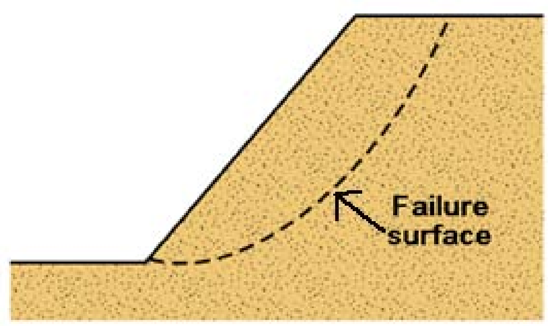
<u>Slope stability of natural slopes</u>

- This part of the course deals with instability processes in **natural slopes**. These include **<u>slope failure</u>** and **<u>slope movement</u>**. These processes are generally conditioned by natural factors, although they may also be triggered by human activity or seismic activity.
- The following sections do not cover the instability of slopes **made artificially** as in the case of quarrying and manual excavation of canals and roads.
- Slope failure is generated by:
  1. The gravitational down slope displacement of soil and rock masses.
  2. Weakening of geological materials, mainly due to weathering and jointing
  3. Action of other natural and environmental phenomena, e.g. rain fall and seismic and volcanic activity.
- Slope movements (e.g. landslides) occur due to ground adjustments to recover equilibrium under changing conditions.
- These processes create potential geological risks, as they can cause economic loss and social damage. Landslides in natural slopes may involve the movement of millions of cubic meters of material

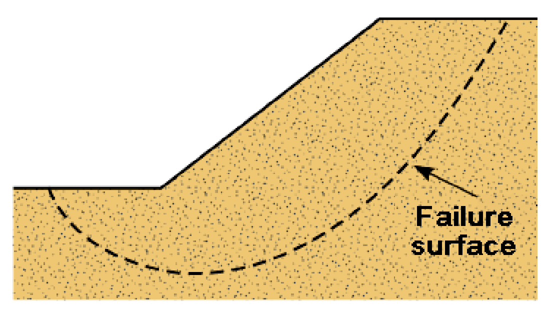
<u>Types of slope failure</u>

<u>1- Failure of Soil slopes</u>

- Soil slopes <u>generally</u> fail along **<u>curved surfaces</u>** with the shape of the failure mainly conditioned by the morphology, stratigraphy and lithology of the slope.
- There are three types of failure of soil slops:
  1. Slip surface is **<u>roughly circular</u>** with its lower end cutting the slope at its lower end. This occurs when the slope consists either of homogeneous soil or variable strata with homogeneous geotechnical properties.
  2. The failure surface may be almost circular, passing under the slope base.



Rotational toe failure



Deep rotational failure

3- Slip surface is a plane surface or polygonal surface (made up of several planes). This type is very unusual and occurs when strata or layers are of different strength.

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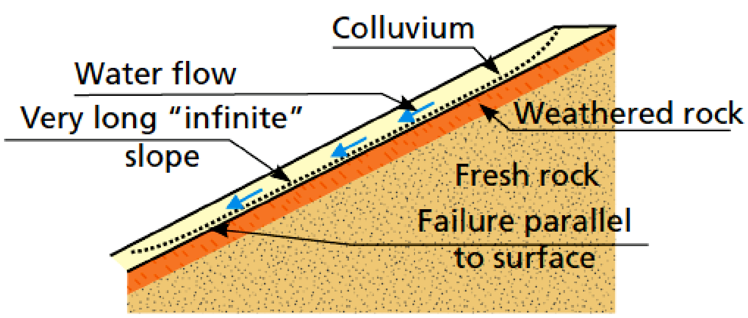
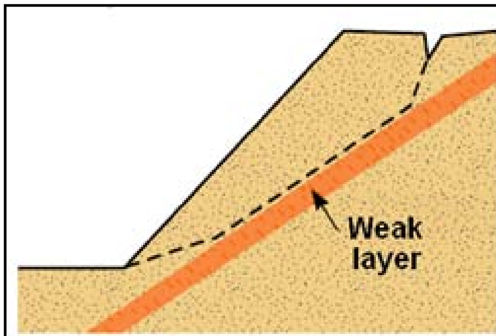


Plane failure



Polygonal-type failure

Failure of soil along a curved plane

2- Failure of Rock slopes

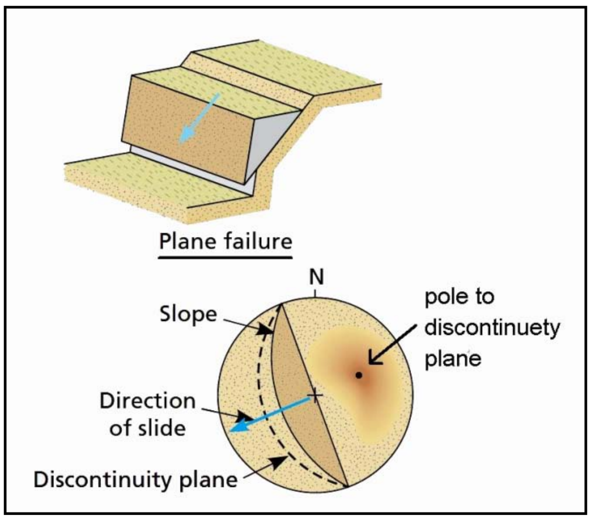
The most frequent failure types are: plane failure, wedge failure, toppling, buckling, non-planar failure and rock avalanch. and rock falls

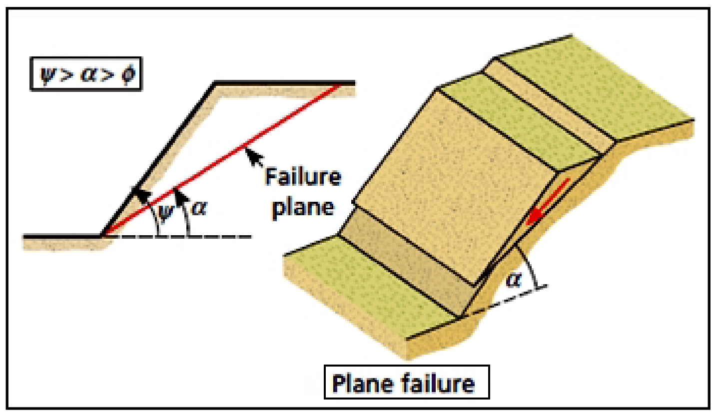
a- Plane failure

Plane failure takes place along a pre-existing discontinuity, such as a bedding plane, tectonic joint or fault.

Failure occurs when:

- Discontinuities are striking parallel or almost parallel to slope.
- Discontinuities must daylights the slope (dip towards the slope at a lower angle).
- Angle of dip of discontinuity **(α)** **<** angle of slope (ψ) .
- Angle of dip of discontinuity **(α)**. **>** friction angle of the discontinuity (**ϕ**).



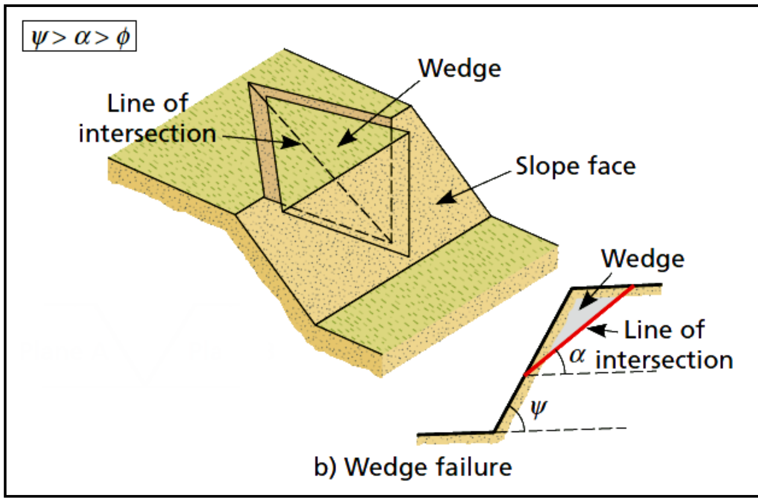


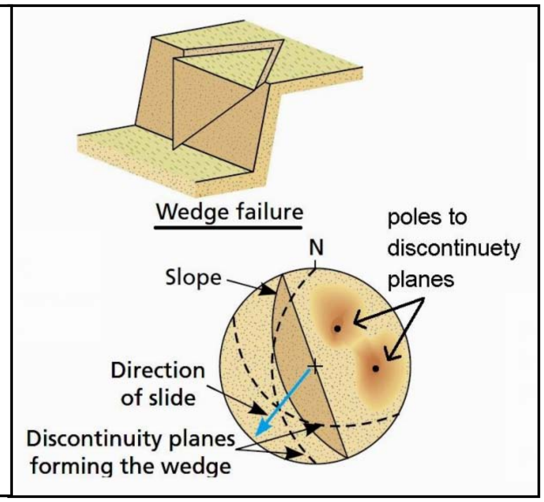
b- Wedge failure

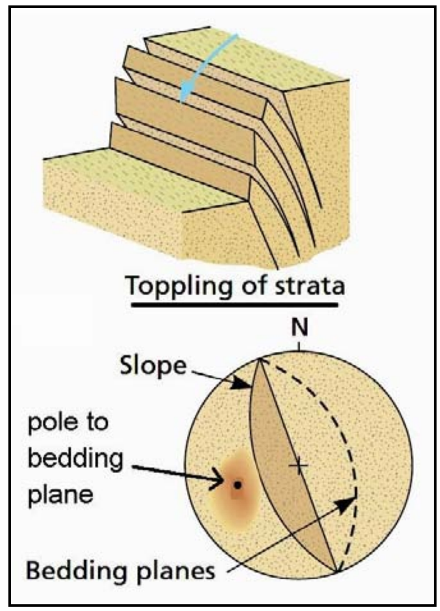
This failure type consists of a sliding wedge-shaped block formed by two discontinuity planes whose line of intersection dips towards the slope face (daylights the slope surface).

Failure occurs when:

- The two planes must be exposed on the slope face.
- The line of intersection of the two planes plunges towards (daylights) the slope.
- The angle of plunge of the line of intersection of the two planes (α) **<** angle of slope (ψ)**.**
- The angle of plunge of the line of intersection of the two planes (α). **>** friction angle of the discontinuity (ϕ)**.**

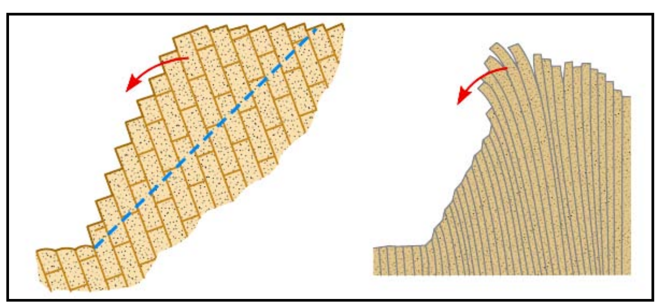






c- Toppling

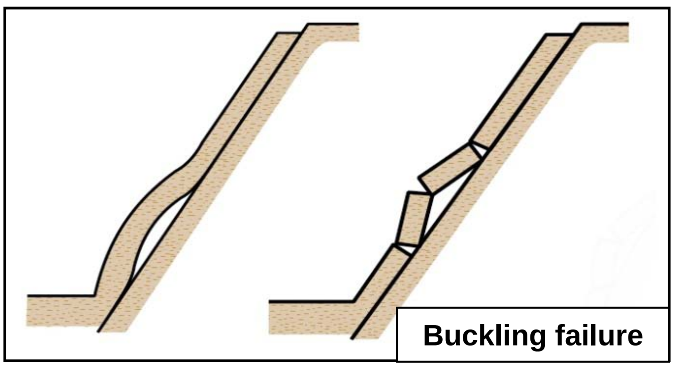
Toppling occurs on slopes in rock masses where the strata dip steeply away from the slope, striking parallel or sub-parallel to it. In block toppling the strata generally form columns defined by discontinuity sets normal to each other. Toppling results in retrogression back (retreat) of scarps.



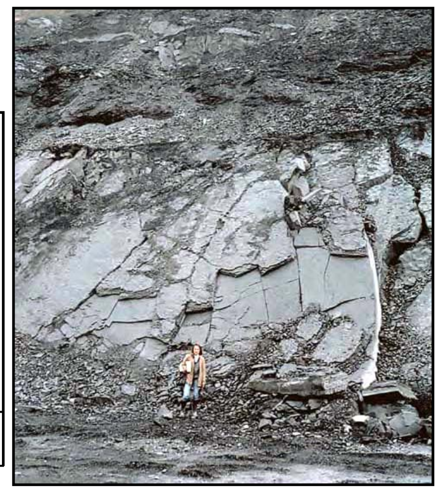
Toppling may also occur in stiff soils.

Exposures favorable for toppling

d- Buckling



Buckling failure



Failure by Buckling is the bending of a layer lying parallel to the slope, that may be fractured at a later step.

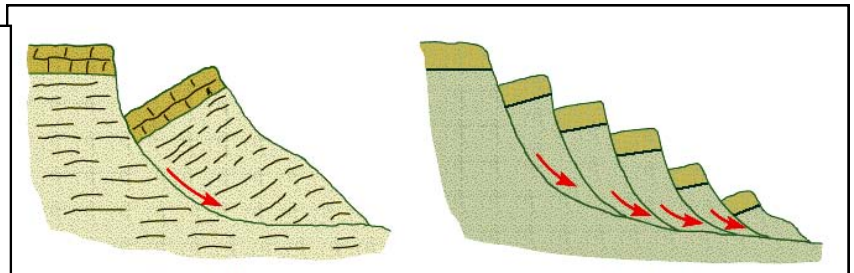
Failure occurs when:

a) Buckling occurs along bedding planes parallel to the slope ($\psi = \alpha$).
b) The dip of bedding is greater than the friction angle ($\alpha > \phi$)..
c) A necessary condition is that the strata are sufficiently thin in relation to slope height to be able to buckle.

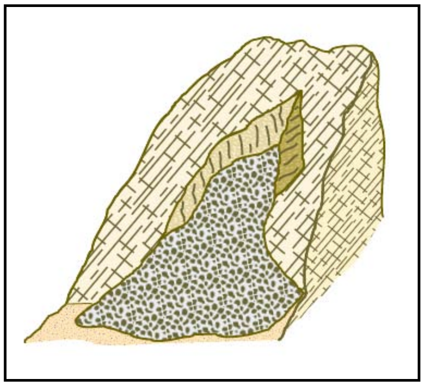
e- Non-planar failure (rotational failure- Slumps)

Non-planar and even circular failure may occur in very weak or heavily jointed rock masses showing isotropic behavior. In such cases, the rock mass behaves like a soil.

Non-planar rotational failure **in rocks** is commonly termed **Slumps.** Slump is a curved gravitation fault formed along steep slopes and could be single or multiple. Slumping may also occur in stiff soils.

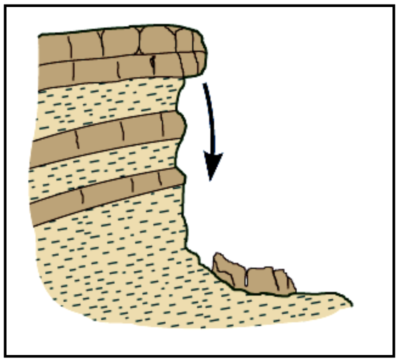


<u>f- Rock avalanches and rock falls:</u>



Avalanches are large-scale rock failure that occur in rocks of <u>low cohesion on steep slopes</u>.
Rocks travel down steep slopes at great speed that may reach over 100 km/h.

Rock falls are <u>very quick free falls</u> of rock blocks which are dislodged from pre-existing discontinuity planes (tectonic, bedding surfaces, tension cracks).



It takes place due to differential weathering of weak strata where hard beds are exposed out of the slope surface and became unstable and susceptible to fall.

The movement may be by a vertical fall, by a series of bounces or by rolling down the slope face. They are common on steep slopes and cliffs.

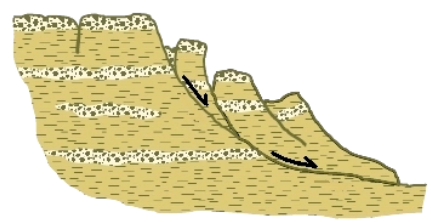
Rock avalanche

Sedimentary succession susceptible for rock fall

Types of Slope movements

Slope movement of soil parallel to the slope plane. There are two main types of slope movements:

1- Landslides



Slump faults in soil

Landslides are movements of masses of soil or weak rock which slide parallel to the slope surface, moving in relation to the substratum. without having well-defined failure surfaces.
The mass is generally displaced as a whole, behaving as a unit; the rate of movement may vary considerably, but these processes tend to move rapidly and involve big rock volumes. The mass may continue to move for hundreds of meters.

Rotational landslides are slump faults but occur in cohesive, “homogeneous” soils.

2- Flows:

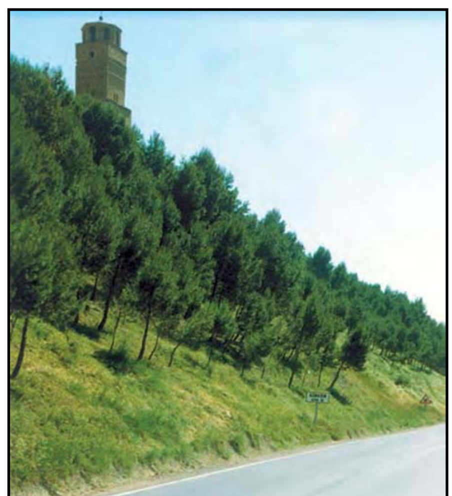
Mud flow

Flows are mass movements of soil (mud flows) or debris (debris flows) with a **high water content**, where the material behaves as a fluid.

The mass undergoes continuous deformation, but without having well-defined failure surfaces.

Water is the main triggering factor because water decreases the strength of materials having low cohesion. This may occur on slopes with low gradients (even less than 10º). The displaced masses may reach several kilometers.

Mud flows: occur in fine and homogeneous materials and can move at a speed of many meters per second. The loss of strength is usually caused by water saturation. Mudflows are generally small scale and slow, but sometimes, especially in saturated conditions, they are extensive and fast, with catastrophic consequences when they reach populated areas



Soil creep

Soil creep: is a gradual very slow movement of soil causing continuous deformation that becomes progressively noticeable on slopes over time. This movement can be detected from inclined fences, and bent trees.

Debris flows: They occur on slopes covered with loose or non-consolidated material especially where there is no vegetation cover. Debris flows originate in areas where slope ranges from 20º to 45º.

Causes of slope movements

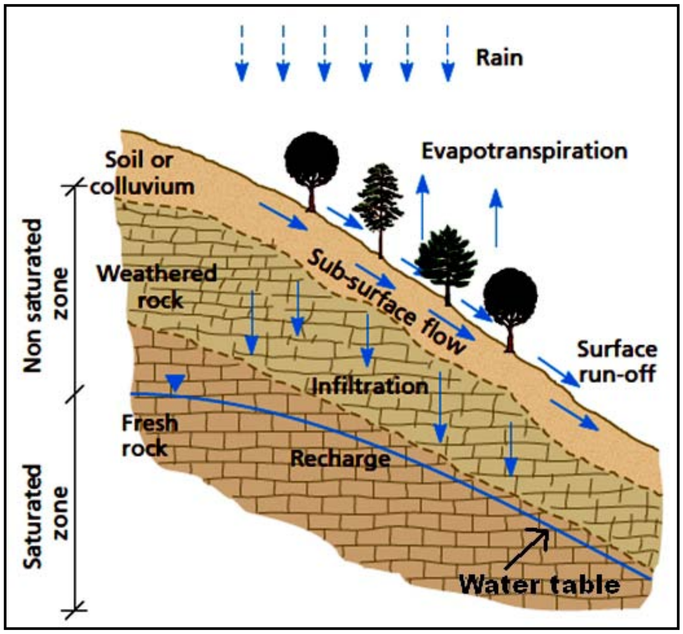
- The factors controlling slope movements are those able to modify the internal and external forces acting on the ground. Slope movements would not occur without the presence of pre-existing instability conditions.
- The factors controlling slope movements are grouped in to two main groups:

1- **Pre-existing (passive) factors:** the physical characteristics and strength of the materials, discontinuities, hydrogeological conditions and morphology of the ground itself.

2- **Triggering (active) factors:** are external factors which trigger instability and are responsible in general for the size and speed of movements (e.g. rain, earthquakes). These factors are explained in the following:

a) Rainfall and climatic conditions:

The triggering of slope movements by rainfall and climatic factors is basically depends on the volume, intensity and distribution of rainfall, and to the climatic regime (wet and dry cycles).



Rainwater infiltrated in to the ground results in the sub-surface flow of water in the soil under slope. That increases the pore pressures, reduces the soil cohesion and triggers surface movements.

Intense precipitation lasting hours or days may trigger **surface movements** such as landslides and mud or debris flows,

Climatic related actions are seasonal **freeze-thaw processes** and **wet and dry cycles**, cause superficial movements in soil slopes and rock falls in hard rock masses,

b) Changes in water level:

The elevation of the water level on slopes, as a result of prolonged periods of rain or the filling of reservoirs or lakes, increases pore pressures in soils and may trigger or accelerate landslides.

c) Erosion at the foot of slopes:

Erosion or undercutting at the foot of slopes, scarps and cliffs, gives rise to modification of the state of stress that may cause instability and generate landslides or rock falls.

Coastal slopes exposed to the action of waves and tides are hazardous zones for instability. Collapse of karstic cavities may trigger instability.

d) Earthquakes:

Earthquakes can trigger all kinds of slope movements, depending on ground conditions, magnitude of earthquakes and distance from its epicenter.

e) Volcanism:

Volcanic eruptions can cause landslides of considerable volume and speed on the slopes of volcanic cones. Ash and pyroclastic deposits lying on cone slopes are able to landslide and flow processes when the materials are saturated by rainfall.

f) Human actions:

Human impact is one of the most important factor which can modify the forces acting on natural slopes and generating instability. Examples are: Excavations, the construction of dams, the load from buildings, embankments, waste heaps on slopes, and nearby blasting activities.

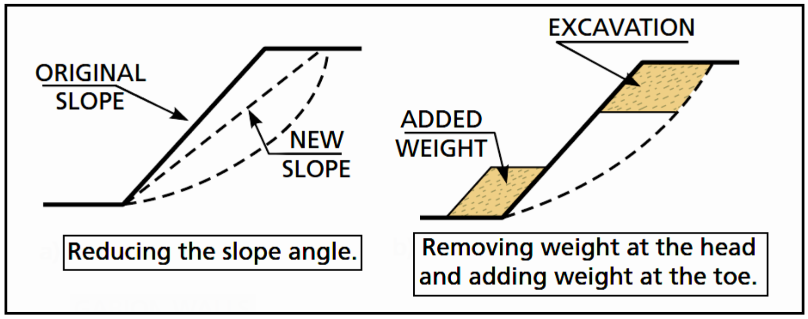
Stabilization methods

Designing and applying of stabilization methods needs an understanding of the following:

1) Ground properties and their geotechnical behavior.
2) Type of failure and mechanism, including the speed and direction of movement and geometry of the failure surface.
3) Geological, hydrogeological and other factors influencing and causing instability. These factors will also define the most appropriate stabilization measures in each case. Data on the position of water tables, water pressure and the permeability of the materials are important.

Stabilizing methods may involve:

1) Modifying the slope geometry.
2) Drainage.
3) Increasing ground strength by inserting resistant structural elements into the slope.
4) Constructing walls or other retaining elements
5) Surface protection methods.



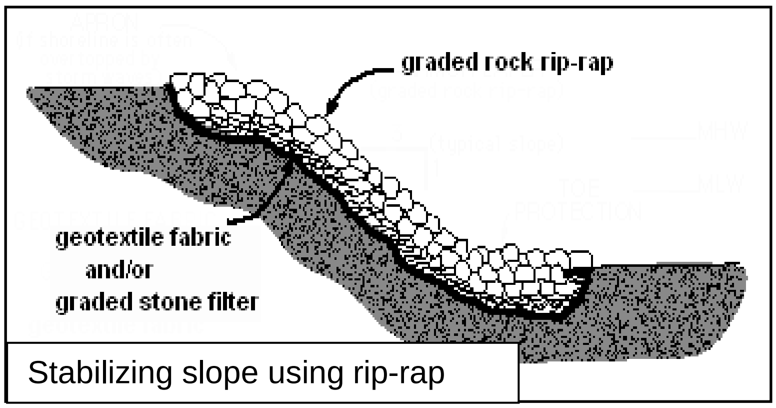
Reducing the slope angle.
Removing weight at the head and adding weight at the toe.

1. <u>Modifying the geometry</u>

Modifying the slope geometry redistributes forces (due to the weight of the materials) to obtain a new, more stable configuration.

This is most often done by:

a) Reducing the slope angle.
It is not always possible to reduce the general angle of the slope or unload at its head, because of difficult access to the upper part of the slope, or the large volume of material to be removed.

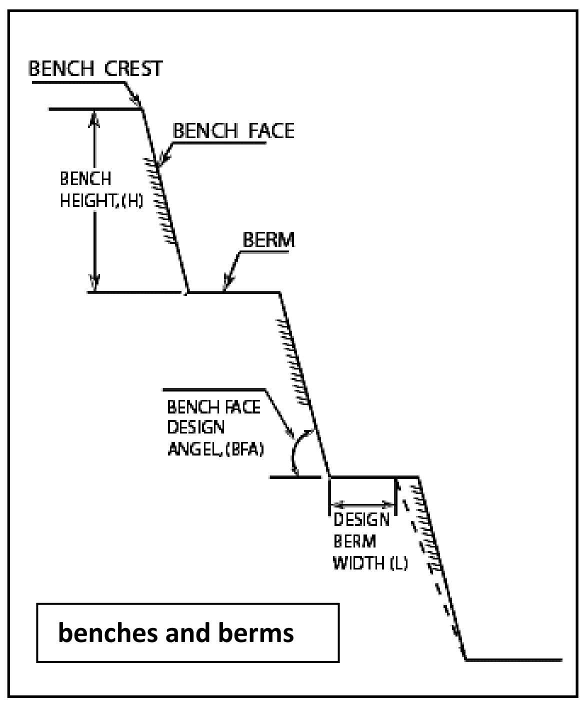


Stabilizing slope using rip-rap

b) Removing weight at the head of the slope.

c) Increasing weight at the slope toe using <u>rip-rap</u>:
Changing slope geometry is mainly done by increasing weight at the slope base. A quick solution to increase weight on sliding slopes is to put rip-rap at the slope toe.

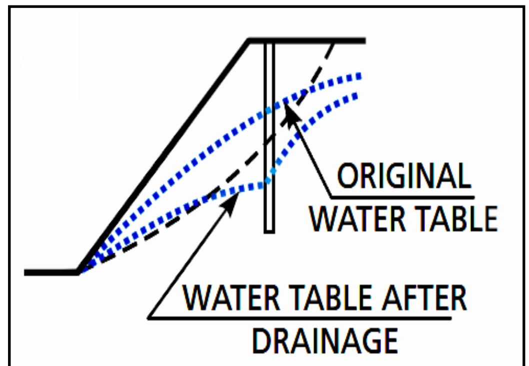
d) Constructing benches and berms (stepping):
Slope stepping involves the construction of benches and berms that help to prevent failures affecting the whole slope.



benches and berms

Stabilization of slope by benches and berms

2. Drainage methods



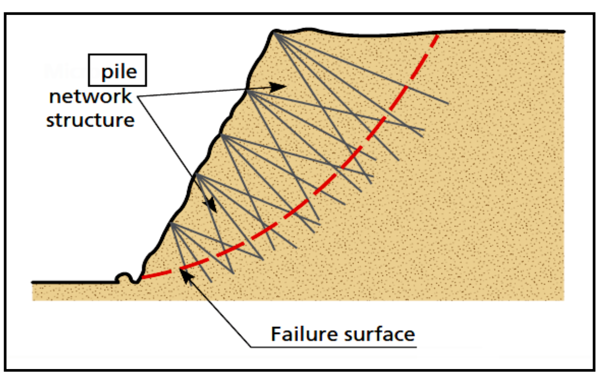
Drainage, lowering of water table.

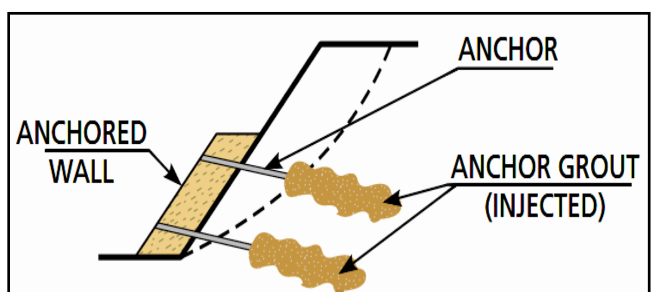
Drainage methods aim to reduce the amount of water present in the slope and the pore pressures in pore spaces, that are destabilizing factors in slope failure.
Evacuating water can be done by constructing horizontal drainage channels or tubes at ground level or at depth within the slope. Also, suction of water through vertical drainage wells drilled below the water table can be used.

3. Resistant structural elements

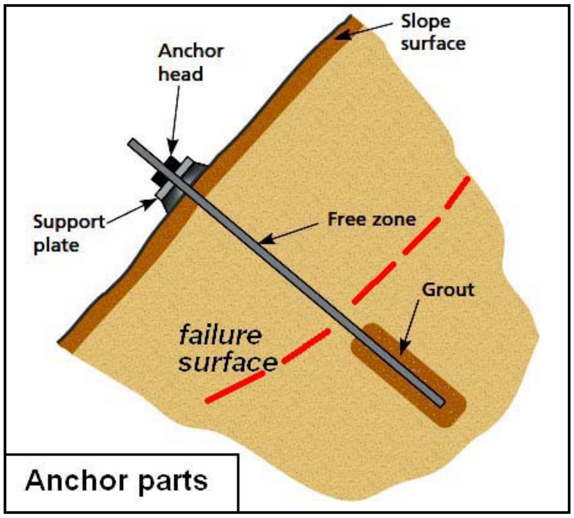
Resistant elements are inserted in the ground to increase shear strength by:

a) Installing elements that improve the shear strength of the failure surface, e.g. concrete **piles**. (steel tube filled with injected concrete).
b) Installing elements that increase shear strength on the failure surface by increasing the frictional forces on it, e.g. **anchors** and bolts (small anchor). Anchors are usually 15–40 m long. They are inserted into holes drilled into the rock or soil, which are then injected with cement or grout (e.g. concrete or Epoxy).

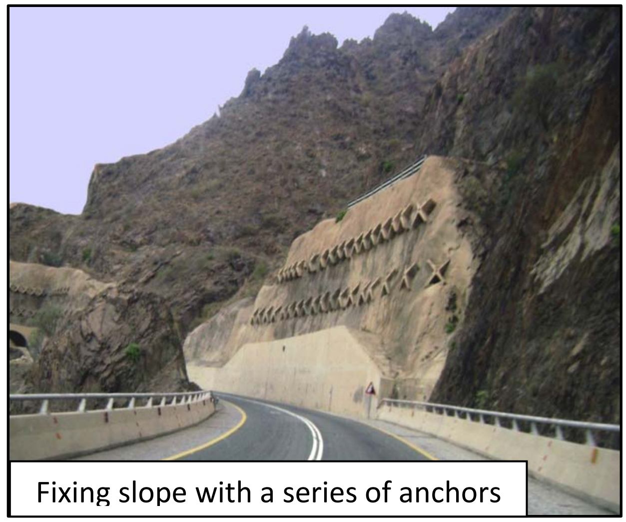


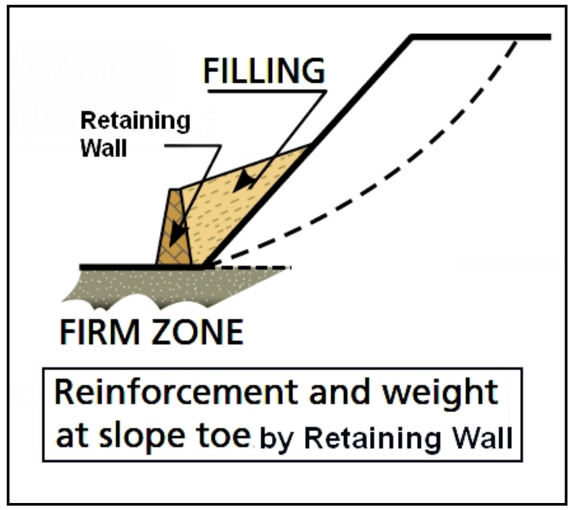


Reinforcement with anchors and wall.



Anchor parts


Fixing slope with a series of anchors

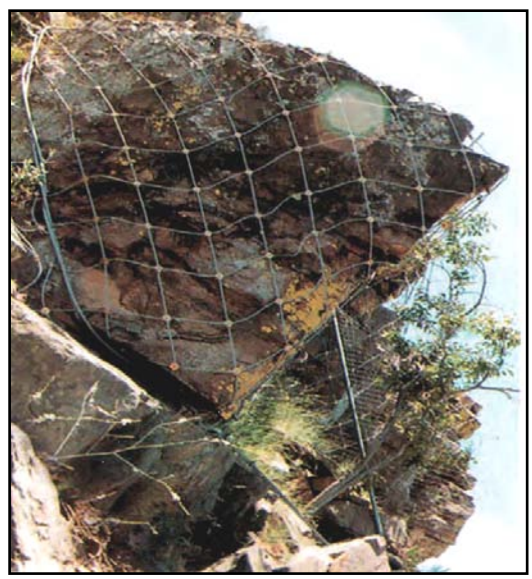


Reinforcement and weight at slope toe by Retaining Wall

4. **<u>retaining (supporting) Walls</u>**

Retaining Walls are built at the toe of a slope to reinforce it and prevent deterioration in this area which is critical for slope stability. The space between the wall and the slope subsequently filled in.
The disadvantage of Retaining Walls is that they do not prevent sliding from surfaces above or below the wall.

5. **<u>Surface protection methods</u>**



a. Installing wire meshes on rock slopes.
b. Shotcreting soil slopes: shooting slopes covered with a steel mesh with concrete.
c. Laying geotextiles: covering the ground with special type of textile to prevent infiltration of rain water into soil slopes.
d. Using plant species to help reinforce the ground surface of slopes excavated in soils.

<u>Arabic translation of some terms as used in geological engineering:</u>

Pile خازوق

driven pile خازوق الدق

grout, grouting حفن التربه

anchor (n) مثبت للتربه

anchor (v) تثبيت التربه

bolt = small anchor

retaining wall حائط تدعيم (تثبيت)

rip rap تتبيش (تغطيه بأحجار دبش)

grout ماده لاحمه لملئ الشقوق

Grouting **عملية الحقن**