

SEACAP 21/004 Landslide Management

Mainstreaming Slope Stability Management

Theme 8 Remedial Measures: Design

8.3 Cross Section Design

8.4 Earthworks Design (including 8.7 slope drainage)

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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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This session will address the following questions:

When there are stability problems on an existing road alignment:

- how do you diagnose the cause using slope stability analysis and backanalysis?
- How do you improve the existing stability?

When designing a new road alignment:

- how do you minimise negative impacts on existing slopes?
- How do you design new earthworks (overview only)?

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Theme 8.3 - Cross Section Design

The choice of cross section depends on balancing the needs to:

- provide a good road alignment
- maintaining good slope stability
- minimising construction costs.

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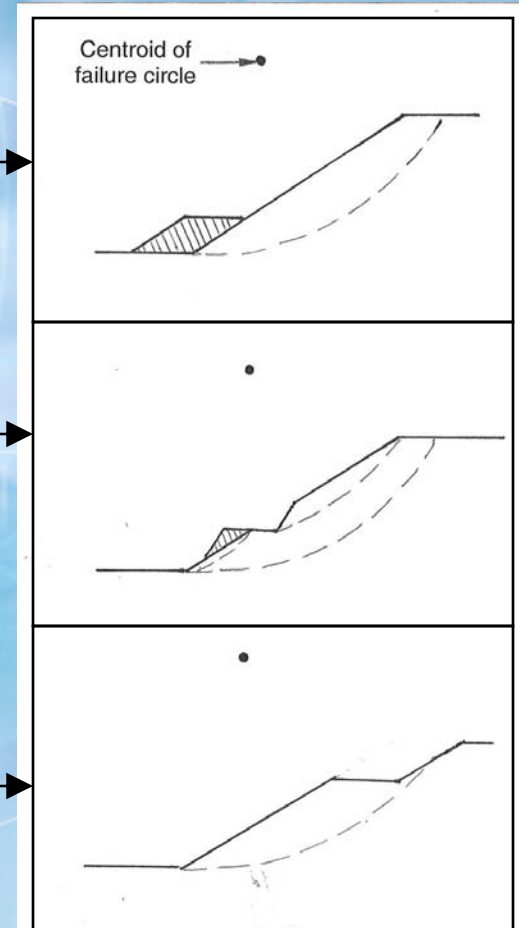
Cross section	Advantages	Disadvantages
Full Cut	Reduces need for compaction. Reduces need for retaining walls. Improves stability when at the top of a slope.	Reduces stability of the slopes above the cut. Maximises spoil generation which then needs to be disposed of. Heaping spoil on downslope side of road also reduces stability of slopes below.
Balanced cut and fill	Relatively little transport of material.	Placed fill needs to be carefully compacted to avoid differential movement between cut and fill sections causing damage to road. On slopes steeper than 30 degrees retaining walls likely to be required. Reduces slope stability locally on both sides of road.
Full fill	Reduces instability issues by avoiding cutting into slope. Improves stability when at the toe of a slope by toe loading and/or scour protection. Improves pavement drainage if placed on existing terrace.	Hauling plant required to transport large amounts of fill required. Compaction plant often required to achieve traffickable surface. On steep slopes costly retaining walls likely to be needed.

Table of advantages and disadvantages to each road cross section

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Choice of cross section to minimise soil slope instability:

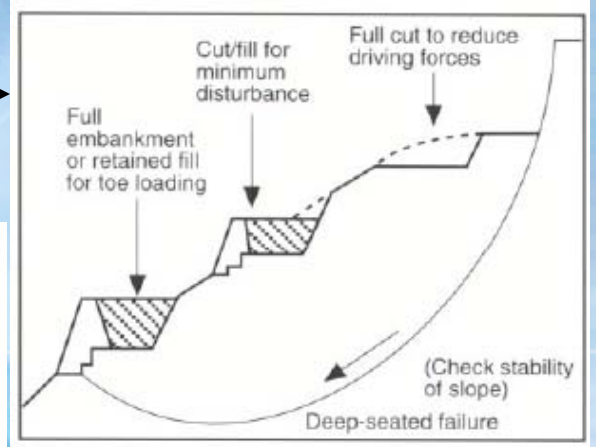
- 1) Fill at toe to increase resisting force
(FOS increases)
- 2) Balanced cut and fill
(little difference to FOS for whole slope instability, reduced FOS for local instability)
- 3) Cut at crest to reduce driving force
(FOS increases)



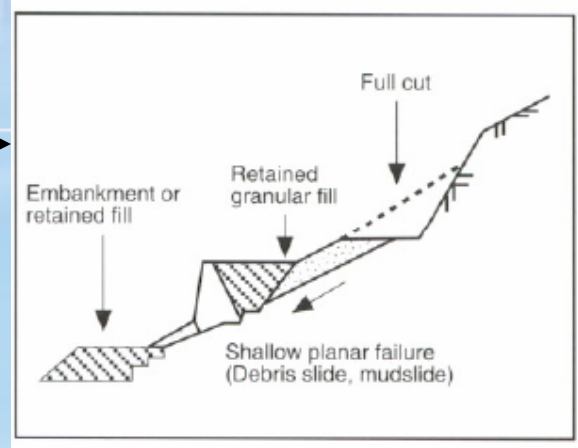
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Minimising negative impacts on sites of existing slope failures

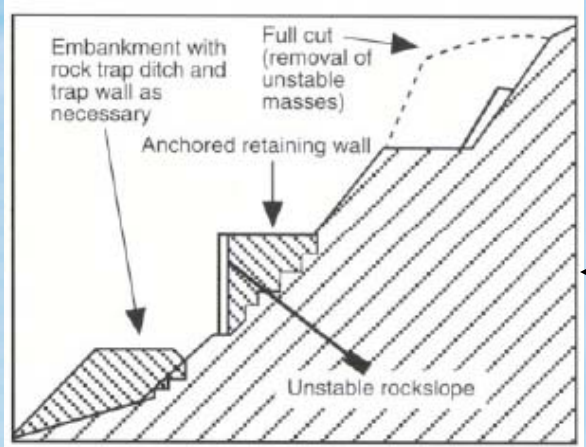
Deep seated failure →



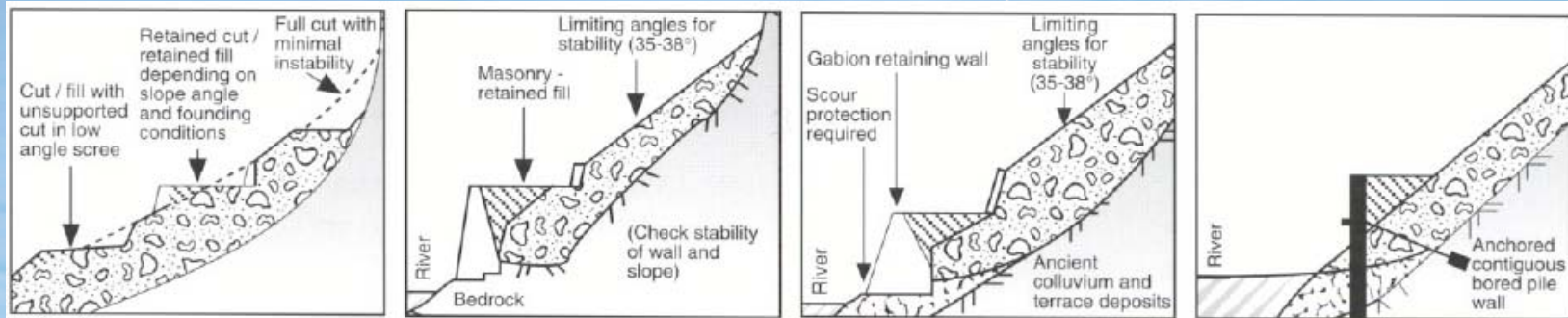
Shallow planar failure →



← Unstable rock



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Only likely to be possible without instability in gentle slopes. Future instability likely unless slope remediation undertaken.

Toe erosion controlled. Temporary support likely to be needed for wall construction. Slope above road still liable to failure. Revetment or retaining structure also needed above road if slope is cut.

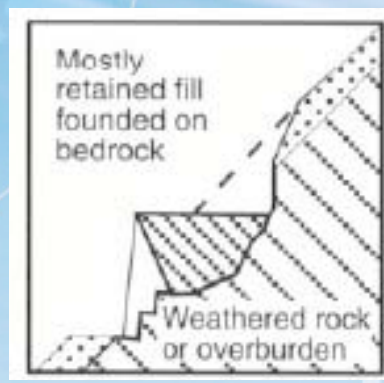
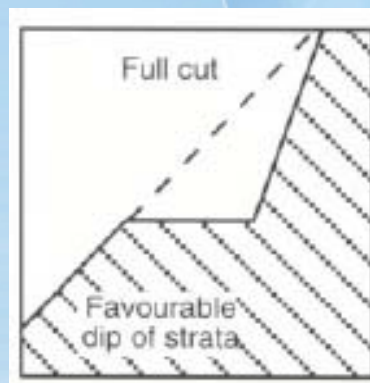
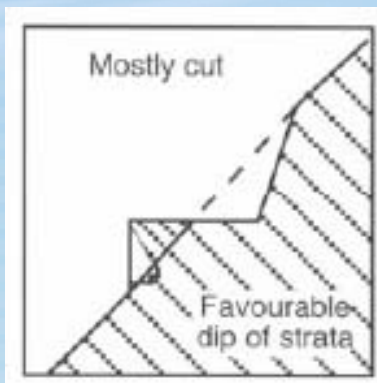
Anchored retaining wall expensive and requires specialist equipment. Difficult to construct on unstable slope but minimises excavation into slope and no temporary slope support needed. Good if space is tight.

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If the dip of the rock is into the slope then either a full cut or part cut solution is likely to be best. Blocks of rock may be unstable in the cut face if it is heavily jointed.

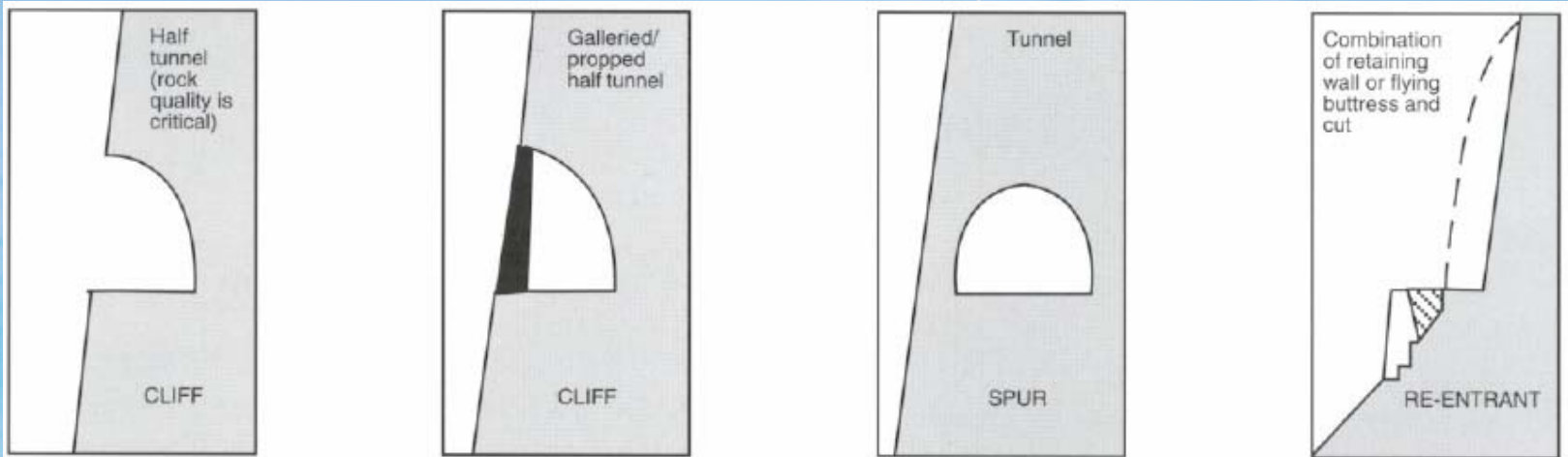
If the rock dips parallel to the slope then any cut will cause significant failures.

If there is a significant weathered rock then place retained fill founded on rock. Cut above road through overburden will need to be less than internal angle of friction of material.



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Roads in steep rock slopes



Only feasible in strong massive bedrock with planes of weakness dipping into hillside.

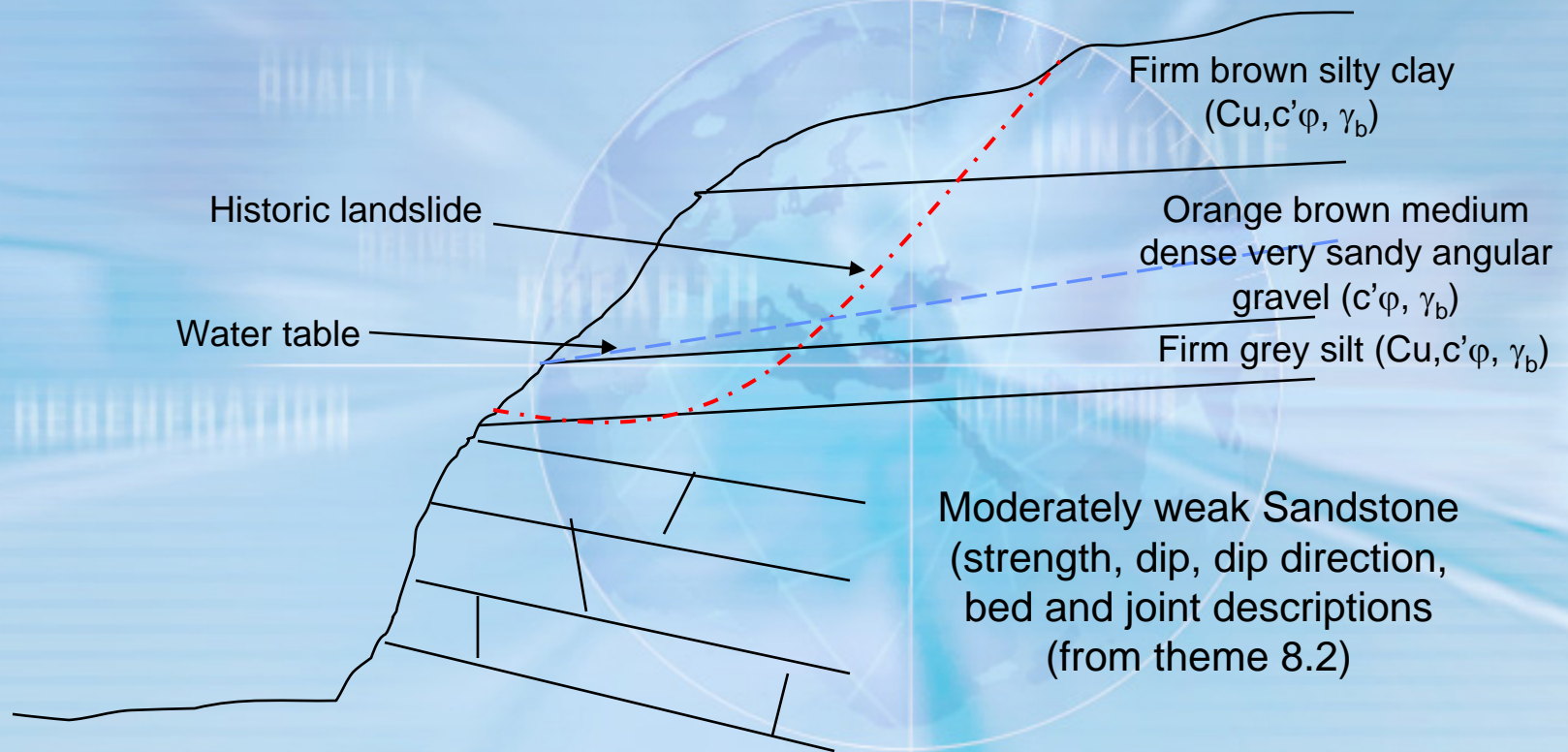
Very expensive may be more cost effective to divert road and provide half tunnel

Short span bridges, masonry buttresses used to cross re-entrants. Rockfalls can be a problem.

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Theme 8.4 - Earthworks Design

Ground model



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Factors of safety, governs chance of failure and likelihood of movements requiring repair.

<p>FOS=1.1 Low to mod risk</p>	<p>Road is not highly used Gravel tracks which can be easily repaired Road closure is acceptable Regular inspection, and maintenance will be implemented. Short design life Reasonable certainty in ground model (e.g. good GI data or where backanalysis of existing slopes corresponds well with GI and observations)</p>
<p>FOS=1.2</p>	<p>Road closure will result in economic loss or risk human safety Maintenance will not be implemented Road surfaces are less movement tolerant. Some uncertainty in soil model (e.g. due to little GI or rapidly varying soil conditions).</p>
<p>FOS=1.3</p>	<p>Very long maintenance free design life required High speed traffic and hard road surfaces prohibit movement Very high road usage where failure results in large economic and human loss</p>

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Earthworks design - Cuttings

PARTNERING

QUALITY

DELIVER

INTEGRITY

INNOVATE

REGENERATION

RESILIENCE

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Behaviour of cuts in clays and silts

Short term

Exhibit high cohesion and no/little friction

Consistency	Undrained shear strength
Very soft	< 20 kPa
Soft	20-40 kPa
Firm	40 -75 kPa
Stiff	75 – 150 kPa
Very Stiff	150 – 300 kPa
Hard	> 300 kPa
Correlation between consistency and C_u	

Exudes between fingers when squeezed

Moulded with light finger contact

Moulded with firm finger pressure

Cannot be moulded, indented with thumb only

In short term, cuts in clay can stand at steep angles (60 degrees) unsupported.

Max Height of cut slope is approximately $H = 2C_u/\gamma_b$

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Behaviour of cut slopes in clay/silt

In long term

- Cohesion drops $c' < 10\text{kPa}$ typical and friction increases $\phi' = 20\text{-}30^\circ$ depending on plasticity.
- Safe cut slope angle is much lower (20° is typical).
- Short term conditions may last between 2 weeks and 1 year depending on permeability of soil. i.e. short time in silt, longer in clay.
- Long term conditions may take 20-50 years to establish.
- Between the two situations there is a transition with gradually decreasing cohesion.

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Soil type	Typical slope angle
High plasticity clay	<1(V):3(H)
Low plasticity clay/silt	1(V):2.25(H) to 1(V):3(H)
Uncemented granular soils	1(V):2.25(H) to 1(V):1.5(H)
Cemented granular soils	1(V):1.5(H)
Rock slopes	>1:1

Typical cut slope angles in UK where long design life for deep cuts with, FOS=1.3 no maintenance requirement.

Actual cut could be steepened for:

- Lower FOS
- Shorter design life
- Small cut heights

Shallower cut angles could be needed for:

- Steep slopes above cut
- High ground water

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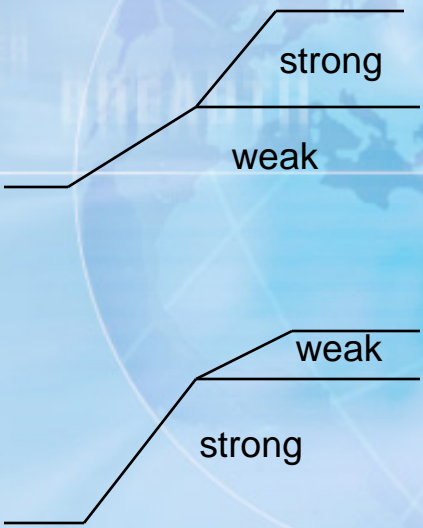
Soil type	Water table	Cut slope gradient (V/H) Cut height (metres)		
		0-3	4-6	7-10
Clayey silts (transported)	Low	1.5	1.0	0.8
	Moderate	1.2	1.0	0.5
	High	1.0	0.8	NA
Silts	Low	1.0	50.8	>_0.8
	Moderate	1.0	550.8	5_0.8
	High	1.0	0.8	NA
Coarse-grained colluvium	Low	1.0	1.0	0.8
	Moderate	1.0	1.0	550.8
	High	1.0	0.8	NA
Silty clays (residual)	Low	1.5	1.5	1.0
	Moderate	1.2	1.2	1.0
	High	1.0	1.0	NA

Note The above slope angles have been derived from stability charts with assumed c' and ϕ' values and an average factor of safety of 1.1. Slope gradients have not been given for 7-10 m high cuts with a high groundwater as this condition is unlikely to occur in granular soils, whose permeability is relatively high. This table is for illustration purposes only.

Cutting slope angles from ORN16

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Cutting profiles

Single slope	Multi-slope	Benched
<p>For single strength soil</p>	<p>Where soil strength varies with depth.</p> 	<p>Surface water energy reduced – erosion reduced</p> <p>Ponding on benches can lead to failure</p> <p>Benches catch falling debris.</p> <p>Debris must be cleared to avoid overloading</p> <p>Easier to vegetate benches than steep slope.</p>

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Face erosion/weathering causes:

- washout of uncemented granular soils,
- loss of cementation in cemented soils,
- rapid softening of clays.

Caused by:

- Rapid surface water flows
- Water ponding on ground surface
- Vegetation growth on face, burrowing and icing
- Water seepage from face

Face protection methods include:

- Drainage (will cover slope drainage in later session)
- Vegetation to bind surface together
- Face covering e.g. revetment.

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If a cut cannot be achieved within the space available at a sufficiently flat angle to provide the required factor of safety then slope stabilisation measures will be required.

Situations where this may be the case are:

- Where you are cutting into natural slopes which were already close to their limiting angle of stability before the works,
- Where the road must cut through the toe of an existing slip
- Where failures occur during or after construction

We will cover slope stabilisation measures in the next session.

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Earthworks Design - Embankments

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Unretained fill/embankments tend to fail because:

- Embankment side slopes are too steep,
- There is inadequate embankment drainage,
- Of erosion of the slope immediately below the embankment
- Inadequate foundation surface preparation ,vegetation or topsoil left in place, lack of benching
- Planes of weakness in ground below embankment e,g pre-existing slip, unfavourable orientation of rock bedding
Inadequate embankment drainage

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Typical embankment side slopes – After excavation, transport and compaction fills retain little cohesion. Side slopes dictated by friction.

Fill type	Typical Friction angle	Side slope angle for FOS=1.1	Side slope angle for FOS=1.2
Clay – High plasticity	20-25°	18-23°	17-21°
Clay/Silt – Low plasticity	25-30°	23-27°	21-25°
Sand	30-35°	27-32°	25-30°
Gravel	35-40°	32-37°	30-35°

Rough guide to side slope angles for well compacted fill embankments with good drainage and where founding soils are better or the same as the embankment fill.

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Compaction –

Usually compact in layers using compaction plant which achieves 95% proctor compaction.

Hand compaction using hand rammers may only achieve 80%. Can cause settlement and damage to road therefore where possible leave for one wet season before releveling the surface and laying hard top.



Sheeps foot roller used for compacting clay fills.

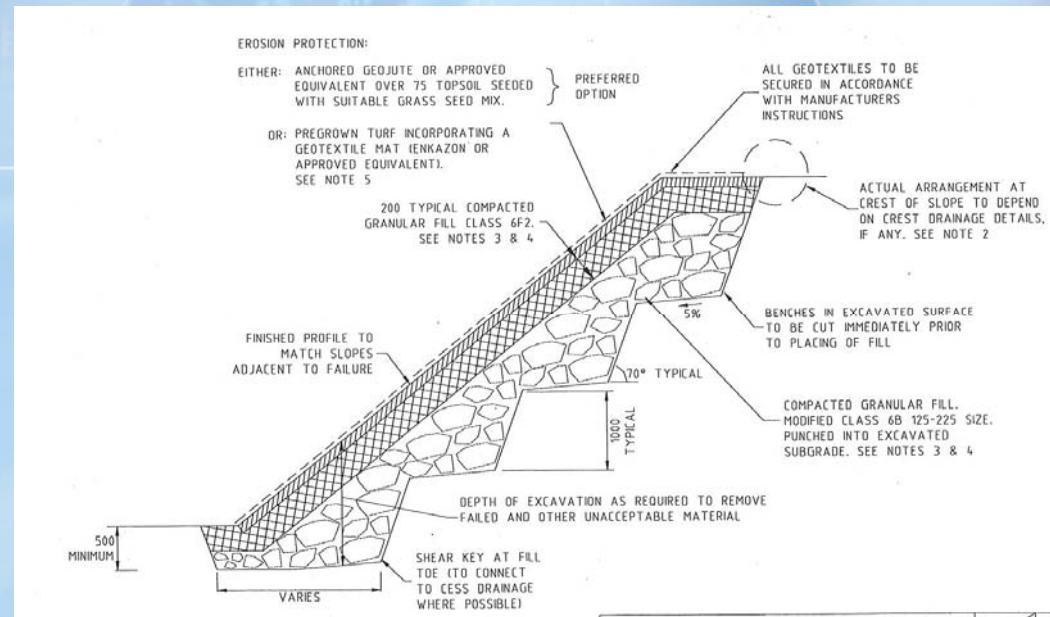
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Benching –

- Very important to avoid weak plane at contact between embankment and underlying soil.
- Benches slope away from slope to avoid water ponding and softening of soil
- Height of bench dictated by soil type and bench width governed by compaction plant and slope angle.

Example benching detail.

Source “Standard
Network Rail Details”



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Embankments founded on clay

In the short term

Clay exhibits high cohesion (C_u) but little or no friction ($\phi_u=0$). In other words adding weight to the soil does not improve the strength.

$$(\tau = C_u + \sigma_v' \tan \phi_u, \text{ but } \phi_u = 0 \text{ so } \tau = C_u)$$

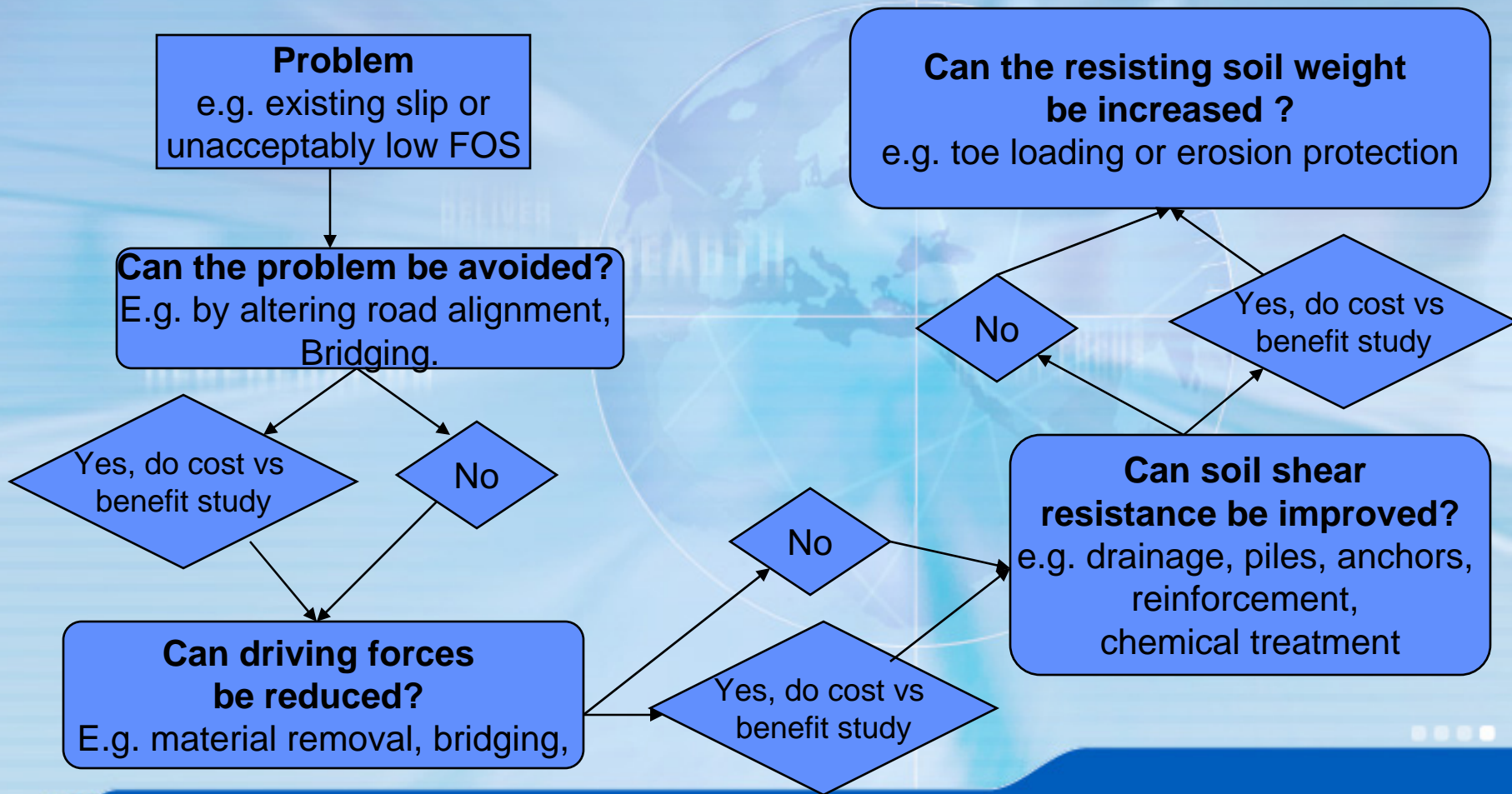
In the long term

Clay exhibits low cohesion ($c'=0-10\text{kPa}$ typically) and higher friction ($\phi'=20$ to 30° typically). The soil strength is enhanced by the weight of the overlying embankment.

When designing embankments on clay soils, we analyse both short and long term but short term usually governs stability.

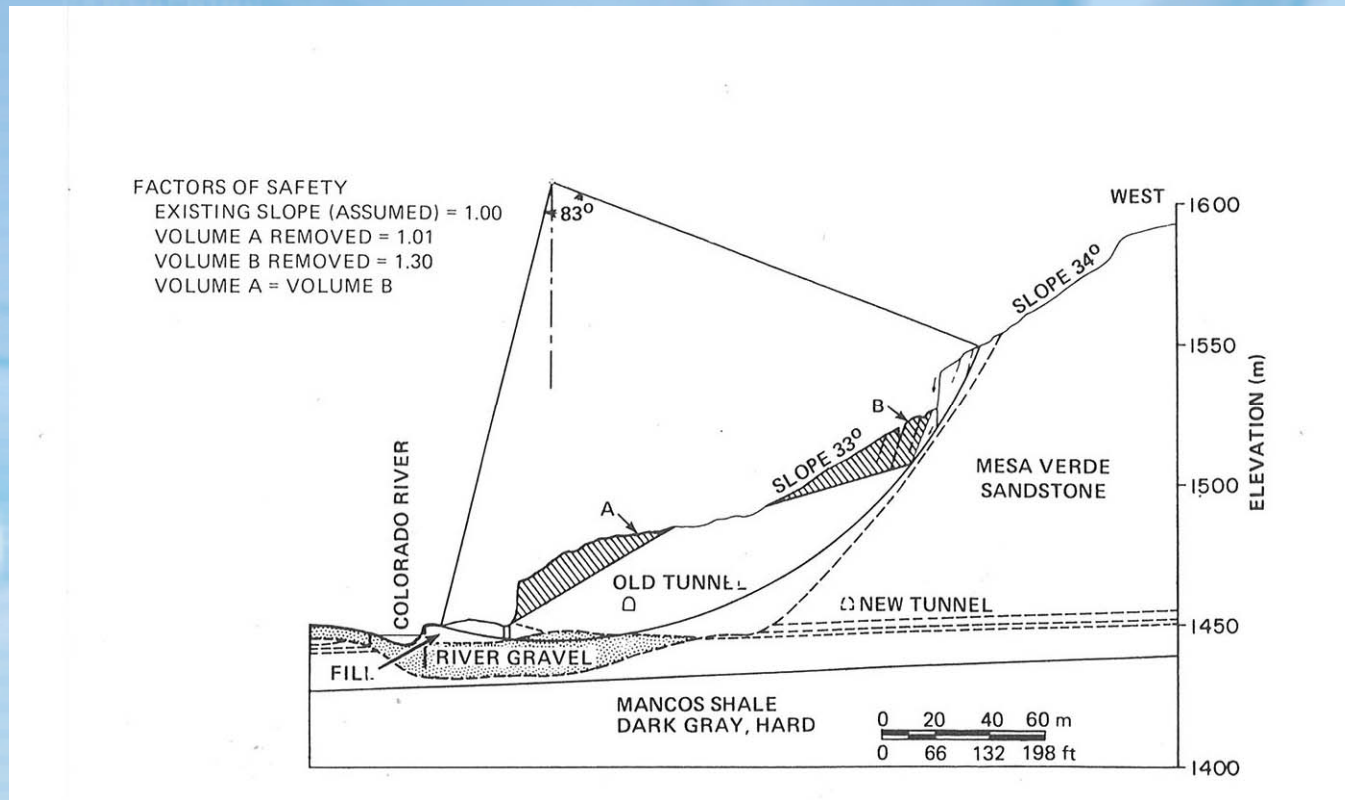
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8.4 Earthworks Design - Slope remediation



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Reduce driving forces by removing material



Stabilisation of a slide in the Colorado River Valley

Source "Landslides – Analysis and Control" Transportation Research Board National Academy of Sciences

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Reduce driving forces by use of light weight fill

This only applies where the driving forces are provided by new road embankment.

Light weight fill materials include:

- Pulverized Fuel Ash – PFA – unit weight 15kN/m^3
- Encapsulated sawdust and wood fibre – Above water table asphalt used to delay decaying process.
- Polystyrene – unit weight $=7\text{kN/m}^3$
- Light weight aggregate – unit weight may be as low as 4kN/m^3
- Tyre bails
- Seashells

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Improve soil shear resistance by slope drainage

Two main functions:

1) A method of increasing resisting forces by improving shear resistance

or

2) A method of reducing erosion from surface water

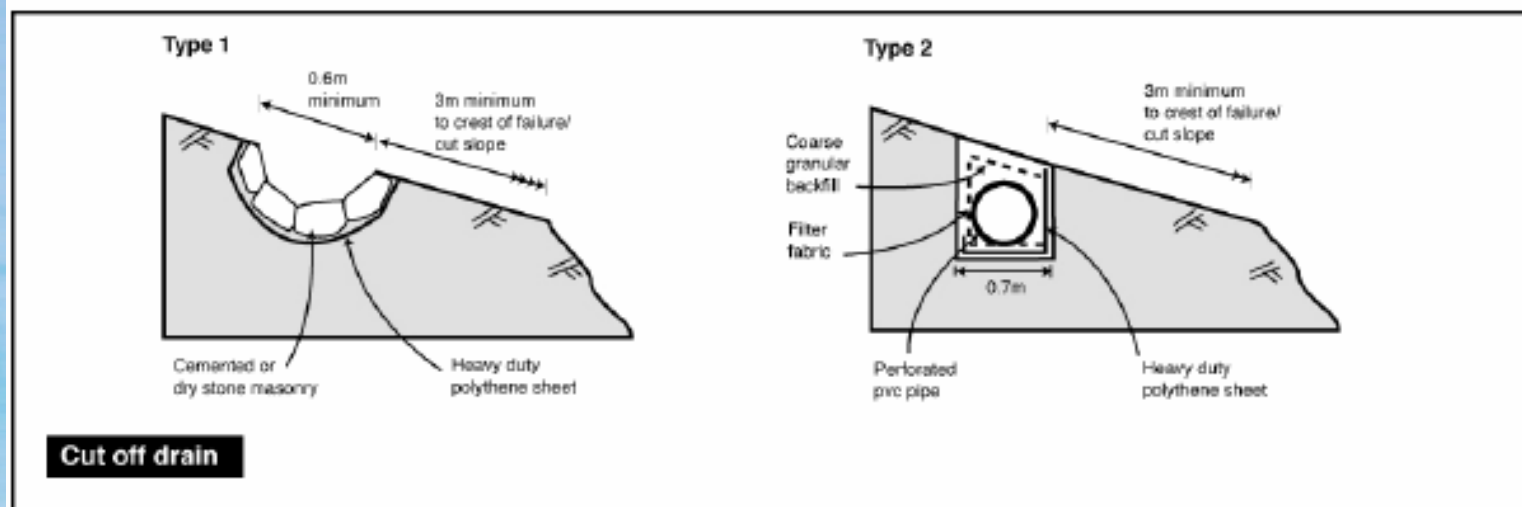
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An overview of the different methods of ground water control

Function	Type	Advantage	Limitation
Interception of surface run-off above slope	Unlined cut-off drain	Inexpensive	May create line of instability beyond crest; may be prone to erosion; usually not maintained
	Lined cut-off drain	Less prone to erosion and leakage	Requires frequent inspection for damage/blockage; inspection access may be difficult
Interception of surface runoff on slope	Slope surface drain	Less prone to leakage	Rigid mortared masonry construction incapable of withstanding small movements
	Branch drain	Inexpensive. Often used with bio-engineering	Dry stone pitching less rigid than slope surface drain
Interception of high/perched water table	Herringbone drain	Able to intercept water up to approx 1.5m depth below slope face; good for intercepting surface seepage or springs; can accommodate some slope movement	May only have limited effect on overall slope stability for deep-seated failures
	Counterfort drain	Able to intercept water up to 3-4m depth below slope face; can act as a stabilising buttress if base below slip surface	Usually needs to be machine dug; difficult to construct in bouldery material
Interception of deep water table	Horizontal or vertical drains	Only feasible method of intercepting groundwater at depth	Comparatively costly; drilling equipment required; may not always be successful
Diversion or improvement of watercourse or gully	Lined channel or Cascade	May be necessary if existing watercourse is direct cause of instability	Usually very expensive and often difficult to construct. If diverted, may overload new watercourse.
Reduction of erosion in gully	Check dam	Relatively cheap, often necessary below culvert outlets	Effective only for a limited length of gully in steep terrain

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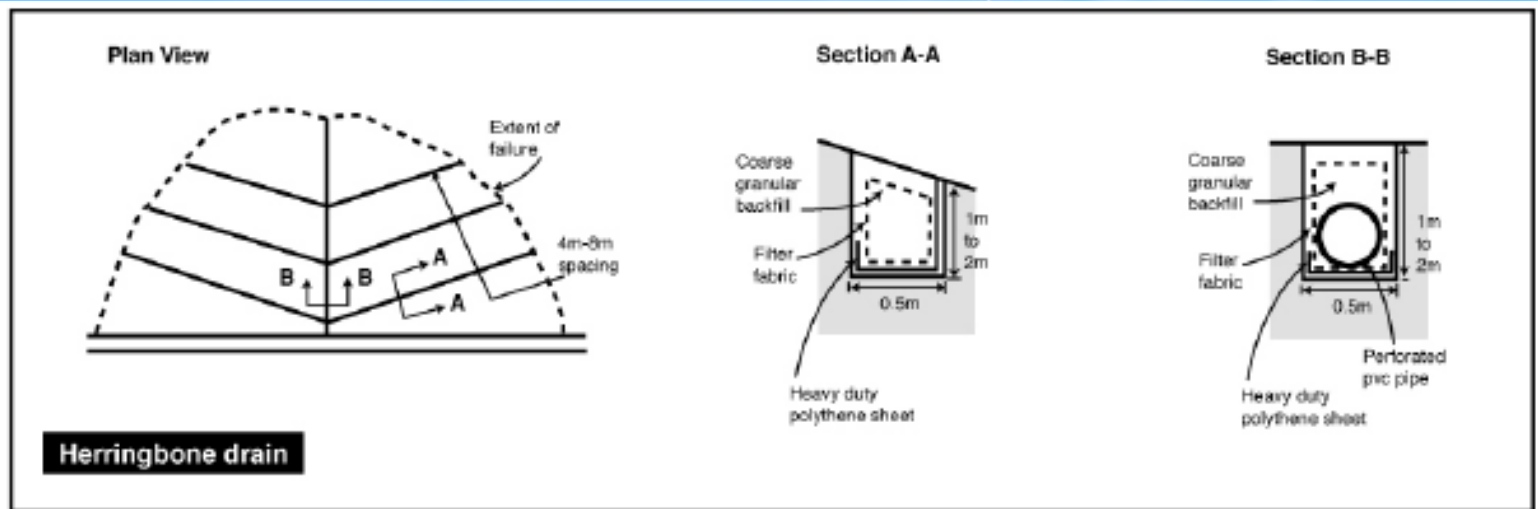
Cut off drain



- Run along crest of slope on across slope above line of slope failure - Used to intercept surface water.
- Regular inspection and maintenance necessary. Blockage or damage can lead to water being diverted into the slope causing new instability.
- End of drainage run must link into properly designed gully to carry water down slope and into streamway at base.

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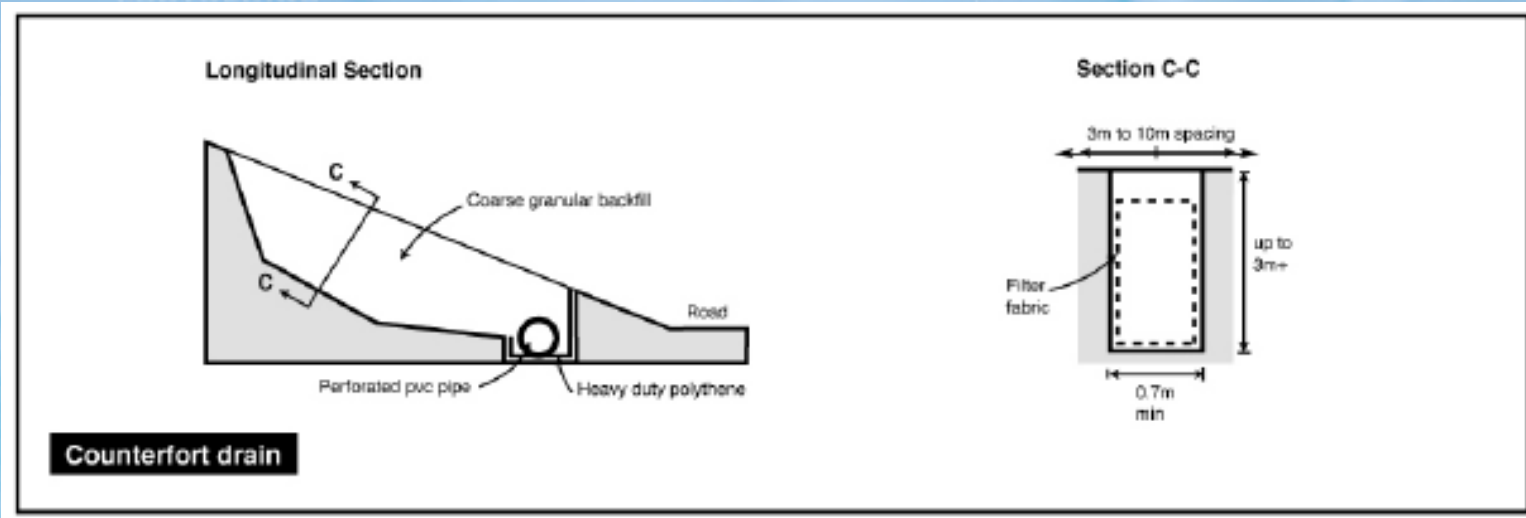
Herringbone drains



- Used to collect surface runoff and near surface ground water.
- Often no more than about 1m deep trench lined with filter fabric and polythene sheet on downslope face then filled with coarse gravel fill and flexible perforated pipe where high flows are expected.
- Care to avoid instability during construction.
- Drain must be connected into properly designed toe drain or streamway.

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Counterfort Drains



- used to depress a high water –table.
 - Run directly down slope and dug to a depth of 3m or more at 3-10 m centres.
- Trench lined with filter fabric and filled with coarse gravel and flexible perforated pipe where high flows are expected.
- Reduce risk of slope instability due to orientation.
 - Drain must be connected into properly designed toe drain or streamway.

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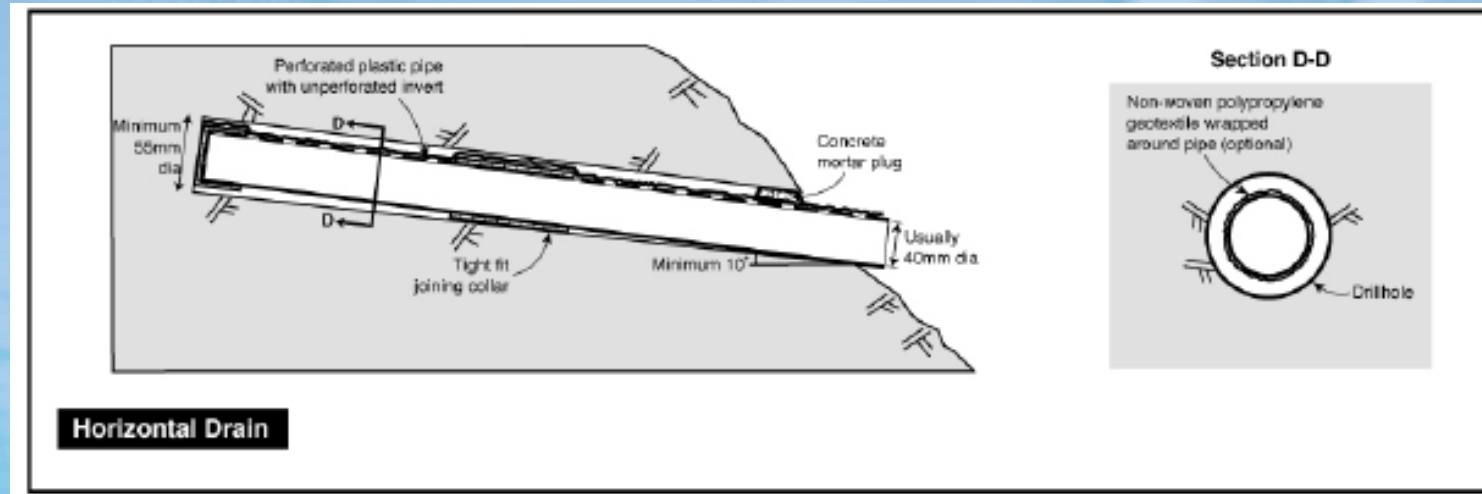
Example of counterfort drains to stabilise cutting flanks



Old counterfort drains uncovered during excavation works at toe of cutting (drains are about 2m deep, 0.5m wide and 6m centres)

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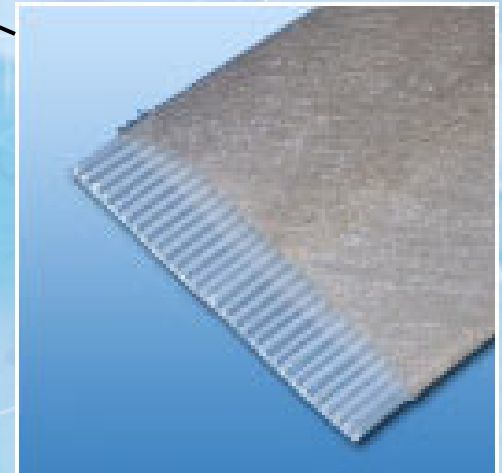
Horizontal drains



- Used to relieve pore pressures at depth.
- Specialist equipment needed to drill hole and install perforated plastic pipe wrapped in filter fabric. Often fan of drains installed at 5 degrees upwards.
- Expensive to install
- Success relies on intercepting high permeability subsoil or seepage paths within subsoil.

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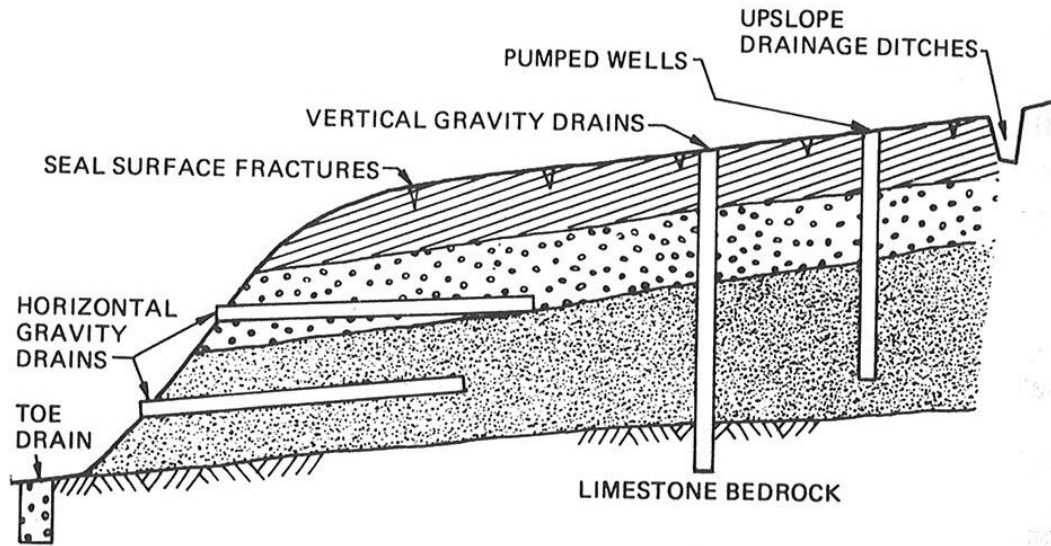
Example of fabric horizontal drains driven into soil slopes



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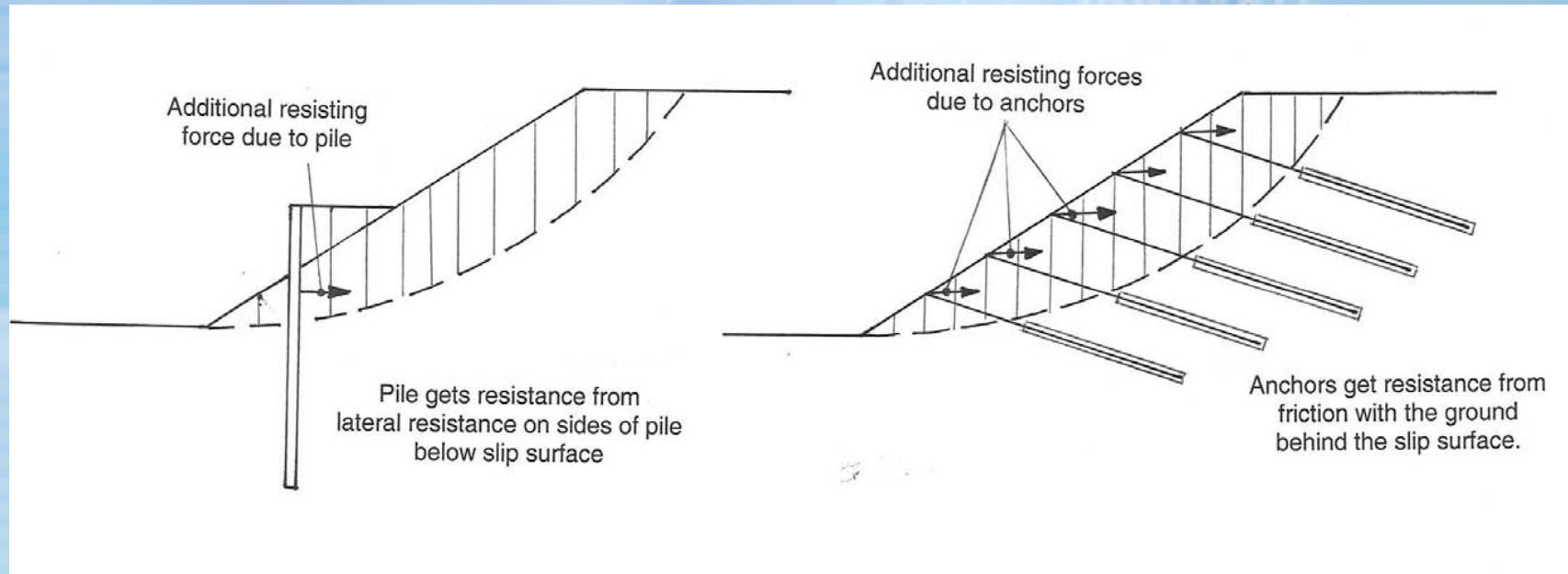
Vertical drains

Figure 8.6. Horizontal and vertical drains to lower groundwater in natural slopes.



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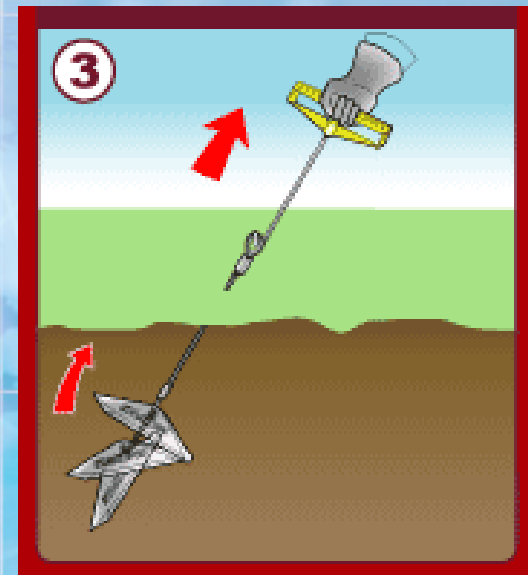
Improve resisting forces using piles or anchors



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Dead man anchors

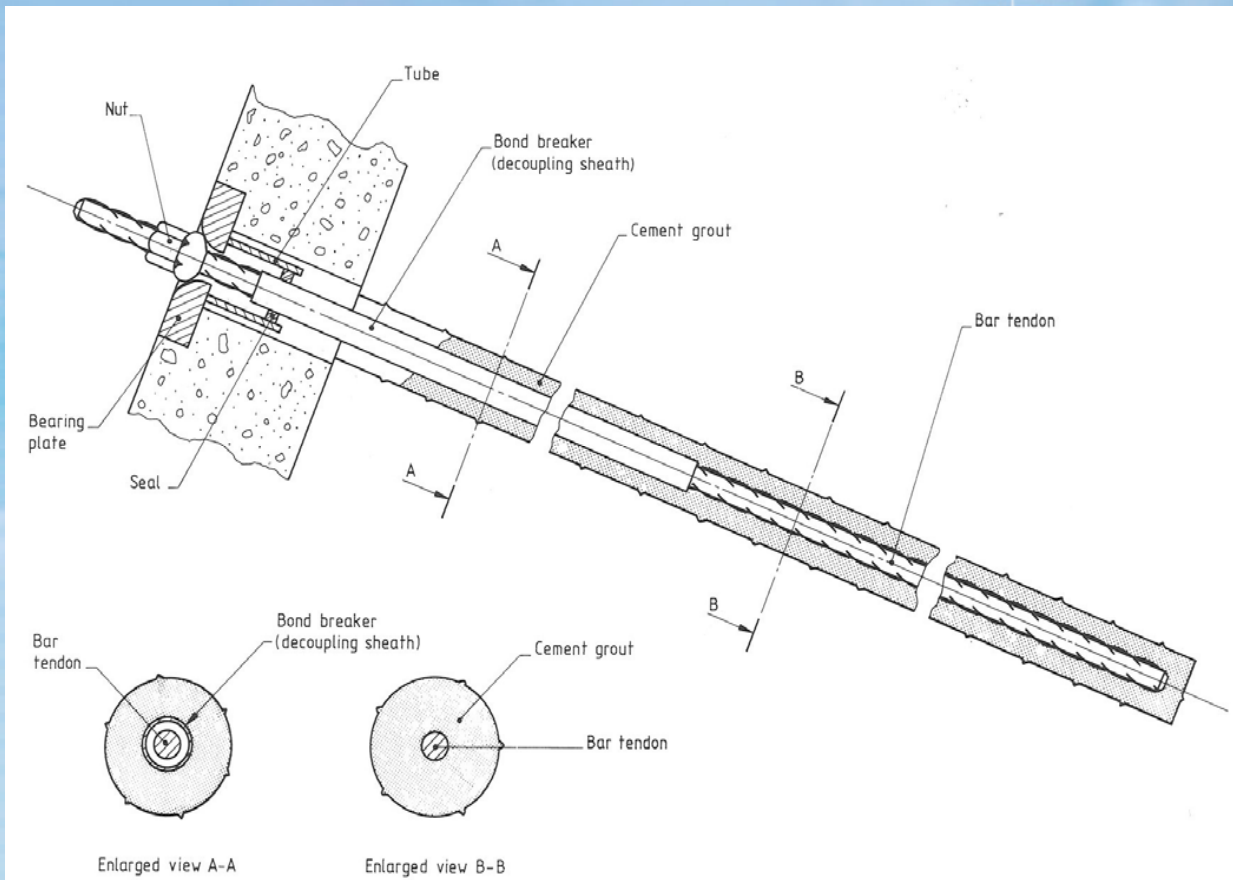
Get resistance from bearing of
plate within ground.



Picture taken from Platipus website

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Grouted Anchor



Gets resistance from friction over grouted length behind slip surface

Figure from BS8081

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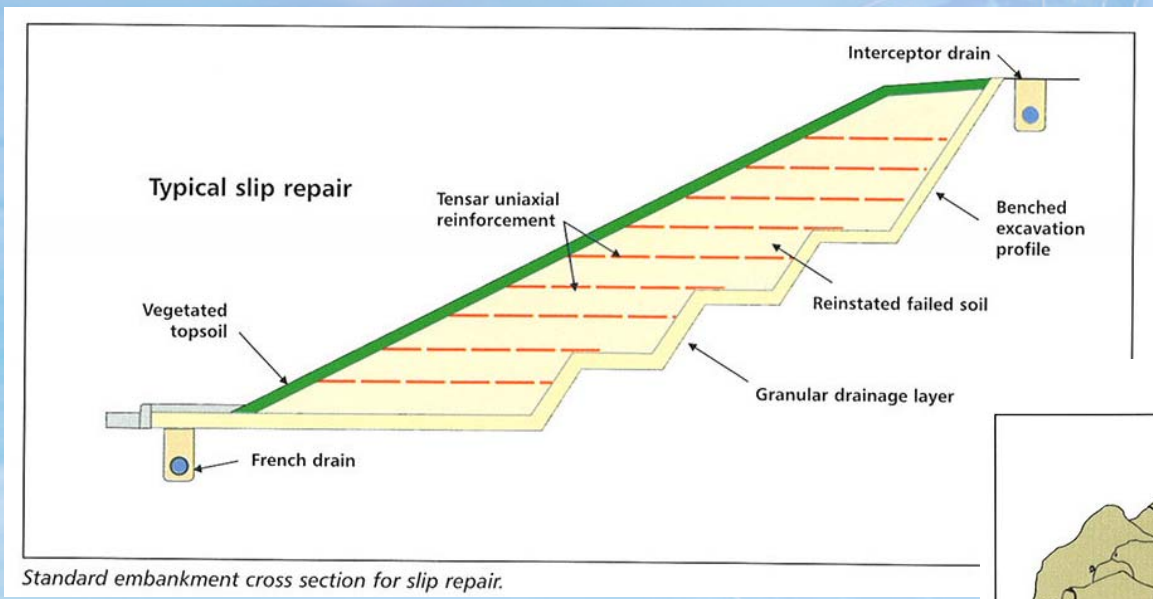
Increase shear resistance with reinforcement.

Two commonly used reinforcement types:

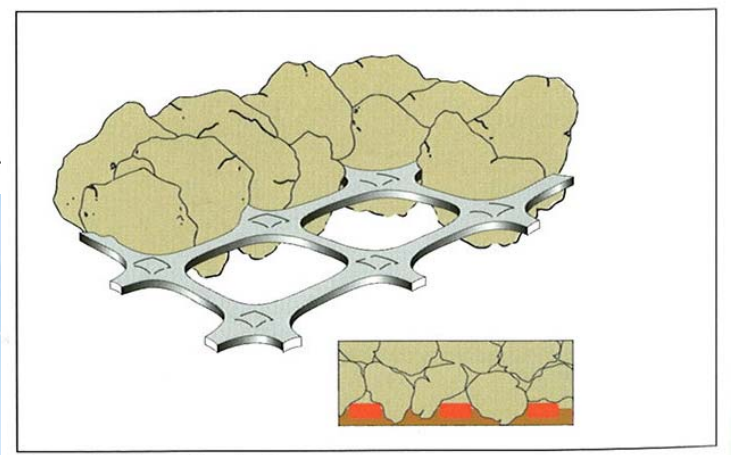
- 1) Geogrid or metal strips laid into newly constructed fill.
- 2) Soil nails installed in existing slopes

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Geogrid reinforcement



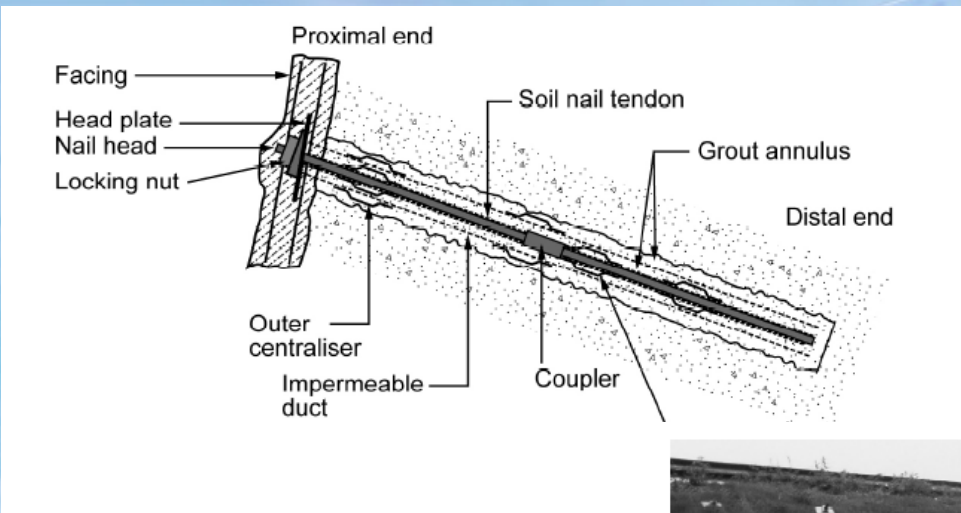
Pictures taken from Tensar brochure.



The mechanism of Interlock.

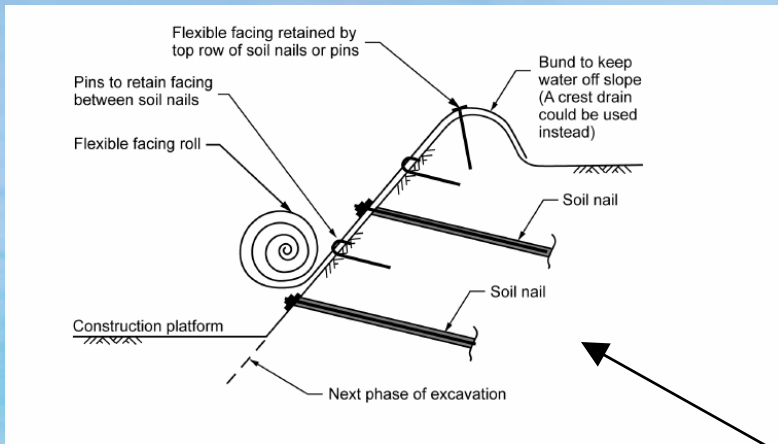
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Soil nails



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Facings – soft facings for shallow slopes



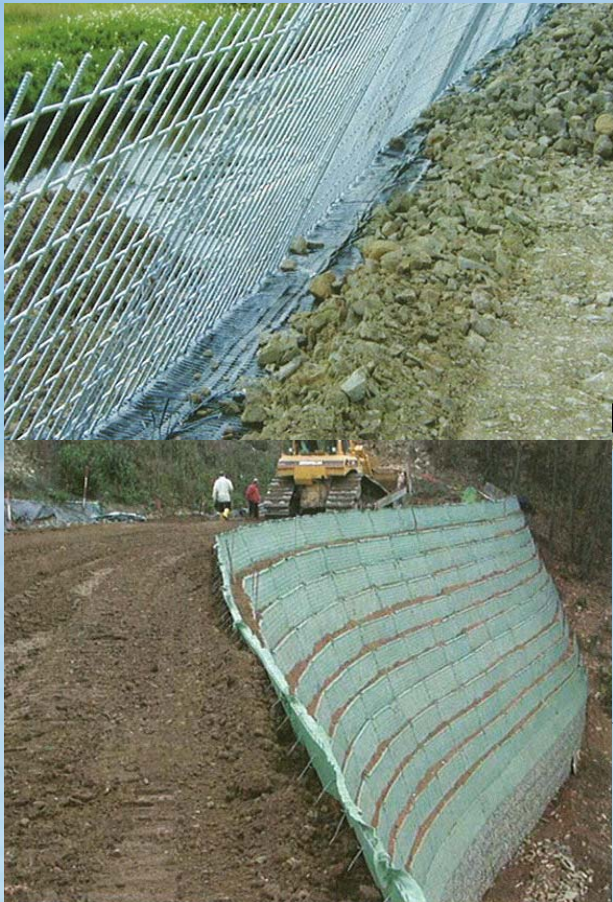
Combined erosion protection and light face restraint mesh facing for soil nailed slope.

Geogrid wrapped around soil bags to provide temporary facing until vegetation takes hold.

Photos from CIRIA C637 and Tensar website

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Harder facings for steeper slopes

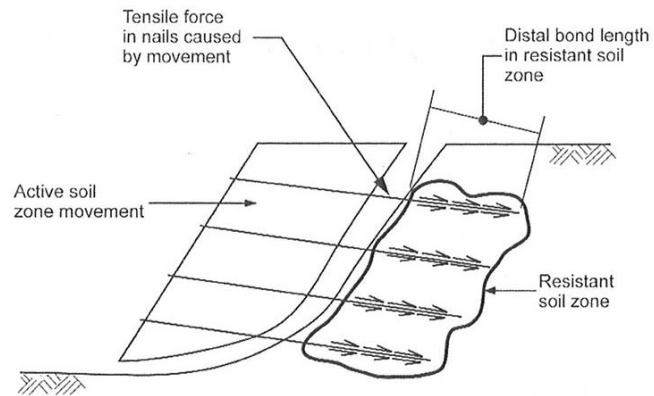


Geogrid connected to gabion facing

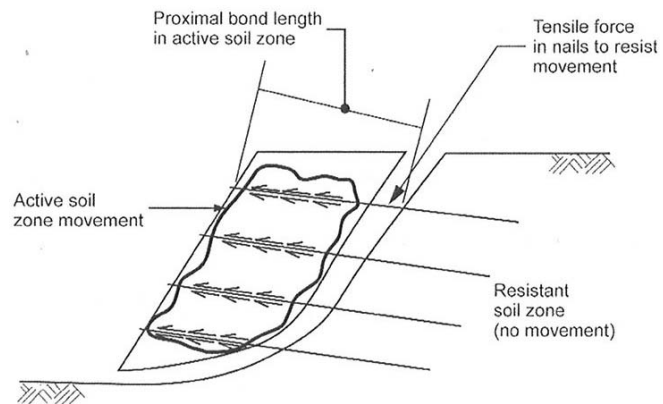
Steel facing provides both formwork and structural facing. Lined with geotextile to retain soil until vegetation gets established.

Photos taken from Tensar Brochure

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Bond in resistant soil zone



Bond in active soil zone

Note: Arrows represent direction of tensile stress



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Increasing soil resistance by chemical treatment

- Again there are many different forms of chemical treatment. Two of most common are mixing soil with lime or cement.
- Chemical is added in situ using an auger to create columns or layers of increased strength.
- Lime increases strength and stiffness of high plasticity clay
- Cement works in either clay or sand.
- Expensive and required specialist equipment and careful site control.

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Increase the resisting forces by toe loading.

This can be achieved by forming an embankment at the toe of the problem slip. If space is limited then a retaining wall may be needed to hold the added fill in place.

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In this session we have looked at:

- 1) How do you design cross sections to minimise negative impact on slope stability.
- 2) What do you need to consider when constructing new cut or embankments
- 3) When you have diagnosed a problem, the process that you go through to determine the best solution.
- 4) Some of the many slope remediation methods available.