Design of Heel Slab:

The heel slab design is similar to that of the stem. In the heel slab the downward load is due to the weight of soil and self weight and upward reaction is due to soil reaction. The net load acts downwards.

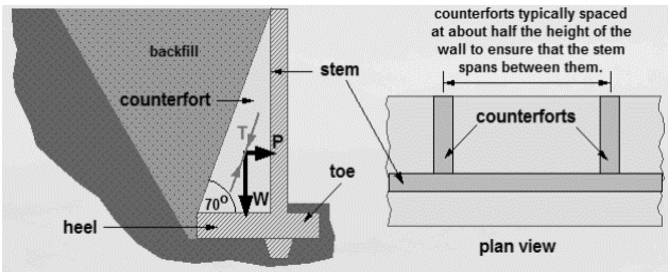
The - ve bending moment will occur nearer to Counterfort = $(pl^2)/12$

The +ve bending moment will occur nearer to Counterfort = $(pl^2)/16$

Where 'p' is the net downward pressure per unit area.

Design of Counterfort:

1) Spacing of Counterfort:
   Spacing of counterfort depends on various factors such as height of retaining wall, cost of steel and concrete, allowable soil pressure and cost of frame work. Keeping the spacing between counterfort closer, reduces the thickness of vertical slab and heel slab. However the quantity of concrete, steel and cost of form work increases. Thus the best spacing is one which design is economical spacing of counterfort varies from 0.3H to 0.6H, where H is the height of retaining wall.



2) Counterfort size and Reinforcement:
   Counterfort acts as a cantilever beam. They are designed considering a load from the stem portion between the adjacent counterforts. The distance between the points B and B' is considered as an effective depth of counterfort (d_1).
   The stem and the counterfort are subjected to active earth pressure making a tendency to move out. This causes a tension on the inclined side of the counterfort. Thus the main steel provided on the inclined side. The section has to be checked for shear and anchorage. In order to connect the counterfort with the base slab vertical two legged

stirrups are provided. Similarly to hold the stem and the counter fort, horizontal two legged stirrups are provided. These stirrups are under tension.

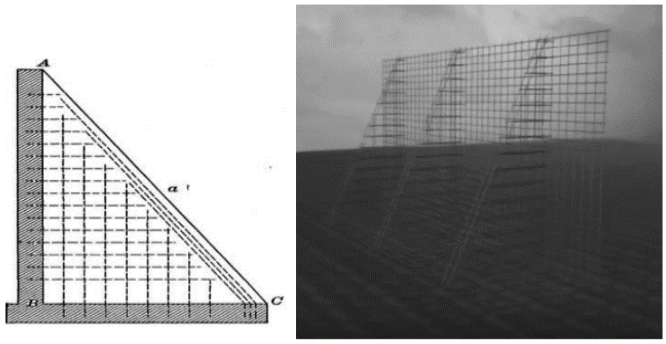


Fig: Reinforcement details of Counterfort walls.

Note:
We can also use an expression to get an idea clear span of counterfort (l)

$$l = 3.5(H/\gamma)^{0.25}$$

l = clear spacing between two counterfort
H = Total height of a retaining wall
γ = Unit wt. of soil/ backfill

1) **Design a counterfort type retaining wall by using the following data**

Height of the backfill above groundlevel = 6m

SBC of soil (q_0) = 160 KN/m^2

Angle of repose of soil (Φ) = 30^o

Unit weight of Soil (γ) = 16 KN/m^3

Friction coefficient between counterfort and soil μ = 0.5

Use M20 grade concrete and Fe 415 Steel

Solution :

Step 1: Minimum Depth of foundation

$$Y_{min} = \frac{q0}{\gamma}((1 - \sin\Phi)/(1 + \sin\Phi))^2$$

$$Y_{min} = 160/16\ ((1\text{-}\sin 30)/(1+\sin 30))^2$$

$$= 1.11 \text{ m}$$

∴ Provide a minimum depth of foundation as 1.2 m

∴ Total height of retaining structure $= 6 + 1.2$

$$= 7.2\ m$$

Step 2: Width of base slab

$$b = 0.6H$$

$$= 0.6 \times 7.2$$

$$= 4.32\ m$$

∴ Provide width of base slab as 4.5 m

Step 3: Width of toe slab

Width of toe slab = αb

$$\alpha = 1 - (\frac{q0}{2.2\ \gamma H})$$

$$= 1\text{-}(160/(2.2 \times 16 \times 7.2)$$

$$\alpha = 0.368$$

∴ ∝b= 0.368 x 4.5

$$= 1.656 \text{ m}$$

∴ Provide the toe slab as 1.5 m

Assume thickness of stem as 200 mm and thickness of heel slab as 450 mm

Note: Last two assumptions are made from the reference of cantilever retaining wall.

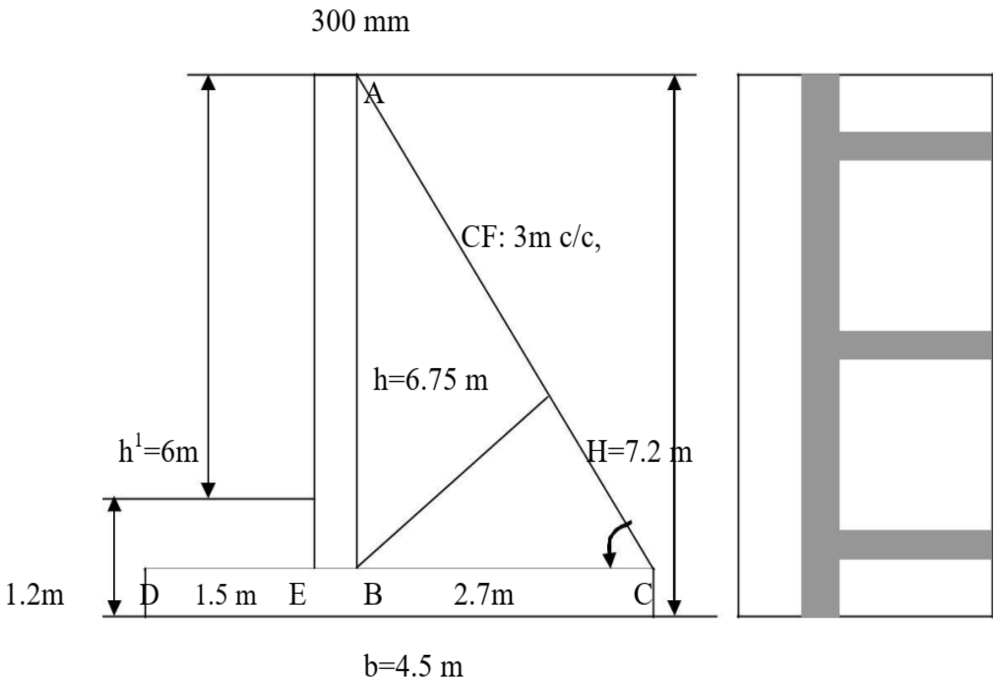
Height of the stem (H1) =Total height (H) – Thickness of base slab

$$H1 = 7.2 - 0.45$$

$$H1 = 6.75m$$

Width of heel slab $= 4.5 - 1.5 - 0.3$

$= 2.7\ m$



Check for stability

Let us assume

W1 = weight of stem / m length

W2 = weight of base slab / m length

W3 = weight of soil on heel slab / m length

Weights	Force (KN / m length)	Distance from D to location of force (m)	Moment of Resistance (M_R) KN- m
W1	0.3 x 6.75 x 1 x 25) = 50.625	$(1.5 + 0.15) = 1.65$	50.625 x 1.65 = 83.531
W2	4.5 x 0.45 x 1 x 25 = 50.625	$(4.5 / 2) = 2.25$	50.625 x 2.25 = 113.906
W3	2.7 x 6.75 x 1 x 16 = 291.6	$1.5 + 0.3 + (2.7/2) = 3.15$	291.6 x 3.15 = 918.54
	$\sum W = 392.85$		**$\sum M_R = 1115.97$**

$\therefore$ Total resisting moment $\sum M_R = 1115.97$ KN.m

Horizontal earth pressure, $P_H = K_a \alpha \left(\frac{H^2}{2}\right)$

$= 0.333 \times 16 \times (7.2^2/2)$

$P_H = 138.102\ KN$

Overturning moment (M_o) = $P_H \times \left(\frac{H}{3}\right)$
(Moment about at Point B)

$= 138.102 \times \frac{7.2}{3}$

$M_o = 331.444$ KN.m

Factor of safety against overturning

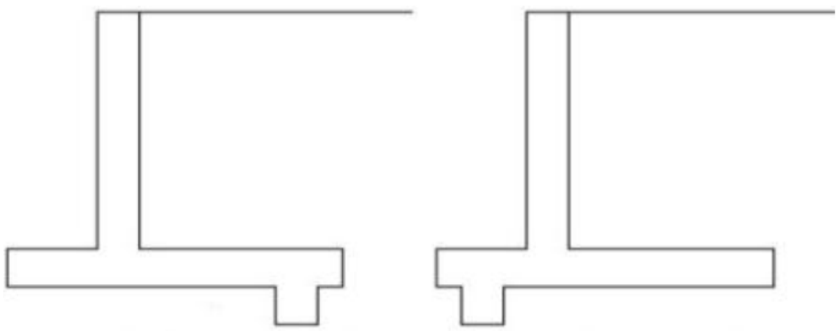
$= (\sum M_R)/ M0 = \frac{1115.977}{331.444} = 3.367 > 2$

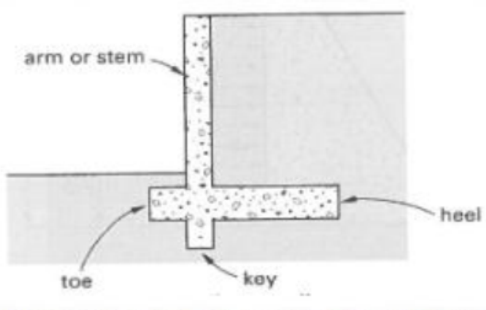
$\therefore$ Safe in overturning

Resisting force = $\sum \mu.W = 0.5 \times 392.85 = 196.425$kN

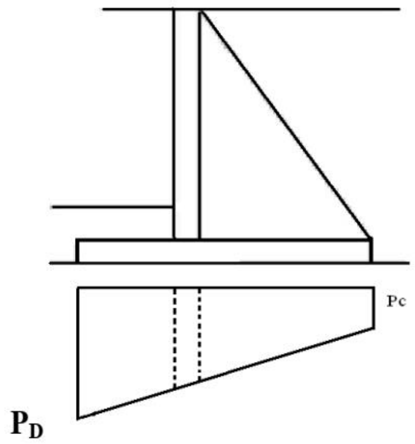
Factor of safety against sliding = $\sum \mu.W$ / PH = 196.425/138.102 = 1.422 < 1.5

$\therefore$ It's not safe against sliding, therefore need to provide shear Key.





Different locations of shear key in retaining wall



Pressure distribution at base

Net moment = M = 1115.977 -531.444 = 784.533kN.m.

Let x be the distance from the toe where the resultant R acts,

x = M / ∑W = 784.533/392.85 = 1.997 m

Eccentricity = e = b/2 - x = 4.5/2 – 1.997 = 0.253 < b/6 (= 0.75 m) Whole base is under compression.

Maximum pressure at toe

= P_D = ∑W / b (1+(6e/b))

= 392.85/4.5 (1+ 6 x 0.253/4.5)

= 116.749 kN/m^2

Minimum Pressure at heel

= P_B = ∑W / b (1- (6e/b))

= 57.851 kN/m^2

Design of Heel Slab:

For design of heel slab we need to calculate the spacing between counterforts. Because in the counterfort retaining wall, the bending moment on stem and heel slab is depends on this spacing only. The heel slab is designed as a continuous slab supported on counterforts. The downward force will be maximum at the edge of the slab where intensity of soil pressure is minimum.

∴ Clear span between counterforts $l = 3.5(H/\gamma)^{0.25}$

$= 2.866$ m

$\cong 3$ m

∴ Provide clear span between counterfort as 3 m and assume the thickness of counterfort as 0.3m

∴ An effective span between the counterfort $L = \left(\frac{0.3}{2}\right) + 3 + \left(\frac{0.3}{2}\right)$

$L = 3.3$ m

Note: In Case of Cantilever retaining wall, we considered the total self weight of soil / backfill on a heel slab. But in the case of counterfort retaining wall, due to the presence of counterfort on heel slab consider 1 m strip for design.

Therefore consider 1 m strip at a Point C

At point C

Self weight of heel Slab $= 0.425 \times 25 = 11.25$ kN/m² (↓)

Self weight of backfill in 1m strip at point C $= 6.75 \times 16 = 108$ kN/m² (↓)

Upward soil reaction at C $= 57.185$ kN/m² (↑)

Total Pressure intensity at point C $= 11.25 + 108 - 57.185$

$W_c = 62.065$ kN/m²

Factored Load $= 1.5 \times 62.065$

$W_u = 93.0975$ kN/m²

Maximum Negative moment (M_1) in heel Slab

Moment at Support, (M_1) $= (W_u l^2)/12$

$= (93.0975 \times 3.3^2)/12$

$= 84.486$ kN-m

Maximum Positive moment (M_2) in heel Slab

Moment at Span, (M_2) $= (W_u l^2)/16$

$= (93.0975 \times 3.3^2)/16$

$= 63.364$ kN-m

Note: Compared to positive span moment, the negative moment is greater in heel slab. There depth has to be increased for higher moment.

$M_1 = 0.138\ f_{ck}\ bd^2$

$84.486 \times 10^6 = 0.138 \times 20 \times 1000 \times d^2$

$d = 175$ mm

Base on Shear the effective depth has to be calculated. Whichever'd' is greater has to be taken into consideration.

Shear Force (v) per unit width in Heel Slab

$V_u = W_u l/2$

$= (93.0975 \times 3.3) / 2$

$= 153.611$ KN

Effective depth calculation in heel slab based on shear

$\tau_c = \frac{V_u}{b\,d}$ Note $\tau_v = \tau_c$

For under reinforced section assume p_t = 0.5%, from table 19 of IS 456:2000, for M_{20} grade concrete $\tau_c = 0.48 N/mm^2$

$\therefore d = 320$ mm

Note: Based on the moment calculation the effective depth is 175mm and based on shear it is 320 mm. if we provide 175mm the structure is safe in bending and weak in shear. But if we provide 320 mm its safe in both shear and bending.

Assume a clear cover of 60mm and 12 mm diameter

Total depth of heel slab (D) = 320 + 60 + (12/2)

= 386 mm

∴ Provide a total depth of heel slab of 400 mm.

Effective depth for 400 mm depth = 400 – 60 - (12/2)

= 334 mm

∴ Provide a total depth of heel slab of 400 mm and effective depth of 334 mm

A_{st} calculation for support and span moments in heel slab

A_{st1} amount of steel reinforcement at Support

A_{st2} amount of steel reinforcement at Span

Calculation for tension reinforcement at support (A_{st1})

$$M_1 = 0\ .87\ f_y\ A_{st}\ d\ \frac{(1 - f_y\ A_{st})}{(fck\ b\ d)}$$

$$= 734.628\ mm^2$$

Assume 12 mm Ø bar

$$\text{Spacing of a bar} = \pi \frac{x\ (\ (12)^2 / 4)}{734.628}\ x\ 1000$$

$$= 153.952\ mm$$

$$A_{st\ provi} = \pi \frac{x\ (\ (12)^2 / 4)}{150}\ x\ 1000$$

∴ Provide 12 mm Ø bar with 150 mm c/c, $A_{st\ provi} = 753.982\ mm^2$

Calculation of tension reinforcement for span moment (A_{st2})

Maximum positive moment (M_e) = $(W_u l^{2)}/16 = (3/4)\ A_{st1}$

$(A_{st2}) = (3/4)\ A_{st1}$

$= 565.487\ mm^2$

Assume 12 mm Ø bar

$$\text{Spacing of a bar} = \pi \frac{x\ (\ (12)^2 / 4)}{565.487}\ x\ 1000$$

$$= 200\ mm$$

∴ Provide 12 mm Ø bar with 200 mm c/c spacing

Calculation of minimum reinforcement

$A_{st} = 0.12\%\ bd$

$= (0.12/100)\ x\ 1000\ x\ 400$

$A_{st} = 480\ mm^2$

Assume 8 mm Ø bar

∴ Spacing between distribution bars = $\pi \frac{x((8)^2/4)}{480}$ x 1000

= 100 mm

∴ Provide 8 mm Ø bar with 100 mm c/c on both top and bottom of heel slab.

Design of Counterfort:

We can design a counterfort as a cantilever beam or beam with varying depth or Tee beam.

Here we consider to design a counterfort as beam with varying depth.

Beam with varying depth

$\tau_v = \frac{V_u \pm (Mu/d)\tan\beta}{b\,d}$, where β angle between the top and bottom edges of the beam.

Note: The negative sign in the formula applies when the bending moment M_u increases numerically in the same direction as an effective depth is increased and the positive sign when the moment decreases numerically in this direction.

$\tau_v = \frac{V_u - (Mu/d)\tan\beta}{b\,d}$ this is our case since increasing moment in the direction of increasing effective depth.

∴ Shear force due to lateral soil pressure at P_B =½(k_a.γ.H_1)H_1 x l

Where H_1 - height of stem, l - span between two counterforts

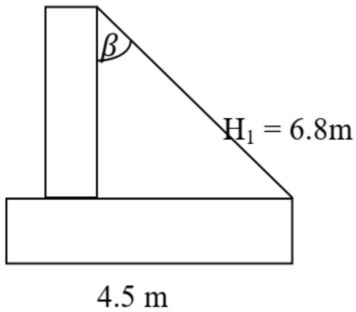
Shear force due to lateral soil pressure at P_B = ½(k_a.γ.H_1)H_1 x l

= ½(0.333 x 16 x 6.8)6.8 x 3.3

V = 406.505 KN

Factored shear force = V_u = 1.5 x 406.505

= 609.758 KN



Bending moment at point B (M_u) = V_u x (H_1/3)

M_u = 1382.11 KN.m

Effective depth calculation based on moment

$M_u = 0.138\ f_{ck}\ bd^2$

$1382.117 \times 10^6 = 0.138 \times 20 \times 300 \times d^2$

d = 1292.155 mm

Effective depth calculation based on shear

$V_u = 609.758KN$; $M_u = 1382.117$ KN

$$\tau_v = \frac{V_u - (Mu/d)\tan\beta}{b\ d}$$

Note $\tau_v = \tau_c$

Let us assume $P_t = 0.5\ \%$, $\therefore \tau_c = 0.48\ N/mm^2$

$\tan \beta = (2.7/\ 6.8)$

$\beta = 21.656$

$$0.48 = \frac{609.758 \times 10^3 - \frac{(1382.11 \times 10^6)}{d} \times 0.397}{300 \times d}$$

d = 1297 mm

Total depth of counterfort at its base (D) = 2.7 m

$\therefore$ D= 2700mm

Assume clear cover 60mm and 12mm dia bar.

$\therefore d_{avi}$ = 2700-60-(12/2)

= 2634 mm

$d_{avi} > d_{req}$ for both cases (shear and moment). Hence this structure is safe.

A_{st} calculation in counterfort

$$M_u = 0.87\ f_y A_{st}\ d \cos\beta \ \frac{(1 - f_y A_{st})}{(fck\ b\ d)}$$

$A_{st} = 1634.928mm^2$

Provide 16mm dia bar

∴ No.of bars = 1634.928 /($(\pi/4)$x 16^2) = 8 No.s

∴ Provide 4 no. of 16 mm dia bar + 4 no. of 16 mm dia bar

Spacing of bars = $\frac{(\pi/4) \times 16^2}{4\ (\pi/4) \times 16^2}$ x 1000 = 250 mm c/c

∴ Provide 2 layers of 16 mm dia bar with 250 mm c/c

Lecture 09

REFERENCE:

1. Steel Water Storage Tanks: Design, Construction, Maintenance, and Repair 1st Edition, Kindle Edition by Steve Meier, American Water Works Association.

2. Elementary Structural Design & Drawing (In 3 Vols.) Vol. I: Structural Design & Drawing Kindle Edition by D. Krishnamurthy (Author) Format: Kindle Edition

3. Structural Design & Drawing-Vol. 3 [Print Replica] Kindle Edition by D. Krishnamurthy (Author) Format: Kindle Edition

4. The Dock Manual: Designing/Building/MaintainingJan 4, 1999 by Max Burns

5. Designing Steel Structures for Fire SafetyMay 6, 2009 by Jean Marc Franssen and Venkatesh Kodur

6. Reference Book: Design of Steel Structures by S K Duggal