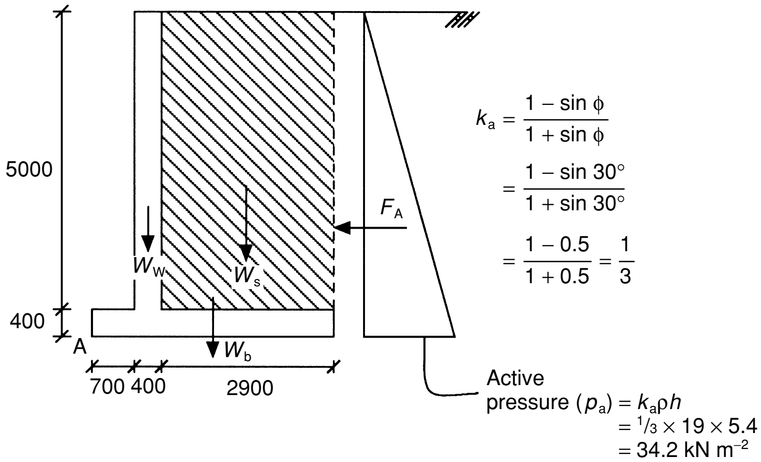
Example 3.16 Design of a cantilever retaining wall (BS 8110)

The cantilever retaining wall shown below is backfilled with granular material having a unit weight, ρ, of 19 kNm^{-3} and an internal angle of friction, ϕ, of 30°. Assuming that the allowable bearing pressure of the soil is 120 kNm^{-2}, the coefficient of friction is 0.4 and the unit weight of reinforced concrete is 24 kNm^{-3}

1. Determine the factors of safety against sliding and overturning.
2. Calculate ground bearing pressures.
3. Design the wall and base reinforcement assuming f_{cu} = 35 kNm^{-2}, f_y = 500 kNm^{-2} and the cover to reinforcement in the wall and base are, respectively, 35 mm and 50 mm.



SLIDING

Consider the forces acting on a 1 m length of wall. Horizontal force on wall due to backfill, F_A, is

$$F_A = 0.5 p_a h = 0.5 \times 34.2 \times 5.4 = 92.34 \text{ kN}$$

and

Weight of wall (W_w)	$= 0.4 \times 5 \times 24 = 48.0$ kN
Weight of base (W_b)	$= 0.4 \times 4 \times 24 = 38.4$ kN
Weight of soil (W_s)	$= 2.9 \times 5 \times 19 = 275.5$ kN
Total vertical force (W_t)	$= 361.9$ kN

Friction force, F_F, is

$$F_F = \mu W_t = 0.4 \times 361.9 = 144.76 \text{ kN}$$

Assume passive pressure force (F_P) = 0. Hence factor of safety against sliding is

$$\frac{144.76}{92.34} = 1.56 > 1.5 \quad \text{OK}$$

OVERTURNING

Taking moments about point A (see above), sum of overturning moments (M_{over}) is

$$\frac{F_A \times 5.4}{3} = \frac{92.34 \times 5.4}{3} = 166.2 \text{ kNm}$$

Example 3.16 *continued*

Sum of restoring moments (M_{res}) is

$$M_{res} = W_w \times 0.9 + W_b \times 2 + W_s \times 2.55$$
$$= 48 \times 0.9 + 38.4 \times 2 + 275.5 \times 2.55 = 822.5 \text{ kNm}$$

Factor of safety against overturning is

$$\frac{822.5}{166.2} = 4.9 > 2.0 \quad \text{OK}$$

GROUND BEARING PRESSURE

Moment about centre line of base (M) is

$$M = \frac{F_A \times 5.4}{3} + W_W \times 1.1 - W_S \times 0.55$$
$$= \frac{92.34 \times 5.4}{3} + 48 \times 1.1 - 275.5 \times 0.55 = 67.5 \text{ kNm}$$
$$N = 361.9 \text{ kN}$$
$$\frac{M}{N} = \frac{67.5}{361.9} = 0.187\ m < \frac{D}{6} = \frac{4}{6} = 0.666 \text{ m}$$

Therefore, the maximum ground pressure occurs at the toe, p_{toe}, which is given by

$$p_{toe} = \frac{361.9}{4} + \frac{6 \times 67.5}{4^2} = 116 \text{ kNm}^{-2} < \text{allowable } (120 \text{ kNm}^{-2})$$

Ground bearing pressure at the heel, p_{heel}, is

$$p_{heel} = \frac{361.9}{4} - \frac{6 \times 67.5}{4^2} = 65 \text{ kNm}^{-2}$$

BENDING REINFORCEMENT

Wall

Height of stem of wall, h_s = 5 m. Horizontal force on stem due to backfill, F_s, is

$$F_s = 0.5 k_a \rho h_s^2$$
$$= 0.5 \times {}^1/_3 \times 19 \times 5^2$$
$$= 79.17 \text{ kNm}^{-1} \text{ width}$$

Design moment at base of wall, M, is

$$M = \frac{\gamma_f F_s h_s}{3} = \frac{1.4 \times 79.17 \times 5}{3} = 184.7 \text{ kNm}$$

Effective depth

Assume diameter of main steel (Φ) = 20 mm.
Hence effective depth, d, is

$$d = 400 - \text{cover} - \Phi/2 = 400 - 35 - 20/2 = 355 \text{ mm}$$

Ultimate moment of resistance

$$M_u = 0.156 f_{cu} b d^2 = 0.156 \times 35 \times 10^3 \times 355^2 \times 10^{-6} = 688 \text{ kNm}$$

Since $M_u > M$, no compression reinforcement is required.

Example 3.16 *continued*

Steel area

$$K = \frac{M}{f_{cu}bd^2} = \frac{184.7 \times 10^6}{35 \times 10^3 \times 355^2} = 0.0419$$

$$z = d[0.5 + \sqrt{(0.25 - K/0.9)}]$$

$$= 355[0.5 + \sqrt{(0.25 - 0.0419/0.9)}] = 337 \text{ mm}$$

$$A_s = \frac{M}{0.87f_y z} = \frac{184.7 \times 10^6}{0.87 \times 500 \times 337} = 1260 \text{ mm}^2/\text{m}$$

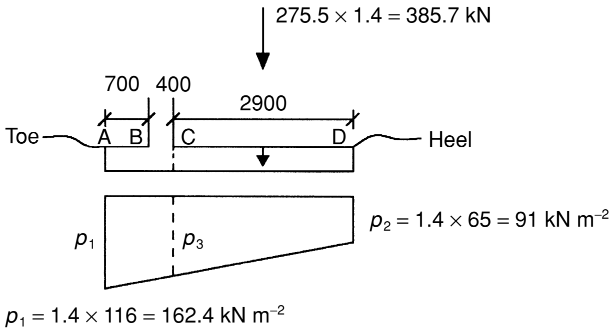
Hence from *Table 3.22*, provide H20 at 200 mm centres (A_s = 1570 mm^2/m) in near face (NF) of wall. Steel is also required in the front face (FF) of wall in order to prevent excessive cracking. This is based on the minimum steel area, i.e.

$$= 0.13\%bh = 0.13\% \times 10^3 \times 400 = 520 \text{ mm}^2/\text{m}$$

Hence, provide H12 at 200 centres (A_s = 566 mm^2)

Base

Heel



$$p_3 = 91 + \frac{2.9(162.4 - 91)}{4} = 142.8 \text{ kNm}^{-2}$$

Design moment at point *C*, M_c, is

$$\frac{385.7 \times 2.9}{2} + \frac{2.9 \times 38.4 \times 1.4 \times 1.45}{4} - \frac{91 \times 2.9^2}{2} - \frac{51.8 \times 2.9 \times 2.9}{2 \times 3} = 160.5 \text{ kNm}$$

Assuming diameter of main steel (Φ) = 20 mm and cover to reinforcement is 50 mm, effective depth, *d*, is

$$d = 400 - 50 - 20/2 = 340 \text{ mm}$$

$$K = \frac{160.5 \times 10^6}{35 \times 10^3 \times 340^2} = 0.0397$$

$$z = 340[0.5 + \sqrt{(0.25 - 0.0397/0.9)}] \le 0.95d = 323 \text{ mm}$$

$$A_s = \frac{M}{0.87f_y z} = \frac{160.5 \times 10^6}{0.87 \times 500 \times 323} = 1142 \text{ mm}^2/\text{m}$$

Hence from *Table 3.22*, provide H20 at 200 mm centres (A_s = 1570 mm^2/m) in top face (T) of base.

Example 3.16 *continued*

Toe

Design moment at point *B*, M_B, is given by

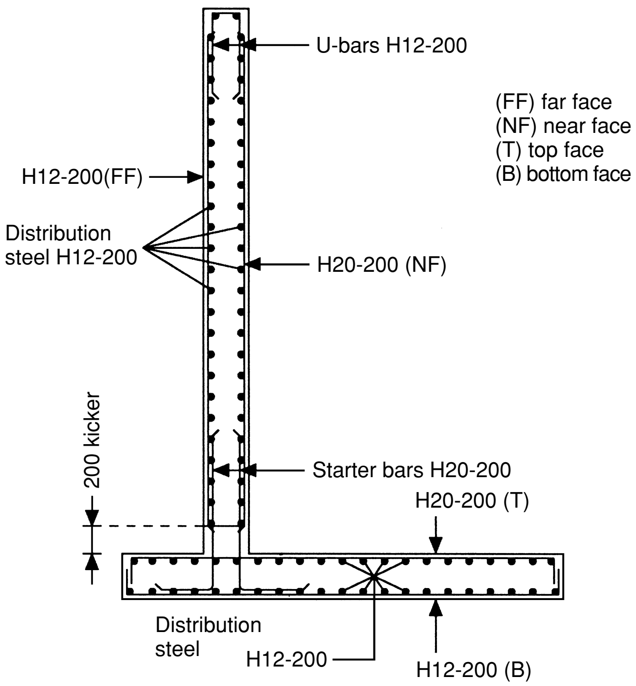
$$M_B \approx \frac{162.4 \times 0.7^2}{2} - \frac{0.7 \times 38.4 \times 1.4 \times 0.7}{4 \times 2} = 36.5 \text{ kNm}$$

$$A_s = \frac{36.5 \times 1142}{160.5} = 260 \text{ mm}^2/\text{m} < \text{minimum steel area} = 520 \text{ mm}^2/\text{m}$$

Hence provide H12 at 200 mm centres (A_s = 566 mm^2/m), in bottom face (B) of base and as distribution steel in base and stem of wall.

REINFORCEMENT DETAILS

The sketch below shows the main reinforcement requirements for the retaining wall. For reasons of buildability the actual reinforcement details may well be slightly different.



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GEOMETRY

Conc. Stem Height	**5.00**	m	
Stem Thickness Top	**40.0**	cm	
Stem Thickness Bot	**40.0**	cm	
Footing Thickness	**40.0**	m	
Toe Length	**0.70**	m	
Heel Length	**2.90**	m	
Soil Cover @ Toe	**0.00**	m	
Backfill Height	**5.00**	m	OK
Backfill Slope Angle	**0.0**	deg	

SEISMIC EARTH FORCES

Hor. Seismic Coeff. kh	**0.00**	
Ver. Seismic Coeff kv	**0.00**	
Seismic Active Coeff. Kae	0.30	
Seismic Force Pae-Pa	-8.8	KN/m

SOIL BEARING PRESSURES

Allow. Bearing Pressure ..	**120.0**	KPa	
Max. Pressure @ Toe	115.0	KPa	OK
Min. Pressure @ Heel	65.1	KPa	
Total Footing Length	4.00	m	
Footing Length / 6	0.67	m	
Resultant Eccentricity e ...	0.18	m	

Resultant is Within the Middle Third

APPLIED LOADS

Uniform Surcharge	**0.0**	KPa
Strip Pressure	**0.0**	KPa

Strip 0.6 m deep, 1.2 m wide @ 0.9 m from Stem

Stem Vertical (Dead)	**0.0**	KN/m
Stem Vertical (Live)	**0.0**	KN/m
Vertical Load Eccentricity	**15.2**	cm
Wind Load on Stem	**0.0**	KPa

BACKFILL PROPERTIES

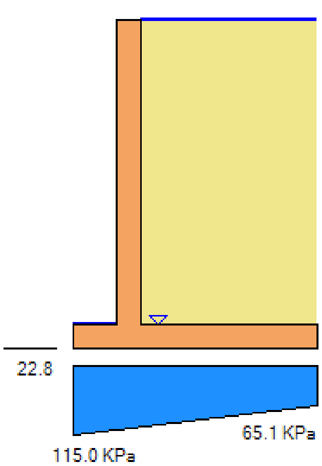
Backfill Density	**19.0**	KN/m³
Earth Pressure Theory	**Rankine Active**	
Internal Friction Angle	**30.0**	deg
Active Pressure Coeff. Ka	0.33	
Active Pressure @ Wall	6.3	KPa/m
Active Force @ Wall Pa	92.3	KN/m
Water Table Height	**0.00**	m

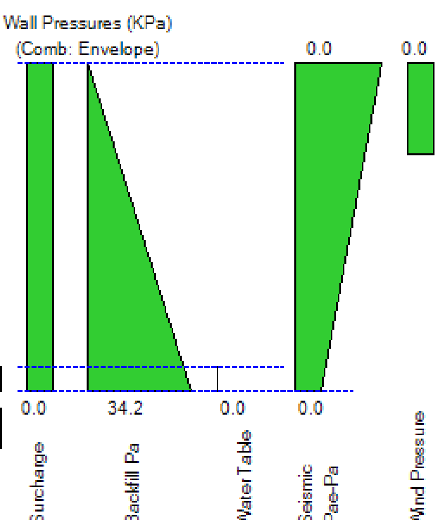
SHEAR KEY DESIGN

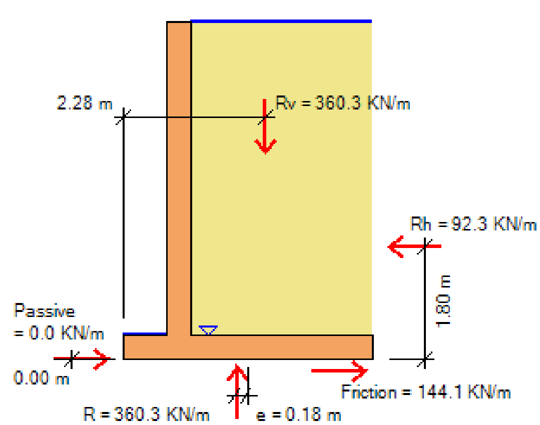
Shear Key Depth	**0.0**	cm
Shear Key Thickness	**0.0**	cm
Max. Shear Force @ Key ..	0.0	KN/m
Shear Capacity Ratio	0.00	OK

No shear key has been specified

Moment Capacity Ratio	0.00	OK







OVERTURNING CALCULATIONS (Comb. D+H+W)

OVERTURNING

	Force KN/m	Arm m	Moment KN-m/m
Backfill Pa	92.34	1.80	166.2
Water Table	0.00	0.13	0.0
Surcharge Hor	0.00	2.70	0.0
Strip Load Hor	0.00	2.50	0.0
Wind Load	0.00	4.64	0.0
Seismic Pae-Pa ...	0.00	3.24	0.0
Seismic Water	0.00	0.13	0.0
Seismic Selfweight	0.00	0.00	0.0
	Rh = 92.34		OTM = 166.2

RESISTING

	Force KN/m	Arm m	Moment KN-m/m
Stem Top	47.12	0.90	42.4
Stem Taper	0.00	1.10	0.0
CMU Stem at Top ..	0.00	0.00	0.0
Footing Weight	37.70	2.00	75.4
Shear Key	0.00	0.70	0.0
Soil Cover @ Toe .	0.00	0.35	0.0
Stem Wedge	0.00	1.10	0.0
Backfill Weight	275.50	2.55	702.5
Backfill Slope	0.00	3.03	0.0
Water Weight	0.00	2.55	0.0
Seismic Pae-Pa	0.00	4.00	0.0
Pa Vert @ Heel	0.00	4.00	0.0
Vertical Load	0.00	0.95	0.0
Surcharge Ver	0.00	2.55	0.0
Strip Load Ver	0.00	2.55	0.0
	Rv = 360.32		RM = 820.3

Arm of Horizontal Resultant = $\frac{166.2}{92.34}$ = 1.80 m

Arm of Vertical Resultant = $\frac{820.3}{360.32}$ = 2.28 m

Overturning Safety Factor = $\frac{820.3}{166.2}$ = 4.94 > 2 OK

STEM DESIGN (Comb. 0.9D+1.6H+E)

Height m	d cm	Mu KN-m/m	ϕMn KN-m/m	Ratio	
5.00	35.5	0.0	0.0	0.00	
4.50	35.5	0.2	112.8	0.00	
4.00	35.5	1.7	123.1	0.01	
3.50	35.5	5.7	123.1	0.05	
3.00	35.5	13.5	123.1	0.11	
2.50	35.5	26.4	123.1	0.21	
2.00	35.5	45.6	151.4	0.30	
1.50	35.5	72.4	241.6	0.30	
1.00	35.5	108.1	241.6	0.45	
0.50	35.5	153.9	241.6	0.64	
0.00	35.5	211.1	241.6	0.87	OK

Shear Force @ Crit. Height .. 117.7 KN/m OK

Resisting Shear ϕVc .... 261.5 KN/m

Use vertical bars D20 @ 20 cm at backfill side

Cut off alternate bars. Cut off length = 2.13 m

Vert. Bars Embed. Ldh Reqd .. 28.4 cm OK

Vert. Bars Splice Length Ld .... 54.6 cm

SLIDING CALCS (Comb. D+H+W)

Footing-Soil Friction Coeff. ..	0.40	
Friction Force at Base	144.1	KN/m
Passive Pressure Coeff. Kp .	3.00	
Depth to Neglect Passive	0.40	m
Passive Pressure @ Wall	Infinity	KPa/m
Passive Force @ Wall Pp	0.0	KN/m
Horiz. Resisting Force	144.1	KN/m
Horiz. Sliding Force	92.3	KN/m

Sliding Safety Factor = $\frac{144.1}{92.3}$ = 1.56 > 1.5 OK

LOAD COMBINATIONS (ASCE 7)

STABILITY	STRENGTH
① D+H+W	① 1.4D
② D+L+H+W	② 1.2D+1.6(L+H)
③ D+H+0.7E	③ 1.2D+0.8W
④ D+L+H+0.7E	④ 1.2D+L+1.6W
	⑤ 1.2D+L+E
	⑥ 0.9D+1.6H+1.6W
	⑦ 0.9D+1.6H+E

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HEEL DESIGN (Comb. 0.9D+1.6H+E)

	Force KN/m	Arm m	Moment KN-m/m
Upward Pressure .	-182.4	1.08	197.3
Concrete Weight ..	24.6	1.45	35.7
Backfill Weight	248.0	1.45	359.5
Backfill Slope	0.0	1.93	0.0
Water Weight	0.0	1.45	0.0
Surcharge Ver.	0.0	1.45	0.0
Strip Load Ver.	0.0	1.45	0.0
	90.1	Mu =	197.9

Shear Force @ Crit. Sect. ..	93.7	KN/m	OK
Resisting Shear ϕVc	249.7	KN/m	

Use top bars D20 @ 20 cm , Transv. D12 @ 20 cm

Resisting Moment ϕMn	230.3	KN-m/m	OK
Develop. Length Ratio at End	0.19		OK
Develop. Length Ratio at Toe	0.52		OK

TOE DESIGN (Comb. 1.2D+1.6(L+H))

	Force KN/m	Arm m	Moment KN-m/m
Upward Presssure	107.4	0.36	38.4
Concrete Weight ..	-7.9	0.35	-2.8
Soil Cover	0.0	0.35	0.0
	99.4	Mu =	35.6

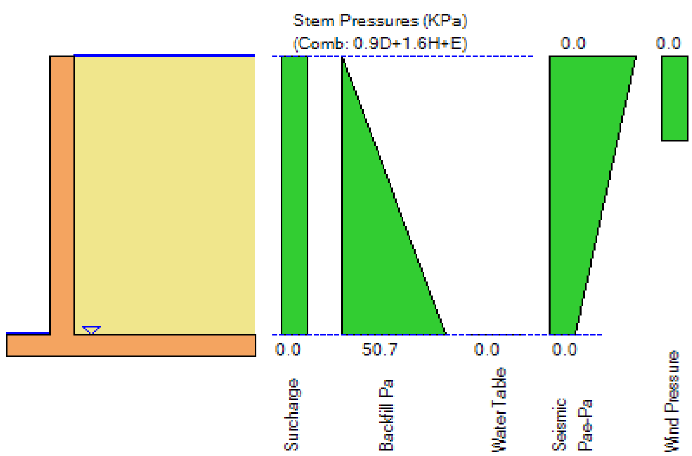
Shear Force @ Crit. Sect. ..	50.6	KN/m	OK
Resisting Shear ϕVc	253.4	KN/m	

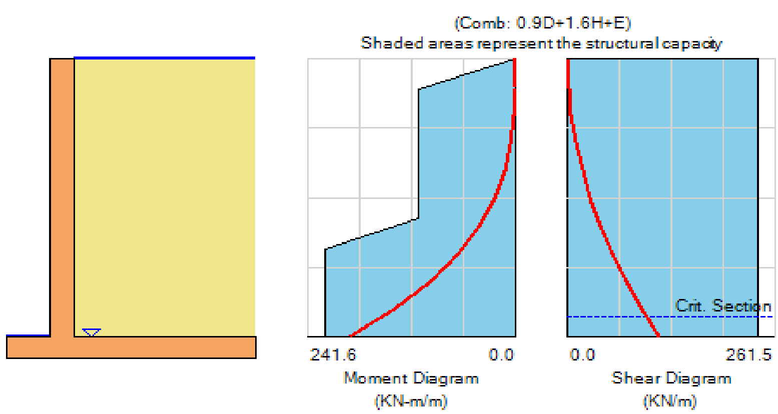
Use bott. bars D12 @ 20 cm , Transv. D12 @ 20 cm

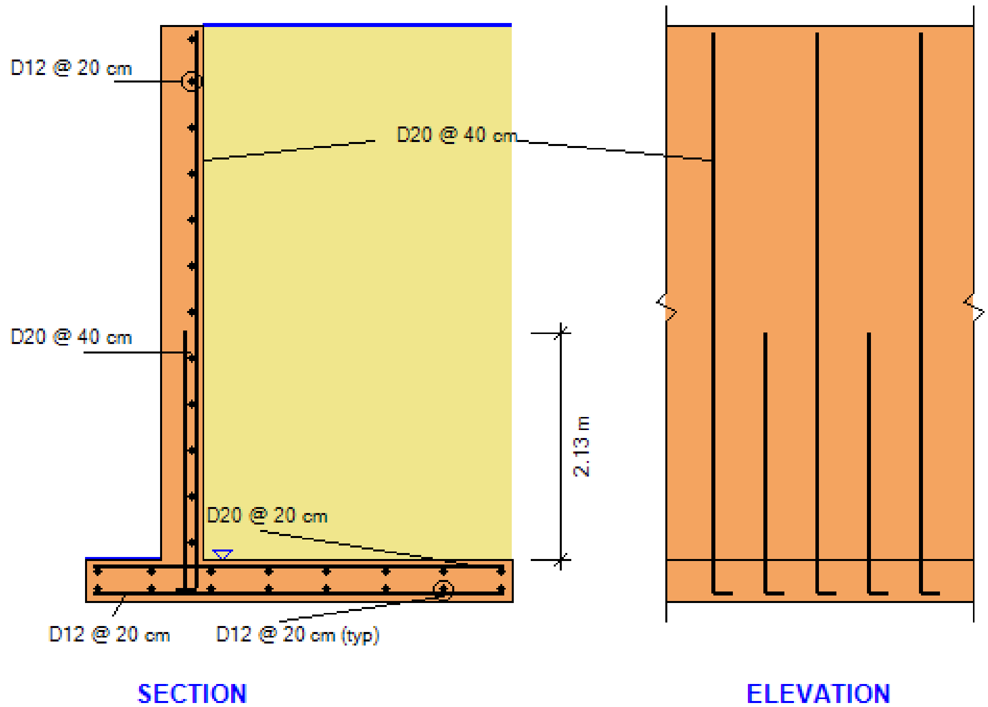
Resisting Moment ϕMn	86.2	KN-m/m	OK
Develop. Length Ratio at End	0.19		OK
Develop. Length Ratio at Stem	0.04		OK

MATERIALS

	Stem	Footing	
Concrete f'c	35.0	35.0	MPa
Rebars fy	500.0	500.0	MPa







DESIGN CODES

General Analysis	IBC-12
Concrete Design	ACI 318-11
Masonry Design	MSJC-11
Load Combinations	ASCE 7-05

Project:	Verification Example	Page # ___
Engineer:	Javier Encinas, PE	6/29/2014
Descrip:	Cantilever Retaining Wall - Metric	

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GEOMETRY				APPLIED LOADS		
Conc. Stem Height	5.00	m		Uniform Surcharge	0.0	KPa
Stem Thickness Top	40.0	cm		Strip Pressure	0.0	KPa
Stem Thickness Bot	40.0	cm		*Strip 0.6 m deep, 1.2 m wide @ 0.9 m from Stem*		
Footing Thickness	40.0	m		Stem Vertical (Dead)	0.0	KN/m
Toe Length	0.70	m		Stem Vertical (Live)	0.0	KN/m
Heel Length	2.90	m		Vertical Load Eccentricity	15.2	cm
Soil Cover @ Toe	0.00	m		Wind Load on Stem	0.0	KPa
Backfill Height	5.00	m	OK	Wind Height from Top	1.52	m
Backfill Slope Angle	0.0	deg				

BACKFILL PROPERTIES

Wall taper $\alpha = aTan\ (taper / H) =$ aTan ((40.0 - 40.0) / 100 / 5.00) = 0.000 rad

Backfill slope $\beta = slope * \pi / 180 =$ 0.0 * 3.14 / 180 = 0.000 rad

Internal friction $\phi = Int.\ friction * \pi / 180 =$ 30.0 * 3.14 / 180 = 0.524 rad

Wall-soil friction $\delta = \phi / 2 =$ 0.524 / 2 = 0.262 rad

Seismic angle $\theta = aTan\ (kh / (1 - kv)) =$ aTan (0 / (1 - 0)) = 0.000 rad

Footing length $ftg = toe + stem + heel =$ 0.70 + 40.0 / 100 + 2.90 = 4.00 m

Height for Stability $Hs = wedge + backfill + footing =$ 0.00 + 5.00 + 40.0 / 100 = 5.40 m

Earth pressure theory = Rankine Active   Moist density = 19 KN/m³   Saturated density = 20 KN/m³

Active coefficient $ka = \dfrac{Cos\,\beta * [Cos\,\beta - (Cos^2\beta - Cos^2\phi)^{1/2}]^2}{Cos\,\beta + (Cos^2\beta - Cos^2\phi)^{1/2}}$ = 0.33

Active pressure $pa = ka * \gamma =$ 0.33 * 19.0 = 6.3 KPa/m of height

- For stability analysis (non-seismic)

Active force $Pa = ka * \gamma * Hs^2 / 2 =$ 0.33 * 19.0 * 5.40² / 2 = 92.3 KN/m

$Pah = Pa * Cos\,\beta =$ 92.3 * Cos (0.000) = 92.3 KN/m , $Pav = Pa * Sin\,\beta =$ 92.3 * Sin (0.000) = 0.0 KN/m

Water force $Pw = (ka * (\gamma s - \gamma w - \gamma) + \gamma w) * (water + footing)^2 / 2$

Pw = (0.33 * (20.4 - 9.8 - 19.0) + 9.8) * (0.00 + 40.0 / 100)² / 2 = 0.0 KN/m

- For stem design (non-seismic)

Active force $Pa = ka * \gamma * H^2 / 2 =$ 0.33 * 19.0 * 5.00² / 2 = 79.2 KN/m

$Pah = Pa * Cos\,\beta =$ 79.2 * Cos (0.000) = 79.2 KN/m , $Pav = Pa * Sin\,\beta =$ 79.2 * Sin (0.000) = 0.0 KN/m

Water force $Pw = (ka * (\gamma s - \gamma w - \gamma) + \gamma w) * (water\ table)^2 / 2$

Pw = (0.33 * (20.4 - 9.8 - 19.0) + 9.8) * 0.00² / 2 = 0.0 KN/m

Active seismic coeff. $kae = \dfrac{Cos^2(\phi - \alpha - \theta)}{Cos\theta * Cos^2\alpha * Cos(\delta + \alpha + \theta) * [1 + (\dfrac{Sin(\phi + \delta) * Sin(\phi - \beta - \theta)}{Cos(\delta + \alpha + \theta) * Cos(\beta - \alpha)})^{½}]^2}$ = 0.30

- For stability analysis (seismic)

Seismic force *Pae = kae * γ * Hs² / 2 * (1 - kv)* = 0.30 * 19.0 * 5.40² / 2 * (1 - 0.0) = 83.5 KN/m

*Paeh = Pae * Cos (δ + α)* = 83.5 * Cos (0.262 + 0.000) = 80.7 KN/m

*Paev = Pae * Sin (δ + α)* = 83.5 * Sin (0.262 + 0.000) = 21.6 KN/m

Water force *Pwe = kh * (γs - γ) * (water + footing)² / 2*

Pwe = 0.00 * (20.4 - 19.0) * (0.00 + 40.0 / 100)² / 2 = 0.0 KN/m

- For stem design (seismic)

Seismic force *Pae = kae * γ * H² / 2* = 0.30 * 19.0 * 5.00² / 2 = 71.6 KN/m

*Paeh = Pae * Cos (δ + α)* = 71.6 * Cos (0.262 + 0.000) = 69.1 KN/m

*Paev = Pae * Sin (δ + α)* = 71.6 * Sin (0.262 + 0.000) = 18.5 KN/m

Water force *Pwe = kh * (γs - γ) * (water table)² / 2*

Pwe = 0.00 * (20.4 - 19.0) * 0.00² / 2 = 0.0 KN/m

OVERTURNING CALCULATIONS (Comb. D+H+W)

- Overturning

Backfill = *Lat factor * Pah* = 1.0 * 92.3 = 92.3 KN/m

Arm = *Hs / 3* = 5.40 / 3 = 1.80 m Moment = 92.3 * 1.80 = 166.2 KN-m/m

Water table = *Lat factor * Pw* = 1.0 * 0.0 = 0.0 KN/m

Arm = *(Water table + Ftg) / 3* = (0.00 + 40.0 / 100) / 3 = 0.13 m Moment = 0.0 * 0.13 = 0.0 KN-m/m

Surcharge = *Lat factor * ka * Surcharge * Hs* = 1.0 * 0.33 * 0.0 * 5.40 = 0.0 KN/m

Arm = *Hs / 2* = 5.40 / 2 = 2.70 m Moment = 0.0 * 2.70 = 0.0 KN-m/m

Strip load = *Σ Lat factor * 2 * Q / π * [β - Sin β * Cos (2α)]* = 0.0 KN/m

Arm = 2.50 m Moment = 0.0 * 2.50 = 0.0 KN-m/m

Wind load = *WL factor * Pressure * Wind height* = 1.0 * 0.0 * 1.52 = 0.0 KN/m

Arm = *Ftg + Stem - Wind height / 2* = 40.0 / 100 + 5.00 - 1.52 / 2 = 4.64 m

Moment = 0.0 * 4.64 = 0.0 KN-m/m

Backfill seismic = *EQ factor * (Paeh - Pah)* = 0.0 * (80.7 - 80.7) = 0.0 KN/m

Arm = *0.6 * Hs* = 0.6 * 5.40 = 3.24 m Moment = 0.0 * 3.24 = 0.0 KN-m/m

Water seismic = *EQ factor * Pwe* = 0.0 * 0.0 = 0.0 KN/m

Arm = *(Water table + Ftg) / 3* = (0.00 + 40.0 / 100) / 3 = 0.13 m Moment = 0.0 * 0.13 = 0.0 KN-m/m

Wall seismic = *EQ factor * (WStem + WTaper + WFtg) * kh* = 0.0 * (0.0 + 0.0 + 37.7) * 0.00 = 0.0 KN/m

Moment = *EQ factor * (WStem * (Ftg + Stem / 2) + WTaper * (Ftg + Stem / 3) + WFtg * Ftg / 2) * kh* =

= 0.0 * (0.0 * (40.0 / 100 + 5.00 / 2) + 0.0 * (40.0 / 100 + 5.00 / 3) + 37.7 * 40.0 / 100 / 2) * 0.00 = 0.0 KN-m/m

Hor. resultant Rh = 92.3 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 = 92.3 KN/m

Overturning moment OTM = 166.2 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 = 166.2 KN-m/m

Arm of hor. resultant = *OTM / Rh* = 166.2 / 92.3 = 1.80 m

- Resisting

Stem weight *WStem = DL factor * Thickness * Height * γc =* 1.0 * 40.0 / 100 * 5.00 * 23.56 = 47.1 KN/m

Arm = *Toe + Thickness / 2 =* 0.70 + 40.0 / 100 / 2 = 0.90 m Moment = 47.1 * 0.90 = 42.4 KN-m/m

Stem taper *WTaper = DL factor * ΔThick * Height / 2 * γc =* 1.0 * (40.0 - 40.0) / 100 * 5.00 / 2 * 23.56 = 0.0 KN/m

Arm = *Toe + Thick + ΔThick / 3 =* 0.70 + 40.0 / 100 - (40.0 - 40.0) / 100 * 2 / 3 = 1.10 m

Moment = 0.0 * 1.10 = 0.0 KN-m/m

CMU stem at top = 0.0 KN/m

Arm = *Toe + Thickness / 2 =* 0.70 + 0.0 / 100 / 2 = 0.00 m

Moment = 0.0 * 0.00 = 0.0 KN-m/m

Ftg. weight *WFtg = DL factor * Length * Thickness * γc =* 1.0 * 4.00 * 40.0 / 100 * 23.56 = 37.7 KN/m

Arm = *Length / 2 =* 4.00 / 2 = 2.00 m Moment = 37.7 * 2.00 = 75.4 KN-m/m

Key weight *WKey = DL factor * Depth * Thickness * γc =* 1.0 * 0.00 / 100 * 0.0 / 100 * 23.56 = 0.0 KN/m

Arm = *Toe + Thickness / 2 =* 0.70 + 0.0 / 100 / 2 = 0.70 m Moment = 0.0 * 0.70 = 0.0 KN-m/m

Soil cover = *DL factor * Toe * Soil cover * γ =* 1.0 * 0.70 * 0.00 * 19.0 = 0.0 KN/m

Arm = *Toe / 2 =* 0.70 / 2 = 0.35 m Moment = 0.0 * 0.35 = 0.0 KN-m/m

Stem wedge = *DL factor * ΔThick * Height / 2 * γ =* 1.0 * (40.0 - 40.0) / 100 * 5.00 / 2 * 19.0 = 0.0 KN/m

Arm = *Toe + Thick - ΔThick / 3 =* 0.70 + 40.0 / 100 - (40.0 - 40.0) / 100 / 3 = 1.10 m

Moment = 0.0 * 1.10 = 0.0 KN-m/m

Backfill weight = *DL factor * Heel * Height * γ =* 1.0 * 2.90 * 5.00 * 19.0 = 275.5 KN/m

Arm = *Ftg - Heel / 2 =* 4.00 - 2.90 / 2 = 2.55 m Moment = 275.5 * 2.55 = 702.5 KN-m/m

Backfill slope = *DL factor * (Heel + ΔThick) * Wedge / 2 * γ =*

= 1.0 * (2.9 + (40.0 - 40.0) / 100) * 0.00 / 2 * 19.0 = 0.0 KN/m

Arm = *ftg - (Heel + ΔThick) / 3 =* 4.00 - (2.90 + (40.0 - 40.0) / 100) / 3 = 3.03 m

Moment = 0.0 * 3.03 = 0.0 KN-m/m

Water = *DL factor * Heel * Water table * (γs - γ) =* 1.0 * 2.90 * 0.00 * (20.4 - 19.0) = 0.0 KN/m

Arm = *Ftg - Heel / 2 =* 4.00 - 2.90 / 2 = 2.55 m Moment = 0.0 * 2.55 = 0.0 KN-m/m

Seismic Pae-Pa = *EQ factor * (Paev - Pav) =* 0.0 * (21.6 - 21.6) = 0.0 KN/m

Arm = *Footing length =* 4.00 m Moment = 0.0 * 4.00 = 0.0 KN-m/m

Backfill Pav = *Lat factor * Pav =* 1.0 * 21.6 = 0.0 KN/m

Arm = *Footing length =* 4.00 m Moment = 0.0 * 4.00 = 0.0 KN-m/m

Concentrated = *DL factor * Ver load + LL factor * Ver load =* 1.0 * 0.0 + 0.0 * 0.0 = 0.0 KN/m

Arm = *Toe + Stem - Ecc =* 0.70 + (40.0 - 15.2) / 100 = 0.95 m

Moment = 0.0 * 0.95 = 0.0 KN-m/m

Surcharge = *Srch factor * (Heel + ΔThick) * Surcharge* =1.0 * (2.9 + (40.0 - 40.0) / 100) * 0.0 = 0.0 KN/m

Arm = *ftg - (Heel + ΔThick) / 2* = 4.00 - (2.90 + (40.0 - 40.0) / 100) / 2 = 2.55 m

Moment =0.0 * 2.55 = 0.0 KN-m/m

Strip = *Strip factor * Surcharge * Heel* = 1.0 * 0.0 * 2.90 = 0.0 KN/m

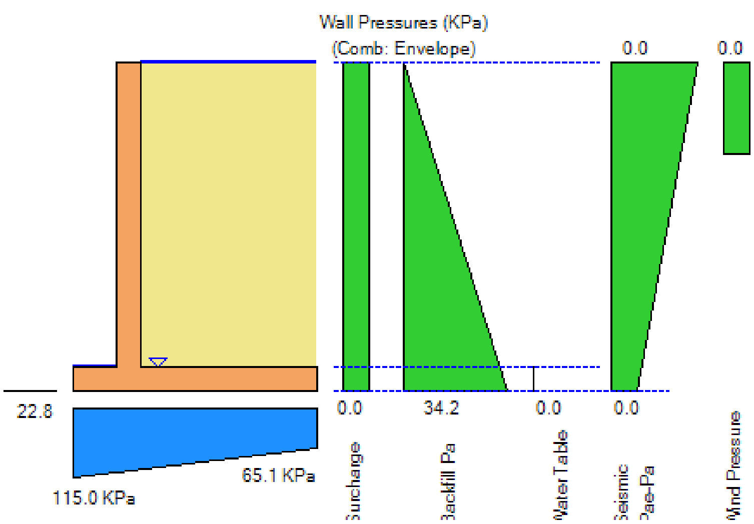
Arm = *Footing - Heel / 2* = 4.00 - 2.90 / 2 = 2.55 m Moment =0.0 * 2.55 = 0.0 KN-m/m

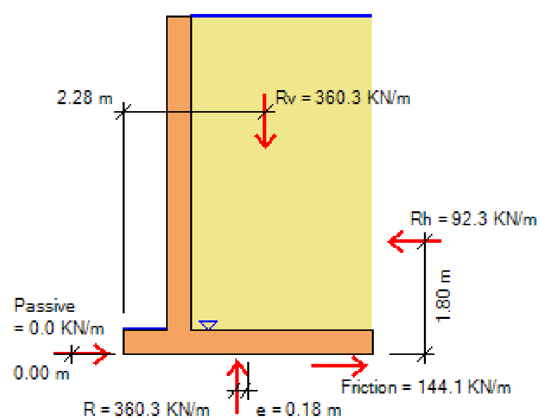
Ver. resultant Rv = *Σ Vertical forces* = 360.3 KN/m

Resisting moment RM = *Σ Moments* = 820.3 KN-m/m

Arm of ver. resultant = *RM / Rv* = 820.3 / 360.3 = 2.28 m

Overturning ratio = *RM / OTM* = 820.3 / 166.2 = 4.94 > 2.00 OK





SOIL BEARING PRESSURES (Comb. D+H+W)

$$\text{Eccentricity} = \frac{Ftg}{2} - \frac{RM - OTM}{Rv} = \frac{4.00}{2} - \frac{820.3 - 166.2}{360.3} = 0.18 \text{ m}$$

Bearing length = *Min (Ftg , 3 * (Ftg / 2 - Ecc))* = Min (4.00, 3 * (4.00 / 2 - 0.18)) = 4.00 m

$$\text{Toe bearing} = \frac{Rv}{Ftg} + \frac{6 * Rv * Ecc}{Ftg^2} = \frac{360.3}{4.00} + \frac{6 * 360.3 * 0.18}{4.00^2} = 115.0 \text{ KPa} < 120.0 \text{ KPa OK}$$

$$\text{Heel bearing} = \frac{Rv}{Ftg} - \frac{6 * Rv * Ecc}{Ftg^2} = \frac{360.3}{4.00} - \frac{6 * 360.3 * 0.18}{4.00^2} = 65.1 \text{ KPa}$$

SLIDING CALCULATIONS (Comb. D+H+W)

Passive coefficient *kp = 1 / ka* = 1 / 0.33 = 3.00 KPa

Passive depth *Dp = Soil cover + Ftg + Key - Neglect depth* = 0.00 + (40.0 + 0.0) / 100 - 0.40 = 0.00 m

Passive pressure top = *kp * γ * Neglect depth* = 3.00 * 19.0 * 0.40 = 22.80 KPa

Passive pressure bot = *kp * γ * (Dp + Neglect depth)* = 3.00 * 19.0 * (0.00 + 0.40) = 22.80 KPa

Passive force = *(Pressure top + Pressure bot) / 2 * Dp* = (22.80 + 22.80) / 2 * 0.00 = 0.0 KN/m

Friction force = *Max (0, Rv * Friction coeff.)* = Max (0, 360.3 * 0.40) = 144.1 KN/m

Sliding ratio = *(Passive + Friction) / Rh* = (0.0 + 144.1) / 92.3 = 1.56 > 1.50 OK

STEM DESIGN (Comb. 0.9D+1.6H+E)

Backfill = *Lat factor * Pah* = 1.6 * 78.7 = 126.7 KN/m

Arm = *Hb / 3* = 5.00 / 3 = 1.67 m Moment = 126.7 * 1.67 = 211.1 KN-m/m

Water table = *Lat factor * Pw* = 1.6 * 0.0 = 0.0 KN/m

Arm = *Water table / 3* = 0.00 / 3 = 0.00 m Moment = 0.0 * 0.00 = 0.0 KN-m/m

Surcharge = *Lat factor * ka * Surcharge * Hb* = 1.6 * 0.33 * 0.0 * 5.00 = 0.0 KN/m

Arm = *Hb / 2* = 5.00 / 2 = 2.50 m Moment = 0.0 * 2.50 = 0.0 KN-m/m

Strip load = *Σ Lat factor * 2 * Q / π * [β - Sin β * Cos (2α)]* = 0.0 KN/m

Arm = 2.50 m Moment = 0.0 * 2.50 = 0.0 KN-m/m

Wind load = *WL factor * Pressure * Wind height* = 0.0 * 0.0 * 1.52 = 0.0 KN/m

Arm = *Stem - Wind height / 2* = 5.00 - 1.52 / 2 = 4.24 m Moment = 0.0 * 4.24 = 0.0 KN-m/m

Backfill seismic = *EQ factor * (Paeh - Pah)* = 1.0 * (69.1 - 69.1) = 0.0 KN/m

Arm = *0.6 * Hb* = 0.6 * 5.00 = 3.00 m Moment = 0.0 * 3.00 = 0.0 KN-m/m

Water seismic = *EQ factor * Pwe* = 1.0 * 0.0 = 0.0 KN/m

Arm = *Water table / 3* = 0.00 / 3 = 0.00 m Moment = 0.0 * 0.00 = 0.0 KN-m/m

Max. shear = 126.7 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 = 126.7 KN/m

Shear at critical section = *Max shear - Max shear / Hb * d* = 126.7 - 126.7 / 5.00 * 35.5 / 100 = 117.7 KN/m

Max. moment = 211.1 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 + 0.0 = 211.1 KN-m/m

Shear strength *φ Vn = φ * 0.17 * (f'c)½ * 10 * d* ACI Eq. (11-3)

φ Vn = 0.75 * 0.17 * (35)½ * 10 * 35.5 = 261.5 KN/m > 117.7 KN/m OK

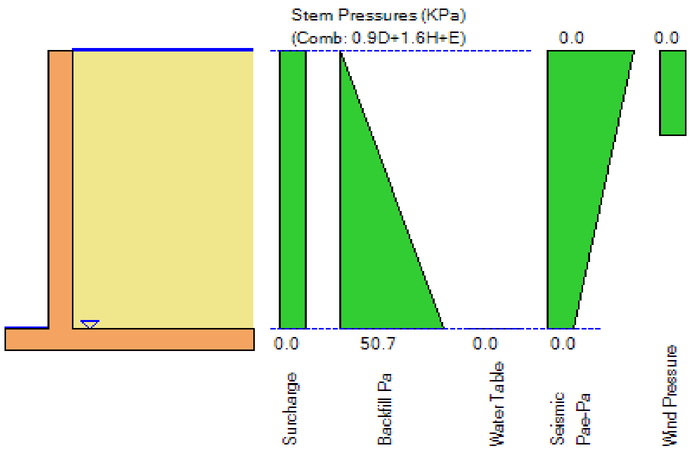
Use D20 @ 20.0 cm As = 15.71 cm²/m *ρ = As / b d* = 15.71 / (100 * 35.5) = 0.0044

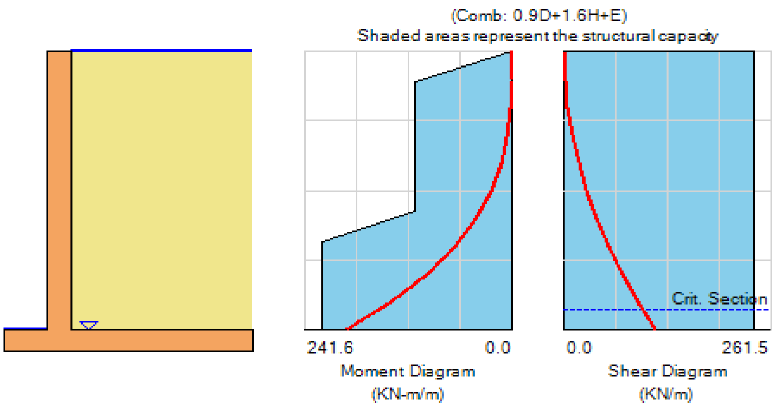
Bending strength *φ Mn = φ * d² * f'c * q * (1 - 0.59 * q)* ACI 10.2.7

φ Mn = 0.90 * 35.5² * 35.0 * 0.063 * (1 - 0.59 * 0.063) = 241.6 KN-m/m > 211.1 KN-m/m OK

Hooked *Ldh = 0.24 * fy / (f'c)½ * db * 0.7* = 0.24 * 500.0 / (35.0)½ * 2.00 * 0.7 = 28.4 cm ACI 12.5

Dev. length at footing = *Ftg - Cover* = 40.0 - 5.0 = 35.0 cm > 28.4 cm OK





HEEL DESIGN (Comb. 0.9D+1.6H+E)

Bearing force = *(Bearing1 + Bearing2) / 2 * Heel =* (15.0 + 110.8) / 2 * 2.90 = 182.4 KN/m

Arm = *(Bearing1 * Heel² / 2 + (Bearing2 - Bearing1) * Heel² / 6) / Force*

= (15.0 * 2.90² / 2 + (110.8 - 15.0) * 2.90² / 6) / 182.4 = 1.08 m

Moment = 182.4 * 1.08 = 197.3 KN-m/m

Concrete weight = *DL factor * Thick * Heel * γc =* 0.9 * 40.0 / 100 * 2.90 * 23.56 = 24.6 KN/m

Arm = *Heel / 2* = 2.90 / 2 = 1.45 m Moment = 24.6 * 1.45 = 35.7 KN-m/m

Backfill weight = *DL factor * Heel * Height * γ =* 0.9 * 2.90 * 5.00 * 19.0 = 248.0 KN/m

Arm = *Heel / 2* = 2.90 / 2 = 1.45 m Moment = 248.0 * 1.45 = 359.5 KN-m/m

Backfill slope = *DL factor * (Heel + ΔThick) * Wedge / 2 * γ =*

= 0.9 * (2.9 + (40.0 - 40.0) / 100) * 0.00 / 2 * 19.0 = 0.0 KN/m

Arm = *Heel * 2 / 3 =* 2.90 * 2 / 3 = 1.93 m Moment = 0.0 * 1.93 = 0.0 KN-m/m

Water = *DL factor * Heel * Water table * (γs - γ)* = 0.9 * 2.90 * 0.00 * (20.4 - 19.0) = 0.0 KN/m

Arm = *Heel / 2* = 2.90 / 2 = 1.45 m Moment = 0.0 * 1.45 = 0.0 KN-m/m

Surcharge = *Srch factor * (Heel + ΔThick) * Surcharge* = 0.9 * (2.9 + (40.0 - 40.0) / 100) * 0.0 = 0.0 KN/m

Arm = *Heel / 2* = 2.90 / 2 = 1.45 m Moment = 0.0 * 1.45 = 0.0 KN-m/m

Strip = *Strip factor * Surcharge * Width* = 0.9 * 0.0 * 1.22 = 0.0 KN/m

Arm = *Distance - ΔStem + Width / 2* = 0.91 - (40.0 - 40.0) / 100 + 1.22 / 2 = 1.45 m

Moment = 0.0 * 1.45 = 0.0 KN-m/m

Max. Shear Vu = -182.4 + 24.6 + 248.0 + 0.0 + 0.0 + 0.0 + 0.0 = 90.1 KN/m

Max. Moment Mu = -197.3 + 35.7 + 359.5 + 0.0 + 0.0 + 0.0 + 0.0 = 197.9 KN/m

Shear strength *φ Vn = φ * 0.17 * (f'c)½ * 10 * d* ACI Eq. (11-3)

φ Vn = 0.75 * 0.17 * (35)½ * 10 * 33.9 = 249.7 KN/m > Vu = 90.1 KN/m OK

Use D20 @ 20.0 cm As = 15.71 cm²/m *ρ = As / b d* = 15.71 / (100 * 33.9) = 0.0046

Bending strength *φ Mn = φ * d² * f'c * q * (1 - 0.59 * q)* ACI 10.2.7

φ Mn = 0.90 * 33.9² * 35.0 * 0.066 * (1 - 0.59 * 0.066) = 230.3 KN-m/m > Mu = 197.9 KN-m/m OK

Cover factor = *Min (2.5, (Cover + db /2, Spacing / 2) / db)* = Min (2.5, (5.1 + 2.00 / 2, 20.0 / 2) / 2.00) = 2.5

Straight *Ld = fy / 1.1 / (f'c)½ * Size * Location / Cover * db* ACI Eq. (12-1)

= 500.0 / 1.1 / (35)½ * 0.8 * 1.3 / 2.5 * 2.00 = 63.9 cm

Hooked *Ldh = 0.24 * fy / (f'c)½ * db * 0.7* = 0.24 * 500.0 / (35.0)½ * 2.00 * 0.7 = 28.4 cm ACI 12.5

Dev. length at toe side = *Ftg - Heel - Cover* = (4.00 - 2.90) / 100 - 5.1 = 104.9 cm > 63.9 cm OK

Dev. length at heel side = *Heel - Cover* = 2.90 / 100 - 5.1 = 284.9 cm > 63.9 cm OK

TOE DESIGN (Comb. 1.2D+1.6(L+H))

Bearing force = *(Bearing1 + Bearing2) / 2 * Toe* = (163.0 + 143.8) / 2 * 0.70 = 107.4 KN/m

Arm = *(Bearing1 * Toe² / 2 + (Bearing2 - Bearing1) * Toe² / 3) / Force*

= (143.8 * 0.70² / 2 + (163.0 - 143.8) * 0.70² / 3) / 107.4 = 0.36 m

Moment = 107.4 * 0.36 = 38.4 KN-m/m

Concrete weight = *DL factor * Thick * Toe * γc* = 1.2 * 40.0 / 100 * 0.70 * 23.56 = 7.9 KN/m

Arm = *Toe / 2* = 0.70 / 2 = 0.35 m Moment = 7.9 * 0.35 = 2.8 KN-m/m

Soil cover = *DL factor * Toe * Height * γ* = 1.2 * 0.70 * 0.00 * 19.0 = 0.0 KN/m

Arm = *Toe / 2* = 0.70 / 2 = 0.35 m Moment = 0.0 * 0.35 = 0.0 KN-m/m

Max. Shear Vu = 107.4 - 7.9 - 0.0 = 99.4 KN/m

Shear at crit. section Vu = *Max shear * (Toe - d) / Toe* = 99.4 * (0.70 - 34.4 / 100) / 0.70 = 50.6 KN/m

Max. Moment Mu = 38.4 - 2.8 - 0.0 = 35.6 KN/m

Shear strength *φ Vn = φ * 0.17 * (f'c)½ * 10 * d* ACI Eq. (11-3)

φ Vn = 0.75 * 0.17 * (35)½ * 10 * 34.4 = 253.4 KN/m > Vu = 50.6 KN/m OK

Use D12 @ 20.0 cm As = 5.65 cm²/m *ρ = As / b d* = 5.65 / (100 * 34.4) = 0.0016

Bending strength *φ Mn = φ * d² * f'c * q * (1 - 0.59 * q)* ACI 10.2.7

φ Mn = 0.90 * 34.4² * 35.0 * 0.023 * (1 - 0.59 * 0.023) = 86.2 KN-m/m > Mu = 35.6 KN-m/m OK

Cover factor = *Min (2.5, (Cover + db /2, Spacing / 2) / db)* = Min (2.5, (5.0 + 1.20 / 2, 20.0 / 2) / 1.20) = 2.5

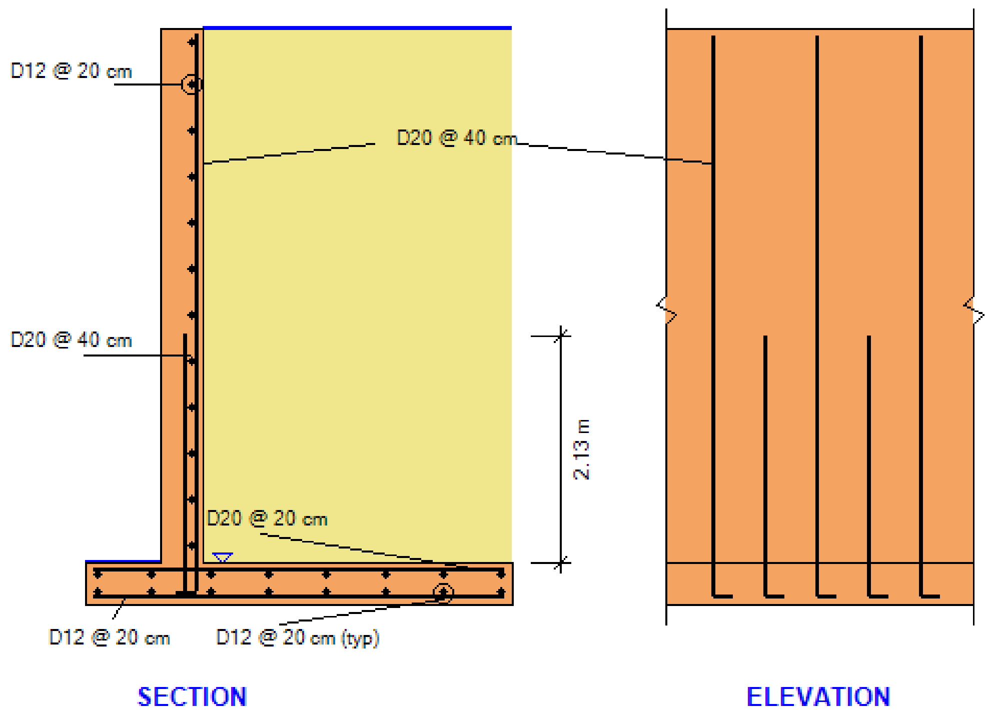
Straight *Ld = fy / 1.1 / (f'c)½ * Size * Location / Cover * db* ACI Eq. (12-1)

= 500.0 / 1.1 / (35)½ * 0.8 * 1.0 / 2.5 * 1.20 = 29.5 cm

Hooked *Ldh = 0.24 * fy / (f'c)½ * db * 0.7* = 0.24 * 500.0 / (35.0)½ * 1.20 * 0.7 = 17.0 cm ACI 12.5

Dev. length at toe side = *Ftg - Toe - Cover* = (4.00 - 0.70) / 100 - 5.0 = 325.0 cm > 29.5 cm OK

Dev. length at toe side = *Toe - Cover* = 0.70 / 100 - 5.0 = 65.0 cm > 29.5 cm OK



SHEAR KEY DESIGN (Comb. 0.9D+1.6H+E)

Shear key depth = 0.0 cm Shear key thickness = 0.0 cm

Passive force = *Lat factor * (Passive1 + Passive2) / 2 * Key* = 1.6 * (22.8 + 22.8) / 2 * 0.0 / 100 = 0.0 KN/m

Shear at crit. section Vu = *Max shear * (Key - d) / Key* = 0.0 * (0.0 - 0.1) / 0.0 = 0.0 KN/m

Arm = *(Passive1 * Key² / 2 + (Passive2 - Passive1) * Key² / 3) / Force*

= (22.8 * 0.00² / 2 + (22.8 - 22.8) * 0.00² / 3) / 0.0 = 0.00 m

Max. moment Mu = 0.0 * 0.00 = 0.0 KN-m/m

Shear strength *φ Vn = φ * 0.17 * (f'c)½ * 10 * d* ACI Eq. (11-3)

φ Vn = 0.75 * 0.17 * (35)½ * 10 * 0.1 = 0.7 KN/m > Vu = 0.0 KN/m OK

Use #4 @ 30.5 cm As = 4.23 cm²/m *ρ = As / b d* = 4.23 / (100 * 0.1) = 0.4231

Bending strength *φ Mn = φ * d² * f'c * q * (1 - 0.59 * q)* ACI 10.2.7

φ Mn = 0.90 * 0.1² * 35.0 * 6.044 * (1 - 0.59 * 6.044) = 0.1 KN-m/m > Mu = 0.0 KN-m/m OK