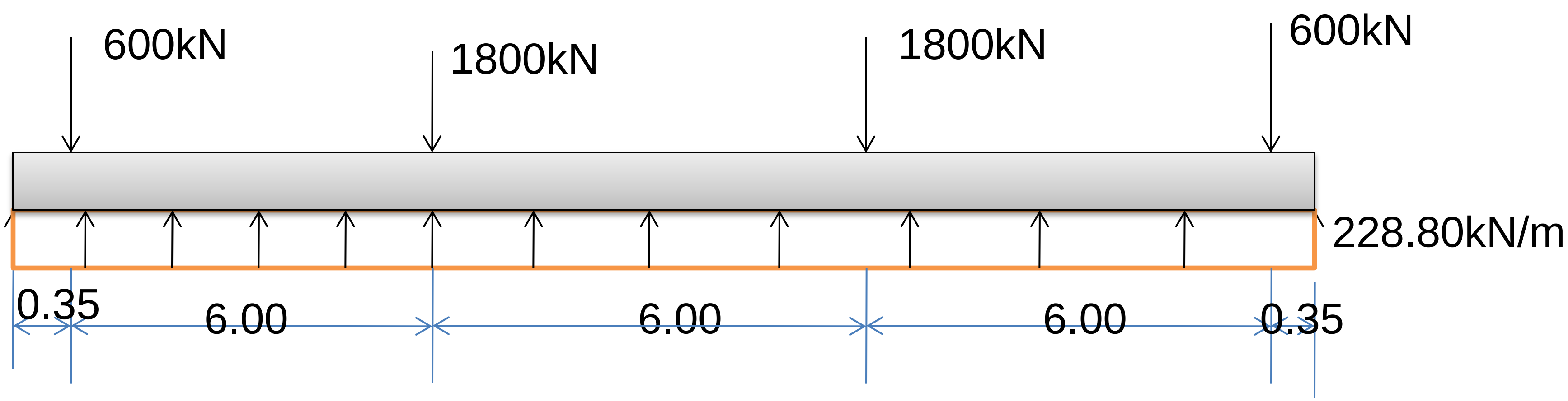


- Soil reaction analysis:- Divide the slab mat into strips in x and y directions



- Strip A, (64.45)*3.55 = 228.80kN/m
- Strip B , (64.45)*5.00 = 322.25kN/m
- Strip C, (64.45)*2.85 = 183.68kN/m
- Strip 1 &Strip 4, (64.45)*3.35 = 215.91kN/m
- Strip 2 & Strip 3 (64.45)*6.00 = 386.70kN/m

- Shear force and Bending moment diagrams for each strip
- Strip A



$$\sum_{i=1}^{4} P_i = 600 + 1800 + 1800 + 600 = 4800kN$$

$\Sigma R = 228.80 * 18.70 = 4278.56kN$

$\Sigma V = \Sigma P - \Sigma R = 4800 - 4278.56 = 521.44 \neq 0$

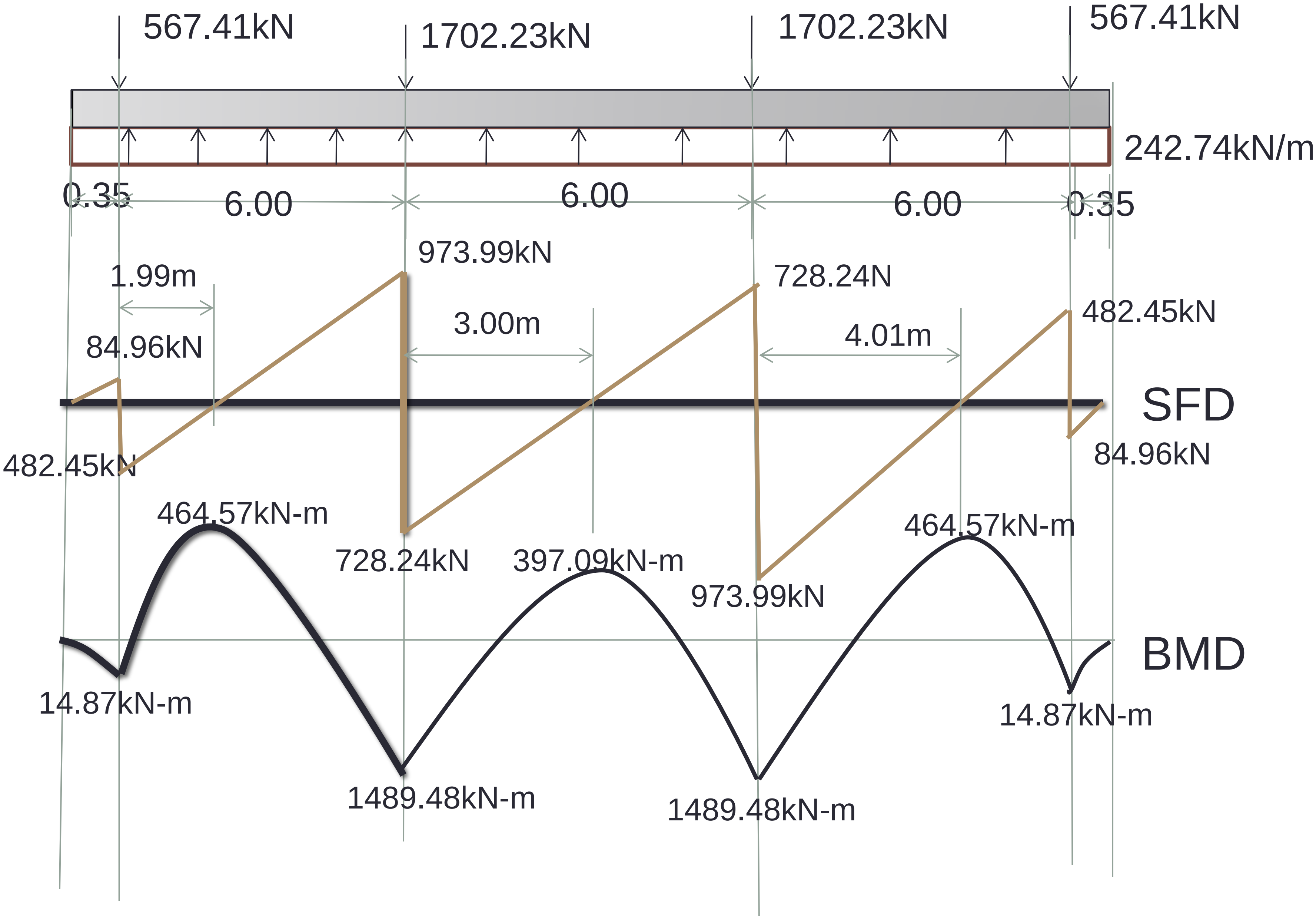
Hence take average of ΣP and ΣR

I.e., (4800 +4278.56)/2 =4539.28kN

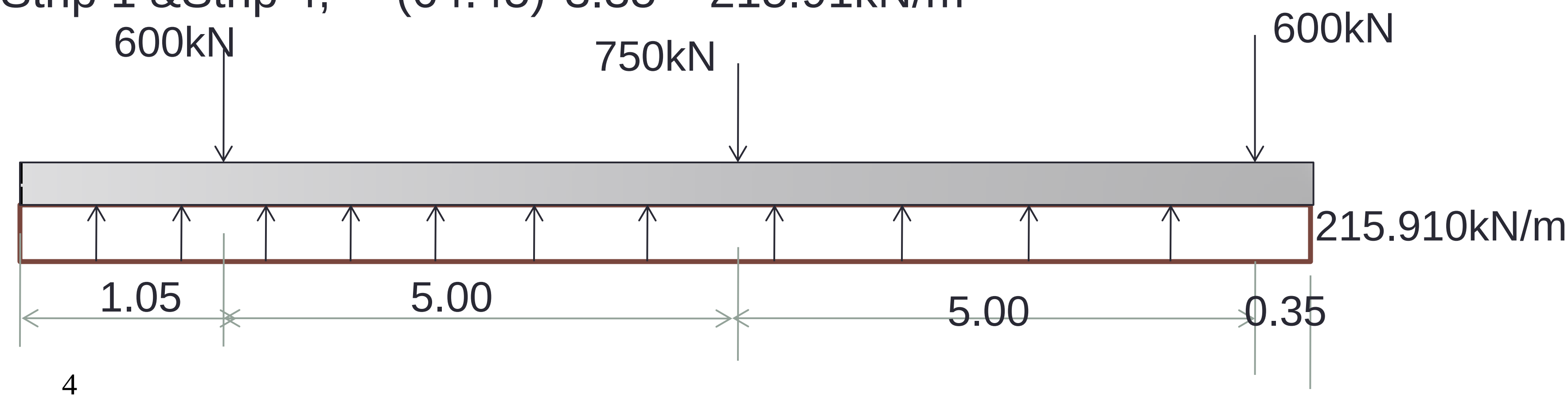
$\sigma_{avg} = (4539.28)/18.70 = 242.74kN/m$

$P_{1avg} = P_{4avg} = (4539.28/4800) * 600 = 567.41kN$

$P_{2avg} = P_{3avg} = (4539.28/4800) * 1800 = 1702.23kN$


567.41kN
1702.23kN
1702.23kN
567.41kN
242.74kN/m
0.35
6.00
6.00
6.00
0.35
973.99kN
1.99m
728.24N
482.45kN
3.00m
4.01m
84.96kN
SFD
482.45kN
84.96kN
464.57kN-m
464.57kN-m
728.24kN
397.09kN-m
973.99kN
BMD
14.87kN-m
14.87kN-m
1489.48kN-m
1489.48kN-m

- Strip 1 &Strip 4, (64.45)*3.35 = 215.91kN/m



$$\sum_{i=1}^{4} P_i = 600 + 750 + 600 = 1950kN$$

ΣR = 215.91* 11.40=2461.37kN

$\Sigma V = \Sigma P - \Sigma R$ = 1950-2461.37 = -511.37 $\neq$ 0

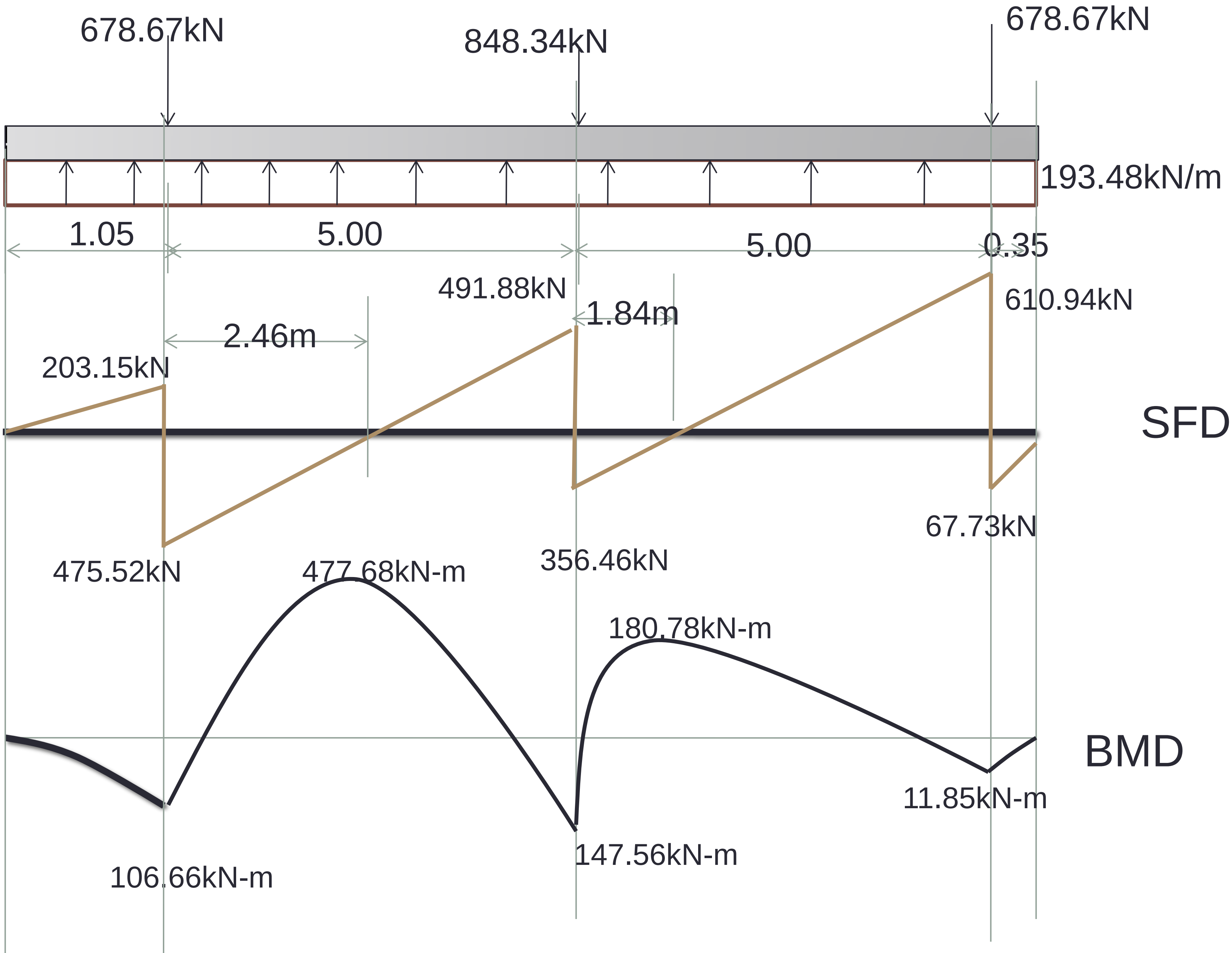
Hence take average of ΣP and ΣR

I.e., (1950+2461.37)/2 =2205.69kN

σ_{avg} = (2205.69)/11.40 =193.48kN/m

$P_{1avg} = P_{3avg}$ = (2205.69/1950) *600 =678.67kN

P_{2avg} = (2205.69/1950) *750 =848.34kN


678.67kN
848.34kN
678.67kN
193.48kN/m
1.05
5.00
5.00
0.35
491.88kN
1.84m
610.94kN
2.46m
203.15kN
SFD
67.73kN
475.52kN
477.68kN-m
356.46kN
180.78kN-m
BMD
11.85kN-m
147.56kN-m
106.66kN-m