9.1 Introduction

In mountainous terrain, safer operation of highways and railways, power generation and transmission facilities, and the safety of residential and commercial developments often require long term stable slopes and control of rock falls. Many transportation systems were constructed over a century ago in the case of railroads, and decades ago in the case of many highways. At that time, the blasting techniques that were often used in construction caused significant damage to the rock mass. Further, deterioration of stability conditions is likely due to weathering of the rock since the time of construction, and loosening of the surficial blocks by ice and water, and also by the growth of tree roots. All these effects can result in on-going instability that may requires a scientific and economical remediation programs.

Open pit mines tolerate a certain degree of slope instability unless there is a hazard to the miners or there is a significant loss of production. For example, minor failures of benches usually have little effect on mining operations unless the fall lands on a haul road and results in tyre or equipment damage.

A number of method have been adopted to stabilize slopes, each of them found to be appropriate for a particular set of conditions.

1. Application of Slope,
2. Purpose of stabilizing,
3. Time available,
4. Accessibility of the site,
5. Types of construction equipment, and
6. The cost of repair.

Various geotechnical, construction and environmental issues must be considered while selecting and designing stabilization measures appropriate for a site. Construction and environmental issues, which can affect the cost and schedule of the work should also be addressed during design phase of the project. Other issues that are frequently important are equipment access, available work time during traffic closures, and disposal of waste rock and soil.

This chapter provides guidelines for selecting the method of slope stabilization that are most appropriate for the topographical, geological and operational conditions at the site. These methods can be mainly classified into three categories:

(a) Removal and Protection,
(b) Drainage of water, and
(c) Reinforcement.
9.2 REMOVAL AND REPAIR

Where rock removal operations are carried out above active highways or railroads, or in urban areas, proper care must be taken to prevent injury or damage from falling of rock. The slope is steep and the toe is close to the highway or railway, there will be no space to excavate a catch ditch or construct a barrier. Therefore, alternative stabilization measures may be to remove loose rock, secure it in place with bolts, or to drape mesh on the slope. It is generally preferable to remove loose rock and eliminate the hazard, provided it form a stable face and not undermine other potentially loose rock on the face.

9.2.1 Excavation & repair

Excavation is a common method for improving the stability of a slope by reducing the magnitude of driving forces that contribute to movements. Unloading is a common technique to reduce the driving forces within a sliding mass. The lightweight (low density) fill materials can also be used to reduce the driving forces. This can also include removing weight from upper part of the slope (head), removing all unstable or potentially unstable materials, flattening and benching of the slopes (Figure 1). In general, rock removal is a preferred method of stabilization because it eliminates the hazard, and no future maintenance is required. However, this method is not effective where the rock is highly degradable, such as shale. In such circumstances, exposure of a new face initiates a new cycle of weathering and leads to instability. A more appropriate stabilization method for this condition is protection of the face with shotcrete and rock bolts, or a tied-back wall.
Figure 1: Stabilization of slope by removal and repairing the potential unstable blocks (TRB, 1996)
9.2.2 Catchment & Wire Netting

Most slopes contain small pieces of rock that could loosen in the future but do not require extensive removal or reinforcement. Catchment can consist of engineered benches, ditches, wide shoulders, berms, steel barriers, nets, fences and concrete walls (Figure 2). The type of catchment to be used depends largely on site conditions, specifically the height and angle of the slope and clearance between slope and the facility.

The catchment area must be accessed periodically to remove the loose debris, which would otherwise defeat its purpose. For flatter slopes where rock falls tend to bounce and roll, a barrier is needed to deflect rocks away from the facility. Key considerations in the design of such barriers are height, location and strength.

![Figure 2: Catchment of a rock fall in hill terrains](image)

Wire netting over the slope face helps to prevent rockfalls from bouncing outward from the toe region. Two types of wire mesh are commonly used for this purpose: welded wire fabric and chain-link mesh.

Pinning the wire mesh to the face holds the rock in place and reduces rock removal at the toe. The pins (typically rock bolts, rock dowels, or reinforcing bars) must be strong and spaced close enough to hold large loose rocks and prevent them from dislodging and tearing the mesh.

Draping the wire mesh involves anchoring the mesh to the crest of the slope and hanging it down over face of the slope. Adjacent sections of the mesh are often either overlapped or tied together with wire. Weights, such as old tyres, concrete blocks, or timbers, may be attached to bottom of the mesh to contain rockfall in the toe region.
9.2.3 Grading & Serrating

Grading involves shaping of the rock slope into a more stable configuration. It may include flattening the slope, leaving benches in the slope face, or sculpting the slope face to a more natural appearance (figure 3).

![Figure 3: Grading of slope](image)

Serrating is cutting of regular, low-height benches into a slope. Generally, the benches are 1-2 m in height and width and extend over the full height of the slope. This technique is normally used on soil or loose, weathered rock slopes that can be excavated by mechanical means. It is frequently used where vegetation is expected to become established.

9.2.4 Benching

Benching is a popular technique used on cut slopes in mining, or where a break in slope is required to retain rockfall in road cuts. It is also useful in breaking up the span of a high rock cut in order to make the slope appearance more natural (Figure 4). Bench heights vary from about 3 to 5 m in highway corridor applications to over 30 m for highwalls in mines.

The purpose of benching a slope is to transform the behavior of one high slope into several lower ones. Benching of slopes is also used to control erosion and establish vegetation. Each bench should have drainage to convey runoff to a suitable discharge outlet. Benches are also used along highway corridors as a means of intercepting rockfall before it reached the roadway.
9.2.5 Resloping and unloading

Where overburden or weathered rock present in the upper portion of a cut, it is often necessary to cut this material at an angle flatter than the more competent rock below. The design procedure for resloping and unloading starts with back analysis of the unstable slope. At places a slide developed, it may be necessary to unload the crest by reducing the driving force of the cut (Figure 5). This operation is usually carried out by excavators and bulldozers.
9.2.6 Lightweight Fill

In embankment constructions, lightweight fill can reduce the driving force of the slope and thereby increase its stability (Figure 6). Materials, such as slag, encapsulated sawdust, expanded shale, cinders, shredded rubber tires, polystyrene foam, and seashells, have been used successfully for this purpose. Selection of a suitable type of material depends on its cost and availability in local areas.

![Figure 6: Application of lightweight fill](image)

9.2.7 Counter berms

A counter berm is used to provide weight thereby increasing the shear strength at the toe region of a slope. This is particularly useful for embankments over soft soil where the ground at the toe can move upward and form a bulge (Figure 7 & 8). By locating a counter berm where the upheaval is expected to occur, the resistance against sliding is also increased. Unless careful investigation and thorough analysis is made, there is a danger that the additional load imposed by the counter berm may increase the driving force rather than providing the added resistance against sliding and lead to failure.

![Figure 7: Counter berm to provide weight at toe of embankment.](image)
9.2.8 Trimming

Failure or weathering of a rock slope may form an overhang on the face, which could be a hazard if it were to fail. In these circumstances, removal of the overhang by trim blasting may be the most appropriate stabilization measure. Methods of controlled blasting are also applicable for this purpose.

9.2.9 Shear Keys

Shear keys are sometimes used to provide additional sliding resistance for a counter term to rock/soil buttress. The main purpose of a shear key is to force the critical slip circle deeper into a stronger underlying formation, thereby increasing the resistance along the slip surface (Figure 9 & 10). This method is very practical and cost effective if the stronger formation is only a few meter below the overlying soft soil. Construction of such shear keys require excavation of a trench at the toe of the slope.

Figure 8: Application of berm to increase slope stability

Figure 9: Working mechanism of shear keys.
Figure 10: making of shear key by replacing loose soil with strong and resists soil

9.2.10 Scaling

Scaling describes the removal of loose non detached rock, soil and vegetation on the face of a slope using hand tools such as scaling bars, shovels and chain saws. Tree roots growing in fractures on the rock face can further widening the fractures causing rock falls. Also, movement of the trees by the wind produces leverage by the roots on loose blocks. The general loosening of the rock on the face by tree roots also permits increased infiltration of water which, in temperate climates, can freeze and expand and cause further opening of the cracks. On steep slopes, workers are usually supported by ropes, anchored at the crest of the slope. A suitable type of rope for these conditions is a steel-core, hemp rope that is highly resistant to cut and abrasion. The scalers work their way down the face to ensure that there is no loose rock above them.
Figure 11: Rock buttress used to control unstable slope (Schuster and Krizek, 1978).
9.3 DRAINAGE AND WATER CONTROL

Drainage of water is an effective method of increasing the stability of a slope. Water in a slope may come from two primary sources: surface water and groundwater. Water control is generally maintained through installation of surface and subsurface drainage devices within and adjacent to potentially unstable slopes. Runoff and infiltration of water along a slope or over a bluff face can often be reduced by planting vegetation on top of the slope or bluff to prevent or minimize erosion.

Surface Drainage Systems: Surface drains and landscape design are used to direct water away from the head and toe of cut slopes and potential landslides and to reduce infiltration and erosion in and along a potentially unstable mass.

Subsurface Drainage Systems: The main functions of subdrains are to remove subsurface water directly from an unstable slope, to redirect adjacent groundwater sources away from the subject property and to reduce hydrostatic pressure beneath and adjacent to engineered structures. Control of subsurface drainage is generally attained by installing a network of horizontal and/or vertical subdrains.

Drainages are the most frequently used means of stabilizing slopes. Slope failures are very often precipitated by a rise in the groundwater level and increased pore pressures. Therefore, lowering groundwater levels and reducing pore pressures is a logical means of improving stability. In addition, improving drainage is often less expensive than other methods of stabilization, and a large volume of ground can frequently be stabilized at relatively low cost. Once a system of drainage has been established, it must be maintained to keep it functional. Various methods of drainage for this purpose are:

(a) Application of external load to the soil mass: its aim is to squeeze out pore water by applying the external loads.

(b) Drainage of pore water by gravity and/or pumping: Well-points are used to drain pore water either by gravity and/or pumping. Vertical sand drains or sand piles are used to expedite drainage of a soil stratum. A proper design of sand-drain installation involves determination of the diameter and the spacing of sand drains, the thickness of the drainage blanket and the amount and duration of surcharge fill loading.

(c) Application of electrical gradient or electro-osmosis: When a direct electric current is passed through a saturated soil, water moves towards the cathode. If this is removed, the soil undergoes consolidation. This phenomenon is called ‘electro–osmosis’. In addition to electro-osmotic consolidation, passage of electric current can cause ion exchange, alteration in arrangement of the particles, and electro-chemical decomposition of the electrodes. The combination of these changes brought about in the soil is called ‘electrical stabilisation’. This procedure has been successfully employed to increase skin friction of piles.
(d) **Application of thermal gradient:** Heating or cooling a soil can cause significant changes in its properties. Even a slight increase in temperature can reduce the electric repulsion between clay particles and can cause slight increase in strength. The main drawback of thermal stabilisation is the cost involved, which makes it seldom cost-competitive with other techniques.

### 9.3.1 Surface Drainage

Surface water allowed to flow down a slope or to pond on benches of a slope can infiltrate into the ground along discontinuities and thereby cause an increase in the driving forces on an unstable area through a buildup in pore pressure. Grading and shaping are major considerations in the control of surface water. Surface water can be controlled through a combination of topographic shaping and runoff control structures (Glover et al. 1978). Topographic shaping is used to control the rate and direction of surface water flow by manipulating the gradient, length, and shape of the slope. Grading benches to divert water away from the slope face and off the bench. Flatten the gradient of the slope to encourage sheet runoff as opposed to channel flow. Surface runoff is usually collected in permanent facilities such as V- or U-shaped concrete lined or semicircular corrugated steel pipe channels and diverted away from the slide mass (figure 12).

In climates experiencing intense rainfall that can rapidly saturate the slope and cause surface erosion, it is beneficial to construct drains both behind the crest and on benches on the face to intercept the water for stability (Government of Hong Kong, 2000). These drains are lined with masonry or concrete to prevent the collected water from infiltrating the slope and are dimensioned to carry the expected peak design flows. The drains are also interconnected so that the water is discharged to the storm drain system or nearby water courses. Where the drains are on steep gradients, it is sometimes necessary to incorporate energy dissipation protrusions in the base of the drain to limit flow velocities. In climates with high rainfall there is usually rapid vegetation growth, and periodic maintenance is required to keep the drains clear.
Figure 12: Network of ditches which converge to carry surface waters away from the instable slope
9.3.2 Subsurface Drainage
The purpose of subsurface drainage is to lower the water table and, therefore, the water pressure to a level below that of the potential failure surfaces. Methods of subsurface drainage include drain holes, pumped wells, and drainage galleries or adits (figure 13). Methods that can be used to accomplish subsurface drainage are

1. Subsurface Drainage Blankets
2. Trenches
3. Horizontal Drains
4. Relief Wells
5. Drain Wells and Stone Columns
6. Wellpoints and Deep Wells
7. Drainage Galleries

Figure 13: Surface and subsurface drainage in the slope.
**Subsurface Drainage Blankets:** Of a thin layer of poor quality saturated soil at a shallow depth is present, it may be practical to remove the poor quality layer and replace it with a well-draining soil fill. The bottom of the excavation should be covered with a layer of filter fabric wrapping a 15 to 60 cm filter stone layer with a perforated pipe embedded in it to capture the flow. In order to avoid blockage of holes by vegetation, the first 1.5 m of the outlet end of the pipe should left unperforated. A drainage ditch should be installed to convey water flow from the outlet of the pipe to a suitable discharge point to minimize surface erosion.

**Trenches:** Deep trenches should be constructed when subsurface water or soil of unknown strength is found at such great depths that stripping of the soil is not practically feasible. Trenches are usually excavated at the steepest stable side slopes for the construction period. Trench so excavated should extend below the water-bearing layer and it should be backfilled with a layer of pervious material encased in filter fabric that has an underdrain pipe running through it. The number of adequate trenches, depends on the hydrogeology and geomorphological condition. If, the slope is in a natural depression of limited aerial extent, one trench normal to the centerline of the site may be sufficient.

**Horizontal Drains**
Horizontal drains, sometime called Hydrauger drains are maintain to insert perforated pipes in a drilled holes of a slope to provide underground drainage. They usually slope upward into the slope to permit groundwater to drain by gravity. The drain pipes are commonly perforated or slotted PVC pipe. The drains are installed by drilling into the slope using a hollow-stem auger, inserting the drain pipe, and withdrawing the auger, leaving the drain in place. The hole is allowed to collapse around the drain pipe. There is no filter between the pipe and the soil. Flows usually decline with time after installation and then fluctuate seasonally through wet and dry periods. Horizontal drains are most effective when placed low in the slope provided that the slope does not contain distinct layers of high permeability above the drains (Figure 14 &15).
Horizontal drains can be used where the depth to subsurface groundwater is so great that the cost of stripping or placing trenches is very expensive. It should be designed specifically to lower the seepage pressures in slopes and prevent failure. The length of horizontal drains largely depends on the geometry of the zone. The length can be determined by drawing a cross section of the slope with its probable critical circle superimposed on a geologic cross section depicting aquifers. The length of the holes should extend beyond the critical failure surface. The length of the holes also depends on the orientation to the critical discontinuities; the optimum design is to intersect the maximum number of significant discontinuities for each unit length (meter, foot, etc.) of hole drilled. If the holes tend to collapse, then perforated drain pipe should be inserted.

Installing horizontal drains is difficult in fine silty sands and soils that contain boulders, rock fragments, open cracks, and cavities. Silty sand tends to collapse and form cavities during drilling, as the initial hole is usually not cased for economic reasons. Such drains should be installed in such a position that it can be cleaned and flushed by pumping water into the drains.

Figure 14: Sub-horizontal drainage to lower groundwater levels for slope stabilization (http://www.sigra.com.au)
Figure 15: Slope Drainage methods (Duncan and Christopher, 2005)
Relief Wells: Relief wells are vertical holes with a diameter of about 40 to 60 cm. A perforated pipe of 10 to 20 cm diameter is placed inside the hole. The annular space between the borehole and the pipe should be filled with filter material. The main function of relief wells is to lower the water pressures in layers that are deep down in the subsoil. A water disposal system using a submersible pump or surface pumping and discharge channels is required to dispose the water from the wells. Disposal of the water may be very costly as effective dewatering system requires frequent maintenance. The spacing between relief wells is very important because it affects the performance and cost of the system. Spacing of 5 to 13 m are common. The depth of relief wells depends on the unstable zone in which stability needs to be improved.

Drain Wells and Stone Columns
Horizontal drains do not provide the most effective means of intercepting seepage where soil strata of varying permeability are oriented horizontally. Vertical drains, which cross the layers, are more effective in such condition. These wells can be drained using deep pumps, but the requirement for continual power and pump maintenance makes this a less desirable alternative.

Wellpoints and Deep Wells
Wellpoints are small-diameter vacuum wells driven or jetted into place. Vacuum is applied to the top of the wellpoints through a header to suck water up the wellpoints. These wells work better in clean sand and poor in fine-grained soils. Maximum effectiveness of these well is limited to 7 to 8 m. Deep wells use submerged pumps to push water to the top of the well and are not limited to a lift of 7 to 8 m. Each well has its own pump and operates independently. The wells are usually 30 to 60 cm in diameter and have filters surrounding a perforated casing. Like wellpoints, they must be operated continuously to remain effective. Dewatering wells are designed primarily to lower the ground-water level to a predetermined depth and to maintain that depth, until all below ground activities have been completed.

Drainage Galleries
Where drainage is needed deep within a hillside, a drainage gallery (tunnel) can be used. Drains can be drilled outward from the tunnel, extending the drainage through the slope. Drainage adits or galleries driven under a pit or into a slope or highwall to intercept the groundwater-can provide an effective method of drainage. Where employed, drain holes should be drilled from the adit upward in a fan pattern to increase drainage effectiveness. For high rock cuts, installation of drain holes at different levels is suggested. Where rock is taken out in several lifts, drain holes should be drilled at the toe of every lift.
9.4 STABILIZATION THROUGH SUPPORT

The main types of reinforcing materials that have been used for stabilization of slope and embankments include steel reinforcement, piles, retaining walls, geo-synthetics, shotcrete, high strength steel tendons. A number of factors are required to be considered for selection of proper reinforcement material for its long-term capacity such as tensile strength, creep characteristics, installation damage, durability, resistance against pullout and reinforcement stiffness and tolerable strain within the slope.

There are number of methods which can be used to stabilized slope, each of them can be appropriate for a particular set of conditions. In choosing most appropriate method among the technically feasible options a number of parameters like the purpose of stabilization, availability of time, accessibility of site and cost of repair are required to be considered.

9.4.1 Steel reinforcement

Steel reinforcement members in the form of rock bolts, cable bolts, resin-grouted thread bars, or rock dowels are used to tie the rock mass together to increase its stability. Whereas rock bolts are commonly used to reinforce the surface or near-surface rock of the excavation, rock anchors are used for supporting deep seated instability modes in which sliding or separation on a discontinuity is possible.

Steel reinforcement members can be either active or passive at the time of installation. An active member is one that starts interacting immediately upon installation while a passive member does not play a role in ground support until the rock mass moves and subsequently loads the fixture. The main advantage of the active system over the passive system is that no movement has to occur before the active system develops its full capacity. Thus, deformation and possible tension cracking of the slope are minimized. Three common types of ground inclusions are ground anchors, soil nails and rock bolts.
9.4.2 Rock anchor

Rock anchors are tendons which are placed in competent rock or soil to control displacements and provide vertical and lateral support for engineered structures and natural slopes. The primary function of rock anchors is to modify the normal and shear forces acting on the sliding planes. These anchors may be fully grouted and untensioned, or anchored at the end and tensioned.

A rock anchor generally consists of a bar or cable of high-strength steel tensioned inside a borehole to about 60 to 70% of its yield strength. Tension in the member is transmitted to the surrounding rock mass by anchorage points at the ends. The length of the rock anchor can be from 3 m to over 100 m. Holes for installation of the anchors are normally drilled that cross the potential failure plane.

Normally, the bottom one-third of the hole is line-loaded with quick-set resin cartridges, and the top two-thirds of the hole is loaded with slow-setting resin cartridges. The threadbar is then inserted into the hole and rotated, usually via the rock drill, to break the plastic containers and mix the resin and the catalyst. After the resin has set, the anchor plate, bevel or flat washers, and the end nut are added. Wedge washer may also be used where the end plate is not perpendicular to the threadbar. The threadbar can be tensioned by tightening the end nut to load the anchor.

Figure 17: Polyester Resin Rock Anchor System (http://www.williamsform.com)
9.4.3 Rock Bolts

Rock bolts are used for reinforcement of rock slope and strengthening closely jointed or highly fissured rocks in cut slopes (Figure 19). These bolts are variable lengths, normally from 1.2m to over 12m, diameters vary from 10mm to 51mm. The use of wire mesh or straps complements the reinforcement achieved with a rock-bolt pattern. In areas of highly jointed or fractured rock, wire mesh can be used to hold the small blocks of rock between the face plates in place.

A general rule for rock-bolt spacing is that the distance between face plates should be approximately equal to three times the average spacing of the planes of weakness in the rock mass and the bolt length should be twice the bolt spacing (Hock and Wood, 1988). Rock bolts generally have heads that expand following installation and are classified according to their method of anchorage: expansion, wedge and grouted.
Figure 19: Rock bolting is using to transfer loads from the unstable zone at the rock face to the stronger interior mass (http://www.moretrench.com)

Figure 20: Application of rock bolt to prevent the rock fall (http://www.dywidag-systems.com)
9.4.5 Rock Dowels

Grouted rock dowels consist of steel reinforcing bars (rebar) that are cemented into boreholes. These bars may or may not be subjected to post-tensioning. Untensioned dowels, therefore, do not provide any additional normal force across the failure plane. However, they provide additional shearing resistance across the potential failure surface plane.

Rock dowels are commonly used to provide support for steeply dipping, slabby rock formations. They are also used to provide anchor keys and tiebacks for shearing resistance at the toe and flanks of retaining walls. Dowels can also be used to anchor draped wire mesh, pin wire mesh to the face of a highwall, hold strapping in place, or anchor restraining nets or cables.

Rock dowels can be anchored in place with pumped grout or by utilizing cartridges of resin similar to the thread bar application. When resin cartridges are used, the rebar is rotated and driven through the cartridges with the drill, thus breaking the package and mixing the resin.
Figure 21: Standard rock bolt and cable bolts

Figure 22: Types of rock bolt and dowels
9.4.6 Soil Nailing

It is a soil reinforcement technique that places closely spaced metal bars or rods into soil to increase the strength of the soil mass by resisting against tensile, shear, and bending stresses imposed by slope movements. Soil nails are either installed in drilled bore holes or secured with grout, or they are driven into the ground. The soil nails are generally attached to concrete facing located at the surface of the structure (figure 23). The function of the facing is to prevent erosion of the surface material surrounding the soil nails, rather than providing structural support.

This is a method of in situ reinforcement utilising passive inclusions that get mobilized in case of slope movement occurs. It can be used to retain excavations and stabilize slopes by creating in situ reinforced soil retaining structures.

![Figure 23: Application of soil nail for reinforcing the slope](image-url)
Figure 24: Application of soil nailing in the field
9.4.7 Piles

Piles are long and relatively slender columns positioned vertically in the ground or at an angle and are used to transfer load to a more stable substratum. These are often used to support or stabilize structures built in geologically unstable areas mainly civil construction. The effectiveness of piles is increased dramatically when they are incorporated into an anchored stabilization system. In addition, piles are used to minimize the effects of scour and undercutting along the foundations of waterfront structures. They are either driven into the ground or are placed in drilled holes. Piles placed in drilled holes directly support the weight of a structure. Driven piles are installed in soft or loosely consolidated material and often do not directly absorb the load of a structure. Rather, the bearing capacity and stability of the soil increases as the soil surrounding the piles densifies due to a decrease in void ratio equivalent to the volume of soil displaced by a driven pile.
Geosynthetics are porous, flexible, man-made fabrics which act to reinforce and increase the stability of structures such as earth fills, and thereby allow steeper cut slopes and less grading in hillside terrain. Geosynthetics of various tensile strengths are used for a variety of stability problems, with a common use being reinforcement of unpaved roads constructed on weak soils. Geosynthetics and Geosynthetics-related materials are generally classified on the basis of their manufacturing process. Geosynthetics can be knitting, woven, non-woven or composite. Related Geosynthetics products in use are webs, mats, nets, grids, plastic sheets or composite structure. Geosynthetics have been used for filtration, drainage, separation, reinforcement, fluid barrier and protection.

**Geosynthetics are classified into the following:**

(a) **Geotextiles:** These are permeable textiles—woven or non-woven synthetic polymers. Woven fabrics consist of two threads (warp and weft) combined systematically by making them cross each other perpendicularly. Threads could be multi-filaments or thick mono filaments, or tape threads. Multi-filament threads are made of polyester and polyamide; polypropylene and polyethylene are used to make tape threads. Non-woven fabrics consist of randomly placed short fibres (60 to 150 mm) or continuous filaments.

(b) **Geogrids:** These are relatively stiff net-like materials with large open spaces between the ribs that make up the structure. They can be used to reinforce aggregate layers in pavements and for construction of geo-cells for improvement of bearing capacity. Geogrids are formed by a regular network of tensile elements with apertures of sufficient size to interlock with surrounding fill material.

(c) **Geomembrances:** A continuous membrane—type liner composed of asphaltic, polymeric materials with sufficiently low permeability so as to control fluid migration. Geomembranes are low permeability geosynthetics used as fluid barriers.

(d) **Geocomposites:** These are various combinations of geotextiles, geogrids, geomembrances and/or other materials to serve all the primary functions with better performance.

Most geosynthetics are made from synthetic polymers such as polypropylene, polyester, polyethylene, polyamide, PVC, etc. These materials are highly resistant to biological and chemical degradation. Natural fibers such as cotton, jute, bamboo, etc., can be used as geotextiles and geogrids, especially for temporary applications. In contrast to the smooth surfaces that steel reinforcements usually have, most geosynthetics have fabric-like surfaces (geotextiles) or grid structures (geogrids) that produce much better bonding between soil and the reinforcement.
Figure 25: installing of Geogrids and growing vegetations
Figure 26: Application of Geosynthetic
9.6 RETAINING WALLS

It is an engineered structure constructed to resist lateral forces imposed by soil movement and water pressure. Retaining walls are commonly used in combination with fill slopes to reduce the extent of a slope to allow a road to be widened and to create additional space around buildings. The three types of retaining walls are gravity, cantilever and anchored. The common terminologies used in retaining wall are shown in Figure 25.

The most important consideration in proper design and installation of retaining walls is to recognize and counteract the fact that the retained material is attempting to move forward and downslope due to gravity. This creates lateral earth pressure behind the wall which depends on the angle of internal friction and the cohesive strength of the retained material, as well as the direction and magnitude of movement the retaining structure undergoes.

Lateral earth pressures are zero at the top of the wall and in homogenous ground increase proportionally to a maximum value at the lowest depth. Earth pressure can push the wall forward or overturn it if not properly considered. Also, any groundwater behind the wall that is not dissipated by a drainage system causes hydrostatic pressure on the wall. Unless the wall is designed to retain water, it is important to have proper drainage behind the wall in order to limit the pressure to the wall's design value. Drainage materials will reduce or eliminate the hydrostatic pressure and improve the stability of the material behind the wall.
Figure 25: Typical View of Retaining Wall
9.6.1  Gravity Walls

A gravity wall is typically made of mortarless stone, masonry units or concrete and relies on its weight for stability (Figure 26 & 27). Gravity is able to hold back the earth or soil, due to its construction. For this purpose, the mass of the structure must be sufficient to develop enough frictional resistance to sliding, and the base or footing of the structure must be wide enough to develop sufficient moment to resist overturning earth forces.

The thickness of the wall at the base exceeds that at the top. Construction of gravity walls demands a high quantity of building materials. That is the reason why these walls are difficult to build and get more cumbersome as they get higher.

Today, taller retaining walls are increasingly built as composite gravity walls such as: geosynthetic or with precast facing; gabions (stacked steel wire baskets filled with rocks); crib walls (cells built up log cabin style from precast concrete or timber and filled with soil); or soil-nailed walls (soil reinforced in place with steel and concrete rods).

![Gravity Retaining Walls](image)

Figure 26: Gravity walls Made of Different Materials
Figure 27: Show force act on gravity wall.
9.6.2  Cantilever Retaining Walls

Cantilever walls are the taller retaining walls having uniform thickness and are tied to a footing. Properly engineered cantilever walls hold back sufficient amount of soil. These walls cantilever loads to a large, structural footing, converting horizontal pressures from behind the wall to vertical pressures on the ground below (Figure 28). Typical basements in a house are an example of these types of retaining walls. Cantilever walls are manufactured in the form of an inverted 'T'. It means that the walls transform horizontal pressures from behind the wall into vertical pressures on the ground below. The footer of cantilever walls should be wide enough to prevent the wall from tipping. The thickness of not only the footer but also that of the wall is important. The wall is built with steel-reinforcement in both the footing and wall structures.

![Cantilever wall](image)

Figure 28: Mechanics of cantilever wall in the soil
9.6.3 Sheet Piling Retaining Walls

Sheet piling retaining walls are utilized for areas having soft soils and tight spaces. Materials such as steel, vinyl or wood planks go into the making of these types of retaining walls. The statistics of the walls include one-third portion above the ground and the rest (two-third) below ground level (Figure 29). A cable or a rod is used as a tie-back anchor to the walls. The rods are placed at a distance and tied to the back of the walls. Proper drainage has to be ensured during construction of such walls to encounter hydrostatic pressure which may cause instability within the walls.

![Diagram of Sheet Piling Retaining Wall]

Figure 29: Sheet piling in the soil
9.6.4 Anchored retaining wall

In this case, a horizontal rod or a helical anchor called tieback is used to reinforce retaining walls for stability (Figure 30). One end of the tieback is secured to the wall while the other end is anchored to a stable structure, such as a concrete deadman which has been driven into the ground or anchored into earth with sufficient resistance. Grouted tiebacks can be constructed as steel rods drilled through a concrete wall out into the soil or bedrock on the other side (Figure 31). Grout is then pumped under pressure into the tieback anchor holes so that the rods can utilize soil resistance to prevent tieback pullout and wall destabilization.

Figure 30: Anchored wall in the soil
Figure 31: Application of tieback on the piles through competent layer of rock
Gabions are cages, cylinders, or boxes filled with soil or sand that are used in civil engineering and road wall particularly in hilly region. For dams or foundation construction, cylindrical metal structures are used. Gabions are multi-celled, welded wire or rectangular wire mesh boxes, which are then rockfilled, and used for construction of erosion control structures and to stabilize steep slopes (Figure 32). Their applications include

- Retaining walls,
- Bridge abutments,
- Wing walls,
- Culvert headwalls,
- Outlet aprons,
- Shore and beach protection walls, and
- Temporary check dams.

Figure 32: Application of Gabions wall near road cut hilly.
9.7 OTHER METHODS FOR STABILIZATION

9.7.1 Grouting

Grouting is a cement, silicate, or acrylamide based slurry, viscose enough to be poured or injected into soil and thereby fill, seal, or compact the surrounding soil. Grouting is done through pressure injection of this slurry in holes drilled into fissured, jointed, permeable rocks and compressible soils to reduce their permeability and increase their strength. The type and amount of grout that is needed in a stabilization of slope is generally based upon grain size distribution, density, water content, and chemistry of the soil, as well as desired function of the grout. Grouting is often viewed as a versatile method of ground improvement for application in difficult soil and rock conditions.

9.7.2 Shotcrete

Shotcrete is pneumatically applied fined grained mortar i.e. usually placed in a 20 to 100 mm layer and is often reinforcement to improve tensile and shear strength. Zones and beds of closely fractured or degradable rock may be protected by applying a layer of shotcrete to the rock face. The shotcrete will control both the fall of small blocks of rock, and progressive raveling that could eventually produce unstable overhangs. Primary function of shotcrete is to provide surface protection. The two common methods of reinforcing are welded-wire mesh, or steel or polypropylene fibres (Figure 33).

Shotcrete is applied either by wet or dry applications. For dry mix shotcrete, additives and mortar are mixed on-site and pumped via compressed air to the nozzle, where the water is added. The wet mix is premixed at a central plant to specifications and then transported to the site in bulk.

An alternative to mesh reinforcement is to use steel or polypropylene fibers that are a component of the shotcrete mix and form a reinforcement mat throughout the shotcrete layer. The steel fibers are manufactured from high strength carbon steel with a length of 30–38mm and diameter of 0.5 mm. The principal function of fibers is to significantly increase the shear, tensile and post crack strengths of the shotcrete compared to non-reinforced shotcrete.

Steel fibers, when added to the mix, increase the tensile strength of the shotcrete by providing numerous bonding surfaces within a small area. The fiber reinforcement also reduces the risk that shrinkage cracks will develop during curing. In many cases, the addition of fibers can replace wire mesh as reinforcement, thus reducing the overall cost.

The addition of drain holes through the shotcrete is essential to eliminate water pressure behind the shotcrete. Small length of steel PVC pipe, inserted prior to shotcrete application into joints in the rock face where seeps have been noted or where seeps may occur, will provide partial drainage. Other drain holes should be created at
regular intervals along the slope face. It is widely used technique for not only stabilization of slope but also used in underground excavations.

Figure 33: Application of shortcut in the loose rock(a) with wire mesh (6).
9.7.3 Vegetation

Bio-technical stabilization and soil bioengineering stabilization both entail the use of live materials – specifically vegetation. Biotechnical stabilization utilizes mechanical elements (or structures) in combination with biological elements (or plant) to arrest and prevent slope failure and erosions. Biotechnical stabilization can be characterized by the conjunctive use of live vegetation with retaining structures. Plant material increases soil strength through the transfer of root tensile strength to soil shear strength, buttressing and arching. Bio-engineering systems provide additional support beyond that which can be provided by single plants. As the plants mature they increase in strength and provide increased resistance to natural forces. Vegetation on slopes provides protection against erosion and shallow sliding. Roots reinforce or bind the soil and provide cohesion that improves stability against shallow sliding. Plant roots reduces pore pressures within slopes by intercepting rainfall (reducing infiltration) and by evapotranspiration (Wu et al., 1994). The small size of flexible roots mobilise their tensile strength by soil–root friction and increasing shear strength of the soil root-matrix whereas, the large size roots intersect the failure plane and act as individual anchors in the soil. Roots can also prevent the generation or propagation of tensile facture or cracks. The Mechanisms of root reinforcement of grass plants and tree is shown in figure 34.

Figure 34. Mechanisms of root reinforcement of grass plants and tree
Figure 35 shows the example of combination of active and passive protection techniques to stabilize the slope.

Figure 35: Application of various slope stabilising measures