DESIGN OF RETAINING WALLS

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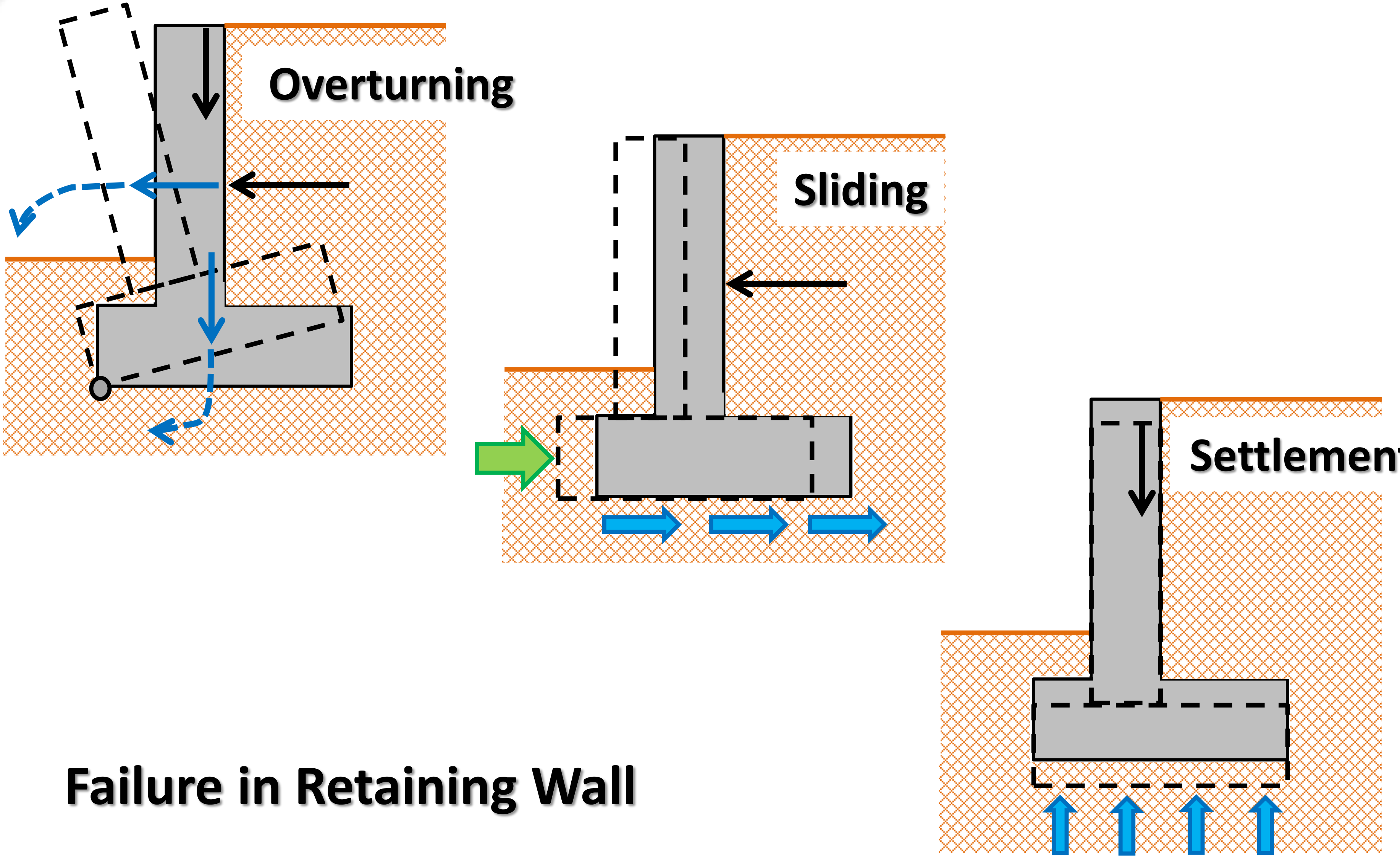
Introduction

- Retaining wall is used to retain earth or other material in **vertical (or nearly vertical)** position at locations where an abrupt change in ground level occurs
- Prevent the **retained earth** from assuming its natural angle of repose
- The retained earth **exerts lateral pressure** on the wall – overturn, slide & settlement
- The wall must be design to be **stable** under the effects of lateral pressure

Introduction



Failure in Retaining Wall

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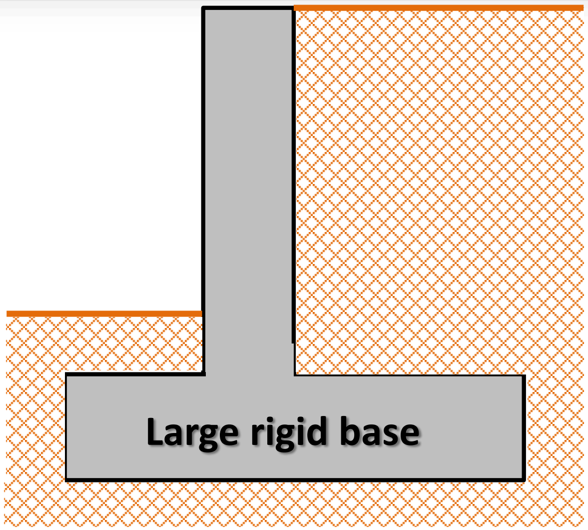
Types of Retaining Walls

Gravity Wall

- Depends entirely on its own **own weight** to provide necessary stability
- Usually constructed of plain concrete or stone masonry
- Plain concrete gravity wall – **height < 3 m**
- In designing this wall, must keep the thrust line within the middle third of the base width – **no tensile stress** to be developed

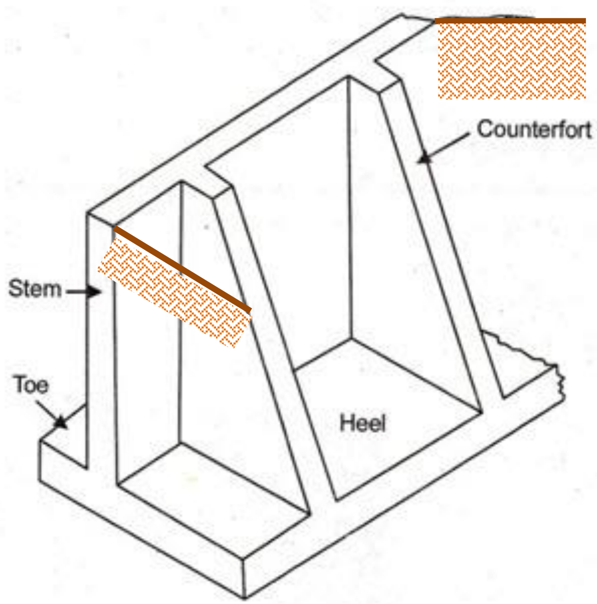
Types of Retaining Walls



Cantilever Wall

- Economical for height of up to **8 m**
- Structure consist of a vertical cantilever spanning from a large **rigid base slab**
- **Stability** is maintained essentially by the weight of the soil on the base slab + self weight of structure

Types of Retaining Walls

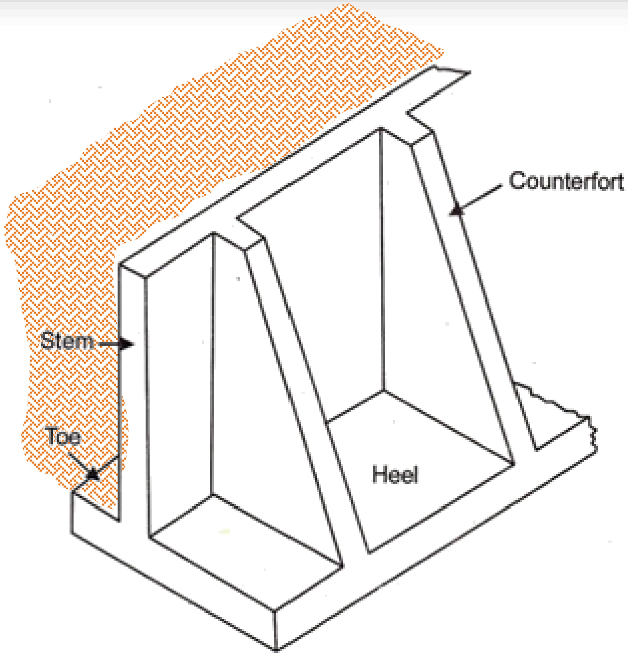


Counterfort Wall

- When the overall height of the wall is **too large** to be constructed economically as a cantilever
- Wall & base are tied together at intervals by **counterfort or bracing** walls
- Bracing in **tension**
- Economical for high wall usually **above 6 – 7 m of backfill**

Types of Retaining Walls

Buttress Wall



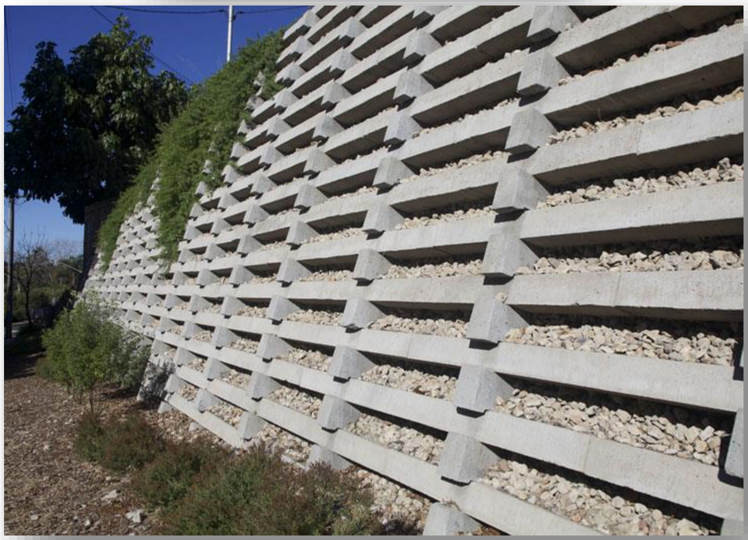
- Similar to counterfort wall, but bracing is constructed **in front** of the wall
- Bracing in **compression**
- More efficient than counterforts, but **no usable** space in front of the wall

Types of Retaining Walls

Gabion Wall

- Made of **rectangular containers**
- Fabricated of heavily galvanized wire, filled with stone and stacked on one another, usually in tiers that step back with the slope
- **Advantages:** conform to ground movement, dissipate energy from flowing water & drain-freely

Types of Retaining Walls



Crib Wall

- **Interlocking** individual boxes made from timber or precast concrete members
- Boxes are filled with crushed stone or other granular materials to create free-draining structure

Types of Retaining Walls

Tieback Wall

- Tieback is a horizontal wire or rod, or a helical anchor use to reinforce retaining wall for stability
- One end of the tieback is secured to the wall, while the other end is anchored to a stable structure i.e. concrete deadman driven into the ground or anchored into the earth with sufficient resistance
- Tieback-deadman structure resists forces that will cause the wall to lean

Types of Retaining Walls

Keystone Wall

- Made up of segmental block units, made to last
- Based around a system with interlocking fibreglass pins connecting the wall unit and soil reinforcement
- Combination of these resulted in a strong, stable and durable wall system
- Offers aesthetic appeal, cost efficiency, easy installation & strength

Analysis & Design

Stability Analysis

- Overturn, Slide & Settle
- Stability check under ultimate limit state: EQU, STR & GEO

Section Design

- Moment Design
- Check for Shear

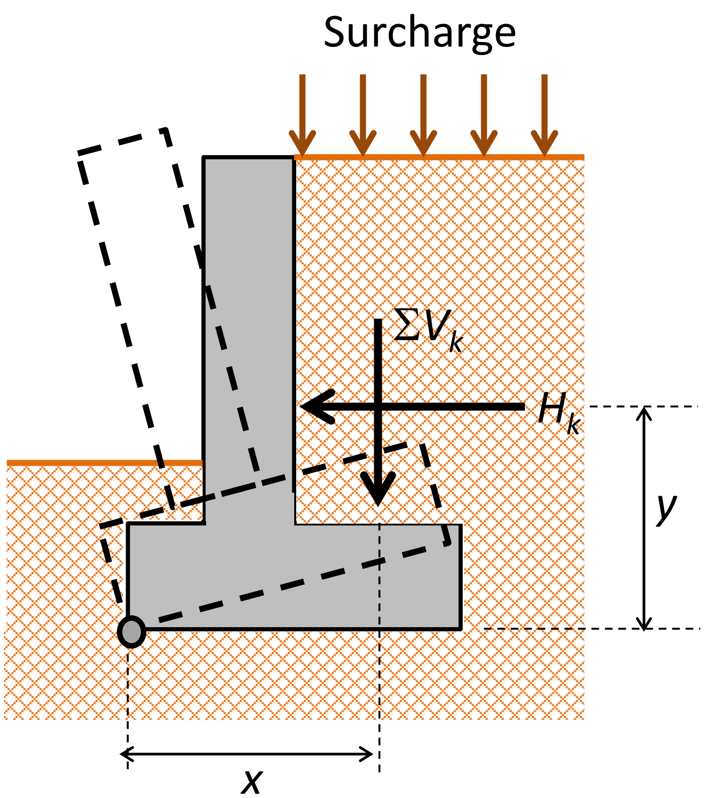
Stability Analysis

(1) Overturning

- Occurs because of **unbalanced moment**
- When overturning moment about toe to due lateral pressure >> resisting moment of self weight of wall & weight of soil above the heel slab
- **Critical condition** occur when maximum horizontal force acts with minimum vertical load

  - γ_f **= 0.9** applied to the **permanent vertical load, ΣV_k**, which is "favourable"
  - γ_f **= 1.1** applied to the **permanent earth loading, H_k** at rear face of the wall, which is "unfavourable"
  - γ_f **= 1.5** applied to **variable surcharge loading (if any)**, which is "unfavourable"

(1) Overturning *(continued)*



Stability Criteria:

$$\gamma_f\left(\sum V_k\,x\right) \geq \gamma_f H_k y$$

or

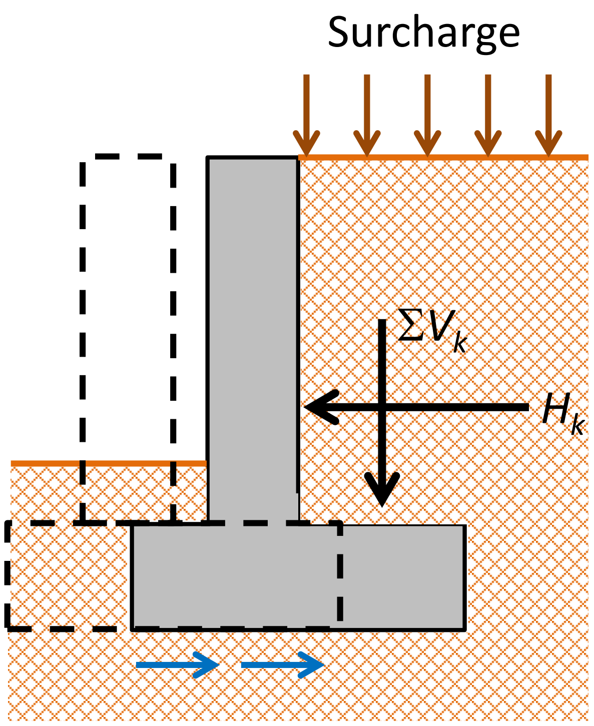
$$0.9\left(\sum V_k\,x\right) \geq \gamma_f H_k y$$

(2) Sliding

- Resistance against sliding provided by **friction** between the bottom surface of the base slab and soil beneath
- Resistance provided by **passive earth pressure** on the front face of the base gives some contribution (often ignored because it is often backfilled)

  - **γ_f = 1.0** applied to the **permanent vertical load, ΣV_k**, which is "favourable"
  - **γ_f = 1.35** applied to the **permanent earth loading, H_k** at rear face of the wall, which is "unfavourable"
  - **γ_f = 1.5** applied to **variable surcharge loading (if any)**, which is "unfavourable"

(2) Sliding *(continued)*



Stability Criteria:

$$\mu\left(\gamma_f \sum V_k\right) \geq \gamma_f H_k$$

or

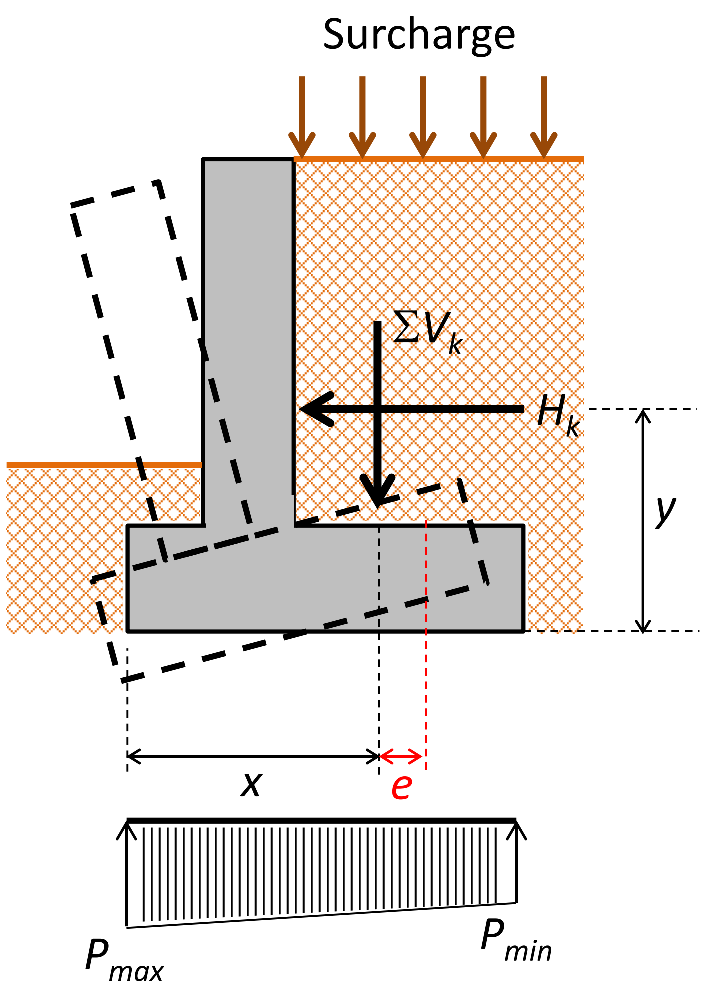
$$\mu\left(1.0 \sum V_k\right) \geq \gamma_f H_k$$

Stability Analysis

(3) Settlement

- Width of base slab must be **adequate** to distribute the vertical force to the foundation soil
- To determine the required size of base, bearing pressure underneath is assessed on the basis of the **ultimate limit state (GEO)**
- Since the base slab of the wall is subjected to the combined effects of an eccentric vertical coupled with an overturning moment, the analysis is similar to that of **foundation design**

(3) Settlement *(continued)*



Stability Criteria:

The maximum bearing pressure ≤ Soil bearing capacity

$$q = \frac{\sum N}{A} \pm \frac{\sum M}{Z} = \frac{\sum N}{A} \pm \frac{\sum My}{I}$$

where:

$$\sum M = \sum Ne + \sum H_k y$$

A = Area of base slab

e = Eccentricity

Z = Section modulus of base about the centroidal axis

(3) Settlement *(continued)*

Ultimate Limit State (ULS)

Load Combination 1

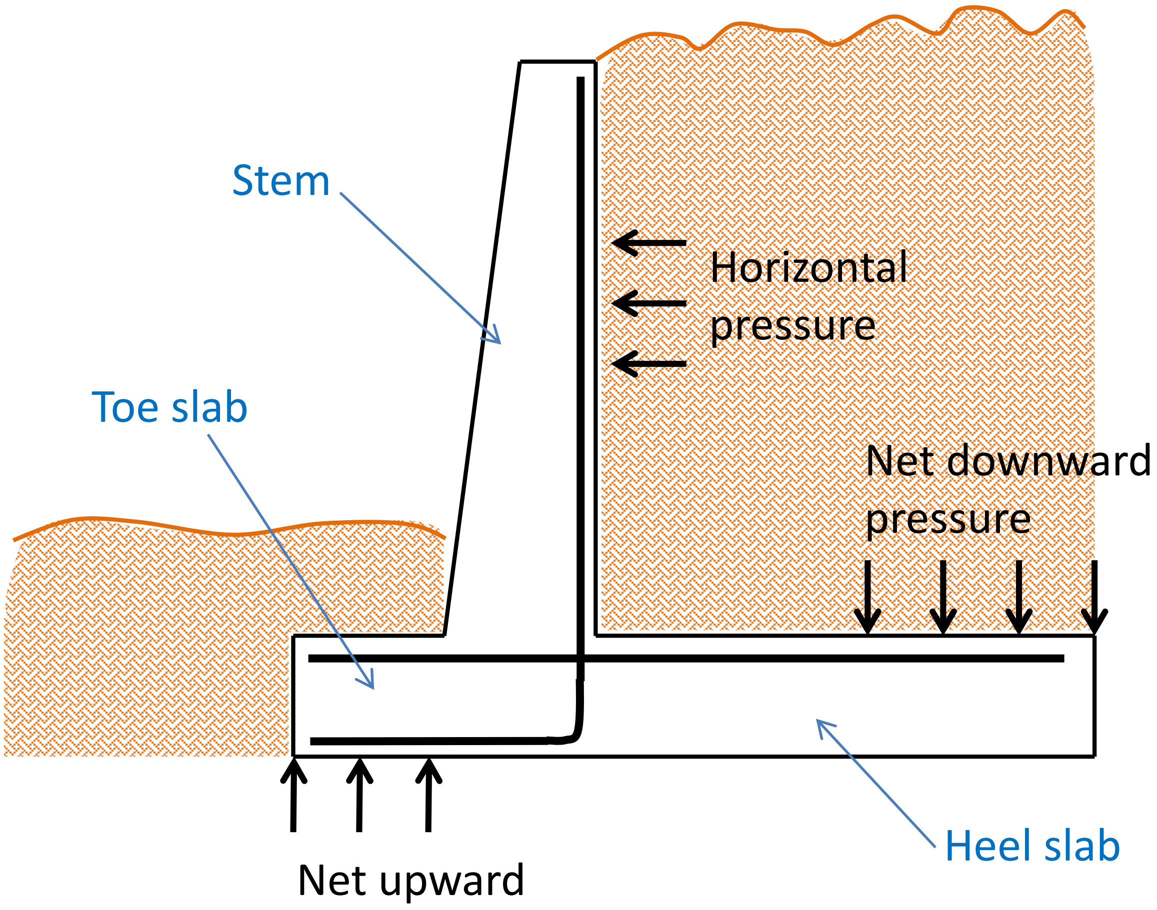
- Moment due to horizontal load on the maximum bearing pressure at the toe of wall is "unfavourable"
- Moment due to weight of wall and earth acting on the heel of wall act in the opposite direction are "favourable"

  - γ_f = **1.0** for weight of wall & soil
  - γ_f = **0** for weight of surcharge
  - γ_f = **1.35** for lateral earth pressure
  - γ_f = **1.5** for lateral surcharge

Load Combination 2

- γ_f = **1.0** for permanent action of both "unfavourable" & "favourable" effects
- γ_f = **1.3** for variable action of "unfavourable" effect
- γ_f = **0** for variable action of "favourable" effect

Element Design & Detailing



Element Design & Detailing

- Three elements of retaining wall: **Stem**, **Toe slab** & **Heel slab** are designed as cantilever slab
- **Stem:** Designed to resist moment caused by force $\gamma_f H_k$ (γ_f = load combination 1)
- **Toe Slab:** Net pressure is obtained by deducting the weight of concrete in the toe slab from upward acting soil pressure
- **Heel slab:** Designed to resist moment due to downward pressure from the weight of retained earth (plus surcharge, if any) and concrete slab
- Safety factor γ_{f1}, $\gamma_{\phi 2}$ and γ_{f3} should be considered to provide a combination which gives the **critical design conditions** (worst combination of 1 & 2)
- **Temperature & shrinkage reinforcement** should be provided transverse to the main reinforcement & near the front face of the stem

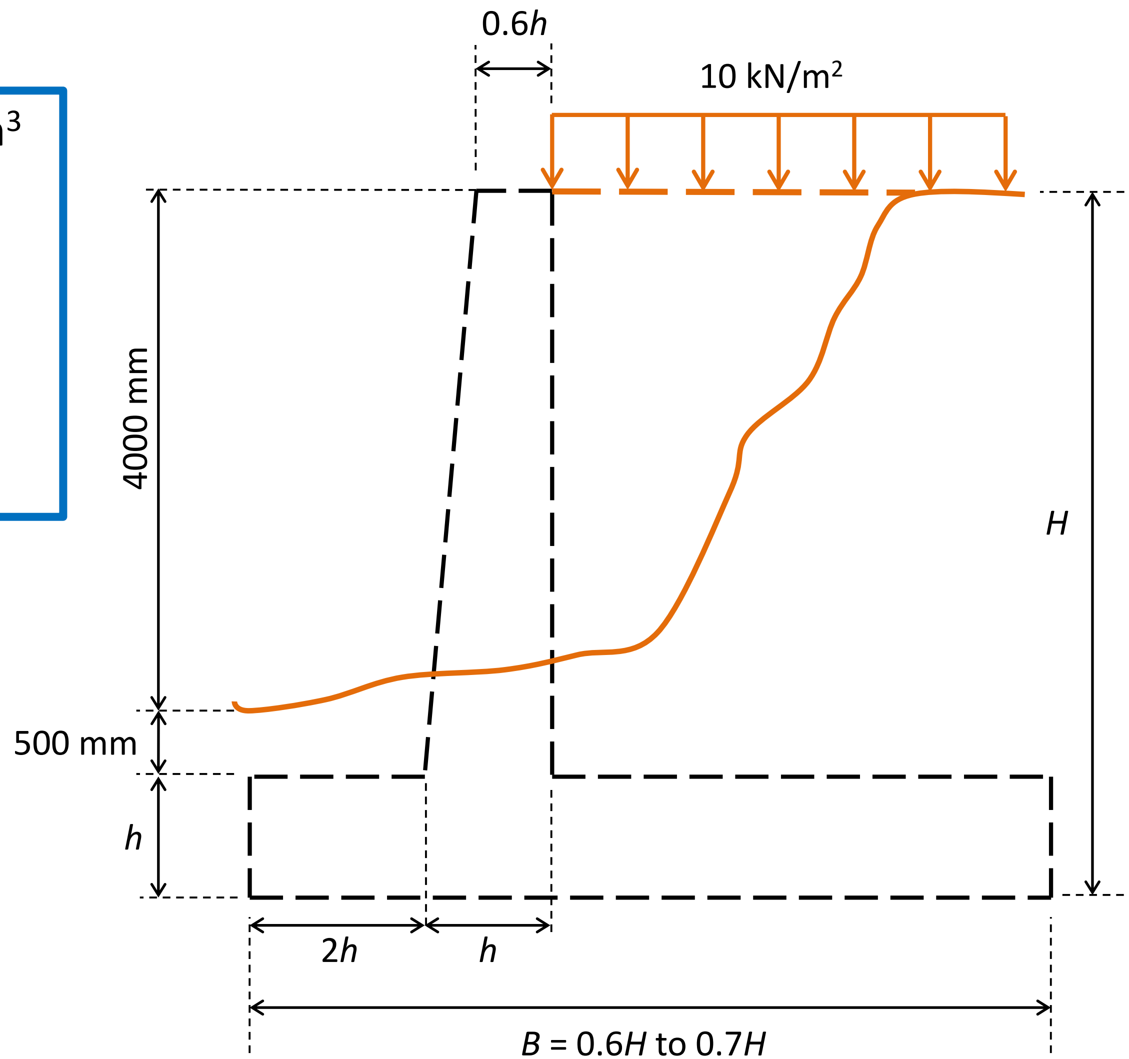
Example 1

CANTILEVER RC RETAINING WALL

Example 1: Cantilever RC Retaining Wall

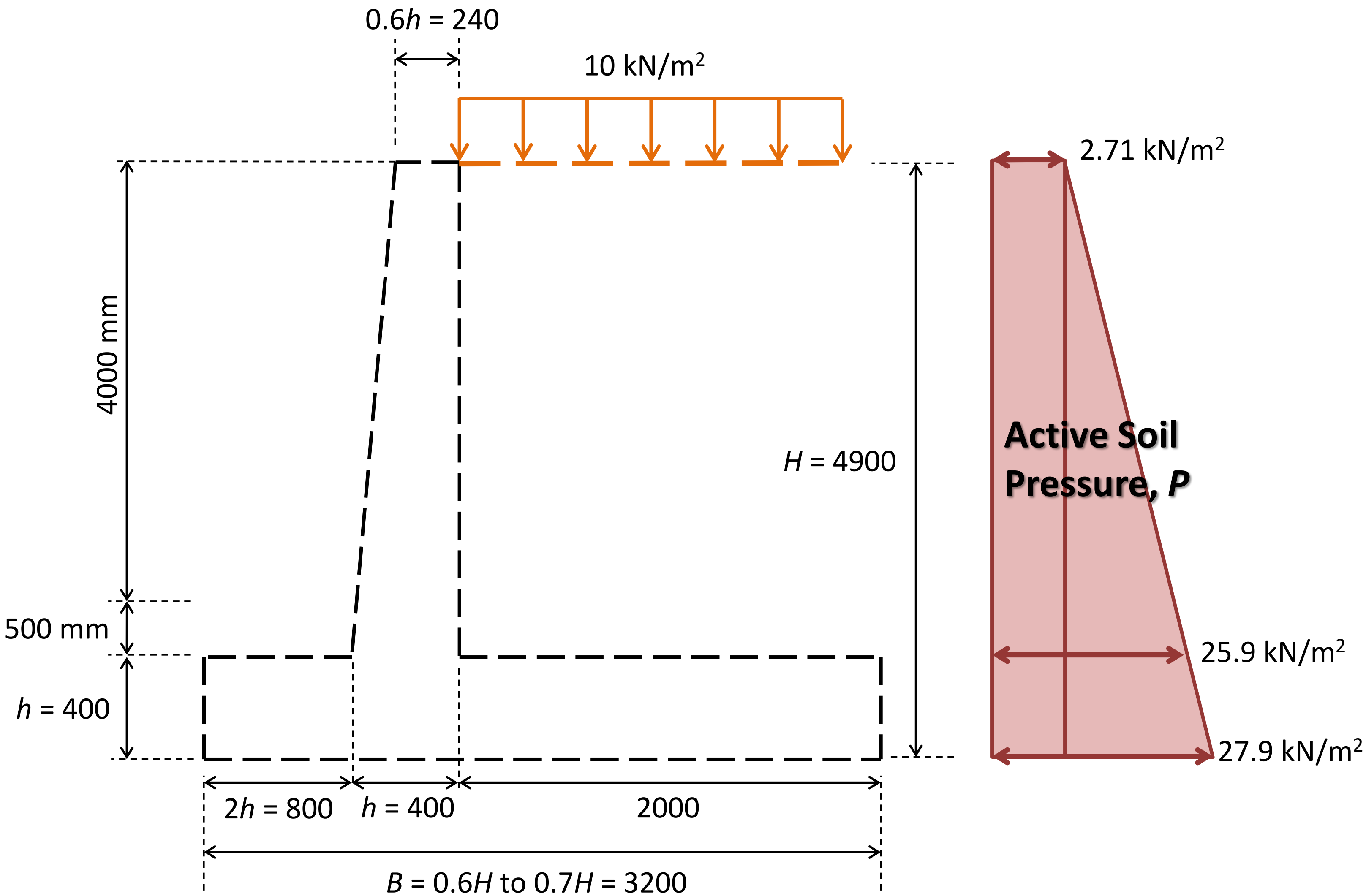
- Well drained sand, γ_{soil} = 19 kN/m^3
- Angle of internal friction, ϕ = 35°
- Cohesion, c = 0
- Safe bearing pressure, q = 200 kN/m^2
- Coefficient of friction with concrete, μ = 0.5

- f_{ck} = 30 N/mm^2
- f_{yk} = 500 N/mm^2
- γ_{conc} = 25 kN/m^3
- Concrete cover = 45 mm
- Bar diameter, ϕ_{bar} = 12 mm



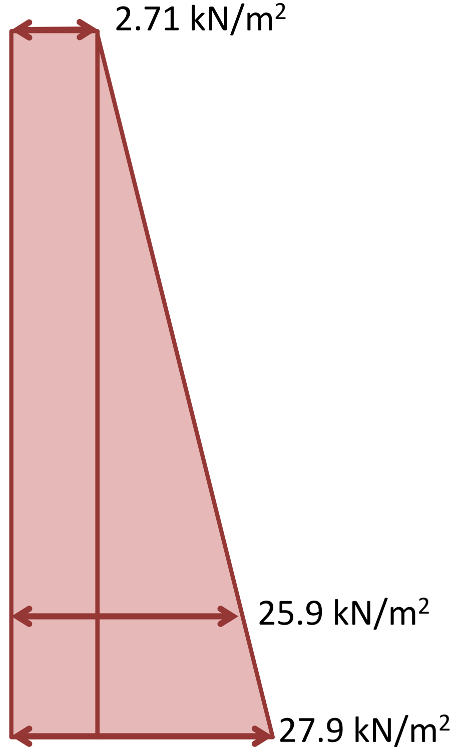
Example 1: Cantilever RC Retaining Wall

Suggest Suitable Dimensions for the RC Retaining Wall



Example 1: Cantilever RC Retaining Wall

Suggest Suitable Dimensions for the RC Retaining Wall



Active Soil Pressure, $\boldsymbol{P = (\gamma H + w)K_a}$

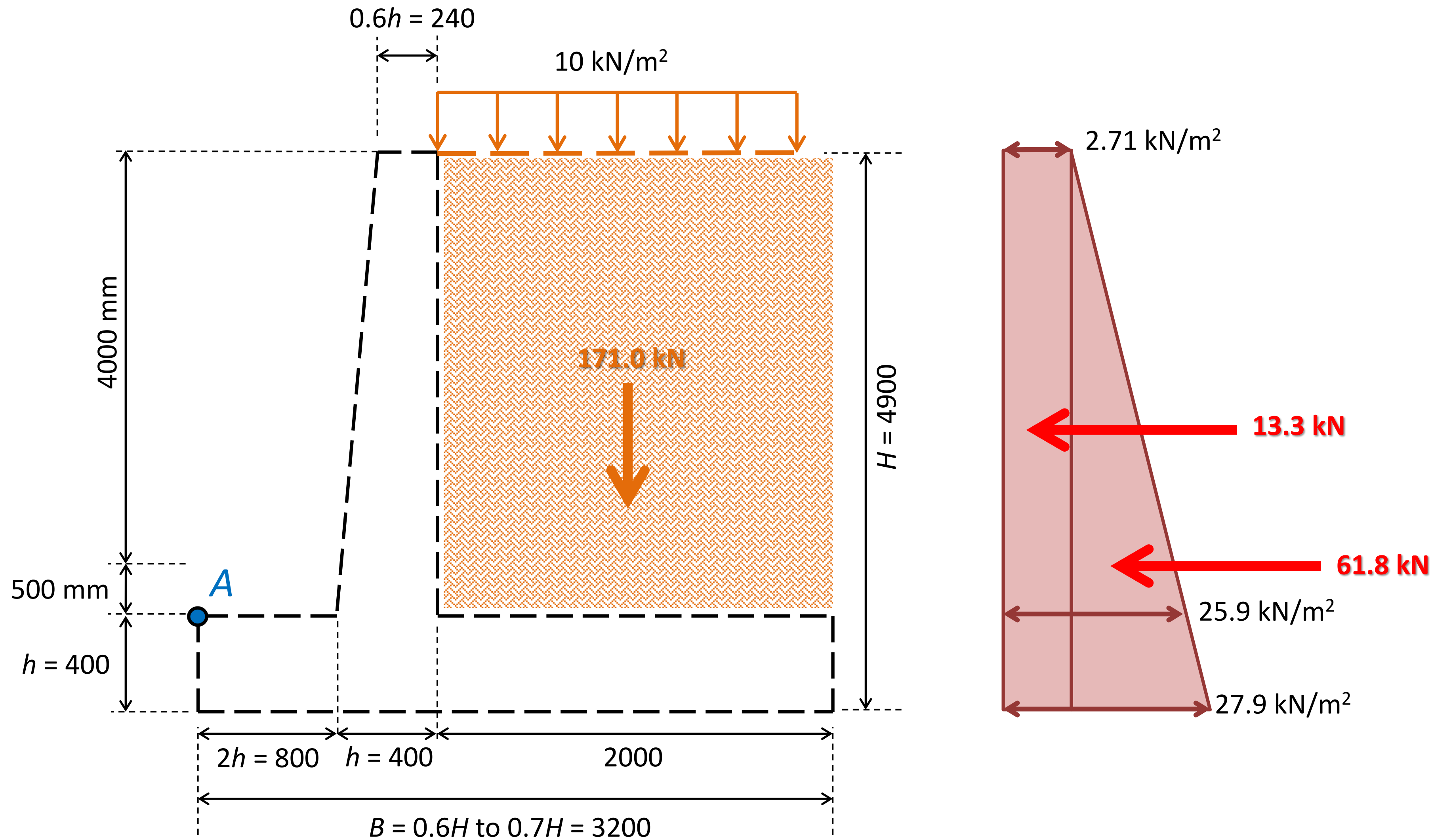
where $K_a = \frac{(1-\sin \emptyset)}{(1+\sin \emptyset)} = \frac{(1-\sin 35)}{(1+\sin 35)} = 0.27$

$$\therefore\ P = (19H + 10)0.27 = 5.15H + 2.71$$

At *H* = 0 m → 2.71 kN/m²
At *H* = 4.5 m → 25.9 kN/m²
At *H* = 4.9 m → 27.9 kN/m²

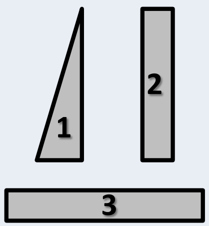
Example 1: Cantilever RC Retaining Wall

Taking Moment at Point A



Example 1: Cantilever RC Retaining Wall

Stability Analysis

Element		Load (kN)	Lever Arm (m)	Moment at Point A (kNm)	
					
Wall		1. (0.5 × 0.16 × 4.50 × 1 m width) × 25.0 = 9.0 2. (0.24 × 4.5 × 1 m width) × 25.0 = 27.0 3. (0.40 × 3.20 × 1 m width) × 25.0 = 32.0	0.91 1.08 1.60	8.2 29.2 51.2	
Soil		(4.50 × 2.00 × 1 m width) × 19.0 = 171.0	2.2	376.2	
Surcharge		(2.00 × 1 m width) × 10.0 = 20.0	2.2	44.0	
Active Pressure • Surcharge • Soil		 2.71 × (4.9 × 1 m width) = 13.3 (27.9 – 2.71) × (4.9 × 1 m width) = 61.8	 2.45 1.63		 32.5 100.9
Total	**Moment, *M***	**Permanent =** **Variable =**		**464.7** **44.0**	**100.9** **32.5**
	Vertical Load, V_k	**Permanent = 239.0** **Variable = 20.0**	-	-	-
	Horizontal Load, H_k	**Permanent = 61.8** **Variable = 13.3**	-	-	-

Example 1: Cantilever RC Retaining Wall

Stability Analysis

1. Stability Against Overturning (at point A):

Check $0.9(\sum V_k x) \geq \gamma_f H_k y$

Overturning Moment = (1.10 × 100.9) + (1.50 × 32.5) = 160 kNm
Restraining Moment = (0.90 × 464.7) + (0 × 44.0) = 418 kNm

Since Overturning Moment < Restraining Moment → OK

Example 1: Cantilever RC Retaining Wall

Stability Analysis *(continued)*

2. Sliding

Check $\mu(1.0\sum V_k) \geq \gamma_f H_k$

=

Sliding Force = (1.35 × 61.8) + (1.50 × 13.3) = 103 kN

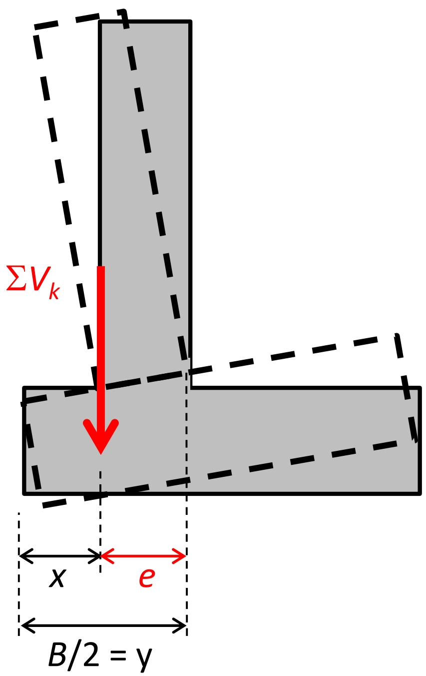
Friction Force = 0.45 [(1.0 × 239.0) + (0 × 20.0)] = 108 kN

Since Sliding Force < Friction Force → OK

Example 1: Cantilever RC Retaining Wall

Stability Analysis *(continued)*

3. Settlement



ΣV_k = 239.0 + 20.0 = 259.0 kN

ΔM = 464.7 + 44.0 – 100.9 – 32.5 = 375.3 kNm

$$\therefore x = \frac{\Delta M}{\sum V_k} = \frac{375.3}{259.0} = 1.45 \text{ m}$$

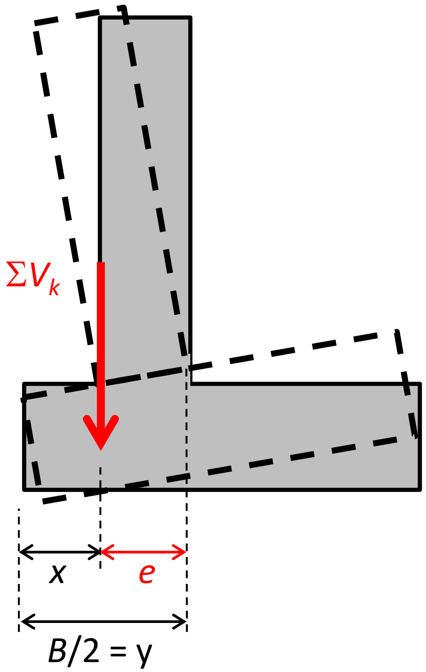
Eccentricity, $e = B/2 - x$ = 1.60 – 1.45 = 0.15 m < $B/6$ = 0.53 m

➔ **No negative pressure**

Example 1: Cantilever RC Retaining Wall

Stability Analysis *(continued)*

3. Settlement



$A = B \times 1.0$ m width = $3.20 \times 1.0 = 3.2$ m²/m width

$y = 3.20 / 2 = 1.60$ m

$I = 1.0 \times 3.20^3/12 = 2.73$ mm⁴

Bearing Pressure, $q = \frac{\sum N}{A} \pm \frac{\sum My}{I}$

$= \left(\frac{259.0}{3.2}\right) \pm \left(\frac{259.0 \times 0.15 \times 1.60}{2.73}\right) = 80.9 \pm 22.9 \text{ kN/m}^2$

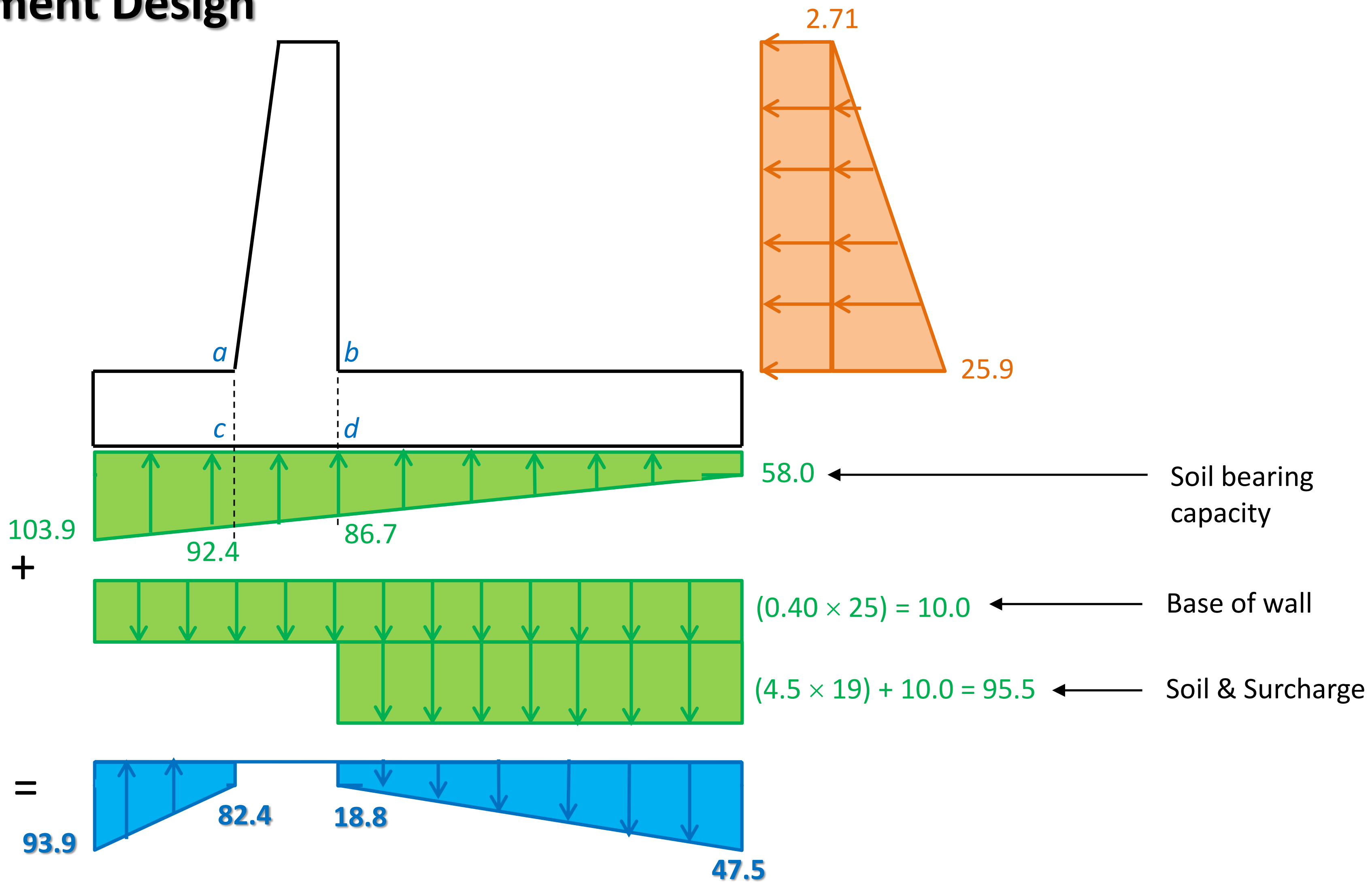
$q_{Ed,min} = 58.0$ kN/m²

$q_{Ed,max} = 103.9$ kN/m²

Soil bearing capacity, q_{Ed} = 200 kN/m² ➔ OK

Example 1: Cantilever RC Retaining Wall

Element Design



Example 1: Cantilever RC Retaining Wall

Main Reinforcement

h = 400 mm, b = 1000 mm
Effective depth, $d = h - c - 1.5\phi_{bar}$ = 400 – 45 – (0.5 × 12) = 349 mm

(i) Wall Stem

$$M_{ab} = 1.5\left[2.71 \times \frac{4.5^2}{2}\right] + 1.35\left[(25.9 - 2.71) \times \frac{4.5}{2} \times \frac{4.5}{3}\right] = 41.1 + 105.5 = 146.7 \text{ kNm/m}$$

$$K = \frac{M_{Ed}}{f_{ck}bd^2} = \frac{146.7 \times 10^6}{30 \times 1000 \times 349^2} = 0.040 < K_{bal} = 0.167$$

∴ Compression reinforcement is **NOT** required

$$z = d\left[0.25 - \left(\frac{K}{1.134}\right)\right] = 0.96d > 0.95d$$

$$A_{s,req} = \frac{M_{Ed}}{0.87 f_{yk} z} = \frac{146.7 \times 10^6}{0.87 \times 500 \times 0.95 \times 349} = \mathbf{1017\ mm^2/m}$$

Provide H12-100 (A_s = 1131 mm²/m)

Example 1: Cantilever RC Retaining Wall

Main Reinforcement *(continued)*

(ii) Toe

$M_{ac} = 1.35\left[82.4 \times \frac{0.80^2}{2}\right] + 1.35\left[(93.9 - 82.4) \times \frac{0.80}{2} \times \frac{2}{3} \times 0.80\right]$ = 35.6 + 3.3 = 38.9 kNm/m

$K = \frac{M_{Ed}}{f_{ck}bd^2} = \frac{38.9\times10^6}{30\times1000\times349^2} = 0.011 < K_{bal}$ = 0.167

$\therefore$ Compression reinforcement is **NOT** required

$z = d\left[0.25 - \left(\frac{K}{1.134}\right)\right] = 0.99d > 0.95d$

$A_{s,req} = \frac{M_{Ed}}{0.87f_{yk}z} = \frac{38.9\times10^6}{0.87\times500\times0.95\times349} =$ **270 mm²/m**

Provide H12-150 (A_s = 754 mm²/m)

Example 1: Cantilever RC Retaining Wall

Main Reinforcement *(continued)*

(iii) Heel

$M_{bd} = 1.35\left[18.8 \times \frac{2.00^2}{2}\right] + 1.35\left[(47.5 - 18.8) \times \frac{2.00}{2} \times \frac{2}{3} \times 2.00\right]$ = 50.8 + 51.6 = 102.4 kNm/m

$K = \frac{M_{Ed}}{f_{ck}bd^2} = \frac{102.4 \times 10^6}{30 \times 1000 \times 349^2} = 0.011 < K_{bal}$ = 0.167

∴ Compression reinforcement is **NOT** required

$z = d\left[0.25 - \left(\frac{K}{1.134}\right)\right] = 0.97d > 0.95d$

$A_{s,req} = \frac{M_{Ed}}{0.87 f_{yk} z} = \frac{102.4 \times 10^6}{0.87 \times 500 \times 0.95 \times 349} =$ **710 mm²/m**

Provide H12-150 (A_s = 754 mm²/m)

Example 1: Cantilever RC Retaining Wall

Minimum & Maximum Area of Reinforcement

$$A_{s,min} = 0.26\left(\frac{f_{ctm}}{f_{yk}}\right)bd = 0.26\left(\frac{2.90}{500}\right)0.0013bd \geq 0.0013bd$$

$\therefore A_{s,min} = 0.0013bd = 0.0013 \times 1000 \times 349 = 454\ \text{mm}^2/\text{m}$

$A_{s,max} = 0.04A_c = 0.04bh = 0.04 \times 1000 \times 400 = 16000\ \text{mm}^2/\text{m}$

Provide Secondary Bar H12-200 ($A_{s,prov}$ = 566 mm^2/m)

Example 1: Cantilever RC Retaining Wall

Shear

(i) Wall

$$V_{ab} = 1.50[2.71 \times 4.5] + 1.35\left[(25.9 - 2.71) \times \frac{4.5}{2}\right] = 88.7 \text{ kN/m}$$

$$V_{ac} = 1.35(93.9 + 82.4) \times \frac{0.80}{2} = 95.2 \text{ kN/m}$$

$$V_{bd} = 1.35\left(18.8 + 47.5 \times \frac{2.00}{2}\right) = 89.5 \text{ kN/m}$$

$$\therefore \boldsymbol{V_{Ed} = 95.2 \text{ kN/m}}$$

$$k = 1 + \sqrt{\frac{200}{d}} = 1 + \sqrt{\frac{200}{349}} = 1.76 < 2.0$$

$$\rho_l = \frac{A_{sl}}{bd} = \frac{754}{1000 \times 349} = 0.0022 \leq 0.02$$

Example 1: Cantilever RC Retaining Wall

Shear

$$V_{Rd,c} = \left[0.12k(100\rho_l f_{ck})^{1/3}\right]bd$$
$$= \left[0.12 \times 1.76(100 \times 0.0022 \times 30)^{1/3}\right]1000 \times 349 = 137199 \text{ N} = 137.2 \text{ kN}$$

$$V_{min} = \left[0.035k^{3/2}\sqrt{f_{ck}}\right]bd$$
$$= \left[0.035 \times 1.76^{3/2}\sqrt{30}\right]1000 \times 349 = 155817\ N = 155.8 \text{ kN}$$

V_{Ed} (95.2 kN) < V_{min} (155.8 kN) ➔ OK

Example 1: Cantilever RC Retaining Wall

Cracking

h = 400 mm > 200 mm

Steel stress under quasi-permanent action, $f_s = \left(\frac{f_{yk}}{1.15}\right)\left(\frac{A_{s.req}}{A_{s,prov}}\right)\left(\frac{N_{quasi}}{N_{ult}}\right)$

$= \left(\frac{500}{1.15}\right)\left(\frac{1017}{1131}\right)\left(\frac{245}{352.7}\right)$= 272 N/mm^2

For design crack width 0.3 mm:
Maximum allowable bar spacing = 150 mm

Wall: 100 mm < 200 mm
Toe: 150 mm < 200 mm
Heel: 150 mm < 200 mm

Cracking OK

Example 1: Cantilever RC Retaining Wall

Detailing