Lecture 06

Design of Reinforced Concrete Retaining Walls

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- RC cantilever retaining wall

- Stability evaluation of retaining wall

- Earth pressure and Soil parameters

- Design of RC cantilever retaining wall

- Design Example

- Practical Design Examples

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Learning Outcomes

❑ **At the end of this lecture, students will be able to;**

➢ *Identify* different types of retaining walls

➢ *Explain* failure mechanism of retaining walls

➢ *Analyze* and *Design* RC Cantilever Wall

General

❑ **Introduction**

- A retaining wall is a structure that holds or retains soil masses of earth or other loose material behind it.

- Used in the construction of railways, highways, bridges, canals, basement walls in buildings, walls of underground reservoirs, swimming pools etc.

General

❑ **Introduction**

General

❑ Types of Retaining Walls

- Retaining walls are generally classified based on the method of attaining stability against the lateral load imposed by the retained earth.
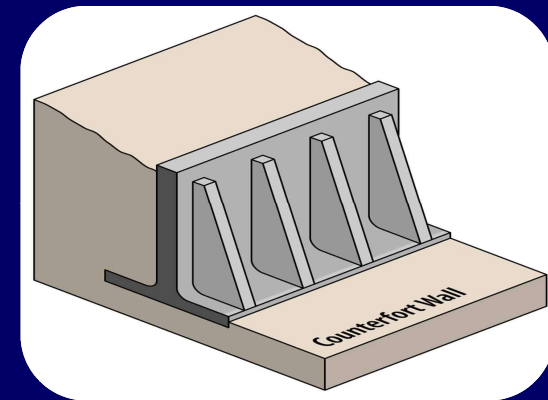

Gravity Wall

Uses its own weight and that of the retained soil for stability and are either lightly reinforced or contain no reinforcement.

Cantilever Wall

Weight of the soil on the heel of the footing provides the primary contribution to overall stability.

Counterfort Wall

Similar to Cantilever wall but the stem is stiffened by buttresses, to achieve more strength

General

❑ **Selection of Suitable Type of Retaining Wall**

- Gravity walls are economical only for relatively low walls; possibly up to about 10 ft.

- Cantilever Retaining Walls are generally economical up to a height of approximately 20ft.

- For greater heights or for the conditions where the backfill pressure is unusually high, Counterfort or Buttress Retaining Walls are recommended.

- This lecture is only focused on the structural analysis and design of Cantilever retaining wall.
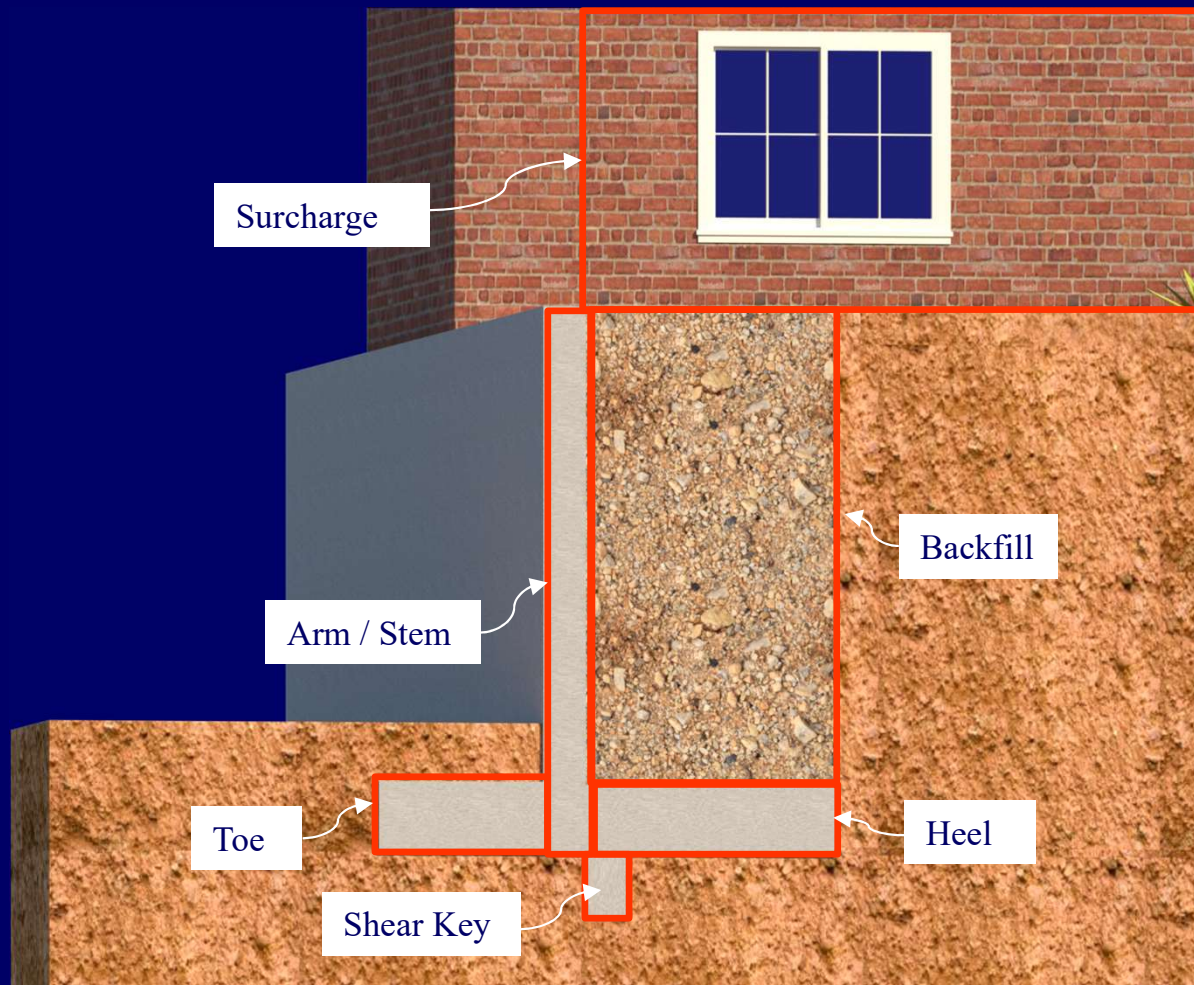
RC Cantilever Retaining Wall

❑ **Different Terms Related to Retaining Wall**

- A typical Cantilever retaining wall is an assembly of the following components

   1. Stem: Stem is a Vertical arm that provides horizontal resistance against the overturning force of the soil

   2. Base: It is a horizontal footing that is typically divided into two parts, the Toe and the Heel.

   3. Key: A key is basically a small vertical element constructed below the footing (base) to increase sliding resistance.

- Illustration of these components have been shown on the next slide.
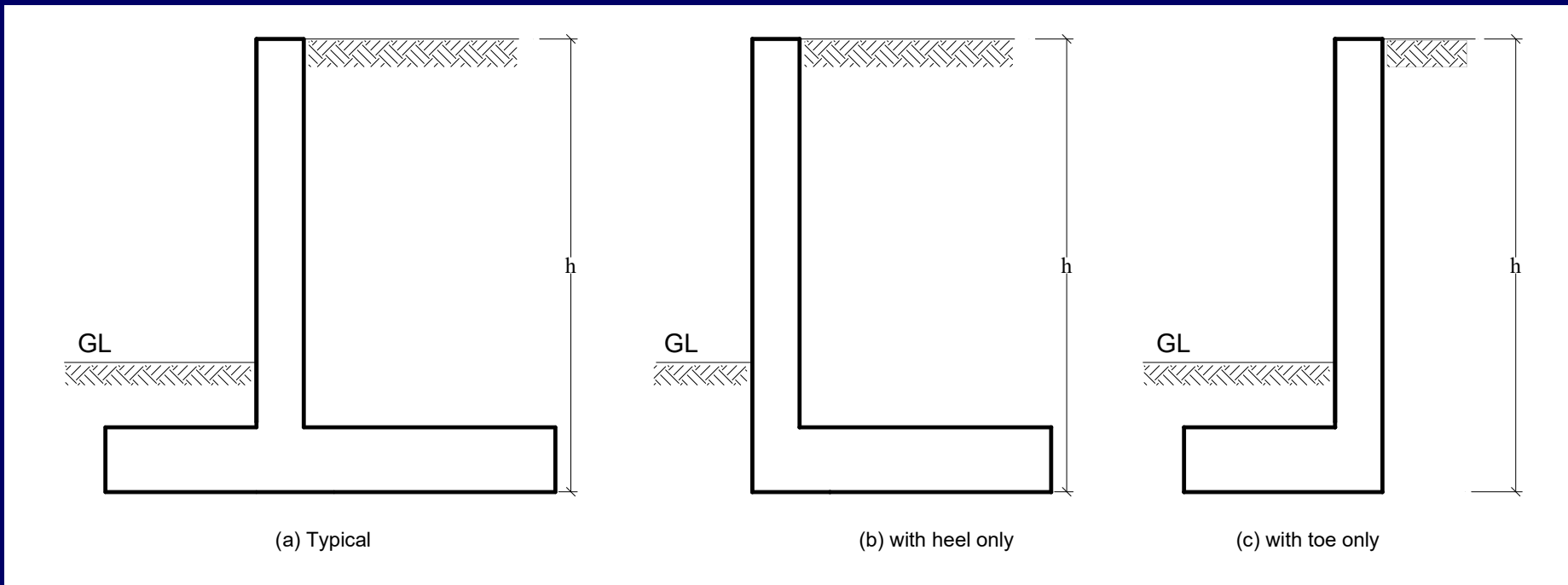
RC Cantilever Retaining Wall

❑ **Different Terms Related to Retaining Wall**

RC Cantilever Retaining Wall

❑ **Types of cantilever Retaining Walls**

(a) Typical   (b) with heel only   (c) with toe only
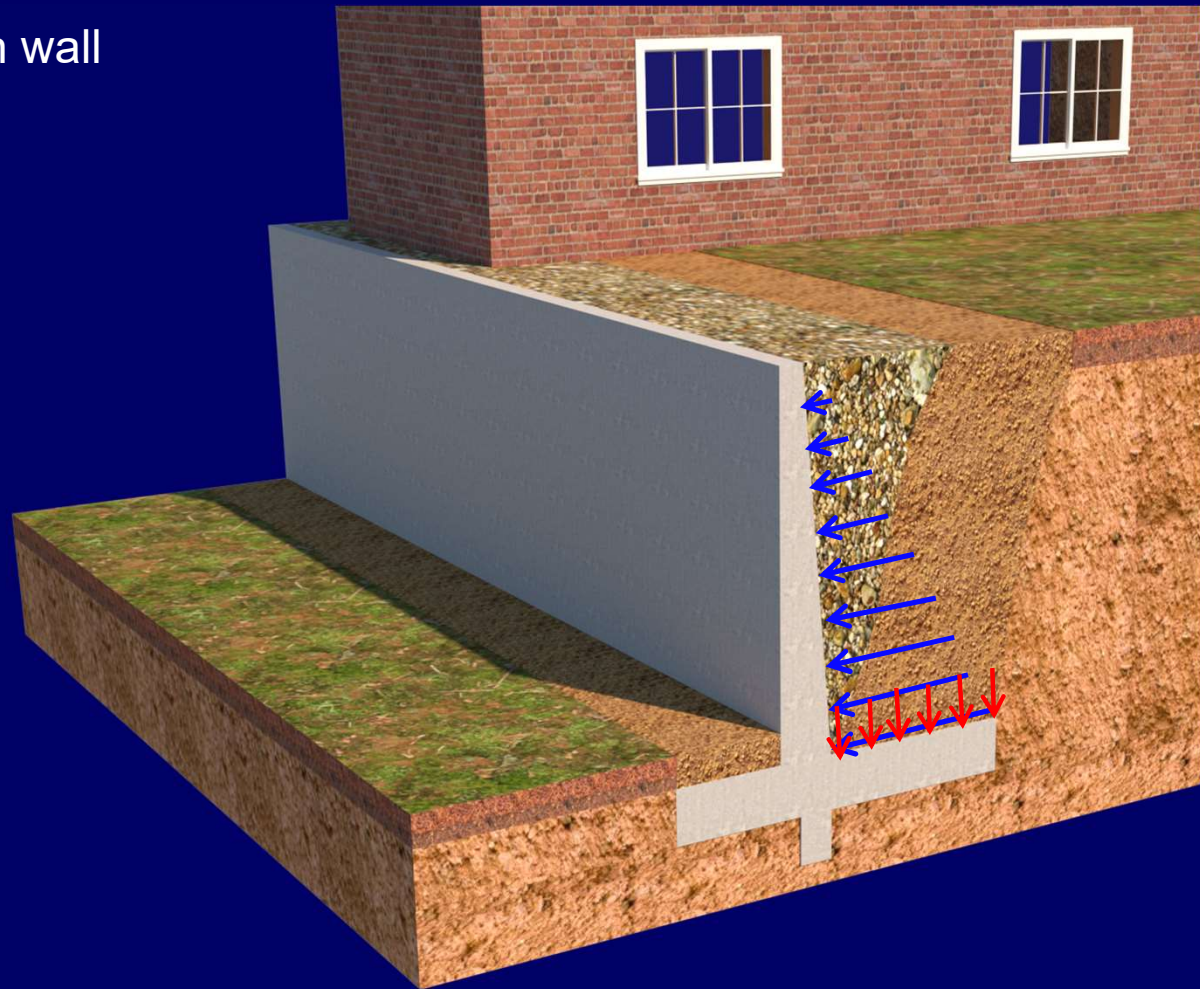
RC Cantilever Retaining Wall

- **Behavior of Cantilever Retaining Wall**
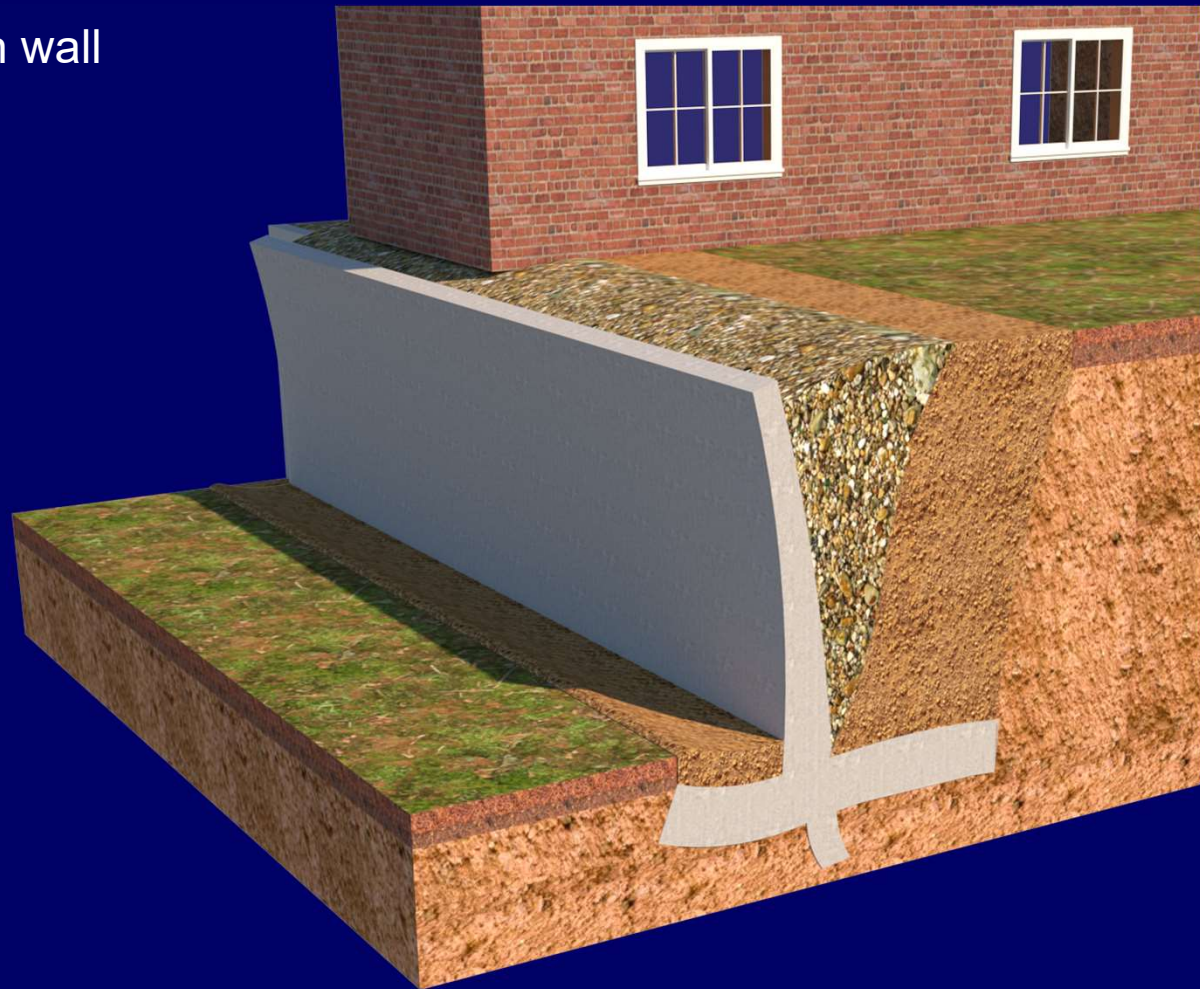
  - Applied loading on wall

RC Cantilever Retaining Wall

❑ **Behavior of Cantilever Retaining Wall**

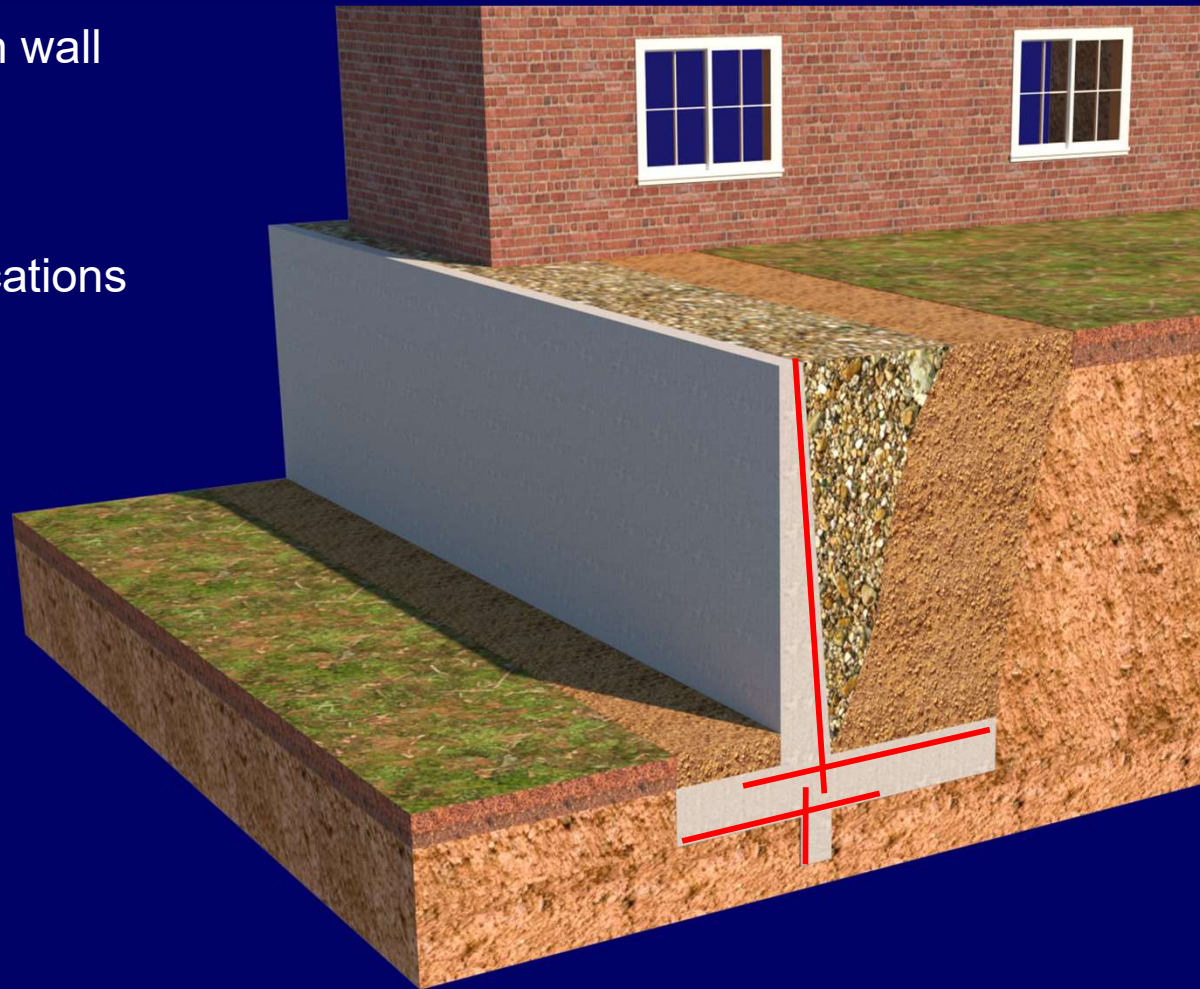- Applied loading on wall

- Deflected shape

RC Cantilever Retaining Wall

❑ **Behavior of Cantilever Retaining Wall**

- Applied loading on wall

- Deflected shape

- Reinforcement locations

RC Cantilever Retaining Wall

❑ **Various Failure Modes**

- RC retaining wall may fail in two different ways:
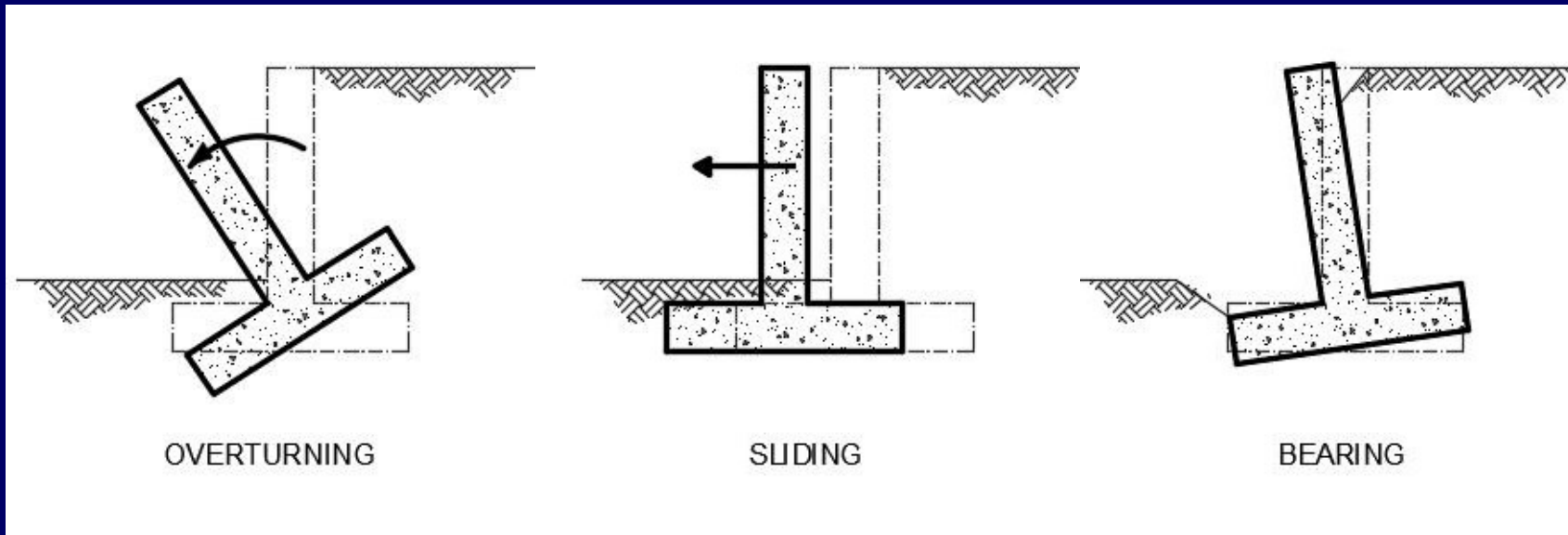
1. **Stability Failure**

- The wall as a whole may be bodily displaced by the earth pressure, without breaking up internally. This can be

  I.   Overturning

  II.   Sliding

  III. Bearing / Settlement

RC Cantilever Retaining Wall

❏ **Various Failure Modes**

1. **Stability Failure**

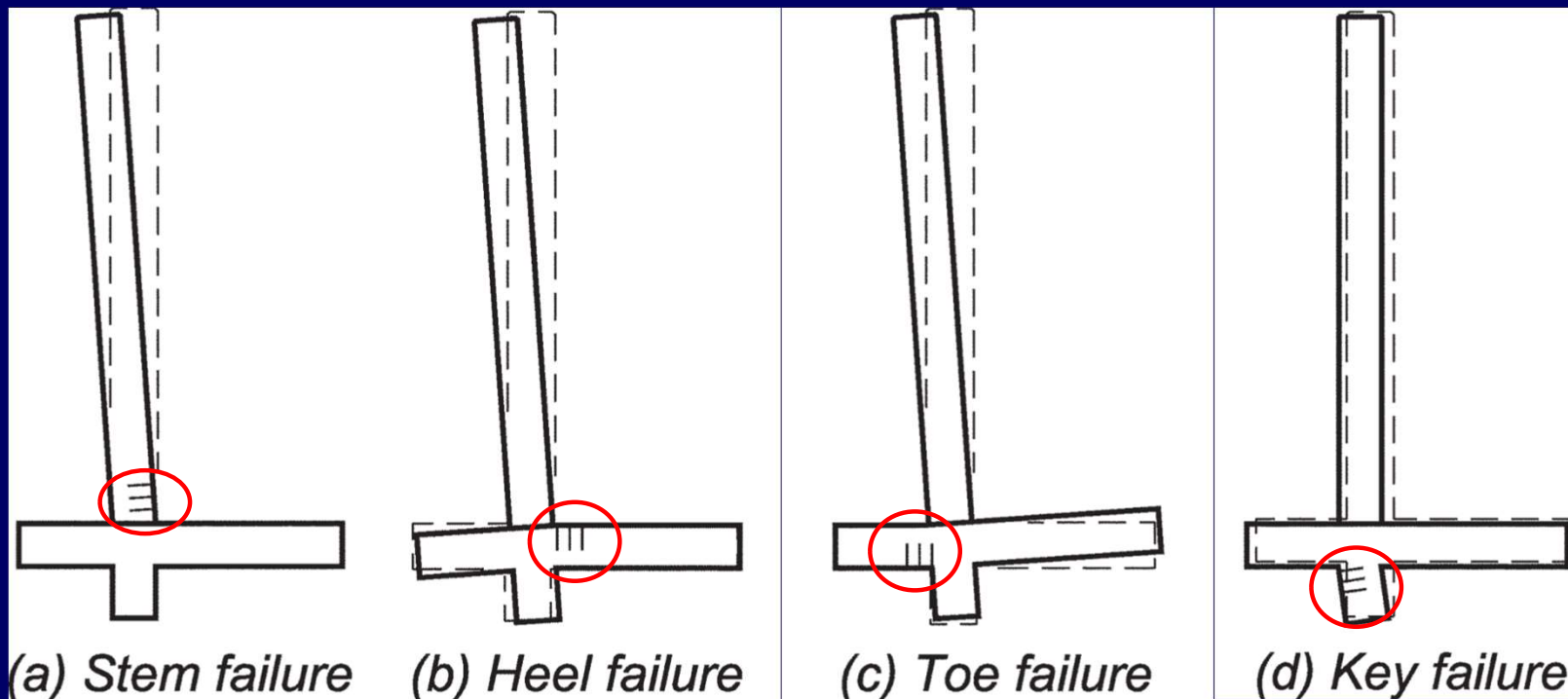OVERTURNING   SLIDING   BEARING

RC Cantilever Retaining Wall

❑ **Various Failure Modes**

2. **Body Failure**

- The individual structural parts (stem, toe, heel) of the wall may not be strong enough to resist the acting forces.

(a) Stem failure   (b) Heel failure   (c) Toe failure   (d) Key failure

RC Cantilever Retaining Wall

❑ **Various Failure Modes**

Animation explaining behavior of Cantilever retaining wall under lateral pressure

Earth Pressure and Soil Parameters

❑ **Various Conditions of Loading**

1. **Horizontal surface of fill at the top**

- From Rankine's formula, we have

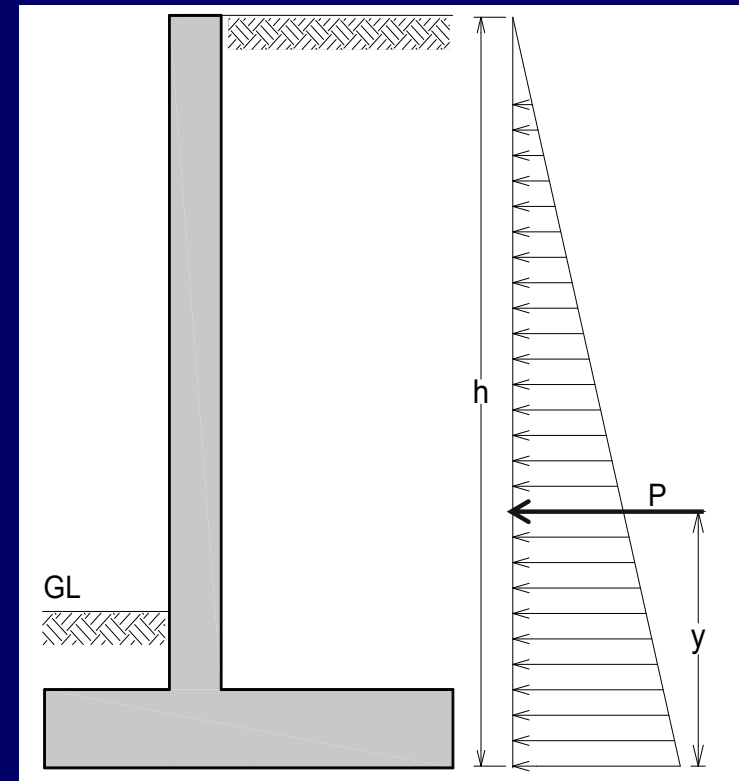$$p_a = K_a \gamma_s h \quad \text{Where,} \quad K_a = \frac{1 - \sin(\emptyset)}{1 + \sin(\emptyset)}$$

The Resultant of this pressure is

$$P = \frac{1}{2}(p_a)(h) = \frac{1}{2}K_a\gamma_s h^2$$

And the location of "P" from the base is

$$y = \frac{h}{3}$$

Earth Pressure and Soil Parameters

❑ **Various Conditions of Loading**
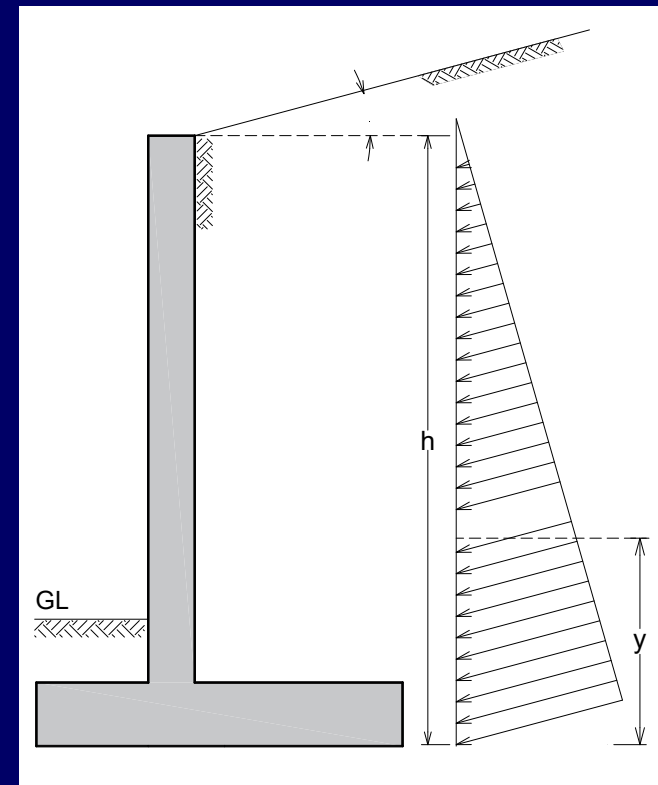
2. **Inclined surface of fill at top**

- The Resultant of this pressure is

$$P = \frac{1}{2}(p_a)(h) = \frac{1}{2}K_a\gamma_s h^2$$

And the location of "P" is given by

$$y = \frac{h}{3}$$

Here, $\delta = \emptyset K_a = \cos\emptyset$

Earth Pressure and Soil Parameters

❑ **Various Conditions of Loading**

3. **Horizontal surface of fill carrying UDL surcharge**

- The increase in pressure caused by uniform surcharge "S" is computed by converting its load into an equivalent imaginary height of earth h_s above the top of the wall such that,
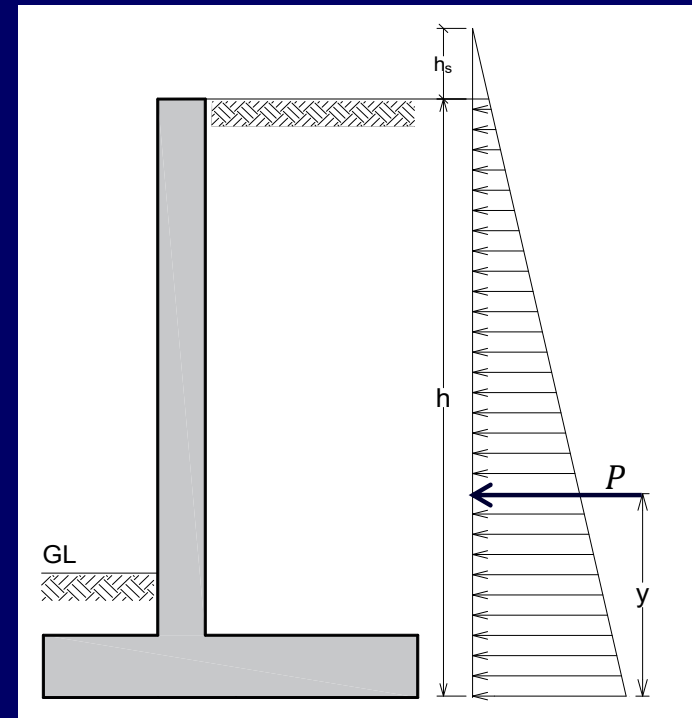
$h_s = S/\gamma$

Then Resultant of pressure is

$$P = \frac{1}{2} K_a \gamma_s h(h + 2h_s)$$

And the location of "P" from the base is

$$y = \frac{h^2 + 3hh_s}{3(h + 2h_s)}$$

Earth Pressure and Soil Parameters

❑ Soil Parameters

- The following table gives representative values of typical soil parameters, often used in engineering practice.

Table: Unit weight (γ_s), effective angles of internal friction (φ'), and the coefficient of friction with concrete (μ)					
S. No	Type of Soil	Typical parameters			Remarks
		Unit Weight γ_s (pcf)	Internal friction angle φ' (degrees)[1]	Coefficient of friction μ [2]	
1	Sand or gravel without fine particles, highly permeable	110 to 120	30 to 40	0.5 to 0.6	Should be used as backfill for retaining walls wherever possible
2	Sand or gravel with silt mixture, low permeability	120 to 130	25 to 35	0.4 to 0.5	
3	Silty sand, sand and gravel with high clay content	110 to 120	25 to 30	0.3 to 0.4	The value of Φ may be un-conservative under saturated conditions
4	Medium or stiff clay	100 to 120	25 to 35	0.2 to 0.4	
5	Soft clay, silt	90 to 110	20 to 35	0.2 to 0.3	

[1] The φ values do not account for probable additional pressures due to pore water, seepage, frost, etc.

[2] Coefficient of friction between concrete and various soils.

Stability Evaluation of Retaining Wall

❑ **Stability checks**

- To evaluate the stability of retaining wall against overturning, sliding and bearing pressure, the following three factors of safety must be computed and compared with recommended values suggested in ACI Reinforced Concrete Design Handbook Volume-2_Special Topics, MNL-17(21).

  1. **Factor of safety against overturning (FS_{OT})**

  2. **Factor of safety against sliding (FS_{SL})**

  3. **Factor of safety against bearing (FS_{BR})**

Stability Evaluation of Retaining Wall

❑ **Stability Checks**

1. **Factor of safety against overturning**

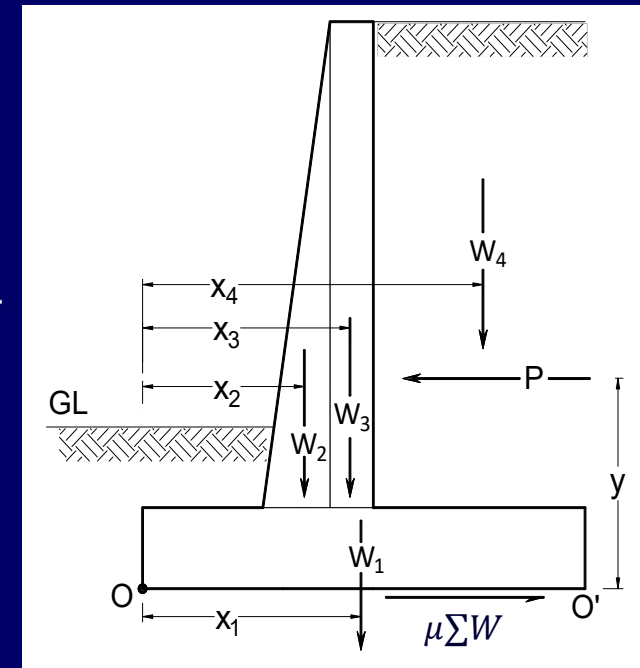   - The factor of safety against overturing about the tip of toe is given by

   $$FS_{OT} = \frac{Restoring\ Moment}{Overturning\ moment} = \frac{M_R}{M_{OT}}$$

   Where;

   $$M_R = \sum(Wx) = W_1 x_1 + W_2 x_2 + W_3 x_3 + W_4 x_4$$

   $$M_{OTM} = P\ y$$

   - General recommended value for factor of safety against overturning FS_{OT} is ≥ 2.0.

Stability Evaluation of Retaining Wall

❑ Stability Checks

2. **Factor of safety against sliding**

- The factor of safety against sliding at base is given by;
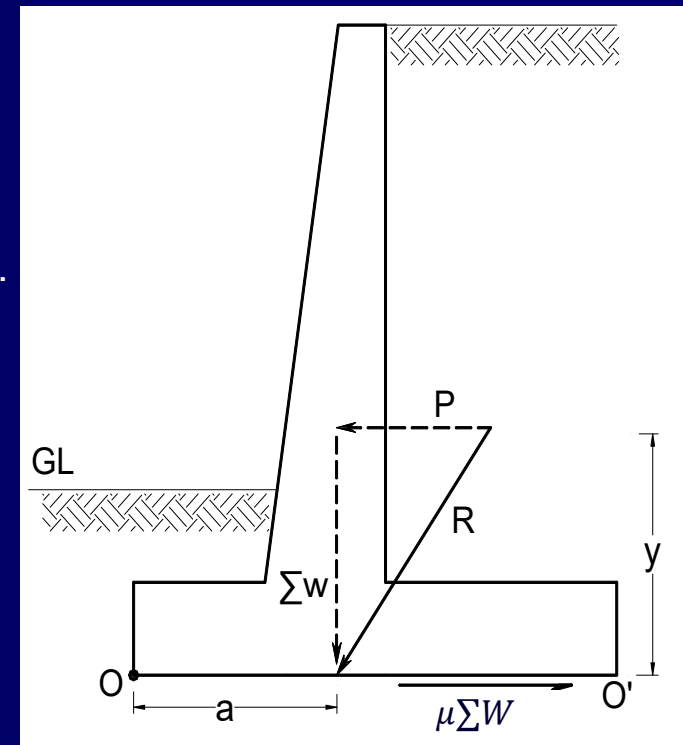
$$FS_{SL} = \frac{\mu \sum W}{P}$$

Where;

μ = Coefficient of friction b/w soil and concrete.

$\sum W$ = Total weight of retaining wall including front fill and backfill.

P = Active soil pressure.

- General recommended value for factor of safety against sliding FS_{SL} is ≥ 1.5.

Stability Evaluation of Retaining Wall

❑ Stability Checks

3. **Factor of safety against bearing**

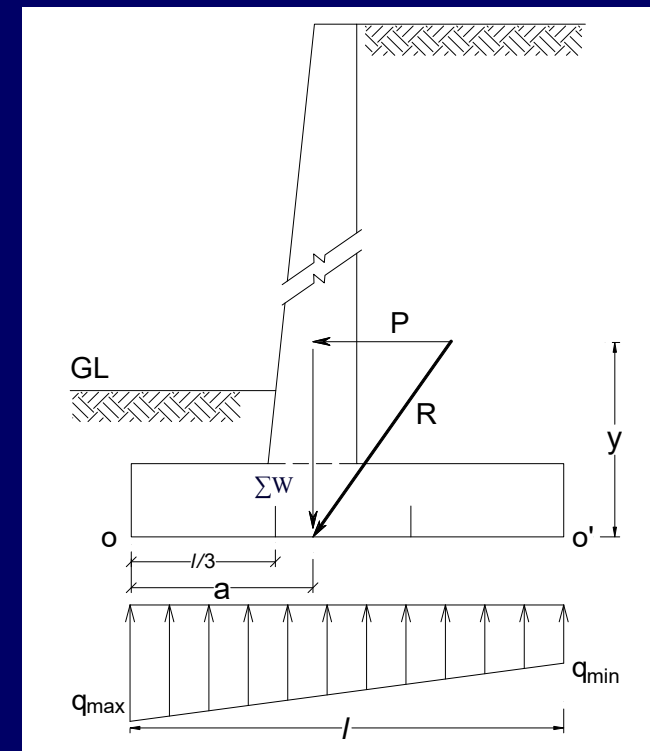- The factor of safety against bearing can be determined as;

$$FS_{BR} = \frac{q_a}{q_{max}}$$

Where;

q_a = Allowable bearing capacity of soil

q_{max} = Maximum soil bearing pressure

- General recommended value for factor of safety against bearing FS_{BR} is ≥ 3.
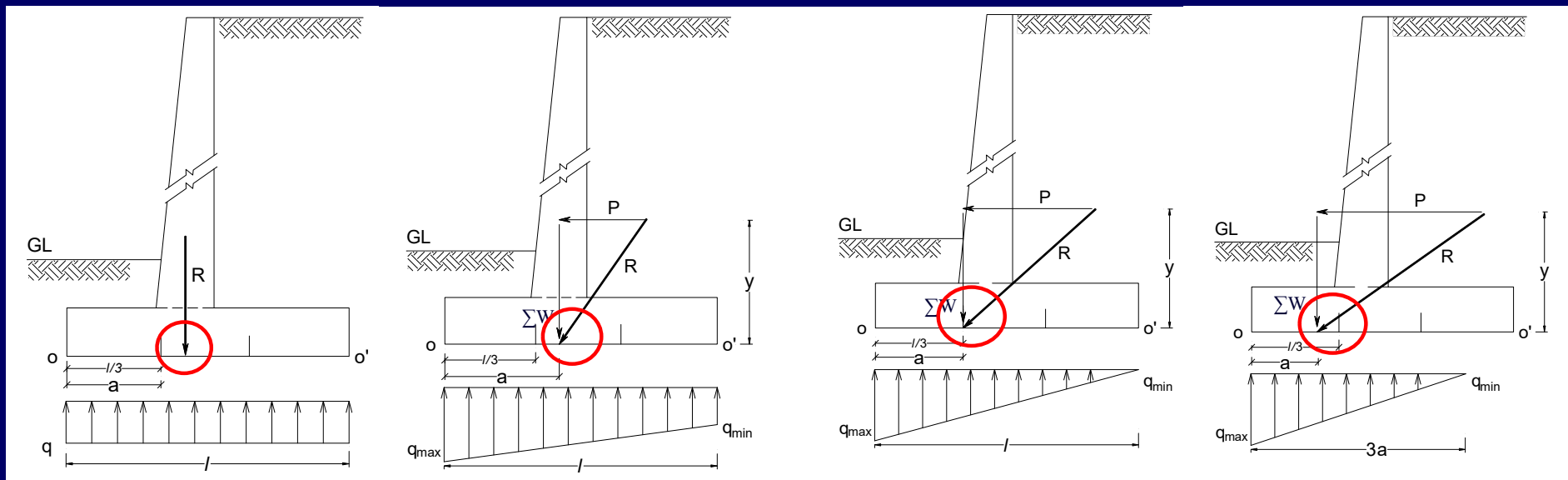
Stability Evaluation of Retaining Wall

❑ **Stability Checks**

3. **Factor of safety against bearing**

- The bearing pressure diagram of soil below the base, depends on the location of resultant as shown below.

P = 0   R = $\sum W$

R at mid location

R = P +$\sum W$

R within middle third

R at edge of middle third

R outside middle third
(uplift pressure at Heel)

Stability Evaluation of Retaining Wall

❑ **Stability Checks**

3. **Factor of safety against bearing**

   ❑ **Calculation of bearing pressure**
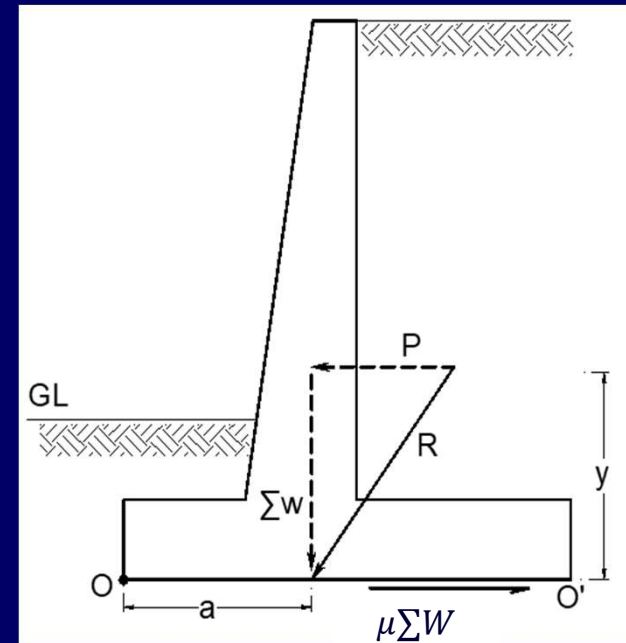
Let "a" be the location of resultant R from the exterior end of toe (point O). Then we have;

$$\Delta M = M_R - M_{OT}$$

Since, $\Delta M = (\sum W)a$

Therefore, solving for a gives;

$$a = \frac{M_R - M_{OT}}{\sum W}$$

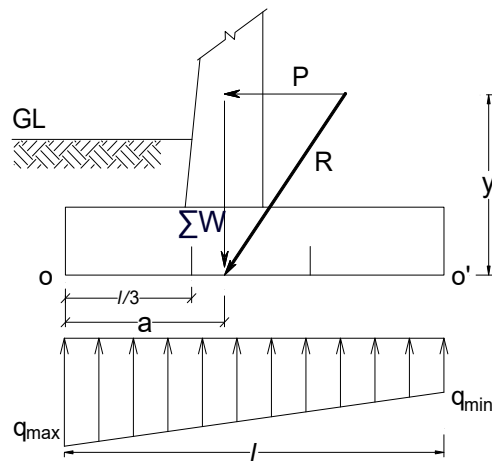# Stability Evaluation of Retaining Wall

❑ **Stability Checks**

3. **Factor of safety against bearing**

   ❑ **Calculation of bearing pressure**

Case 1: a > *l*/3   **Case 2: a = *l*/3**   **Case 3: a < *l*/3**

$$q_{max} = (4l - 6a)\frac{\sum W}{l^2}$$

$$q_{min} = (6a - 2l)\frac{\sum W}{l^2}$$
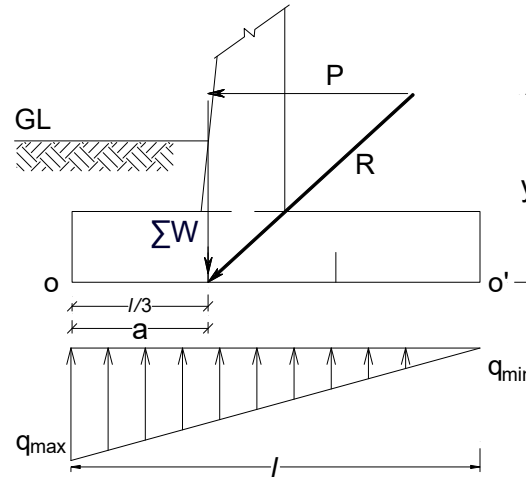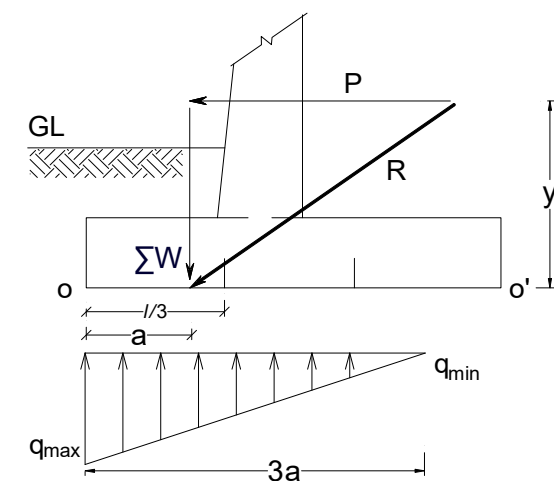
$$q_{max} = \frac{2\sum W}{l}$$

$$q_{min} = 0$$

$$q_{max} = \frac{2\sum W}{3a}$$

$$q_{min} < 0$$

Design of RC Cantilever Retaining Wall

❑ **Design Criteria**

- The stem of a cantilever retaining wall shall be designed as a one–way slab in accordance with the applicable provisions of Chapter 7 (one - way slabs).   (ACI 318 -19, section 13.3.6.1)

- The base is designed as one–way shallow foundation using applicable provisions of Chapter 7 (one - way slabs) and Chapter 9 (Beams).   (ACI 318 -19, section 13.3.2.1)

Design of RC Cantilever Retaining Wall

❑ **Load Combinations**

- Load combination relating to structural design of retaining walls shall be in accordance with ACI 318 -19, section 5.3.1.

  - U = 1.2D + 1.6L + 1.6H

Design of RC Cantilever Retaining Wall

❑ **Preliminary Sizes**

- ACI recommends the dimensions from the guidelines presented by "Bowels" in the fifth edition of *"Foundations Analysis and Design"*, for preliminary calculations.

- In case of surcharge, "h" is replaced by h_{eq} = h + h_s where;
  h_s = height of surcharge

b_{base} = (0.4 - 0.7)h

t_{base} = (0.07 - 0.1)h

t_{stem} = (0.07 - 0.12)h

but not less than 8″

b_{toe} = (0.25 - 0.33)b_{base}

b_{heel}= b_{base} - b_{toe} - t_{stem}
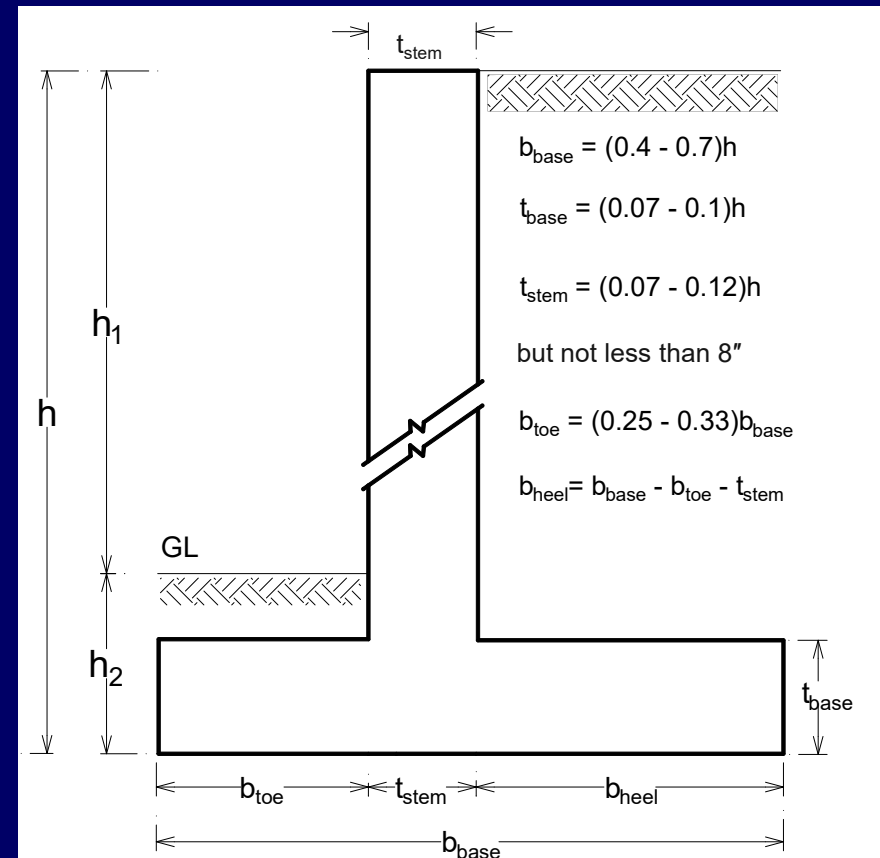
Design of RC Cantilever Retaining Wall

❑ **Preliminary Sizes**

- The estimated sizes must be checked with the minimum thickness requirements for one-way cantilever slabs provided in ACI 318-19 Table 7.3.1.1

Table 7.3.1.1— Minimum thickness of solid nonprestressed one-way slabs	
Support condition	**Minimum h [1]**
Simply supported	$l/20$
One end continuous	$l/24$
Both ends continuous	$l/28$
Cantilever	$l/10$

- l = Span length (Center to center length for interior spans, clear projection for cantilevers) (Section 2.2)
- [1] For f_y other than 60,000 psi, the expressions in the table shall be multiplied by $(0.4 + f_y/100,000)$

Design of RC Cantilever Retaining Wall

❑ **Concrete Clear Cover**

- ACI 318-19, section 20.5.1.3.1,Non-prestressed cast-in-place concrete members shall have specified clear cover for reinforcement at least that given in Table 20.5.1.3.1.

- The minimum specified clear cover is 3 inches for horizontal concrete members cast permanently in contact with the ground, and 2 inches for vertical members.

2″ cover on all sides

3″ cover on all sides
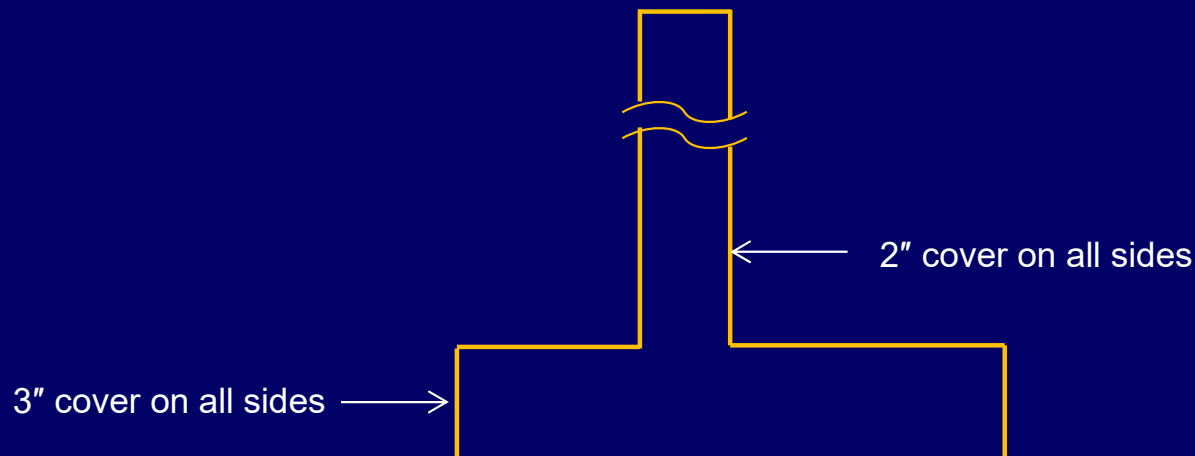
Design of RC Cantilever Retaining Wall

❑ **Reinforcement Limits and Detailing**

- Overall reinforcement requirement of retaining wall is shown below:
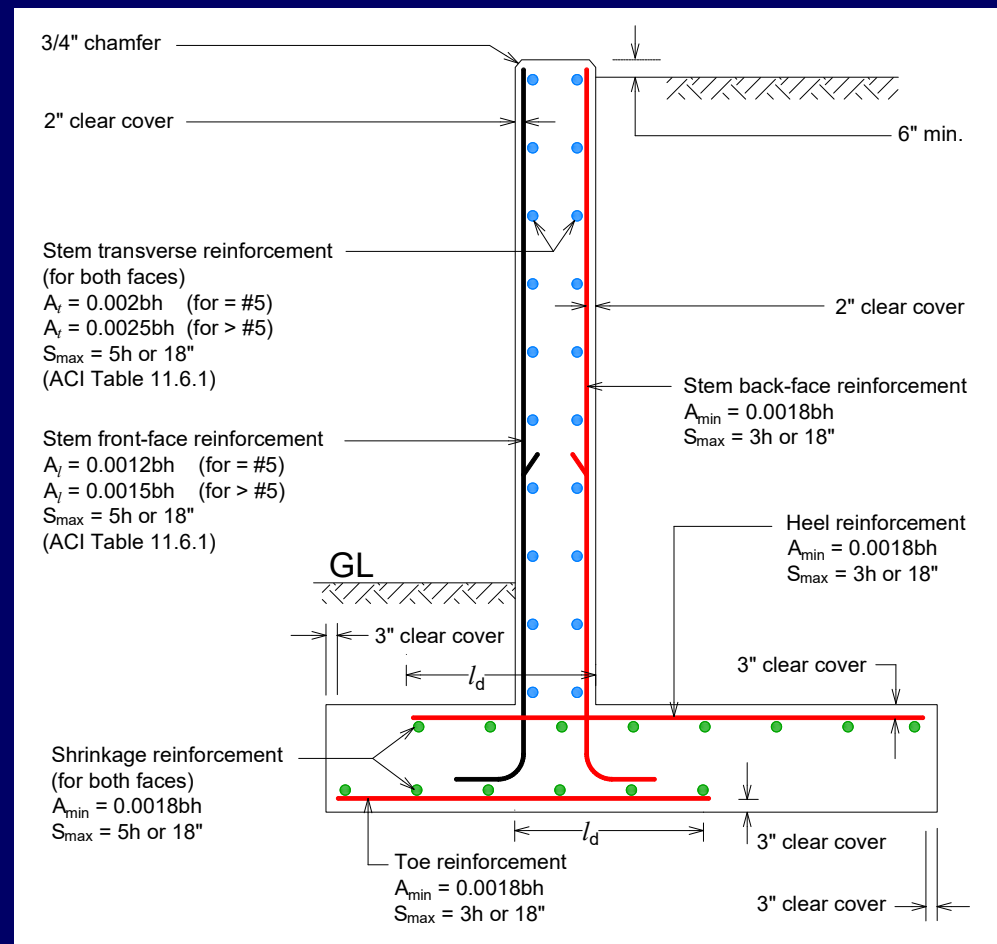
Design of RC Cantilever Retaining Wall

❑ **Drainage and Other Details**

- A proper drainage system must be provided to retaining wall for collecting and redirecting rainwater away from the wall, otherwise the retaining wall may fail. Drainage can be provided in various ways, but two common ways are:
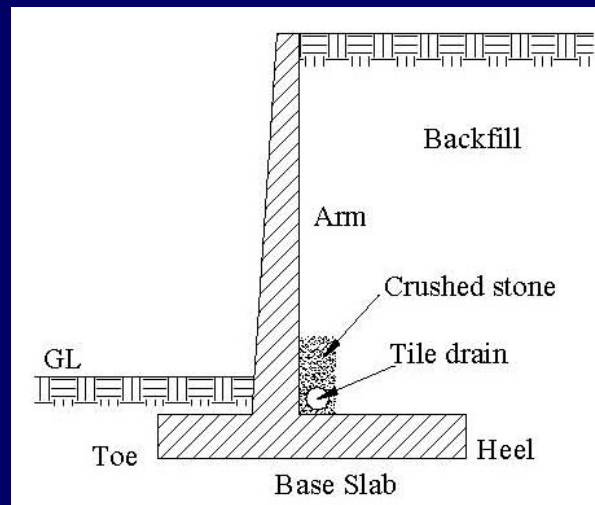
Longitudinal Drains
To prevent outflow to seep into
the soil underneath the wall

Weep Holes
usually spaced horizontally at an
interval of 5 to 10 ft.

Design of RC Cantilever Retaining Wall

❑ **Summary of Design Steps**

```
┌─────────────────────────┐     ┌─────────────────────────┐     ┌─────────────────────────┐
│ Choose Preliminary      │     │ Calculate Horizontal    │     │ Calculate Vertical load │
│ Dimensions and verify   │ ──▶ │ load and Overturning    │ ──▶ │ and Restoring Moment    │
│ with ACI minimum        │     │ Moment                  │     │                         │
│ thickness requirements  │     │                         │     │                         │
└─────────────────────────┘     └─────────────────────────┘     └─────────────────────────┘
                                                                              │
                                                                              ▼
┌─────────────────────────┐     ┌─────────────────────────┐     ┌─────────────────────────┐
│ Analyze and Design Heel │ ◀── │ Analyze and Design Stem │ ◀── │ Apply Stability Checks  │ ◀── │ Calculate Soil Bearing Pressure │
└─────────────────────────┘     └─────────────────────────┘     └─────────────────────────┘
          │
          ▼
┌─────────────────────────┐     ┌─────────────────────────┐     ┌─────────────────────────┐     ┌─────────────────────────┐
│ Analyze and Design Toe  │ ──▶ │ Design Key (if required)│ ──▶ │ Detail reinforcement as │ ──▶ │ Provide drainage system │
│                         │     │                         │     │ per ACI requirements    │     │                         │
└─────────────────────────┘     └─────────────────────────┘     └─────────────────────────┘     └─────────────────────────┘
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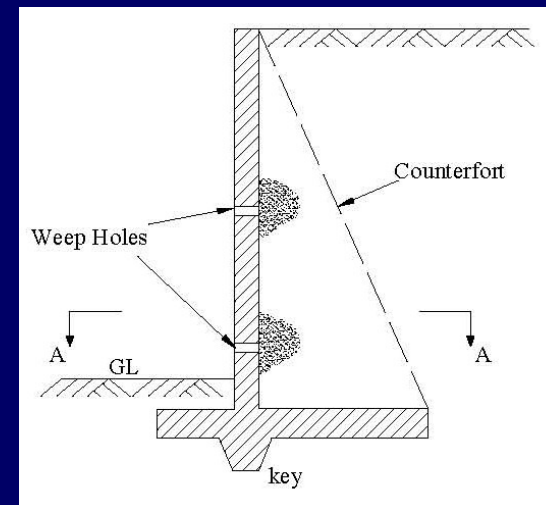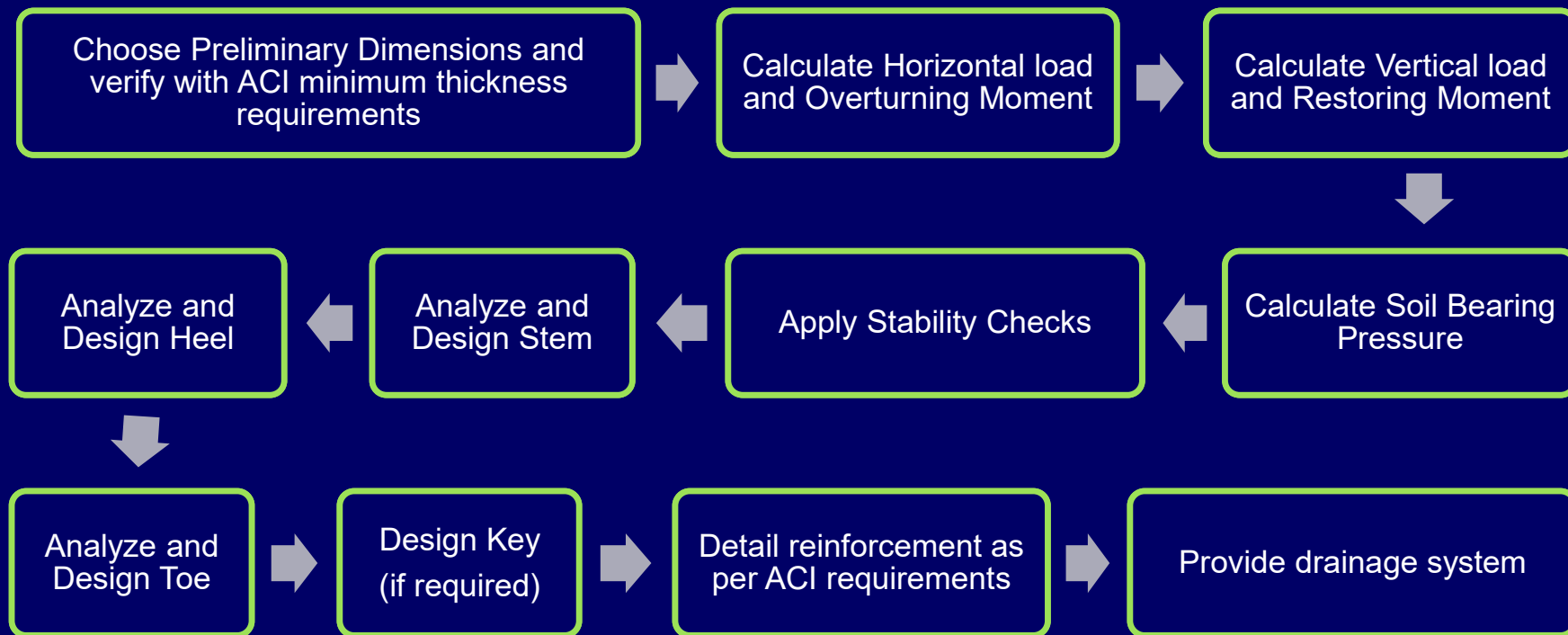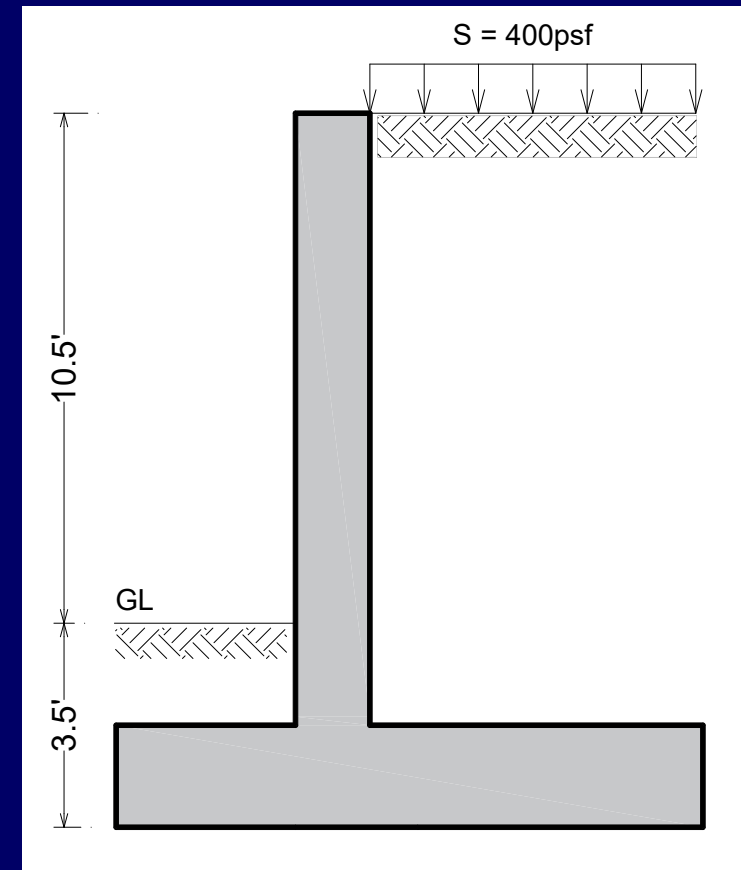
Design Example

❑ Problem Statement

- *Design* the cantilever retaining wall for the following data:

  - Height of stem from GL, h_1 = 10.5'

  - Depth of base from GL, h_2 = 3.5'

  - Surcharge, S = 400 psf

  - Allowable bearing capacity, q_a = 8 ksf

  - Base friction coefficient, $\mu = 0.6$

  - Internal friction angle , $\emptyset = 30º$

  - Unit weight of Soil, $\gamma_s = 120$ pcf

  - $f'_c = 4.5\ ksi\ and\ f_y = 60\ ksi$

Design Example

❑ **Solution**

➢ **Step 1: Preliminary dimensions**

Equivalent depth of surcharge is calculated as

$$h_s = \frac{S}{\gamma} = \frac{400}{120} = 3.33'$$
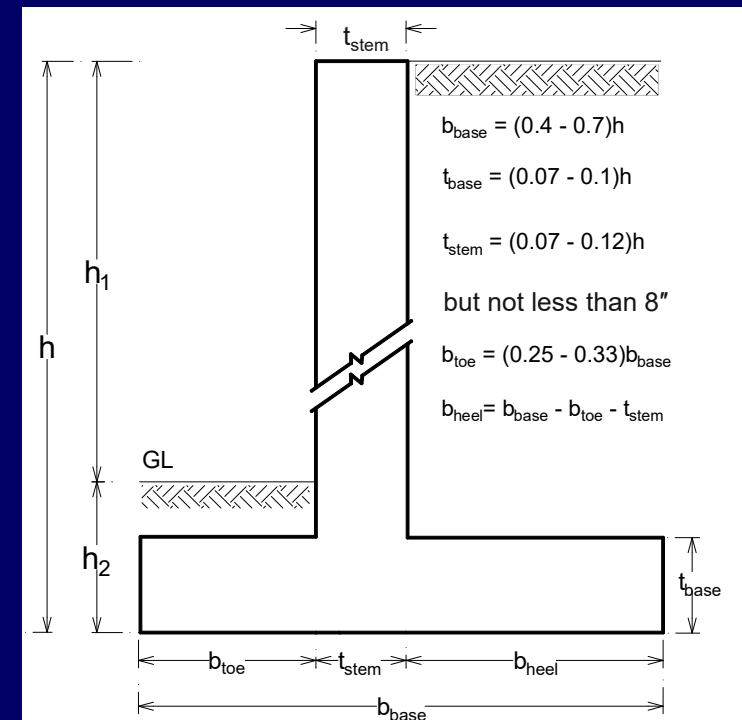
$$h_{eq} = h + h_s = 14 + 3.33 = 17.33'$$

Let $b = 0.58 h_{eq} = 0.58(17.33) = 10'$

$$t_{base} = 0.1(17.33) \times 12 = 21''$$

$$t_{stem} = 0.07(17.33) \times 12 = 15''$$

$$b_{toe} = 0.3b = 0.3(10) = 3'$$

$$b_{heel} = 10 - 3 - 1.25 = 5.75'$$

$b_{base} = (0.4 - 0.7)h$

$t_{base} = (0.07 - 0.1)h$

$t_{stem} = (0.07 - 0.12)h$

but not less than 8″

$b_{toe} = (0.25 - 0.33)b_{base}$

$b_{heel} = b_{base} - b_{toe} - t_{stem}$

Design Example

❑ Solution

➢ **Step 1: Preliminary dimensions**

Check the dimensions against the minimum thickness requirements provided in Table 7.3.1.1.

Minimum thickness requirements		
Components	**Minimum h**	**Remarks**
Stem/Arm	$\dfrac{12.25 \times 12}{10} = 14.7"$	OK
Heel	$\dfrac{5.75 \times 12}{10} = 6.9"$	OK
Toe	$\dfrac{3 \times 12}{10} = 3.6"$	OK
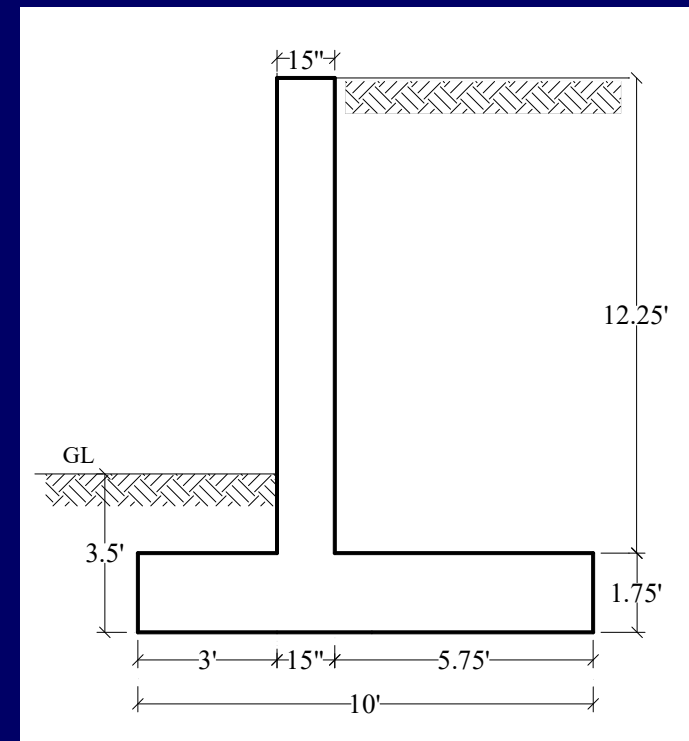
Design Example

❑ Solution

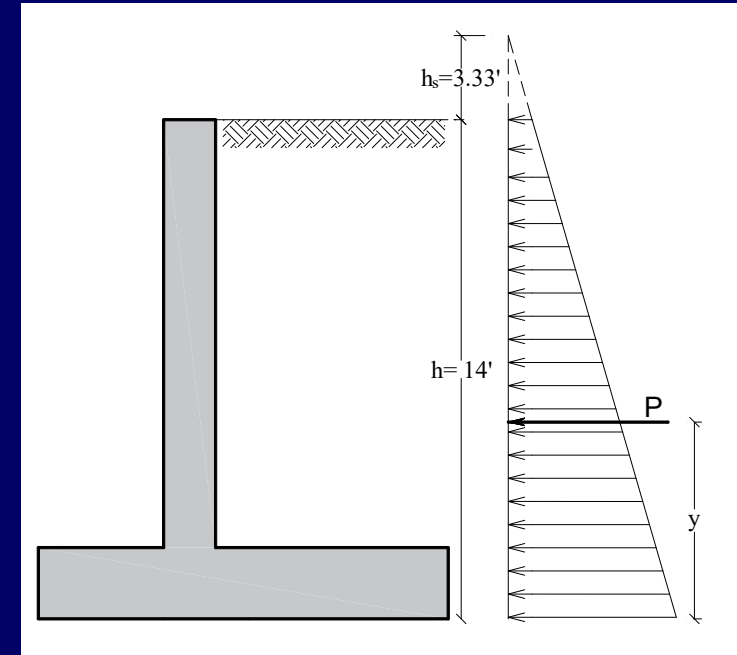➢ **Step 2: Calculation of Horizontal load and Overturning Moment**

$$K_a = \frac{1 - \sin(\emptyset)}{1 + \sin(\emptyset)} = \frac{1 - \sin(30)}{1 + \sin(30)} = 0.33$$

$$P = \frac{1}{2}[K_a \gamma_s h(h + 2h_s)]$$

$$P = \frac{1}{2}[0.33 \times 0.120 \times 14 (14 + 2 \times 3.33)]$$

On solving, we get

$$P = 5.73 kips$$
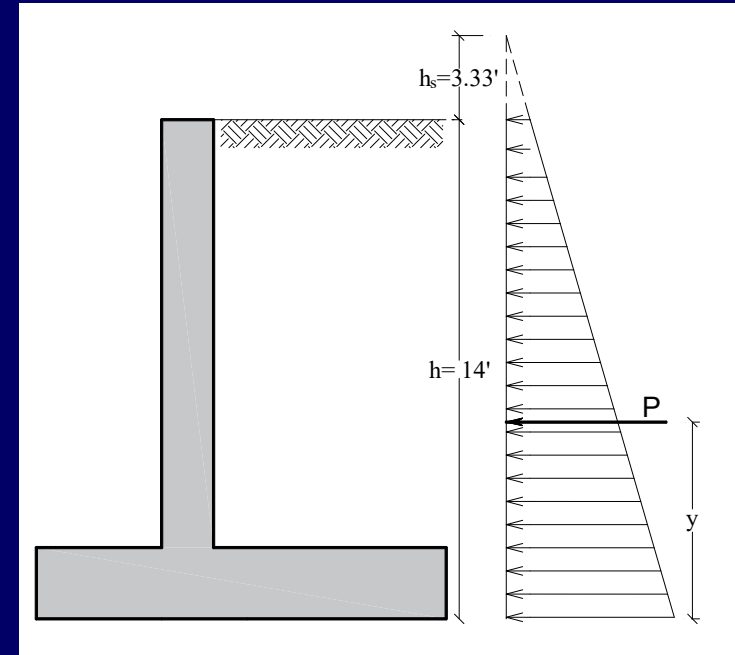
Design Example

❑ Solution

➢ **Step 2: Calculation of Horizontal load and Overturning Moment**

$$y = \frac{h^2 + 3hh_s}{3(h + 2h_s)}$$

$$y = \frac{14^2 + 3 \times 14 \times 3.33}{3(14 + 2 \times 3.33)} = 5.42'$$

So, overturning moment about the tip of toe can be determined as,

$$M_{OT} = Py = 5.73 \times 5.42 = 31.06 \, kip.ft$$

Design Example

❑ Solution

➢ **Step 3: Calculation of Vertical load and Restoring Moment**

- Vertical load and restoring or stabilizing moment due to the weight of retaining wall and the soil is calculated and shown below

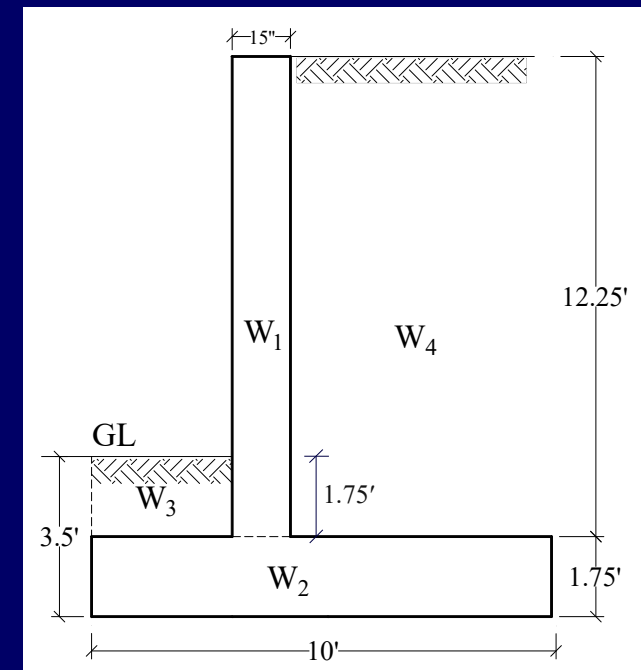 - **Self weight of Retaining wall**

    $W_1 = A_1\gamma_c = (1.25 \times 12.25)0.150 = 2.30 \; k/ft$

    $W_2 = A_2\gamma_c = (1.75 \times 10)0.150 = 2.63 \; k/ft$

  - **Self weight of Soil**

    $W_3 = A_3\gamma_s = (1.75 \times 3)0.120 = 0.63 \; k/ft$

    $W_4 = A_4\gamma_s = (5.75 \times 12.25)0.120 = 8.45 \; k/ft$

Design Example

❑ Solution

➤ **Step 3: Calculation of Vertical load and Restoring Moment**

● Vertical load and restoring or stabilizing moment due to the weight of retaining wall and the soil is calculated and shown below
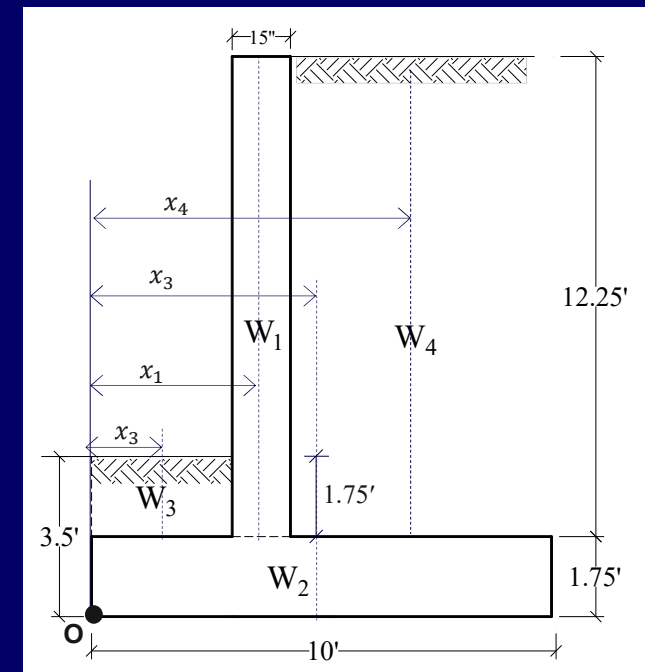
▪ **Moment arms about Point O**

$$x_1 = 3 + \frac{1.25}{2} = 3.63 \, ft$$

$$x_2 = \frac{10}{2} = 5.0 ft$$

$$x_3 = \frac{3}{2} = 1.5 \, ft$$

$$x_4 = 10 - \frac{5.75}{2} = 7.13 ft$$

Design Example

❑ Solution

➢ **Step 3: Calculation of Vertical load and Restoring Moment**

S. No.	W (kip/ft)	x (ft)	Wx (kip.ft/ft)
1	2.30	2.63	8.35
2	2.63	5.0	13.15
3	0.63	1.5	0.95
4	8.45	7.13	60.25
Sum	**14.01**		**82.69**

Hence, we get;

Vertical Load, $= \sum W = 14.01 \text{kips/ft}$

Restoring Moment, $M_R = \sum Wx = 82.69 \text{kip. ft/ft}$

Design Example

❑ **Solution**

➢ **Step 4: Calculation of Bearing pressure**
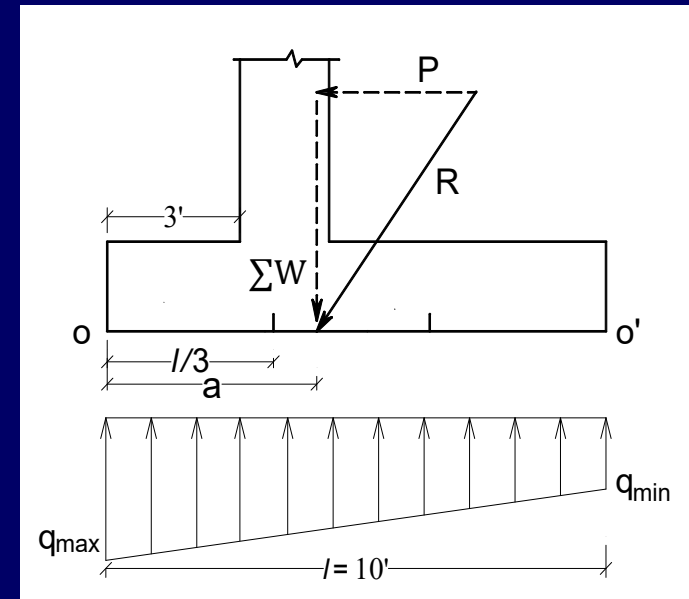
To find the point of action "a" , we have

$$a = \frac{M_R - M_{OT}}{\sum W}$$

$$a = \frac{82.69 - 31.06}{14.01} = 3.68'$$

Now,

$$\frac{l}{3} = \frac{10}{3} = 3.33' < 3.68'$$

Hence, the resultant lies within the middle third of the base.

Design Example

❑ Solution

➢ **Step 4: Calculation of Bearing pressure**
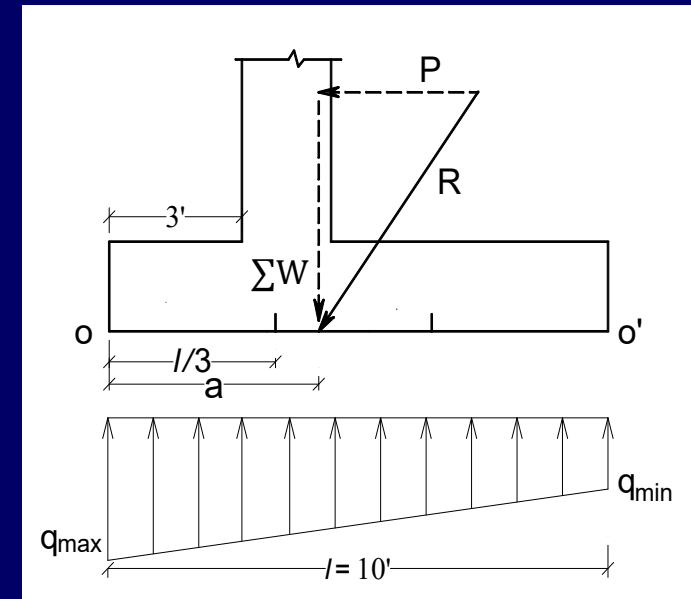
$$q_{max} = (4l - 6a)\frac{\Sigma W}{l^2}$$

By substituting values;

$$q_{max} = (4 \times 10 - 6 \times 3.68)\frac{14.01}{10^2} = 2.51 ksf$$

Similarly,

$$q_{min} = (6a - 2l)\frac{\Sigma W}{l^2}$$

$$q_{min} = (6 \times 3.68 - 2 \times 10)\frac{14.01}{10^2} = 0.29 ksf$$

Design Example

❑ Solution

➤ **Step 5: Applying stability checks**

1. F.O.S against Overturning

$$FS_{OT} = \frac{M_R}{M_{OT}} = \frac{82.69}{31.06} = 2.67 > 2 \Rightarrow OK!$$

2. F.O.S against Sliding

$$FS_{SL} = \frac{\mu \sum W}{P} = \frac{0.6(14.01)}{5.73} = 1.47 \approx 1.5 \Rightarrow OK!$$

3. FOS against Bearing

$$FS_{BP} = \frac{q_a}{q_{max}} = \frac{8}{2.51} = 3.19 > 2 \Rightarrow OK!$$

Design Example

❑ **Solution**

➢ **Step 5: Applying stability checks**

❑ **Concluding remarks**

- The retaining wall preliminary dimensions are adequate to resist overturning, sliding and prevent bearing failure of soil.

- In the subsequent steps, each component of retaining wall is designed for strength.

- If any of the determined dimensions are not satisfactory, then all the previous steps must be revised.

Design Example

❑ **Solution**

➢ **Step 6: Analysis and Design of Stem**

❑ **Analysis for Shear**

General equation of **factored** active earth pressure w.r.t bottom of stem is given by:

$$P_u = 1.6\left\{\frac{1}{2}\left[K_a\gamma_s h(h + 2h_s)\right]\right\} = 1.6\{0.0198h\,(h + 6.66\}$$

After simplification, we get

$$P_u = 0.0317h^2 + 0.211h --- (1)$$

Design Example

❑ Solution

➢ **Step 6: Analysis and Design of Stem**

❑ **Analysis for Flexure**

We have $M_u = Py$

$$y = \frac{h^2 + 3hh_s}{3(h + 2h_s)} = \frac{h^2 + 9.99h}{3(h + 6.66)}$$

Now general bending moment equation is given by,

$$M_u = P_u \, y = (0.0317h^2 + 0.211h) \times \frac{h^2 + 9.99h}{3(h + 6.66)}$$

$$M_u = \frac{0.031h^4 + 0.528h^3 + 2.108h^2}{3(h + 6.66)} --- (2)$$

Design Example

❑ Solution

➢ **Step 6: Analysis and Design of Stem**

❑ **Analysis for Flexure**

- As per ACI 318 -19, section 13.3.6.3, the critical section of stem for both flexure and shear should be taken at the interface between the stem and footing.

- Using equation (1) and (2) the shear and bending moments diagrams for the stems have been drawn and shown on the next.
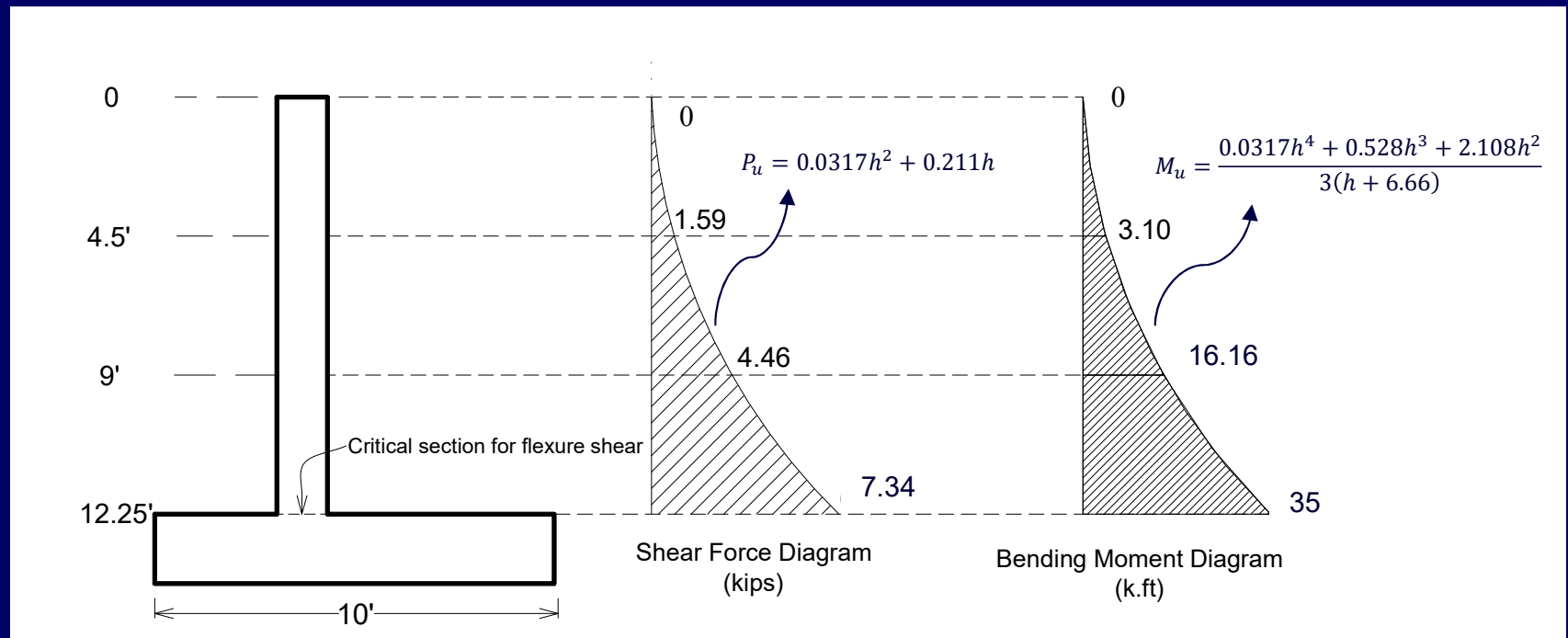
Design Example

❑ **Solution**

➤ **Step 6: Analysis and Design of Stem**

❑ **Analysis for Flexure**

Shear Force Diagram (kips) with values: 0, 1.59, 4.46, 7.34

$P_u = 0.0317h^2 + 0.211h$

Bending Moment Diagram (k.ft) with values: 0, 3.10, 16.16, 35

$$M_u = \frac{0.0317h^4 + 0.528h^3 + 2.108h^2}{3(h + 6.66)}$$

Wall section dimensions: 0, 4.5', 9', 12.25', 10', Critical section for flexure shear

Design Example

❑ Solution

➤ **Step 6: Analysis and Design of Stem**

❑ **Design for Shear**

From Shear force diagram we have V_u = 7.34 kips
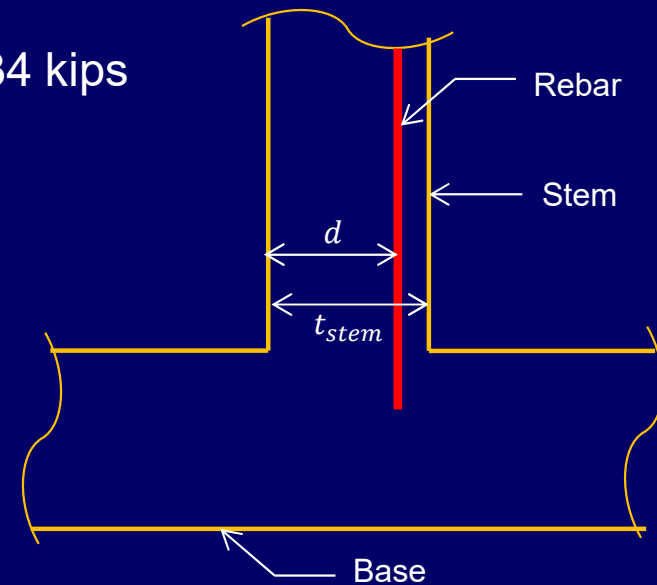
$$d = t_{stem} - Cc - \frac{d_b}{2}$$

Using 2" clear cover, and assuming #6 bar,

$$d = 15 - 2 - 6/16 = 12.63''$$

$$\emptyset V_c = \emptyset 2\sqrt{f_c'}bd$$

$$= (0.75)2\sqrt{4500} \times 12 \times 12.63 = 15.24 kips$$

$$\emptyset V_c > V_u \Rightarrow OK!$$

Rebar

Stem

d

t_{stem}

Base

Design Example

❑ Solution

> ➤ **Step 6: Analysis and Design of Stem**

❑ Design for Flexure (Vertical reinforcement at the back face)

For h = 12.25′; M_u = 35.0 ft-kip/ft = 420.0 in-kip/ft

$$A_{s,min} = 0.0018bh = 0.0018(12 \times 15) = 0.324 in^2$$

$$\emptyset M_n = \emptyset A_s f_y \left(d - \frac{a}{2} \right) ; \quad \emptyset M_n = 0.9 \times 0.324 \times 60 \left(12.63 - \frac{0.424}{2} \right)$$

$$= 217.18 \, in. k/ft < M_u$$

Therefore, from calculations, A_s = 0.63 in^2, using #6 bar, spacing = 8.4″c/c

Maximum spacing for main steel reinforcement is:

● 3h = 3 x 15 = 45″ ; 18″ => OK! , Hence, finally provide #6 @ 8″ c/c

Design Example

❑ **Solution**

➢ **Step 6: Analysis and Design of Stem**

❑ **Design for Flexure (Vertical reinforcement at the back face)**

Similarly for other depths, the design is given in tabular form as below:

Depth (ft)	Thickness of arm (in)	Moment (in-kip/ft)	As,min (sq.in)	øMn (in-kip/ft)	Governing Moment	Governing Area of steel	Design spacing	Max spacing	Final spacing
		Table for Design of main bars in Arm of retaining wall							
0	15.00	0	0.324	217.18	217.18	0.324	16.3"	18"	@16" c/c
4.5	15.00	37.2	0.324	217.18	217.18	0.324	16.3"	18"	@16" c/c
9	15.00	194.88	0.324	217.18	217.18	0.324	16.3"	18"	@8" c/c
12.25	15.00	420.0	0.324	217.18	420.0	0.63	8.3"	18"	@8" c/c

From a depth of 12.25 ft to 9 ft, provide #6 @ 8″, and from 9 ft to top end, provide #6 @ 16″.

Design Example

❑ **Solution**

➢ **Step 6: Analysis and Design of Stem**

❑ **Vertical reinforcement at the front face**

$A_s = 0.0012 \times 12 \times 15 = 0.216$ in^2 (From slide No. 31)

Using #4 bar with area $A_b = 0.20$ in^2

Spacing = Area of one bar A_b/A_{st} = $(0.20 /0.216) \times 12 = 11.1''$

Maximum spacing should not exceed;

- 5h = 5 x15 =75″ or 18″

Provided spacing is OK!. Finally provide #4 @ 10″

Design Example

❑ **Solution**

➤ **Step 6: Analysis and Design of Stem**

❑ **Horizontal /Transverse reinforcement**

A_{st} = 0.0020bh   (From slide No. 31)

A_{st} = 0.0020 × 12 × 15 = 0.36 in^2/ft

This is the total required area of horizontal reinforcement, i-e for both faces.

So, for each face, A_{st} = 0.36/2 = 0.18in^2/ft

Using #4 bar with A_b = 0.20in^2

Spacing = (0.20/0.18) x 12 = 13.3″ < 18″ => OK!

Finally, Use #4 @ 10″ c/c

Design Example

❑ **Solution**

➢ **Step 6: Analysis and Design of Stem**

❑ **Calculation of development length**

As per ACI 318, section 25.4.3.1, development length l_{dh} for deformed bar, is largest of :

1. $\dfrac{9f_y}{550\sqrt{f_c'}} d_b = \dfrac{9(60000)}{550\sqrt{4500}}(0.75) = 10.98"$

2. $8d_b = 8(0.75) = 6"$

3. $6"$

Therefore, $l_{dh} = 10.98"$
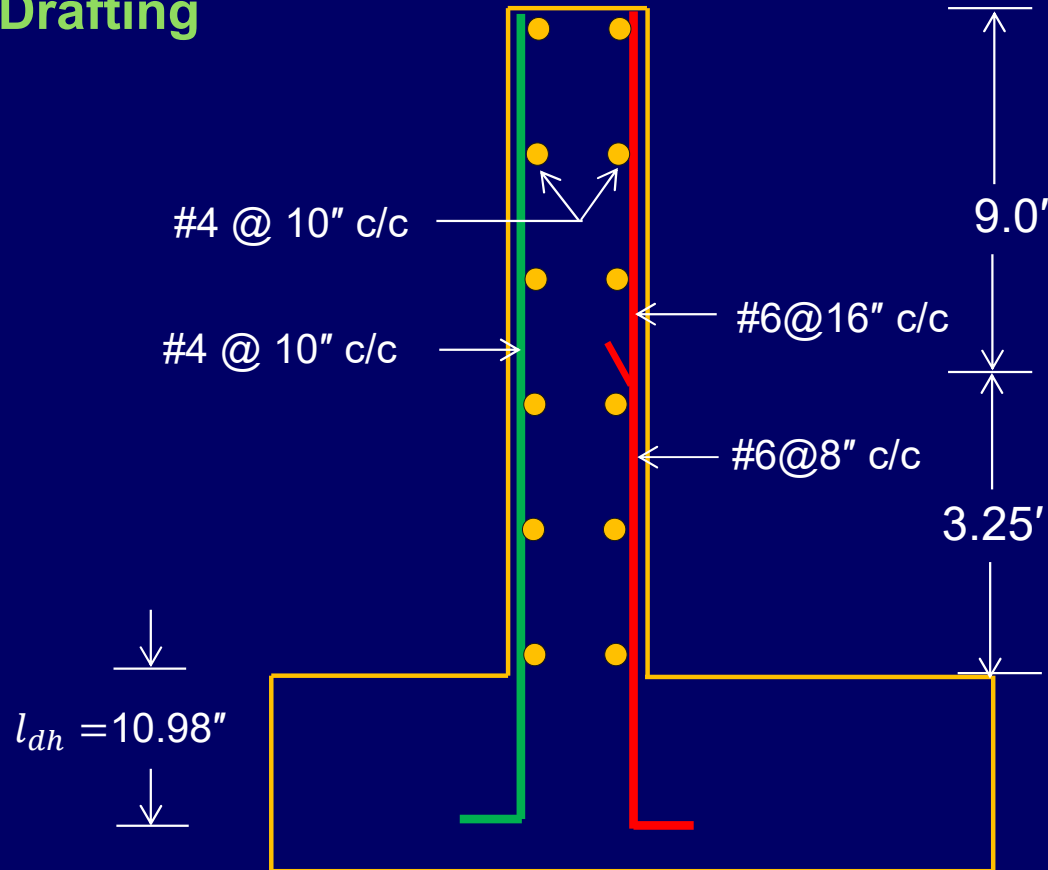
Since, $l_{dh} = 10.98" < depth\ of\ base \Rightarrow OK!$

Rebar

Stem

21"

l_{dh}

Base
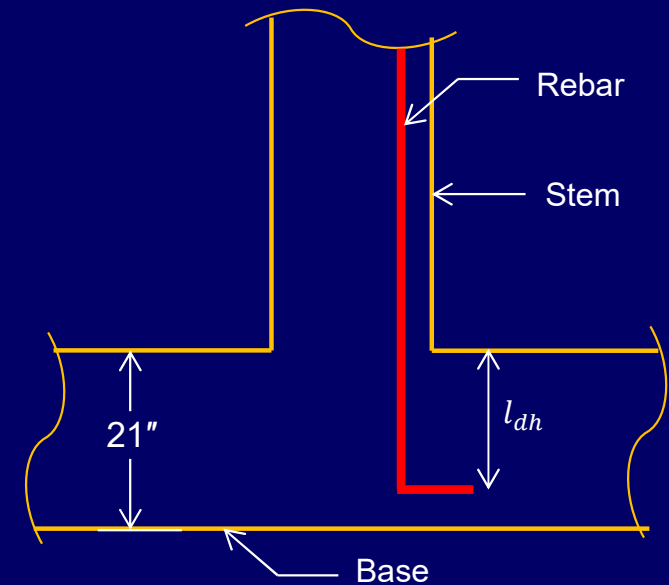
Design Example

❑ Solution

➢ **Step 6: Analysis and Design of Stem**

❑ **Drafting**

#4 @ 10″ c/c

#4 @ 10″ c/c

#6@16″ c/c

#6@8″ c/c

9.0′

3.25′

$l_{dh} =$ 10.98″

Design Example

❑ **Solution**

➢ **Step 7: Analysis and Design of Heel**

❑ **Loads**

Component	Factored Load (k/ft)
Self weight of heel	$1.2\gamma h_b = 1.2(0.15)(1.75 \times 1)$ $= 0.32$
Earth fill load	$1.6\gamma hb = 1.6(0.12)(12.25 \times 1)$ $= 2.35$
Surcharge Load	$1.6\gamma h_s b = 1.6(0.12)(3.33 \times 1)$ $= 0.64$
Total:	W_u = 0.32 +2.35+0.64 $= 3.31$ k/ft

Surcharge — 3.33'

Earth fill — 12.25'

Heel — 1.75'
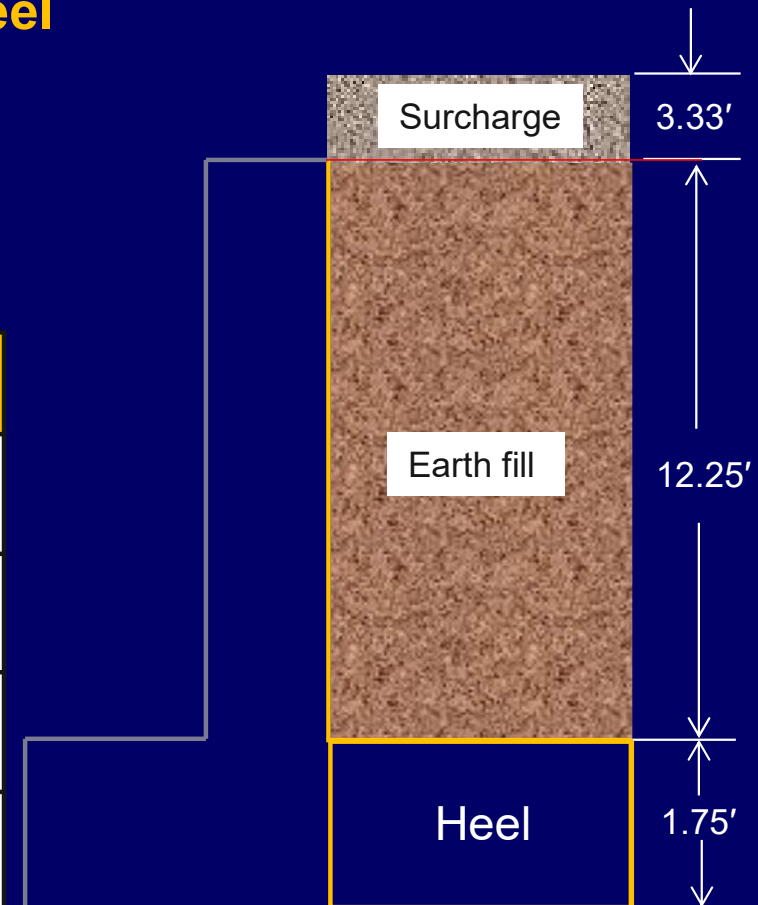
Design Example

❑ Solution

➢ **Step 7: Analysis and Design of Heel**

❑ **Analysis for Shear**

Taking 3" clear cover, and assuming #6 bar,

$d = 21 - 3 - 6/16 = 17.63''$
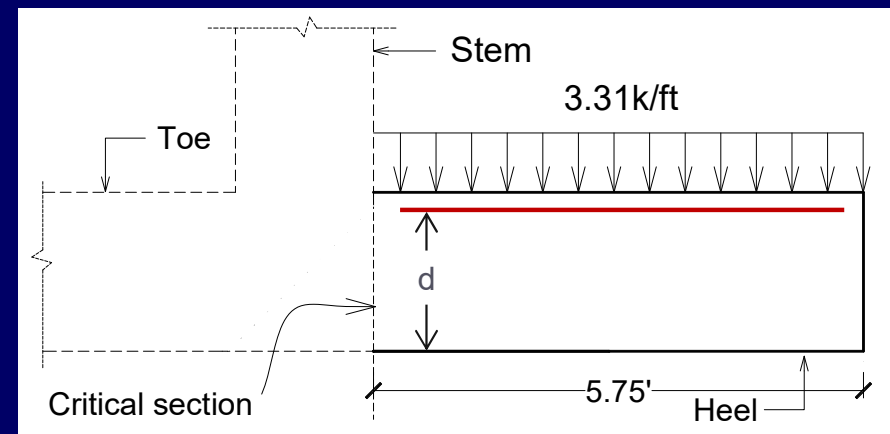
Shear force at critical location is,

$V_u = 3.31 \times (5.75) = 19.0 kips$

❑ **Analysis for Flexure**

$M_u = 3.31 \times 5.75 \times \left(\dfrac{5.75}{2}\right)$

$M_u = 54.71 ft.kip \ or \ 656.62 in.kip/ft$

Design Example

❑ **Solution**

  ➢ **Step 7: Analysis and Design of Heel**

  ❑ **Design for Shear**

  From Shear force diagram we have V_u = 19.0 kips

  Design shear capacity of concrete is given as:

  $$\emptyset V_c = \emptyset 2\sqrt{f_c'}bd$$

  $$\emptyset V_c = (0.75)2\sqrt{4500} \times 12 \times 17.63 = 21.29 kips$$

  $$\emptyset V_c > V_u \Rightarrow OK!$$

Design Example

❑ **Solution**

➢ **Step 7: Analysis and Design of Heel**

❑ **Design for Flexure (Longitudinal reinforcement)**

M_u = 656.62 in-kip/ft

$$A_{min} = 0.0018bh = 0.0018(12 \times 21) = 0.454 in^2$$

$$ØM_n = 0.9 \times 0.454 \times 60 \left(17.63 - \frac{0.593}{2} \right) = 424.95 \ in.kip/ft < M_u$$

Therefore, from calculations, A_s = 0.71 in^2, using #6 bar, spacing = 7.44″c/c

Maximum spacing for main steel reinforcement is:

- 3h = 3 x 21 = 63″ ; 18″ => OK! Hence, finally provide #6 @ 7″ c/c.

Design Example

❑ **Solution**

➢ **Step 7: Analysis and Design of Heel**

❑ **Transverse reinforcement**

Minimum shrinkage reinforcement is given by

$$A_{shrinkage} = 0.0018bh = 0.0018(12 \times 21) = 0.454 in^2/ft$$

Divide this equally between two faces,

$$A_{shrinkage} = \frac{0.454}{2} = 0.227 in^2/ft \quad for \ each \ face$$

Design Example

❑ Solution

> ➤ **Step 7: Analysis and Design of Heel**

❑ **Transverse reinforcement**

Using #4 bar with A_b = 0.20in^2

Spacing = (0.20/0.227) x 12 = 10.57″c/c

Maximum spacing for shrinkage should be least of

- 5h = 5 x 21 = 105″ or 18″

 Provided spacing is OK!.

 Finally provide #4@10″ c/c on top and bottom face of heel

Design Example
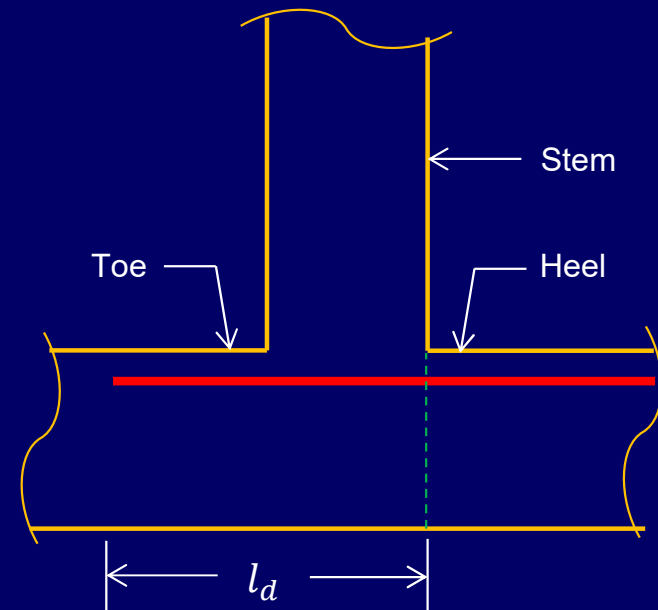
❑ **Solution**

➢ **Step 7: Analysis and Design of Heel**

❑ **Calculation of development length**

Development length of Heel reinforcement into Toe as per ACI 318-19, section 25.4.2.4 is given by

$$l_d = \frac{0.039 f_y}{\sqrt{f_c'}} d_b$$

$$l_d = \frac{0.039(60000)}{\sqrt{4500}}(0.75) = 26.16'' \approx 27''$$
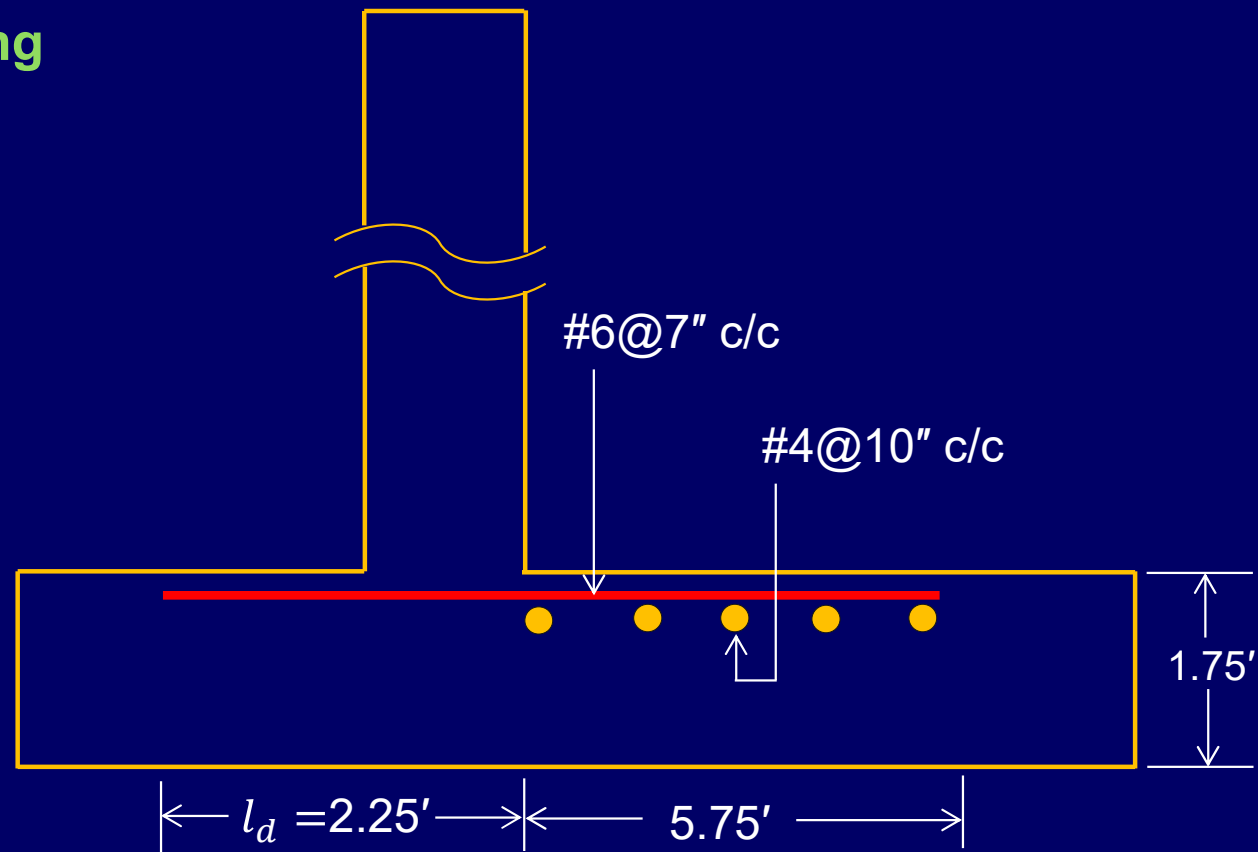
Therefore, $l_d = 2.25'$

Stem

Toe

Heel

l_d

Design Example

□ **Solution**

➢ **Step 7: Analysis and Design of Heel**

□ **Drafting**

Design Example

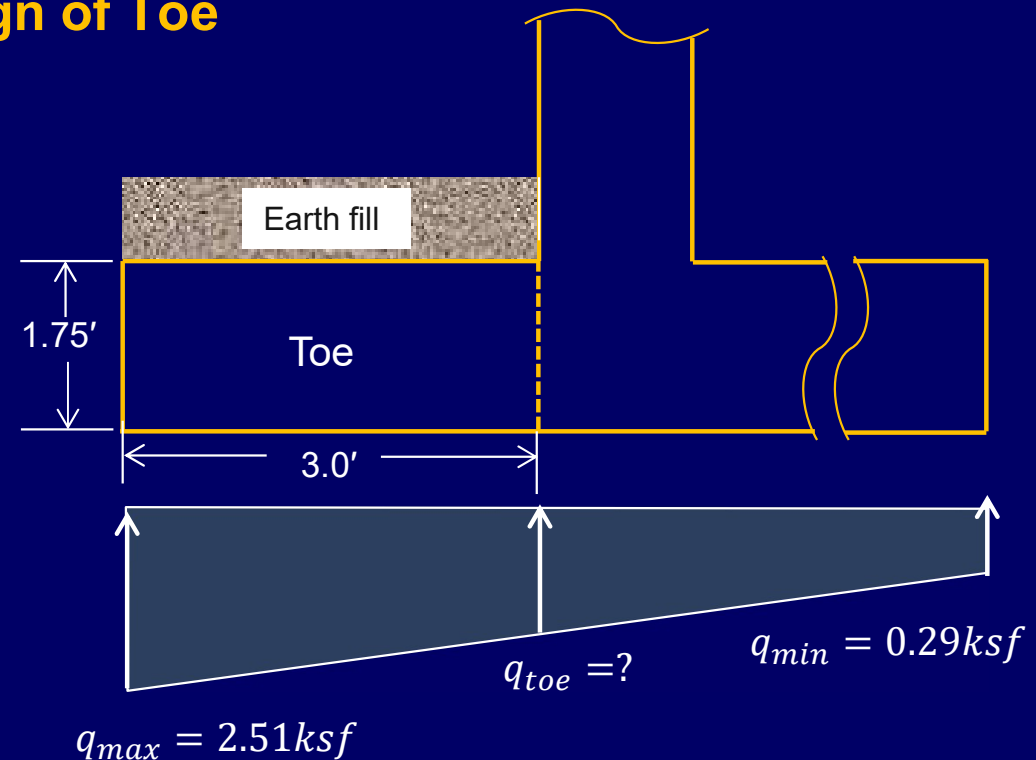## ❑ Solution

➢ **Step 8: Analysis and Design of Toe**

❑ **Loads**

Weight of Earth fill = Ignored

Self weight of Toe = Ignored

Factored q_{max} = 1.6 x 2.51 = 4.01

Factored q_{min} = 1.6 x 0.29 = 0.46

Now, the factored soil pressure at interior end of toe slab can be determined using similarity of triangles as shown on next slide.
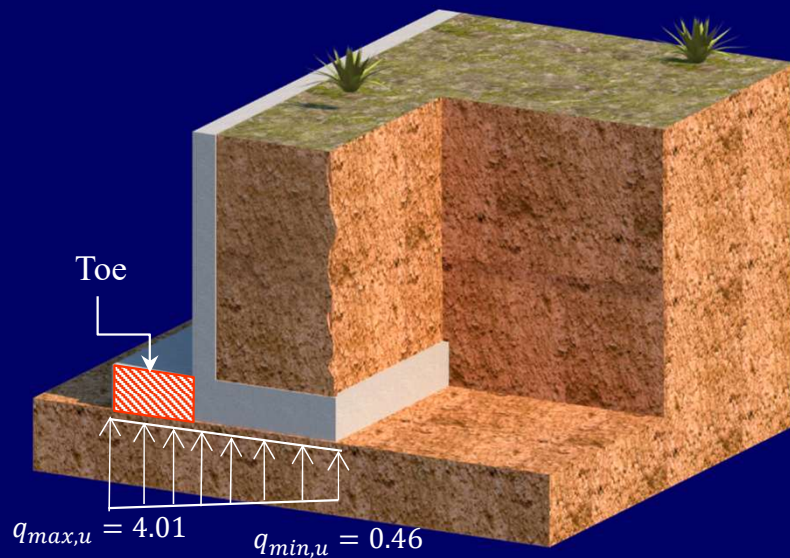

Earth fill

1.75′

Toe
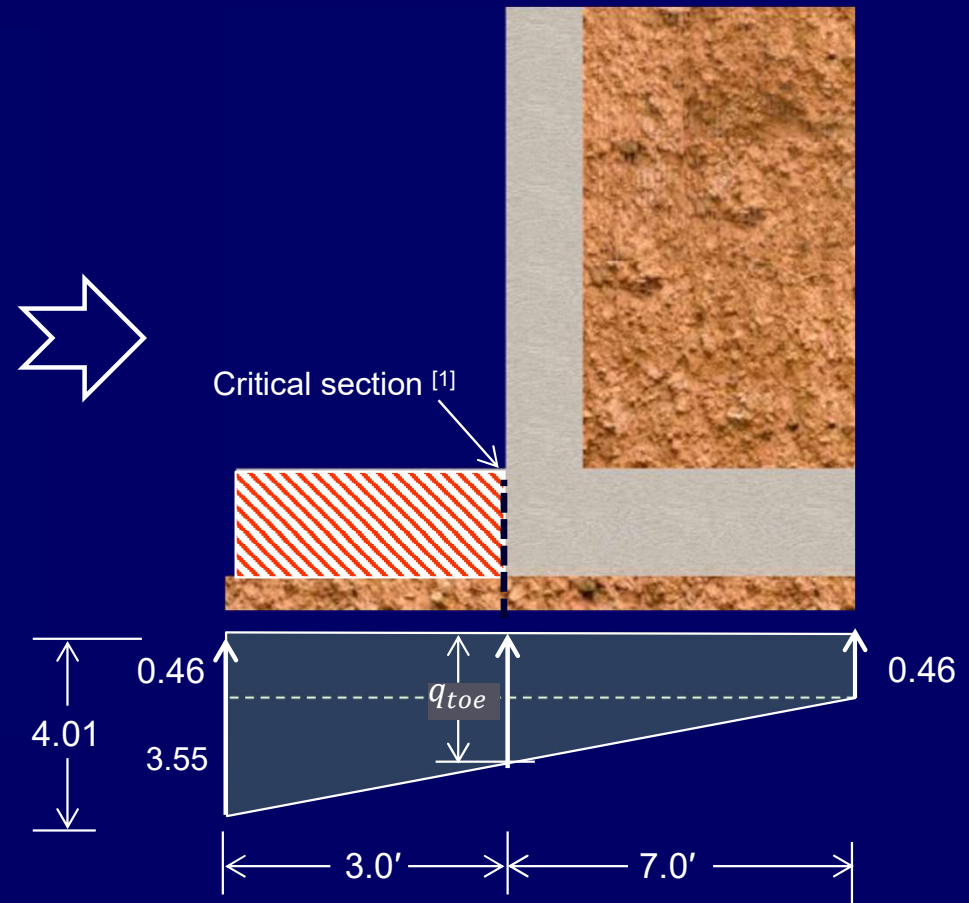
3.0′

$q_{toe} = ?$

$q_{min} = 0.29ksf$

$q_{max} = 2.51ksf$

Design Example

❑ **Solution**

➢ **Step 8: Analysis and Design of Toe**

❑ **Loads**

Toe

$q_{max,u} = 4.01$ $q_{min,u} = 0.46$

Critical section [1]

0.46 q_{toe} 0.46

4.01

3.55

|← 3.0' →|← 7.0' →|

Note:

[1] Although the ACI Code recommends taking the critical section of the toe at a distance of d from the face of support, here we chose to take the critical section at the interface to make the case simple.

Design Example

❑ Solution

➢ **Step 8: Analysis and Design of Toe**

❑ **Loads**

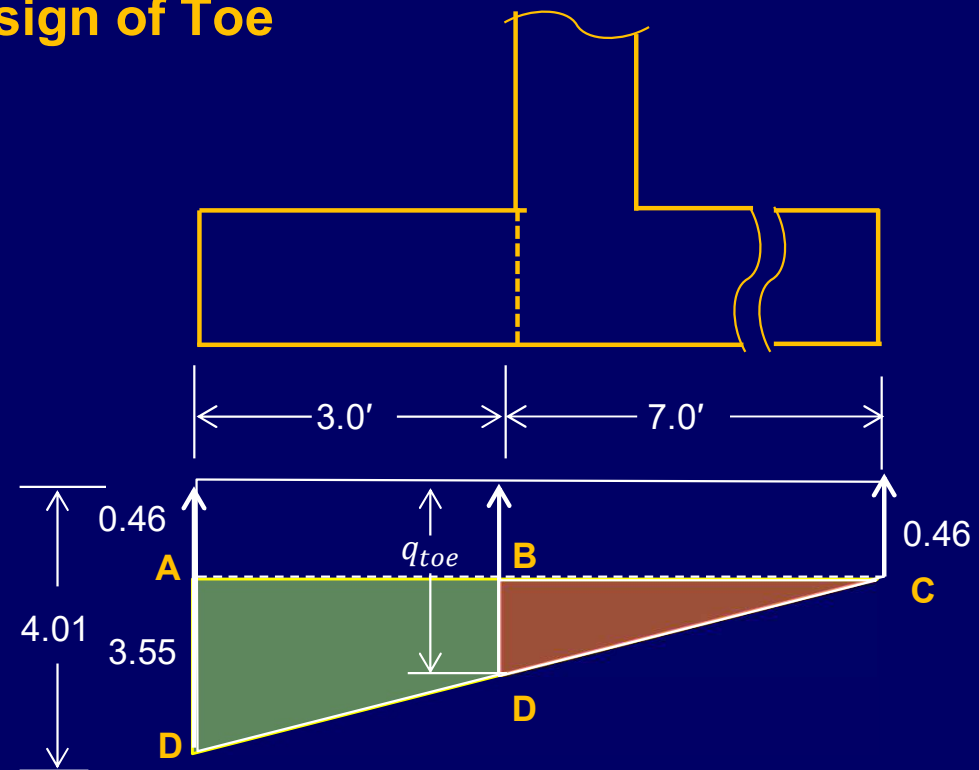From $\Delta ACD \Leftrightarrow \Delta BDC$

$$\frac{BD}{AD} = \frac{BC}{AC}$$

$$\frac{BD}{3.55} = \frac{7}{10}$$

$$BD = 2.48'$$

Now,

$$q_{toe} = 0.46 + 2.48 = 2.94 ksf$$

Design Example

❑ Solution

➢ **Step 8: Analysis and Design of Toe**

❑ **Analysis for Shear**

$$V_u = W_u = Area\ of\ shaded\ region$$
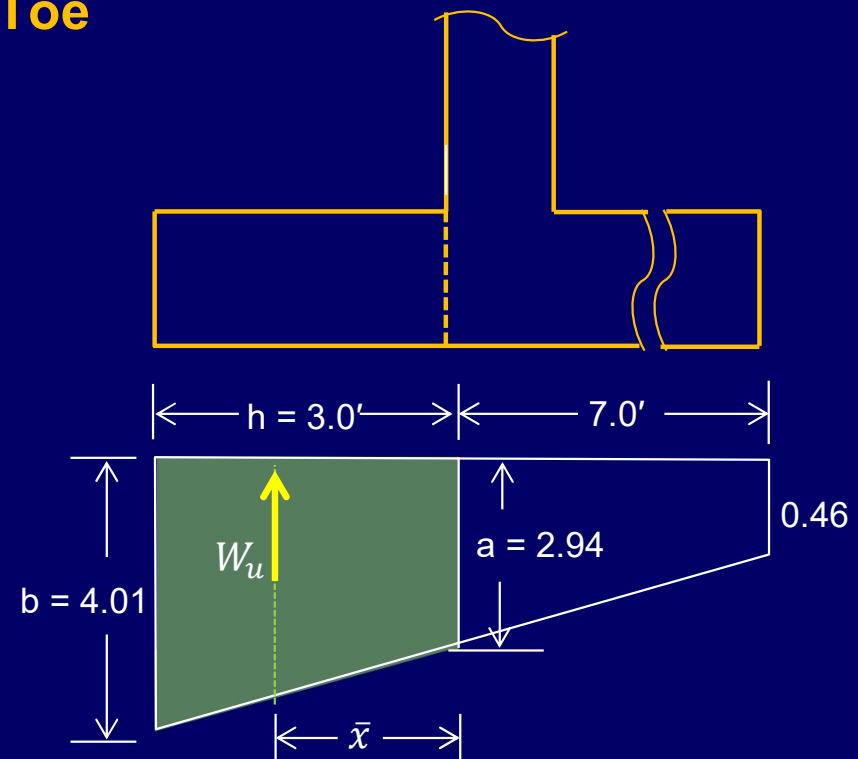
$$V_u = \frac{4.01 + 2.94}{2} \times 3 = 10.42 kips$$

❑ **Analysis for flexure**

$$M_u = W_u \times \bar{x} = 10.42\bar{x}$$

From figure, $\bar{x} = 1.58'$

So, $M_u = 10.42 \times 1.58 = 16.46\ kip.ft/ft$

$$\bar{x} = \frac{h}{3}\left(\frac{a+2b}{a+b}\right)$$

Design Example

❑ Solution

➢ **Step 8: Analysis and Design of Toe**

❑ **Design for Shear**

From Shear force diagram we have V_u = 10.42 kips

Design shear capacity of concrete is given as:

$$\emptyset V_c = \emptyset 2\sqrt{f_c'}\,bd = 0.75 \times 2\sqrt{4500} \times 12 \times 17.63 = 21.29\ kips$$

$$\emptyset V_c > V_u \Rightarrow OK!$$

Design Example

❑ **Solution**

➢ **Step 8: Analysis and Design of Toe**

❑ **Design for Flexure**

M_u = 16.46x 12 = 197.52 in-k/ft

$$A_{s,min} = 0.0018bh = 0.0018(12 \times 21) = 0.454 in^2$$

$$\emptyset M_n = 0.9 \times 0.454 \times 60 \left(17.63 - \frac{0.593}{2} \right) = 424.95 in.k/ft > M_u$$

Therefore. A_{min} governs. Now using #6 bar, spacing = 11.63″c/c

Maximum spacing for main steel reinforcement is:

● 3h = 3 x 21 = 63″ ; 18″ => OK! Hence, finally provide #6 @ 10″ c/c

Design Example

❑ Solution
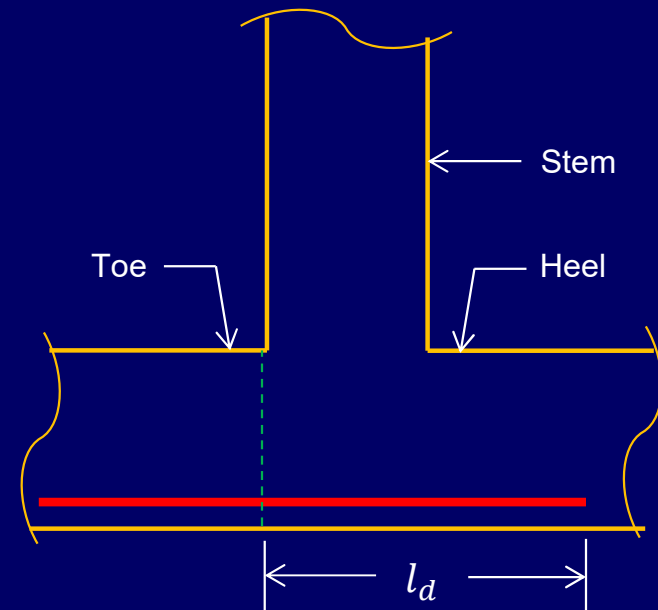
➢ **Step 8: Analysis and Design of Toe**

❑ **Calculation of development length**

Development length of Toe reinforcement into heel as per ACI 318-19, section 25.4.2.4 is given by

$$l_d = \frac{0.039 f_y}{\sqrt{f_c'}} d_b$$

$$l_d = \frac{0.039(60000)}{\sqrt{4500}}(0.75) = 26.16" \approx 27"$$
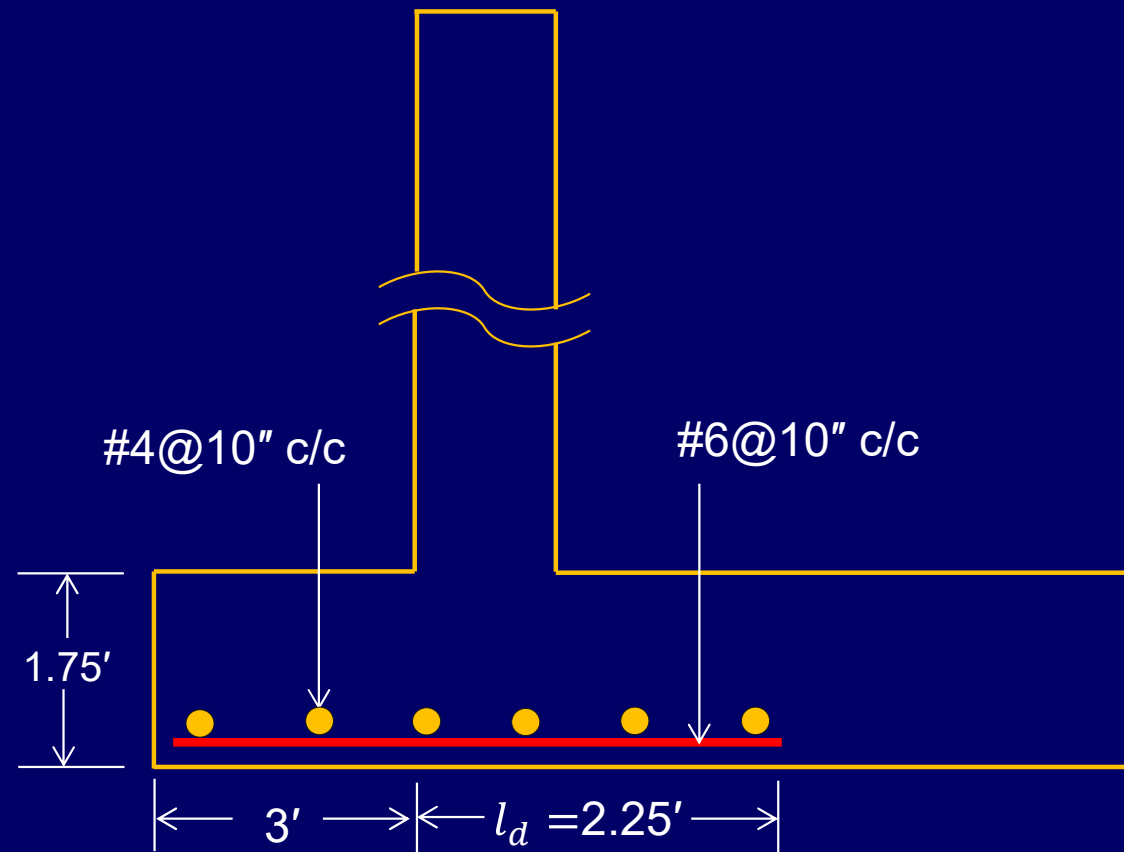
Therefore, $l_d = 2.25'$

Stem

Toe   Heel

l_d

Design Example

□ **Solution**

➢ **Step 8: Analysis and Design of Toe**

□ **Drafting**

#4@10″ c/c   #6@10″ c/c
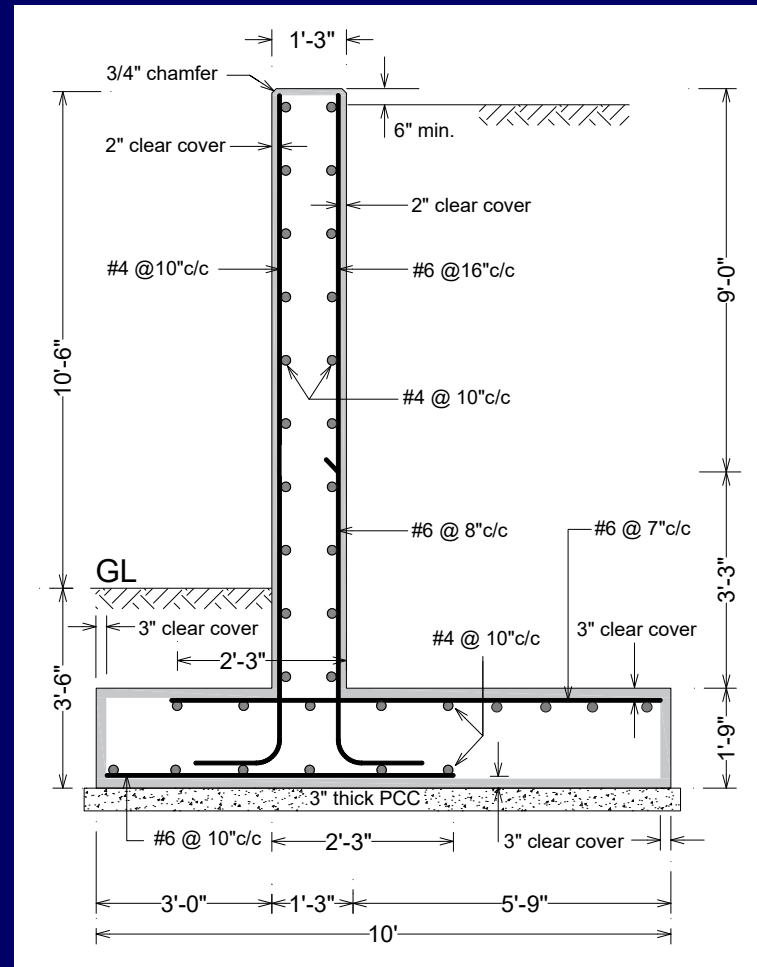
1.75′

3′ l_d =2.25′
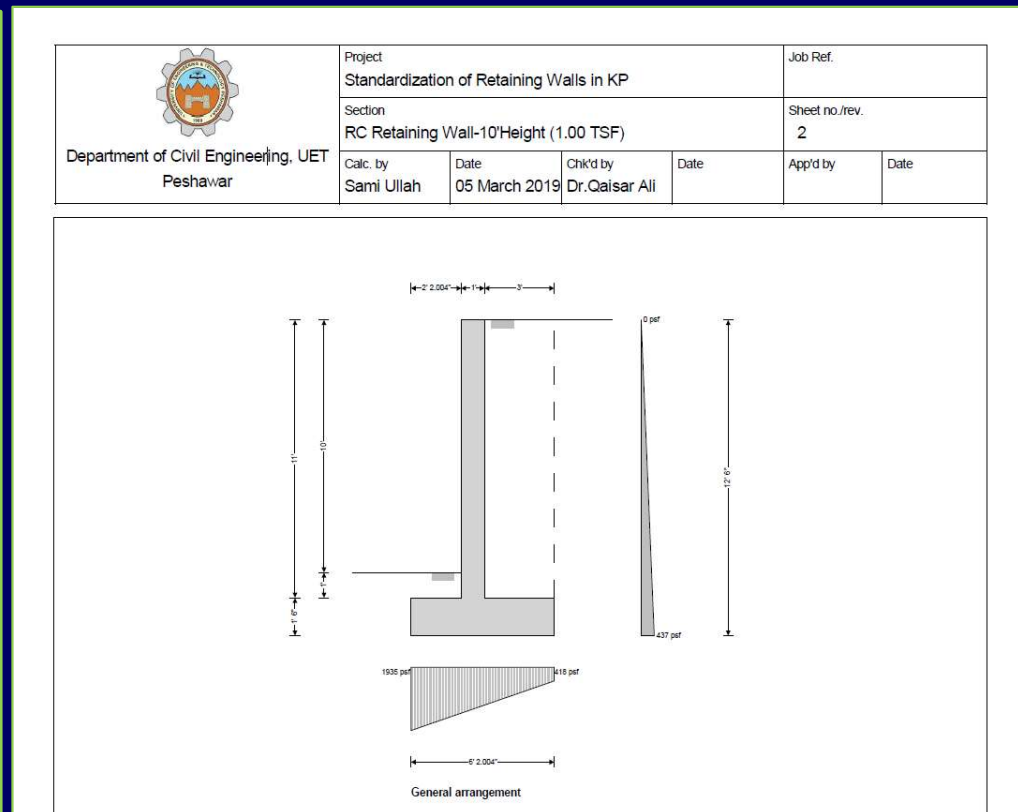
Design Example

❑ **Solution**

➢ **Step 9: Drafting**

Practical Design Examples

❑ **Tekla Tedds for Analysis and Design of RC Cantilever Retaining Wall**

Practical Design Examples

❑ **Modular Design of RC Retaining Walls**

Height (ft)	Bearing Capacity (Ton/sft)	Drawing
10	1.00	RW-H10-BC1.00
10	1.50	RW-H10-BC1.50
20	1.00	RW-H20-BC1.00
20	1.50	RW-H20-BC1.50
25	1.00	RW-H25-BC1.00
25	1.50	RW-H25-BC1.50

Various failures of Retaining wall at Nathia Gali

Practical Design Examples

❑ **Pictures of Retaining Wall Construction**

Practical Design Examples

❑ **Pictures of Retaining Wall Construction**

References

- ACI Reinforced Concrete Design Handbook (Volume: 2)_Special Topics, MNL - 17(21)

- Building Code Requirements for Structural Concrete (ACI 318-19)