SEACAP 21\004 Landslide Management

Mainstreaming Slope Stability Management

Theme 8 Remedial Measures: Design
8.5 and 8.6 Retaining Walls

Theme 8 Contents

Part 1 - Slopes

1) Overview of basic soil mechanics (Introduction),
2) Soil Slope stability analysis (Theme 8.1).

- **why slopes fail,**
- **failure shapes**
- **how each is analysed**
- **Use of slope stability analysis programs.**
- **Forward and backanalysis to diagnose problems.**

3) Rock Slope stability (Theme 8.2)
4) Cross section design (Theme 8.3)
5) Earthworks design

- new cuttings and embankments (Theme 8.4)
- Remedial works to improve stability (Theme 8.4)

Part 2 – Retaining walls

6) Overview of soil mechanics (Introduction)
7) Gravity retaining wall design (Themes 8.5 and 8.6)
8) Embedded retaining walls (Themes 8.5 and 8.6)
9) Reinforced soil walls (Themes 8.5 and 8.6)

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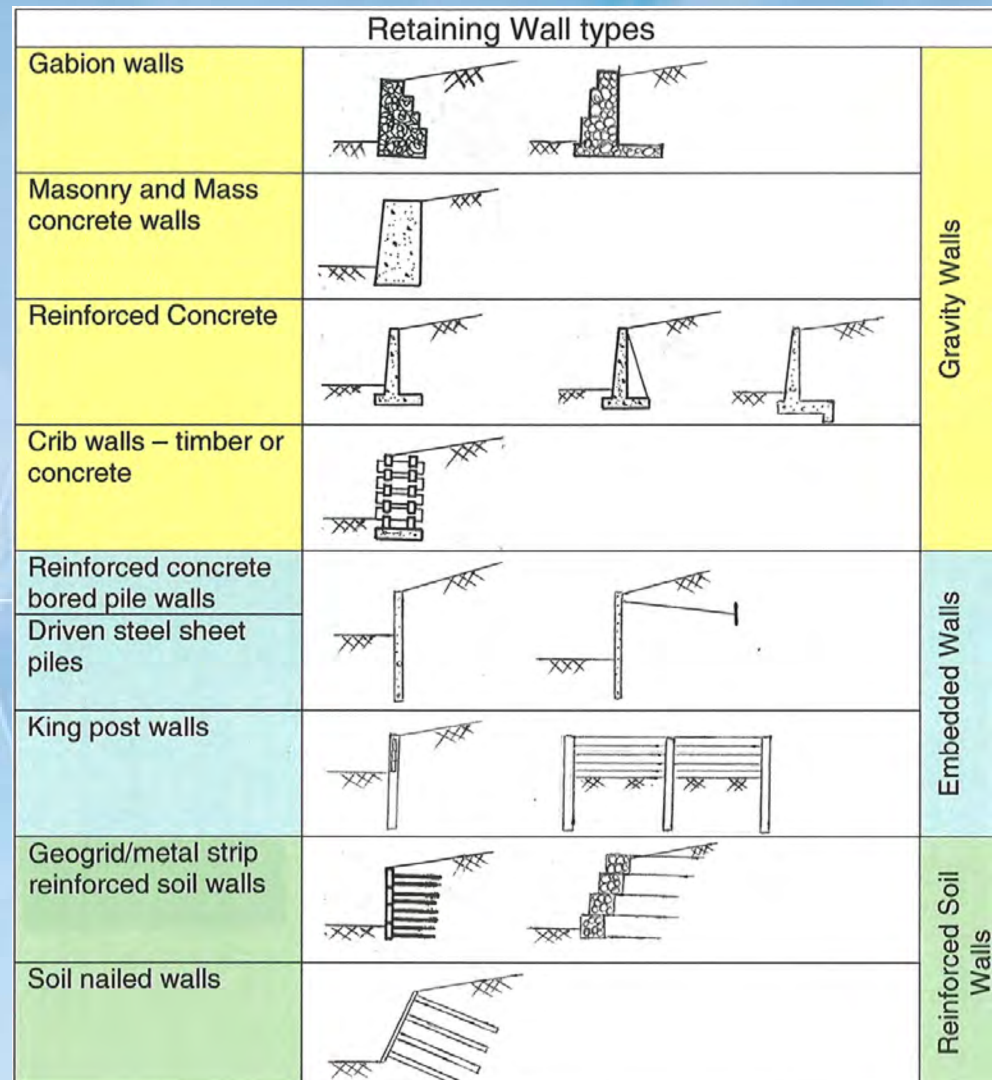
Many different types of retaining walls used across the world



Retaining Wall types		
Gabion walls		Gravity Walls
Masonry and Mass concrete walls		Gravity Walls
Reinforced Concrete		Gravity Walls
Crib walls – timber or concrete		Gravity Walls
Reinforced concrete bored pile walls		Embedded Walls
Driven steel sheet piles		Embedded Walls
King post walls		Embedded Walls
Geogrid/metal strip reinforced soil walls		Reinforced Soil Walls
Soil nailed walls		Reinforced Soil Walls

The objectives of this session are:

- To cover some basic soil mechanics to help us understand how retaining walls work.
- To consider the forces which act on the different types of retaining walls and what failure mechanisms must be considered.
- To examine advantages and disadvantages of each wall type and when they can be used
- To concentrate on gravity retaining walls but to also give an overview of all the other wall types.

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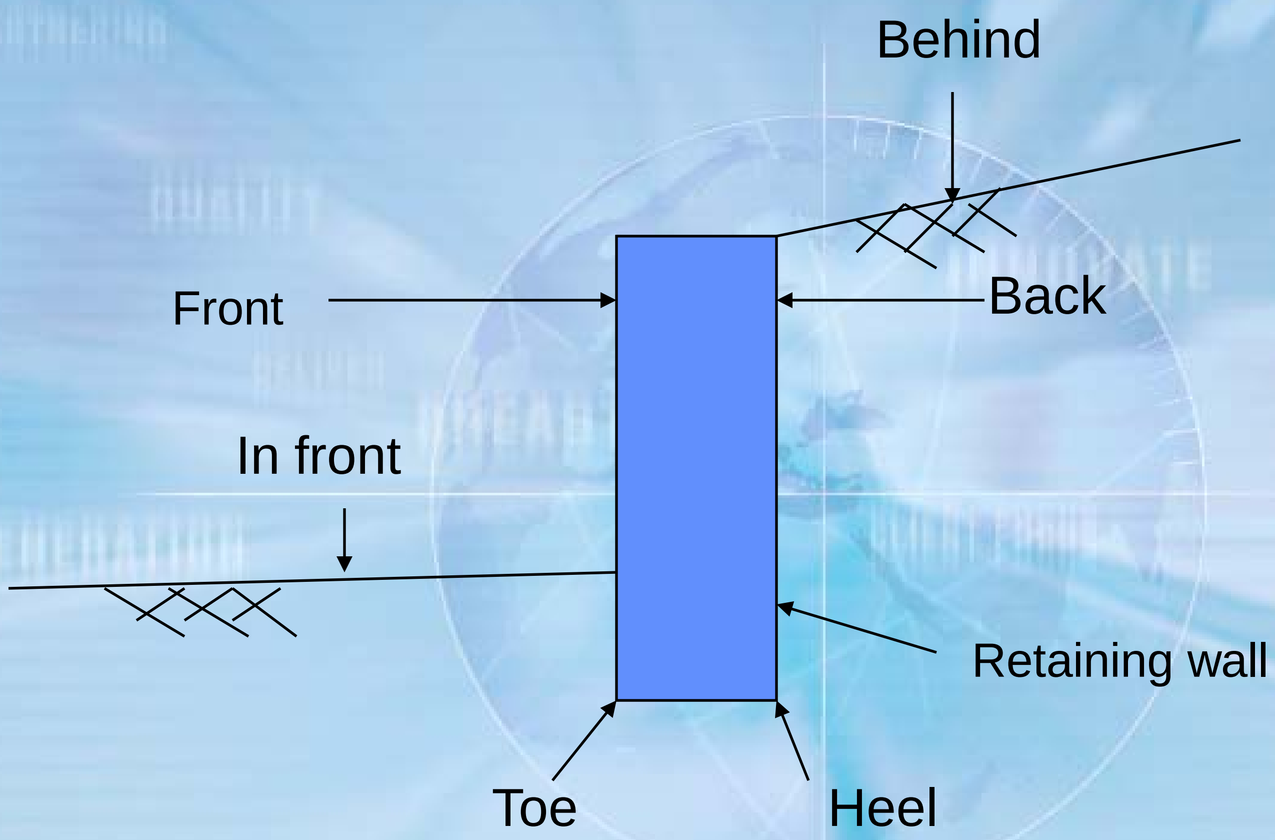

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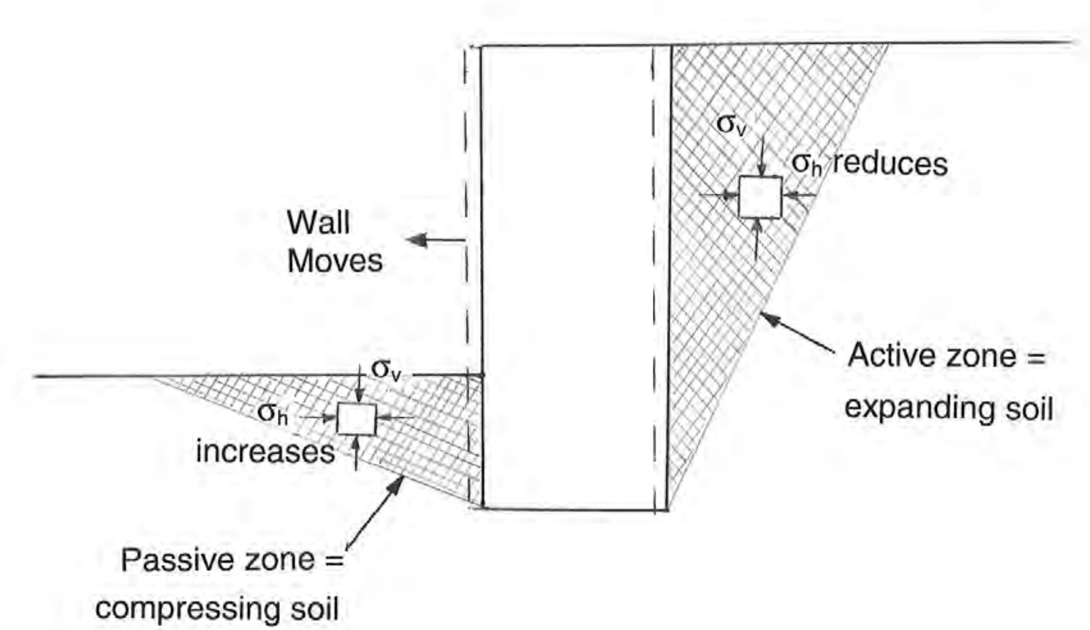

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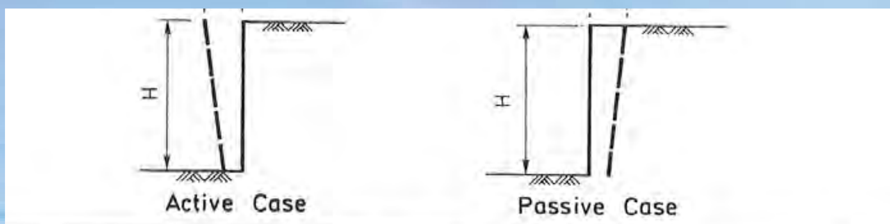
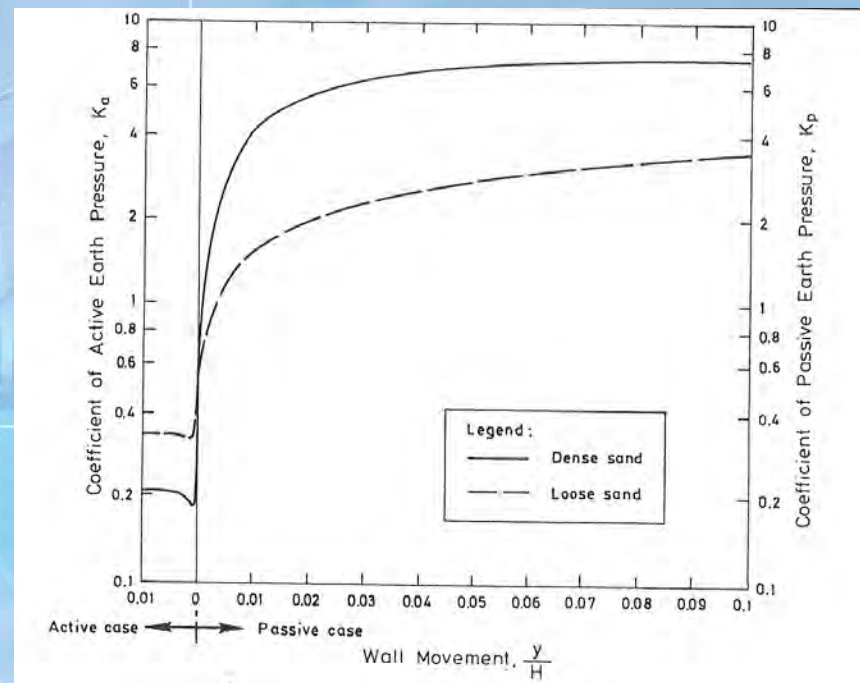


Soil Type	Movement for the Development of Failure Conditions, $\frac{y}{H}$	
	Active Case	Passive Case
Dense sand	0.001	0.02 – 0.06
Loose sand	0.005	0.06 – 0.35
Stiff clay	0.01	0.02
Soft clay	0.02	0.04

Notes : (1) Figure based on data given by Canadian Geotechnical Society (1985) and Rowe & Peaker (1965).
(2) Figure only applicable for rigid walls and soil with K_o less than unity.



Diagrams taken from Hong Kong Geoguide 1
“Guide to Retaining Wall Design”

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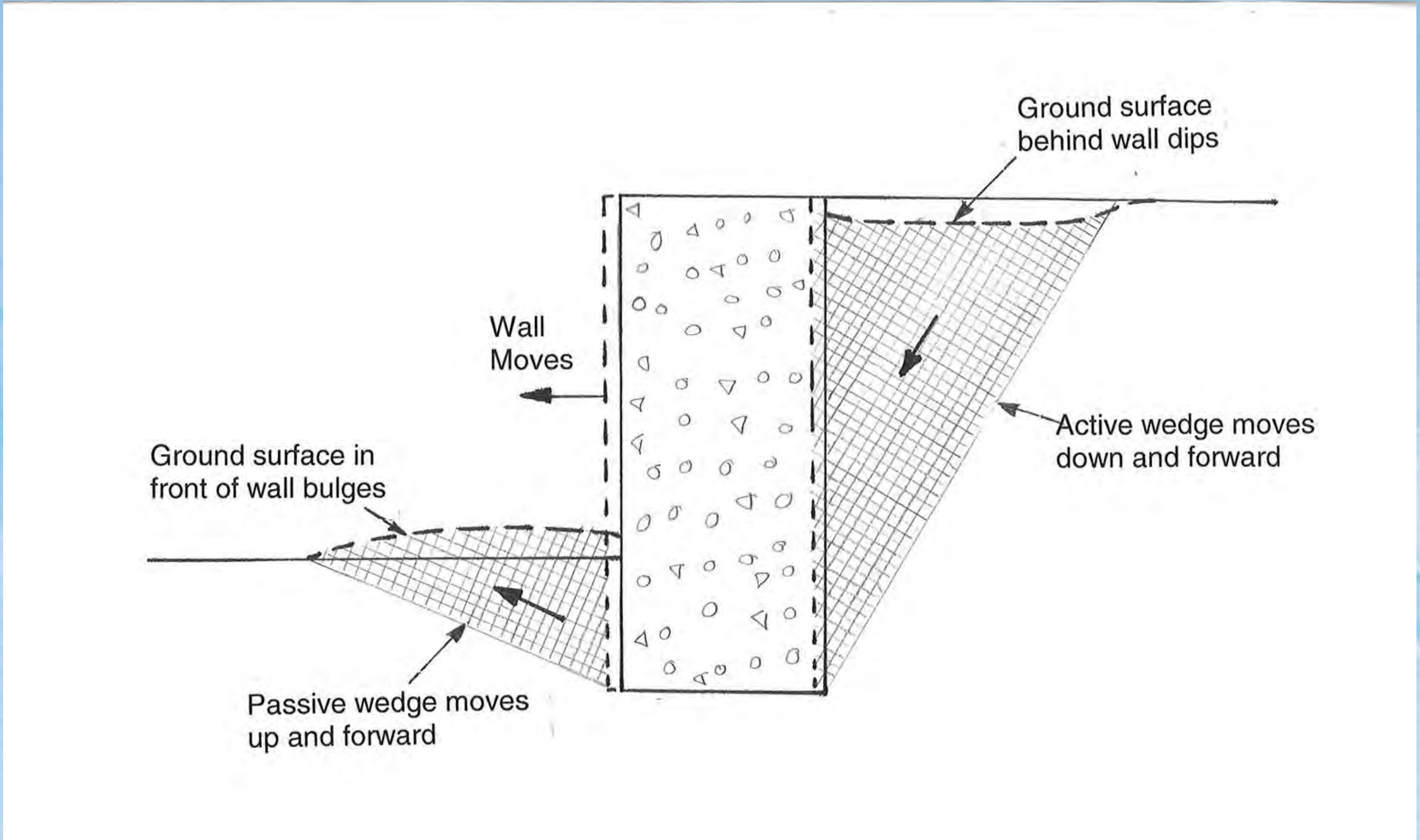

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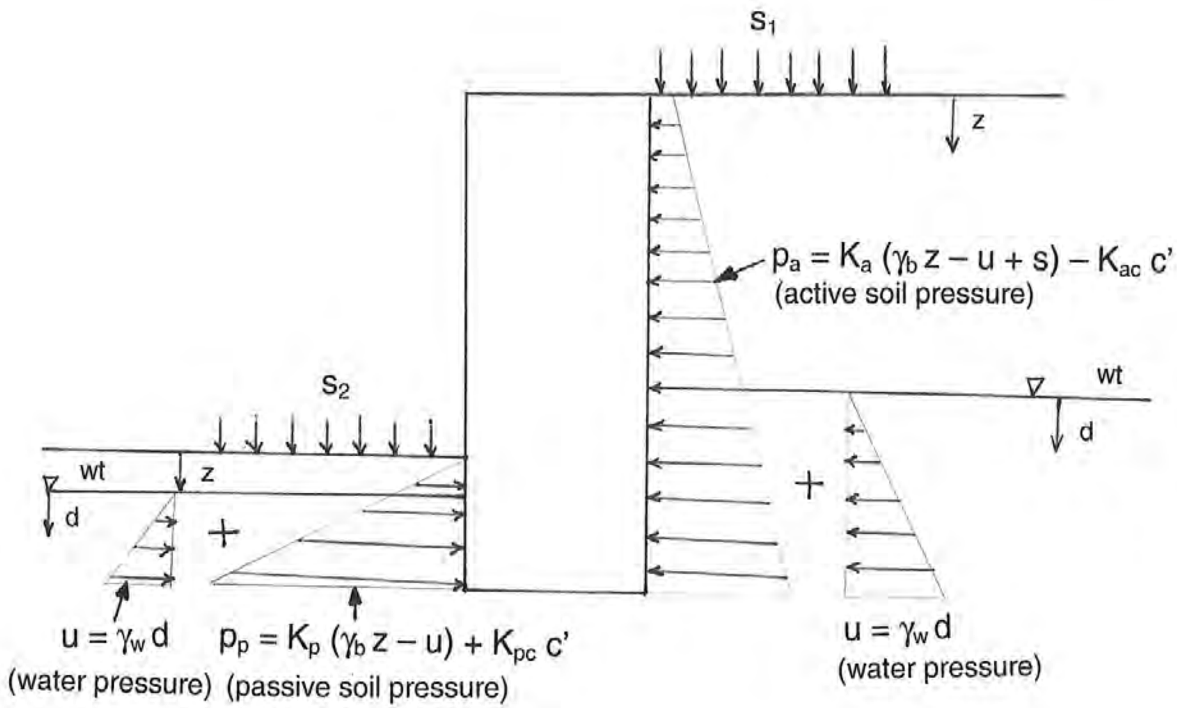

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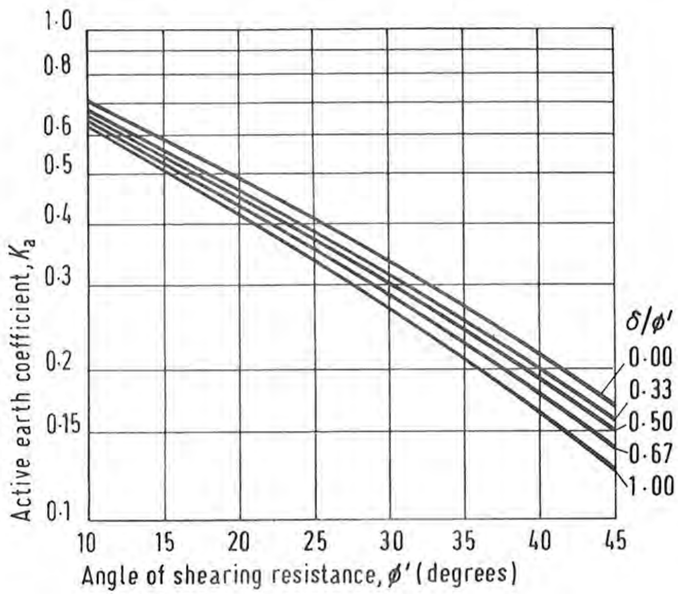

Figure 39 *Coefficients of active earth pressure (horizontal component) for horizontal retained surface (after Caquot and Kerisel[19])*

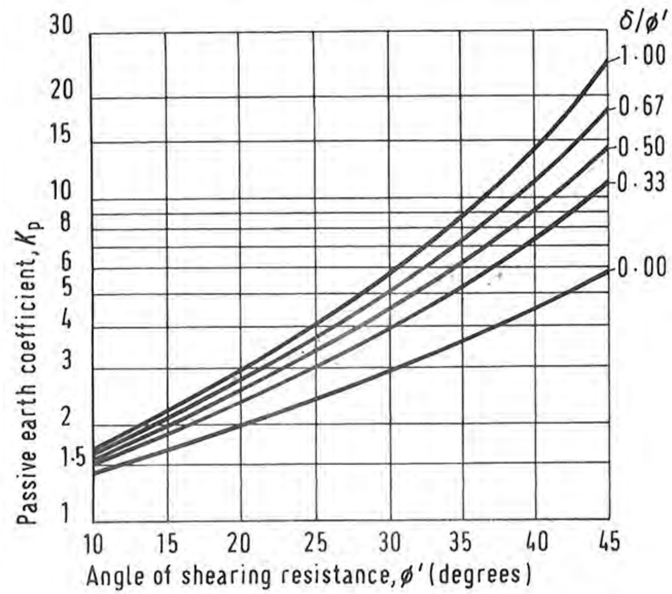

Figure 40 *Coefficients of passive earth pressure (horizontal component) for horizontal retained surface (after Caquot and Kerisel[19])*

Ka and Kp vary with soil strength (φ) and wall/soil friction (δ)

Graphs from CIRIA 104

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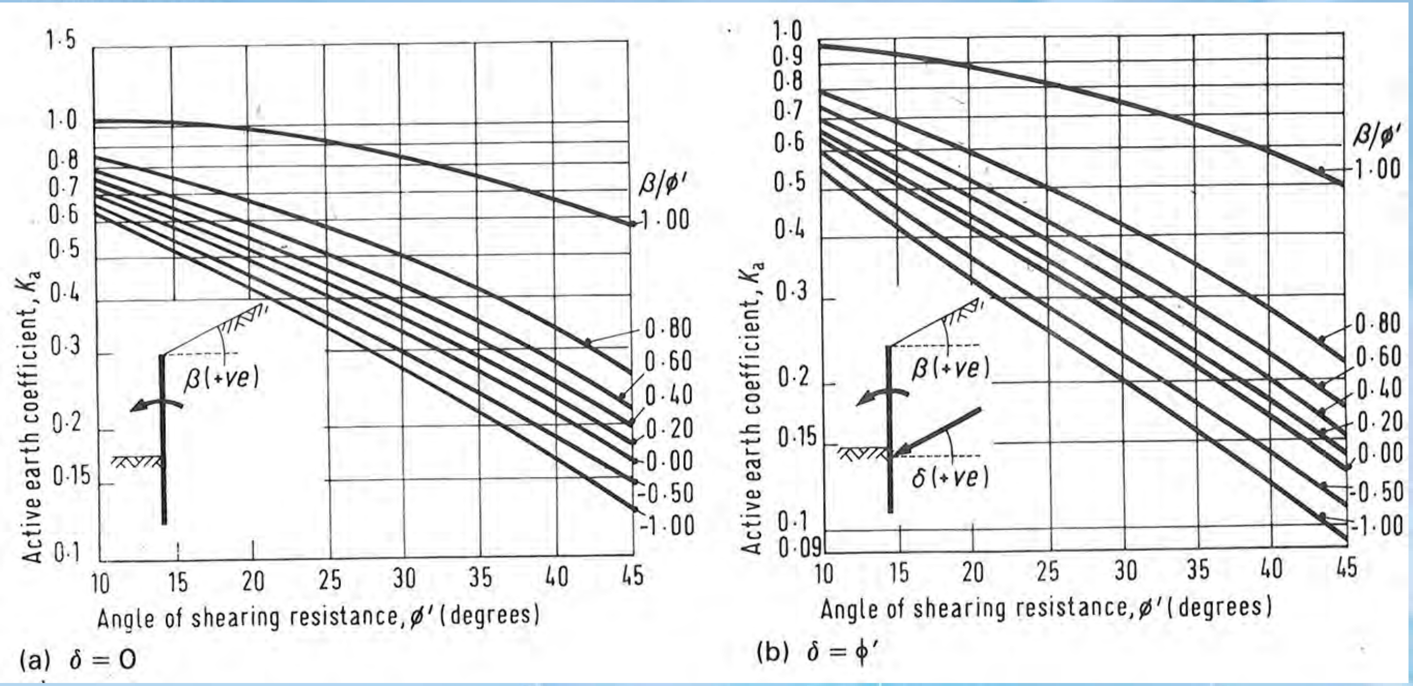
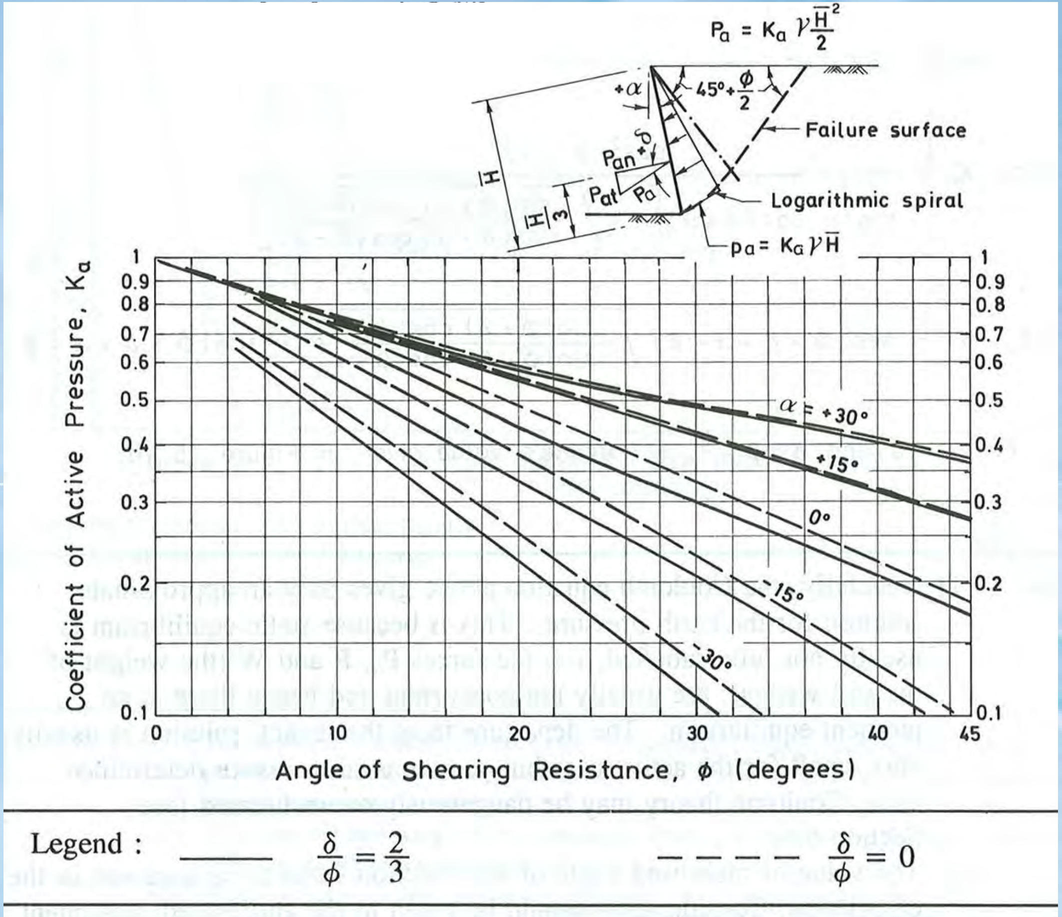


Ka and Kp also vary with slope angle (β)

Graphs from CIRIA 104

Ka also varies with inclination of the back of the wall (α)

Graph from "Navdoc"



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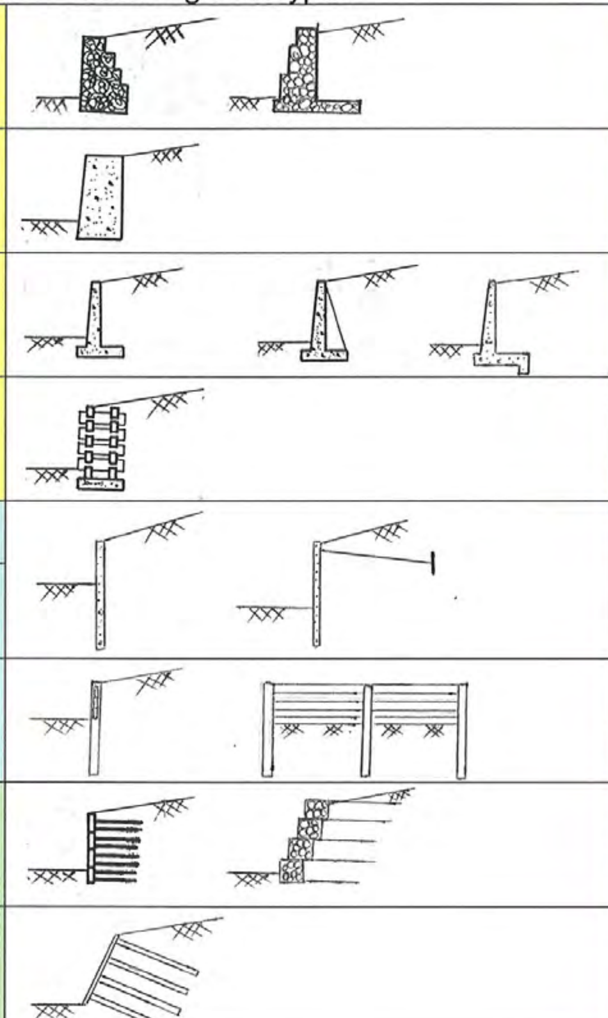

Retaining Wall types

Gabion walls	Gravity Walls
Masonry and Mass concrete walls	Gravity Walls
Reinforced Concrete	Gravity Walls
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← Part 1

Gravity walls

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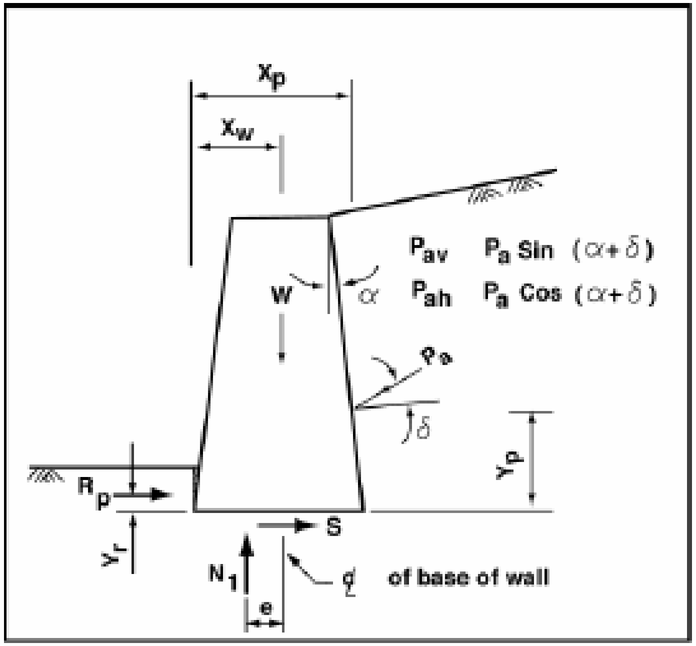
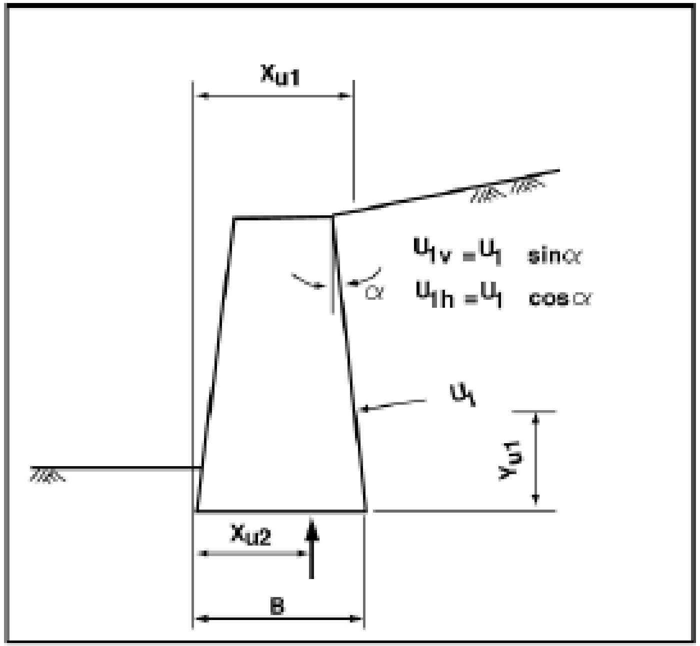


Forces on retaining walls
(water forces not shown)



Water forces on retaining wall

Forces acting on Gravity Retaining wall

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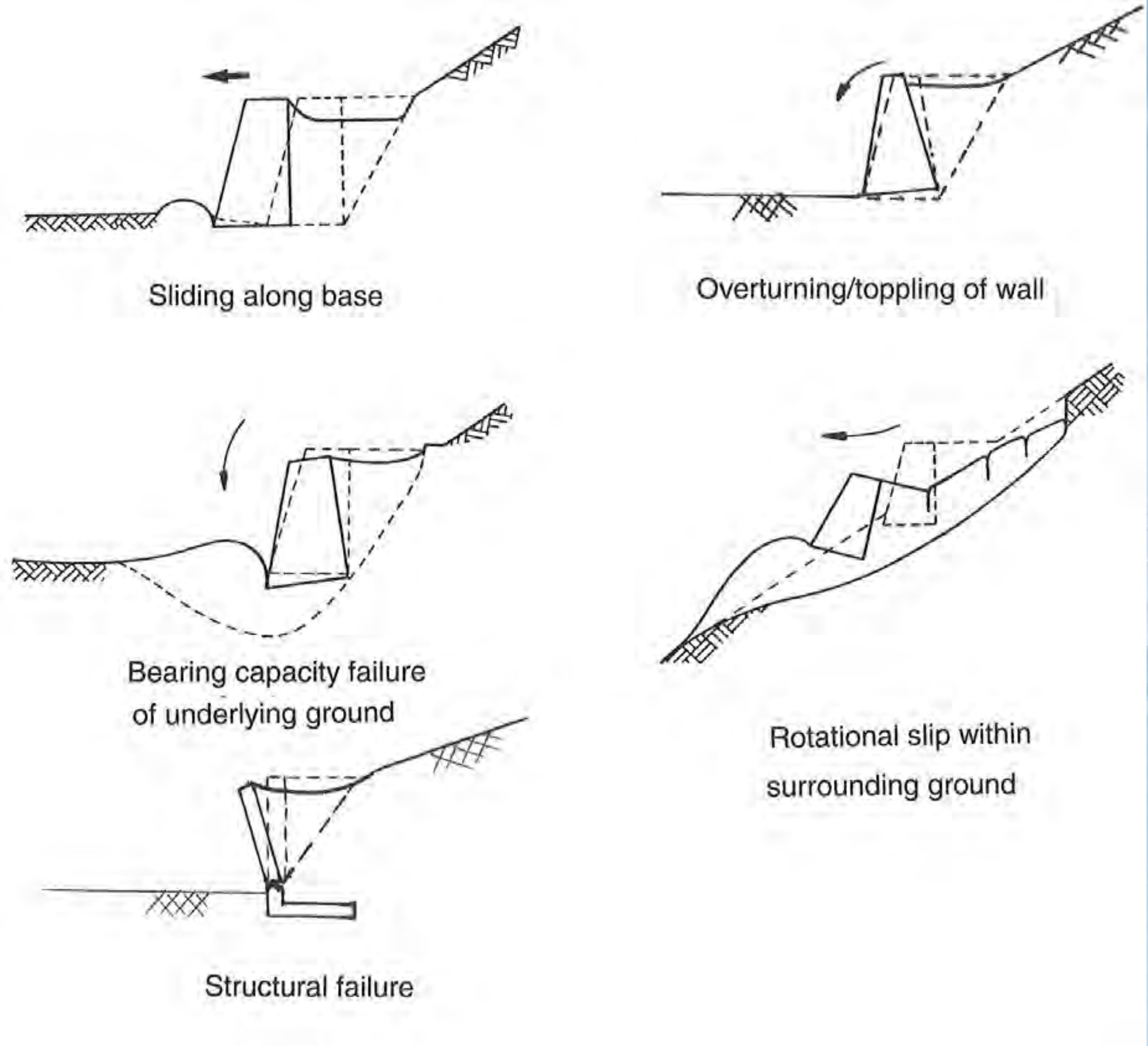

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Factors of safety = <u>Resisting forces/moments</u>
Activating forces/moments

Many different methods of assessing factor of safety (depending which code of practice is used) but one possible set of factors is given below:

Failure mechanism	**Activating forces/moments**	**Resisting forces/moment**	**Factor of safety**
Overturning about wall toe	Active earth pressure Water on wall back	Wall weight Passive pressure	2
Sliding	Active earth pressure Water on back of wall	Friction on wall base Passive pressure	1.5
Bearing	Pressure at wall base due to weight	Bearing capacity of soil	2 to 3

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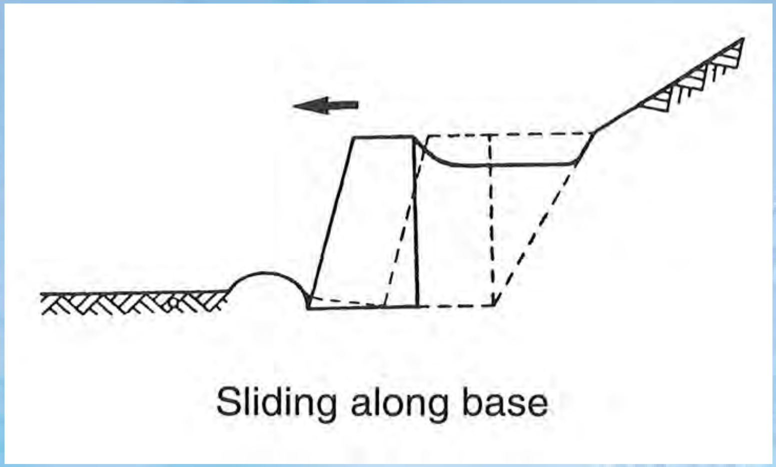

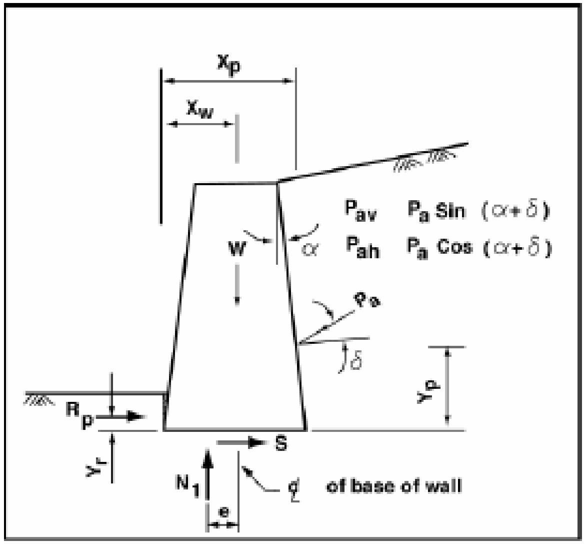

Forces on retaining walls
(water forces not shown)

Sliding

Factor of safety = <u>Horizontal resisting forces</u> = 1.5
Horizontal activating forces

Activating forces Fa = Active force, horizontal component (Pah) + Water pressure on back (U)

Resisting forces Fr = Friction on base (S) + Passive force on front (Rp)

$= N_1 \tan\delta_b + R_p$ where $N_1 = W + P_{av} - U$

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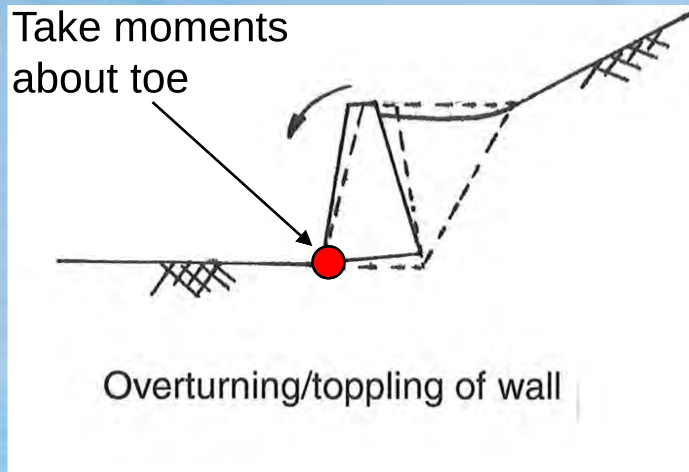
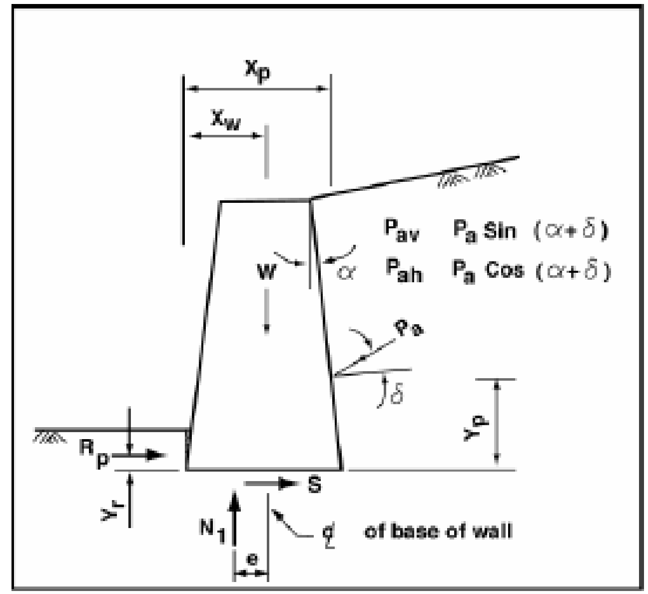




Forces on retaining walls
(water forces not shown)

Overturning

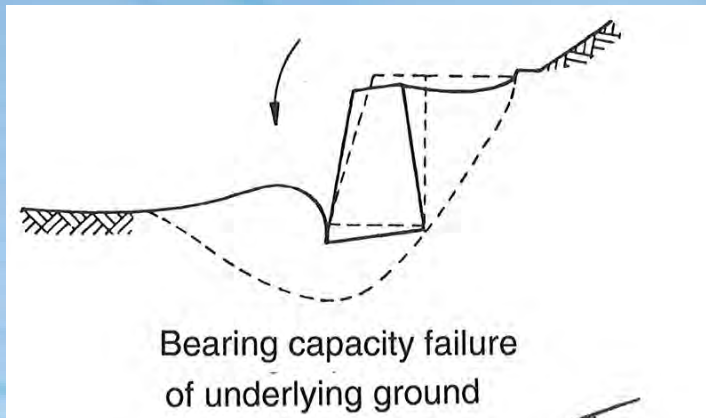
Factor of safety = $\frac{\text{Resisting moments}}{\text{Overturning moments}}$ = 2

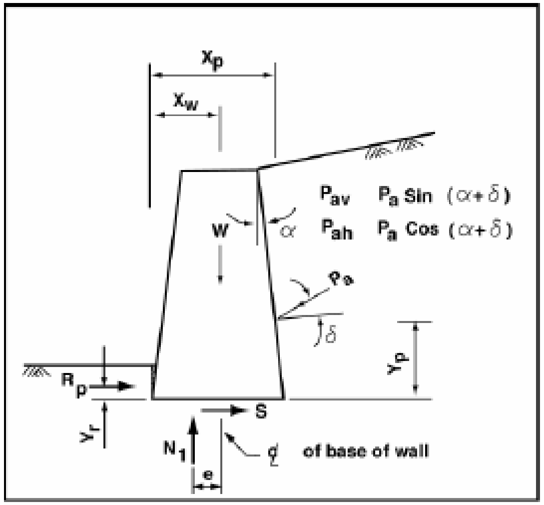
Overturning moment Mo = Moments due to active earth pressures + moments due to water pressures on back and underside of wall.

$$M_o = P_{ah}y_p - P_{av}x_p + U_{ih}y_{u1} - U_{1V}x_{u1} + U_2x_{u2}$$

Resisting Moment pressure. M_r = Moment due to wall weight + Moment due to passive

$$M_r = W\,x_w + R_p y_r$$





Forces on retaining walls
(water forces not shown)

Bearing Failure

Factor of safety = $\frac{\text{Bearing capacity of ground } (q_f)}{\text{Mobilised base pressure } (q_{mob})}$ = 2 to 3

From the overturning calculation you know N_1, M_o and M_r

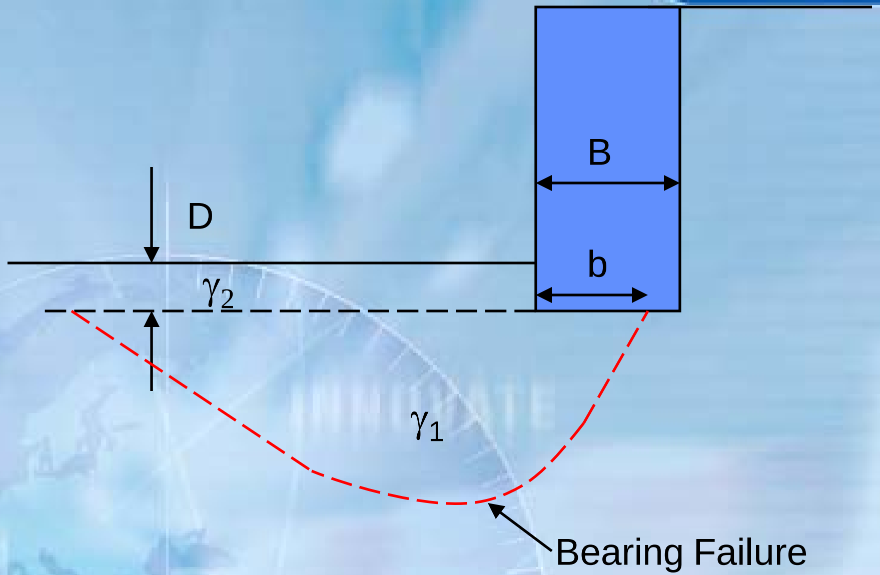
Eccentricity of the reaction from the centreline $e = B/2 - (M_r - M_o)/N_1$

Where B is the base width of the wall

Mobilised base pressure (q_{mob}) = $N_1/(B-2e)$ kN/m/m run of wall.

Bearing capacity (q_f)

$$q_f = \tfrac{1}{2}\,\gamma_1\, b\, N_\gamma + c' N_c + \gamma_2\, D\, N_q$$

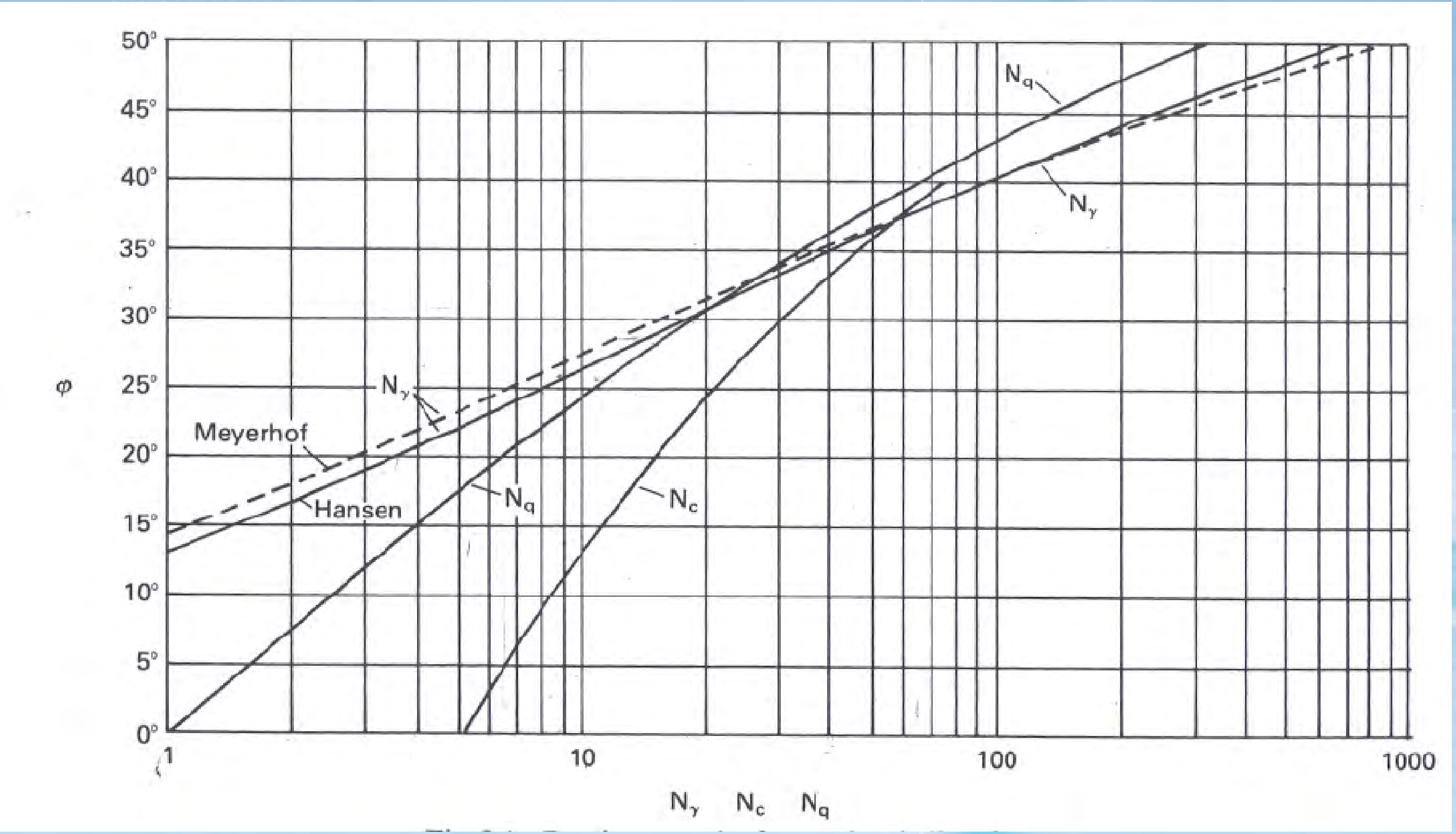


N_γ, N_c N_q are bearing capacity factors which can be derived from the graph on the next slide.

γ_1 and γ_2 are unit weights = γ_b if the soil is above the water table and $\gamma_b - \gamma_w$ if soil is below water table.

b is the width of the loaded area b=B-2e

Bearing capacity factors for walls founded at shallow depths



Graph taken from “Soil Mechanics” by R.F.Craig

Bearing capacity of clay soils
(under short term loading)

$$q_f = Cu\ Nc + \gamma_b\ D$$

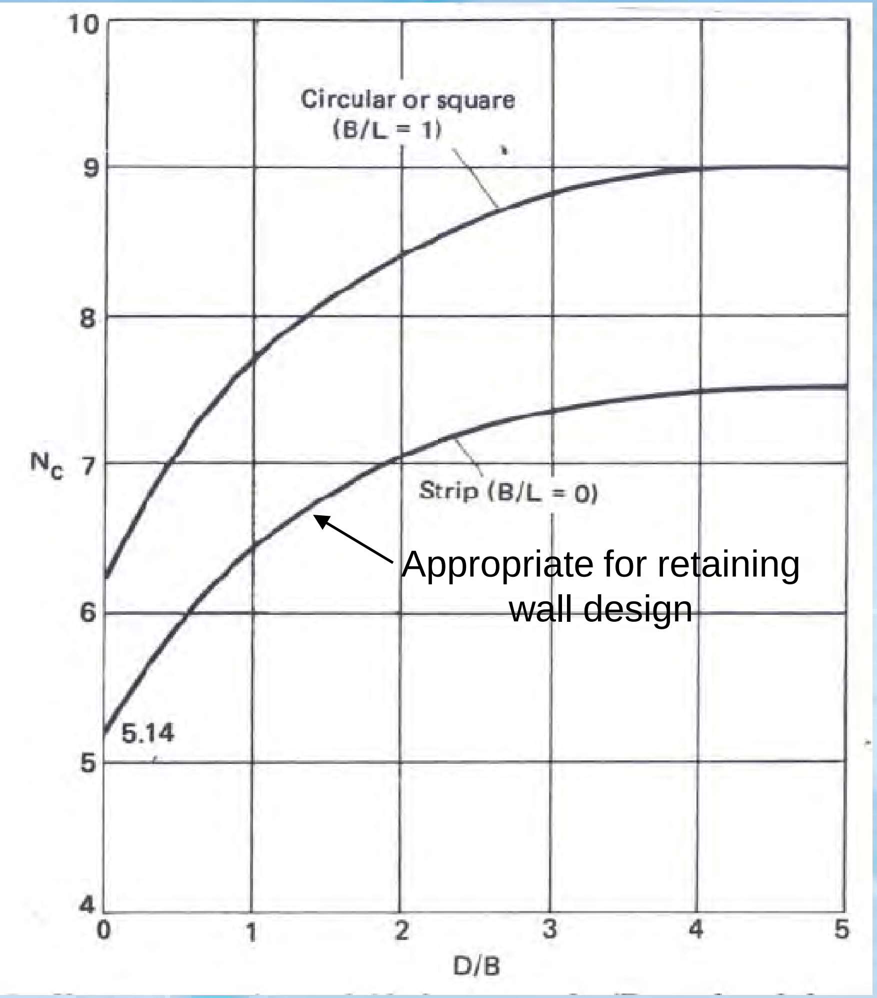
Where D is the depth of the wall base below adjacent ground level.

γ_b = bulk unit weight of the soil

Cu is the undrained shear strength

Nc is the bearing capacity factor which can be taken from the adjacent graph.

B is the wall base width.



Skempton's values of Nc for $\varphi_u = 0$

Taken from "Soil Mechanics" by R.F.Craig

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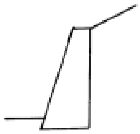
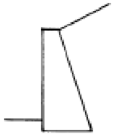
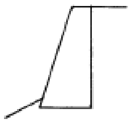
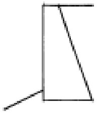
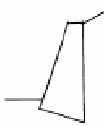
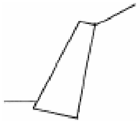
Shape and location	Advantages	Disadvantages
a 	Lower toe pressure, greater resistance to overturning	Greater wall height for a fixed retained slope angle
b 	Smaller wall height for fixed retained slope angle	Lower resistance to overturning, higher toe pressure Higher active earth pressures due to sloping back of wall
c 	Lower toe pressure, greater resistance to overturning	Greater wall height for fixed height of retained soil
d 	Smaller wall height for fixed height of retained soil	Higher toe pressure, greater extent of excavation into road – more disruption to traffic Higher active earth pressures due to sloping back of wall
e 	Greater resistance to sliding	Shape not suitable for gabion construction, increased volume of excavation, positive drainage required at heel to prevent ponding and foundation softening.
f 	Greater resistance to sliding and overturning, ground bearing pressures evened out Active earth pressures reduced due to sloping back	Tilted shape more difficult to construct in gabion, increased volume of excavation, compaction behind wall more difficult, positive drainage required at heel to prevent ponding and foundation softening

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Gabion Retaining Walls

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Gabion walls

Advantages:

- No specialist equipment required
- Can construct by hand
- Can use locally won rockfill
- Flexible
- Freedraining so no need to worry about build up of pore pressures behind
- Good base friction providing placed directly on underlying soil.

Gabion Walls

Disadvantages:

- not as durable as a concrete or masonry wall
- Low unit weight. Less resistance per unit volume of wall. Rockfill can be grouted in order to increase unit weight of wall.
- Flexibility
- Potential for loss of material through wall due to water flow. Recommend geotextile behind wall to stop wash out.
- Not particularly well suited to rapidly varying base level. Can be overcome by founding on a concrete or mortared masonry base but this defeats some of the benefits of a gabion wall.

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Flexibility

Advantage – Good on soft ground, can tolerate differential settlements. Good as a catch wall, deformation means can absorb impact energy.

Disadvantage – Not very good immediately below a road where wall deformation leads to road damage.

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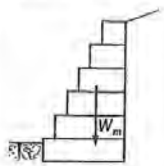
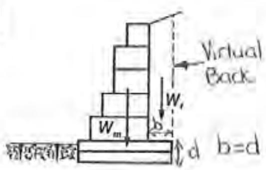
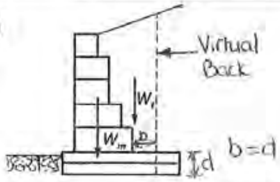
Gabion Wall shapes	Advantages	Disadvantages
a) 	Simple to construct. Greater overturning resistance and toe pressure (due to longer lever arm).	Wall height for fixed slope angle is higher.
b) 	Greater sliding resistance due to tilted base. Lower wall height for fixed slope angle.	Greater excavation due to tilted base. Increased active earth pressures due to wall back slope.
c) 	Greater sliding resistance due to tilted base. Sloping wall back reduces active earth pressures.	Greater excavation due to tilted base. Fill compaction behind wall is more difficult.
d) 	Extended base so greater overturning and sliding resistance.	Greater volume of excavation.
e) 	Extended base so much greater sliding resistance and slightly greater overturning resistance.	Much greater volume of excavation.

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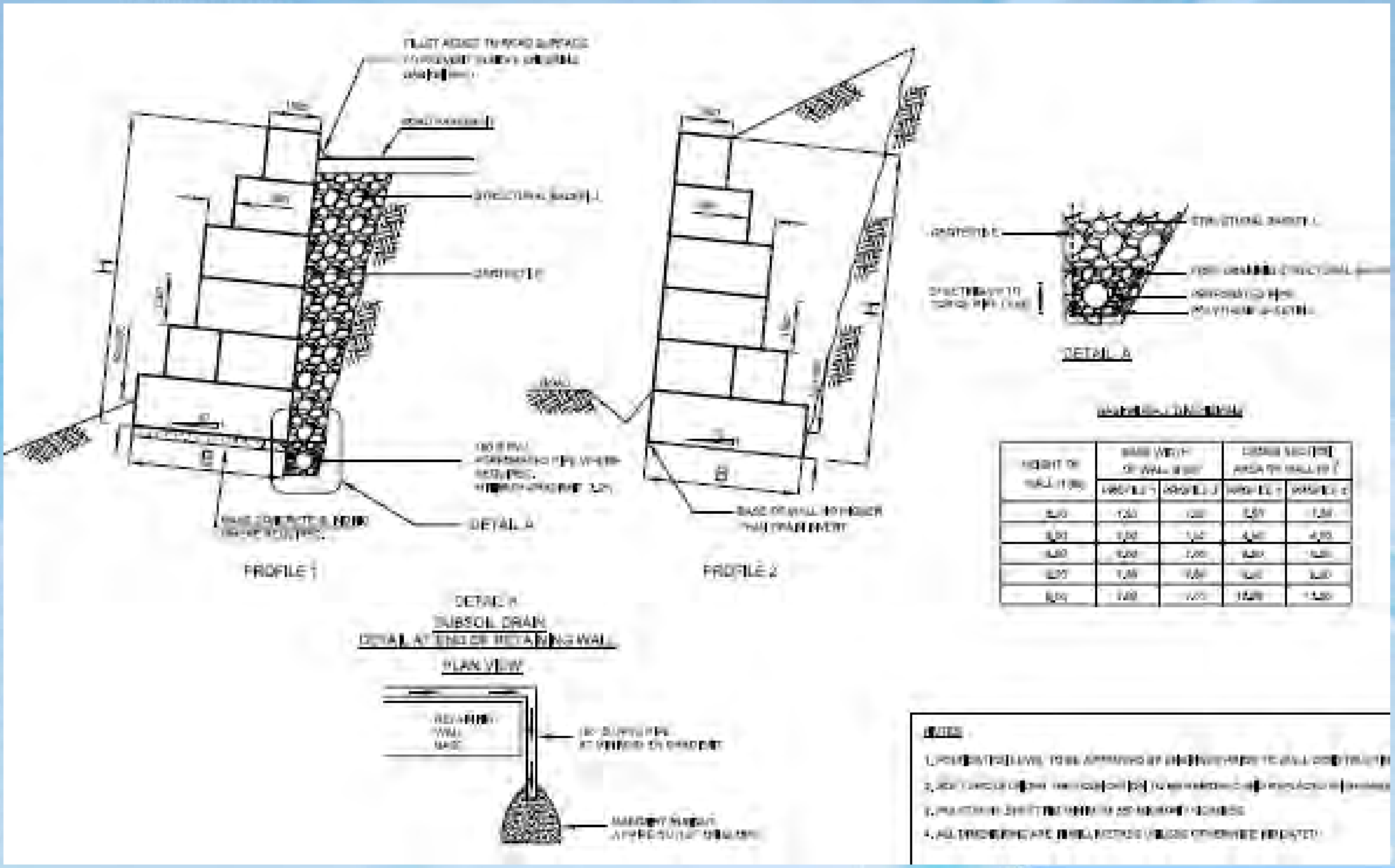

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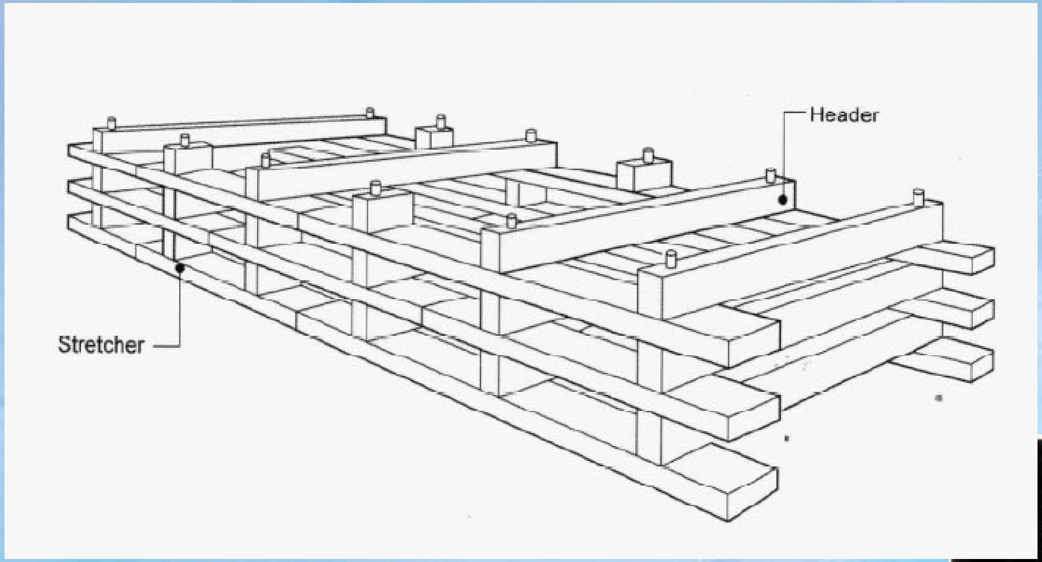

Crib Walls

Advantages of crib walls

- Can be built by hand providing crib sections are not too large.
- Relatively easy to build/ rapid construction.
- Crib wall section can be pre-cast and transported to site and held in stock for emergency works.
- Wall is free draining so no need to include drainage.
- Some flexibility although not as good as gabions
- Looks good
- Top level can be varied easily

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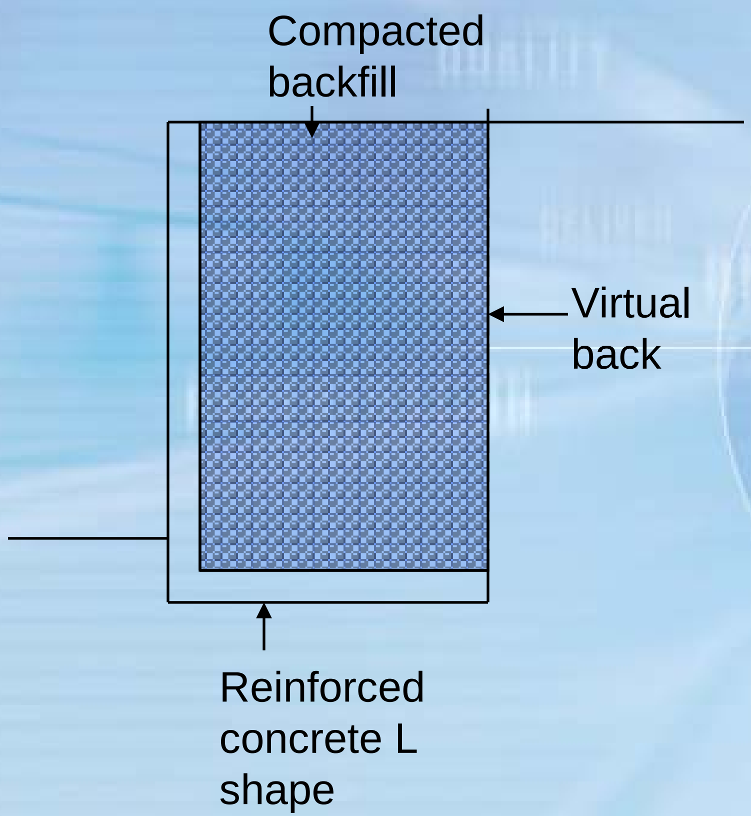
Disadvantages of crib walls

- Usually requires a concrete base
- Timber is not highly durable.
- Precasting works needed for concrete walls + transport to site.
- Not very economical for short lengths of wall.
- Not particular well suited to rapidly varying base level. Can be overcome by founding on a concrete slab/base wall.
- Unit weight of wall is slightly higher than gabions but not as high as concrete walls so wider wall required to provide same resistance.

Reinforced Concrete Walls

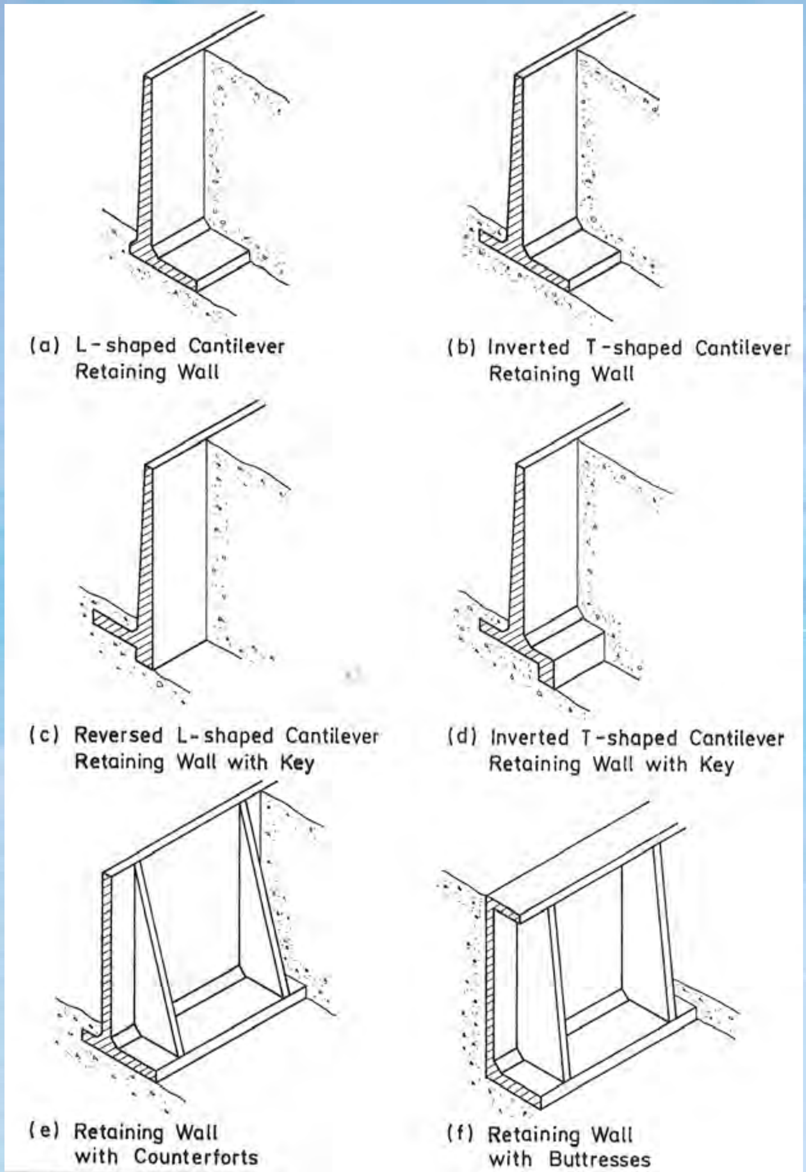


Advantages of concrete walls

- unit weight of wall is high compared to crib or gabion walls. Therefore generally wall is less wide than crib or gabion wall.
- Excavated material can be replaced over wall, low volume of imported materials
- Highly durable
- Small walls can be pre-cast and lifted into place.
- Stiff wall therefore good below and immediately adjacent to road pavements

Disadvantages of concrete walls

- requires reinforced concrete plant and skills.
- Not naturally permeable, must include weep holes or other drainage to ensure active zone is drained.
- Unless concrete is roughened or cast directly against gravel, base friction is not as good as gabions.
- Not very flexible, needs competent foundation soil.



Reinforced Concrete Wall Shapes

Mortared Masonry Walls

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Advantages of mortared masonry walls

- well suited to rapidly varying ground levels.
- High unit weight so wall generally less wide than lighter crib or gabion walls
- Durable.
- Provide good support to roads.
- Looks good

Disadvantages of mortared masonry walls

- very prone to damage under differential movements. Need to be founded on competent soils/rock. If on soils then concrete base slab usually needed. Regular movement joints (say every 5m) required especially at change in height or foundation level.
- Not permeable therefore weep holes must be provided+ zone of free draining fill behind wall. Danger of drainage clogging.
- Good quality materials required.

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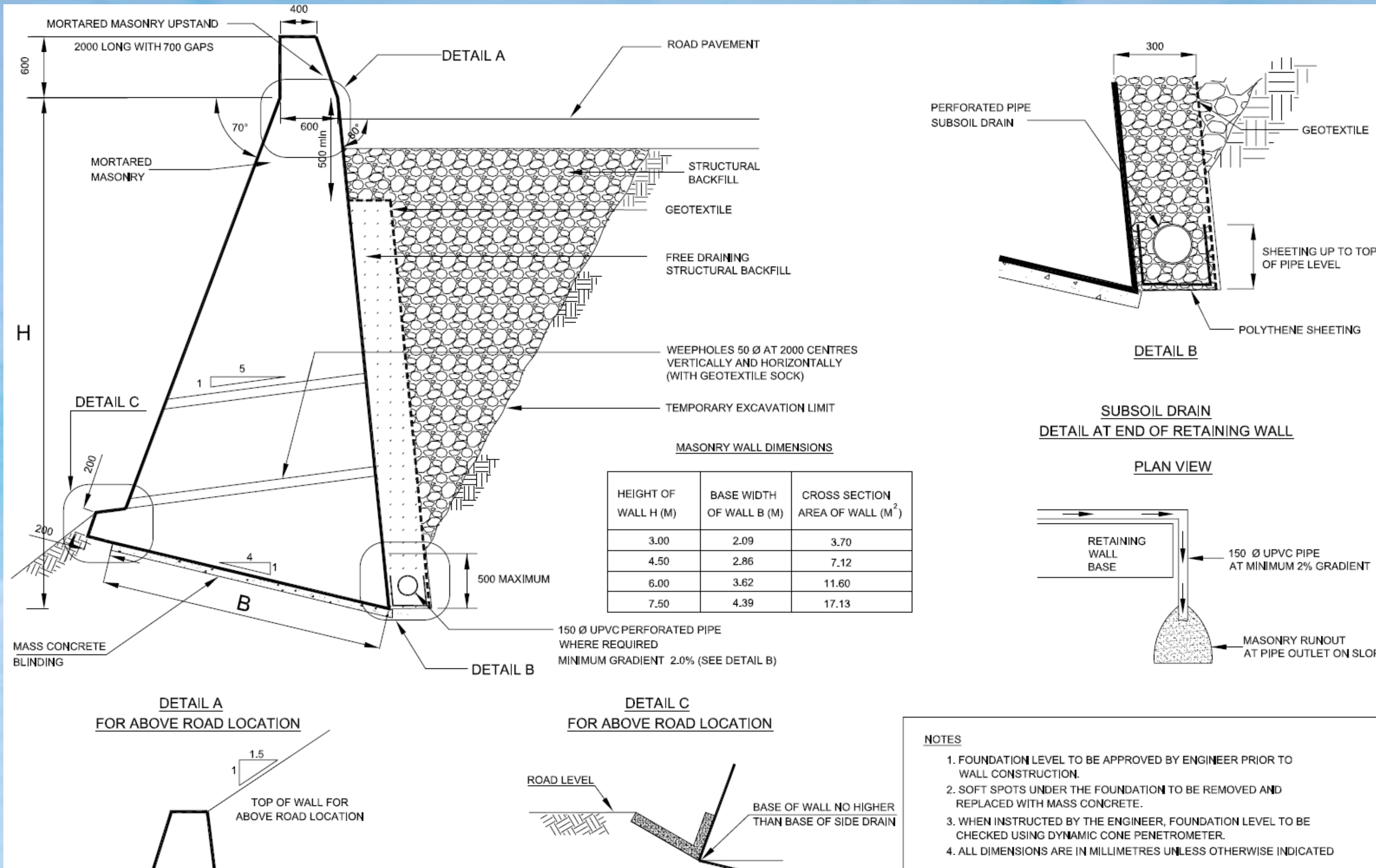

MASONRY WALL DIMENSIONS

HEIGHT OF WALL H (M)	BASE WIDTH OF WALL B (M)	CROSS SECTION AREA OF WALL (M^2)
3.00	2.09	3.70
4.50	2.86	7.12
6.00	3.62	11.60
7.50	4.39	17.13

NOTES

1. FOUNDATION LEVEL TO BE APPROVED BY ENGINEER PRIOR TO WALL CONSTRUCTION.
2. SOFT SPOTS UNDER THE FOUNDATION TO BE REMOVED AND REPLACED WITH MASS CONCRETE.
3. WHEN INSTRUCTED BY THE ENGINEER, FOUNDATION LEVEL TO BE CHECKED USING DYNAMIC CONE PENETROMETER.
4. ALL DIMENSIONS ARE IN MILLIMETRES UNLESS OTHERWISE INDICATED

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Typical Composite Wall

Dry Stone

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Wall backfill and drainage

Issues:

1) Good compaction of backfill
2) Ensure no build up of water pressures behind wall (very important).
3) Ensure no washout of backfill through the wall. Gabion, crib walls and composite masonry walls are particularly problematic.

Backfill types:

Clay – hard to compact, shrink/swell, low permeability.

Sand – Careful drainage design needed, washout big problem

Gravel – Better but drainage and geotextile still recommended

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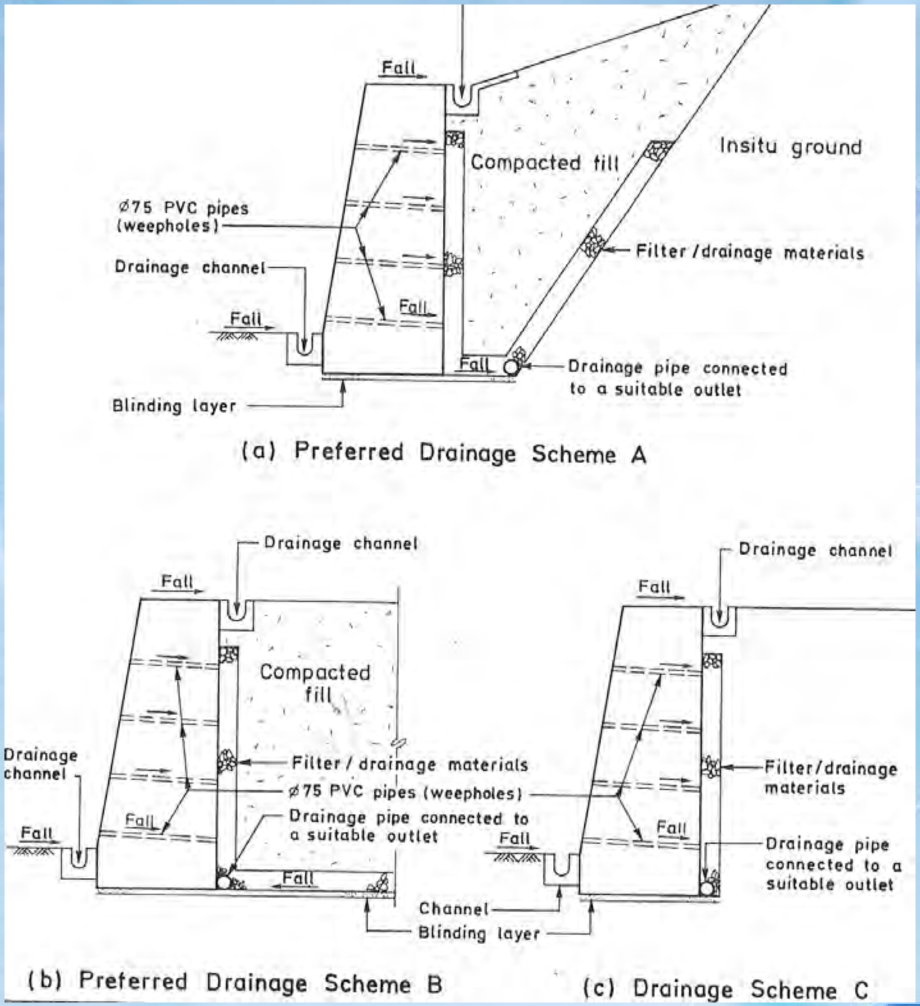

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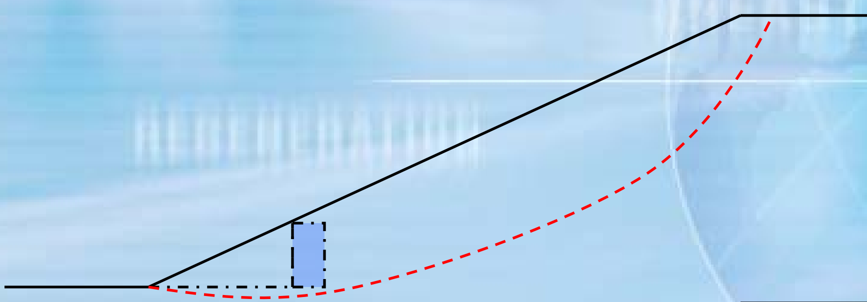
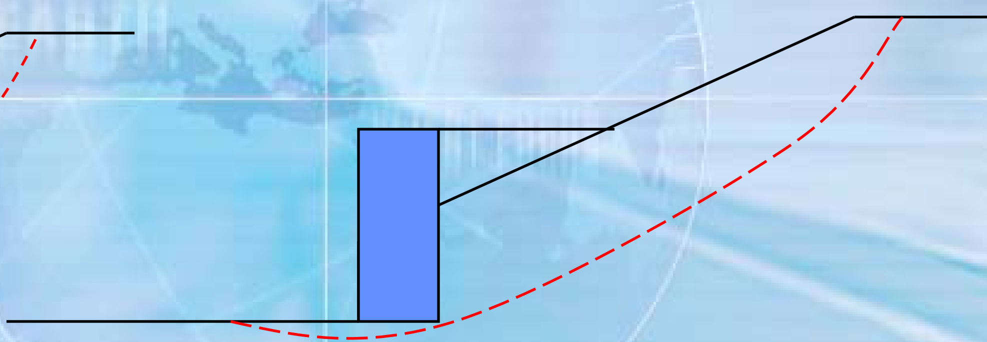
General comments about gravity walls:

1) **Unlike piled walls, gravity walls contribute very little to slope stability unless part of a toe filling scheme.**



E.G if you need to cut the toe out of a marginally stable slope. (FOS=1)

Wall has similar weight to soil, so still considerable more weight removed than added >> reduction in FOS.



Very large wall likely to be needed to compensate for weight removed and keep FOS=1. Excavation to install wall likely to be excessive.

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General comments about gravity walls:

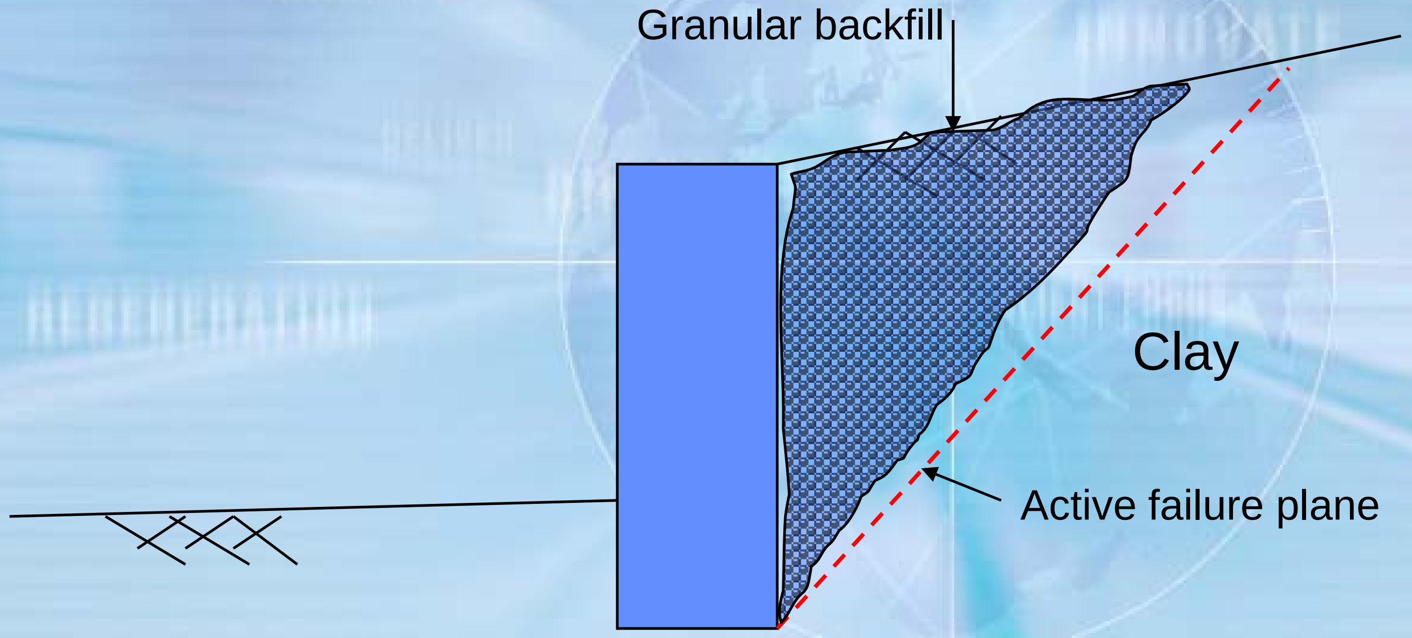
2) When assessing the passive resistance make sure that you have allowed for:

- future excavations in front of the wall e.g. to install drainage or other services.
- Future soil erosion
- Actual topography in front of wall (resistance reduces if ground slopes away from wall)
- Don't include any benefit from temporary surcharges.

Gravity wall design typically includes very little or no passive resistance.

General comments about gravity walls:

3) Most critical active wedge may run behind granular backfill.



General comments about gravity walls:

4) Need to design temporary excavation of slope to make space for wall construction:

- Firm/stiff clay will remain stable over short periods (a couple of weeks) at steep cut angles without any support.
- Dense granular soils above the water table will probably also remain stable at about 45 degrees or sometimes steeper for short periods.
- In these soils construct walls in short lengths to minimise time that unsupported cut is open.
- Loose granular soils, wet soils and soft clays will need support.

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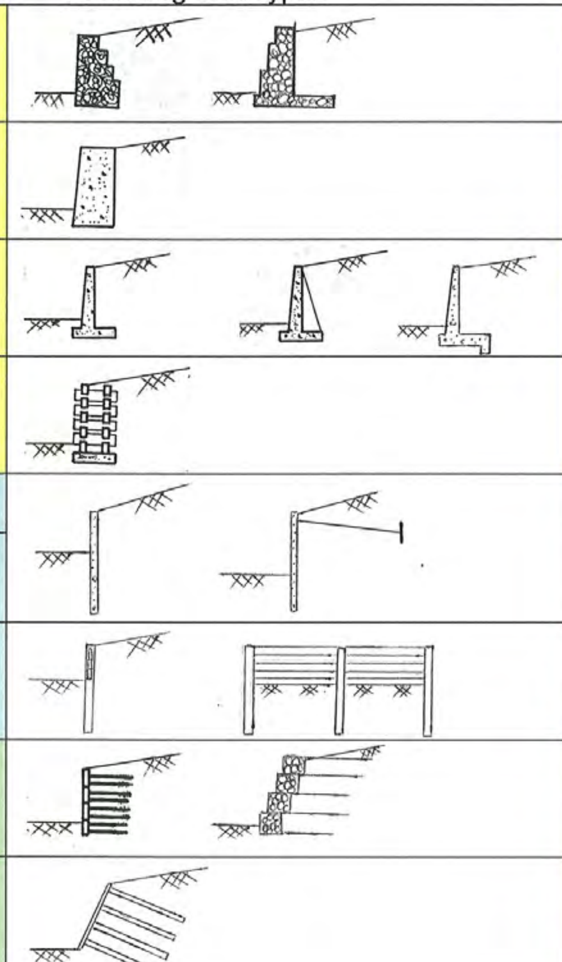
Retaining Wall types	
Gabion walls	Gravity Walls
Masonry and Mass concrete walls	Gravity Walls
Reinforced Concrete	Gravity Walls
Crib walls – timber or concrete	Gravity Walls
Reinforced concrete bored pile walls	Embedded Walls
Driven steel sheet piles	Embedded Walls
King post walls	Embedded Walls
Geogrid/metal strip reinforced soil walls	Reinforced Soil Walls
Soil nailed walls	Reinforced Soil Walls



} **Embedded Walls**

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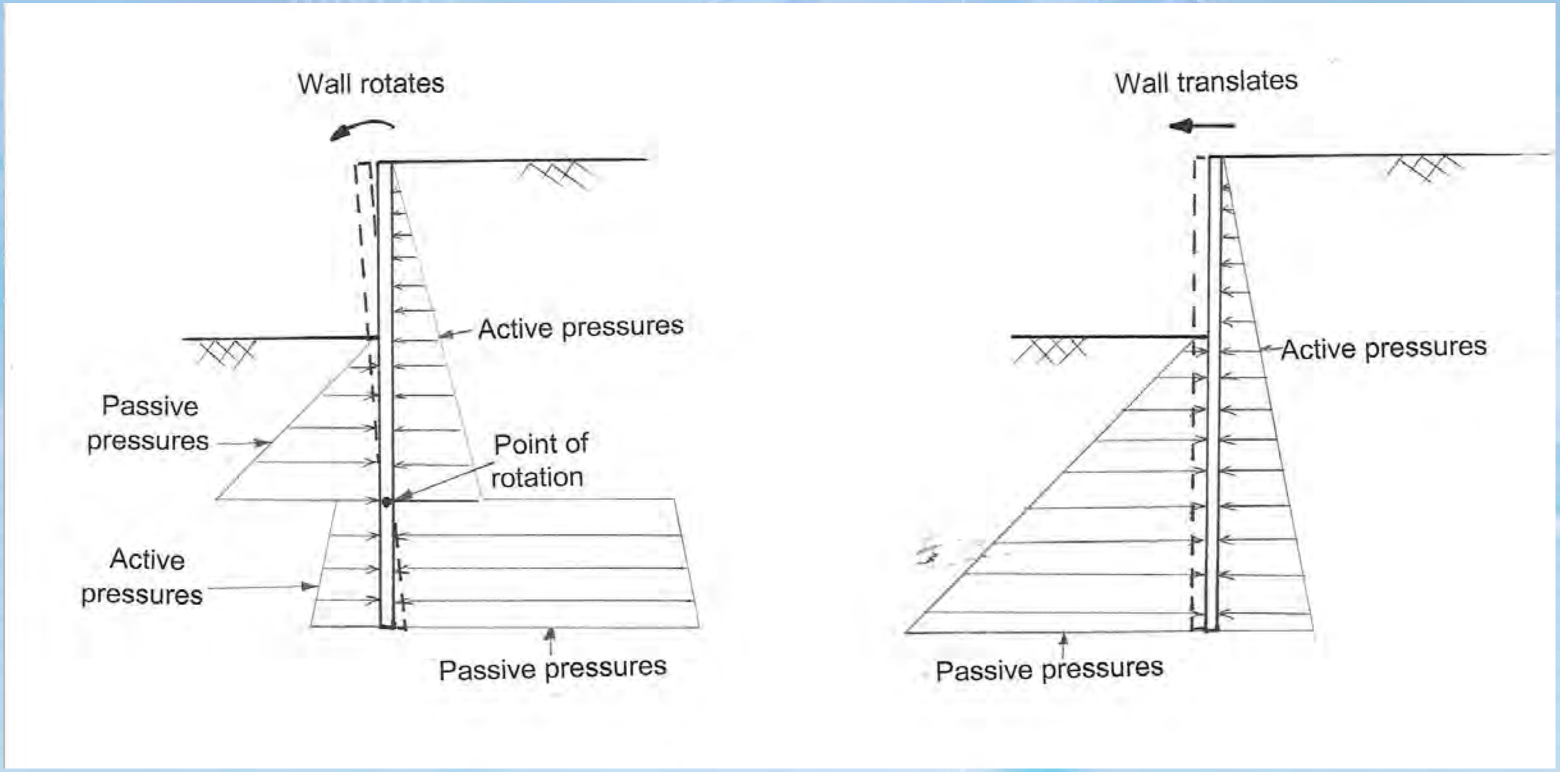
Limiting lateral pressures on sides of embedded wall (water pressure not shown for clarity)



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Cantilevered Anchored Propped

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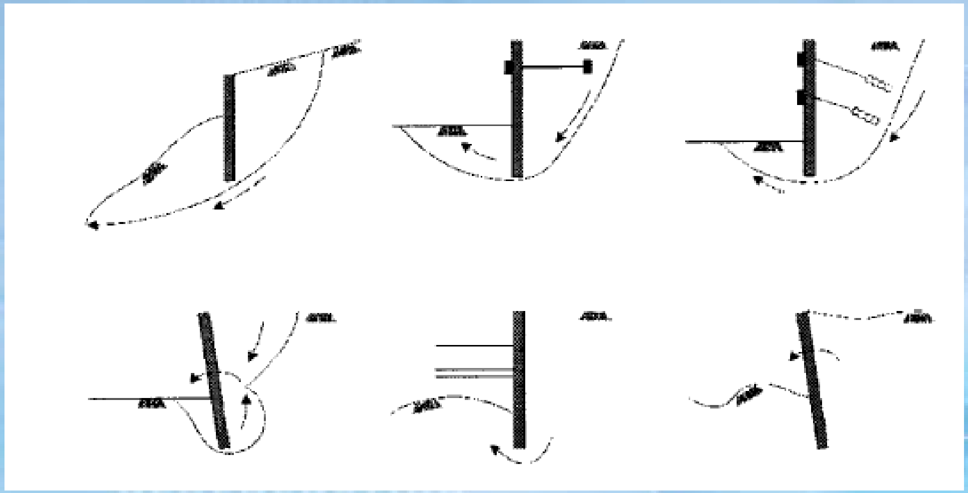
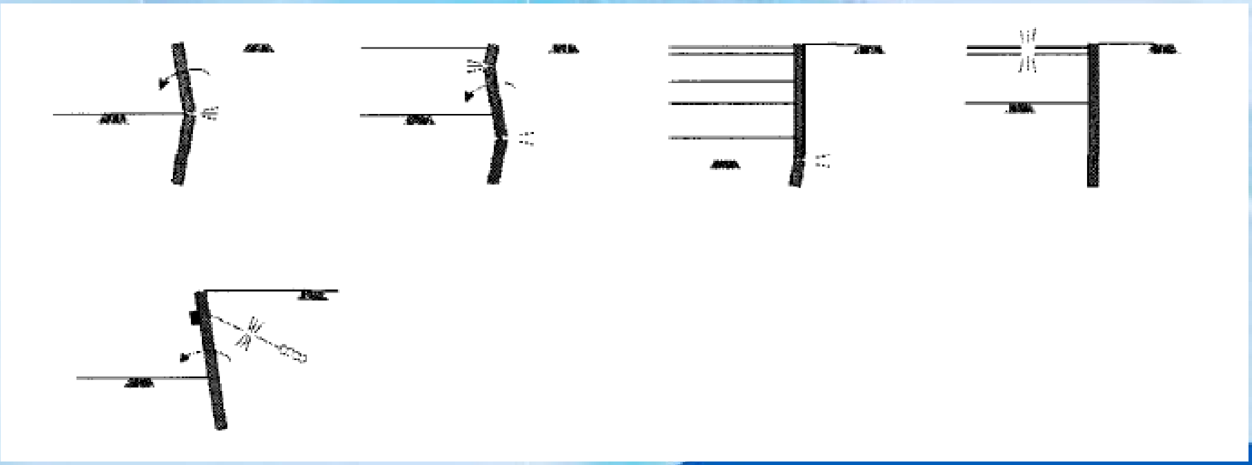


Rotational failures

Pictures taken from
CIRIA C580



Structural failures

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Embedded walls versus gravity walls.

Advantages of embedded walls:

- Embedded walls take up little lateral space
- Can be installed without excavation behind the wall and therefore reduces temporary works (good in very weak or wet soils)
- Can be used to help stabilise slopes if embedded below slip surface.
- Stiff therefore good when excavation required beside movement sensitive structures/infrastructure.

Embedded walls versus gravity walls.

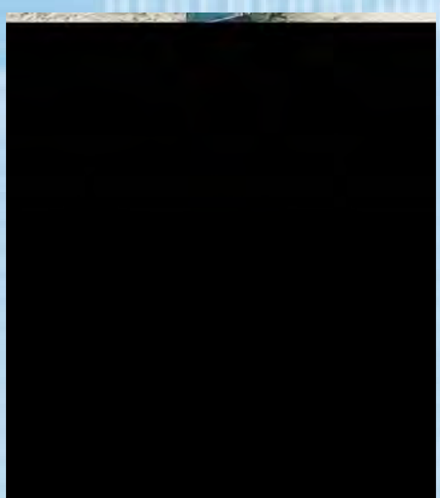
Disadvantages of embedded walls:

- require specialist equipment, and access for piling rigs etc
- Require more detailed design calculations
- Expensive
- Anchors and steel piles corrode and need to be protected or designed with adequate initial steel section to allow for corrosion.
- Some are impermeable so drainage needs to be carefully considered in design and construction.

Embedded Wall types

Sheet piles

- •Corrodes
- •Noisy but quick to install
- •Difficult to install in very hard ground or bouldery ground
- • Blocks water flow but not completely water tight.



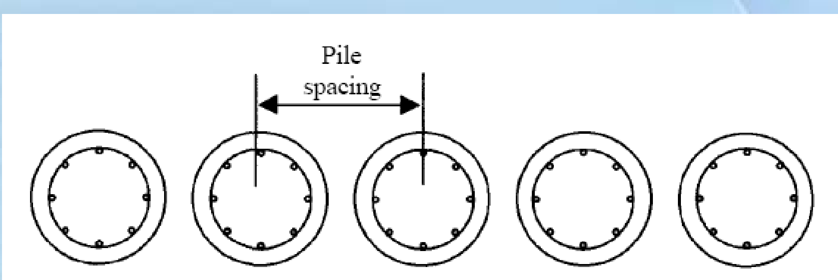
Interlocking steel lengths installed using vibration or driving techniques – Photo from CIRIA C580

Contiguous bored pile walls

- Closely spaced (but not touching reinforced concrete piles installed by boring techniques.
- Wall is permeable. Soil washout can occur between piles.
- Guidewalls usually constructed at ground surface to provide good verticality and lateral positioning for walls.
- Reinforced concrete pile cap usually provided.
- Separate facing usually provided to improve looks.

Anchored contiguous piled wall

Photo from CIRIA C580

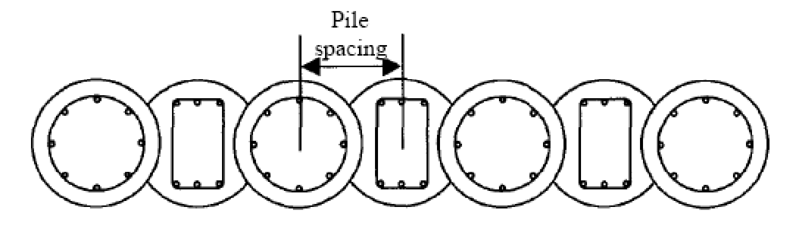


Diameter mm	Spacing mm	Diameter mm	Spacing mm	Diameter mm	Spacing mm
300	400	900	1000	1800	1900
450	550	1050	1150	2100	2200
600	700	1200	1300	2400	2500
750	850	1500	1600		

Bored Secant Piled Walls

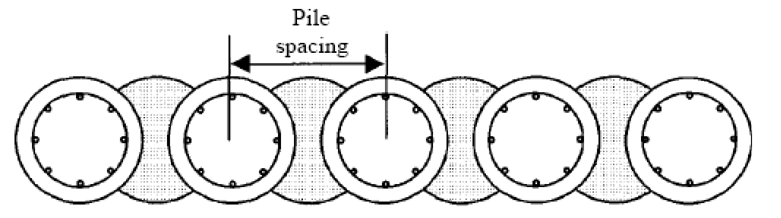
- Intersecting bored piles installed by boring techniques.
- Wall is reasonably water tight.
- Guidewalls required to provide good verticality and lateral positioning for walls.
- Reinforced concrete pile cap usually provided.
- Separate facing usually provided to improve looks.

Hard/hard walls – all piles are reinforced concrete



Diameter mm Male and female	Spacing mm
750	650
880	760
1180	1025

Photos and tables from CIRIA C580



Hard/soft walls – female piles are soft cement grout only

Diameter mm Male	Female	Spacing[(1)] mm	Diameter mm Male	Female	Spacing [(1)] mm
450	450	600	900	600	1100
600	600	800	1200	600	1400
750	750	1000	1200	750	1450

Note

1. The gap between the male piles should not exceed 40 per cent of the diameter of the soft piles.

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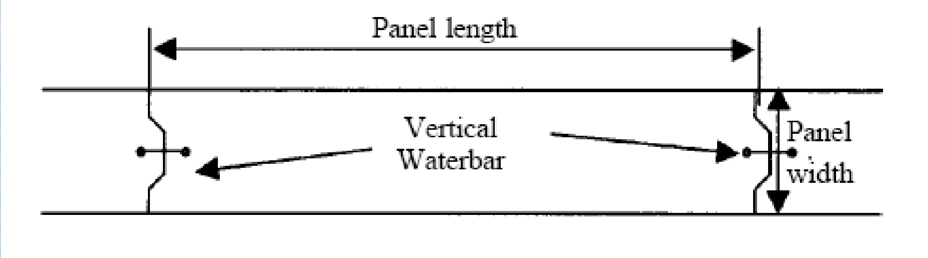
Diaphragm walls

- Oblong reinforced concrete panels excavated using grab or hydrophrase.
- Wall is water tight and very stiff.
- Separate facing usually provided to improve looks.
- Generally very expensive and require large batching plant on site (not good for sites with limited space)



King post walls

- concrete or wooden planks slid between driven or augered H posts (steel) backfilled with concrete.
- Steel posts corrode.
- Generally cheaper than other wall types
- Planks can be preformed and transported to site.
- Pile installation difficult in very hard or bouldery ground.

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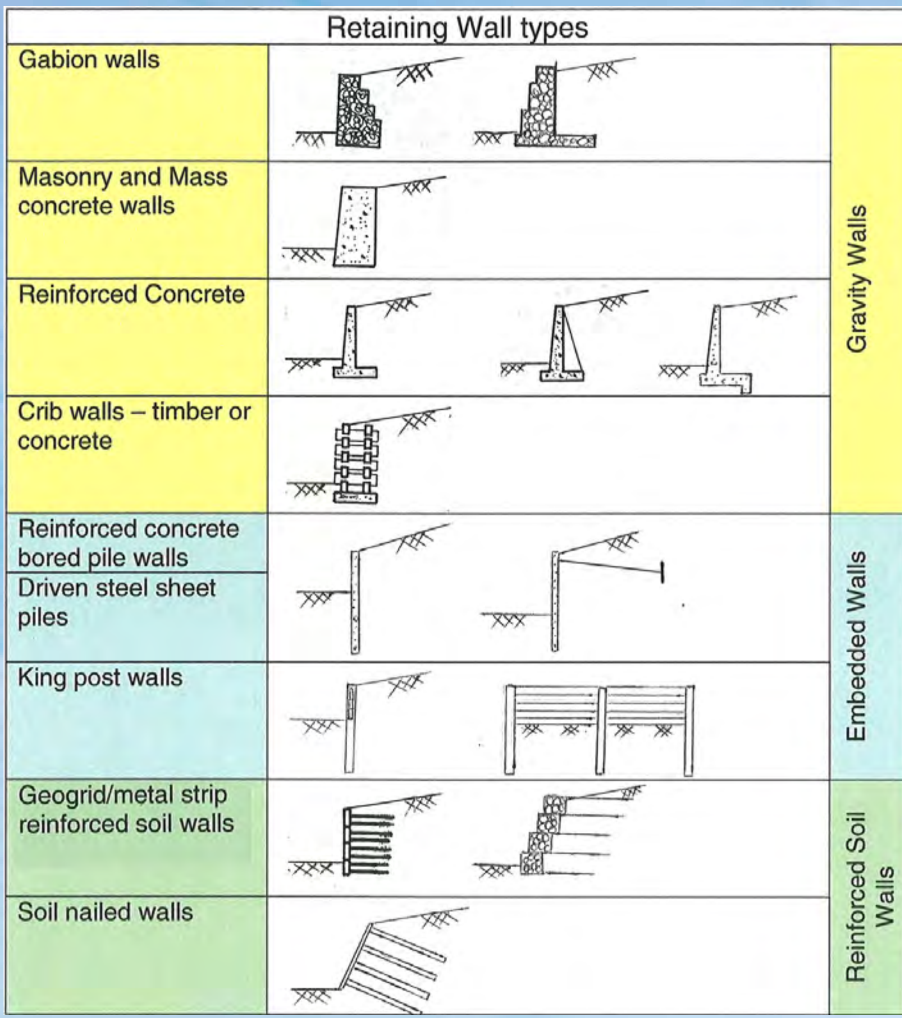

Retaining Wall types		
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} Reinforced Soil

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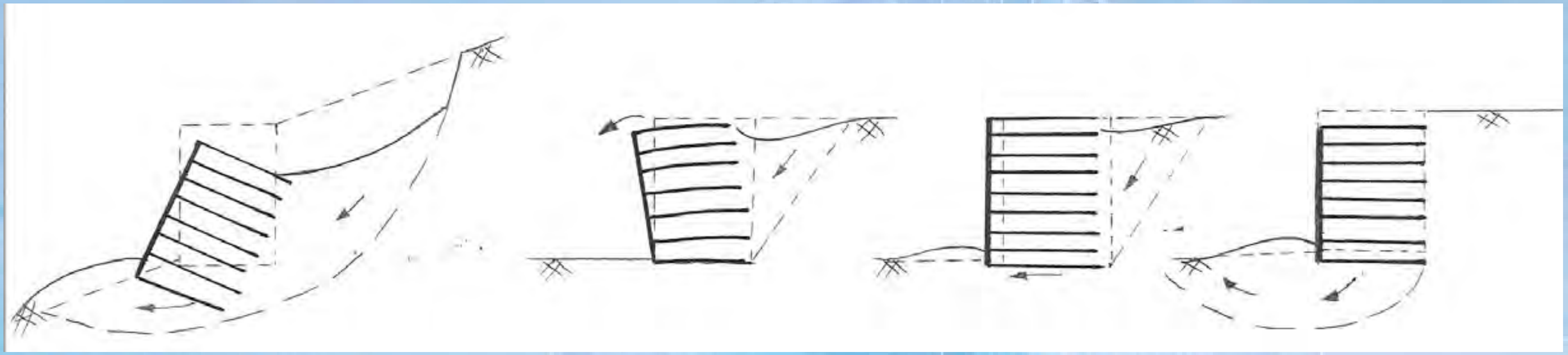
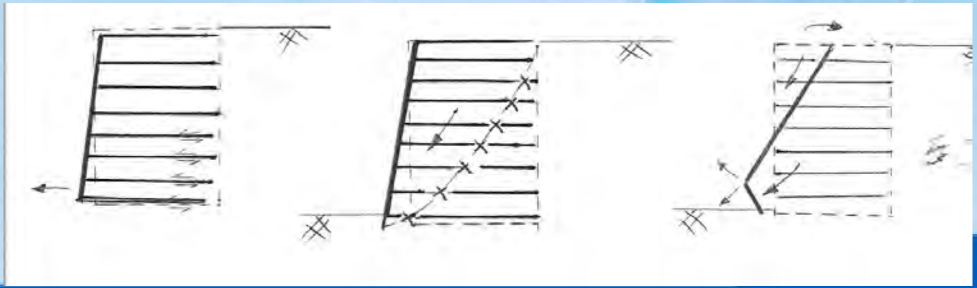
External Failures

Global slope failure | Overturning | Sliding | Bearing failure



Internal Failures

Pullout – shear failure at reinforcement/soil interface | Reinforcement rupture | Facing failure



Geogrid or metal strip reinforcement walls

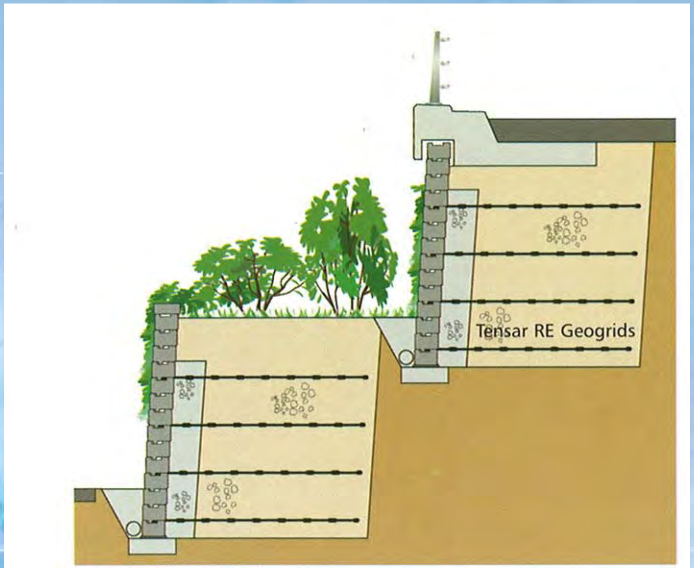
•Connected to hard structural facing e.g. blocks or gabions

•No specialist equipment required for construction.

•Can be constructed by hand

•Provided backfill is compacted well and founding strata reasonably competent can support a road.

•Built into the ground therefore probably only cost effective if constructing wall in excavated or slipped material.



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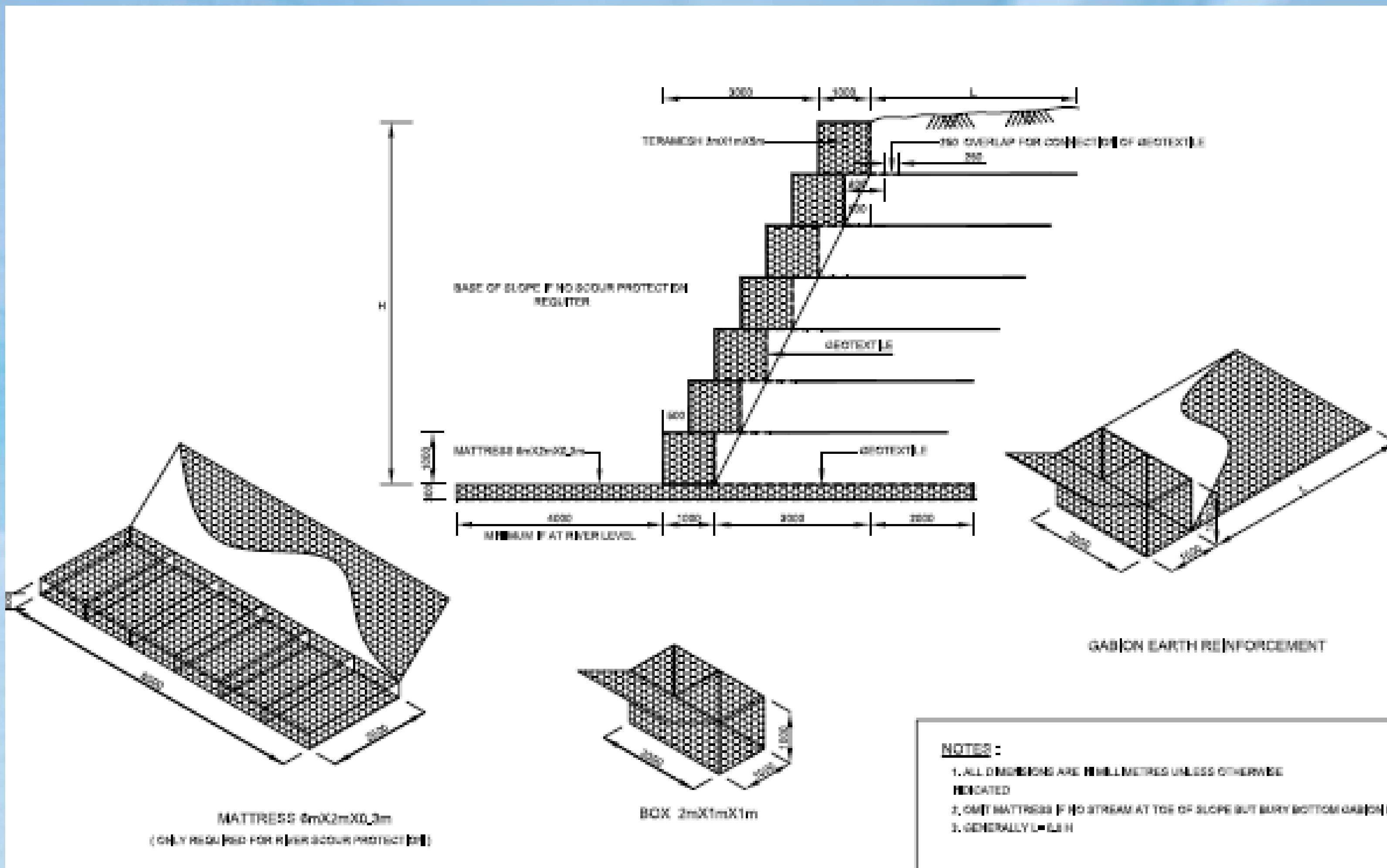
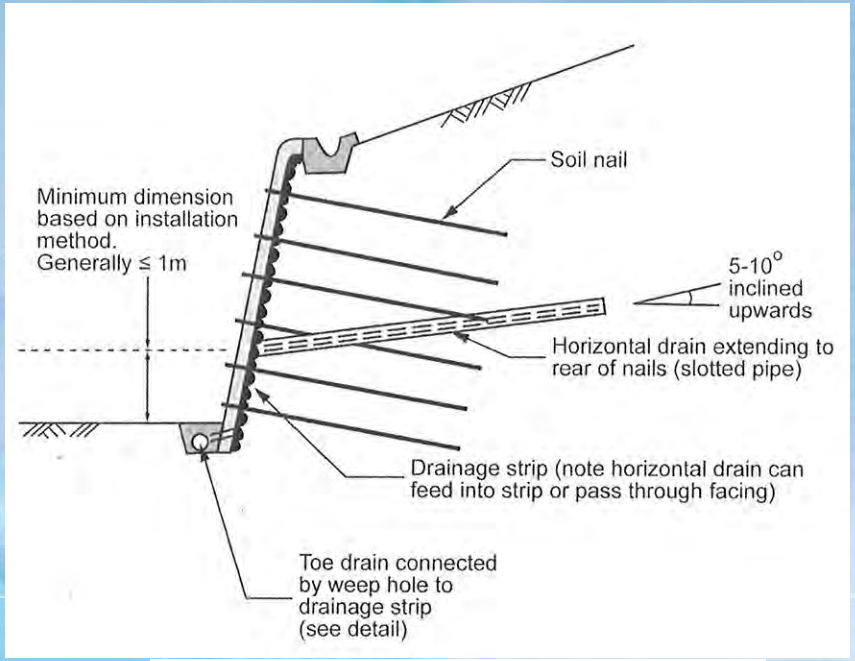


Soil nailed walls

•Connected to hard structural facing e.g. shotcrete or steel.

•Specialist equipment required for installation.

•Nails can be installed directly into natural cut face (usually working from top down as slope is excavated).



Pictures taken from CIRIA C673