• 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
Failure in Retaining Wall

- Overturning
- Sliding
- Settlement
Types of Retaining Walls

Gravity Wall

- Depends entirely on its 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 used to reinforce the 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
(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

  - $\gamma_f = 0.9$ applied to the **permanent vertical load**, $\Sigma V_k$, which is “favourable”
  - $\gamma_f = 1.1$ applied to the **permanent earth loading**, $H_k$ at rear face of the wall, which is “unfavourable”
  - $\gamma_f = 1.5$ 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).

\[ \gamma_f = 1.0 \] applied to the permanent vertical load, \( \Sigma V_k \), which is "favourable"

\[ \gamma_f = 1.35 \] applied to the permanent earth loading, \( H_k \) at rear face of the wall, which is "unfavourable"

\[ \gamma_f = 1.5 \] applied to variable surcharge loading (if any), which is "unfavourable"
Stability Analysis

(2) Sliding (continued)

Stability Criteria:

\[
\mu \left( \gamma_f \sum V_k \right) \geq \gamma_f H_k \\
\text{or}\\
\mu \left( 1.0 \sum V_k \right) \geq \gamma_f H_k
\]
(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.
Stability Analysis

(3) Settlement (continued)

Stability Criteria:

The maximum bearing pressure $\leq$ Soil bearing capacity

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

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"
  - \( \gamma_f = 1.0 \) for weight of wall & soil
  - \( \gamma_f = 0 \) for weight of surcharge
  - \( \gamma_f = 1.35 \) for lateral earth pressure
  - \( \gamma_f = 1.5 \) for lateral surcharge

**Load Combination 2**
- \( \gamma_f = 1.0 \) for permanent action of both "unfavourable" & "favourable" effects
- \( \gamma_f = 1.3 \) for variable action of "unfavourable" effect
- \( \gamma_f = 0 \) for variable action of "favourable" effect
Element Design & Detailing

- Net downward pressure
- Net upward pressure
- Horizontal pressure
- Stem
- Toe slab
- Heel slab
Three elements of retaining wall: **Stem**, **Toe slab** & **Heel slab** are designed as cantilever slab

**Stem:** Designed to resist moment caused by force $\gamma_f H_k$ ($\gamma_f =$ 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 $\gamma_{f1}$, $\gamma_{f2}$ and $\gamma_{f3}$ 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, $\gamma_{\text{soil}} = 19$ kN/m$^3$
- Angle of internal friction, $\phi = 35^\circ$
- Cohesion, $c = 0$
- Safe bearing pressure, $q = 200$ kN/m$^2$
- Coefficient of friction with concrete, $\mu = 0.5$

- $f_{ck} = 30$ N/mm$^2$
- $f_{yk} = 500$ N/mm$^2$
- $\gamma_{\text{conc}} = 25$ kN/m$^3$
- Concrete cover = 45 mm
- Bar diameter, $\phi_{\text{bar}} = 12$ mm
Example 1: Cantilever RC Retaining Wall

Suggest Suitable Dimensions for the RC Retaining Wall

- \( h = 400 \text{ mm} \)
- \( 2h = 800 \text{ mm} \)
- \( h = 400 \text{ mm} \)
- \( 2000 \text{ mm} \)
- \( B = 0.6H \text{ to } 0.7H = 3200 \text{ mm} \)
- \( 0.6h = 240 \text{ mm} \)
- \( 10 \text{ kN/m}^2 \)
- \( 2.71 \text{ kN/m}^2 \)
- \( 25.9 \text{ kN/m}^2 \)
- \( 27.9 \text{ kN/m}^2 \)
- \( H = 4900 \text{ mm} \)
- \( 500 \text{ mm} \)
- \( 4000 \text{ mm} \)

Active Soil Pressure, \( P \)
Example 1: Cantilever RC Retaining Wall

Suggest Suitable Dimensions for the RC Retaining Wall

**Active Soil Pressure,** \( P = (\gamma H + w)K_a \)

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

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

At \( H = 0 \) m \( \Rightarrow 2.71 \text{ kN/m}^2 \)
At \( H = 4.5 \) m \( \Rightarrow 25.9 \text{ kN/m}^2 \)
At \( H = 4.9 \) m \( \Rightarrow 27.9 \text{ kN/m}^2 \)
Example 1: Cantilever RC Retaining Wall

Taking Moment at Point A

\[ \text{h} = 400 \text{ mm} \]

\[ \text{B} = 0.6H \text{ to } 0.7H = 3200 \]

\[ 0.6h = 240 \]

\[ 10 \text{ kN/m}^2 \]

\[ 172.0 \text{ kN} \]

\[ 2.71 \text{ kN/m}^2 \]

\[ 13.3 \text{ kN} \]

\[ 61.8 \text{ kN} \]

\[ 25.9 \text{ kN/m}^2 \]

\[ 27.9 \text{ kN/m}^2 \]
## Example 1: Cantilever RC Retaining Wall

### Stability Analysis

| Element       | Load (kN)                                                                 | Lever Arm (m) | Moment at Point A (kNm) |\[
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall</td>
<td>1. ((0.5 \times 0.16 \times 4.50 \times 1 \text{ m width}) \times 25.0 = 9.0)</td>
<td>0.91</td>
<td>8.2</td>
</tr>
<tr>
<td></td>
<td>2. ((0.24 \times 4.5 \times 1 \text{ m width}) \times 25.0 = 27.0)</td>
<td>1.08</td>
<td>29.2</td>
</tr>
<tr>
<td></td>
<td>3. ((0.40 \times 3.20 \times 1 \text{ m width}) \times 25.0 = 32.0)</td>
<td>1.60</td>
<td>51.2</td>
</tr>
<tr>
<td>Soil</td>
<td>((4.50 \times 2.00 \times 1 \text{ m width}) \times 19.0 = 171.0)</td>
<td>2.2</td>
<td>376.2</td>
</tr>
<tr>
<td>Surcharge</td>
<td>((2.00 \times 1 \text{ m width}) \times 10.0 = 20.0)</td>
<td>2.2</td>
<td>44.0</td>
</tr>
</tbody>
</table>
| Active Pressure|\[
|               | • Surcharge \((2.71 \times (4.9 \times 1 \text{ m width}) = 13.3\)     | 2.45          | 32.5                   |
|               | • Soil \((27.9 - 2.71) \times (4.9 \times 1 \text{ m width}) = 61.8\)    | 1.63          | 100.9                  |

### Total

<table>
<thead>
<tr>
<th></th>
<th>Permanent = 239.0 \hspace{1cm} Variable = 20.0</th>
<th>Permanent = 61.8 \hspace{1cm} Variable = 13.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment, (M)</td>
<td>(464.7\hspace{1cm}44.0\hspace{1cm}100.9\hspace{1cm}32.5)</td>
<td></td>
</tr>
<tr>
<td>Vertical Load, (V_k)</td>
<td>- \hspace{1cm} - \hspace{1cm} - \hspace{1cm} -</td>
<td>- \hspace{1cm} - \hspace{1cm} - \hspace{1cm} -</td>
</tr>
<tr>
<td>Horizontal Load, (H_k)</td>
<td>- \hspace{1cm} - \hspace{1cm} - \hspace{1cm} -</td>
<td>- \hspace{1cm} - \hspace{1cm} - \hspace{1cm} -</td>
</tr>
</tbody>
</table>
Stability Analysis

1. Stability Against Overturning (at point A):

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

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

   **Since Overturning Moment < Restraining Moment**  → **OK**
Stability Analysis (continued)

2. Sliding

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

= Sliding Force = $(1.35 \times 61.8) + (1.50 \times 13.3) = 103$ kN
Friction Force = $0.45 [(1.0 \times 239.0) + (0 \times 20.0)] = 108$ kN

Since Sliding Force < Friction Force $\Rightarrow$ OK
Example 1: Cantilever RC Retaining Wall

Stability Analysis (continued)

3. Settlement

\[ \sum V_k = 239.0 + 20.0 = 259.0 \text{ kN} \]
\[ \Delta M = 464.7 + 44.0 - 100.9 - 32.5 = 375.3 \text{ kNm} \]

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

Eccentricity, \( e = \frac{B}{2} - x = 1.60 - 1.45 = 0.15 \text{ m} < \frac{B}{6} = 0.53 \text{ m} \)

\( \Rightarrow \) No negative pressure
Example 1: Cantilever RC Retaining Wall

Stability Analysis (continued)

3. Settlement

\[ A = B \times 1.0 \text{ m width} = 3.20 \times 1.0 = 3.2 \text{ m}^2/\text{m width} \]
\[ y = 3.20 / 2 = 1.60 \text{ m} \]
\[ I = 1.0 \times 3.20^3/12 = 2.73 \text{ mm}^4 \]

Bearing Pressure,
\[ q = \frac{\sum N}{A} \pm \frac{\sum My}{I} \]
\[ = \left( \frac{259.0}{3.2} \right) \pm \left( \frac{259.0 \times 0.15 \times 1.60}{2.73} \right) = 80.9 \pm 22.9 \text{ kN/m}^2 \]

\[ q_{Ed,\text{min}} = 58.0 \text{ kN/m}^2 \]
\[ q_{Ed,\text{max}} = 103.9 \text{ kN/m}^2 \]

Soil bearing capacity, \( q_{Ed} = 200 \text{ kN/m}^2 \)
\[ \Rightarrow \text{OK} \]
Example 1: Cantilever RC Retaining Wall

Element Design

\[ a = 2.71 \quad b = 25.9 \]

\[ c = \frac{0.40 \times 25}{58.0} = 0.80 \]

\[ d = 4.5 \times 19 + 10.0 = 95.5 \]

Soil bearing capacity
Base of wall
Soil & Surcharge

\[ 103.9 + 92.4 + 86.7 = 93.9 + 82.4 + 18.8 + 47.5 = 25.9 \]

Soil bearing capacity
Base of wall
Soil & Surcharge
Main Reinforcement

$h = 400$ mm, $b = 1000$ mm

Effective depth, $d = h - c - 1.5 \phi_{bar} = 400 - 45 - (0.5 \times 12) = 349$ 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

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

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

Provide H12-100 ($A_s = 1131 \text{ mm}^2/\text{m}$)
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

\[ K = \frac{M_{Ed}}{f_{ck}bd^2} = \frac{38.9 \times 10^6}{30 \times 1000 \times 349^2} = 0.011 < K_{bal} = 0.167 \]

\[ \therefore \text{Compression reinforcement is NOT required} \]

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

\[ A_{s,req} = \frac{M_{Ed}}{0.87f_{yk}z} = \frac{38.9 \times 10^6}{0.87 \times 500 \times 0.95 \times 349} = 270 \text{ mm}^2/\text{m} \]

Provide H12-150 (\( A_s = 754 \text{ mm}^2/\text{m} \))
Main Reinforcement (continued)

(iii) Heel

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

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

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

\[ A_{s,req} = \frac{M_{Ed}}{0.87 f_{yk} z} = \frac{102.4 \times 10^6}{0.87 \times 500 \times 0.95 \times 349} = 710 \text{ mm}^2/\text{m} \]

Provide H12-150 (\( A_s = 754 \text{ mm}^2/\text{m} \))
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 (\(A_{s,prov} = 566 \text{ mm}^2/\text{m}\))
Example 1: Cantilever RC Retaining Wall

Shear

(i) Wall

\[ V_{ab} = 1.50[2.71 \times 4.5] + 1.35 \left[ (25.9 - 2.71) \times \frac{4.5}{2} \right] = 88.7 \text{ kN/m} \]
\[ V_{ac} = 1.35(93.9 + 82.4) \times \frac{0.80}{2} = 95.2 \text{ kN/m} \]
\[ V_{bd} = 1.35 \left( 18.8 + 47.5 \times \frac{2.00}{2} \right) = 89.5 \text{ kN/m} \]
\[ \therefore V_{Ed} = 95.2 \text{ kN/m} \]

\[ k = 1 + \sqrt{\frac{200}{d}} = 1 + \sqrt{\frac{200}{349}} = 1.76 < 2.0 \]
\[ \rho_l = \frac{A_{sl}}{bd} = \frac{754}{1000 \times 349} = 0.0022 \leq 0.02 \]
Shear

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

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

\[ V_{Ed} \ (95.2 \text{ kN}) < V_{min} \ (155.8 \text{ kN}) \]

\[ \Rightarrow \text{OK} \]
Cracking

$h = 400\ \text{mm} > 200\ \text{mm}$

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

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

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

Wall: $100\ \text{mm} < 200\ \text{mm}$
Toe: $150\ \text{mm} < 200\ \text{mm}$
Heel: $150\ \text{mm} < 200\ \text{mm}$

Cracking OK
Example 1: Cantilever RC Retaining Wall

Detailing

![Diagram of a Cantilever RC Retaining Wall with dimensions H12-100, H12-200, H12-150, and H12-200]