Foundation Design - Structure

Notation:

a = equivalent square column size in spread footing design
= depth of the effective compression block in a concrete beam
A = name for area
A_g = gross area, equal to the total area ignoring any reinforcement
A_{req} = area required to satisfy allowable stress
A_s = area of steel reinforcement in concrete design
A_1 = area of column in spread footing design
A_2 = projected bearing area of column load in spread footing design
b = width of retaining wall stem at base
= rectangular column dimension in concrete footing design
= width, often cross-sectional
b_f = width of the flange of a steel or cross section
b_o = perimeter length for two-way shear in concrete footing design
B = spread footing or retaining wall base dimension in concrete design
= dimension of a steel base plate for concrete footing design
B_s = width within the longer dimension of a rectangular spread footing that reinforcement must be concentrated within for concrete design
c = rectangular column dimension in concrete footing design
C = dimension of a steel base plate for concrete footing design
d = effective depth from the top of a reinforced concrete member to the centroid of the tensile steel
= name for diameter
d_b = bar diameter of a reinforcing bar
d_f = depth of a steel column flange (wide flange section)
e = eccentric distance of application of a force (P) from the centroid of a cross section
f = symbol for stress
f'_c = concrete design compressive stress
f_y = yield stress or strength
$F_{horizontal\text{-}resisting}$ = total force resisting horizontal sliding
$F_{sliding}$ = total sliding force
F_x = force in the x direction
h_f = height of a concrete spread footing
H = height of retaining wall
H_A = horizontal force due to active soil pressure
l_d = development length for reinforcing steel
l_{dc} = development length for column
l_s = lap splice length in concrete design
L = name for length or span length
L_m = projected length for bending in concrete footing design
L' = length of the one-way shear area in concrete footing design
M = moment due to a force
M_n = nominal flexure strength with the steel reinforcement at the yield stress and concrete at the concrete design strength for reinforced concrete flexure design
$M_{overturning}$ = total overturning moment
$M_{resisting}$ = total moment resisting overturning about a point
M_u = maximum moment from factored loads for LRFD beam design
N = name for normal force to a surface
o = point of overturning of a retaining wall, commonly at the "toe"
p_A = active soil pressure
P = name for axial force vector
P_{dowels} = nominal capacity of dowels from concrete column to footing in concrete design
P_D = dead load axial force
P_L = live load axial force
P_n = nominal column or bearing load capacity in concrete design
P_u = factored axial force
$q_{allowable}$ = allowable soil bearing stress in allowable stress design
q_{net} = net allowed soil bearing pressure

q_u = factored soil bearing capacity in concrete footing design from load factors
R = name for reaction force vector
SF = shorthand for factor of safety
t = thickness of retaining wall stem at top
T = name for tension force vector
V_n = nominal shear capacity
V_{u1} = maximum one-way shear from factored loads for LRFD beam design
V_{u2} = maximum two-way shear from factored loads for LRFD beam design
W = name for force due to weight
$\bar{y}$ = the distance in the y direction from a reference axis to the centroid of a shape
β_c = ratio of long side to short side of the column in concrete footing design
ϕ = resistance factor
γ_c = density or unit weight of concrete
γ_s = density or unit weight of soil
ρ = reinforcement ratio in concrete beam design = A_s/bd
υ_c = shear strength in concrete design

Foundation Materials

Typical foundation materials include:

- plain concrete
- reinforced concrete
- steel
- wood
- composites, ie. steel tubing filled with concrete

Foundation Design

Generalized Design Steps

Design of foundations with variable conditions and variable types of foundation structures will be different, but there are steps that are typical to every design, including:

1. Calculate loads from structure, surcharge, active & passive pressures, etc.
2. Characterize soil – hire a firm to conduct soil tests and produce a report that includes soil material properties
3. Determine footing location and depth – shallow footings are less expensive, but the variability of the soil from the geotechnical report will drive choices
4. Evaluate soil bearing capacity – the factor of safety is considered here
5. Determine footing size – these calculations are based on working loads and the allowable soil pressure
6. Calculate contact pressure and check stability
7. Estimate settlements
8. Design the footing structure – design for the material based on applicable structural design codes which may use allowable stress design, LRFD or limit state design (concrete).

Shallow Foundation Types

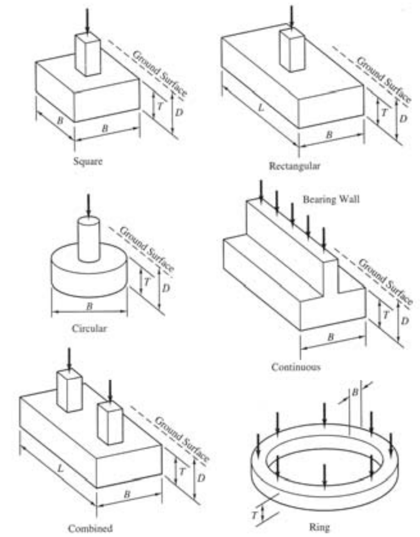


Figure 5.1 Spread footing shapes and dimensions.

Considered simple and cost effective because little soil is removed or disturbed.

Spread footing – A single column bears on a square or rectangular pad to distribute the load over a bigger area.

Wall footing – A continuous wall bears on a wide pad to distribute the load..

Eccentric footing – A spread or wall footing that also must resist a moment in addition to the axial column load.

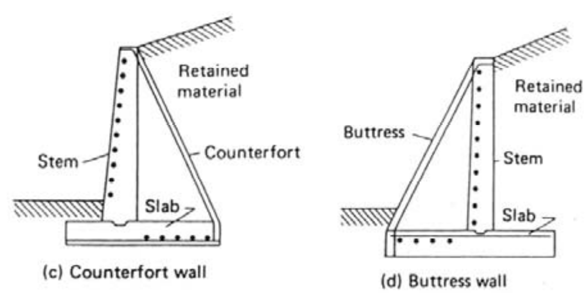
Combined footing – Multiple columns (typically two) bear on a rectangular or trapezoidal shaped footing.

Unsymmetrical footing – A footing with a shape that does not evenly distribute bearing pressure from column loads and moments. It typically involves a hole or a non-rectangular shape influenced by a boundary or property line.

Strap footing – A combined footing consisting of two spread footings with a beam or strap connecting the slabs. The purpose of this is to limit differential settlements.

Mat foundation – A slab that supports multiple columns. The mat can be stiffened with a grid or grade beams. It is typically used when the soil capacity is very low.

Deep Foundation Types



Considerable material and excavation is required, increasing cost and effort.

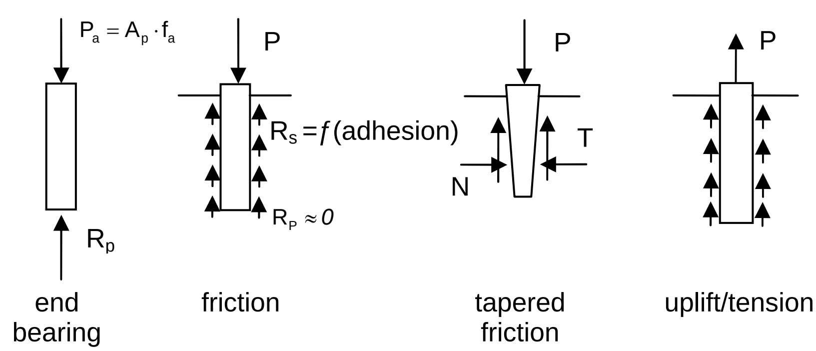
Retaining Walls – A wall that retains soil or other materials, and must resist sliding and overturning. Can have counterforts, buttresses or keys.

Basement Walls – A wall that encloses a basement space, typically next to a floor slab, and that may be restrained at the top by a floor slab.

Piles – Next choice when spread footings or mats won't work, piles are used to distribute loads by end bearing to strong soil or friction to low strength soils. Can be used to resist uplift, a moment causing overturning, or to compact soils. Also useful when used in combination to control settlements of mats or slabs.

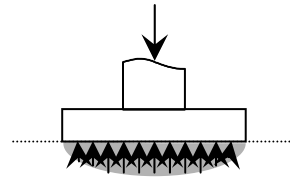
Drilled Piers – Soil is removed to the shape of the pier and concrete is added.

Caissons –Water and possibly wet soil is held back or excavated while the footing is constructed or dropped into place.



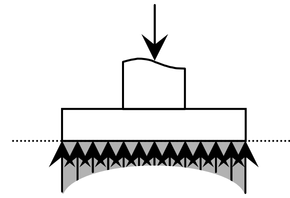
Pile Types

Loads and Stresses



RIGID footing on sand

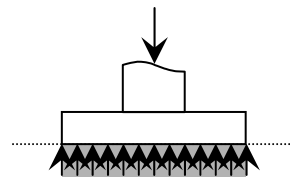
Bearing loads must be distributed to the soil materials, but because of their variability and the stiffness of the footing pad, the resulting stress, or soil pressure, is not necessarily uniform. But we assume it is for design because dealing with the complexity isn't worth the time or effort.



RIGID footing on clay

The increase in weight when replacing soil with concrete is called the overburden. Overburden may also be the result of adding additional soil to the top of the excavation for a retaining wall. It is extra *uniformly distributed load* that is considered by reducing the allowable soil pressure (instead of increasing the loads), resulting in a net allowable soil pressure, q_{net}:

$$q_{net} = q_{allowable} - h_f(\gamma_c - \gamma_s)$$



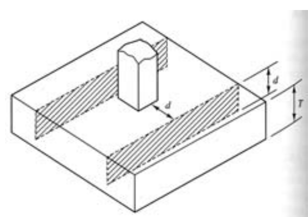
IDEAL

In order to design the footing size, the actual stress P/A must be less than or equal to the allowable pressure:

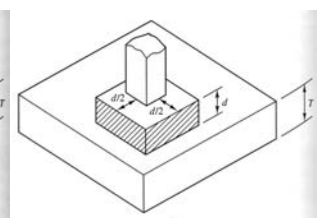
$$\frac{P}{A} \le q_{net}$$

Design Stresses

The result of a uniform pressure on the underside of a footing is identical to a distributed load on a slab over a column when looked at *upside down.* The footing slab must resist bending, one-way shear and two-way shear (punching).



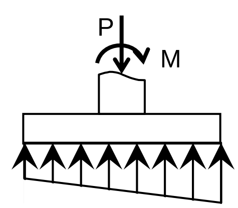
one-way shear



two-way shear

Stresses with Eccentric Loading

Combined axial and bending stresses increase the pressure on one edge or corner of a footing. We assume again a linear distribution based on a constant relationship to settling. If the pressure combination is in tension, this effectively means the contact is gone between soil and footing and the pressure is really zero. To avoid zero pressure, the eccentricity must stay within the kern. The maximum pressure must not exceed the net allowable soil pressure.



Overturning is considered in design such that the resisting moment from the soil pressure (equivalent force at load centroid) is greater than the overturning moment, M, by a factor of safety of at least 1.5

$$SF = \frac{M_{resist}}{M_{overturning}} \ge 1.5$$

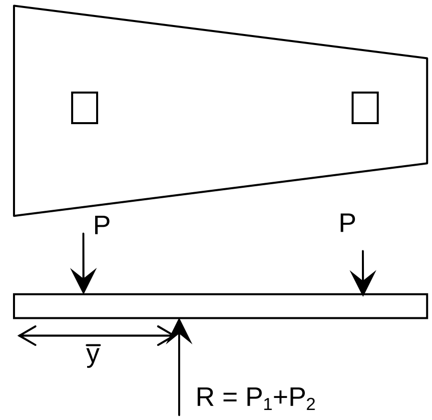
where

M_{resist} = average resultant soil pressure x width x location of load centroid with respect to column centroid

$M_{overturning}$ = P x e

Combined Footings

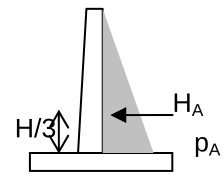
The design of combined footing requires that the centroid of the area be as close as possible to the resultant of the two column loads for uniform pressure and settling.



Retaining Walls

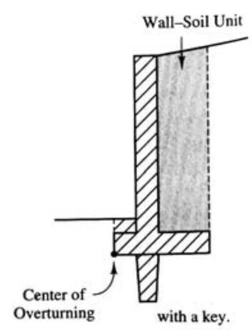
The design of retaining walls must consider overturning, settlement, sliding and bearing pressure. The water in the retained soil can significantly affect the loading and the active pressure of the soil. The lateral force acting at a height of H/3 is determined from the active pressure, p_A, (in force/cubic area) as:

$$H_A = \frac{p_A H^2}{2}$$



Overturning is considered the same as for eccentric footings:

$$SF = \frac{M_{resist}}{M_{overturning}} \geq 1.5 - 2$$



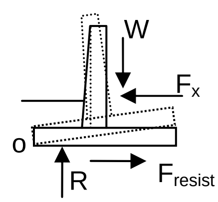
where

M_{resist} = summation of moments about "o" to resist rotation, typically including the moment due to the weight of the stem and base and the moment due to the passive pressure.

$M_{overturning}$ = moment due to the active pressure about "o".

Sliding must also be avoided:

$$SF = \frac{F_{horizontal-resist}}{F_{sliding}} \geq 1.25 - 2$$



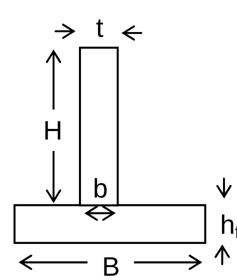
where

$F_{horizontal-resist}$ = summation of forces to resist sliding, typically including the force from the passive pressure and friction (F=μ·N where . μ is a constant for the materials in contact and N is the normal force to the ground acting down and is shown as R).

$F_{sliding}$ = sliding force as a result of active pressure.

For sizing, some rule of thumbs are:

- footing size, B
- reinforced concrete, B ≈ 2/5 - 2/3 wall height (H)
- footing thickness, h_f ≈ 1/12 - 1/8 footing size (B)
- base of stem, b ≈ 1/10 - 1/12 wall height ($H+h_f$)
- top of stem, t ≥ 12 inches



Design of Isolated Square and Rectangular Footings (ACI 318-02)

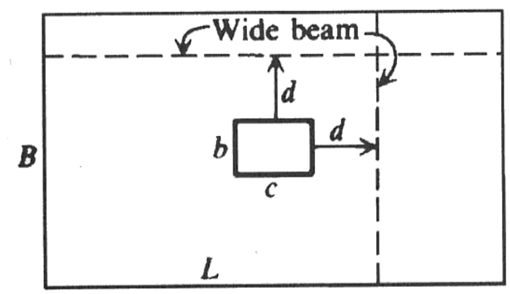
NOTE: This procedure assumes that the footing is concentrically loaded and carries no moment so that the soil pressure may be assumed to be uniformly distributed on the base.

1) Find service dead and live column loads:

P_D = Service dead load from column

P_L = Service live load from column

$P = P_D + P_L$ (typically – see **ACI 9.2**)



2) Find design (factored) column load, Pu:

$P_U = 1.2P_D + 1.6P_L$

3) Find an approximate footing depth, h_f

$h_f = d + 4"$ and is usually in multiples of 2, 4 or 6 inches.

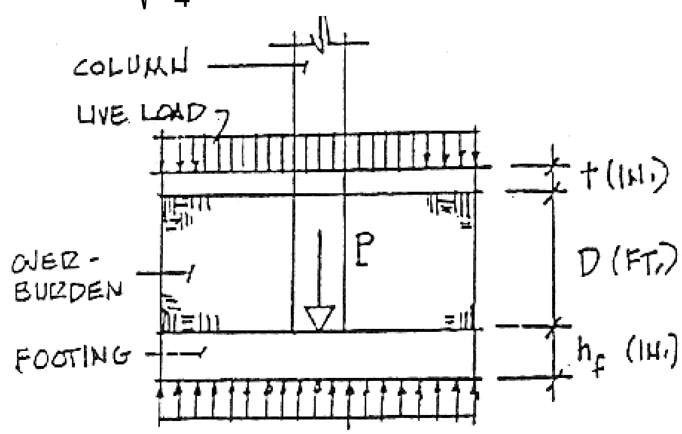
a) For rectangular columns $4d^2 + 2(b+c)d = \dfrac{P_u}{\phi \upsilon_c}$

b) For round columns $d^2 + ad = \dfrac{P_u}{\phi \upsilon_c}$ $a = \sqrt{\dfrac{\pi d^2}{4}}$

where: a is the equivalent square column size

$\upsilon_c = 4\sqrt{f'_c}$ for two-way shear

$\phi = 0.75$ for shear

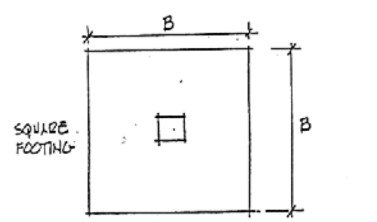


4) Find net allowable soil pressure, q_{net}:

By neglecting the weight of any additional top soil added, the net allowable soil pressure takes into account the change in weight when soil is removed and replaced by concrete: $q_{net} = q_{allowable} - h_f(\gamma_c - \gamma_s)$

where γ_c is the unit weight of concrete (typically 150 lb/ft^3)

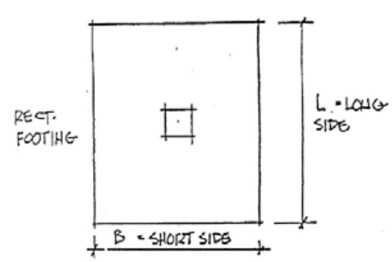
and γ_s is the unit weight of the displaced soil



5) Find required area of footing base and establish length and width:

$$A_{req} = \frac{P}{q_{net}}$$

For square footings choose $B \geq \sqrt{A_{req}}$



For rectangular footings choose $B \times L \geq A_{req}$

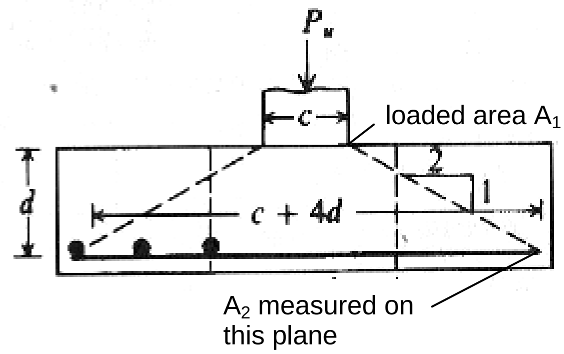
6) <u>Check transfer of load from column to footing:</u> **ACI 15.8**

a) Find load transferred by bearing on concrete in column: **ACI 10.17**

basic: $\phi P_n = \phi 0.85 f_c' A_1$ where ϕ = 0.65 and A_1 is the area of the column

with confinement: $\phi P_n = \phi 0.85 f_c' A_1 \sqrt{\frac{A_2}{A_1}}$ where $\sqrt{\frac{A_2}{A_1}}$ cannot exceed 2.

IF the column concrete strength is lower than the footing, calculate ϕP_n for the column too.



b) Find load to be transferred by dowels:

$\phi P_{dowels} = P_u - \phi P_n$

IF $\phi P_n \geq P_u$ only nominal dowels are required.

c) Find required area of dowels and choose bars

Req. dowel $A_s = \frac{\phi P_{dowels}}{\phi f_y}$ where ϕ = 0.65 and f_y is the reinforcement grade

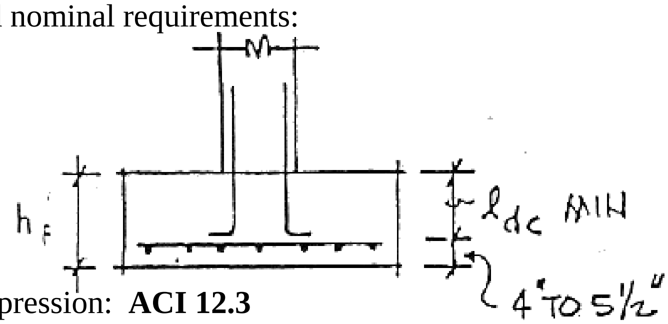
Choose dowels to satisfy the required area and nominal requirements:

i) Minimum of 4 bars

ii) Minimum $A_s = 0.005 A_g$ **ACI 15.8.2.1**

where A_g is the gross column area

iii) 4 - #5 bars



d) Check dowel embedment into footing for compression: **ACI 12.3**

$l_{dc} = \frac{0.02 f_y d_b}{\sqrt{f_c'}}$ but not less than $0.0003 f_y d_b$ or 8" where d_b is the bar diameter

NOTE: The footing must be deep enough to accept l_{dc}. Hooks are not considered effective in compression and are only used to support dowels during construction.

e) Find length of lapped splices of dowels with column bars: **ACI 12.16**

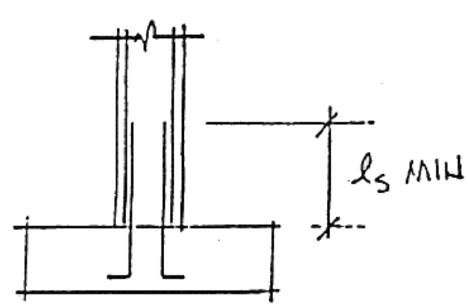
l_s is the largest of:

i) larger of l_{dc} or $0.0005 f_y d_b$ (f_y of grade 60 or less)

of smaller bar $(0.0009 f_y - 24) d_b$ (f_y over grade 60)

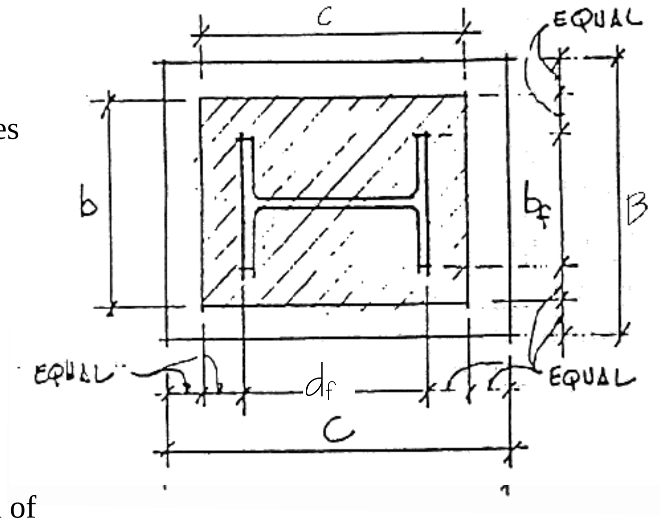
ii) l_{dc} of larger bar

iii) not less than 12"



See **ACI 12.17.2** for possible reduction in l_s

7) Check two-way (slab) shear:



a) Find dimensions of loaded area:

i) For concrete columns, the area coincides with the column area, if rectangular, or equivalent square area if circular (see 3)b))

ii) For steel columns an equivalent loaded area whose boundaries are halfway between the faces of the steel column and the edges of the steel base plate is used: **ACI 15.4.2c**.

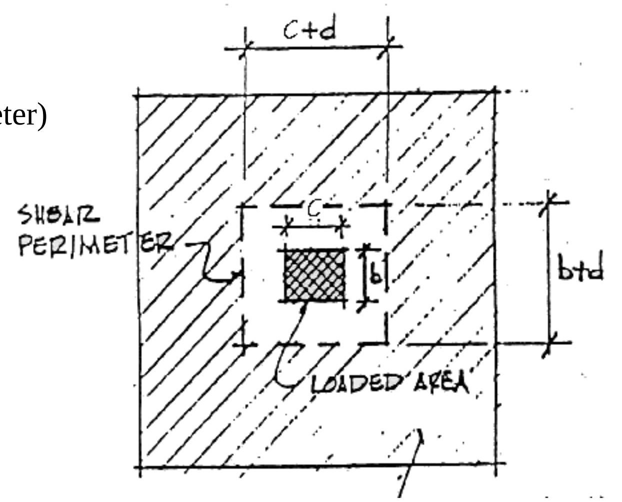
$b = b_f + \frac{(B - b_f)}{2}$ where b_f is the width of column flange and B is base plate side

$c = d_f + \frac{(C - d_f)}{2}$ where d_f is the depth of column flange and C is base plate side

b) Find shear perimeter: **ACI 11.12.1.2**

Shear perimeter is located at a distance of $d/2$ outside boundaries of loaded area and length is $b_o = 2(c + d) + 2(b + d)$

(average d = h_f – 3 in. cover – 1 assumed bar diameter)



c) Find <u>factored</u> net soil pressure, q_u:

$$q_u = \frac{P_u}{B^2} \text{ or } \frac{P_u}{B \times L}$$

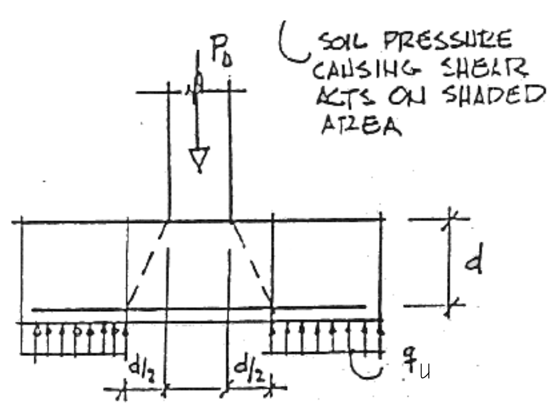
d) Find total shear force for two-way shear, V_{u2}:

$$V_{u2} = P_u - q_u(c + d)(b + d)$$

e) Compare V_{u2} to two-way capacity, ϕV_n:

$$V_{u2} \le \phi\left(2 + \frac{4}{\beta_c}\right)\sqrt{f'_c}\,b_o d \le \phi 4\sqrt{f'_c}\,b_o d$$ **ACI 11.12.2.1**

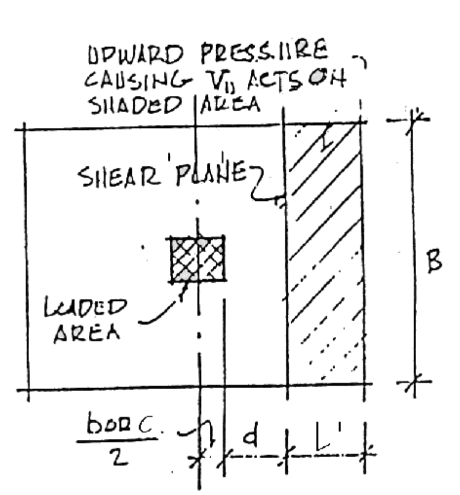
where ϕ = 0.75 and β_c is the ratio of long side to short side of the column



NOTE: This should be acceptable because the initial footing size was chosen on the basis of two-way shear limiting. If it is not acceptable, increase h_f and repeat steps starting at b).

8) Check one-way (beam) shear:

The critical section for one-way shear extends across the width of the footing at a distance *d* from the face of the loaded area (see 7)a) for loaded area). The footing is treated as a cantilevered beam. **ACI 11.12.1.1**



a) Find projection, *L'*:

i) For square footing:

$$L' = \frac{B}{2} - (d + b/2)$$ where b is the smaller dim. of the loaded area

ii) For rectangular footings:

$$L' = \frac{L}{2} - (d + \bullet/2)$$ where • is the dim. parallel to the long side of the footing

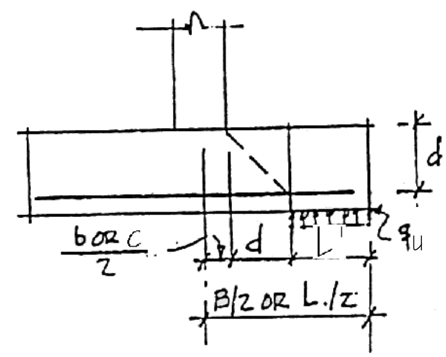
b) Find total shear force on critical section, V_{u1}:

$$V_{u1} = BL'q_u$$

c) Compare V_{u1} to one-way capacity, ϕV_n:

$$V_{u1} \le \phi 2\sqrt{f'_c}Bd$$ **ACI 11.12.3.1** where $\phi = 0.75$

NOTE: If it is not acceptable, increase h_f .

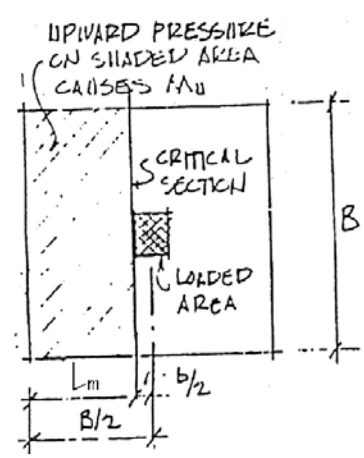


9) Check for bending stress and design reinforcement:

Square footings may be designed for moment in one direction and the same reinforcing used in the other direction. For rectangular footings the moment and reinforcing must be calculated separately in each direction. The critical section for moment extends across the width of the footing at the face of the loaded area. **ACI 15.4.1, 15.4.2**.

a) Find projection, L_m:

$$L_m = \frac{B}{2} - \frac{\bullet}{2}$$ where • is the smaller dim. of column for a square footing. For a rectangular footing, use the value perpendicular to the critical section.

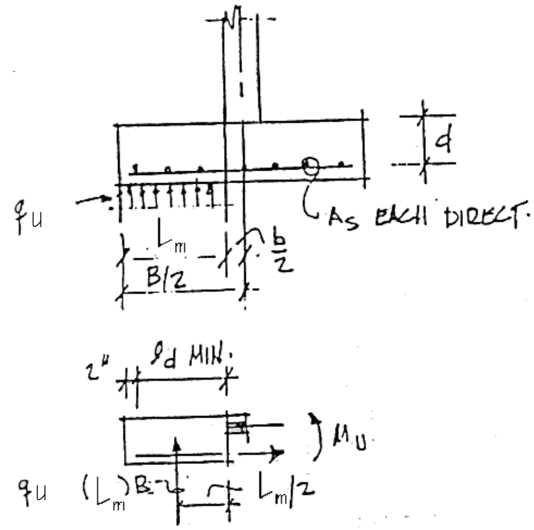


b) Find total moment, M_u, on critical section:

$$M_u = q_u \frac{BL_m^2}{2}$$ (find both ways for a rectangular footing)

c) Find required A_s:

$R_n = \frac{M_n}{bd^2} = \frac{M_u}{\phi bd^2}$, where $\phi = 0.9$, and ρ can be found



found from Figure 3.8.1 of Wang & Salmon.

or:

i) guess a

ii) $A_s = \frac{0.85 f'_c ba}{f_y}$

iii) solve for $a = 2\left(d - \frac{M_u}{\phi A_s f_y}\right)$

iv) repeat from ii) until a converges, solve for A_s

Minimum A_s

= 0.0018bh Grade 60 for temperature and shrinkage control

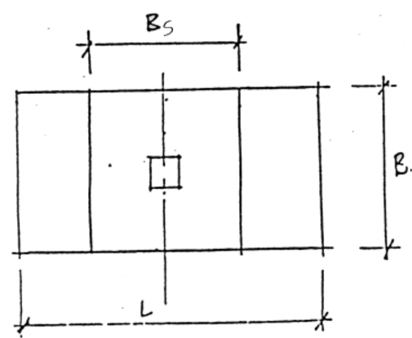
= 0.002bh Grade 40 or 50

ACI 10.5.4 specifies the requirements of **7.12** must be met, and max. spacing of 18"

d) Choose bars:

For square footings use the same size and number of bars uniformly spaced in each direction (**ACI 15.4.3**). Note that required A_s must be furnished in each direction.

For rectangular footings bars in long direction should be uniformly spaced. In the short direction bars should be distributed as follows (**ACI 15.4.4**):



i) In a band of width B_s centered on column:

$$\# \text{ bars } = \frac{2}{L/B + 1} \cdot (\#\textit{bars in } B) \quad \text{(integer)}$$

ii) Remaining bars in short direction should be uniformly spaced in outer portions of footing.

e) Check development length:

Find required development length, l_d, in tension from handout or from equations in **ACI 12.2**. l_d must be less than (L_m – 2") (end cover). If not possible, use more bars of smaller diameter.