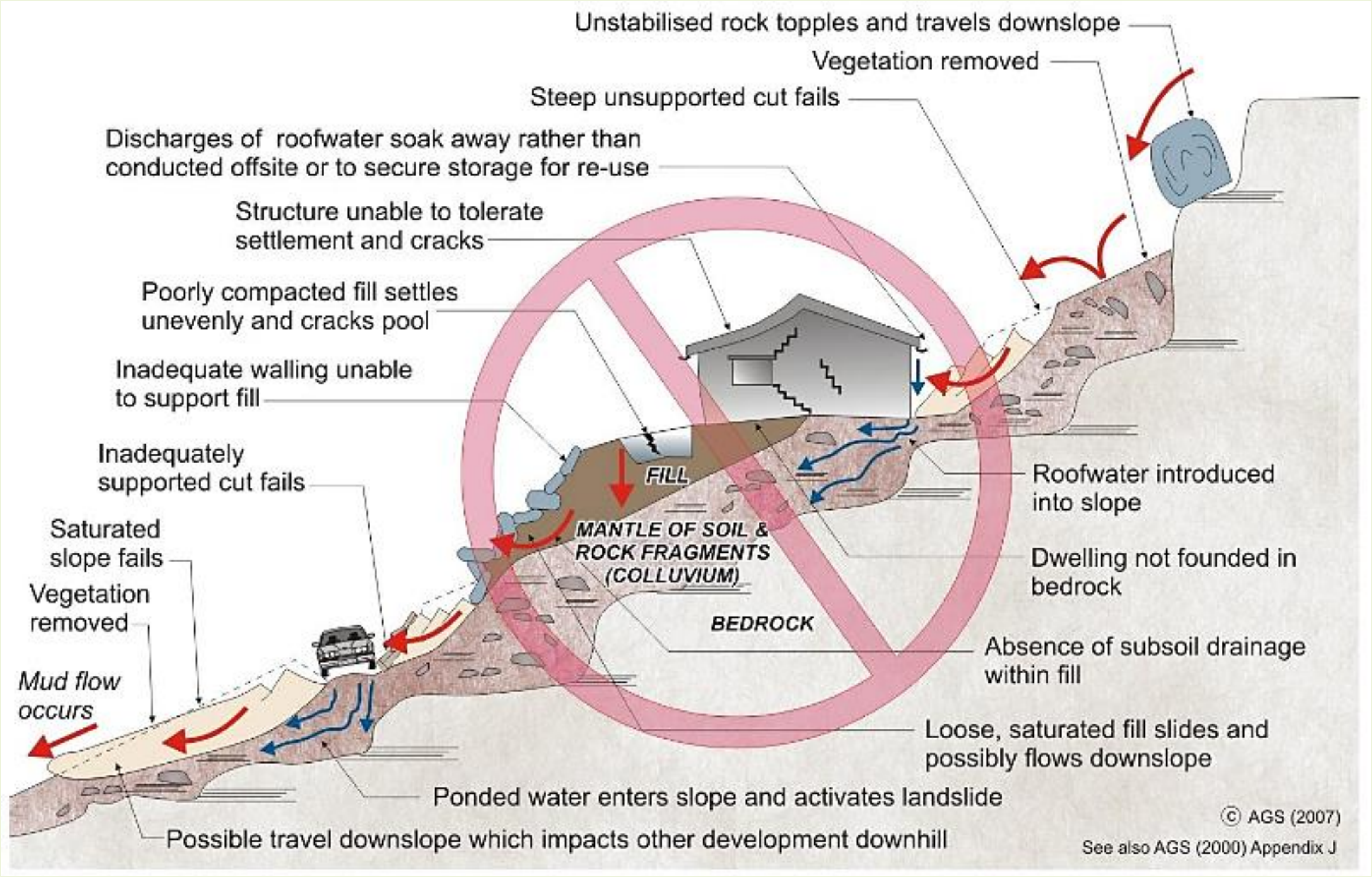
New Technologies for
Rural Road Construction
IIT Guwahati
31 July 2023

Slope Protection and Retention Measures

Arindam Dey
Associate Professor
Department of Civil Engineering
& Center for Disaster Management and Research (CDMR)
Geotechnical Engineering Division
IIT Guwahati

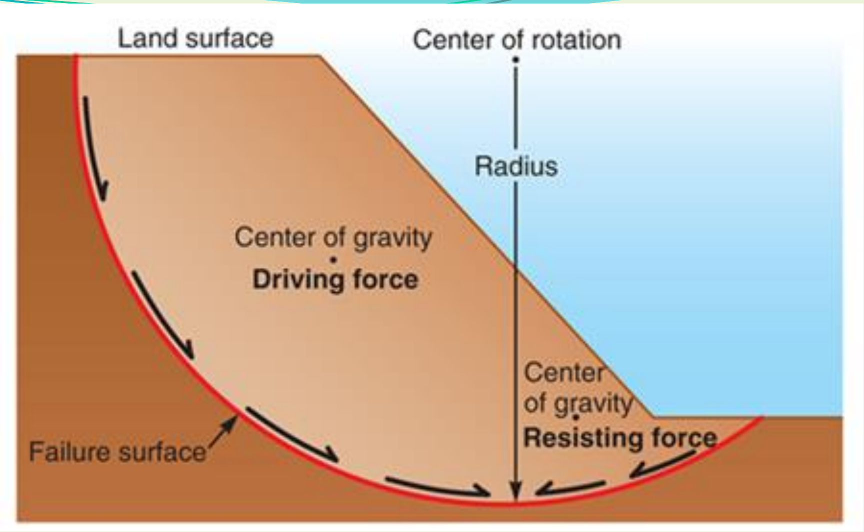
Poor Hillside Practices

Australian Geomechanics Society



Slope Stabilization
Slope Protection
Retention of Slopes

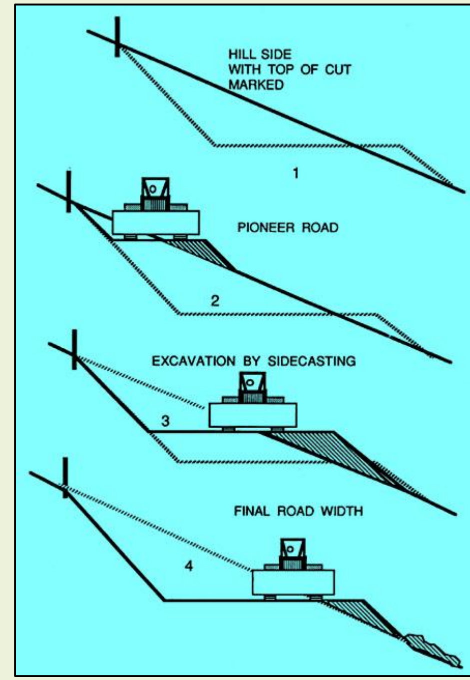
Slope Stabilization

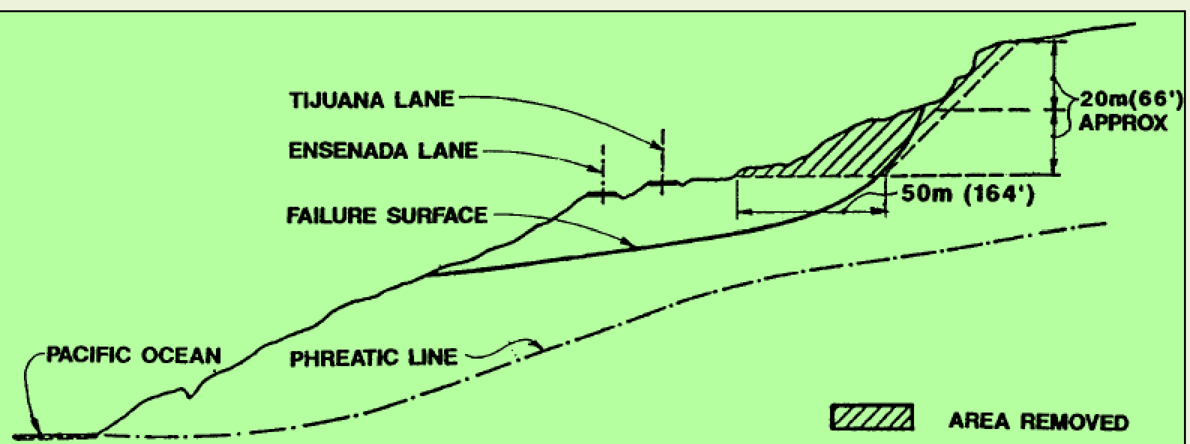


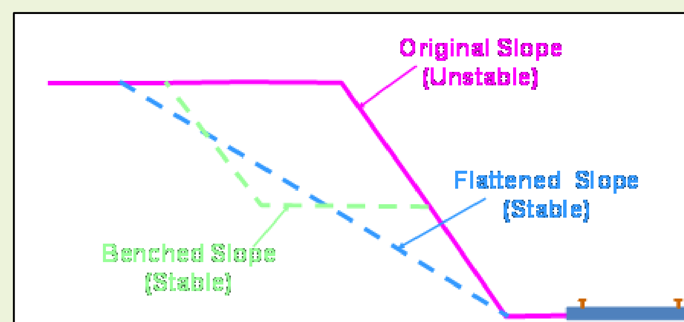
- Myriads of non-unique ways
- Primary objectives
  - *Reduce the driving forces*
    - Excavation of material from appropriate part of unstable ground
    - Drainage of water to reduce the hydrostatic pressures acting on unstable zone
  - *Increase the resisting forces*
    - Drainage that increases the shear strength of the ground
    - Elimination of weak surfaces or other potential failure zones
    - **Building of retaining structures or other supports**
    - Provision of in-situ reinforcement in the ground
    - Chemical treatment to increase the shear strength of the ground
  - *or, Both*

Slope Stabilization Techniques

- Unloading – To reduce the driving forces in a slide mass
  - *Excavation and/or Filling techniques*
    - Removal of the weight from upper part of the slope
    - Removal of all of the potentially unstable materials
    - Flattening or Grading of slopes
    - Benching of slopes
    - Application of a lightweight fill





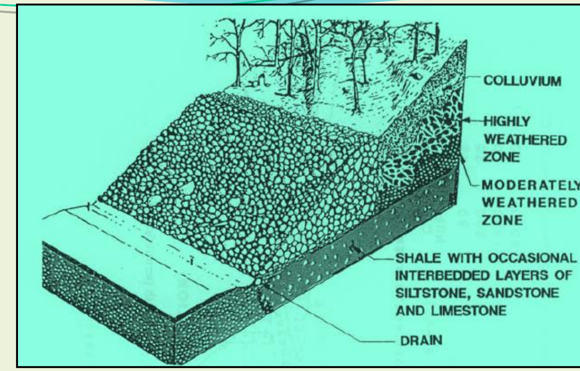


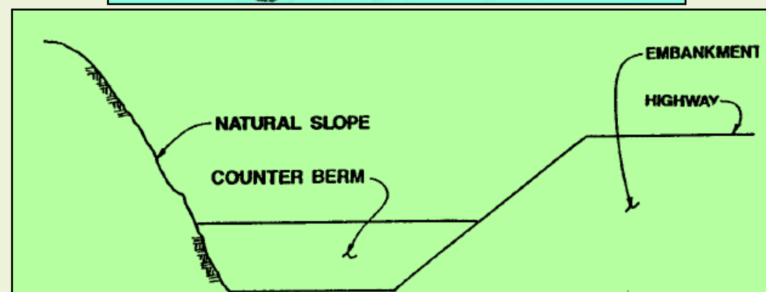
Non-Engineered Benching

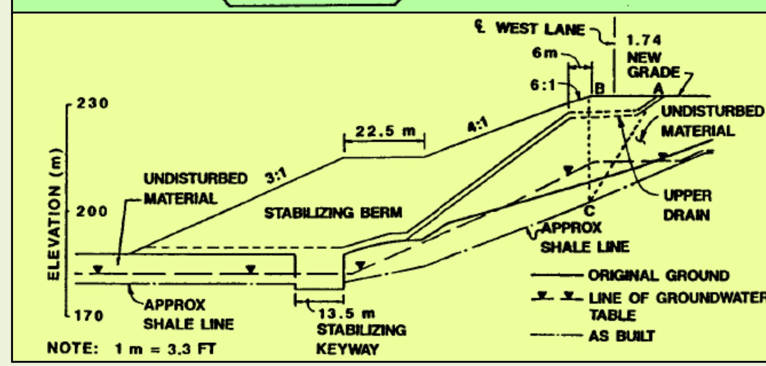
- Mahur, Assam

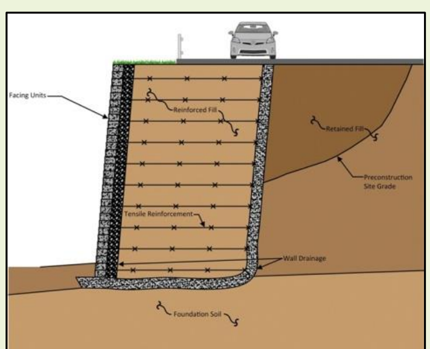
Slope Stabilization Techniques

- Buttressing of slope
  - ❖ *Offset or counter the driving forces of a slope*
  - ❖ *Externally applied force system that increases the resisting force*
- Various techniques of buttressing
  - ❖ *Soil and Rock fill – Toe buttressing*
  - ❖ *Counterberms*
  - ❖ *Shear keys*
  - ❖ *Mechanically stabilized buttresses*
  - ❖ *Pneusol (Tiresoil)*

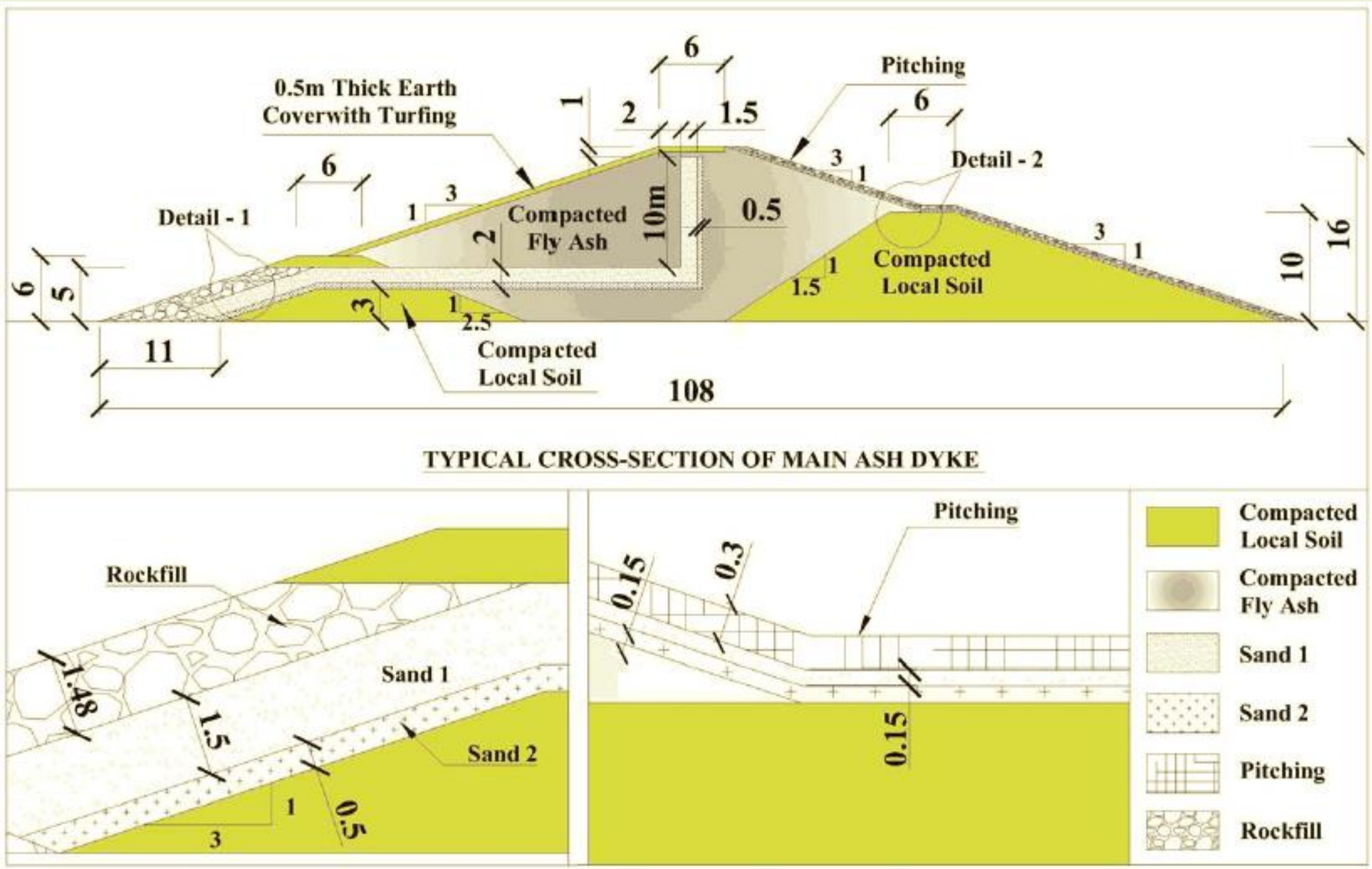






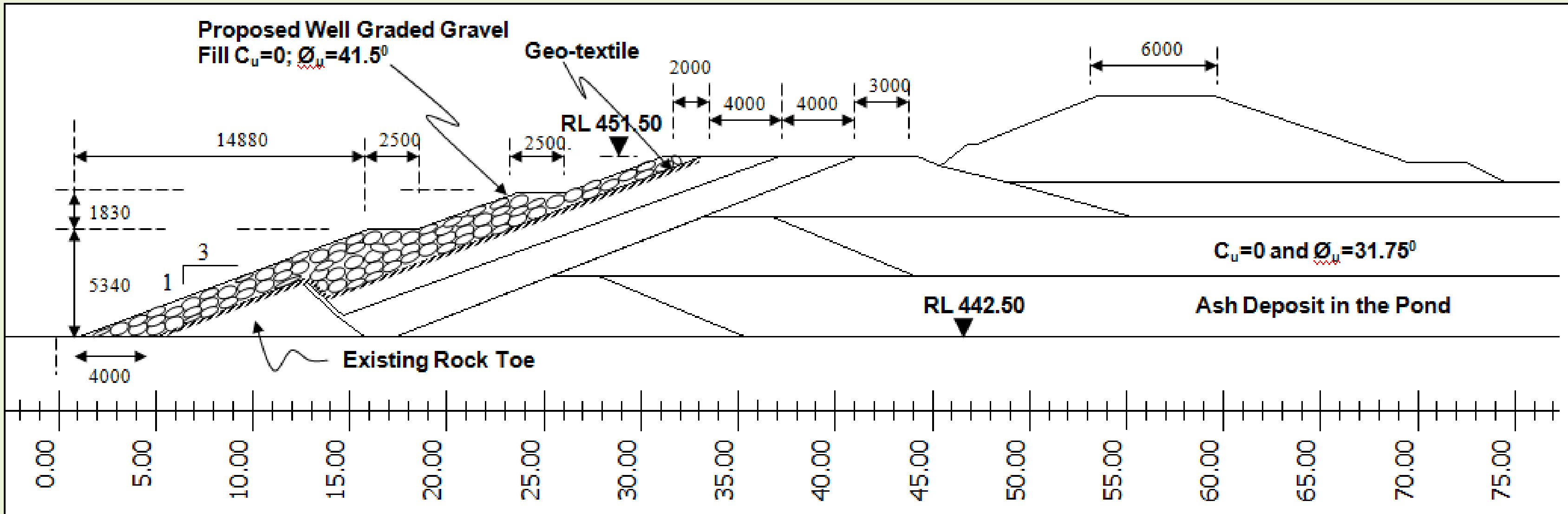


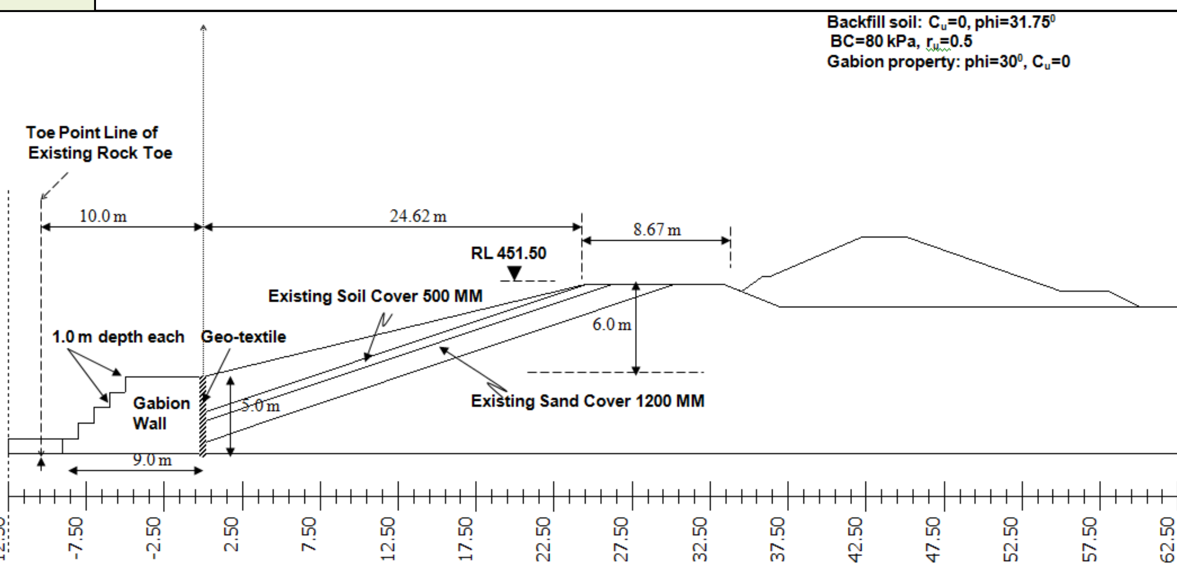
NTPC Ash Dyke, Bongaigaon

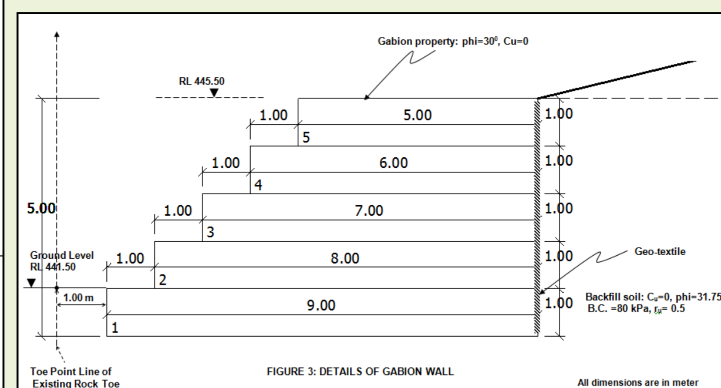


TYPICAL CROSS-SECTION OF MAIN ASH DYKE

NTPC Ash Dyke, Satpura, Sarni





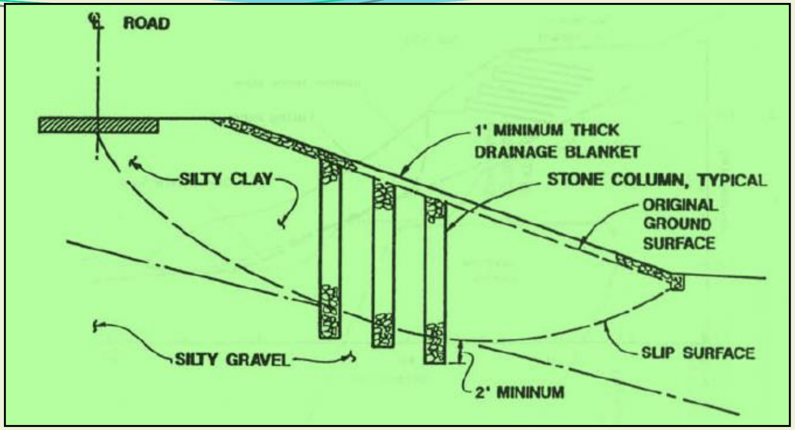


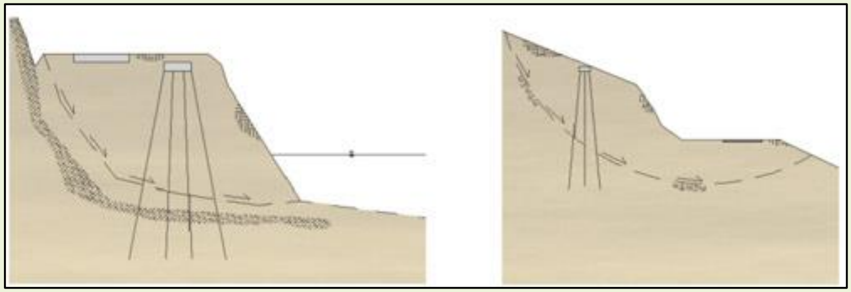
Harangajao, Assam

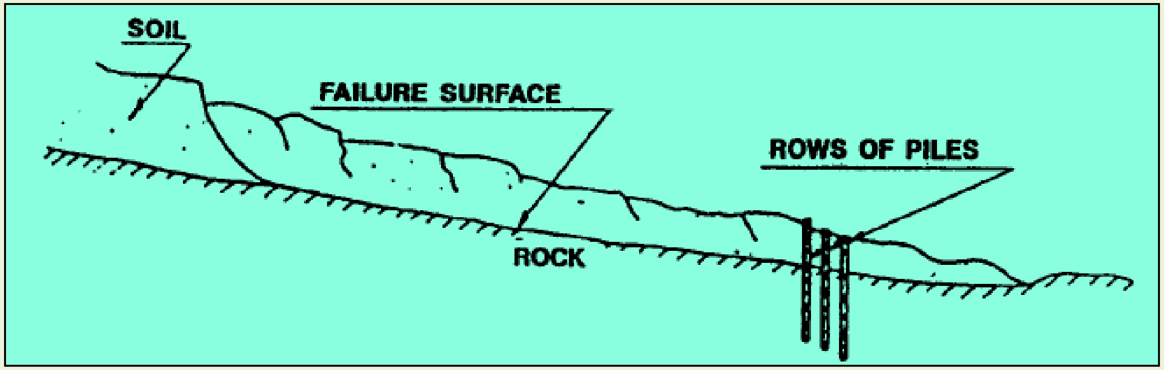
- Toe buttressing with Gabion wall

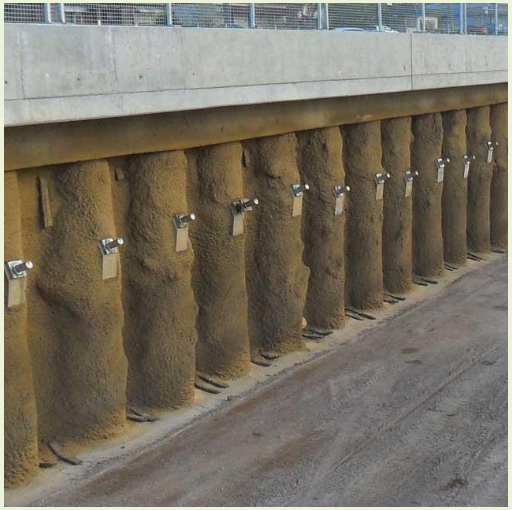
Slope Stabilization Techniques

- Vertical Reinforcement
  - ❖ *Stone columns*
    - Mitigate or prevent landslides
  - ❖ *Reticulated micropiles*
    - Create a monolithic rigid block of reinforced soil to a depth below the critical surface
  - ❖ *Driven piles or Sheet Piles*
  - ❖ *Drilled shafts*



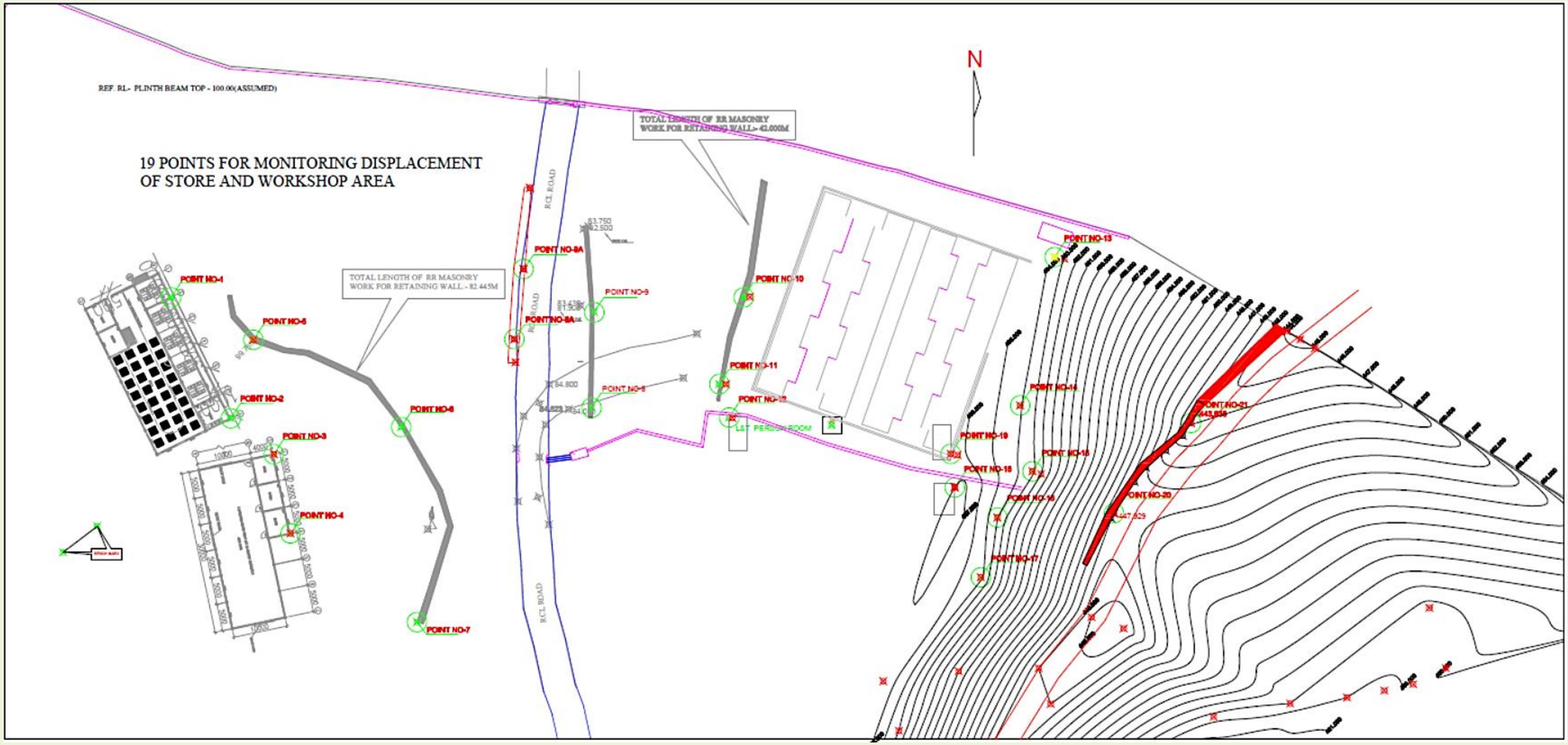






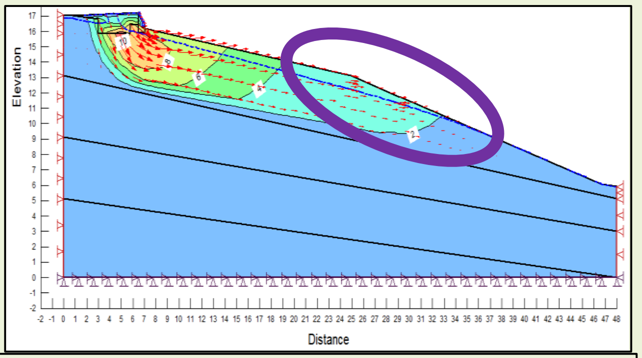
Landslide Mitigation
Calcom Cement Plant, Umrangso, Assam

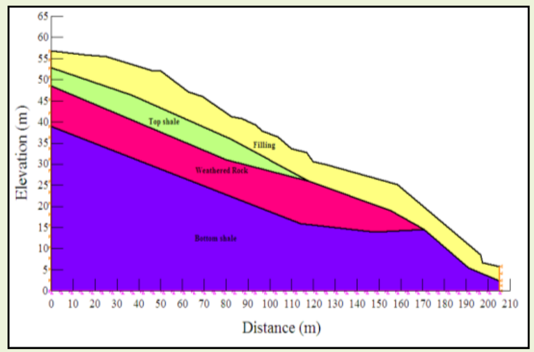
Landslide Mitigation
Calcom Cement Plant, Umrangso, Assam

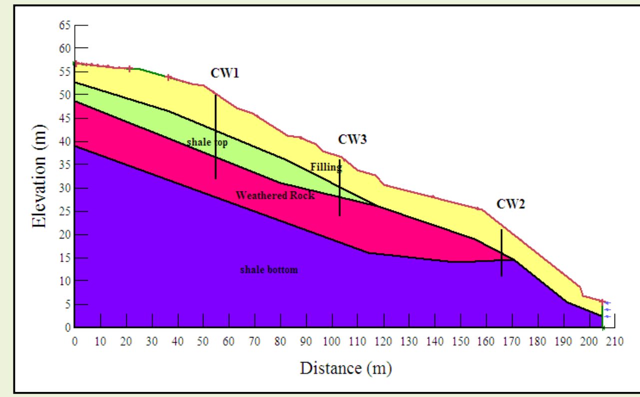


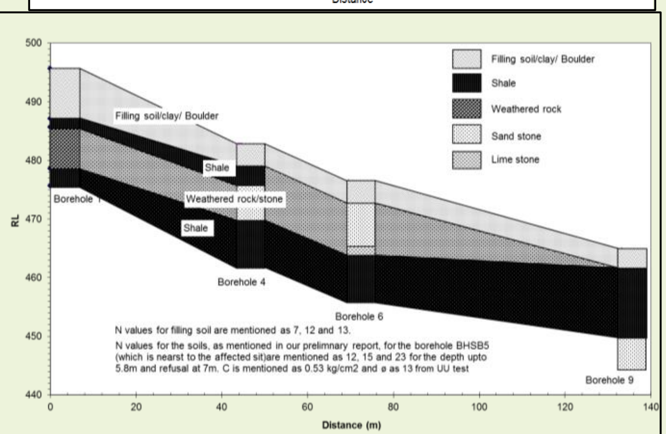
Calcom Cement Plant, Umrangso, Assam

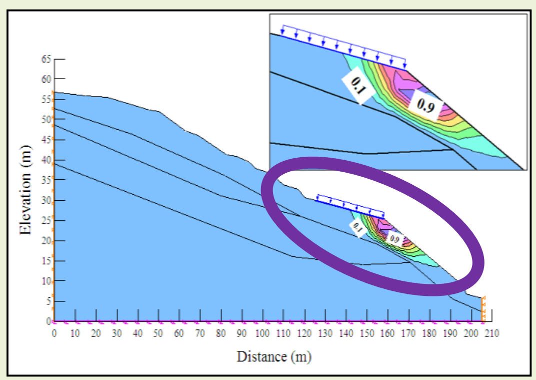
- Application of rows of sheet pile wall for stabilization

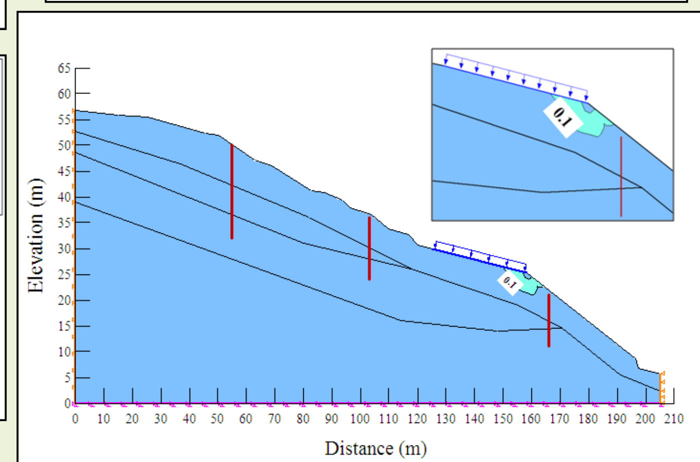




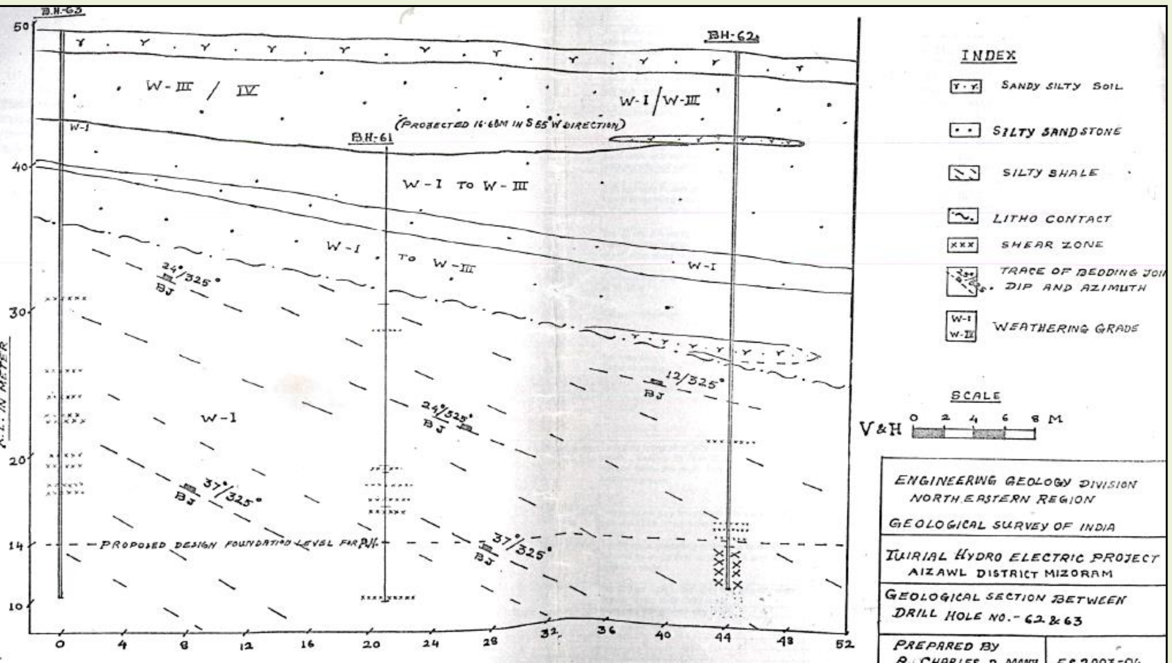






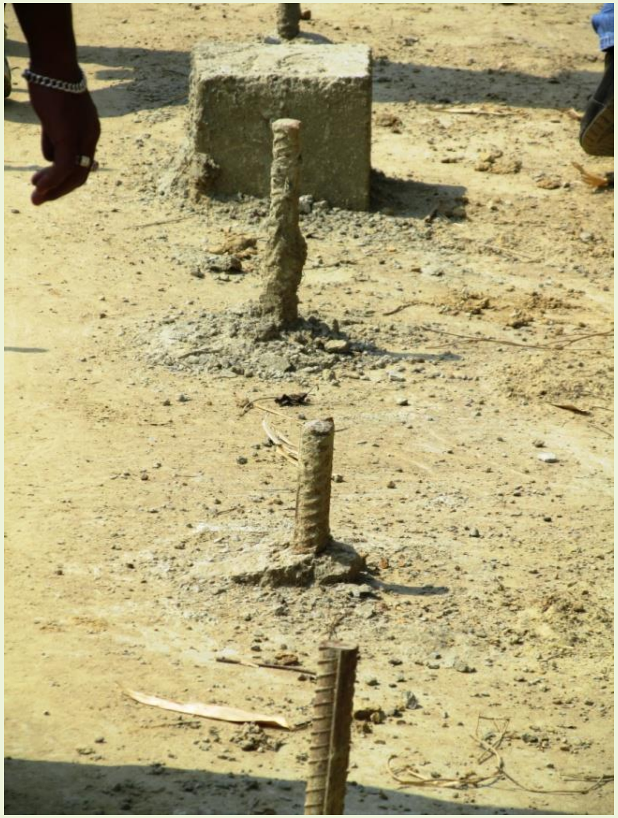


Tuirial Hydroelectric Power Plant Project, Saiphum, Mizoram



Failure of shotcreting without weepholes, Saiphum, Mizoram

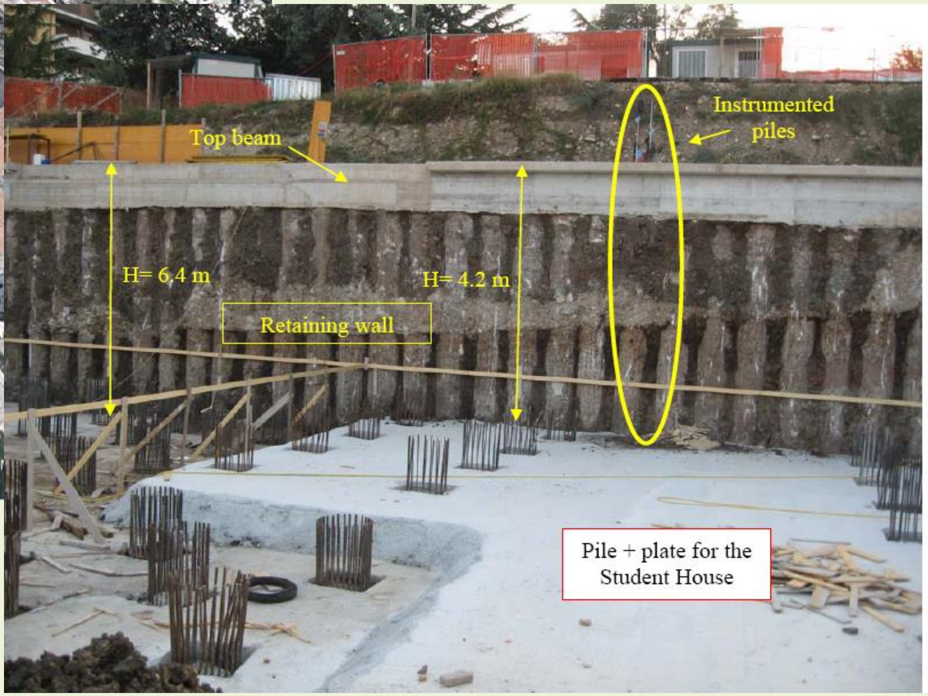
Tuirial Hydroelectric Power Plant Project, Saiphum, Mizoram



Stagewise doweling and micropiling for stabilization

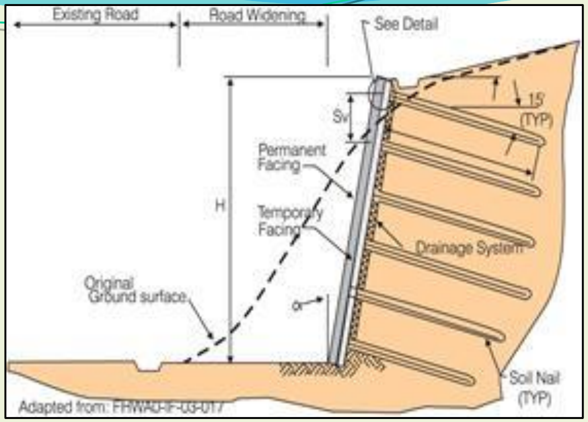
The New Student House (Campobasso, Italy)

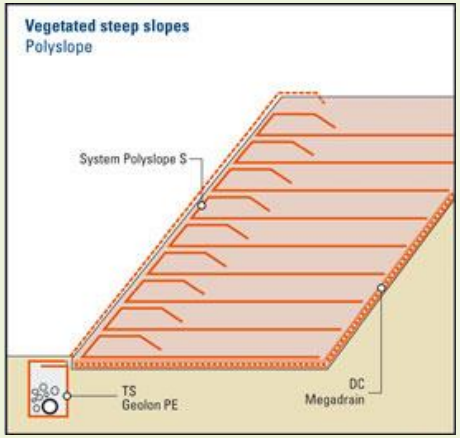
- Application of staggered pile wall for cut slope protection

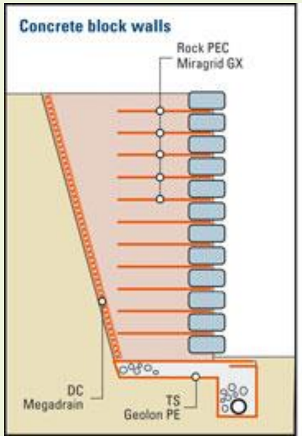


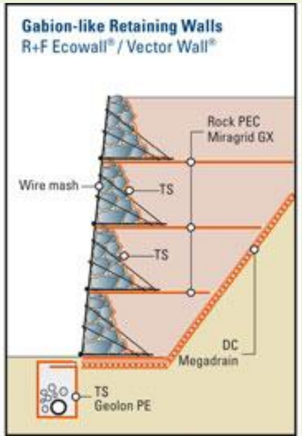
Slope Stabilization Techniques

- Horizontal/Inclined Reinforcement
  - *Soil Nailing*
    - In-situ passive inclusions penetrating the failure plane
    - Mobilize when movement occurs in the soil
  - *Geosynthetic reinforced soil walls*
    - Wrap around geosynthetic faced soil systems
  - *Reinforced retaining walls*
    - Concrete block walls
    - Gabion-faced retaining walls



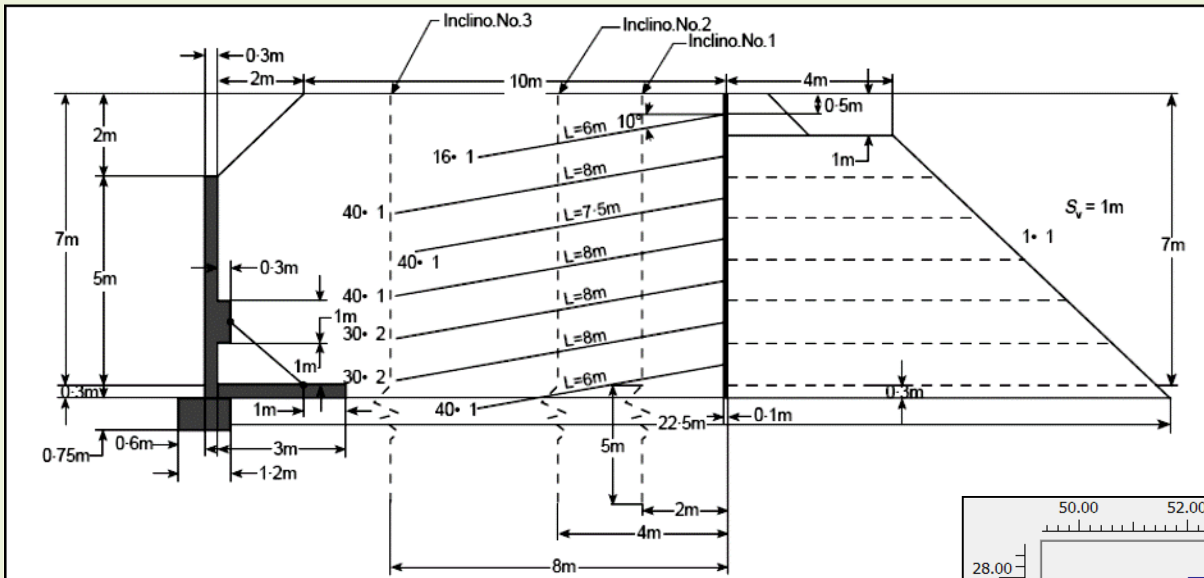


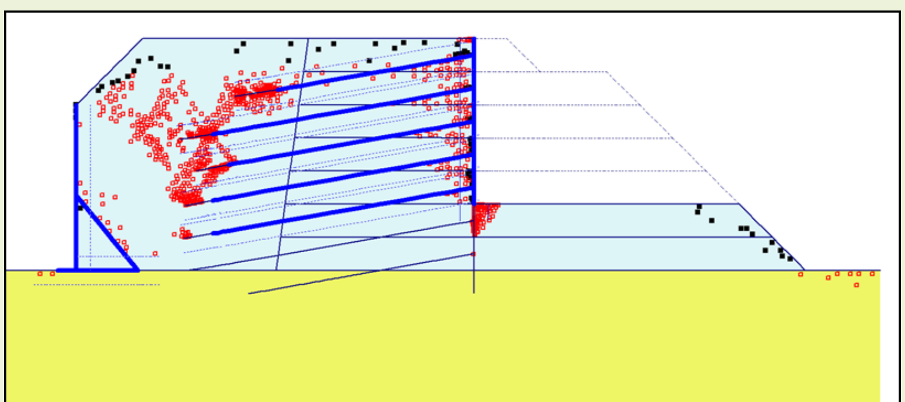


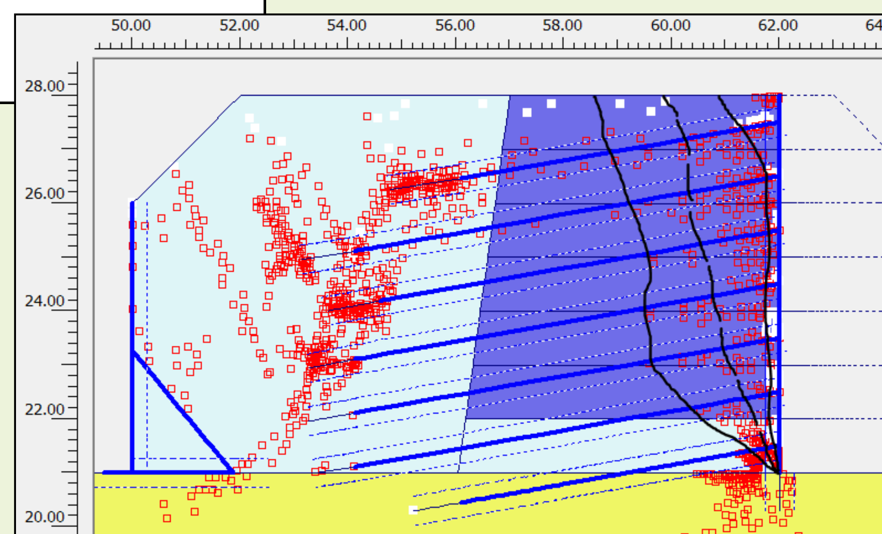


Clouterre Project, France

- Soil nailing to protect vertical cut

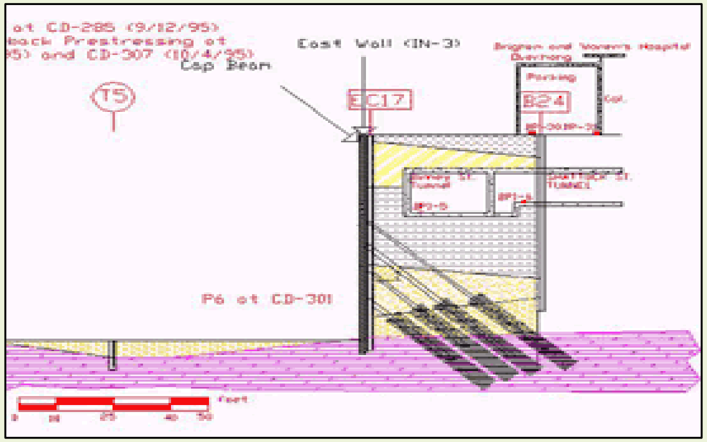


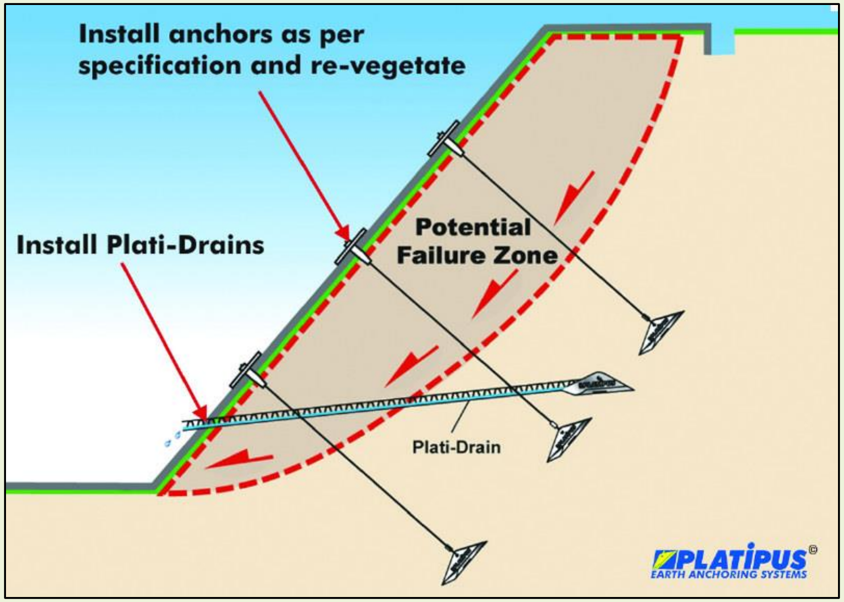




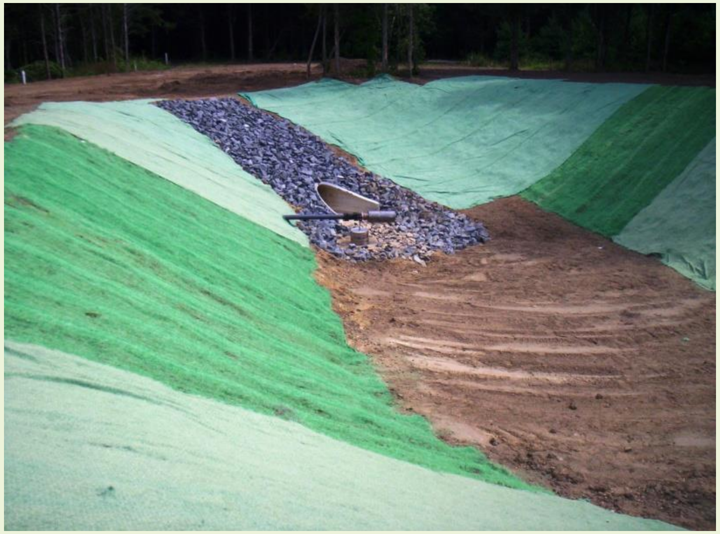
Slope Stabilization Techniques

- Anchored Reinforcements
  - *Tie-back walls*
  - *Anchored slopes*
  - *Vegetated slopes*
    - Reinforcement by roots
    - Check on soil erosion

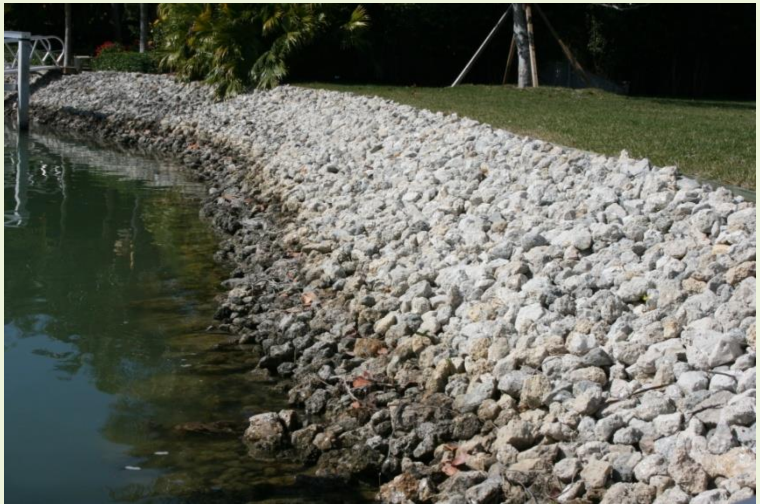




Slope Stabilization Techniques



- Several other stabilization techniques
  - ❖ *Erosion control mats and blankets*
  - ❖ *Biotechnical stabilization / Bioremediation*
  - ❖ *Surface slope protection*
    - Shotcreting
    - Chunam plaster
    - Masonry
    - Riprap



Rainfall-induced Failure of Vertical Cuts

Landslide near Narayana Hospital, 2020

Gauripur Landslide, Opposite to IIT Guwahati

2020

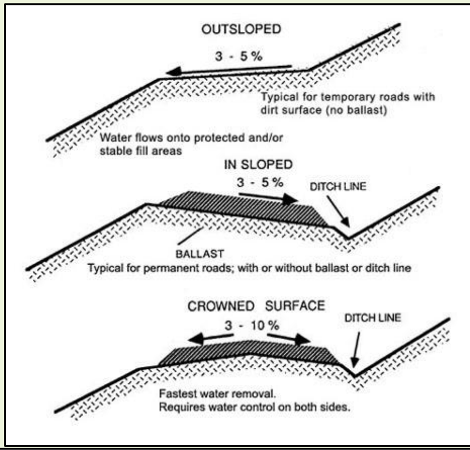
Rainfall-Induced Failure of Slopes

Kullu-Mandi Highway 2023

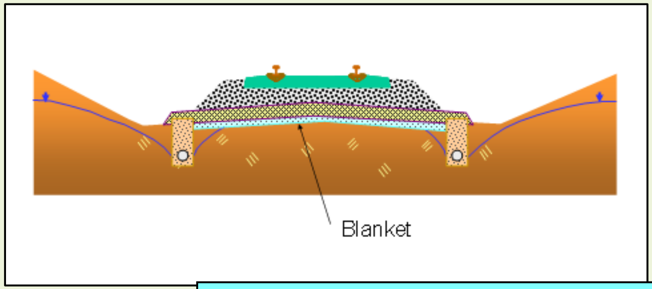
Raj Bhawan, Guwahati, 2020

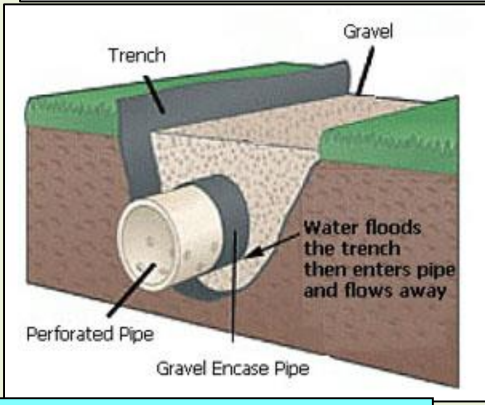
Drainage is the Key

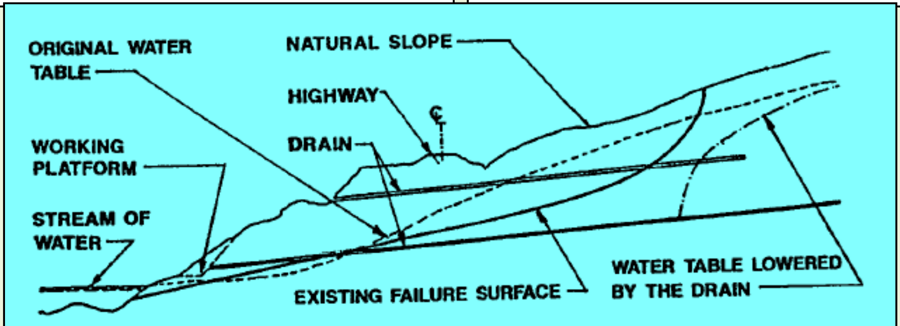
- ***Surface Drainage***
  - Concrete ditch drains or Geopipes
  - Catchment parameters
    - Area and shape of catchment zone
    - Rainfall intensity
    - Steepness and length of slope being
    - Condition of ground surface and nature of the subsurface soils
    - Nature and extent of vegetation
  - Redirection of surface runoff



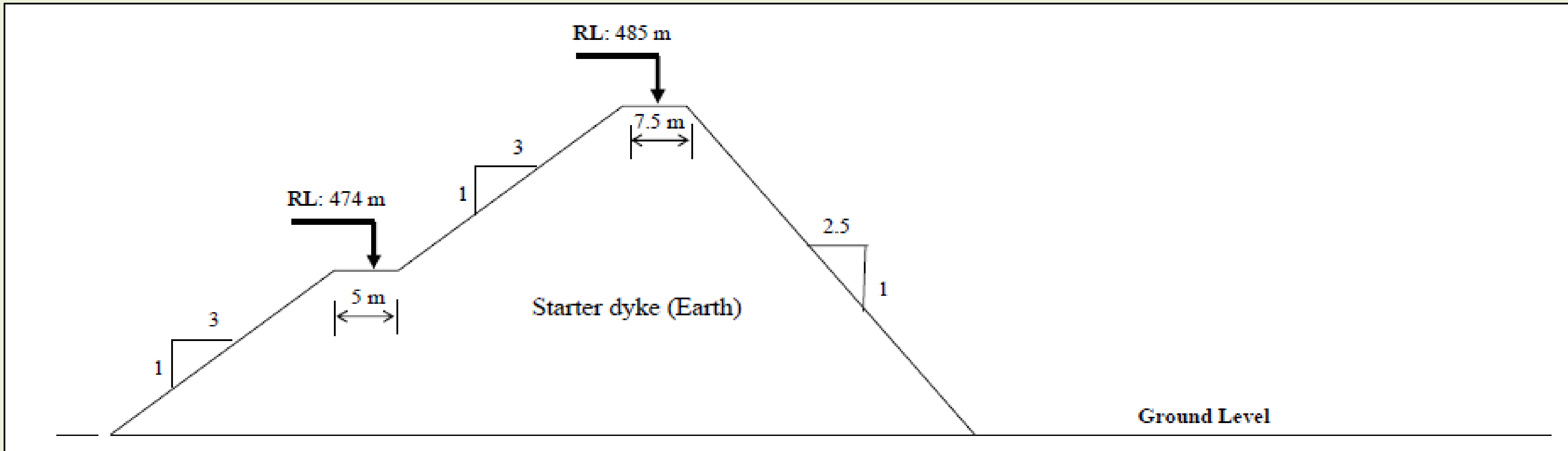
- ***Subsurface drainage***
  - Drain blankets
  - Trenches
  - Cut-off drains
  - Horizontal drains
  - Relief drains
  - Drainage tunnels

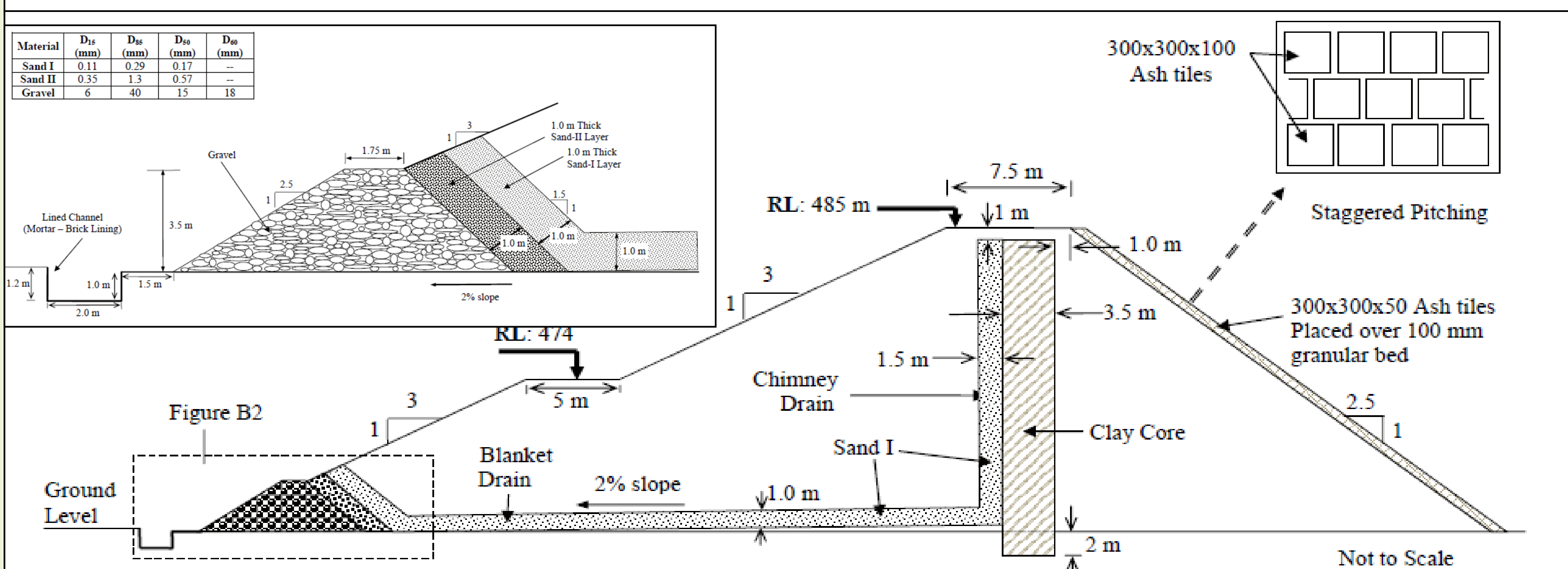






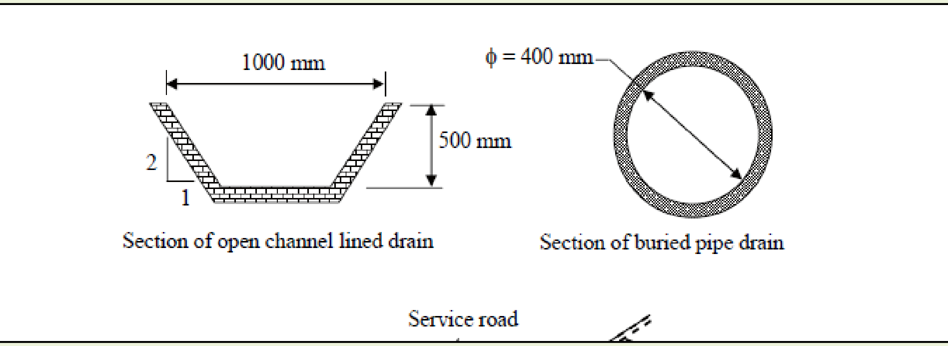
NTPC Ash Dyke, Birsinghpur, MP

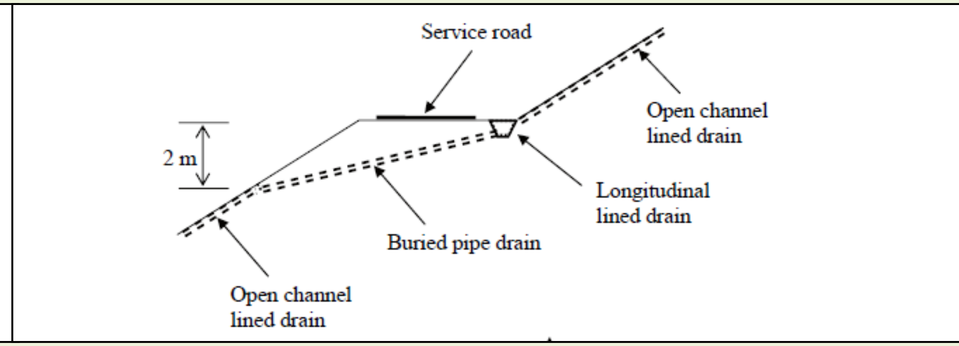


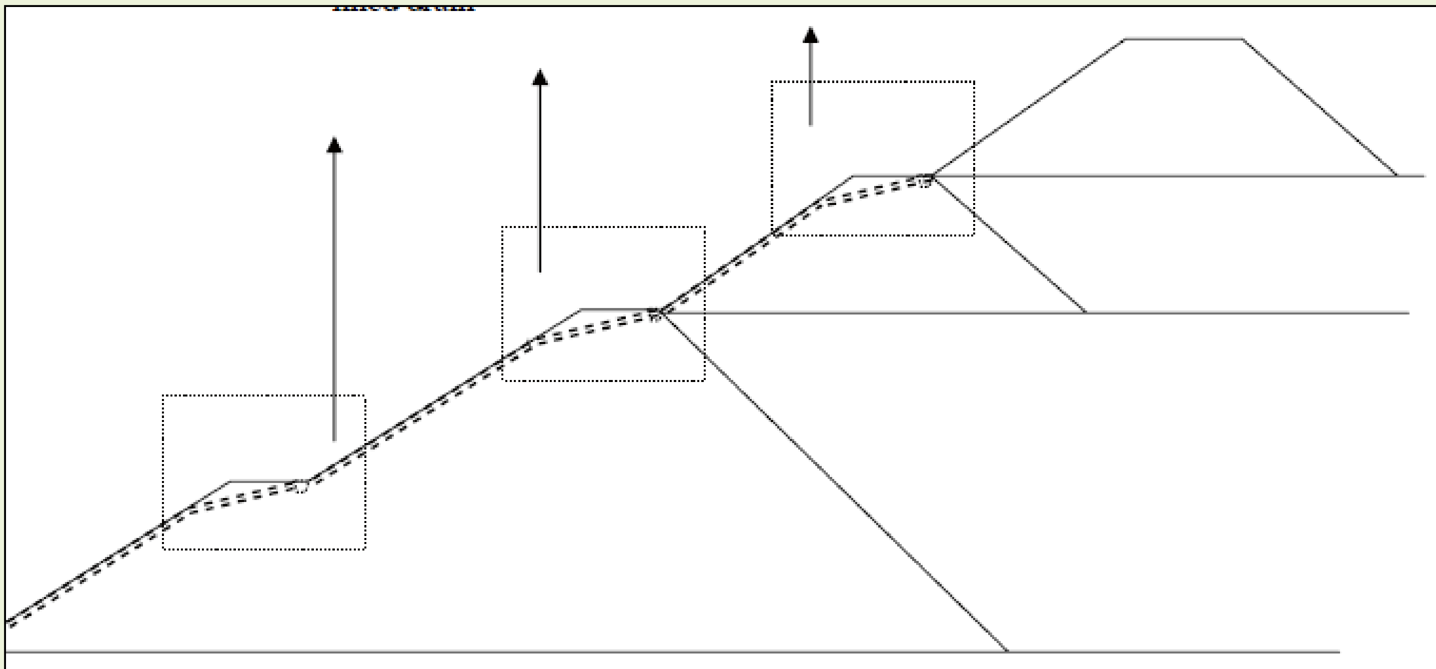


Material	D_{15} (mm)	D_{85} (mm)	D_{50} (mm)	D_{60} (mm)
Sand I	0.11	0.29	0.17	--
Sand II	0.35	1.3	0.57	--
Gravel	6	40	15	18

NTPC Ash Dyke, Birsinghpur, MP







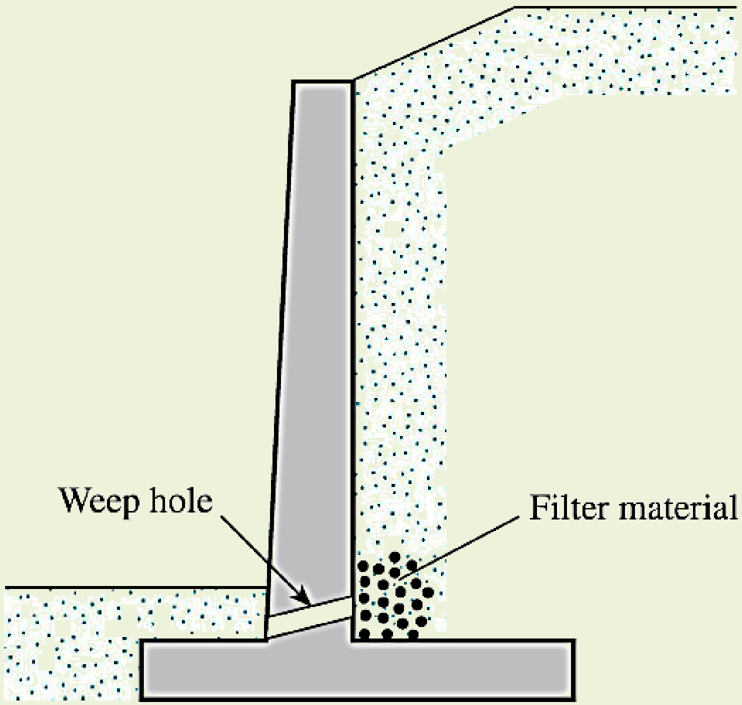
Gabion Wall, Mahur, Assam

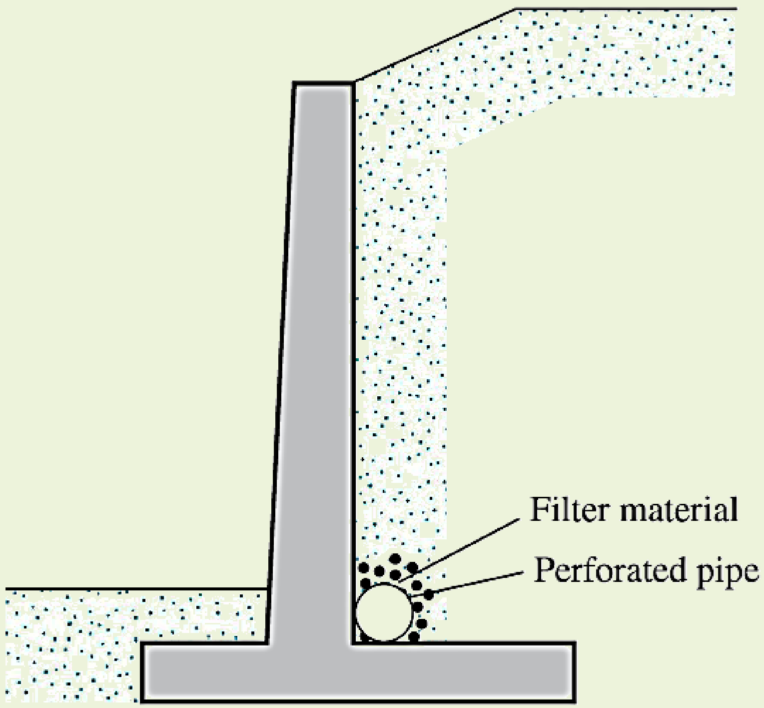
- Free drainage of water

Wall Drainage

- Accumulation of rain water in the back fill results in its saturation, and thus a considerable increase in the earth pressure acting on the wall. This may eventually lead to unstable conditions.

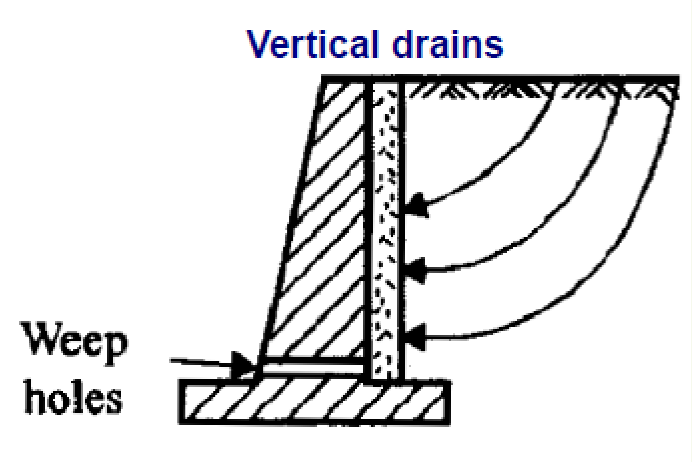
- Two of the options to take care of this problem are the following:
  - ✓ Provision of weep holes w/o geo-textile on the back-face of wall
  - ✓ Perforated pipe draining system with filter

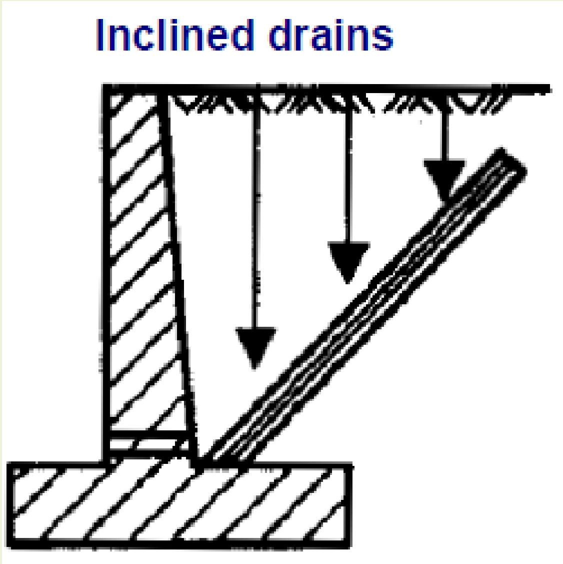


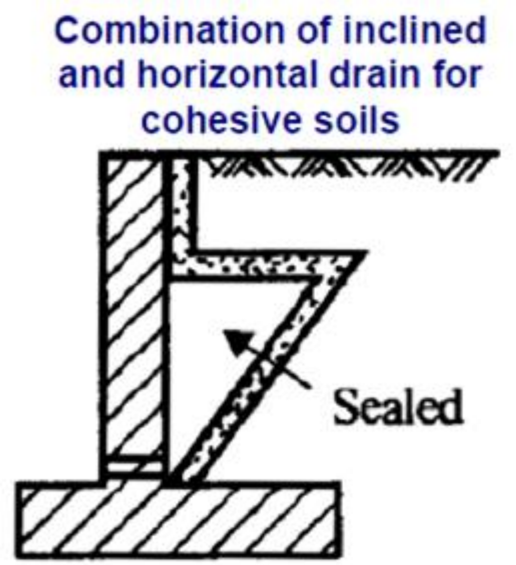


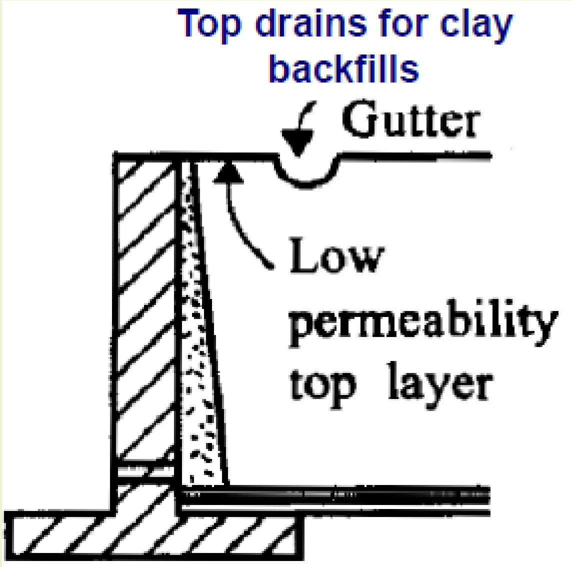
Wall Drainage

- Geotextile material or a thin layer of some other filter may be used on the back face of wall for the full height
    - Prevent the backfill material entering the weep holes and eventually clogging them.

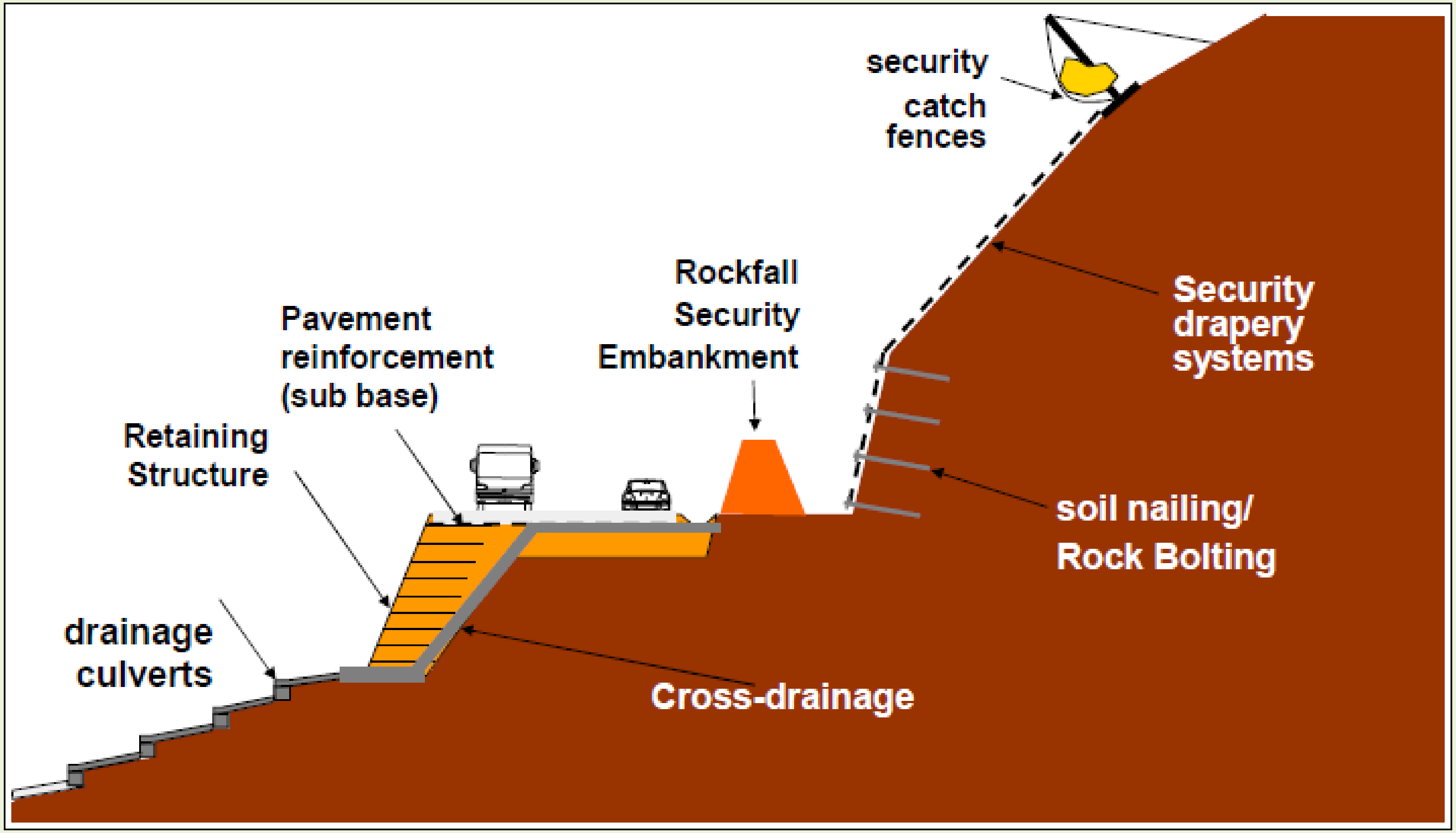








Slope Protection/Stabilization Measures



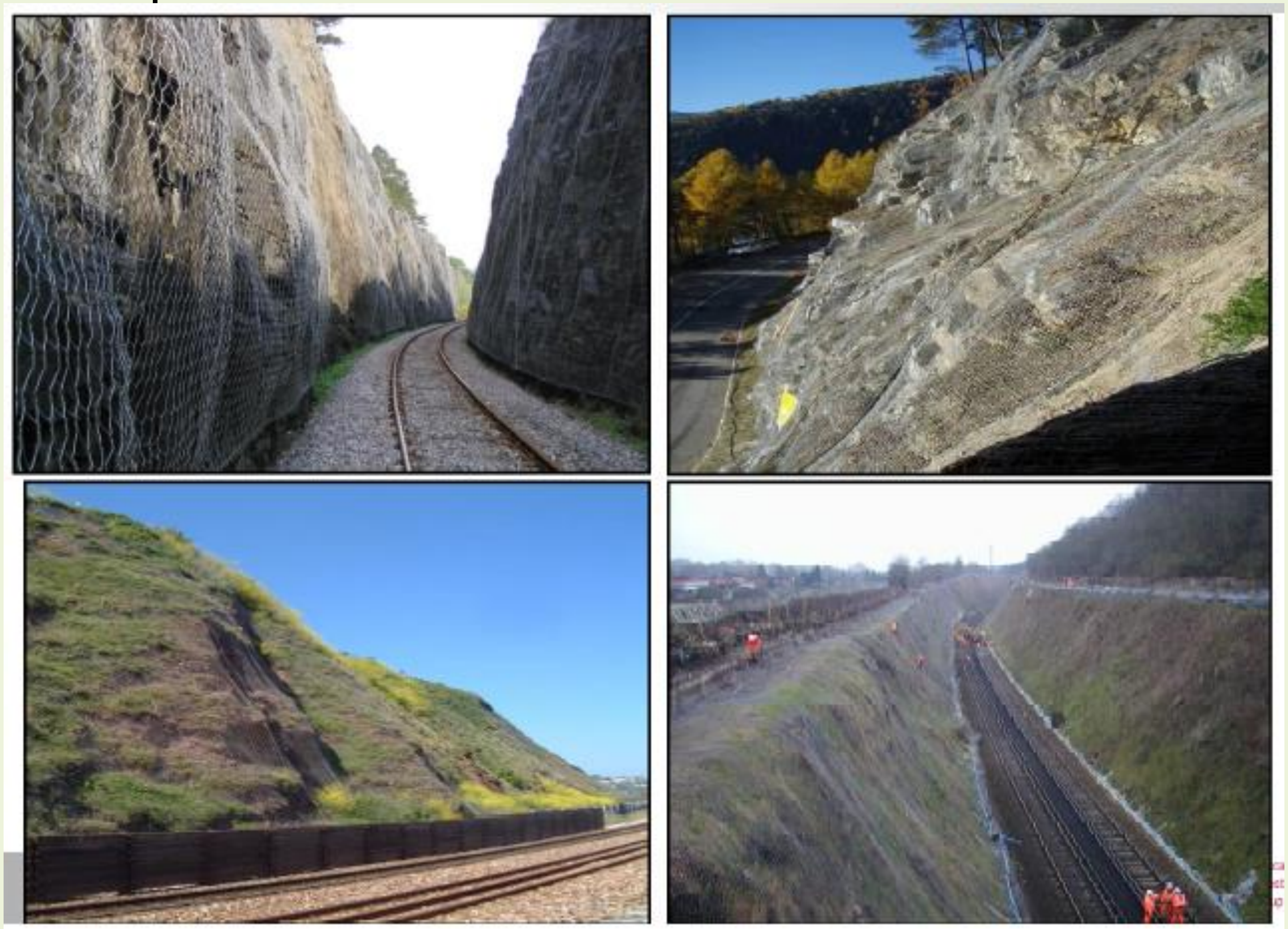
Rockfall at Pandoh, Himachal Pradesh

Some Novel Slope Protection/Stabilization Measures

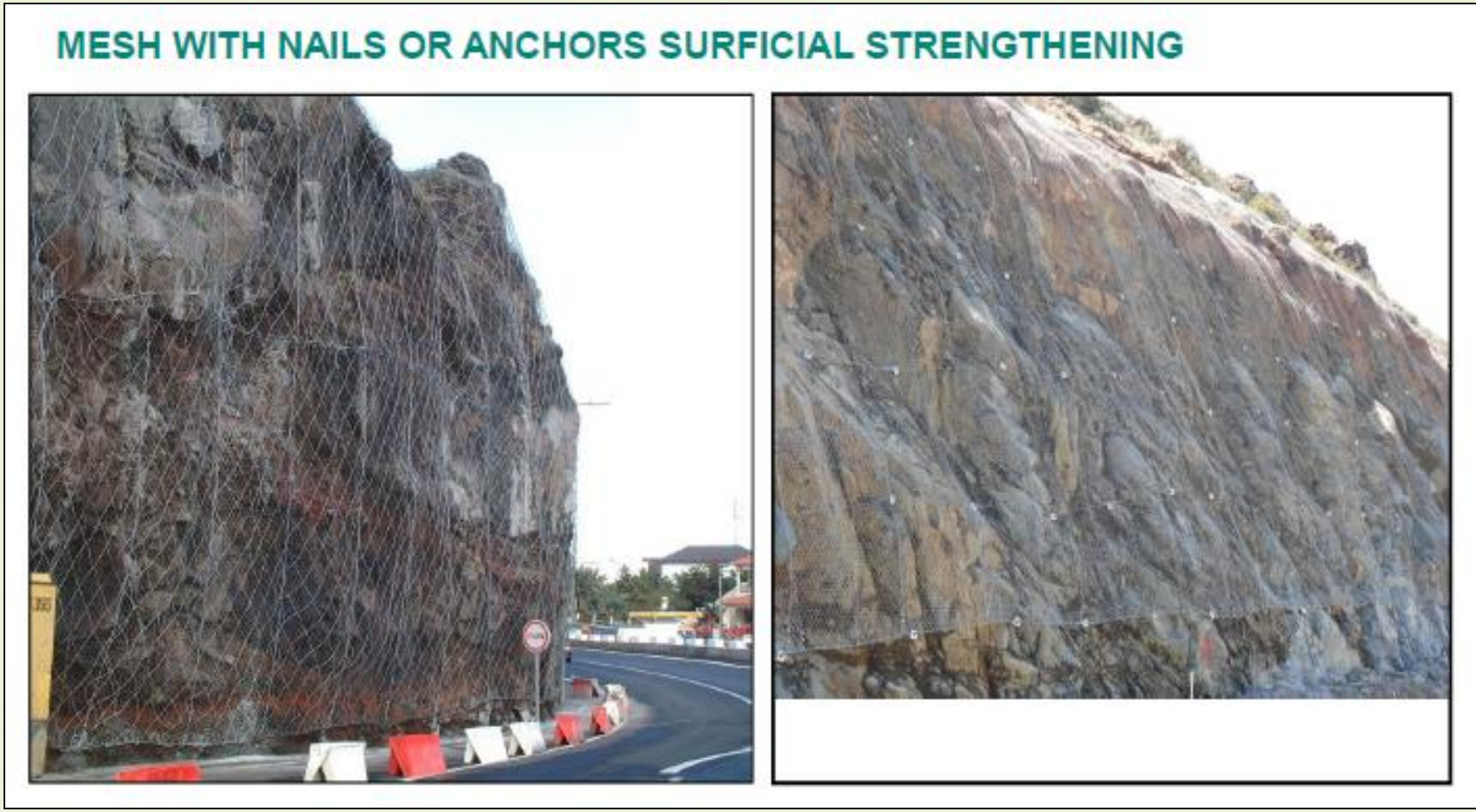
ROCKFALL ATTENUATORS OR HYBRID BARRIERS OR HANGER NETS

Some Novel Slope Protection/Stabilization Measures

- Rockfall protection measures - DRAPERY



Some Novel Slope Protection/Stabilization Measures



RUVOLUM: Free online design and dimensioning tool for Tecco Mesh Drapery protection system

Some Novel Slope Protection/Stabilization Measures

Some Novel Slope Protection/Stabilization Measures

ROCKFALL BARRIERS

STRUCTURAL WALLS

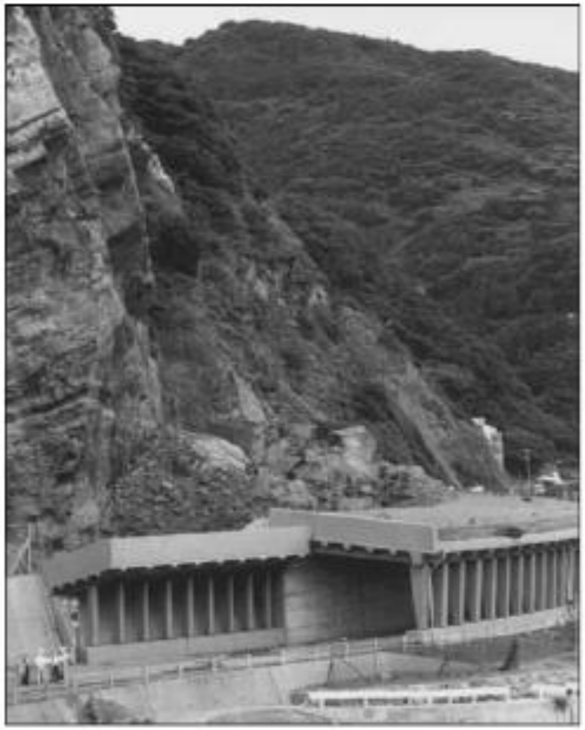
Concrete barriers

Masonry walls, either mortared or dry stack

Timber Soldier-pile walls

Some Novel Slope Protection/Stabilization Measures

ROCK SHEDS AND TUNNELS



Typical Rock shed construction

(a) Reinforced concrete structures with horizontal roof covered with layer of gravel

(b) Sheds constructed with timber and reinforced concrete with sloping roofs that deflect rockfall over the railway

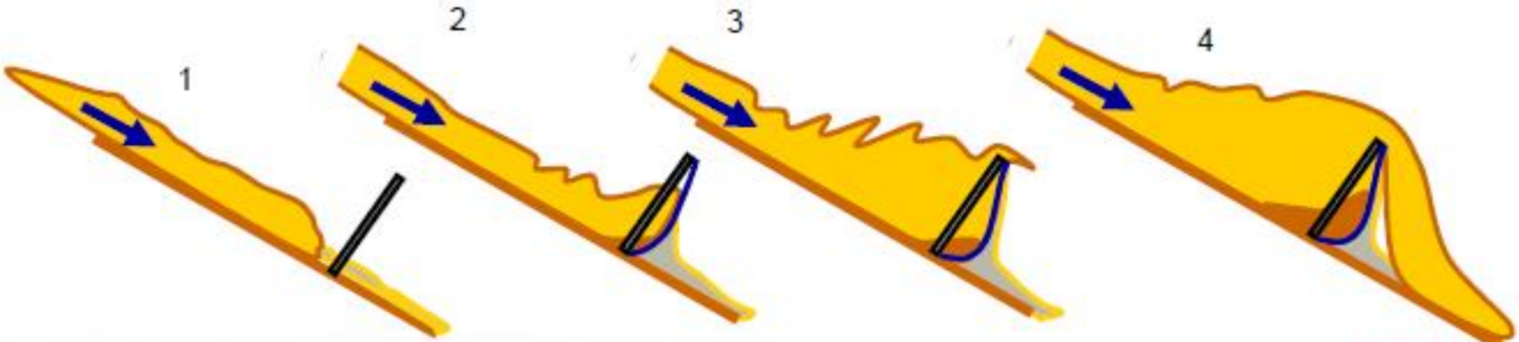
Maccaferri Industrial

Some Novel Slope Protection/Stabilization Measures

DEBRIS FLOW BARRIERS

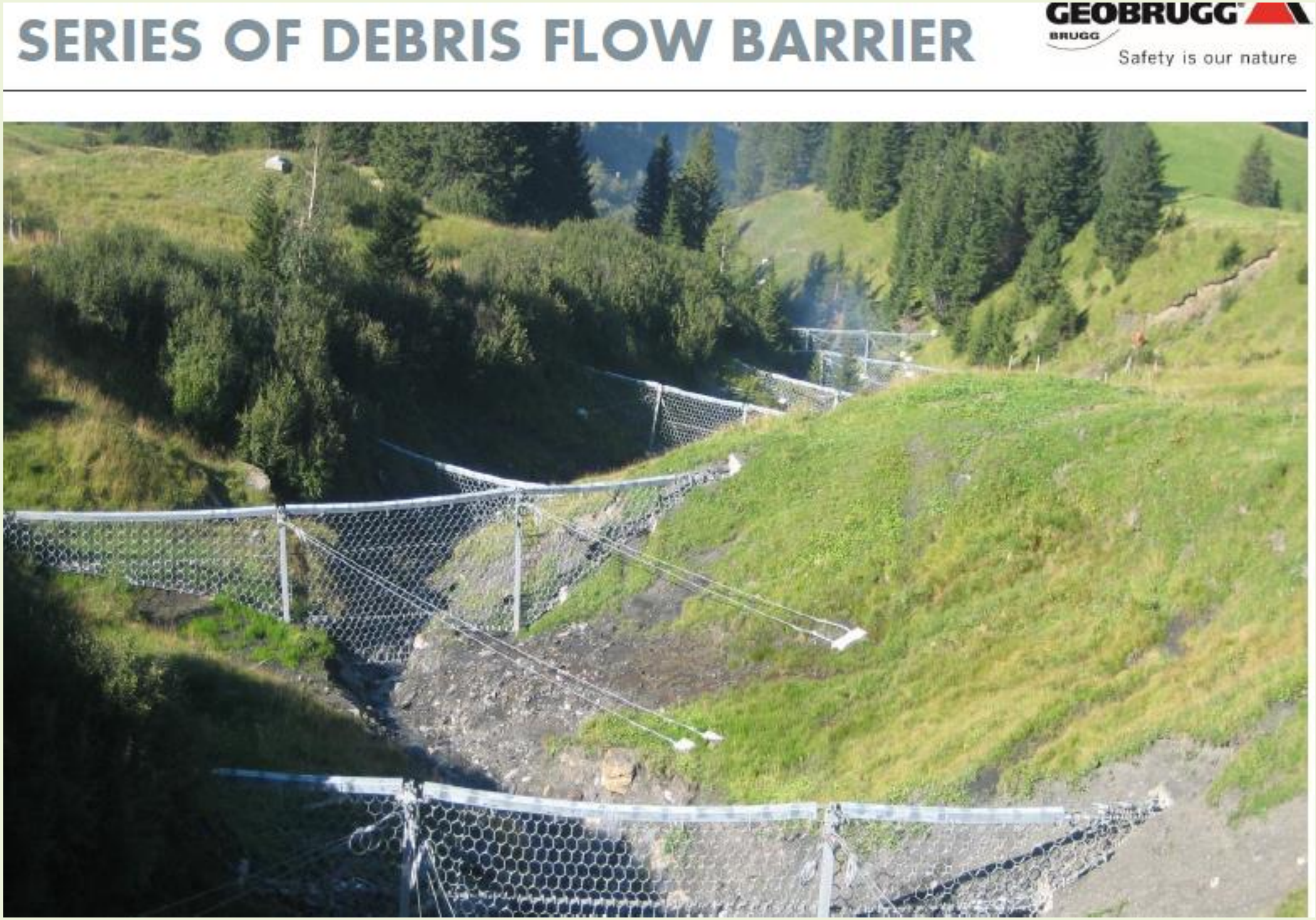
- It is made of flexible ring nets withstands high static & dynamic loads.
- Separates the water from debris thus reducing the destructive force

Debris Flow Barriers



Maccaferri Industrial Group

Some Novel Slope Protection/Stabilization Measures



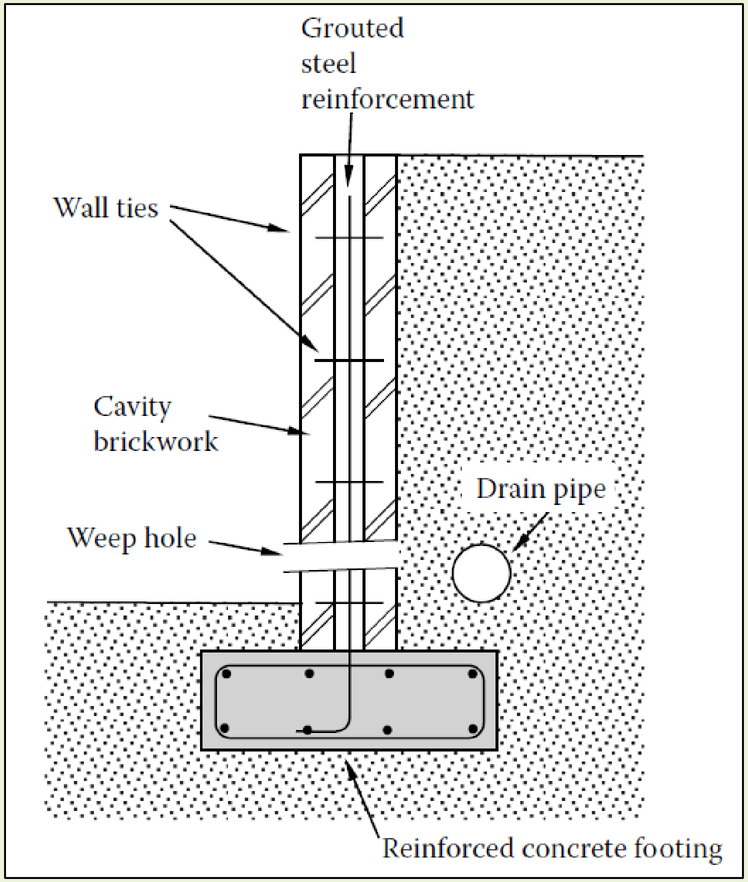
The World of Retention Systems

Slope Retention Systems and Typologies

- **Retention systems**
  - Structures built to retain vertical or near vertical earth slopes and resist lateral thrusts
  - Retention of water, natural soil or fill soil
- **Rigid retention systems**
  - Masonry Retaining Walls
  - Gravity Retaining Walls
  - Semi-gravity retaining walls
- **Semi-rigid retention systems**
  - Cantilever retaining walls
  - Counterfort retaining walls
- **Embedded flexible retention systems**
  - Cantilever Sheet pile walls
  - Anchored bulkheads
  - Bored pile walls
- **Surficial Flexible Retention System**
  - Crib Walls
  - Interlocking Block / Porcupine walls
  - Gabion Walls
- **Composite Retention Systems**
  - Reinforced Soil (MSE) Walls
  - Anchored Earth Walls
  - Soil Nailed / Nailed Soil Slopes

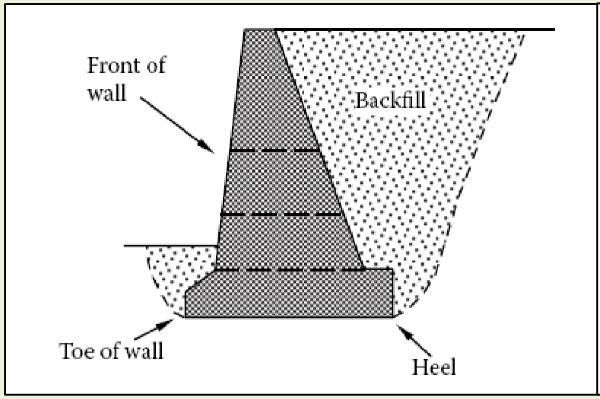
Rigid Retention Systems

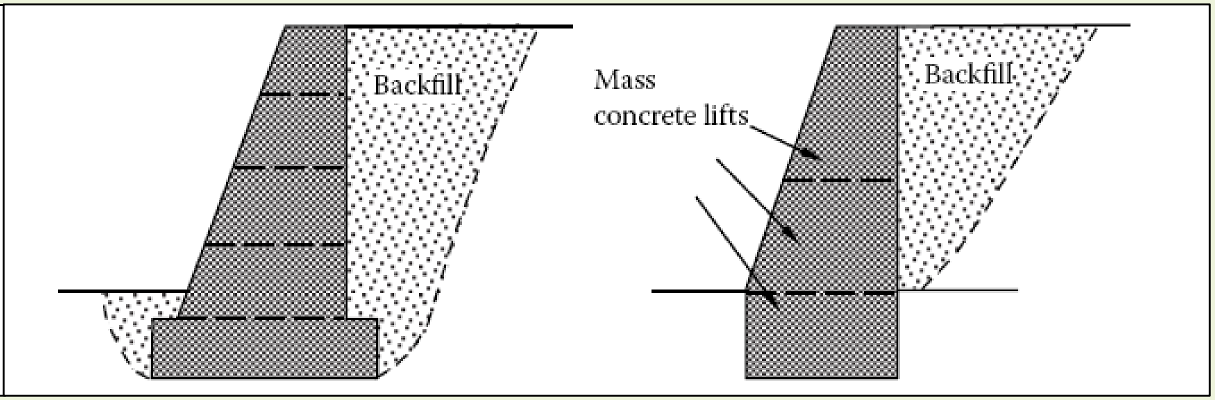
- **Masonry Retaining Walls**
  - Load bearing brickwork
  - Design guidance provided by Brick Development Association **(Haseltine and Tutt 1991)**
  - Modest wall height up to 4 m
    - Mass brickwork suitable for short walls of 1 m
    - Quetta-bond brickwork can support walls up to 3 m
    - Double skinned reinforced and grouted cavity walls may be taller
  - Longevity is the main problem, as service life is lesser when affected by climatic conditions



Rigid Retention Systems

- **Gravity Retaining Walls / Breast Walls**
  - Stability and resistance to deformation is governed by their own weight **(Eurocode 7)**
  - Constructed with plain or reinforced concrete, stone masonry, blockwork, rubble masonry
  - May include base footing (with or without heels), ledge or buttress
  - Cross-section should be such that the resultant earth pressure should not produce any tensile stress in any part of the wall
    - Joints between concrete lifts and masonry blocks may fail in tension
  - Meant for smaller heights less than 3 m
    - Not economical for higher walls **(Teng 1962)**

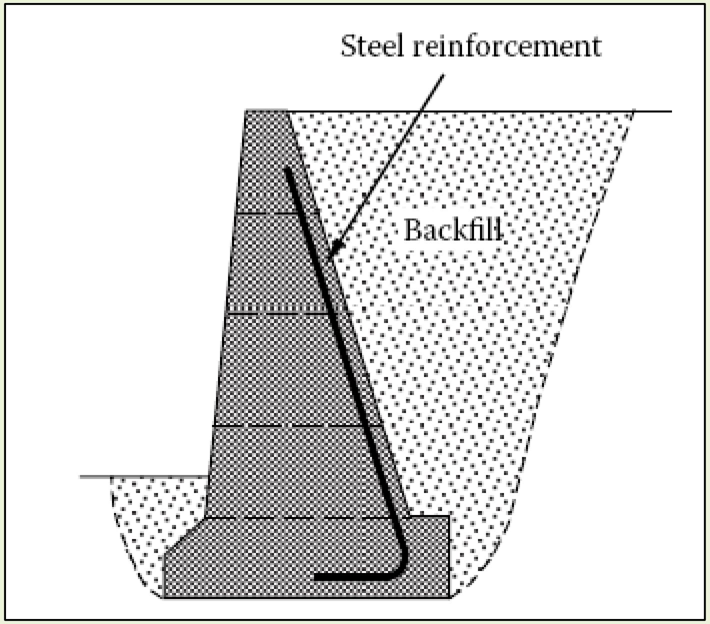


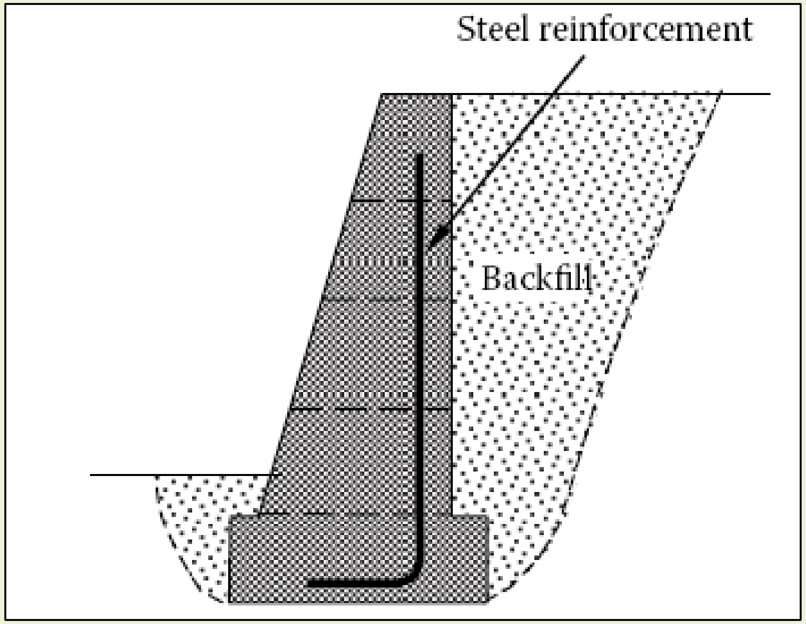


Rigid Retaining Structures

Rigid Retention Systems

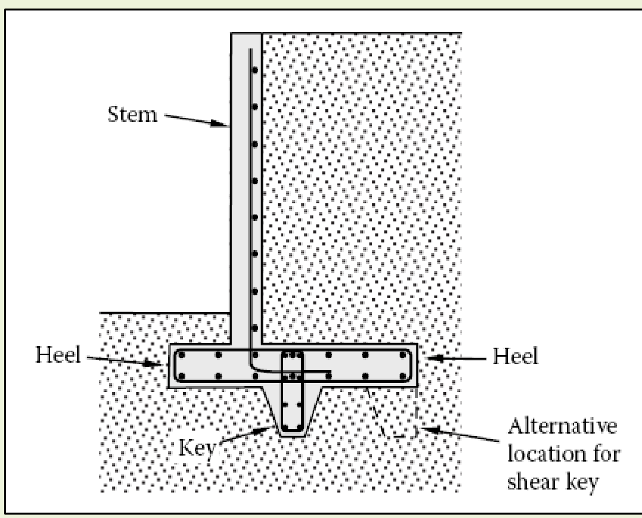
- **Semi-Gravity Retaining Walls**
  - Rely more on internal resistance to bending and shear
    - Less on self-weight than gravity walls
  - Utilization of steel connection between the base and stem, or between concrete lifts
    - Reduces mass of concrete, makes the stem slender, minimize the size of wall sections
    - Induces tensile stiffness across the concrete lifts

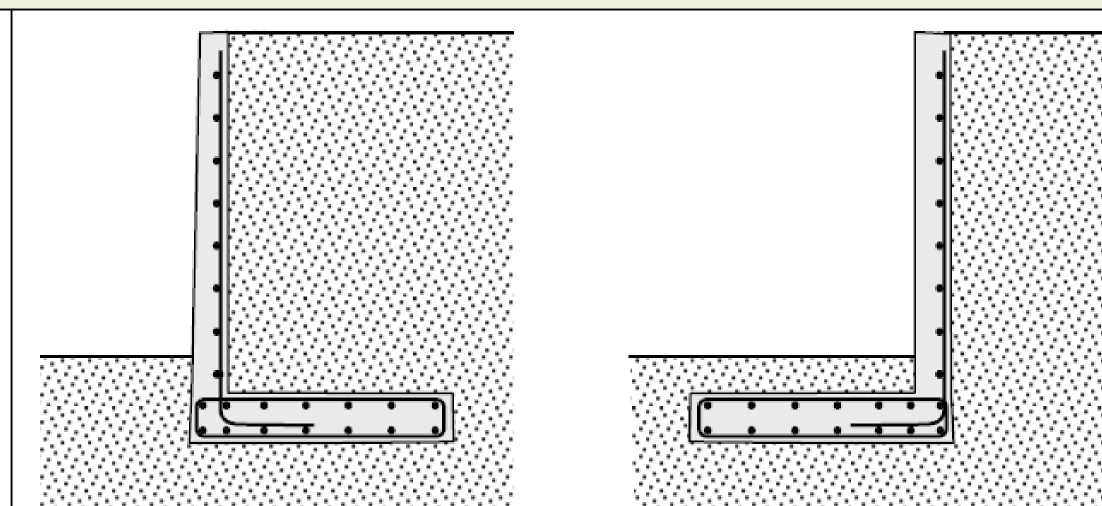




Semi-Rigid Retention Systems

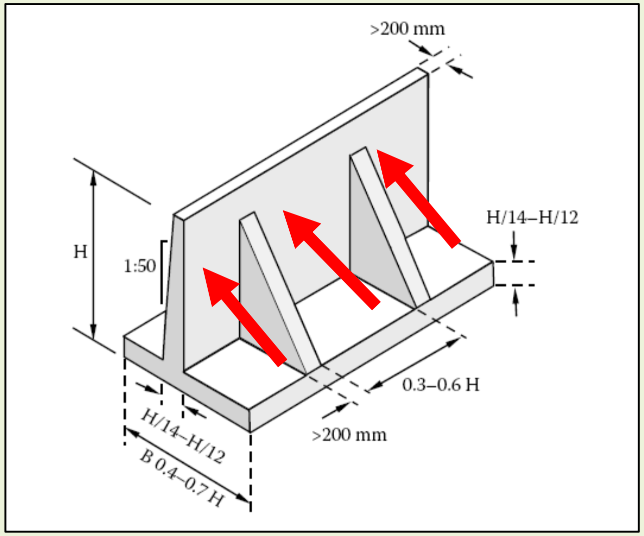
- **Cantilever Retaining Walls**
  - Inverted T- or L-shaped structures
  - Consist of a thin stem and a base slab
  - Economical to a height of about 6-8 m
  - The stem retains the soil mass behind the wall by cantilever action
  - Stability is achieved from the weight of the soil on the heel portion of the base slab
  - Shear key may be used to augment sliding resistance

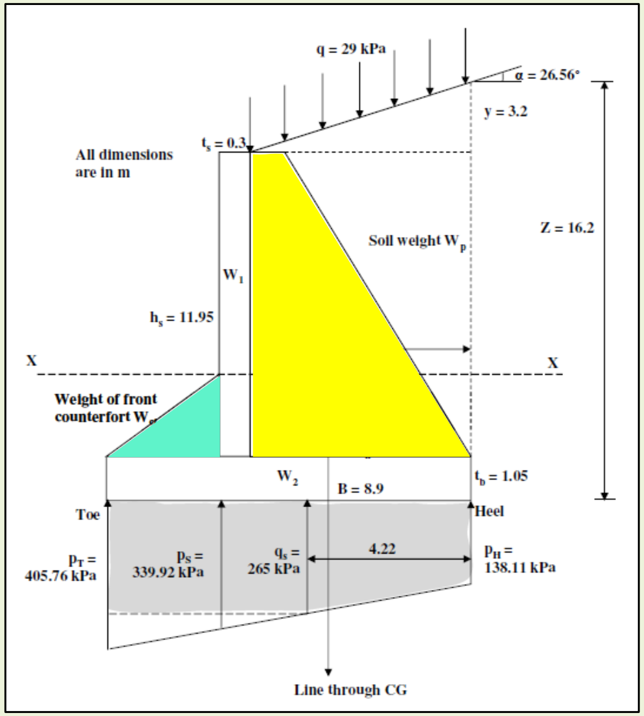




Semi-Rigid Retention Systems

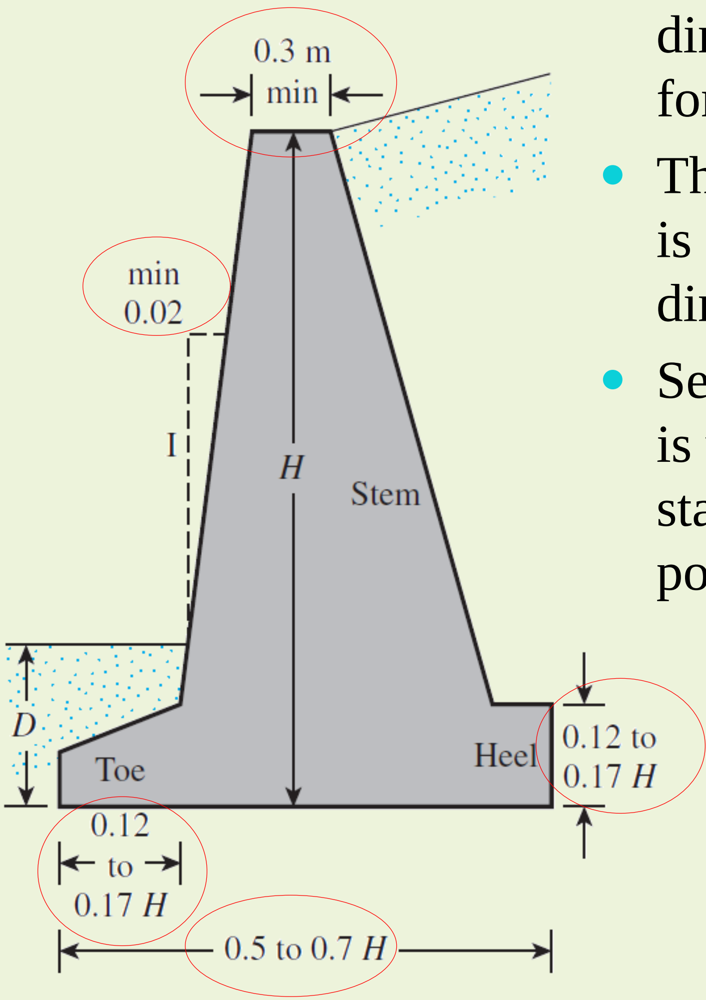
- **Counterfort Retaining Walls or Buttressed Walls**
  - Similar to cantilever walls
  - Counterforts are thin vertical concrete slabs that tie the wall stem and the base slab together
    - Placed at regular intervals along the length of the wall
    - Subjected to tensile stresses
  - Counterforts reduce the bending moments and shear stresses in the stem of the wall
  - Applicable to withstand high lateral pressure originating from the retained backfill
    - Used for very tall walls, 10-12 m high
  - Can have both main and front counterforts
    - Front counterfort is termed as 'buttress'
    - Subjected to compressive stresses





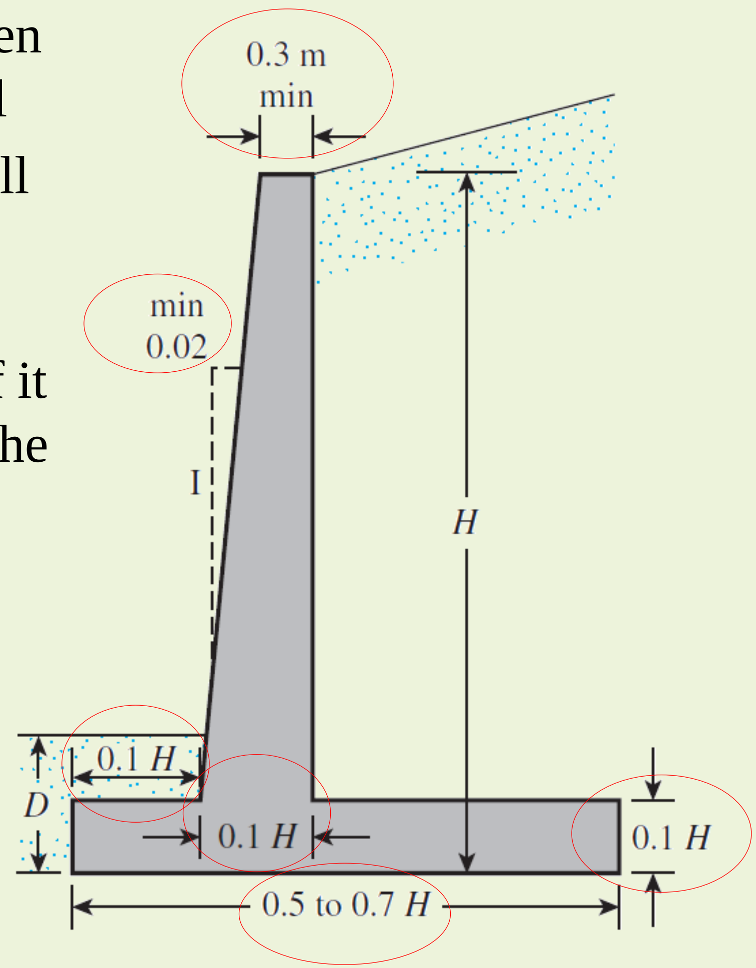
Retaining Wall Design: Proportioning

Gravity



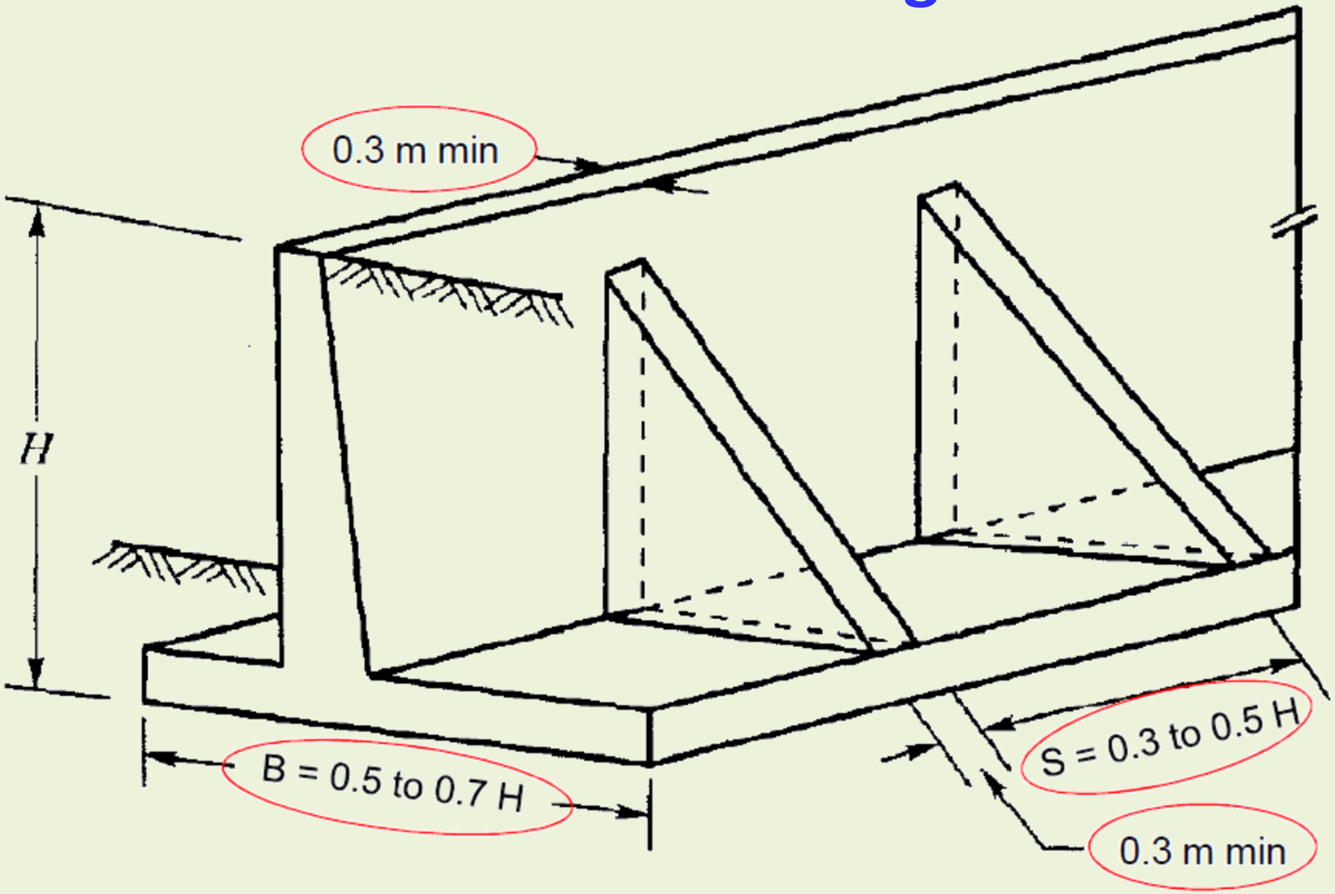
- First, approximate dimensions are chosen for the retaining wall
- Then, stability of wall is checked for these dimensions
- Section is changed if it is undesirable from the stability or economy point of view

Cantilever

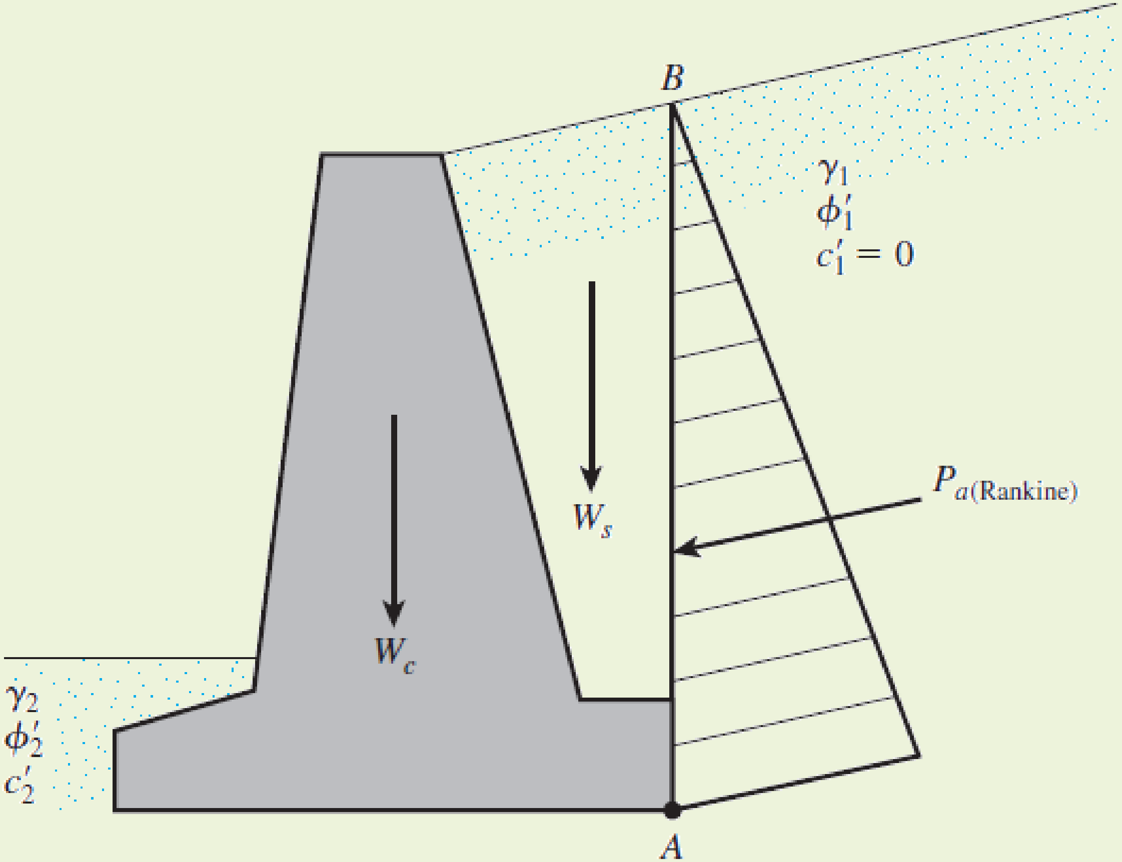


Retaining Wall Design: Proportioning

Counterfort Retaining Wall

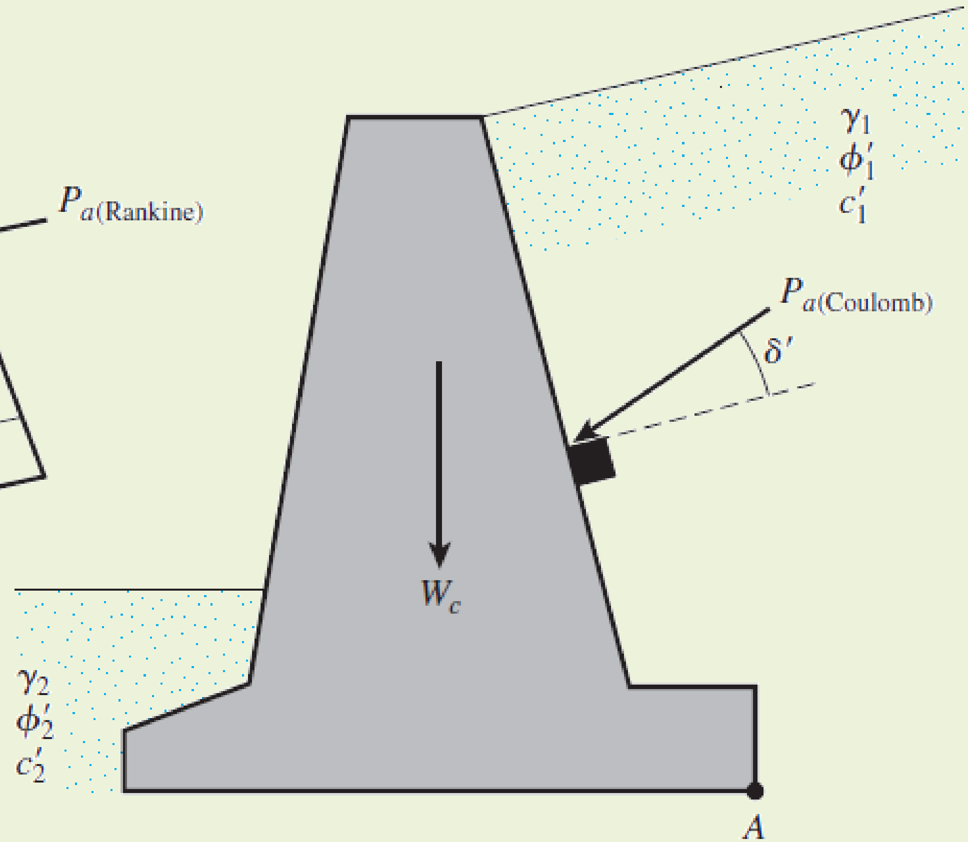


Earth Pressure on Gravity Retaining Wall



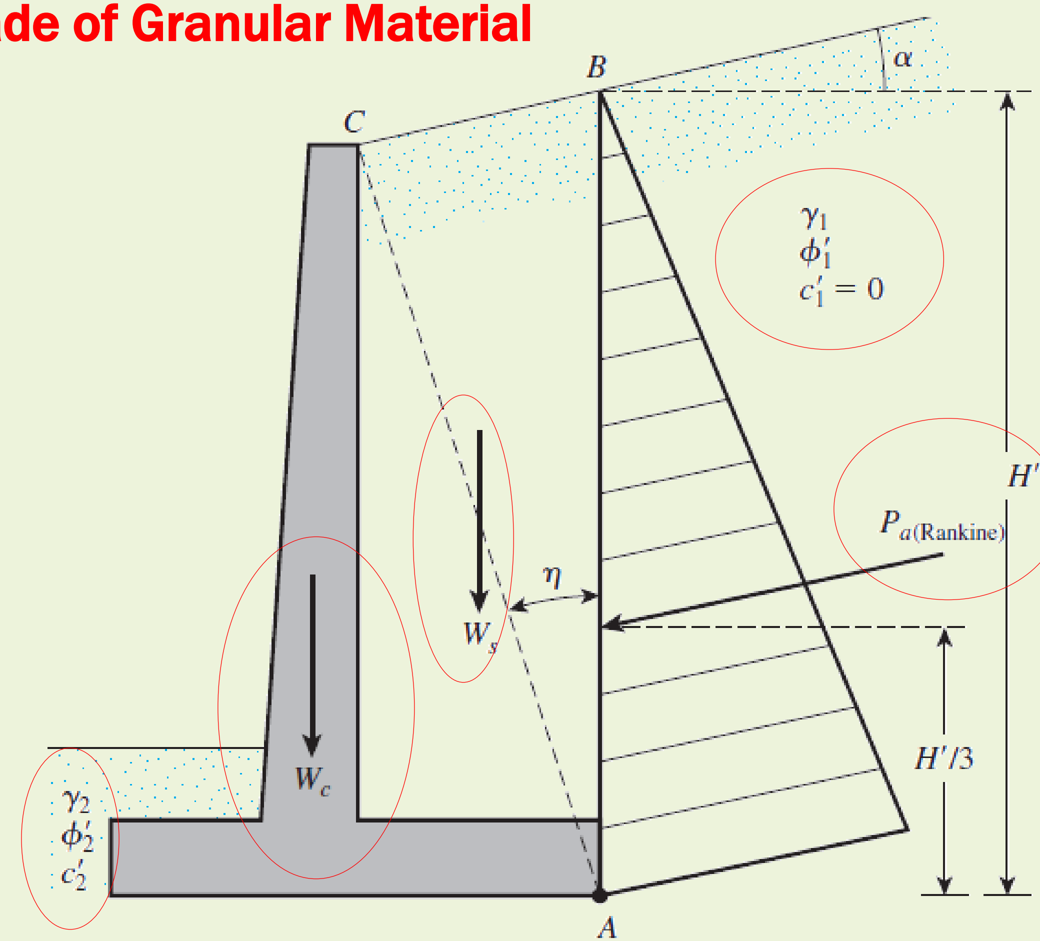
Active Earth Pressure on a Vertical Backface with Inclined Backfill made of Granular Material

Active Earth Pressure on an Inclined Backface with Inclined Backfill made of Granular Material

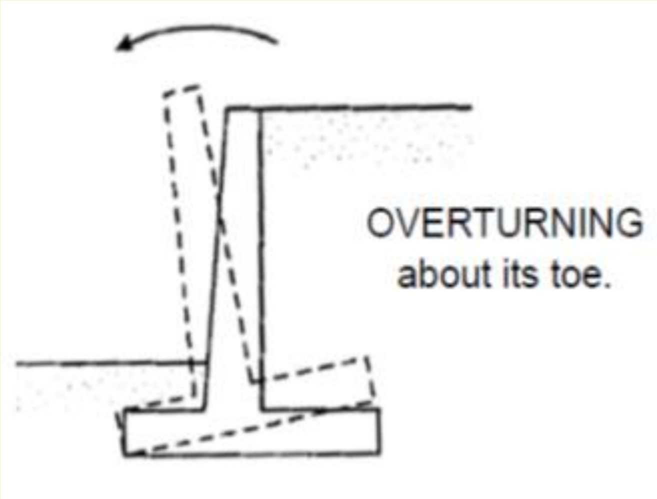


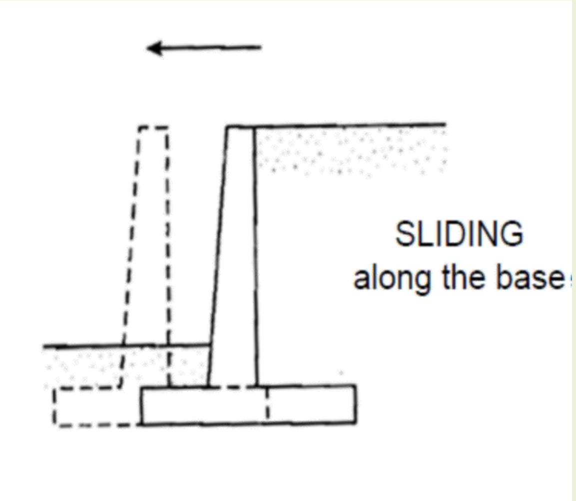
Earth Pressure on Cantilever Retaining Wall

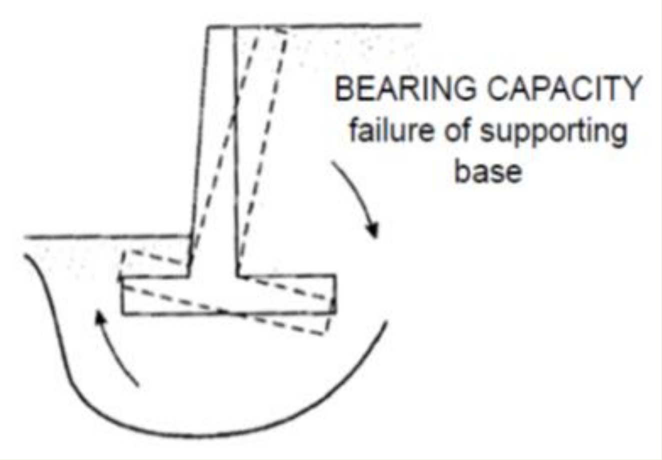
Earth pressure may be calculated at the vertical section going through the heel of wall → **Active Earth Pressure on a Vertical Backface with Inclined Backfill made of Granular Material**



Stability of Retaining Wall

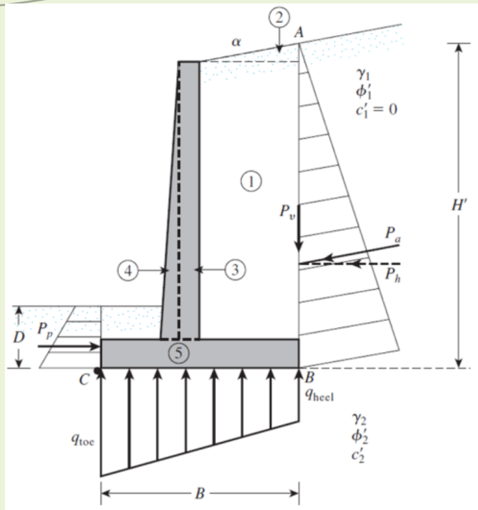






Excessive SETTLEMENT may occur if weak soil layer is located below the foundation within 1.5 times foundation width.

Wall Settlements



➢ Settlement of soil below the wall:

- ✓ Immediate settlement in granular soil
- ✓ Consolidation settlement in cohesive soil

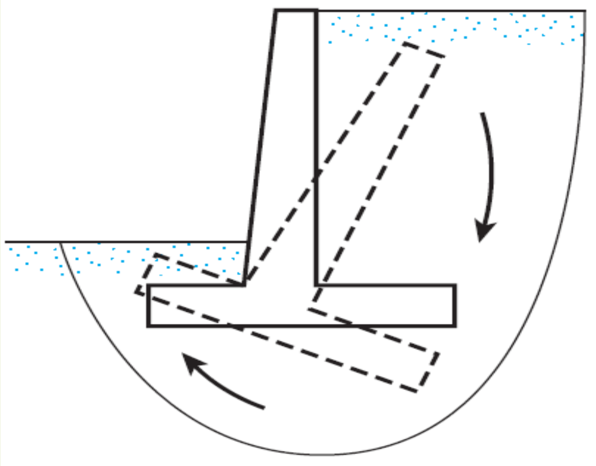
➢ Differential settlement (between heel and toe):

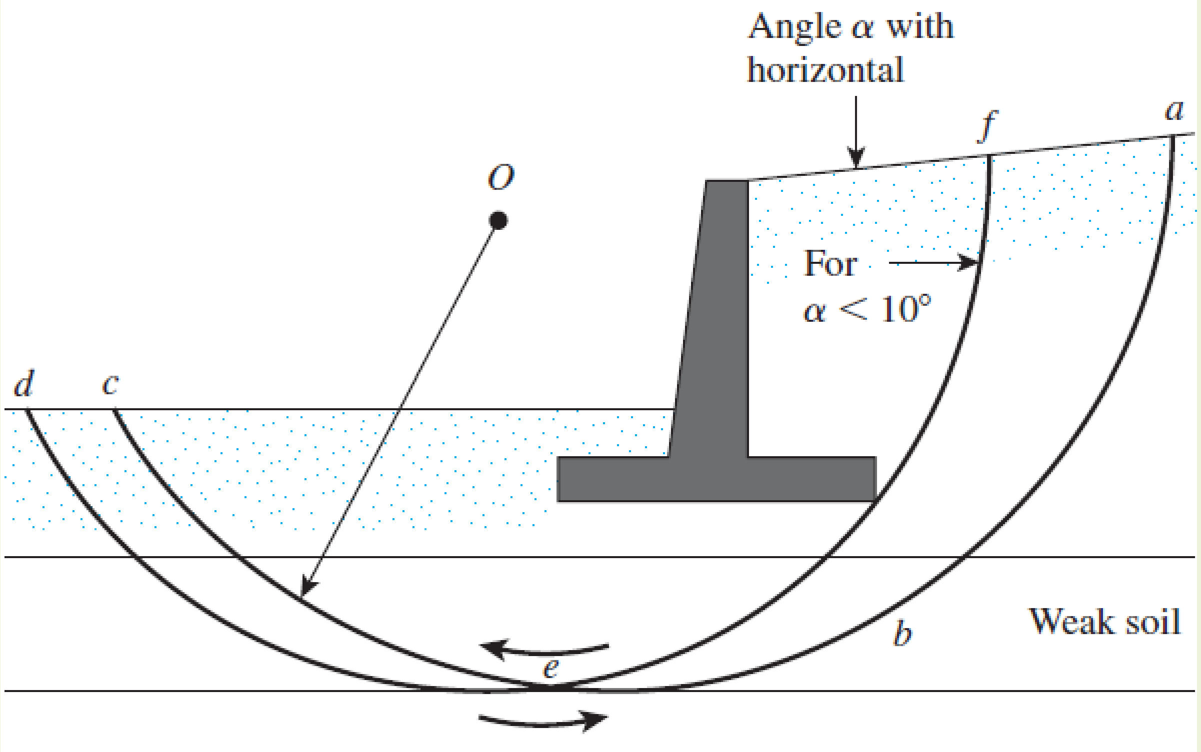
- ✓ Heel settlement is larger when there is substantial increase in backfill load
- ✓ Toe settlements are produced by lateral earth pressure.
  - ✓ To minimize toe settlements, ground may be strengthened
    - ✓ Sand piles, Rock columns, Grouting, Structural piles etc.
- ✓ Differential settlements along the length of wall may produce cracks in wall.
  - ✓ Can be monitored during construction itself
  - ✓ Preventive action may be taken such as ensuring proper compaction of the ground.

Stability of Retaining Wall

- Deep seated shear failure may occur if there is a weak soil layer below the foundation within a depth of about 1.5 times width of foundation.

- The failure surface may be assumed to have cylindrical shape and critical failure surface for sliding may be determined through analysis → Similar to a

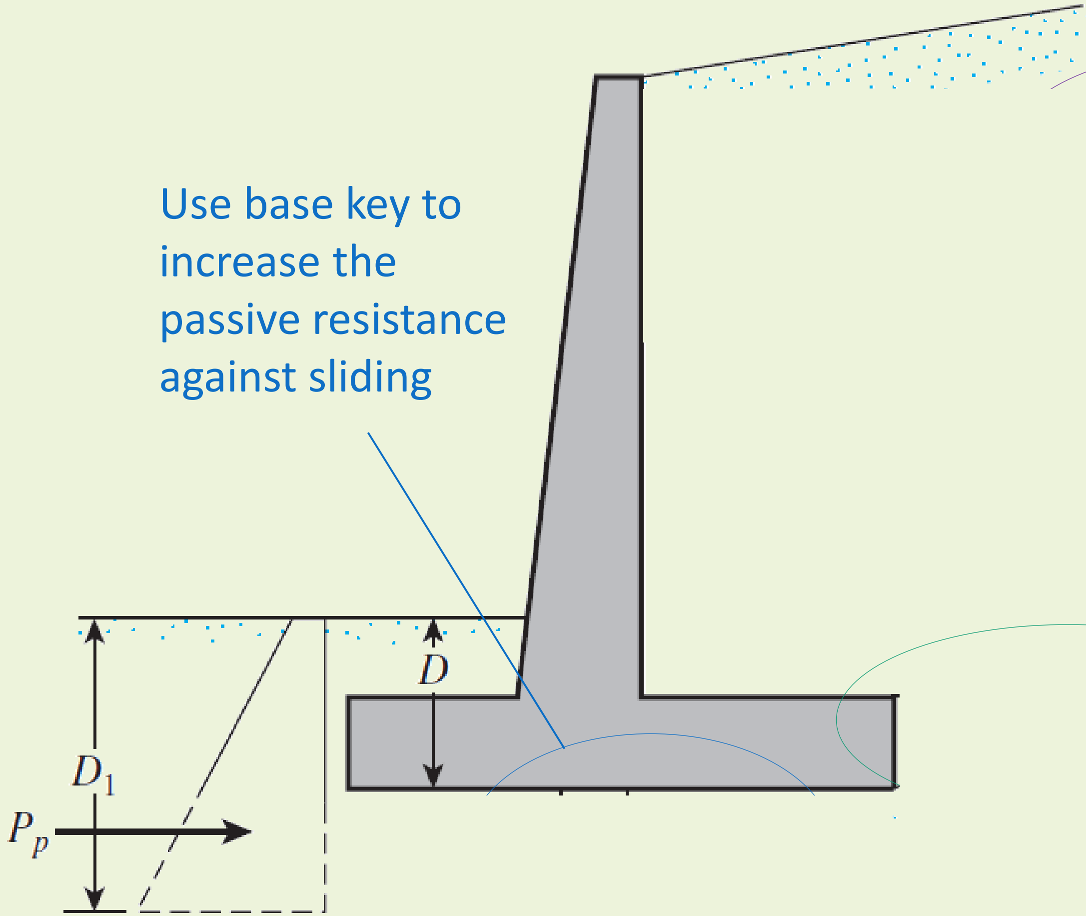




- For backfill with its slope less than 10^0, the critical sliding surface may be assumed to pass through heel of the retaining wall.

Alternative for Improving FoS against SLIDING

Use base key to increase the passive resistance against sliding

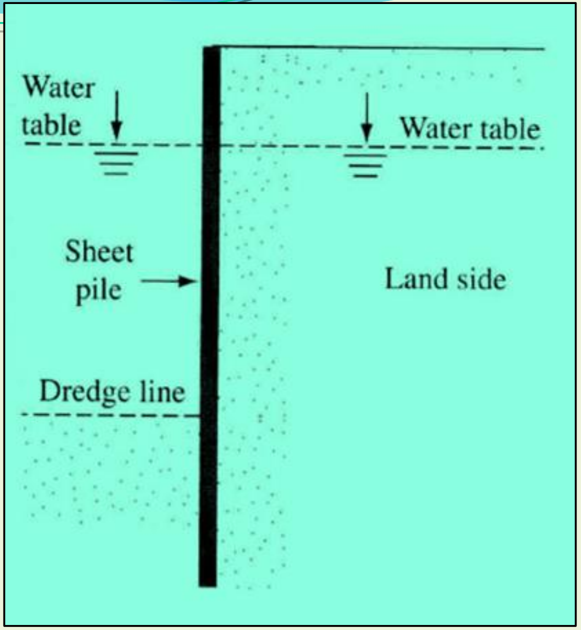


Use a dead man anchor at the stem to transfer a part of sliding force to it

width of
eferably
)

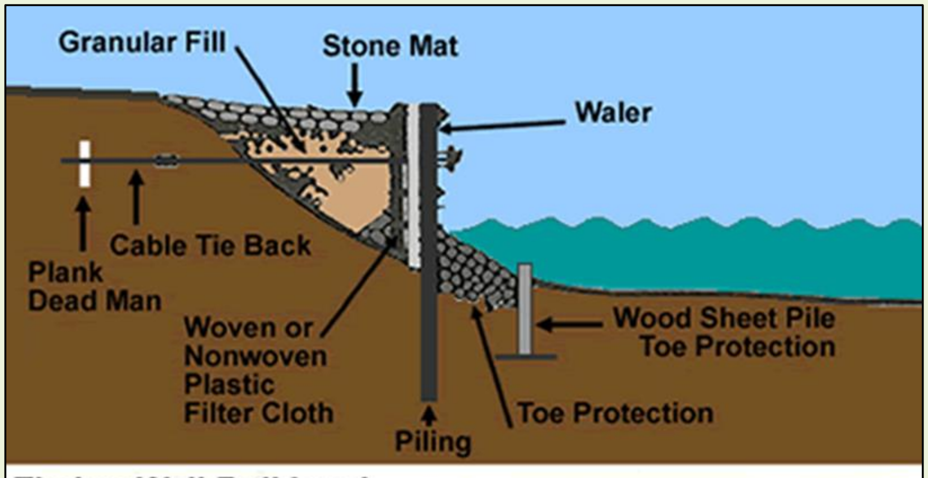
Embedded Flexible Retention Systems

- **Cantilever Sheet Pile Walls**
  - Bending capacity plays a significant role rather than the weight of the retention system
  - Flexible support systems for waterfront structures and temporary excavation works
  - Can be of steel, timber or precast reinforced concrete
  - Often used in unfavourable soil conditions such as soft clays as a foundation is not required
  - Driven from ground surface
    - Easy and quick construction even in presence of water
  - Able to follow construction of complex plan shapes
    - Minimum displacement of soil while driving
  - Can be constructed in situations with low headroom
  - Reduced noise during driving
  - High sustainability due to speed of installation and extraction

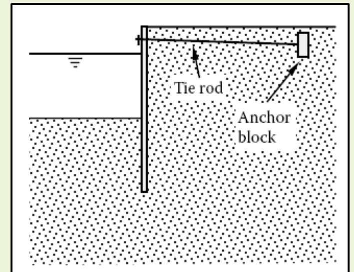


Embedded Flexible Retention Systems

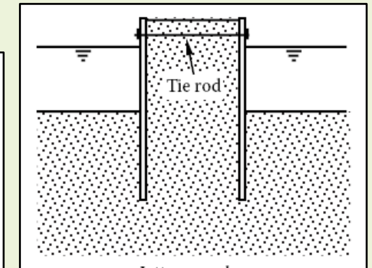
- **Anchored Bulkheads**
  - Used when the height of backfill to be retained is more than 6 m
  - Provision of anchors or tie-back mechanisms to lessen the depth of penetration
    - To sustain the same pressure, lesser depth of penetration required as compared to sheet pile wall
    - Reduction of cross-section area and weight of sheet pile wall



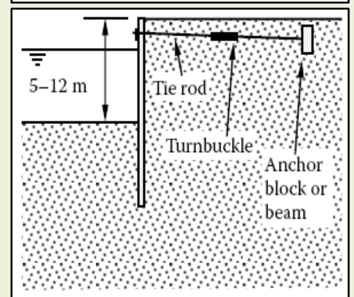
Timber Wall Bulkhead



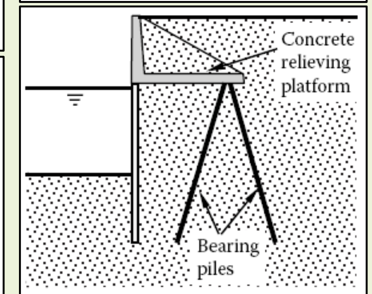
Anchored sheet-pile retaining wall



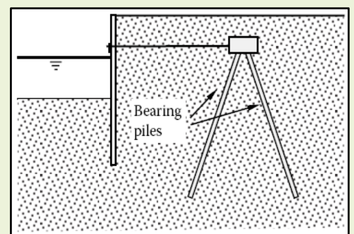
Jetty or mole



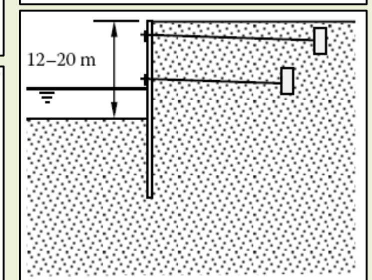
Single anchored wall



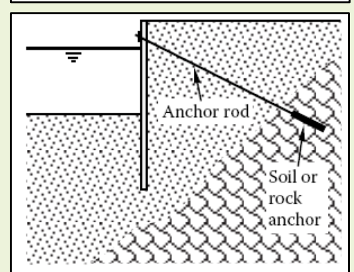
Relieving platform wall



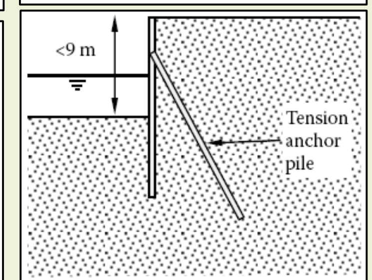
A-frame anchor



Multiple anchored wall



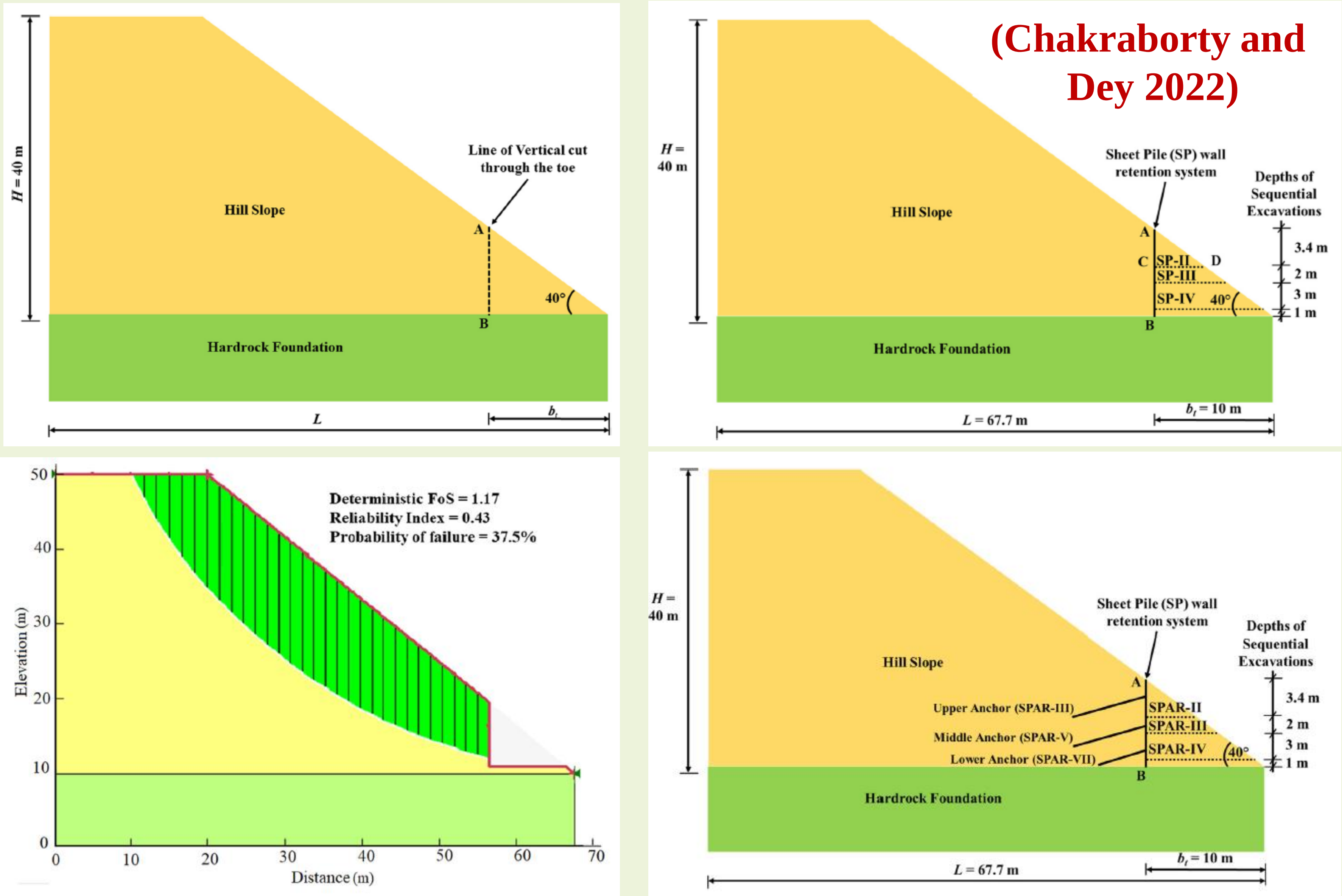
Soil or rock anchors



Raking pile anchor

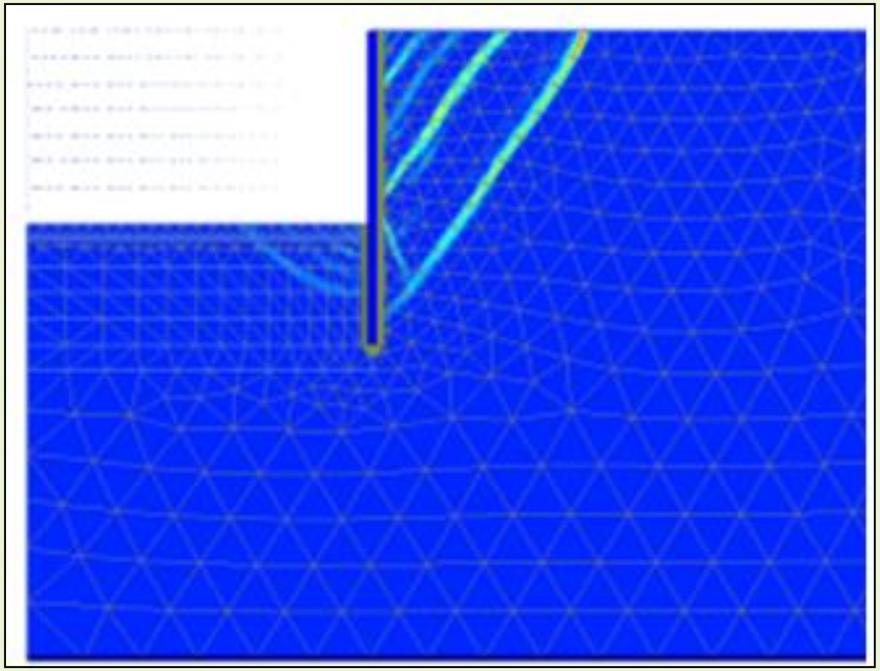
Embedded Flexible Retention Systems

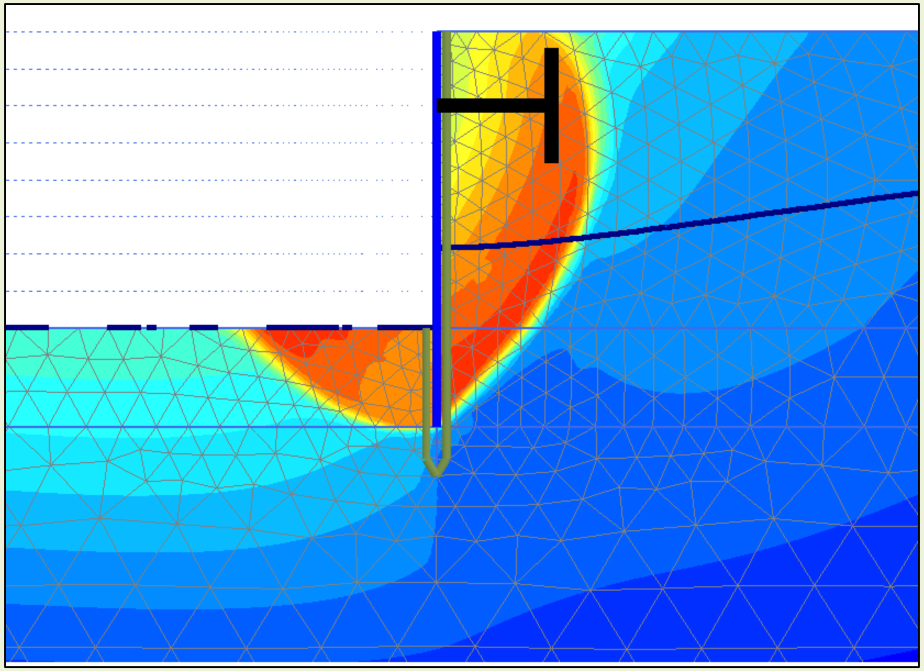
(Chakraborty and Dey 2022)



Dredge Excavations

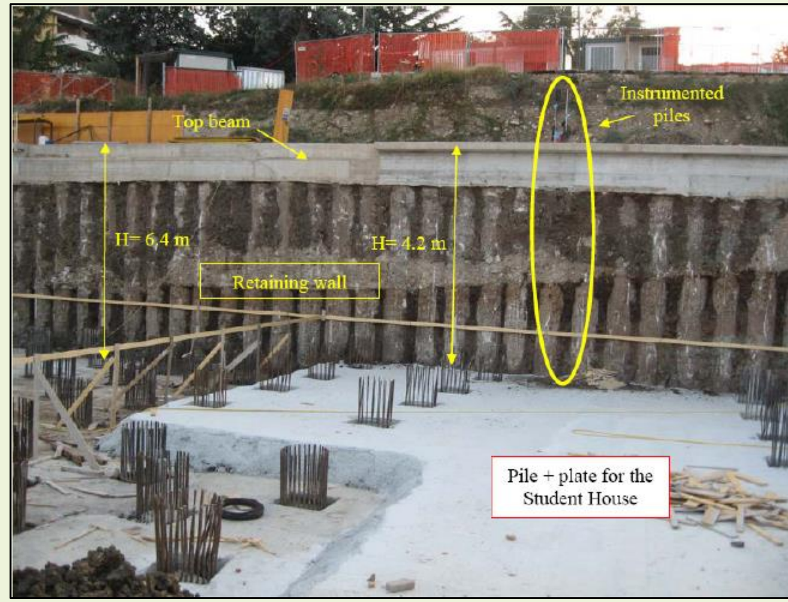
- **Sheet Pile and Tie-back wall for vertical cut protection**

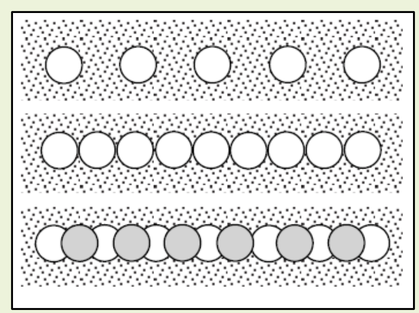


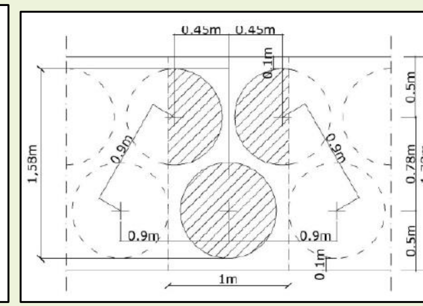


Embedded Flexible Retention Systems

- **Bored Pile Walls**
  - Can be constructed at any ground conditions, and close to the existing structures
  - Can support very high vertical loads is addition to lateral earth pressures
    - Top of the piles are capped with a concrete beam to distribute loads
  - Arrangement of bored piles
    - Intermittent (spacing exceeds diameter)
      - *OC soils or Cemented soils, GWT below excavation level*
    - Contiguous (piles touching each other or having a negligible gap)
      - *Very low permeability soils*
    - Secant (piles interlocking, spacing < diameter)
      - *Primary concrete piles are unreinforced and constructed of cement bentonite, and the secondary piles are installed when the primary ones are still green → Higher bending stiffness.*
    - Scattered contiguous (scattered in multiple layers)

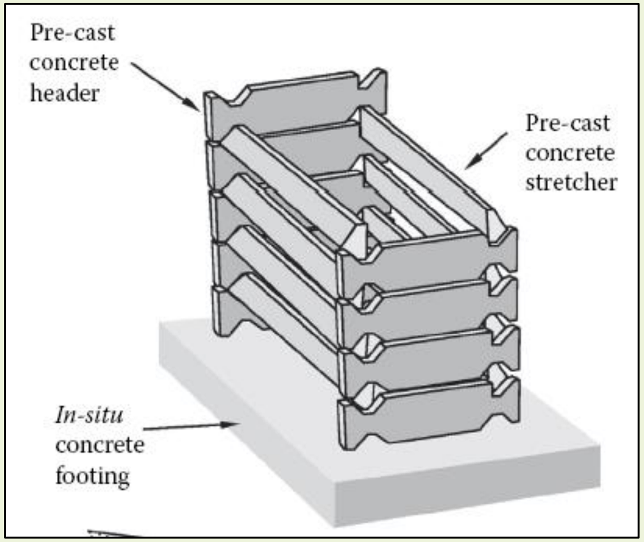


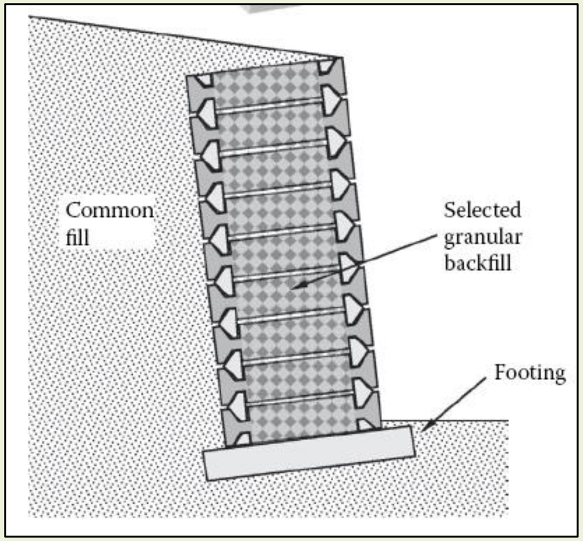




Surficial Flexible Retention Systems

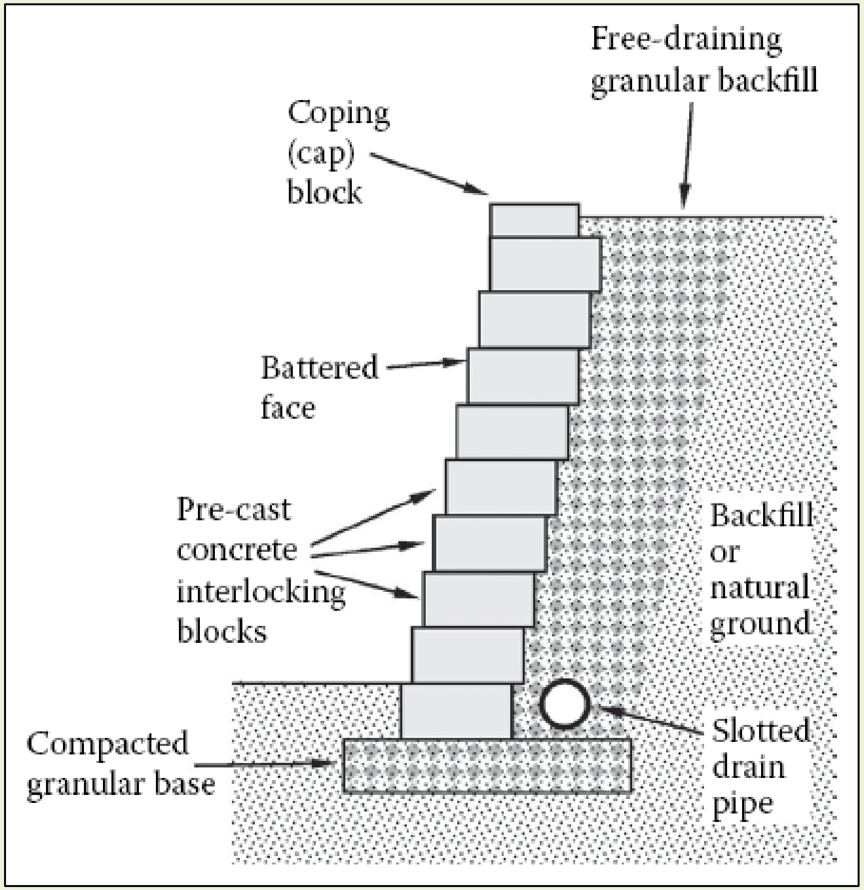
- **Crib Walls**
  - Suitable for walls of small to moderate height (6-9 m) which are subjected to moderate earth pressure
  - Being flexible system, large movements can be tolerated without damage
  - Easy to construct, dismantle, reassemble, reuse; Lesser maintenance cost
  - Backfilling done with compacted granular soil
  - Use of permeable fill improves the drainage of retained soil

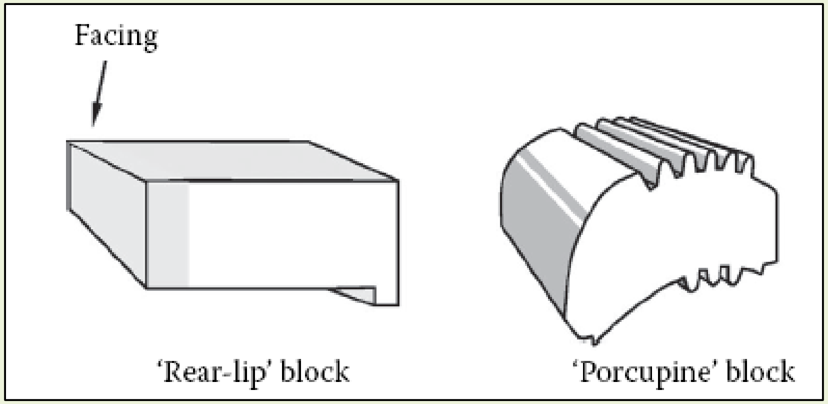




Surficial Flexible Retention Systems

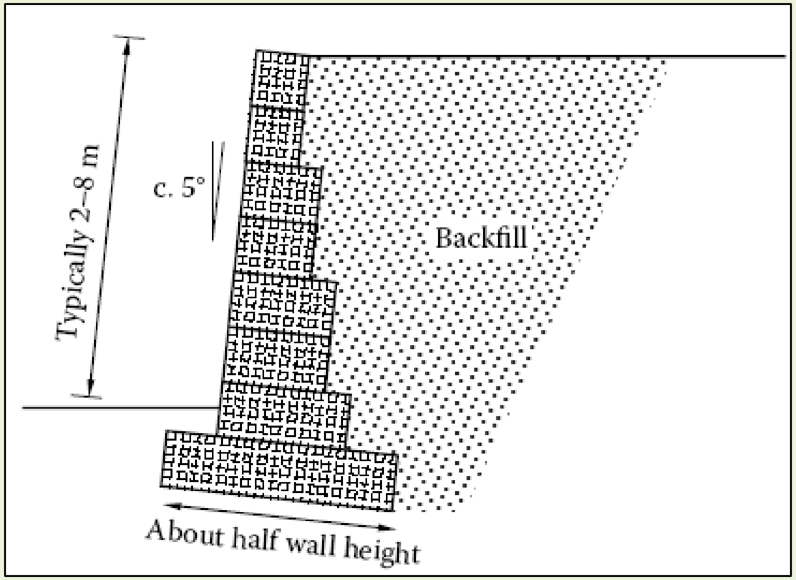
- **Interlocking Block / Porcupine Wall**
  - Utilization of precast concrete blocks that interlock with each other without the use of cement mortar
  - Interlocking achieved with the aid of a rear lip, or protrusions on the upper or lower surfaces
  - Modular nature makes it easy to construct, dismantle and reassemble
    - Routine ‘Porcupine walls’ utilizes concrete blocks weighing around 20 kg, with a built wall face angle of 68-73º, and height up to 3 m



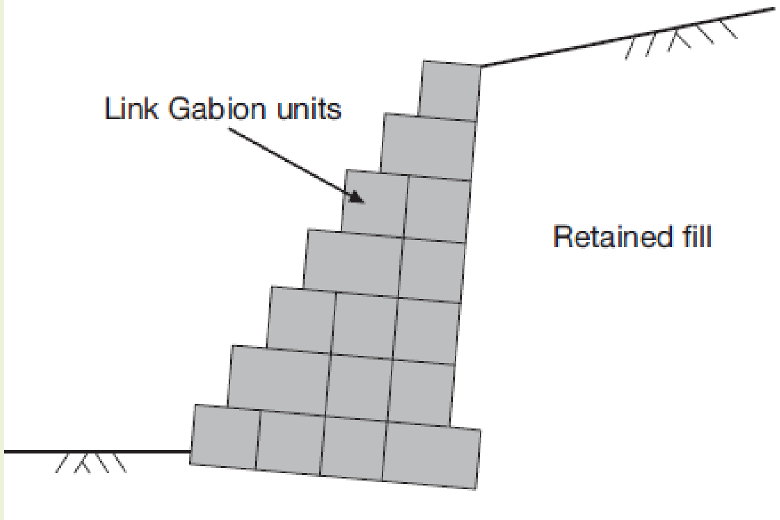


Surficial Flexible Retention Systems

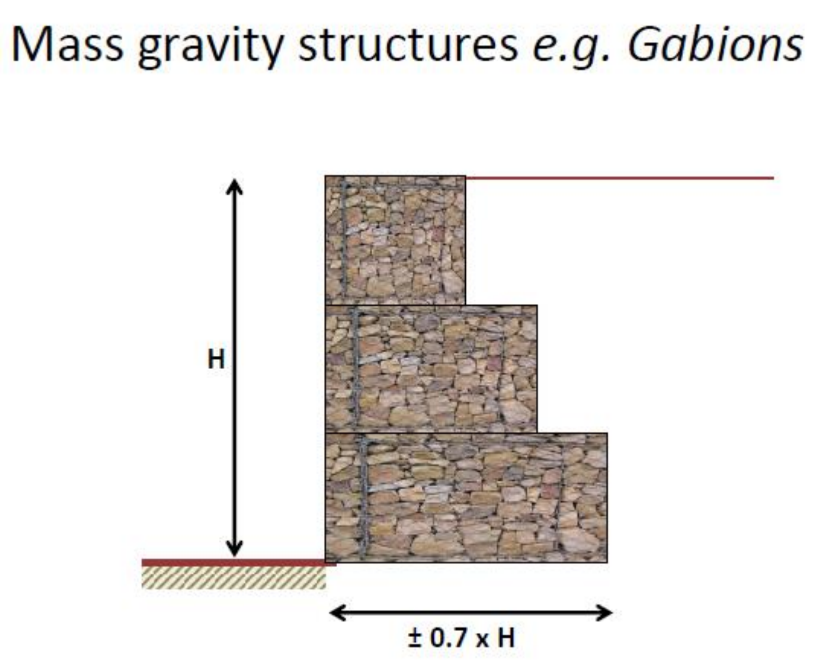
- **Gabion Wall**
  - Gabion consist of a box made of wire or plastic mesh that is used as a basic building unit
  - Filled with in-situ coarse granular material such crushed rock and cobbles
  - Advantageous for flexibility and material transportation to remote areas (only wire mesh is needed to be transported)
  - Particularly good at absorbing impact energy, and are often used as rock fall barriers
  - Possible to repair when damaged, and is recyclable and reusable

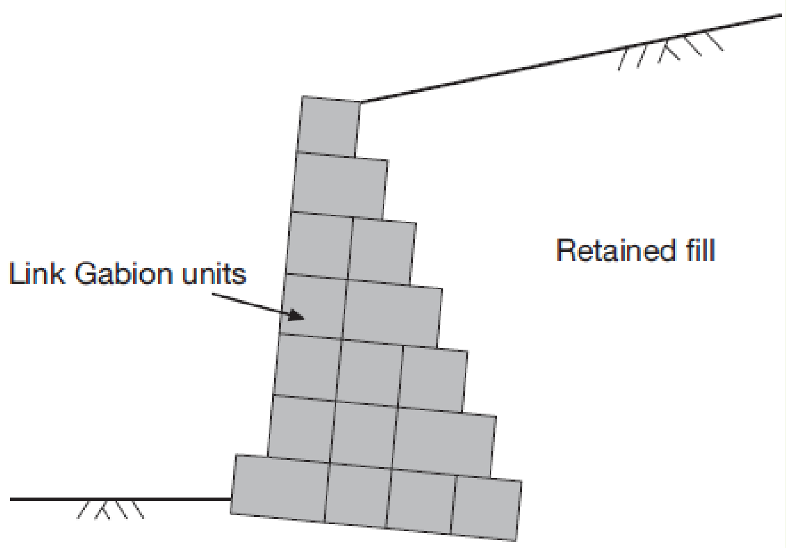


Gabion Walls



(a) Front sloped wall





(b) Rear sloped wall

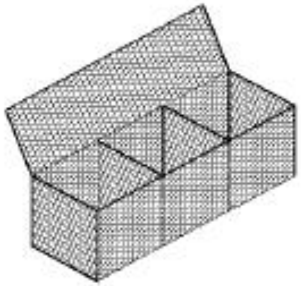
Why Gabion Systems?

- **Flexible** – Unlike welded mesh, concrete blocks, concrete mats or reinforced concrete, double twist woven mesh Gabions & Terramesh systems are able to accommodate substantial differential settlement
- **Monolithic** – the fastening (lacing) procedure ensure the units act as one homogeneous structure
- **Permeable** – pore water pressures are easily dissipated through the structure
- **Durable** – Double twist mesh and heavily galvanised (can have an additional polymer coating) with 45 year old local installations disprove the fallacy that Gabion type structures are temporary solutions
- **Adaptable** – Gabion systems can be stepped, vertical or angled to suit specific project requirements. They can be filled in-situ or prefilled depending on site conditions using various mechanical means to assist with the packing process
- **Economical** – Generally, Gabion installation does not require any special equipment (pliers, temporary formwork, lacing tool etc.)
- **Environmentally friendly** – Vegetation easily establishes, eventually re-creating the pre-existing environment. The added use of bio-degradable coir logs and Jute blankets will accelerate the vegetative process if required

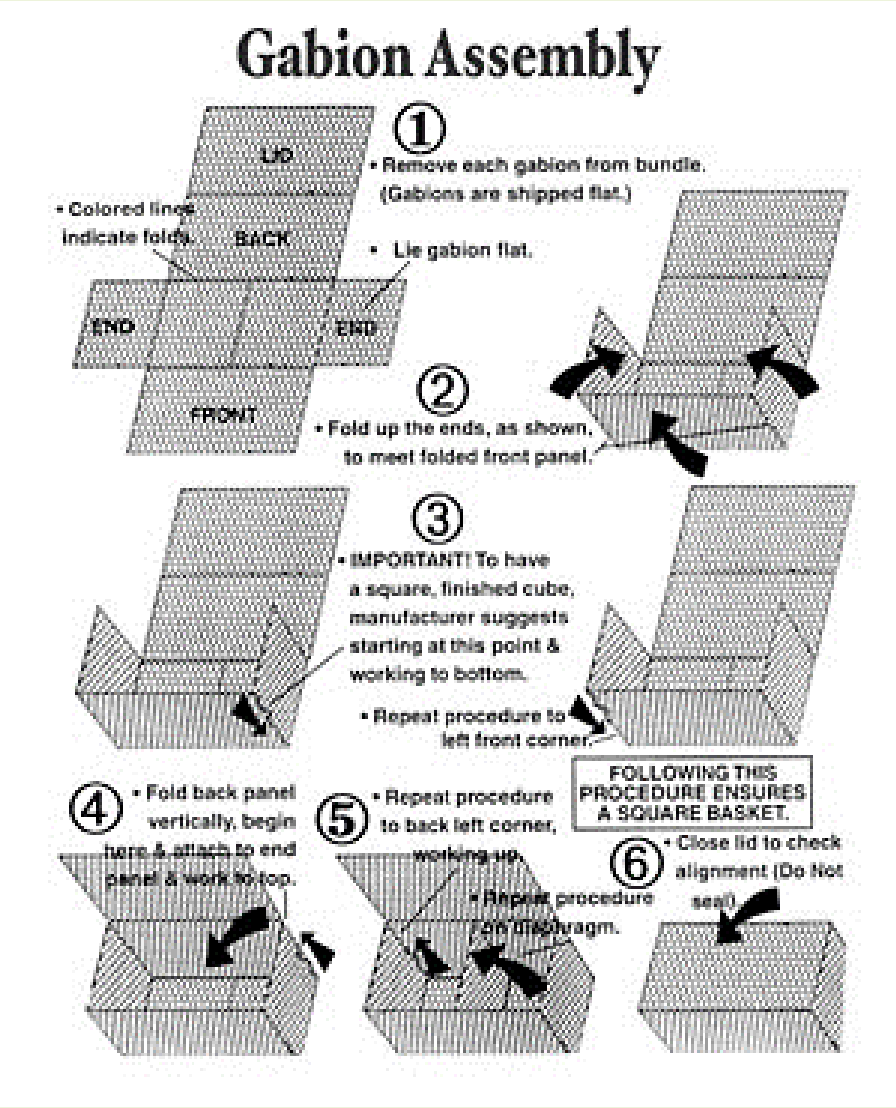
Why Gabion Systems?

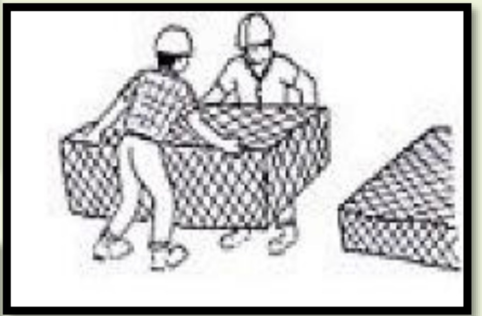
Gabions

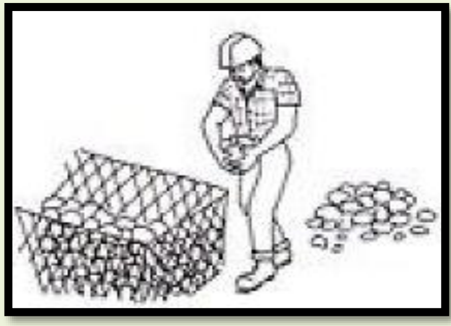
Gabions are flexible cages made of hexagonal double twist heavily galvanised mild steel woven wire mesh with an additional polymer coating if required. These units are laced together, packed with selected stone and act as building blocks. They are used in the construction of retaining walls, weirs, culvert inlet/outlet and other civil structures.

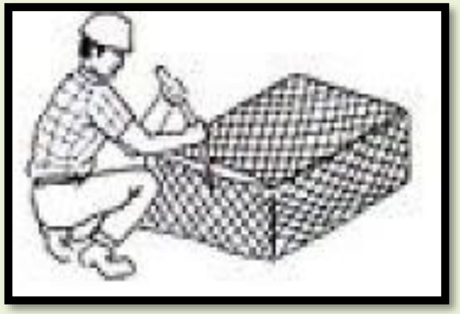


Gabion Preparation





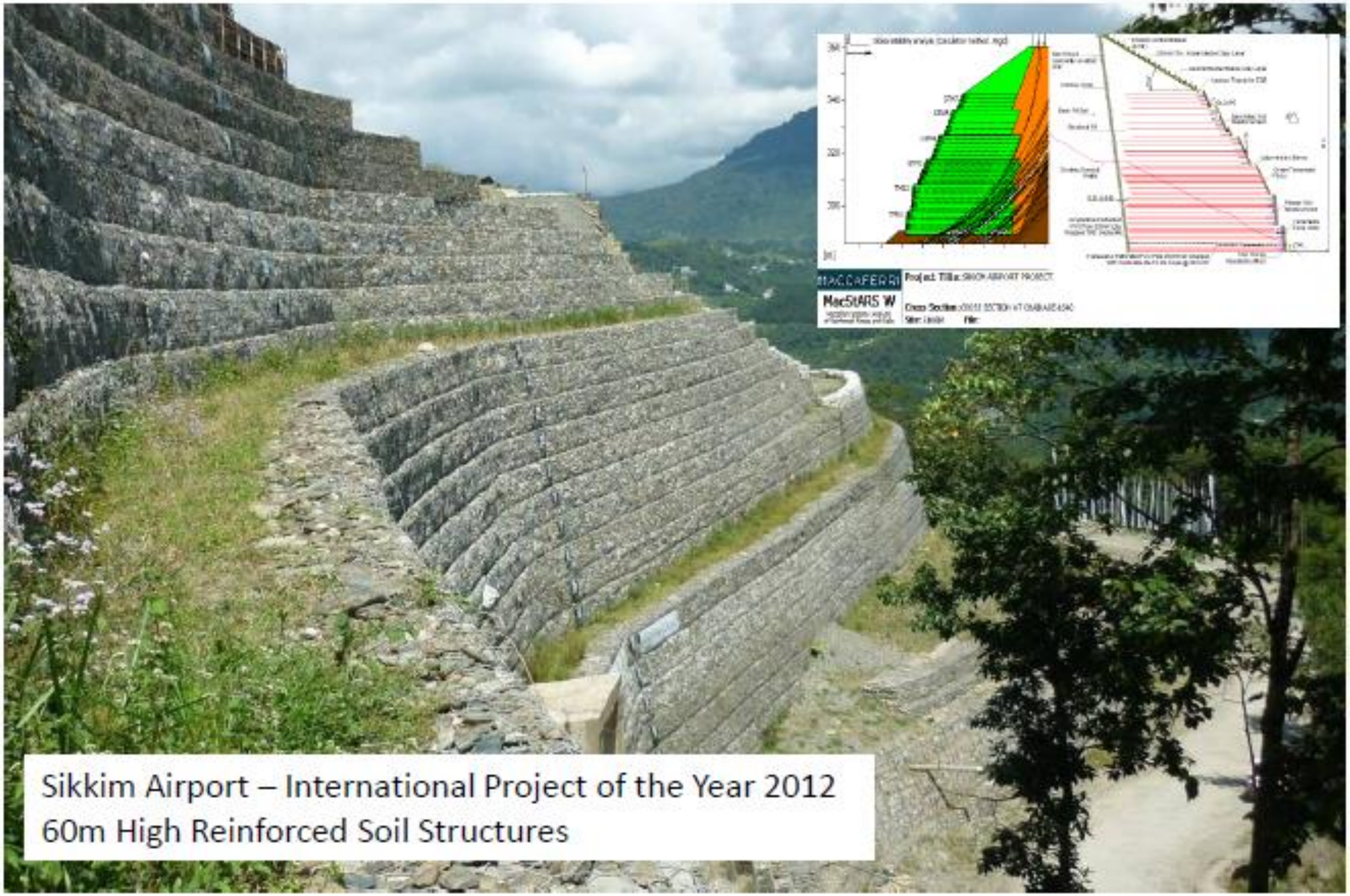




Gabion-faced Anchored Structures

Gabions are commonly used as a flexible facing to soil nailed/anchored structures. They offer all the inherent benefits of a traditional Gabion /Terramesh structure

Sikkim-Pakyong Airport



Applications of Gabions

Applications of Gabions

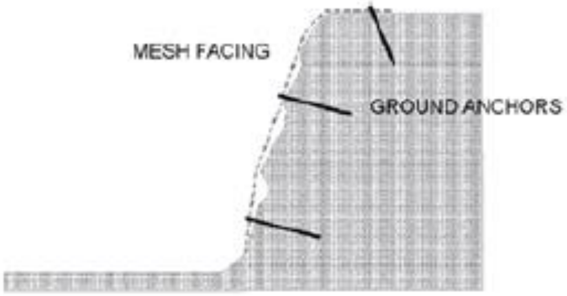
Mass Gravity Retaining Walls

Gabion Revetments

Free Standing Walls

Gabion Cladding

Rockfall Protection

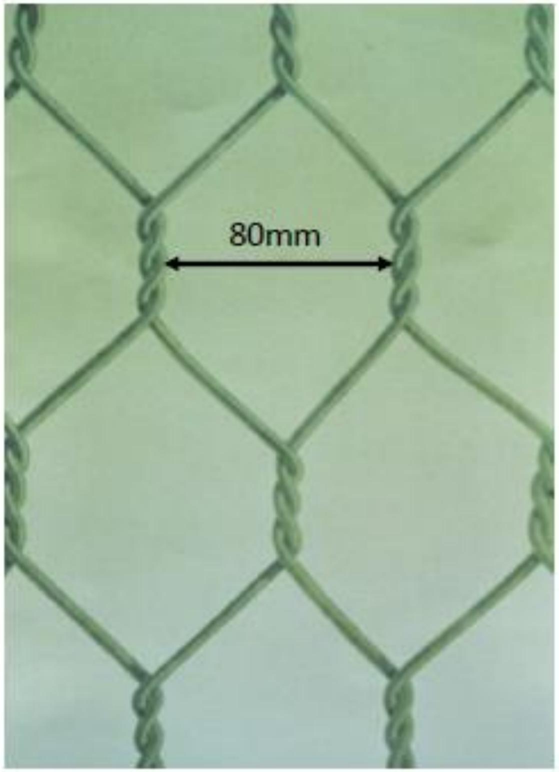


Gabion Applications-Weir Structures

Gabion: Individual System Components

Woven Mesh

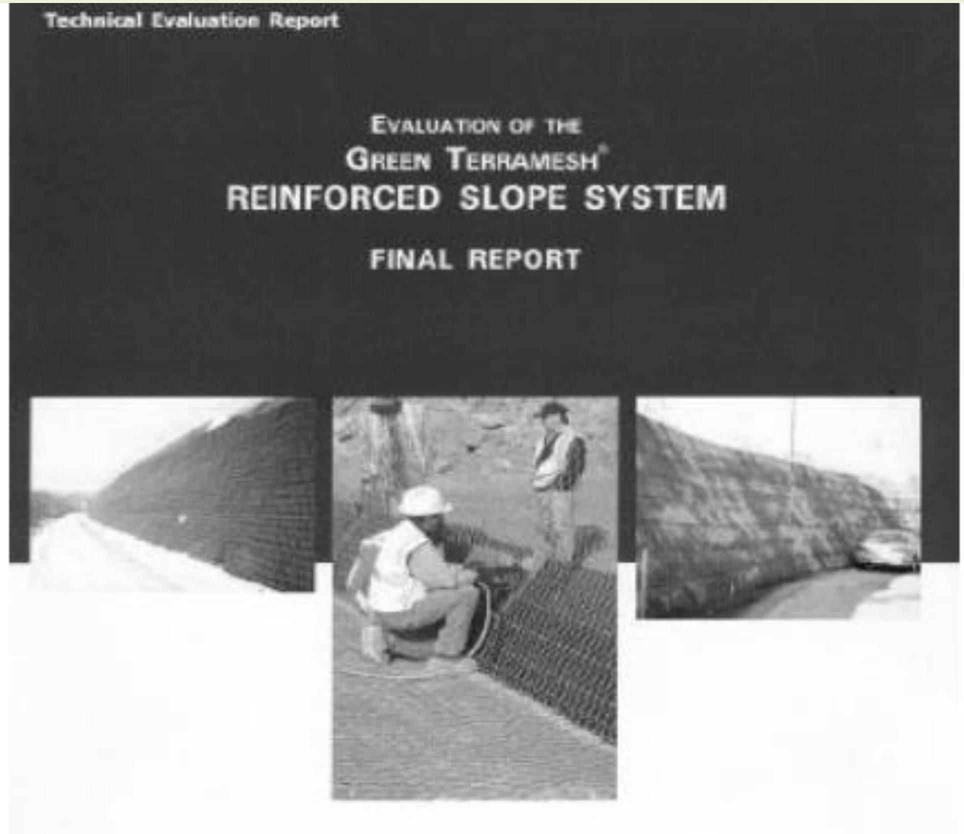
Gabions and Terramesh:
Mesh Type 80 (80 x 100 nominal)
2,7mm mesh wire (3.7mm o/d with polymer coating). Double twist for stress transfer around a wire breakage



Gabion: Individual System Components

Woven Mesh

Mesh selection tools are available depending on the required working life: BBA certificate, EN 10233-3, ASNZS 4534 technical specification, HITEC report and independent test certificates



Gabion: Individual System Components

Geotextile Separator

A geotextile will not perform its function if it is damaged and it's proven that they incur the most damage during installation

If they can withstand installation damage, they generally withstand the in service stresses

We recommend a minimum strength class C (e.g. Bidim A34) be used with mesh systems. It has the required energy absorption (installation damage resistance), permeability and is sufficiently abrasion resistant

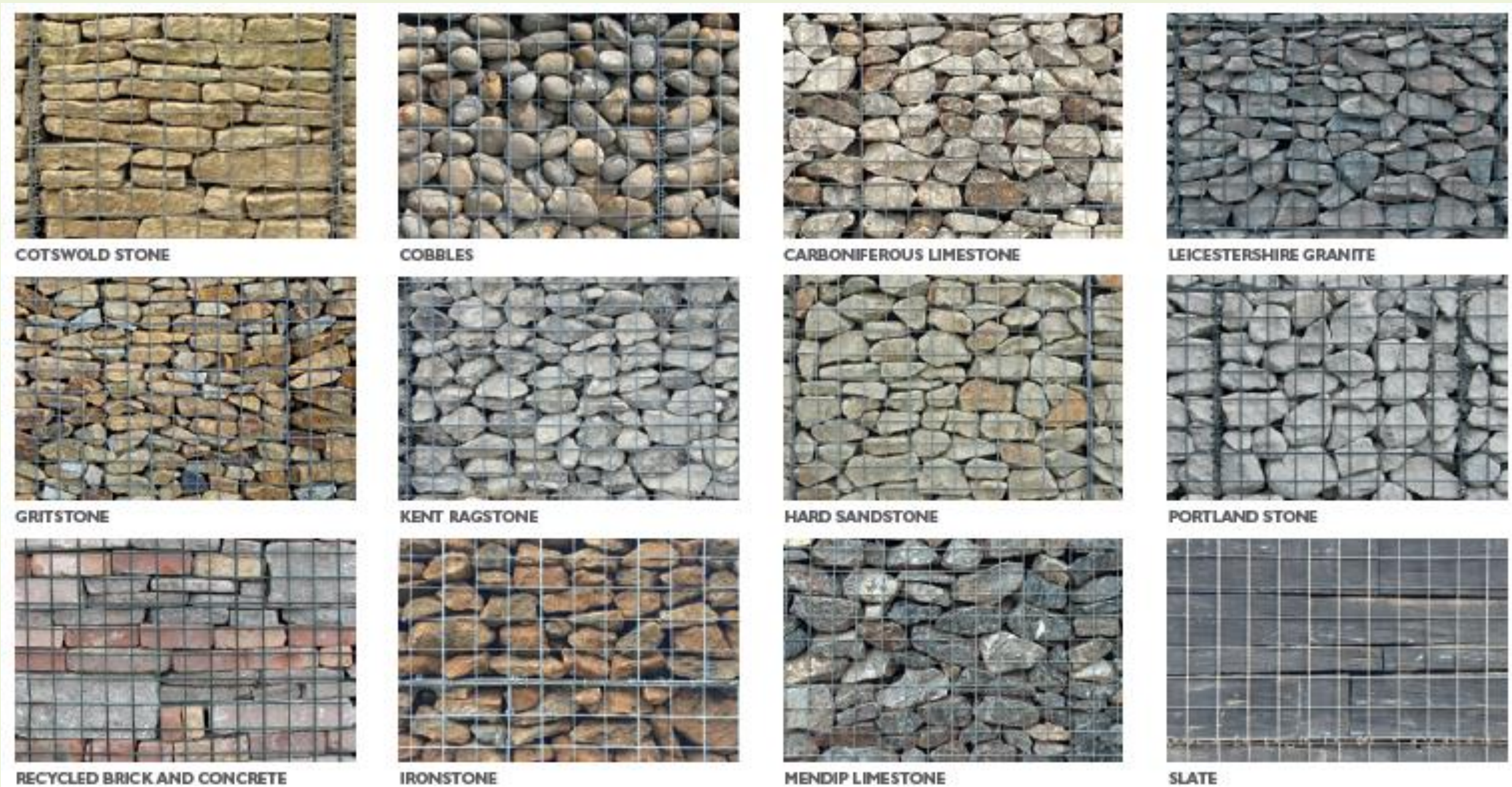
Gabion: Individual System Components

Rock Fill

Rock must be clean, sufficiently durable, non friable and not show any signs of weathering (AS 2758.4 – 2000)
The rock should be evenly graded between 1.5D to 3D (Between 100mm and 250mm normally suffices) and be angular to provide interlock

Type of rock	kg/m³	Suitability
Basalt	2900	Considered Acceptable
Granite	2600	
Hard Limestone	2600	
Calcareous Pebbles	2500	
Dolerite	2400	
Hard Sandstone	2300	Needs further checks
Soft Limestone	2200	

Gabion: Individual System Components



Gabion: Individual System Components

Foundation

The foundation should be:

- Stripped of topsoil/organic material
- Level and compacted
- Sloped if constructing an angled wall
- If on smooth bedrock or concrete, advisable to incorporate shear keys to minimise sliding issues

We want to ensure:

- Uniform foundation pressure
- Minimal differential settlement

Gabion: Individual System Components

Backfill

Compacted in lifts to the required effort as per the specification

- Heavy compaction equipment not closer than 1-1.5m to back of structure
- Walk behind compaction equipment directly adjacent to structure
- Take care not to damage the mesh or geotextile
- Backfill immediately after completing one layer of Gabions/Terramesh

Failure of Gabion Systems

Failures happen, HOWEVER the majority of them are avoidable

Failures are typically as a result of:

- Incorrect products/materials
- Poor designs & inadequate design information
- Sub-standard installation/construction techniques
- Inexperienced supervision
- System misconceptions

Failure of Gabion Systems

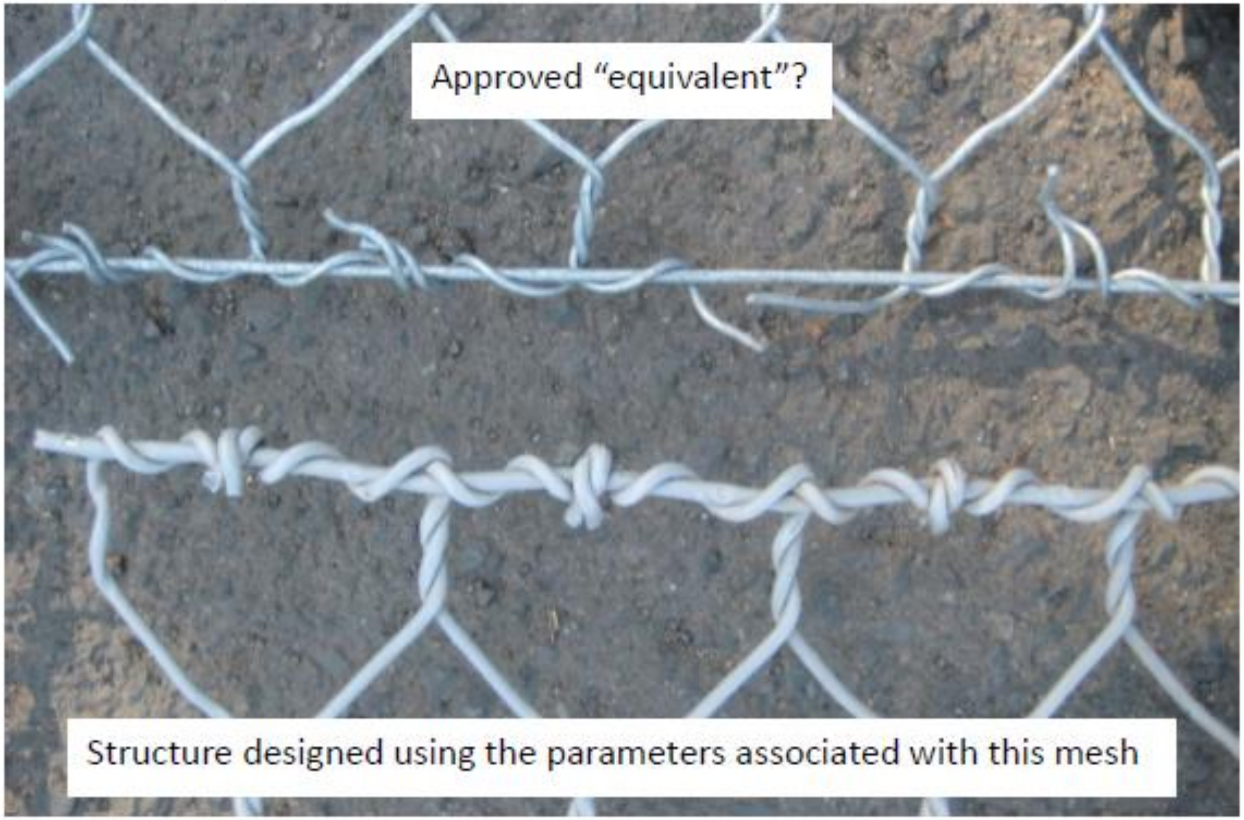
Issues With System Components

Welded Mesh

Failure of Gabion Systems

Issues With System Components

Poor Quality Woven Mesh



Failure of Gabion Systems

Issues With System Components

Wrong grade / type of geotextile

Failure of Gabion Systems

Issues With System Components

Incorrect Rock Fill Grading – too small and too big

Failure of Gabion Systems

Issues With Design Details

Inadequate scour protection

Failure of Gabion Systems

Issues With Design Details

Outflanking

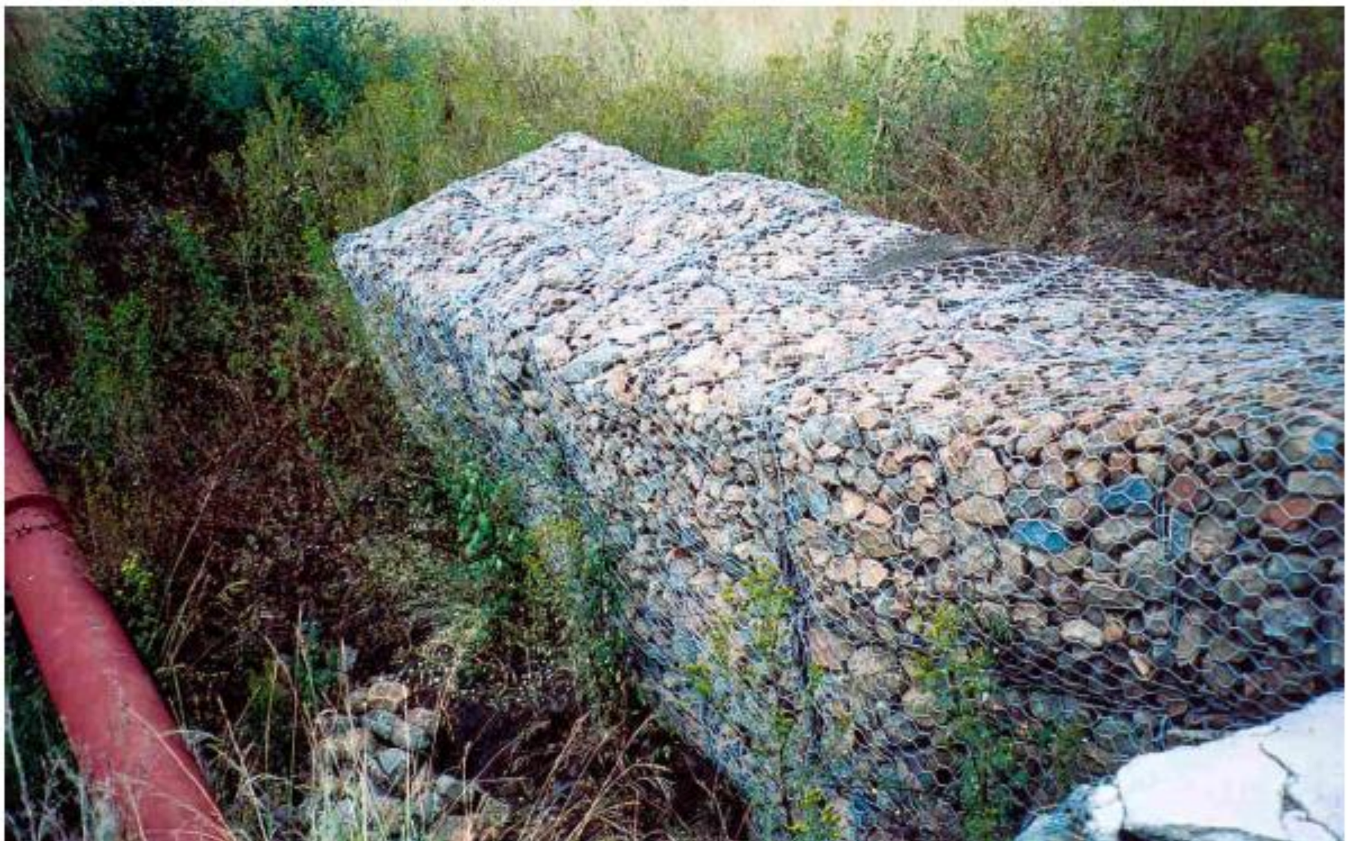
Failure of Gabion Systems

Failure of Gabion Systems

Failure of Gabion Systems

Issues With Design Details

Poor foundation preparation



Failure of Gabion Systems

Issues With Design Details

Drainage behind the reinforced block

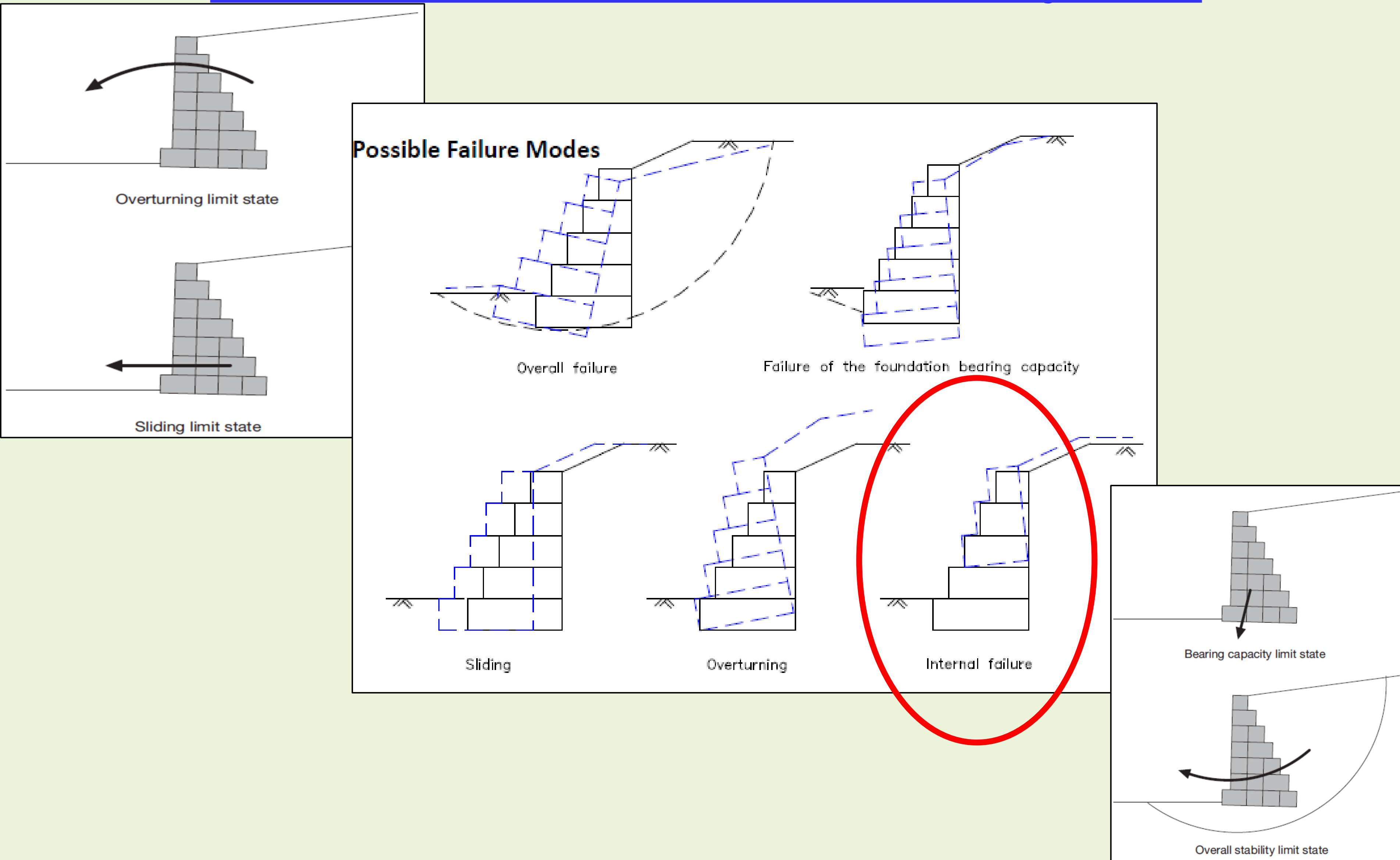
Failure of Gabion Systems

Issues With Design Details

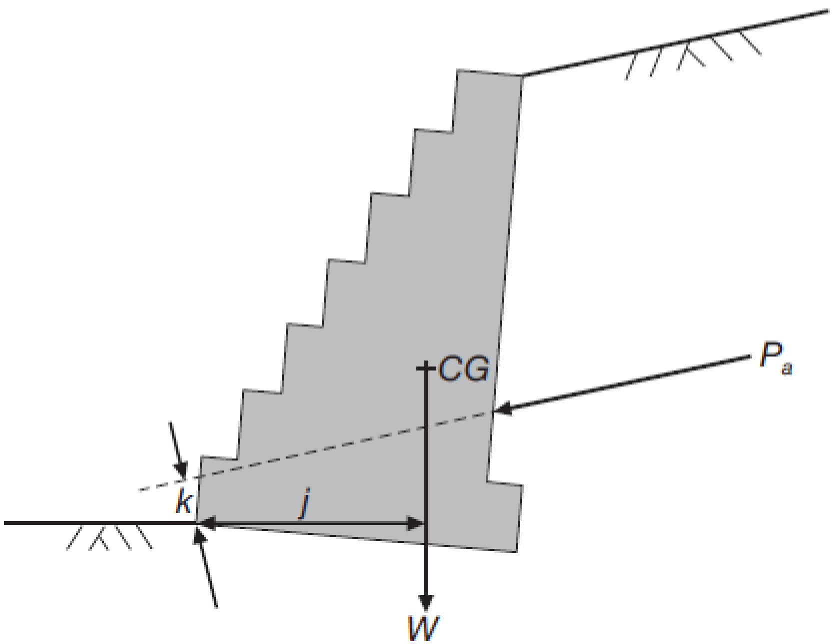
Poor construction techniques and lack of experienced site supervision

Make sure the tender specification states that the contractor must have the necessary experience to carry out the installation

Possible Failure Modes of Gabion Systems



Stability against Overturning



Taking moments around the front toe of the wall,

$M_r \geq F_{so} M_o$

where,

$M_r = W.j$ = restoring moment due to weight of the wall,

$M_o = P_a.k$ = overturning moment due to active earth pressure acting on the wall,

F_{so} = factor of safety with regard to overturning (= 1.5).

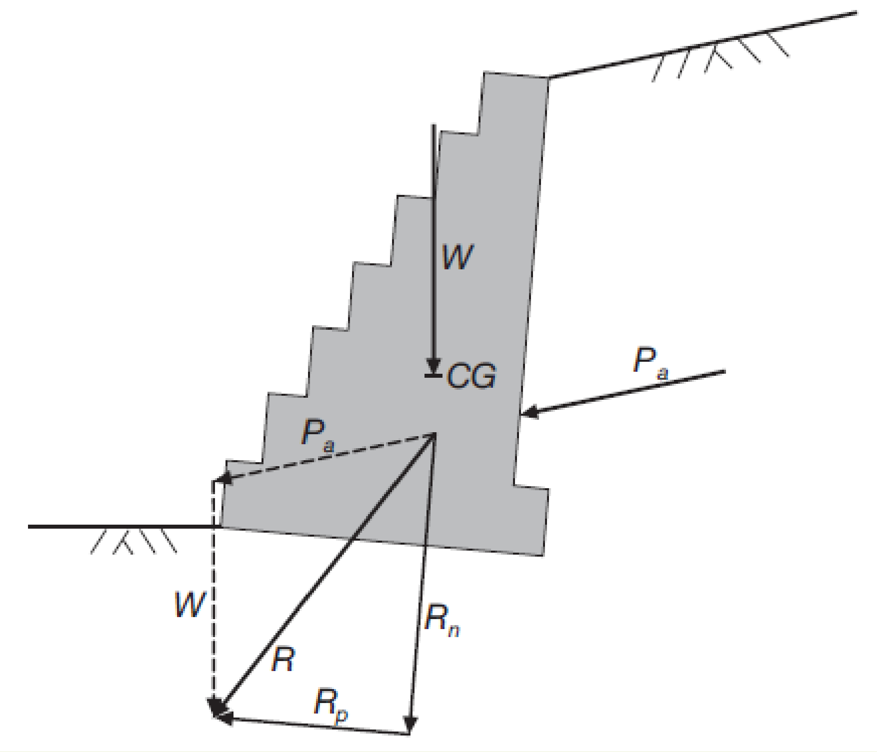
$$W = (1-\nu)\,\gamma_s\,A \quad (1)$$

where, W = the weight of the wall per metre run, ν = the void ratio of the wall rock infill (approximately 0.35), γ_s = the unit weight of the wall rock infill (see Table 7), A = the cross sectional area of the wall.

Table 7- Unit weight of gabion rock infill.

Type of rock infill	Unit weight γ_s (kN/m^3)
Basalt	27
Granite	26
Hard limestone	26
Calcareous pebbles	23
Sandstone	23
Soft limestone	22
Tuff	17

Stability against Sliding



Summing vertical and horizontal forces normal to and parallel to the base of the wall,

$$R_n f \geq F_{ss} R_p$$

where,

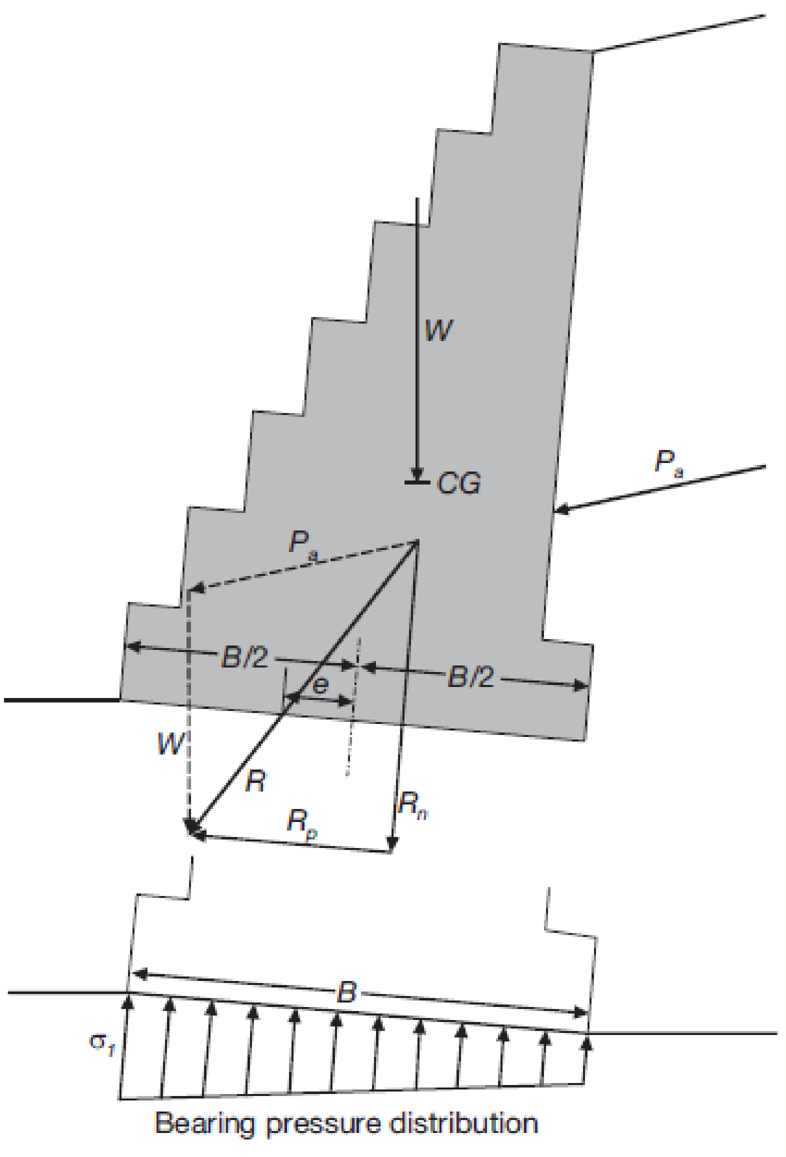
R_n = component of the resultant force R normal to the base of the wall,

f = coefficient of friction at the base of the wall (= tan ϕ', where ϕ' = friction angle of foundation soil),

R_p = component of the resultant force R parallel to the base of the wall,

F_{ss} = factor of safety with regard to sliding (=1.5).

Stability against Bearing Failure



To ensure no bearing failure,

$$\frac{q_u}{F_{sb}} \geq \sigma_1 = \frac{R_n(B+6e)}{B^2}$$

where,

q_u = ultimate bearing capacity of foundation,

F_{sb} = factor of safety against bearing failure (= 2.5),

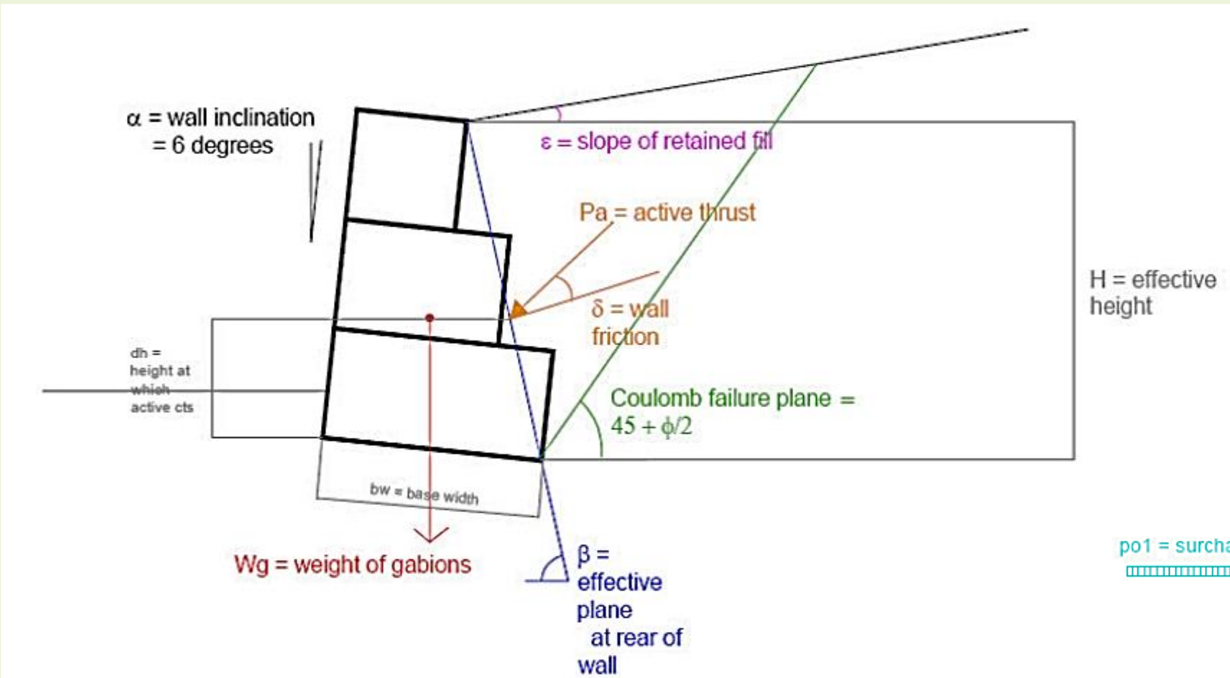
σ_1 = maximum bearing stress on foundation,

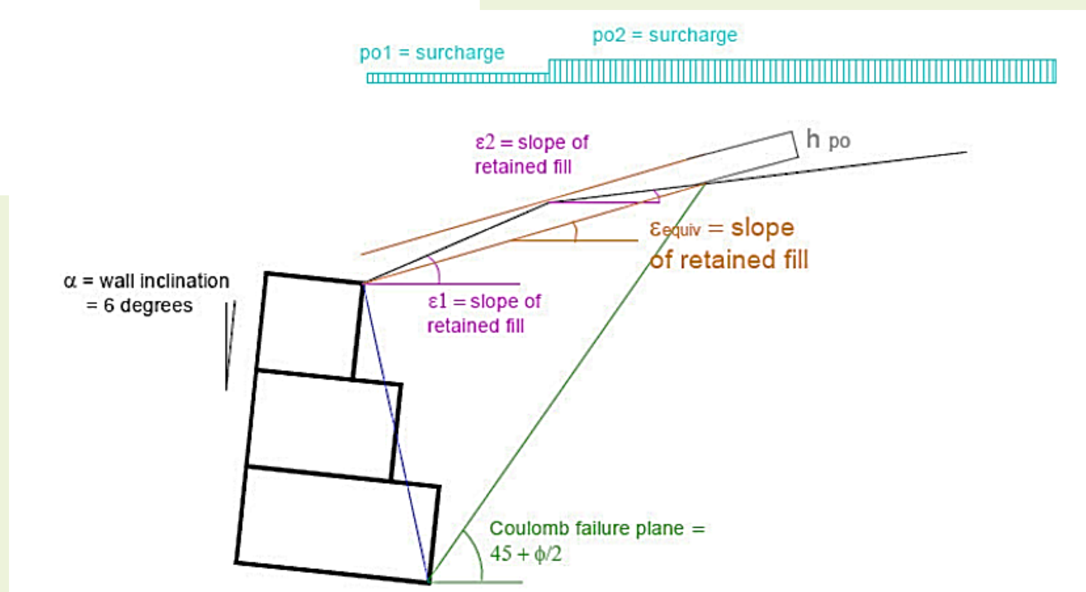
R_n = resultant force normal to base of wall,

B = width of base of wall,

e = eccentricity of resultant force R.

Complex Crest Geometries





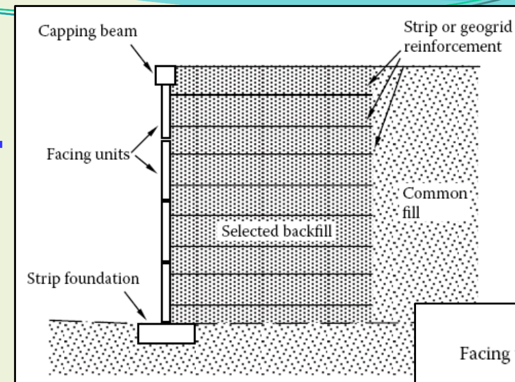
Composite Retention Systems

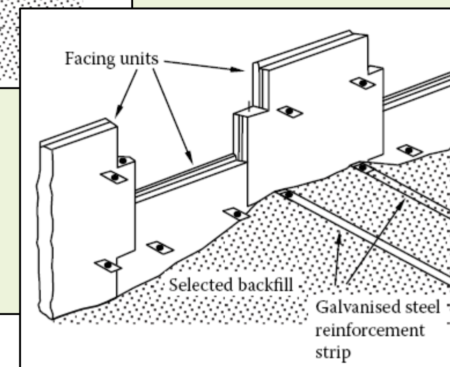
- **Composite Support Systems**
  - Composed of elements from two types of walls – gravity and embedded **(Eurocode 7)**
    - Double sheet pile wall cofferdams
    - Earth structures reinforced by tendons, geotextiles or grouting
    - Structures with multiple rows of ground anchorages
    - Nailed soil walls

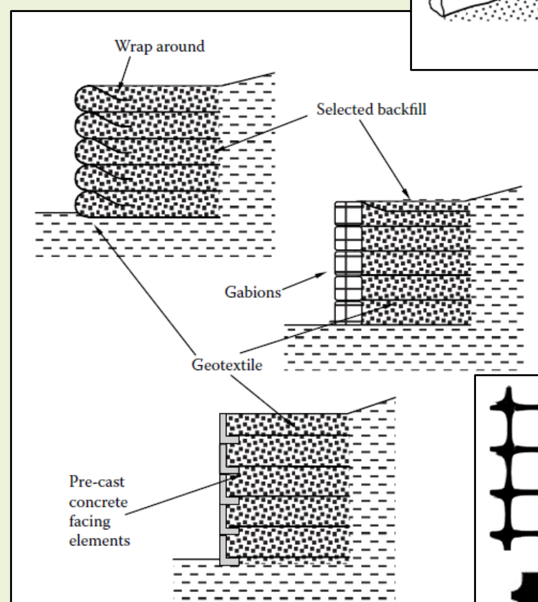
	In-situ ground	Compacted backfill
Reinforced	Soil nailing **Stronger Ground**	Mechanically stabilised earth **All grounds**
Anchored	**Less flexible systems** Anchored shotcrete or pre-cast facings	**Flexible systems** Anchored earth

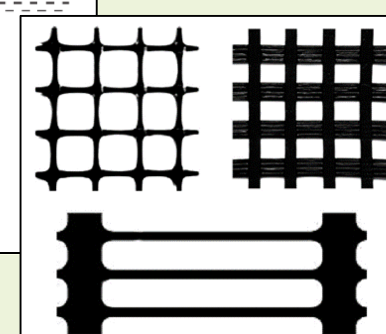
Composite Retention Systems

- **Reinforced Mechanically Stabilized Earth (MSE) Walls**
  - ❖ Comprise strip footing, facing, reinforcement and capping beam
  - ❖ Combination of compacted backfill and large number of closely spaced reinforcing elements
  - ❖ Lightweight facing to support the face material
  - ❖ Reinforcements are initially loaded only under the overburden pressure from soil and any applied loads
  - ❖ The interaction mechanism of the embedded reinforcement initiates as the wall deforms
    - ▪ Bond stresses are developed all along the reinforcement length
  - ❖ Polymer grid reinforcement (PGR) in the Geosynthetic reinforced walls (GRW) walls
    - ▪ Flexibility is the major advantage
    - ▪ Large settlements and differential rotations are tolerated









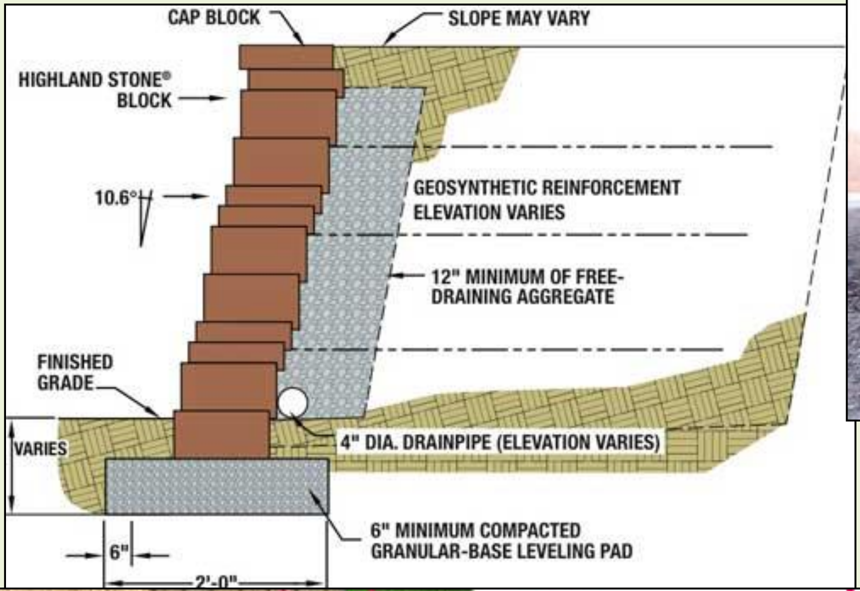
Hausmann 1990

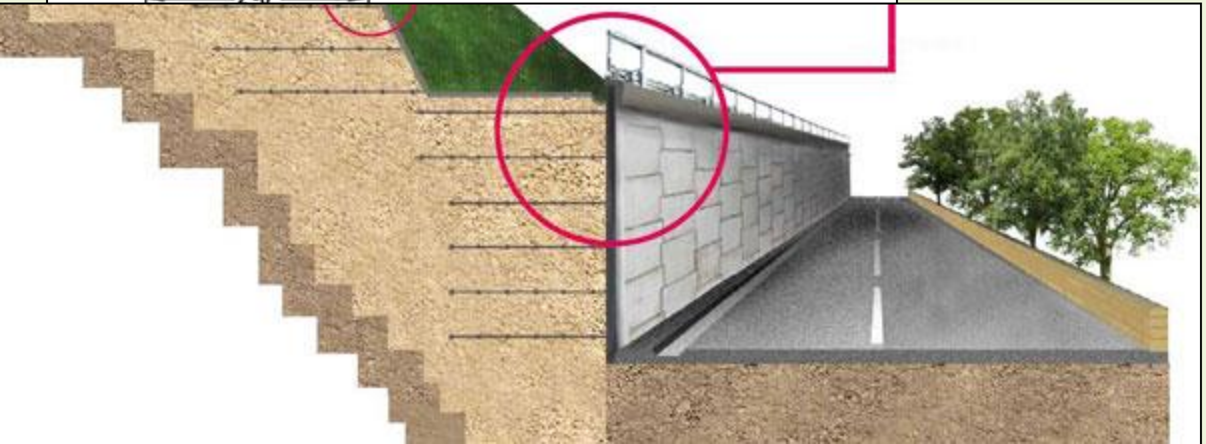
Reinforced Soil Walls

- **Reinforced soil walls**
  - Advantages over conventional type of walls
    - More economical if wall heights are large and subsoil is poor
    - Can be rapidly constructed
    - Require simple equipment for construction
    - Flexible structures
      - *Soil forms bulk of their volume*
      - *Greater ability to withstand differential settlement than the rigid retaining walls*
    - Large base-to-height ratio
      - *Foundation stress distribution s nearly uniform*
      - *Less stress concentration at the toe*

Applications

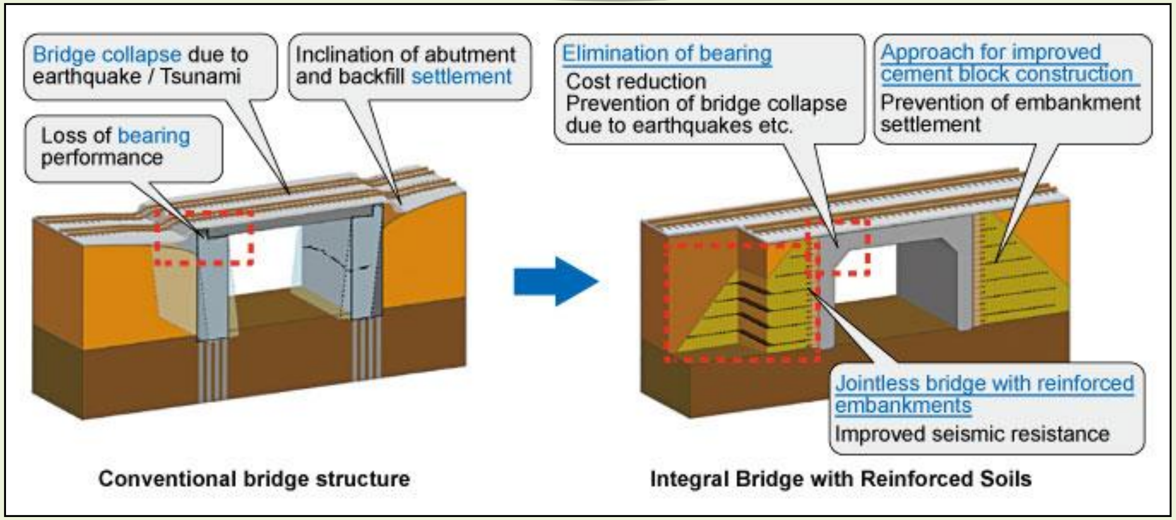
- **Retaining walls**





Applications

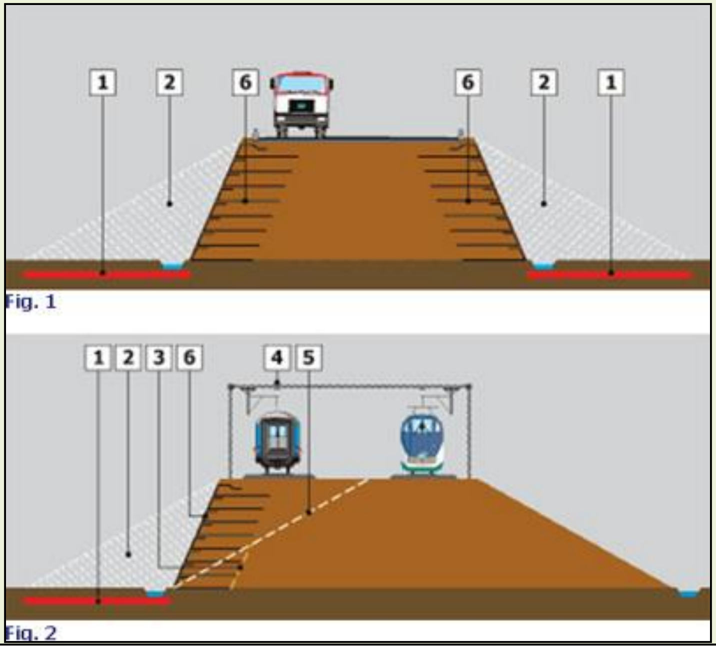
- **Bridge abutments**

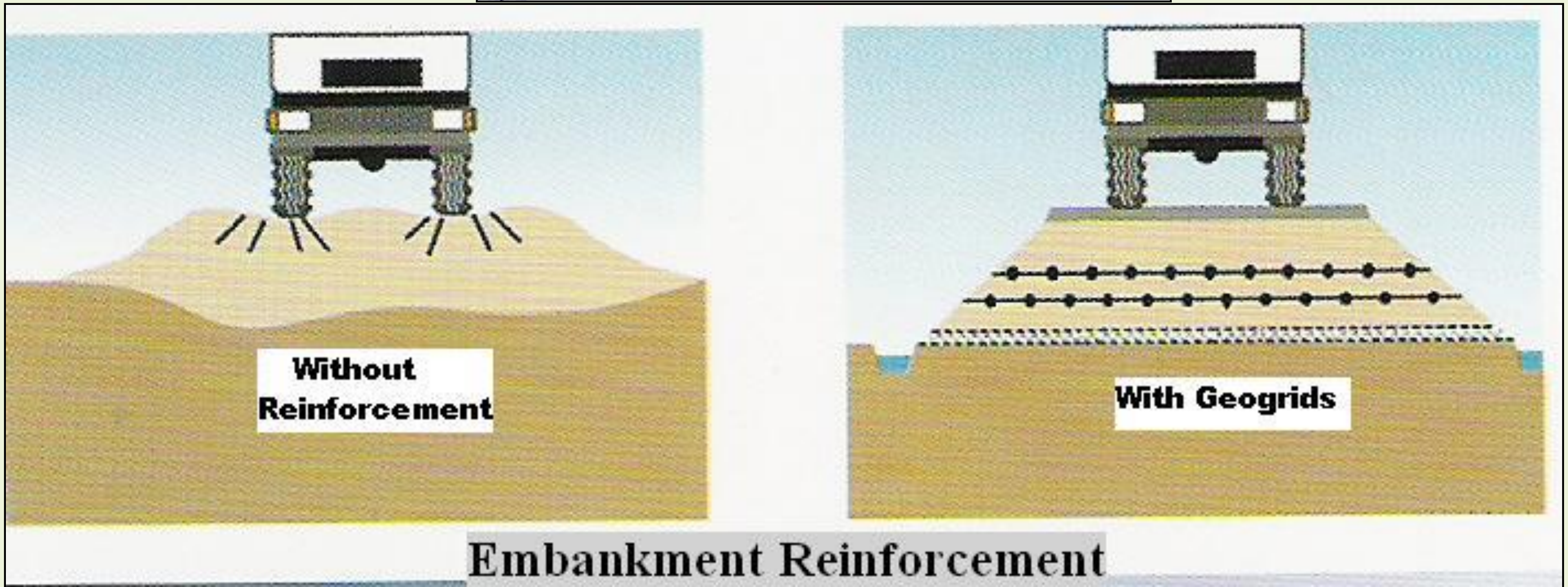


Guwahati-Shillong Byepass

Applications

- **Embankments**





Components of Reinforced Soil Walls

Reinforced Soil

Soil or Fill Matrix

- Granular medium desirable
- Local soil
- Borrowed soil
  - Suitability of the soil for reinforced soil structure

Reinforcement

- Steel
- Aluminium
- Rubber
- Concrete
- Glass
- Fibre-wood
- Thermoplastics

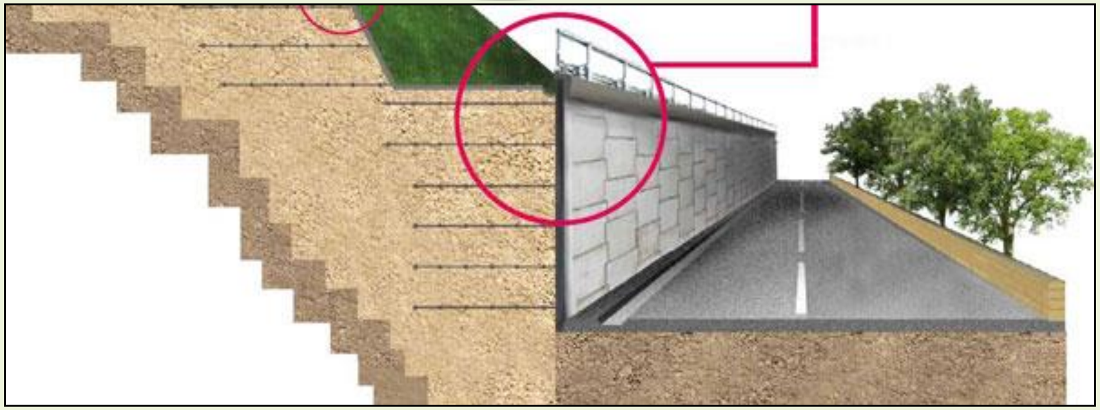
- Strips
- Grids
- Sheets
- Mats
- Ropes

Facing (optional)

- Steel
- Aluminium
- Rubber
- Concrete
- Glass
- Fibre-wood
- Thermoplastics
- Bricks

- Wrap
- Modular
- Block
- Continuous

Soil or Fill Matrix



- **Choice of fill matrix**
  - Type of structure
  - Stability conditions
    - Short-term (constructional) or long-term (post-constructional) stability
  - Physico-chemical properties of material
  - Economy
- **Soil fill**
  - Granular frictional soils
    - Mostly with frictional characteristics having good compression behavior
    - Poor/No tension behavior
  - Fine-grained cohesive soils
    - Exhibit some tension resistance due to the cohesive bond (e.g. vertical cuts up to some height can stand without any support)
    - Large height of vertical or near-vertical cuts requires to be reinforced

Soil or Fill Matrix

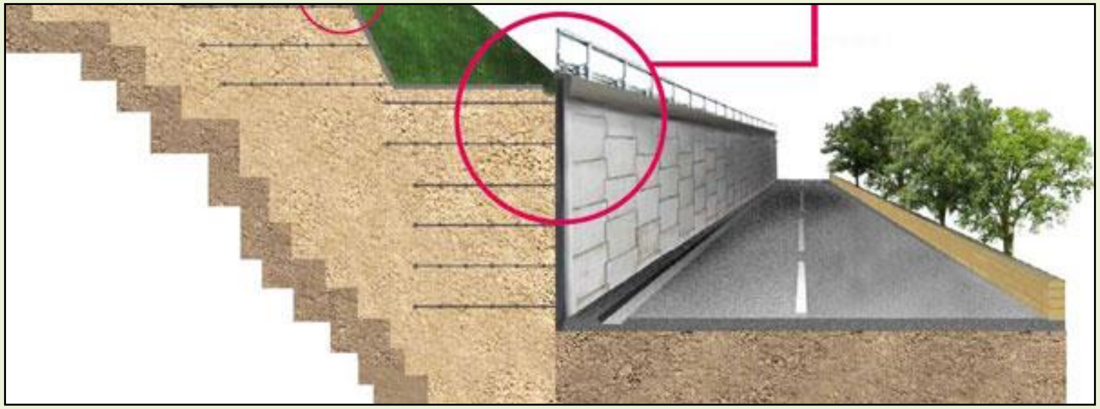
- **Local *c-φ* soil in reinforced soil structure**
  - Compromise between a pure frictional and fine-grained soils
    - Benefits of granular frictional soils
    - Economic availability of fine-grained soils

- **Minimum specification for the fill soil (US DOT, 1978)**

B.S.S. Size	Grading limits percentage passing by weight	Remarks
125 mm	100	The fill shall be finer than these grading limits.
90 mm	85	
10 mm	25	
600 micron	10	
63 micron	10	
2 micron	> 10	
Liquid limit	> 45%	
Plasticity Index	> 20%	
ϕ	< 20°	

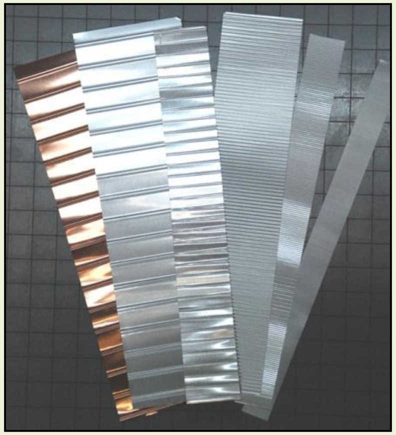
Reinforcement

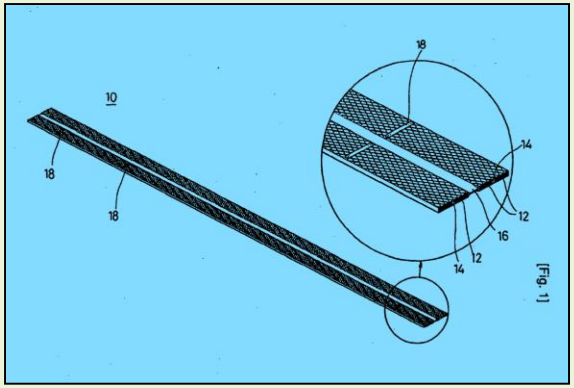
- **Reinforcements**
  - Tension resistant elements
    - *Form* - Sheet, strips, nets, or mats
    - *Composition* - Metal, synthetic fibres, or fibre-reinforced plastics
    - Main purpose
      - *Reduction or suppression of tensile strain developed due to gravity or boundary forces*
      - *Orientation – Direction of tensile strains*

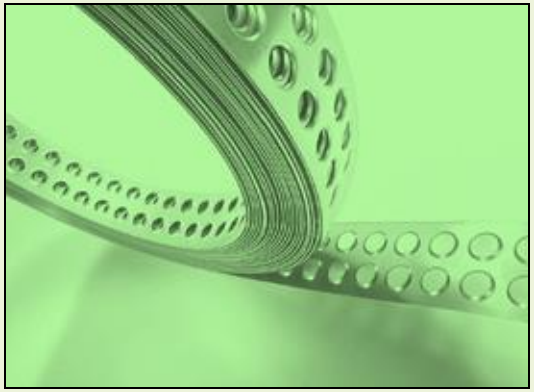


Reinforcement

- **Strip reinforcement**
  - Flexible linear elements
    - Thickness : 3-9 mm
    - Breadth : 40-120 mm
  - Plain, grooved or ribbed
  - Materials
    - Metals
      - *Galvanized steel*
      - *Aluminum-Magnesium alloy*
      - *Chrome Stainless steel*
        - Check for durability against corrosion
    - Bamboo
    - Polymers
    - Glass-fibre reinforced plastics





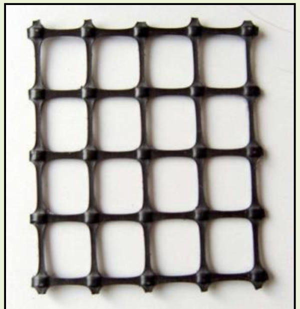


Reinforcement

- **Grid reinforcement**
  - Flexible elements made up of transverse and longitudinal members
    - Transverse member run parallel to the face or free-edge of the structure
      - *Act as anchors and passive reinforcements*
      - *Stiffer than the longitudinal members*
    - Longitudinal members
      - *High modulus of elasticity and not susceptible to creep*
  - Materials
    - Metals
    - Punched Polymers → Geogrids
      - *Uniaxial → Reinforced retaining wall*
      - *Biaxial → Foundation beds*

        Railways and roadway subgrade

        Embankment foundations

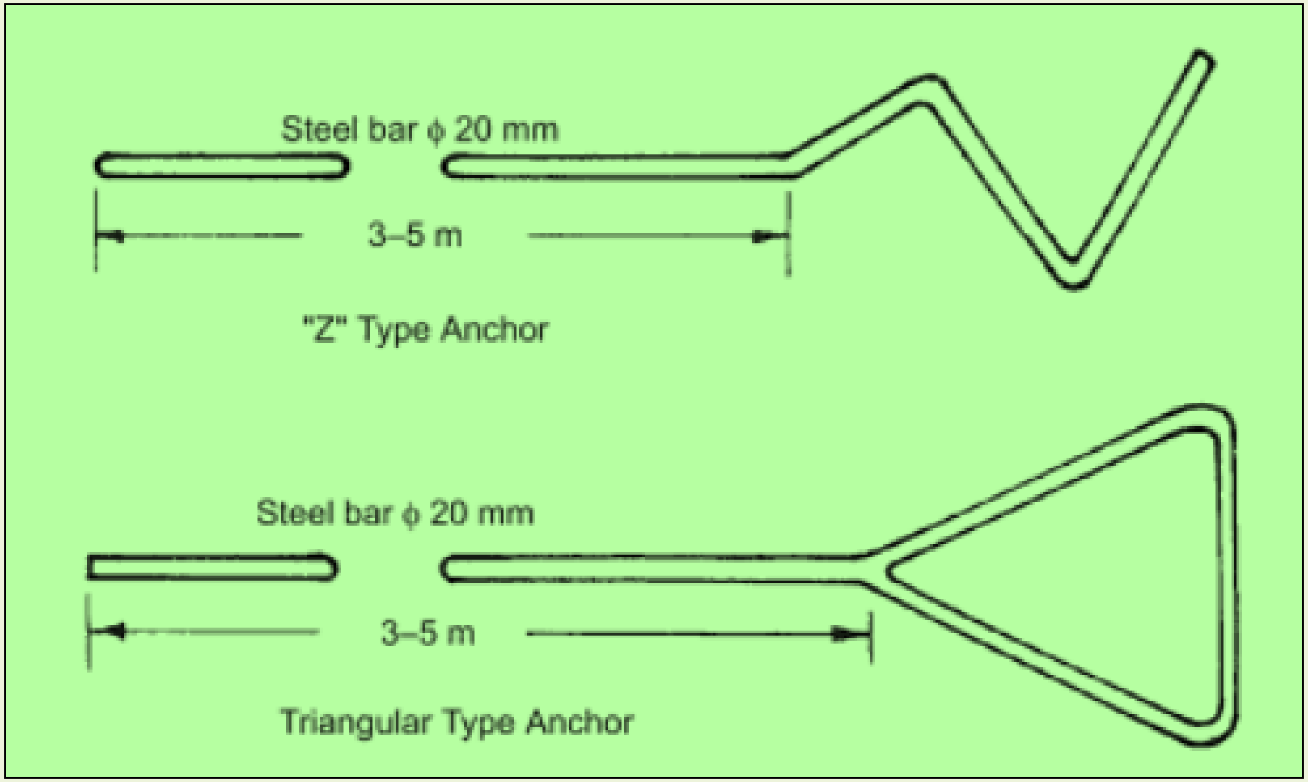


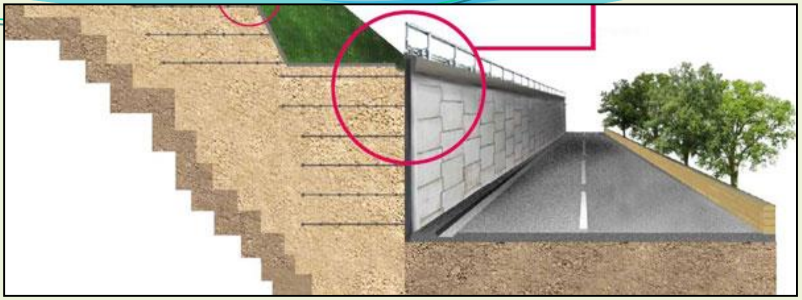
Reinforcement

- **Sheet reinforcement**
  - Galvanized steel, textile fabric or expanded metal
  - Geotextiles → Textile fabrics
    - Most common nowadays
    - Porous
      - *Permeability in the range of coarse gravel to fine sand*
    - Manufacturing
      - *Woven → from continuous monofilament fibers*
      - *Non-woven → Staple fibers laid in random pattern and mechanically entangled*
        - Fibers may be bonded or interlocked

Reinforcement

- **Anchor reinforcement**
  - Flexible linear elements with distortions at the end



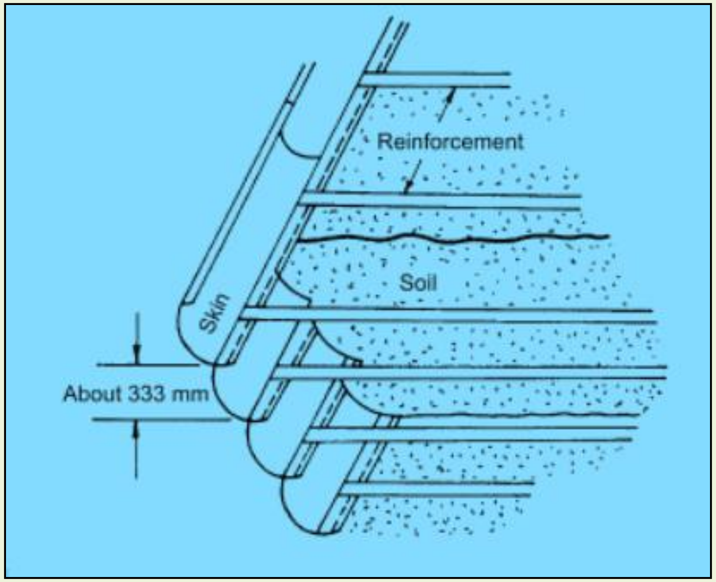


Facings

- **Facing in reinforced soil structures**
  - Required for vertical or near-vertical structures
  - Main purpose
    - Retains the soil between the reinforcement in the immediate vicinity to the edge of the structure (Prevent surface erosion)
  - Does not affect the overall stability of the structure
    - Affect the local stability
    - Should be able to adopt to deformations without distortions and introduction of stresses
  - Materials
    - Galvanized steel, Stainless steel, Aluminum, Bricks, Precast concrete panels, Precast concrete slabs, Geotextiles, Geogrids, Plastics, Glass-reinforced plastics, Timber
      - *Metal and precast concrete panels are mostly used*
        - Ease in handling and assembling

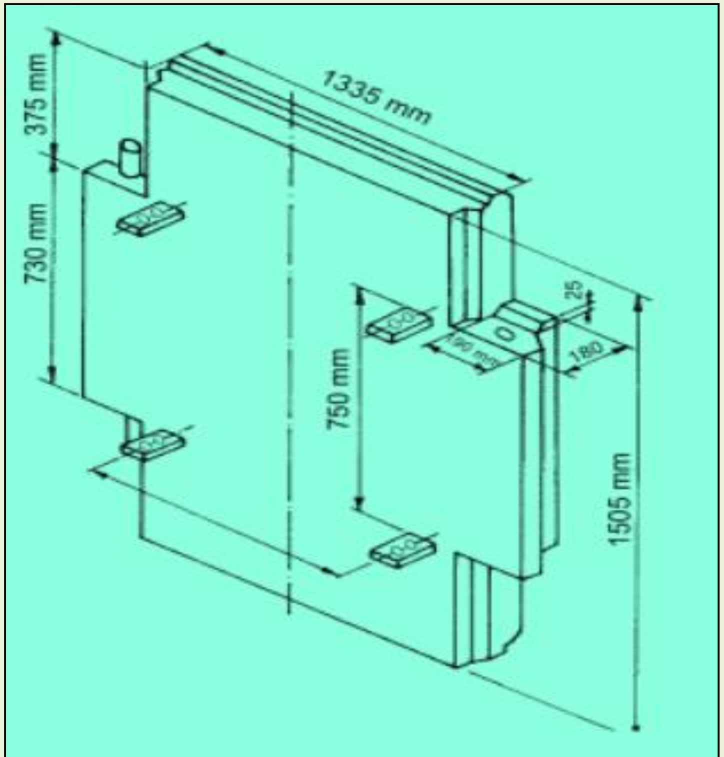
Facing

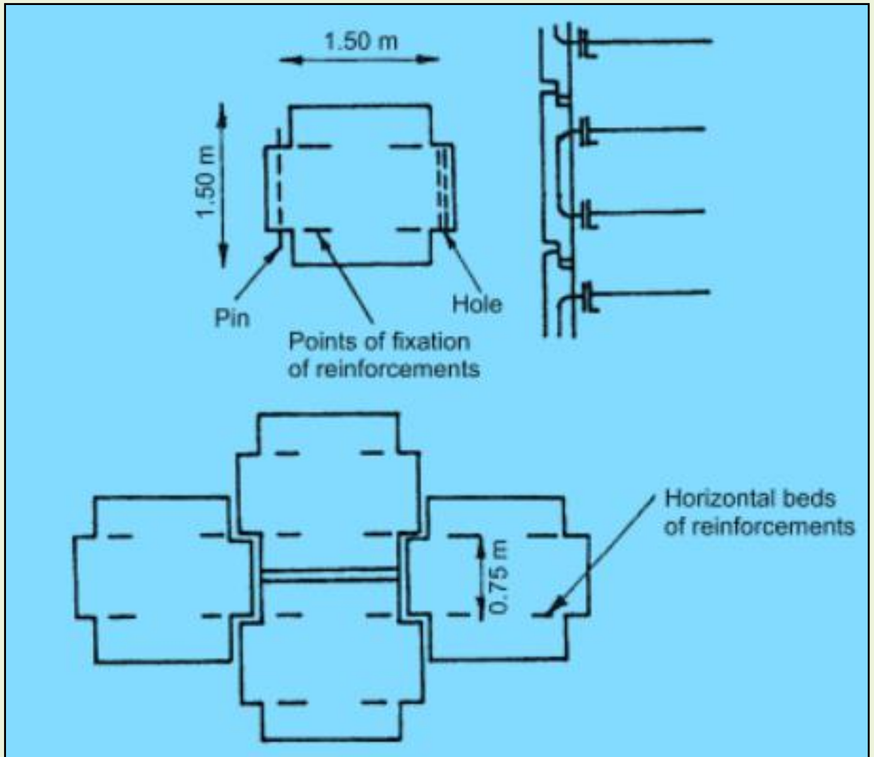
- **Metal facing**
  - Mild steel, Galvanized steel or Aluminum
    - Same property as the reinforcement strips
  - Facing is semi-elliptical
    - Continuous horizontal joint along one edge
  - Holes are provided for bolting of reinforcing elements
  - Very flexible
    - Can adapt to significant deformation



Facing

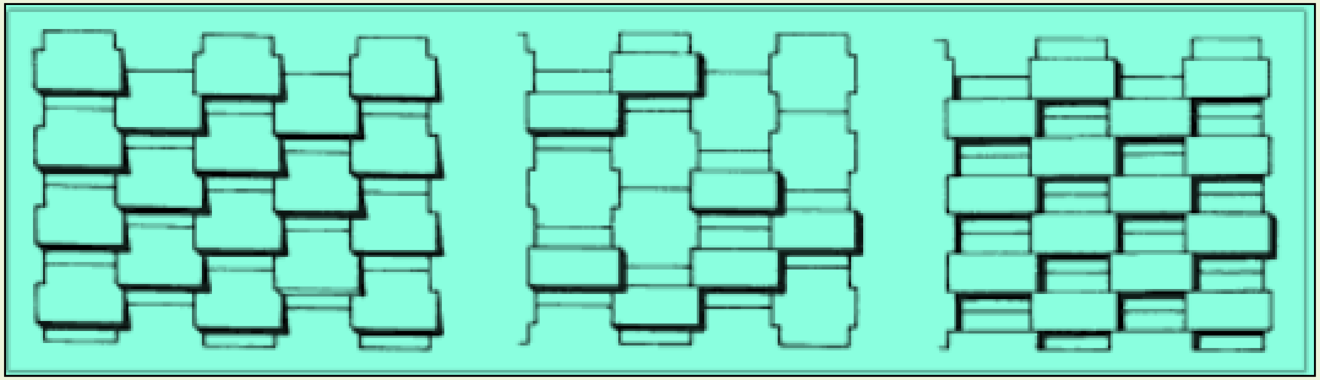
- **Concrete Panel Facing**
  - Cruciform shaped
    - Vertical dowel-groove system to accommodate other adjacent panels
      - *Dowels allow for restricted lateral and rotational movement*
        - Renders the entire facing structure as flexible





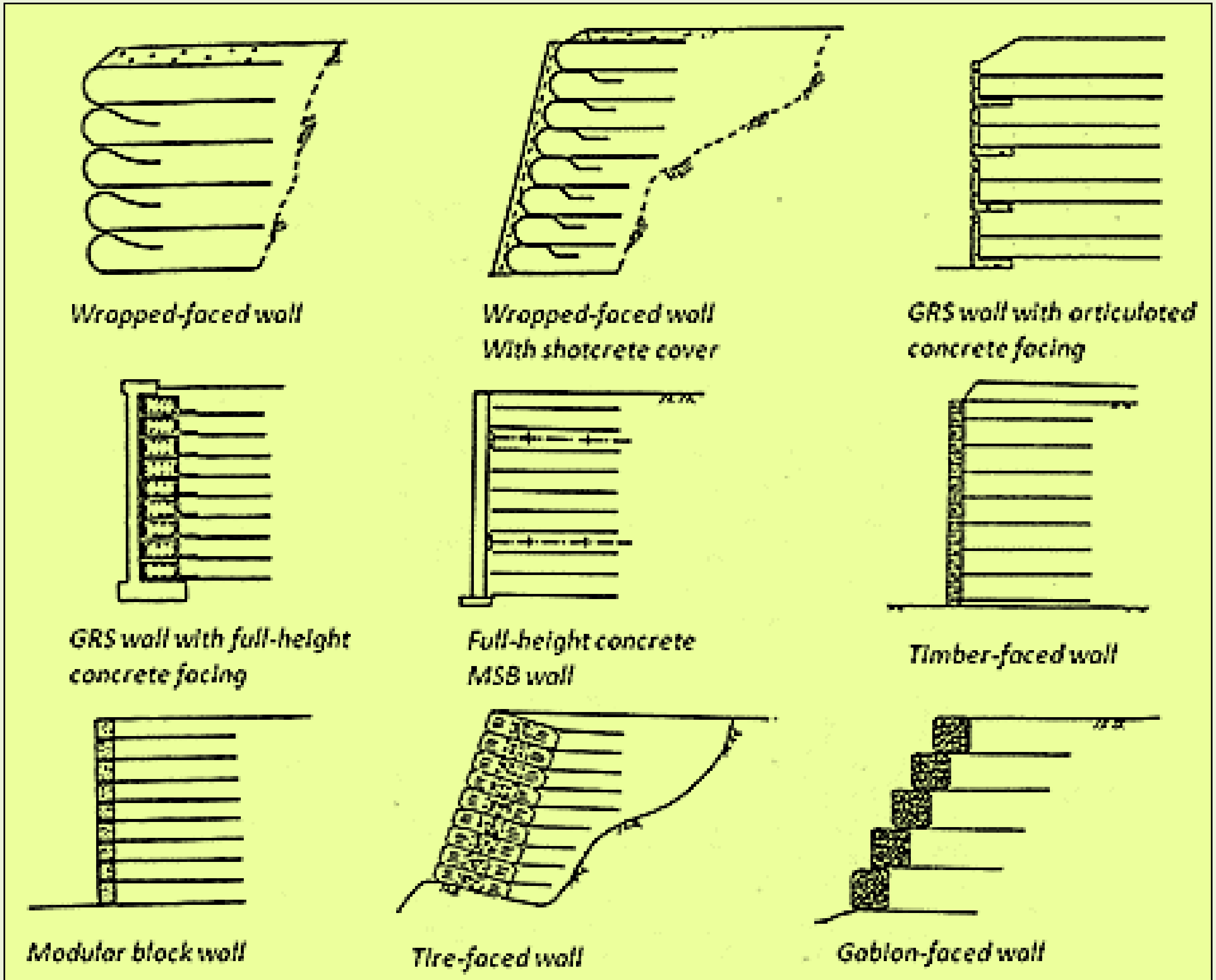
Facing

- **Concrete Panel Facing**
  - Various architectural forms are created



Facing

- **Other types of facings**



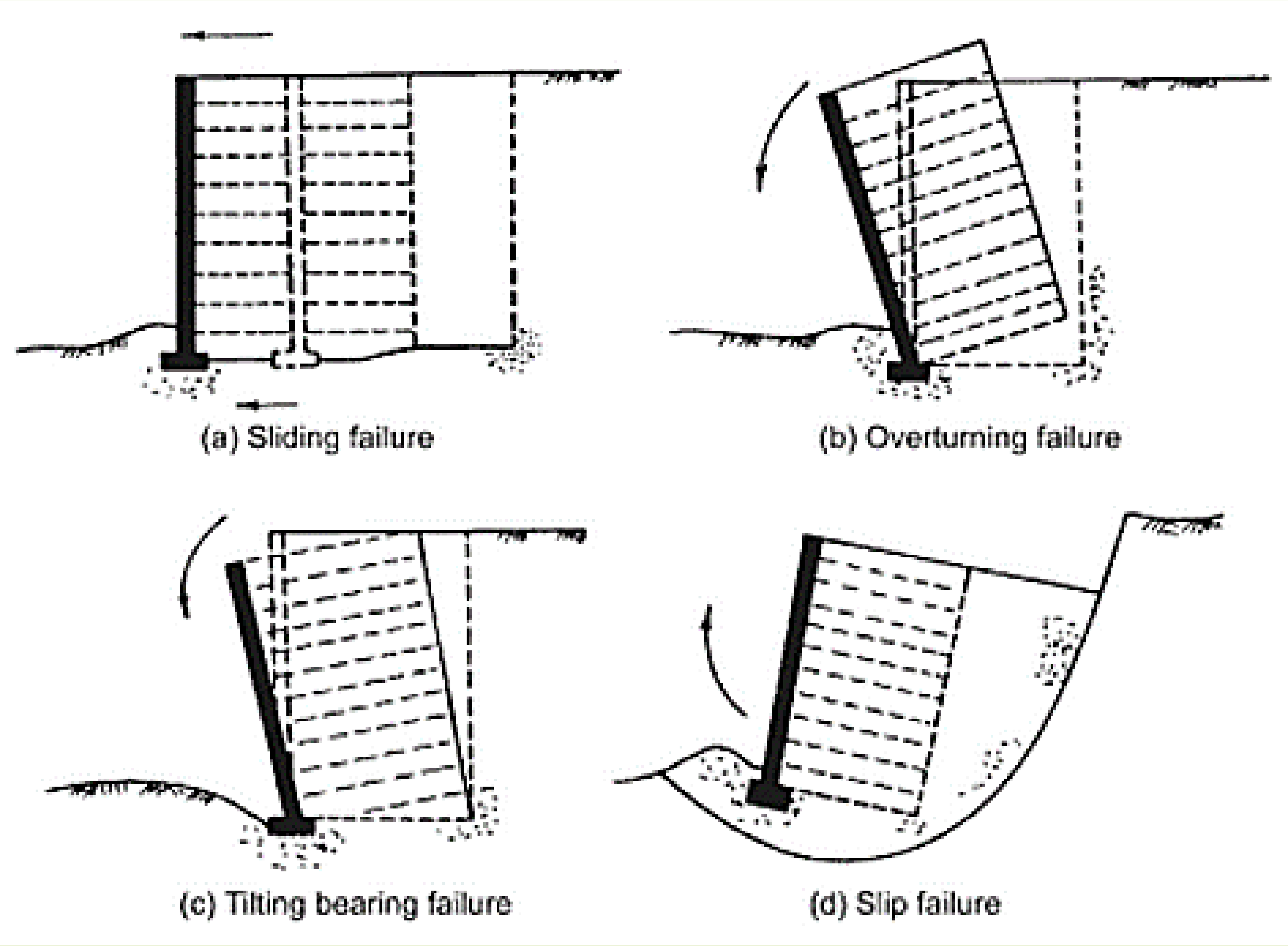
Wrap-Face Geosynthetic Wall

Stability Analysis of RE/MSE Walls

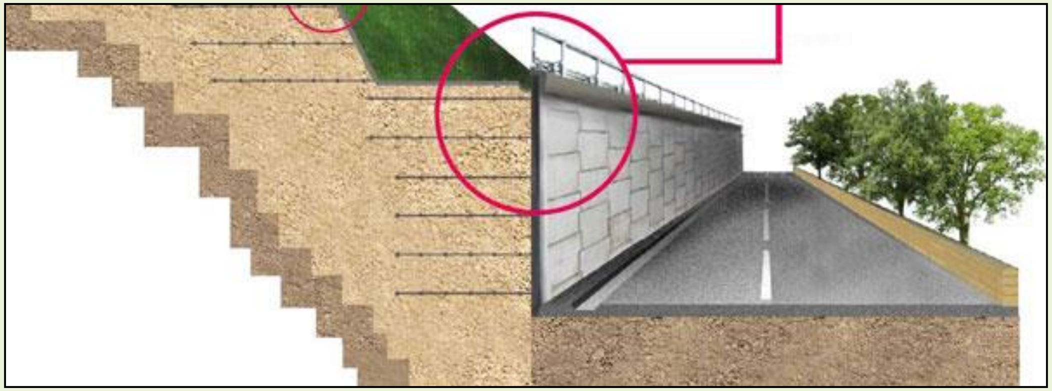
- **External stability**
  - Assumption
    - Reinforced soil wall behaves as an integral unit
    - Behaves as a rigid gravity structure
  - Conforms to simple laws of statics

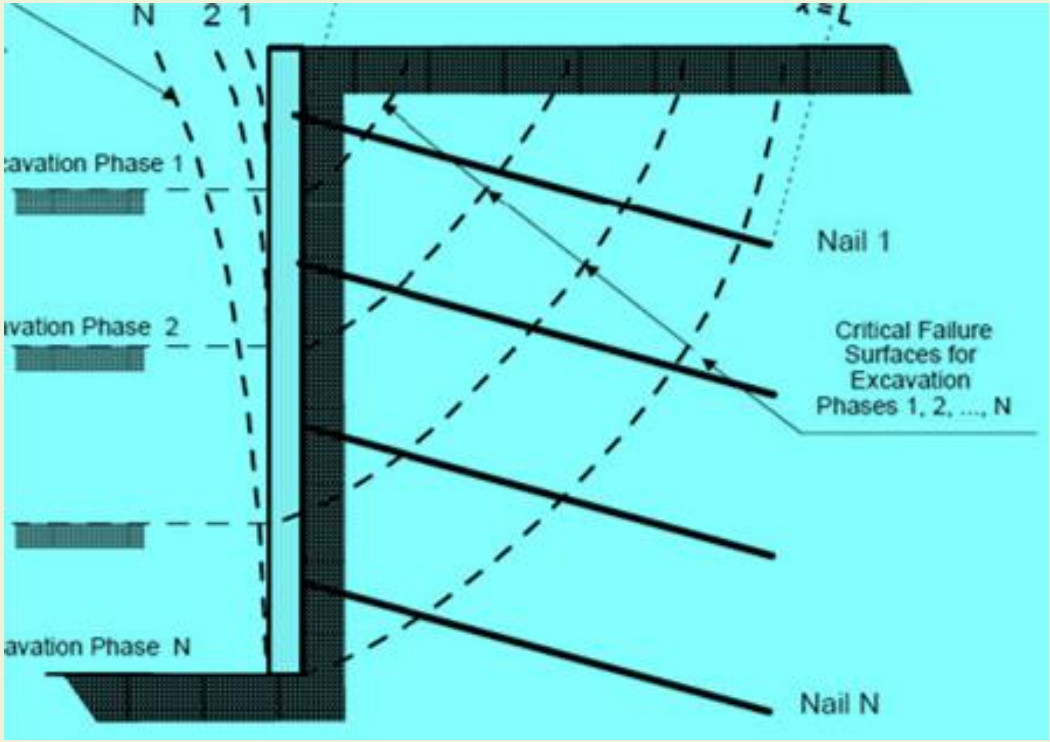
- **Internal stability**
  - Deals with design of reinforcement in regard to its
    - Length and Cross-section
      - *Against tension failure*
    - Sufficient anchorage length into the stable soil

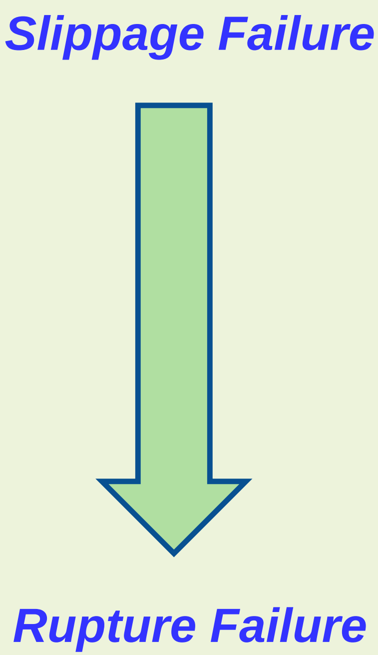
External Stability



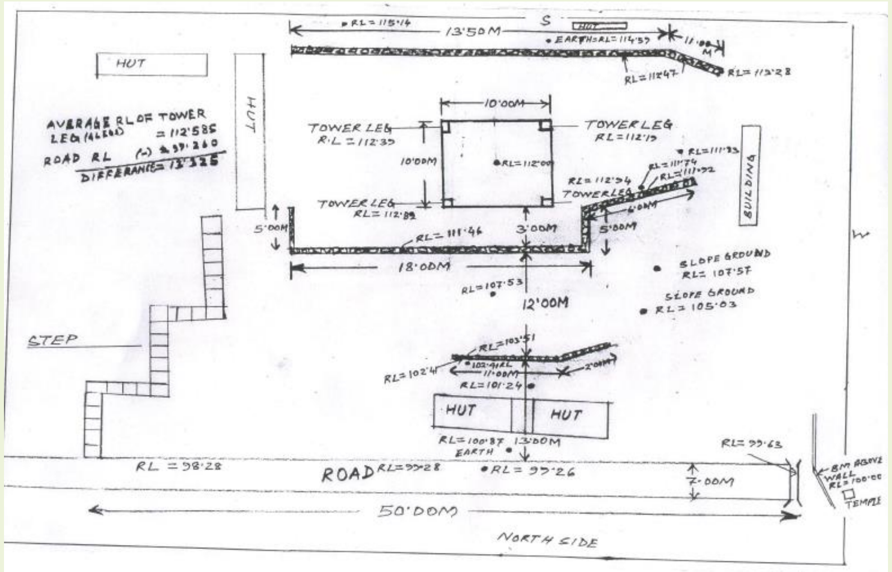
Internal Stability: Failure of Reinforcement



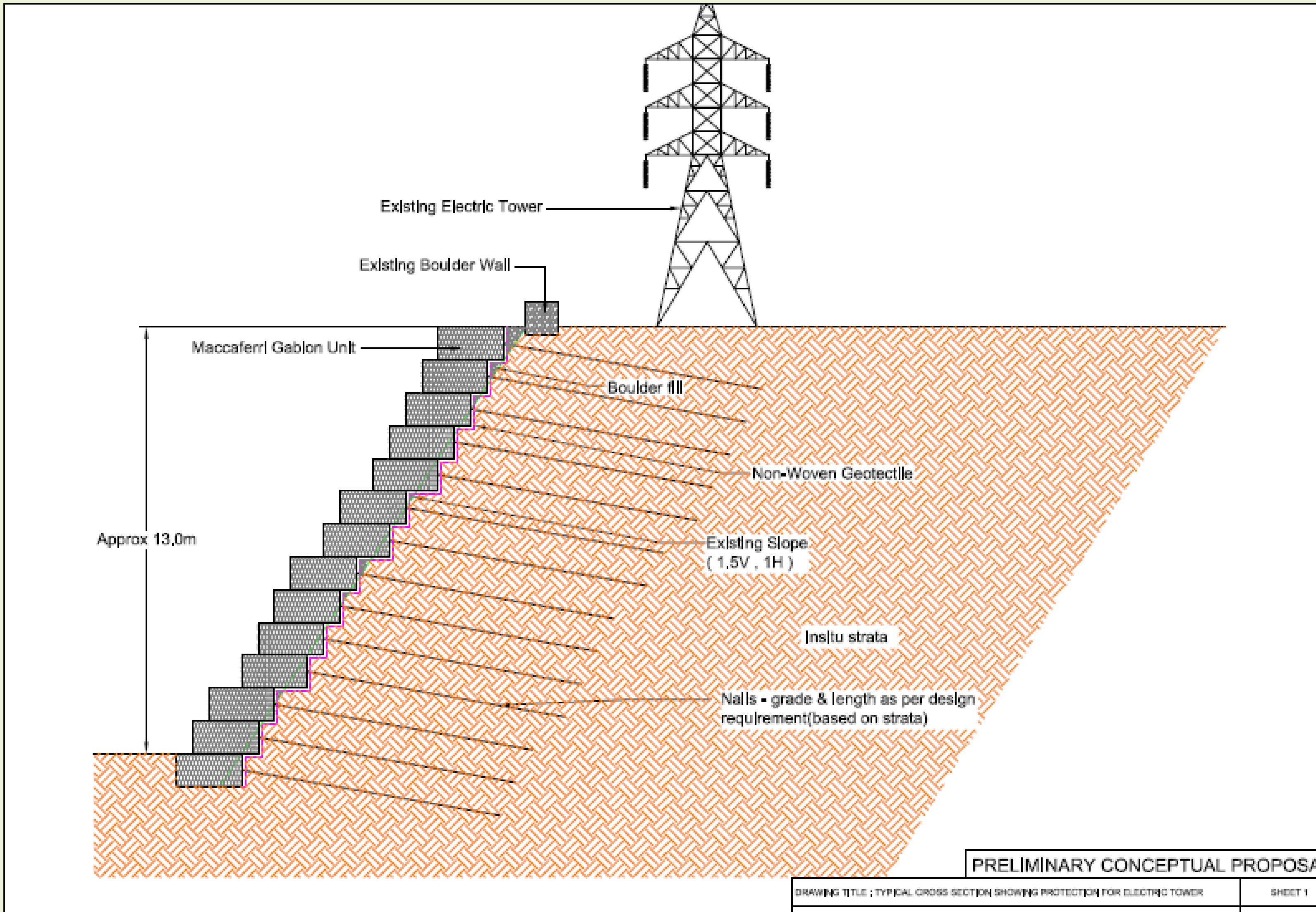




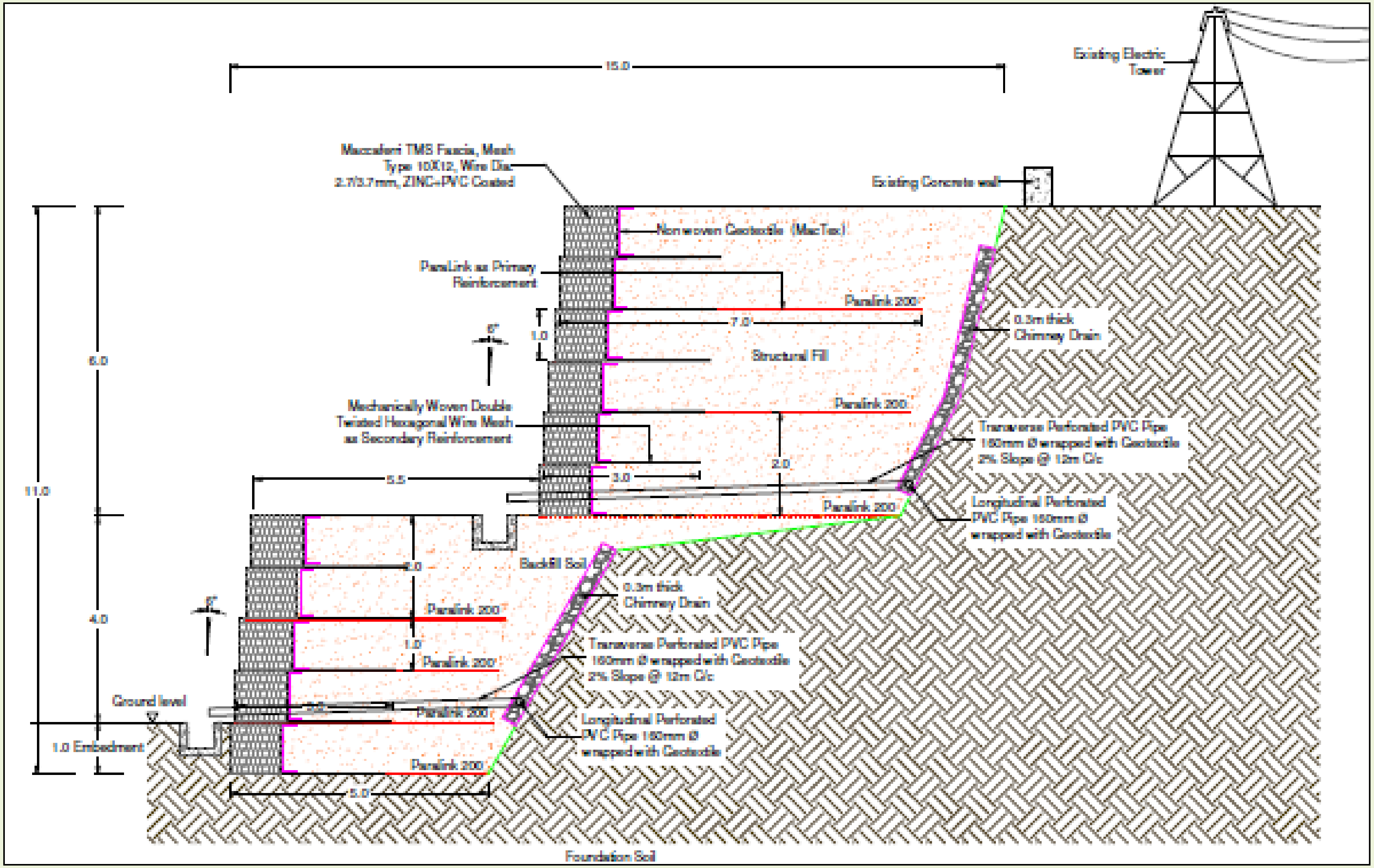
AEGCL Transmission Tower Slope, Sarusajai, Guwahati



AEGCL Transmission Tower Slope, Sarusajai

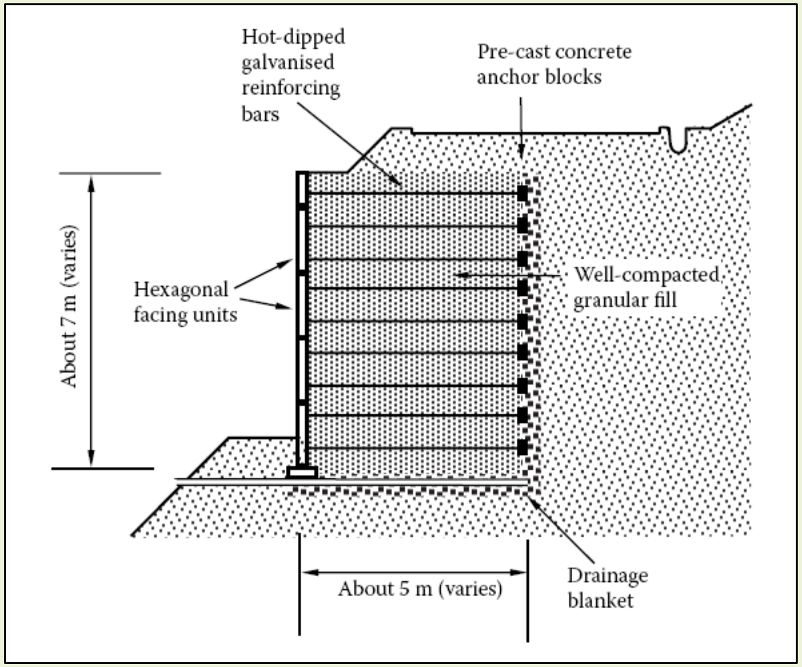


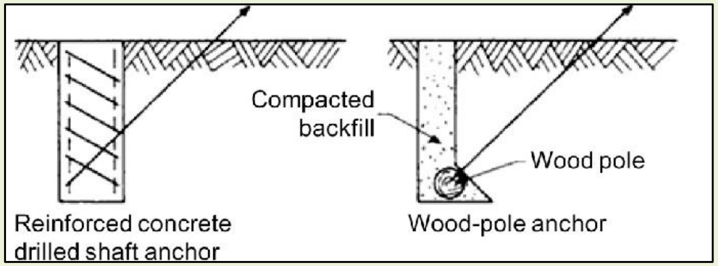
AEGCL Transmission Tower Slope, Sarusajai

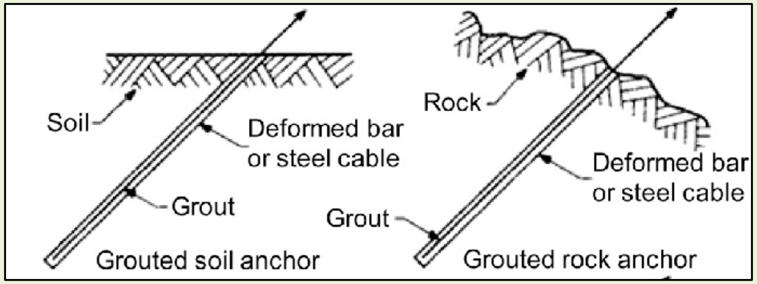


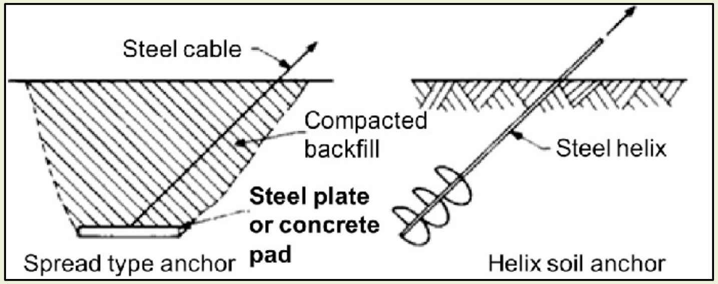
Composite Retention Systems

- **Anchored Earth**
  - Closely spaced passive anchors embedded in engineered fill
  - Composed of a bar or strip with relatively small surface area, terminating at a passive block or hoop at the rear of the backfill
  - Anchored earth transmits load from the wall facing directly to the remote block or hoop
  - Lightweight facings are used





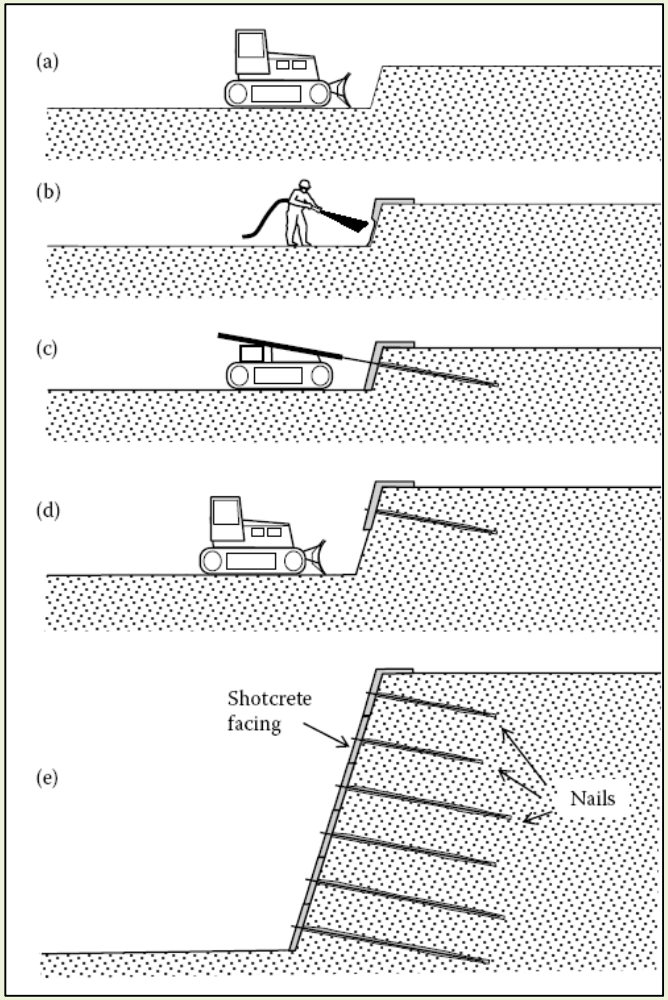




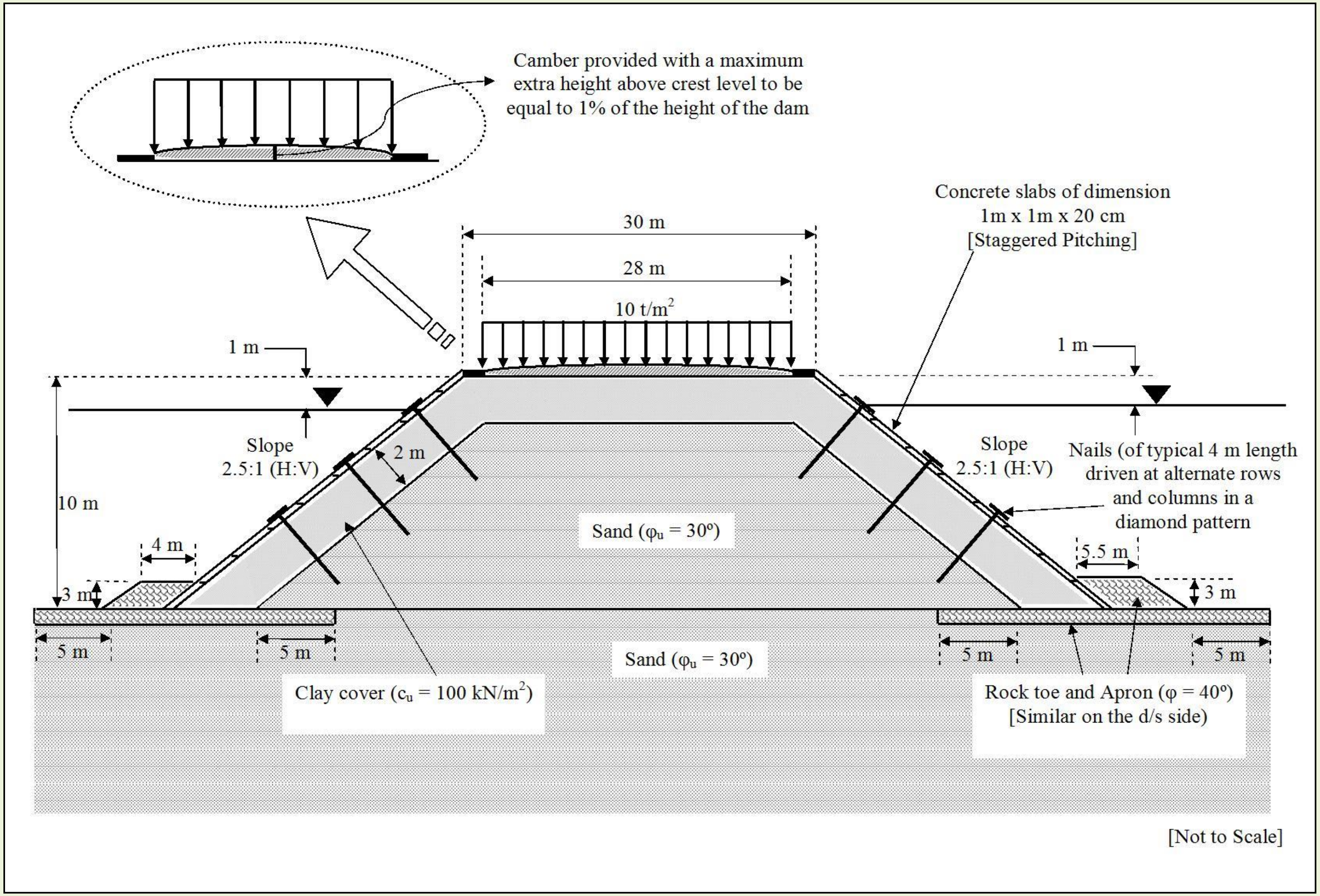
Tindharia Project West bengal

Composite Retention Systems

- **Soil Nailing and Nailed Soil Slopes**
  - In-situ ground reinforcement technique
  - Steel bars are driven, drilled and grouted, or fired ballistically into the excavated face
  - Nail installation proceeds in parallel to the top-down staged excavation
    - Simultaneous usage of shotcrete of steel-mesh facia panels
  - Best suited to near vertical faces in relatively good ground

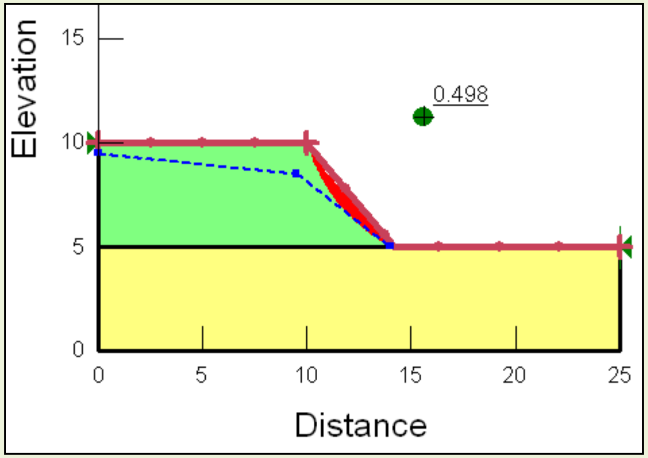


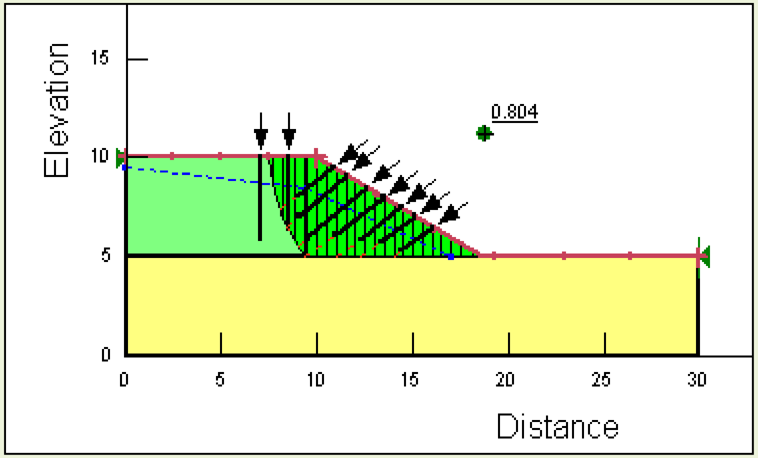
Protective Embankment of Ganga Barrage, Kanpur

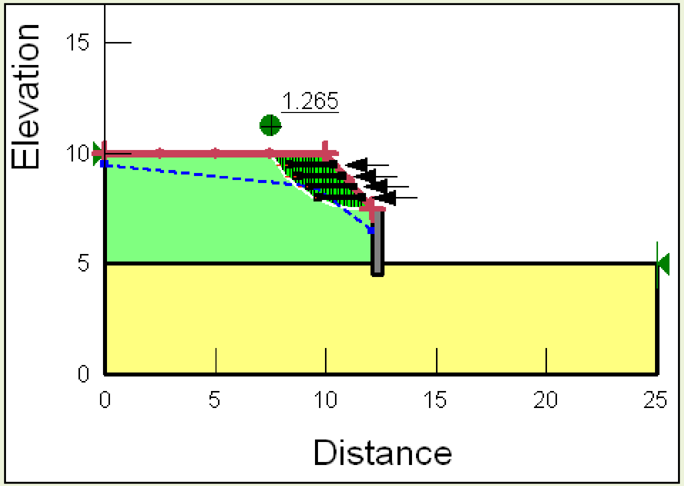


Simultaneous Stabilization Schemes

- **Identifying the combination of stabilization measures to obtain optimal stability solutions**







Road Caving at Mandi, Himachal Pradesh

Road Caving at Mandi, Himachal Pradesh

Protecting road by arranging soil-filled drums???

Road Caving at Mandi, Himachal Pradesh

Protecting road by arranging soil-filled drums???

Road Caving at Mandi, Himachal Pradesh

Protecting road by arranging soil-filled drums???

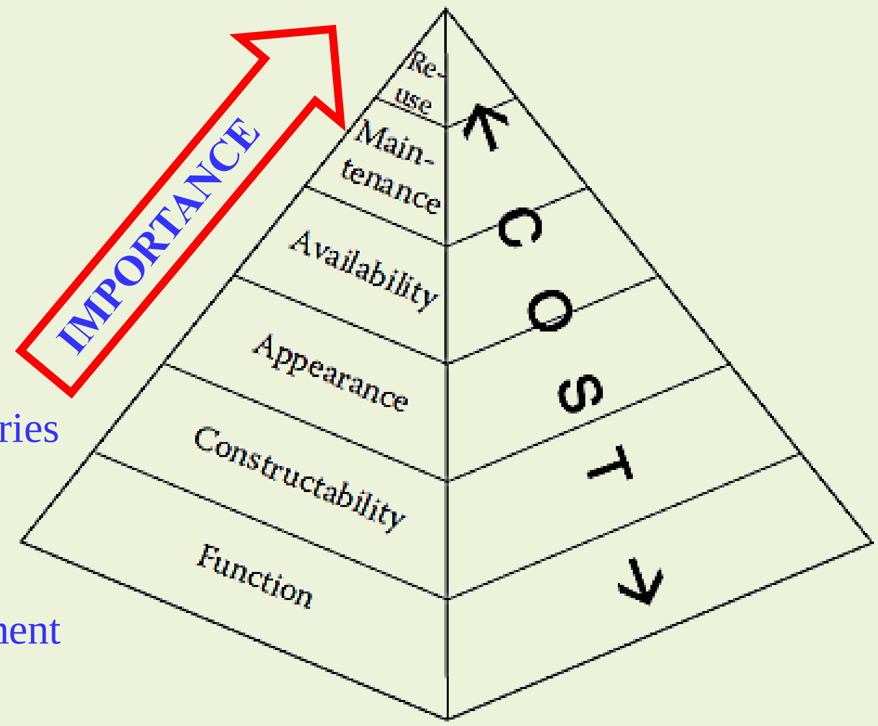
It was never meant to work out

Road Caving at Mandi, Himachal Pradesh

Gabion Wall became the saviour

Preliminary Selection of Retention Systems

- **Factors influencing the choice of retention systems**
  - Height of the ground to be supported
  - Type of retained soil
  - Type of foundation soil
  - Groundwater regime
  - Adjacent structures
    - Magnitude of external loads
    - Allowable movements
  - Available space for construction and machineries
  - Experience and local practice
  - Available standards and Codes of practice
  - Available construction techniques and equipment
  - Cost – A Major Issue

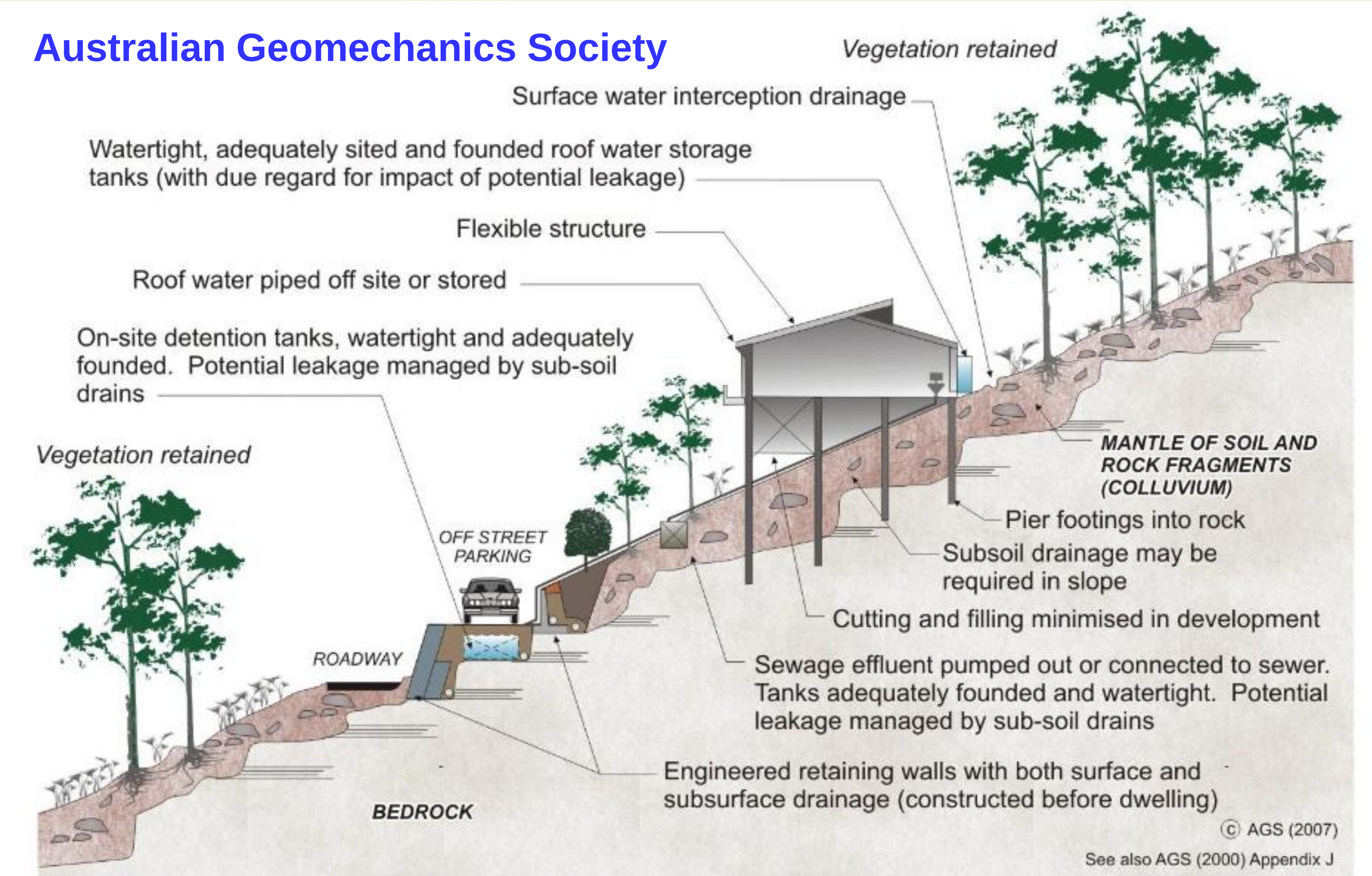


The Great Pyramid of Hierarchy

Final Remarks

- **Slope protection works is influenced by several factors**
  - Geometry and composition of the slope
  - Degree of seismicity and strong motion characteristics
  - Presence of joints, bedding planes, fractures, shear zones
  - Topographic amplification and wave directivity
  - Geohydrologic conditions
  - Spatial variability of soil properties and ambient conditions
- **Variety of mitigation techniques against instability**
  - Choice depends on the type of slope, composition, and causative factors
- **Domain of slope stability and landslides is interdisciplinary**
  - Geotechnologists, Geologists, Hydrologists, Climatologists, Seismologists, Earth Science experts, Instrumentation and Signal processing experts, Transportation engineers to achieve a sustainable hillslope practice

Good Hillside Practices



Softwares

- PLAXIS
- GeoStudio
- FLAC
- GTS Midas
- Talren
- Geo5
- OASYS
- Rocscience
- Gawacwin - Gabion wall design
- Wallap - Retaining wall design
- ReSSA - Reinforced Slopes - MSE walls
- TEDDS - Geotechnical/Structural Retaining wall design software; Inclined Gabion Structure

Thank You for Patient Hearing

http://www.iitg.ac.in/arindam.dey/homepage/index.html#

https://www.researchgate.net/profile/Arindam_Dey11