



MAHARASHTRA STATE BOARD OF TECHNICAL EDUCATION MUMBAI

“Frame and Non-Frame Methods of Protection of Soil Slope”

UNDER THE GUIDANCE OF

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ABSTRACT

Soil slopes along highways, railways, hill settlements, canals, dams and embankments are constantly exposed to rain, seepage, erosion, earthquakes and human interference. When the driving forces acting on a slope exceed the shearing resistance of the soil, the slope fails, and the result can be loss of life, damage to property and long interruptions of transport links. Slope protection is therefore a central subject in geotechnical and transportation engineering.

This report studies the two broad families of slope protection measures. **Frame (structural) methods** use engineered structural elements such as retaining walls, crib walls, gabions, reinforced earth walls, soil nails, ground anchors, piles and RCC grid beams to physically hold or reinforce the soil mass. **Non-frame (non-structural) methods** use vegetation, bio-engineering, geosynthetics, drainage, regrading, benching and surface covers to reduce erosion, lower pore water pressure and improve the soil's own strength without a rigid supporting frame. The report explains the mechanics of slope failure, the principles of stability analysis, the working, design aspects, construction and limitations of each method, a comparison between the two families, criteria for selecting a method, and recent trends.

Keywords: slope stability, landslide, retaining wall, soil nailing, ground anchor, geosynthetics, bio-engineering, erosion control, factor of safety.

1. Introduction

1.1 Background

A slope is an inclined ground surface. It may be natural, such as a hillside, river bank or valley wall, or man-made, such as a road cutting, railway embankment, earth dam, canal bank or excavation for a building basement. Every slope is in a delicate balance. Gravity pulls the soil downward, while the shear strength of the soil, which comes from cohesion and internal friction, resists movement. As long as resistance exceeds the driving force, the slope stands. The moment the balance is upset, a slide begins.

India is among the countries most affected by landslides. The Himalayas, the North-Eastern hills, the Western Ghats and the Nilgiris regularly experience slope failures during the monsoon. Roads in hill states are cut through steep terrain, which makes cut slopes and fill slopes a continual maintenance burden. Rapid urbanisation on hill sites, deforestation and unplanned excavation have increased the problem. For these reasons slope protection is not an optional extra but a basic requirement of safe infrastructure.

1.2 Need for Slope Protection

Slope protection is needed for the following reasons:

- To safeguard human life and property located above or below a slope.

- To keep highways, railways and pipelines open throughout the year, especially during heavy rain.
- To prevent surface erosion, which removes fertile topsoil and silts up drains, streams and reservoirs.
- To increase the factor of safety of an existing slope that has become marginal due to changes in loading, water or geometry.
- To permit steeper and therefore more economical cuttings where land is scarce or expensive.
- To protect the environment by restoring vegetation and reducing sediment release.

1.3 Objectives of the Seminar

1. To understand the causes and mechanisms of soil slope failure.
2. To study the principles of slope stability analysis.
3. To classify and describe frame methods of slope protection.
4. To classify and describe non-frame methods of slope protection.
5. To compare the two approaches and understand how a method is selected for a given site.
6. To review field practice, relevant Indian guidelines and emerging trends.

1.4 Scope and Limitations

The report is a literature-based study meant for undergraduate level. It covers soil slopes. Rock slope stabilisation, which depends on joints and discontinuities, is touched upon only where relevant. Numerical values quoted are typical and indicative. A real design must always be based on site investigation, laboratory testing and the governing codes and specifications.

2. Fundamentals of Slope Stability

2.1 Shear Strength of Soil

The stability of a slope depends on the shear strength of the soil along a potential failure surface. The Mohr-Coulomb criterion expresses shear strength in terms of effective stress:

$$\tau = c' + (\sigma - u) \tan \phi'$$

where τ is the shear strength, c' is the effective cohesion, σ is the total normal stress on the surface, u is the pore water pressure and ϕ' is the effective angle of internal friction. The equation shows why water is so damaging. A rise in pore water pressure u reduces the effective normal stress, and shear strength falls even though the soil itself has not changed. This is the reason most slope failures occur during or just after heavy rain.

Two kinds of analysis are commonly used. A **total stress analysis** with undrained strength is appropriate for short-term conditions in saturated clays, for instance just after construction of a cutting. An **effective stress analysis** with drained parameters is appropriate for the long-term condition, which is usually the critical case for permanent cut slopes.

2.2 Driving and Resisting Forces

The forces that tend to cause sliding, called driving forces, include the weight of the soil mass, surcharge loads from buildings, traffic or stockpiles, water pressure in tension cracks, seepage forces and earthquake inertia forces. The forces that oppose sliding, called resisting forces, come mainly from the soil's shear strength along the failure surface, and may be supplemented by structural elements such as walls, anchors and piles, or by roots and geosynthetic reinforcement.

2.3 Factor of Safety

The factor of safety (FoS) is the ratio of available resisting force or strength to the force or strength required for equilibrium:

FoS = Shear strength available / Shear stress mobilised along the failure surface

A slope with FoS equal to 1.0 is on the verge of failure. Design values depend on the importance of the structure, the reliability of soil data and the consequences of failure. Typical minimum values adopted in practice are about 1.3 to 1.5 for permanent slopes under normal conditions, a lower value such as 1.1 to 1.2 for temporary slopes or for the seismic case, and higher values for slopes whose failure would be catastrophic. The relevant code or project specification should always be followed.

2.4 Causes of Slope Failure

Causes of slope failure are usually grouped into those that increase shear stress and those that reduce shear strength.

Factors that increase shear stress

- Removal of lateral support through excavation, undercutting by a river or sea, or previous slides.
- Addition of load at the crest through buildings, embankments, vehicles or dumped material.
- Increase in unit weight of soil due to saturation after rain.
- Transient forces such as earthquakes, blasting, machinery vibration and heavy traffic.
- Water pressure in cracks at the upper part of the slope.
- Steepening of the slope by cutting or by erosion at the toe.

Factors that decrease shear strength

- Rise in pore water pressure due to rainfall, rising groundwater, reservoir drawdown or leaking pipes.
- Weathering of soil and rock, which breaks down cementation and lowers cohesion.
- Loss of vegetation and roots, which removes natural reinforcement and exposes soil to erosion.
- Swelling and softening of clays on wetting.
- Presence of weak layers, old slip surfaces, or unfavourable bedding.
- Progressive failure, in which strength at one part of the slope drops to its residual value and the failure spreads.
- Liquefaction of loose saturated sandy soils under earthquake shaking.

2.5 Role of Water

Water is the most common triggering agent. Rainfall infiltrates the soil, raises the water table, increases pore pressure and adds weight. Surface runoff erodes gullies and undercuts the toe. Seepage emerging at the face can carry soil particles out in a process called piping. Rapid drawdown of a reservoir or river leaves the soil mass saturated while the supporting water has disappeared, producing a severe condition for embankments and banks. Controlling water through drainage is therefore a part of almost every slope protection scheme, whether frame or non-frame.

3. Types of Slope Failure

Understanding the type of failure is essential because the best protection method depends on how the slope fails.

3.1 Falls

In a fall, soil or rock detaches from a steep face and descends mostly through free fall, bouncing and rolling. Falls are typical of very steep faces and occur suddenly. Protection includes catch ditches, rockfall nets, barriers and shotcrete or mesh facing.

3.2 Topples

A topple is a forward rotation of a mass about a point below its centre of gravity, common in columnar or jointed material and in vertical cuts in cohesive soil where tension cracks develop.

3.3 Slides

Slides are the most important category for soil slopes. The mass moves along a surface of rupture.

- **Rotational slides (slumps).** The failure surface is curved and concave upward, typical of homogeneous clays and silts. Types of circular failure are the slope failure, toe failure and base failure, depending on where the arc emerges.
- **Translational slides.** The mass moves along a roughly planar surface, often a weak layer, bedrock contact or an old shear plane, particularly in shallow slides in residual soils and colluvium.
- **Compound slides.** The surface is partly curved and partly planar.

3.4 Flows

Flows occur when soil behaves like a viscous fluid. Debris flows and mudflows are fast, highly destructive and triggered by intense rainfall on loose, saturated material. Earthflows and creep are slower. Soil creep is the very slow downslope movement of surface soil, visible as tilted poles and curved tree trunks.

3.5 Spreads

Lateral spreads are movements of fractured ground over a softer or liquefied layer, usually triggered by earthquakes on gently sloping or flat ground.

3.6 Surface Erosion

Although not a slide, surface erosion by raindrop impact, sheet flow and rill and gully formation is a major cause of slope degradation. Eroded rills concentrate flow, deepen and eventually trigger shallow failures. Many non-frame methods are aimed mainly at this process.

3.7 Warning Signs

Field signs of an impending failure include tension cracks at the crest, bulging at the toe, new seepage or wet patches on the face, leaning trees and poles, jammed doors or cracked walls in nearby buildings, and unusual sounds. Monitoring with simple crack gauges, inclinometers, piezometers and survey points helps detect movement early.

4. Slope Stability Analysis

4.1 Purpose

Stability analysis is carried out to find the factor of safety of an existing or proposed slope, to locate the critical failure surface, and to compare alternative protection measures. It is also used to back-calculate soil strength from a slope that has failed, which often yields more reliable parameters than laboratory tests.

4.2 Infinite Slope Method

For shallow translational failures parallel to the ground surface in granular or residual soils, where the depth of failure is small compared to the length of the slope, the infinite slope model applies. For a dry cohesionless soil the factor of safety is:

$$\text{FoS} = \tan \phi / \tan \beta$$

where β is the slope angle. The result shows that a dry sand slope is stable as long as its angle does not exceed the angle of internal friction. When seepage parallel to the slope occurs in a fully saturated cohesionless soil, the factor of safety falls to roughly half of the dry value, which explains why shallow slides are so common after rain.

4.3 Method of Slices

For circular or non-circular surfaces in layered or non-homogeneous soil, the soil mass above the trial surface is divided into vertical slices. Equilibrium of each slice is considered and the results are combined. The common methods are:

- **Fellenius (Ordinary) method.** Ignores forces between slices. Simple and conservative, suitable for hand calculation but can underestimate FoS, especially with high pore pressure.
- **Bishop's simplified method.** Includes normal forces between slices but neglects shear between them. Widely used for circular surfaces and gives realistic results.
- **Janbu's method.** Handles non-circular surfaces, with a correction factor for interslice shear.
- **Morgenstern-Price and Spencer methods.** Rigorous methods satisfying both force and moment equilibrium, suitable for general surfaces.

The analysis is repeated for many trial surfaces to find the one with the lowest factor of safety, called the critical surface. Today this search is done with software, but a student should be able to check a result with a simple hand calculation.

4.4 Taylor's Stability Number

For homogeneous cohesive soils, Taylor's charts relate the slope angle and depth factor to a dimensionless stability number $N = c / (\gamma H F_c)$, where c is cohesion, γ is unit weight, H is slope height and F_c is the factor of safety with respect to cohesion. The charts allow a quick estimate of the safe height or angle of a cutting in clay.

4.5 Earthquake and Pore Pressure Effects

Earthquake loading is commonly handled by the pseudo-static method, where a horizontal seismic coefficient multiplies the weight of the sliding mass to create an additional driving force. More advanced studies use Newmark sliding block analysis to estimate permanent displacement. Pore pressure is included through the pore pressure ratio ru or by defining the piezometric surface in the analysis.

4.6 Modern Tools

Limit equilibrium software such as SLOPE/W, GeoStudio, Slide and similar programs, and finite element programs such as PLAXIS, allow analysis of complex geometry, staged construction, seepage coupling and the effect of reinforcement such as nails, anchors and geosynthetics. The strength reduction technique in finite element analysis gradually lowers soil strength until failure and reports the corresponding factor of safety without assuming a failure surface in advance.

5. Overview and Classification of Slope Protection Methods

5.1 General Principle

Any method of increasing the factor of safety works through one or more of the following actions:

1. Reducing the driving force by flattening the slope, removing weight at the top or reducing water pressure.
2. Increasing the resisting force by adding weight at the toe, installing reinforcement or structural supports, or improving the soil.
3. Protecting the surface from erosion and weathering so that shallow failures do not start.
4. Controlling water on and within the slope.

5.2 Classification

Slope protection methods are broadly classified as follows.

A. Frame (structural) methods

- Retaining structures: gravity walls, cantilever and counterfort walls, crib walls, gabion walls, reinforced earth (MSE) walls
- Soil nailing
- Ground anchors and tie-backs
- Piles, pile walls, micropiles and drilled shafts
- RCC frames, grid beams and lattice frames with anchors or nails
- Shotcrete and wire mesh facing

B. Non-frame (non-structural) methods

- Slope geometry modification: regrading, benching, flattening, counterweight berms
- Vegetative cover and bio-engineering
- Geosynthetics: geotextiles, geogrids, geocells, geomats, erosion control blankets
- Surface and subsurface drainage
- Surface armouring: riprap, stone pitching, turfing, jute netting

- Soil improvement: chemical stabilisation, grouting, compaction

The words frame and non-frame are used in this seminar for a practical distinction. Frame methods rely on a stiff structural element, or a structural framework, to carry load and resist movement. Non-frame methods work with the slope's own material and surface, improving it, covering it or draining it. In real projects the two are often combined, for example a soil-nailed slope with a vegetated face and a drainage system behind it.

6. Frame (Structural) Methods of Slope Protection

6.1 Concept

Frame methods introduce a structural element or a structural framework into or against the slope. The element supplies a resisting force that the soil alone cannot provide. It may act from outside like a wall that holds the soil back, or from within like a nail or anchor that ties the unstable zone to stable ground. These methods give a quick and predictable increase in the factor of safety and are preferred where the slope is steep, space is limited, movement must be stopped quickly, or valuable structures lie above or below the slope.

6.2 Retaining Walls

A retaining wall is a structure that supports soil at a level difference that the soil could not maintain by itself. It resists the lateral earth pressure through its own weight, its structural strength, or a combination of both. The wall must be safe against sliding, overturning, bearing failure of the foundation and overall (deep-seated) slope failure, and its stem and base must be structurally adequate.

6.2.1 Earth Pressure

The lateral pressure on a wall depends on how much the wall moves. If the wall moves away from the soil enough to mobilise full shear strength, the pressure falls to the **active** value. If the wall is prevented from moving, the pressure is higher, called the **at-rest** value. If the wall is pushed into the soil, the **passive** resistance is mobilised. Rankine's and Coulomb's theories are used to compute active and passive coefficients. For a vertical wall with horizontal cohesionless backfill the active coefficient is:

$$K_a = (1 - \sin \phi) / (1 + \sin \phi) = \tan^2(45^\circ - \phi/2)$$

The resultant active thrust on a wall of height H is $P_a = \frac{1}{2} K_a \gamma H^2$ per metre length, acting at $H/3$ above the base. Surcharge, water pressure behind the wall and seismic increments add to this thrust. Water pressure is particularly dangerous, which is why drainage behind every retaining wall is essential.

6.2.2 Stability Checks

For a gravity or cantilever wall the usual external stability checks are:

- **Overturning:** the restoring moment about the toe divided by the overturning moment, commonly required to be not less than about 2.0 for normal conditions.
- **Sliding:** the resisting force along the base, from friction and adhesion, divided by the horizontal thrust, commonly required to be not less than about 1.5.
- **Bearing capacity:** the maximum base pressure must stay below the allowable bearing pressure of the foundation soil, and the resultant should fall within the middle third of the base to avoid tension.
- **Overall stability:** a slip circle passing beneath or behind the wall must have an adequate factor of safety.

These values are indicative; the current code and project specification govern.

6.2.3 Types of Retaining Walls

Gravity walls. Built of stone masonry, plain concrete or brick, these walls depend mainly on self-weight. They are economical for low heights, up to about 3 to 4 metres, and are widely used along hill roads in the form of dry or cement stone masonry walls. Because they are thick, they need adequate foundation width, and they are not suited to very soft foundations.

Cantilever walls. Made of reinforced concrete, with a stem and a base slab that carries the weight of the backfill to help resist overturning. They are thinner and use less material than gravity walls for greater heights, typically up to about 6 to 8 metres, and need skilled formwork and reinforcement detailing.

Counterfort walls. For greater heights, vertical ribs called counterforts tie the stem to the base slab behind the wall, so the stem spans horizontally between ribs instead of acting as a cantilever. This reduces bending moments and concrete quantity at large heights but makes formwork more complex.

Buttress walls. Similar to counterforts, but the ribs are placed on the front, exposed side of the wall.

Crib walls. A crib wall is a box-like framework of interlocking precast concrete, timber or steel members, filled with free-draining granular soil or stone. The filled cells act together as a gravity mass. Crib walls are flexible, free-draining, quick to erect and tolerate some settlement, so they are popular on hill roads. They are used for heights generally up to about 6 to 8 metres or more with careful design, and the infill must be well compacted and kept free-draining.

Gabion walls. Gabions are rectangular baskets of galvanised or PVC-coated steel wire mesh, filled with hard, durable stone. They are stacked and tied together to form a gravity wall. They are flexible, permeable and easy to build with local material and unskilled labour, and the vegetation that grows through the voids blends the structure with the environment. Gabion walls are commonly used for river training, toe protection and low to moderate height hill walls. Wire corrosion, stone size and proper packing are important to long-term performance.

Reinforced earth (MSE) walls. In a Mechanically Stabilised Earth wall, layers of reinforcement, such as metal strips, steel grids, geogrids or geotextiles, are laid within compacted granular backfill and connected to a facing of precast panels, modular blocks or wrapped geosynthetic. Friction between soil and reinforcement turns the backfill into a coherent gravity mass. MSE walls are flexible, economical for heights from a few metres to over 20 metres, quick to build and perform well in earthquakes. They need good quality granular backfill, adequate reinforcement length, commonly about 0.7 times the wall height, and effective drainage.

Soil-nailed and anchored walls. These combine retaining facing with in-situ reinforcement, described in later sections.

6.2.4 Drainage of Retaining Walls

Drainage is non-negotiable. Standard details include a free-draining granular backfill or filter layer behind the wall, a perforated pipe or drain at the base leading to a safe outlet, weep holes through the stem at regular spacing, usually of about 75 to 100 mm diameter and spaced at 2 to 3 metres, and a surface drain at the crest to divert runoff. A properly drained wall may be designed for much lower thrust than an undrained one.

6.2.5 Advantages and Limitations

Advantages: immediate and reliable support, well-understood design, suitable where space is limited, and effective for roadside widening and toe support. Limitations: costly compared with surface methods at large heights, needs a competent foundation, may not stop a deep-seated slide if founded within the moving mass, and a wall that is not drained can fail by water pressure.

6.3 Soil Nailing

6.3.1 Principle

Soil nailing strengthens the ground in situ by inserting closely spaced, passive steel bars, called nails, into the slope. A nail is a steel bar, usually 20 to 40 mm in diameter, placed into a drilled hole and grouted with cement grout over its full length. Nails are "passive" because they are not prestressed at installation. As the soil begins to deform, the nails are mobilised in tension and, to a lesser degree, in shear and bending, and they restrain the movement of the soil mass. The reinforced soil behaves like a composite gravity block, a bit like a reinforced earth wall built from top to bottom in existing ground.

6.3.2 Components

- **Nails:** high-yield deformed steel bars, often with corrosion protection such as grout cover, epoxy coating or a plastic sheath. Length is usually 0.6 to 1.0 times the height of the excavation, and horizontal and vertical spacing about 1.0 to 2.0 metres.
- **Grout:** cement grout filling the drill hole and bonding the bar to the soil.
- **Facing:** usually shotcrete with welded wire mesh or reinforcement, with bearing plates and nuts at nail heads. Facing can be temporary, or permanent with a thicker or architectural finish.
- **Drainage:** strip drains or geocomposite behind the facing and drain holes (horizontal drains) through the slope to relieve pore pressure.

6.3.3 Construction Sequence

1. Excavate a first lift of limited height, commonly 1 to 2 metres, which the soil can stand unsupported for a short time.
2. Drill nail holes at the planned inclination, typically 10 to 20 degrees below horizontal.
3. Insert the nail bar with centralisers and grout the hole.
4. Install drainage elements and place the first layer of shotcrete over mesh.
5. Fix bearing plates and nuts once the grout and shotcrete have gained strength.
6. Excavate the next lift and repeat the cycle until the final depth is reached.

For stabilising an existing failing slope the nails are installed in rows from the top downward, and the process is usually carried out with drilling rigs working from the slope face or from platforms.

6.3.4 Design Considerations

Design checks include internal stability (nail pull-out, nail tensile strength, facing and connection capacity), external stability (sliding, bearing at the base and overall slope stability including the nailed zone), and serviceability (face movement). The bond strength between grout and soil is the key parameter and should be verified by field pull-out tests on trial nails before final design. Guidance such as the FHWA soil nailing manual is widely used internationally; local codes and project specifications should be followed.

6.3.5 Advantages and Limitations

Advantages: lightweight equipment, suitable for restricted sites and steep terrain, little disturbance to the slope and surroundings, can be adapted to variable ground by adjusting nail length, economical for medium heights, good seismic performance because the reinforced mass is flexible. Limitations: not suitable in very soft clays, loose clean sands and ground with a high water table unless drained, requires a face stable for short periods

during excavation, long nails may be restricted by property boundaries, and corrosion protection is needed for permanent works.

6.4 Ground Anchors and Tie-Backs

Ground anchors, also called tie-backs, are prestressed tensile elements that transfer load from the slope face to a stable zone deep in the ground. An anchor has three parts: the **anchor head** at the surface, the **free (unbonded) length** that passes through the potentially unstable ground, and the **fixed (bond) length** that is grouted in the stable stratum and transfers load. The tendon is a high-strength steel strand or bar, tensioned using jacks to a designed load and locked off.

Because anchors are prestressed, they apply an active force to the slope immediately. This confines the soil, increases normal stress on the failure plane and thereby raises shear resistance, and it limits movement of the structure being supported. Anchors are used for tall cuttings, deep excavations, retaining walls, and slides involving large masses where nails would not be sufficient. Typical working loads range from a few hundred kilonewtons to over a thousand, with lengths of 15 to 40 metres in some projects.

Design must check the tendon capacity, grout-to-ground bond capacity, the overall stability of the anchored mass, and the capacity of the anchor head and bearing structure. Testing of each production anchor, including proof loading, is standard. Corrosion protection, via double protection with grout and a corrugated sheath for permanent anchors, is essential for durability. Anchors are more expensive and require specialised equipment and contractors, but give excellent control over deformation.

6.5 Pile and Micropile Stabilisation

Piles. A row of bored cast-in-situ or driven piles, usually of reinforced concrete, passes through the sliding mass into stable ground below the slip surface. The piles act as dowels that resist the shear force transmitted by the moving soil. The stabilising effect depends on pile diameter, spacing, embedment in stable ground, bending strength and the way load is transferred through the soil between piles, a phenomenon called soil arching. A pile cap or capping beam ties the piles together, and tie-back anchors may be added for large thrusts.

Micropiles. These are small-diameter piles, typically 100 to 300 mm, drilled and grouted, with steel reinforcement such as a central bar or casing. Because the equipment is small they can be used in restricted access areas and they can be installed at inclinations, forming a network that reinforces the slope. Micropiles are used both as in-ground reinforcement and to underpin failing structures.

Pile systems provide deep, positive stabilisation for deep-seated slides, particularly where the slip surface is well defined. Their limitations are cost, the need to know the depth of the slip surface accurately, and the risk that soil may flow around or over the piles if spacing, length or stiffness is inadequate.

6.6 RCC Grid Beams and Lattice Frames

A frame in the most literal sense, this system consists of reinforced concrete beams cast in a grid or lattice pattern on the face of the slope, commonly in squares or rhombuses of about 2 to 4 metres. The beams are anchored into the slope by nails or ground anchors placed at the intersections of the grid, so that the frame spreads the anchor load over the surface. The open panels between the beams are filled with vegetation on soil, with stone pitching, with shotcrete, or sometimes with a geosynthetic cover.

This method has two advantages. It provides the structural restraint of anchors or nails along with a continuous face support, and it allows the panels to be vegetated, which blends the slope with the environment and improves surface stability. It has been widely applied to cut slopes along highways and railways in mountainous regions, especially in Asia. The grid beam size, reinforcement and anchor spacing are designed for the loads from the anchors and the earth pressure on the panels, and drainage through the panels must be provided.

6.7 Shotcrete and Wire Mesh Facing

Shotcrete is concrete or mortar sprayed pneumatically at high velocity onto the slope surface, usually over steel mesh or fibres. It seals the surface against weathering, prevents raveling and provides a continuous skin to which nails, anchors and drainage can be connected. On its own it does not provide deep stabilisation, but it prevents shallow failures and local falls and acts as the facing of nailed and anchored slopes. Weep holes and drains must be provided to prevent water pressure from building up behind the shotcrete. For rock slopes, rock bolts with mesh and shotcrete are standard.

6.8 Other Structural Measures

- **Toe berms and buttress fills:** compacted granular or rock-fill placed at the toe adds weight and resistance and also provides drainage. Technically a frame-free measure, it is often used with structural elements.
- **Rockfall barriers and catch fences:** flexible steel net fences designed to absorb the energy of falling rock.
- **Diaphragm and secant pile walls:** used for excavation support, which also acts as a permanent slope retaining structure.
- **Sheet piles:** steel sections driven into the ground, used for temporary excavations, river bank protection and low walls in soft ground.

6.9 Advantages and Disadvantages of Frame Methods as a Group

Advantages

- Immediate, quantifiable increase in the factor of safety, with well-established design procedures.
- Effective for steep slopes, large slides and critical infrastructure.
- Allow limited space use and can support heavy loads from structures above.
- Controlled monitoring and testing of performance are possible, such as anchor load cells and proof tests.

Disadvantages

- High initial cost, often several times that of non-frame methods for the same slope.
- Need skilled labour, specialised equipment and quality control.
- Rigid structures can fail suddenly if overloaded, and poor drainage can undermine them.
- Visual and environmental impact, although facing treatments and vegetation can reduce this.
- Corrosion and durability issues for steel elements in the long term.

6.10 Quality Control and Monitoring for Frame Methods

Quality assurance is critical. Typical measures include checking the verticality and depth of drill holes, grout mix and strength testing, pull-out tests of nails and anchors, verifying tendon corrosion protection, concrete cube tests, checking weep holes and drains for flow, and survey monitoring of the wall or face. Instruments such as inclinometers, load cells on anchors, piezometers and tiltmeters give early warning of unsatisfactory performance, and are particularly justified for large or high-risk projects.

7. Non-Frame (Non-Structural) Methods of Slope Protection

7.1 Concept

Non-frame methods do not rely on a rigid supporting structure. They improve stability by changing the shape of the slope, by controlling water, by covering and binding the surface, or by adding light reinforcement that works together with the soil. They are generally cheaper, easier to construct and more environmentally friendly than frame methods, and they work best for shallow failures, erosion control, and slopes of moderate height and angle. They are also a natural first line of defence on any slope and complement structural measures on larger projects.

7.2 Slope Geometry Modification

7.2.1 Flattening the Slope

Reducing the slope angle reduces the driving component of weight and increases the factor of safety. For dry cohesionless soil the factor of safety is $\tan \phi / \tan \beta$, so halving $\tan \beta$ doubles the factor of safety. Flattening is the simplest and most reliable measure where land is available. For cut slopes in soil, typical stable angles range from about 1 vertical to 1.5 or 2 horizontal for ordinary soils, and flatter for weak or saturated soils, while stronger or cemented soils and weathered rock may stand steeper. Its disadvantages are the large volume of excavation and the extra land it needs.

7.2.2 Benching (Terracing)

A tall slope is divided into a series of steps, called benches or berms, separated by shorter slope sections. A bench of about 2 to 3 metres in width and with a lined drain interrupts surface flow, reducing velocity and erosion, provides access for maintenance, catches falling debris, and improves the overall stability by reducing the average angle. Typical vertical spacing is about 6 to 10 metres in cut slopes, depending on the soil and the local guidelines. Benches should slope slightly inward and carry a lined drain to a safe outlet so that they do not become sources of infiltration.

7.2.3 Unloading the Crest and Loading the Toe

Removing soil from the head of a slide reduces the driving force, while adding a compacted berm at the toe increases the resisting force. The combination is very effective in rotational slides and is a classic stabilisation measure for embankments and landslides. Care is needed so that excavation at the head does not create new instability and that the toe berm does not block natural drainage.

7.2.4 Removal of Unstable Material

Where the unstable mass is small and shallow, the simplest solution is to remove it entirely and, if needed, replace it with compacted, free-draining fill. This is common after minor slips on road cuttings.

7.3 Drainage

Since water is the main cause of slope failure, drainage is probably the most cost-effective of all measures, and the Indian guideline on landslide control gives it a prominent place. Drainage is divided into surface and subsurface.

7.3.1 Surface Drainage

The aim is to keep rainwater out of the slope and to carry runoff down safely without erosion.

- **Catch-water (crest) drains:** lined channels at the top of a cut slope that intercept runoff from the hillside above.
- **Bench drains:** lined drains along berms that collect flow from the slope face.

- **Down-chutes (cascades):** steep, stepped or lined channels that carry water down the slope face to the toe, with energy dissipation at the bottom.
- **Toe drains and cross-drains:** channels and culverts that take water away from the base of the slope.
- **Sealing of cracks and surface treatment:** filling cracks with clay or cement mortar to prevent infiltration.

Drains must be lined, of adequate capacity for the design storm, and maintained, because a blocked or broken drain concentrates water and makes matters worse.

7.3.2 Subsurface Drainage

The aim is to lower the groundwater table and relieve pore pressures inside the slope.

- **Horizontal (sub-horizontal) drains:** perforated pipes, typically of 50 to 75 mm diameter, drilled into the slope at a small upward angle to let groundwater flow out by gravity. They are among the most effective and economical methods for deep slides.
- **Trench (French) drains:** trenches filled with graded filter material and often a perforated pipe, installed across or along the slope to intercept seepage.
- **Drainage blankets and counterfort drains:** granular layers or trenches placed at the toe or within fills to drain seepage and add weight.
- **Drainage galleries and wells:** tunnels or vertical wells with pumping or gravity outlets, used for large landslides.
- **Geocomposite drains:** geosynthetic sheet drains placed behind facings or in trenches.

Filters, either graded aggregate or geotextile, must be provided so that fine soil particles do not wash into and clog the drains.

7.4 Vegetation and Bio-Engineering

7.4.1 Principle

Vegetation protects slopes by several mechanisms. The canopy intercepts rainfall and reduces the impact energy of raindrops. The litter layer and stems slow surface flow and trap sediment. Roots bind the soil, adding apparent cohesion in the root zone and anchoring the shallow soil layer to deeper, firmer layers. Plants also remove water from the soil through transpiration, lowering pore pressure. The combination of civil engineering and plant science is called bio-engineering or soil bio-engineering.

Root reinforcement is often represented as an additional cohesion, commonly a few kilopascals for grasses and shrubs and more for trees, in the root zone, usually the upper one to two metres of the soil. This is why vegetation is effective against shallow slips and erosion but cannot by itself prevent deep-seated failures beyond the reach of roots. Trees may also add weight and, when swayed by wind, create cracks, so species and placement need to be chosen carefully.

7.4.2 Techniques

- **Turfing and sodding:** laying pieces of grass turf on the slope, giving immediate cover. Suitable for gentle slopes and where turf is available.
- **Seeding and hydroseeding:** spreading seed, often mixed with mulch, fertiliser and a binder, in a water slurry sprayed on the slope. Hydroseeding is quick and suitable for large and steep areas.

- **Grass planting using slips or tufts:** commonly used with vetiver grass, whose deep, dense, fibrous root system, extending to 2 to 3 metres or more, has made it a widely used low-cost method of stabilising embankments and cuttings in tropical countries including India.
- **Brush layering and fascines:** layers of live branches placed in horizontal rows in the slope, or bundles of live stems laid in shallow trenches, which sprout and form a network of roots and stems.
- **Live staking and wattling:** driving live cuttings of species that root easily, such as willow, into the slope or along contour lines.
- **Shrubs and tree planting:** for larger and more stable slopes, using native species adapted to the local climate and soil.
- **Vegetated crib and gabion systems:** combining a structural element with plant growth.

7.4.3 Selection of Species

Species should be native or well adapted, fast growing and hardy, with deep and fibrous root systems, able to fix nitrogen where soils are poor, and suitable for local rainfall and temperature. A mixture of grasses, shrubs and trees gives more resilient protection than a single species. Local forest and agriculture departments can advise on suitable plants.

7.4.4 Advantages and Limitations

Advantages: low cost, environmental and visual benefits, self-repairing and improving with time, reduces erosion and runoff, creates habitat. Limitations: slow to establish, little immediate protection, needs maintenance during establishment (watering, fertilising, reseeding), limited to shallow instability, not suitable for very steep or very dry or very shaded sites without additional measures, and its performance depends on season and climate.

7.5 Geosynthetics

Geosynthetics are polymeric materials used with soil, rock or other geotechnical material. They have become one of the most versatile tools in slope protection, serving the functions of reinforcement, separation, filtration, drainage, erosion control and containment.

7.5.1 Types and Functions

- **Geotextiles:** woven or non-woven permeable fabrics. Used for filtration beneath riprap, gabions and drains, for separation of soil layers and for reinforcement in some cases. Woven types provide tensile strength; non-woven types are better for filtration and drainage.
- **Geogrids:** open grid-like structures with high tensile strength and good interlock with soil. Used to reinforce steep slopes and MSE walls, and embankments over soft ground.
- **Geonets and geocomposites:** drainage layers made of a net core with geotextile on one or both sides, used behind walls and under covers.
- **Geocells (cellular confinement systems):** three-dimensional honeycomb-like panels of polymer, filled with soil, sand or gravel and often vegetated. They confine the infill, increase its apparent strength and resist erosion. Used on slopes, channels and for load support.
- **Geomats and erosion control blankets (ECB):** three-dimensional mats or blankets of coir, jute, straw or polymer fibres that protect the soil surface from rain and runoff and help seeds germinate. Natural fibre products such as coir and jute decompose after vegetation is established, while synthetic mats provide long-term reinforcement of the root zone, forming turf reinforcement mats.

- **Geosynthetic clay liners and geomembranes:** impermeable layers used to prevent infiltration where sealing a slope surface is needed, for example on landfill slopes.

7.5.2 Reinforced Steep Slopes

Layers of geogrid or geotextile are placed horizontally during compaction of the fill, typically at vertical intervals of 0.3 to 1.0 metre, to build a slope steeper than the unreinforced soil could stand at, with angles up to about 70 degrees. The face may be wrapped with the geosynthetic and covered with vegetation or erosion mats, or protected with mesh. The reinforcement is designed against internal pull-out and rupture and the whole reinforced block is checked for external sliding and overall stability. Reinforced slopes are economical alternatives to retaining walls where the face may be inclined, and are used widely for embankments, road widening and repairs of failed slopes.

7.5.3 Advantages and Limitations

Advantages: fast installation, light equipment, consistent factory quality, durable if protected from sunlight, often more economical than concrete walls, and flexible in the face of settlement and earthquakes. Limitations: sensitivity to ultraviolet light before cover is placed, possibility of damage during installation and compaction, creep of some polymers under long-term load, need for quality fill, and the need for specialist design for major structures.

7.6 Surface Armouring

- **Riprap and stone pitching:** layers of large, durable stones placed on a granular filter or geotextile on the slope or river bank. They protect against wave action, currents and erosion. Stone size, thickness and filter are designed for the flow velocity and wave conditions.
- **Concrete blocks and articulated mattresses:** interlocking or cable-tied blocks used on embankments, canal linings and river banks.
- **Brick or masonry lining and pitching with mortar:** commonly used for drains and sections of slopes subject to concentrated flow.
- **Jute and coir netting:** biodegradable meshes pegged to the slope, which hold the soil and seed until vegetation grows.
- **Mulching and bituminous or polymer sprays:** temporary surface cover to reduce erosion during the establishment of vegetation.

These methods mainly protect the surface from erosion and do not by themselves increase the deep stability of the slope. Weep holes or filters must allow water to escape from behind hard covers.

7.7 Soil Improvement Techniques

- **Compaction:** properly compacted fill has higher strength and lower permeability. Control of density and moisture is a basic quality requirement for embankments.
- **Chemical stabilisation:** mixing lime, cement, fly ash or other binders into the soil improves its strength and reduces its plasticity and swelling. Lime piles or lime columns have been used to stabilise failing slopes in clay.
- **Grouting:** injection of cement or chemical grout fills voids and cracks, binding soil or rock together and reducing permeability.
- **Electro-osmosis and thermal methods:** specialised methods for dewatering or strengthening fine-grained soils, used in rare situations.

- **Replacement of weak soil:** replacing a weak layer, for instance at the toe, with compacted granular material.

7.8 Rockfall and Debris Control (Light Measures)

Flexible mesh drapes, catch ditches at the toe, and earth bunds absorb or direct the movement of loose material without a rigid structure. Light wire mesh pinned to the surface holds small loose blocks in place, whereas barriers and fences capture falling blocks. These measures fit the non-frame philosophy of managing movement, rather than resisting it with a massive structure, though large flexible barriers are engineered to high standards.

7.9 Advantages and Disadvantages of Non-Frame Methods as a Group

Advantages

- Lower cost and quicker implementation, with simpler equipment and local labour.
- Environmentally friendly, with better appearance and ecological benefits.
- Flexible and adaptable to changing conditions and easy to repair.
- Drainage and vegetation improve stability over time.

Disadvantages

- Limited effectiveness against deep-seated or large slides.
- Slower to achieve full effect, especially vegetation.
- Greater dependence on maintenance, season and climate.
- Often less predictable and harder to quantify in design than structural measures.

8. Comparison of Frame and Non-Frame Methods

Aspect	Frame (structural) methods	Non-frame (non-structural) methods
Basic action	Provide external support or in-ground reinforcement with rigid elements	Improve soil, surface and water conditions, or shape of slope
Typical examples	Retaining walls, soil nails, anchors, piles, grid beams	Regrading, drainage, vegetation, geosynthetics, riprap
Depth of effect	Shallow to deep-seated failures	Mainly shallow failures and erosion, drainage can help deep ones
Speed of effect	Immediate on completion	Gradual, particularly for vegetation
Cost	High initial cost	Low to moderate
Skill and equipment	Specialised contractors and machinery	Mostly simple and local, except for large geosynthetic works
Space needed	Small, suited to restricted sites	Often needs more land, as for flattening

Design certainty	Well-established analytical methods	More empirical, depends on site and climate
Maintenance	Low once built, but drains and steel need inspection	Regular, especially during vegetation establishment
Environmental impact	Higher, visual and material	Lower, often positive
Failure behaviour	May fail suddenly if overloaded or poorly drained	Usually gradual and visible
Suitability	Steep slopes, critical structures, active landslides	Gentle to moderate slopes, erosion control, low-risk areas

In practice the choice is rarely one or the other. Combined or hybrid schemes, such as a soil-nailed slope with a vegetated geomat face, horizontal drains and surface drains, use the strengths of each.

9. Selection of a Suitable Method

9.1 Steps in the Selection Process

1. **Site investigation:** study the topography, geology, soil profile, groundwater, rainfall, history of past movements and surrounding structures. Boreholes, trial pits, geophysical surveys and instrumentation may be needed.
2. **Identify the failure mechanism:** shallow or deep, rotational or translational, rapid or creeping, water-driven or load-driven. The mechanism points directly to suitable measures.
3. **Determine the soil parameters and design conditions:** shear strength (peak and residual), unit weight, pore pressure regime, seismic zone and design rainfall.
4. **Perform stability analysis:** determine the existing factor of safety and the improvement needed.
5. **Shortlist options:** frame, non-frame or combined schemes that meet the required factor of safety.
6. **Evaluate options:** cost (capital and maintenance), constructability, access and space, time, safety during construction, durability, environmental impact and local availability of materials and skills.
7. **Design, construct, monitor and maintain:** with quality control and instrumentation where justified.

9.2 Guide to Matching Method to Situation

- **Erosion and shallow raveling on a gentle to moderate slope:** vegetation, geomats, surface drainage.
- **Shallow slides in residual soil or colluvium:** drainage, regrading, vegetation, geogrid reinforcement, or gabion toe walls.
- **Steep road cuttings with limited space:** soil nailing with shotcrete or grid beams, retaining walls, MSE walls where fill is involved.

- **Deep-seated rotational slides:** unloading the crest, toe berms, horizontal drains, ground anchors, piles.
- **River bank and canal slopes:** riprap, gabion mattresses, geotextile filters, toe protection, vegetation above the water line.
- **Embankments on soft ground:** geosynthetic reinforcement, toe berms, controlled staged construction, drainage.
- **Rock slopes with loose blocks:** rock bolts, mesh, shotcrete, catch ditches, barriers.

9.3 Relevant Indian Guidelines

Students should be familiar with the main Indian references on this subject. These include IS 14680:1999, Landslide Control: Guidelines, which sets out investigation and control measures including drainage, retaining structures and vegetation; the IS 14458 series, Guidelines for Retaining Wall for Hill Area; IS 14496 (Part 2), the guideline for preparation of landslide hazard zonation maps in mountainous terrains; and the IRC Hill Road Manual (IRC:SP:48), which covers drainage, slope protection, retaining structures and bio-engineering for roads in hilly regions. IRC publications on slope protection and soil nailing, and the Geological Survey of India and the National Disaster Management Authority's landslide guidelines, are also useful. Clause numbers and the latest editions should be verified from the originals before quoting them in a report.

10. Illustrative Field Applications

The following are general illustrations of how the methods are applied, not detailed case histories.

10.1 Hill Highways

Roads in the Himalayan and Western Ghat regions are the most common application. Typical slope protection uses a combination of catch-water drains and lined side drains, breast walls (retaining walls on the hill side), gabion and masonry retaining walls on the valley side, shotcrete and soil nails on steep cuts, and vegetation and geomats on gentler cuttings. Landslide-prone stretches are treated with horizontal drains and anchored structures.

10.2 Railway Cuttings and Embankments

High cuttings and embankments on railway lines through hilly terrain, such as the Konkan region, use benching, drainage, soil nailing, rock bolting with mesh, and slope flattening. Because railway tracks are very sensitive to movement and train services are critical, early detection through monitoring is given importance.

10.3 Urban Hill Settlements

Where houses are built on hill slopes, space limits the options. Retaining walls with proper drainage, soil nailing for excavations next to buildings, improved control of domestic and storm water, and restrictions on cutting and loading of slopes are the main measures. Poor drainage from buildings is a frequent trigger of slope failure in such areas.

10.4 Dams, Canals and River Banks

Earth dam slopes are protected on the upstream side by riprap or concrete pitching against wave action, and on the downstream side by turfing and drainage. Canal banks and river banks use riprap, gabions, geosynthetic filters and vegetation, together with toe protection against scouring.

10.5 Open Pit and Excavation Slopes

Deep excavations for basements and metro stations use diaphragm walls, secant piles, soldier piles with lagging and ground anchors or struts. Mine slopes use benching, drainage and monitoring.

11. Economic and Environmental Considerations

11.1 Cost

A full life-cycle view should consider not only construction cost but also maintenance, repair after damage and the cost of failure, including traffic disruption and risk to life. Non-frame measures are often cheaper at the start but need ongoing maintenance, whereas frame measures cost more at the start but may require less attention. For large or critical slopes, an expensive structural measure can still be the cheaper choice overall when failure would be very costly. Costs vary greatly with location and access, so no general figures are given here, and the current Schedule of Rates should be used for estimates.

11.2 Environmental and Social Aspects

Slope works change the landscape. Large concrete structures and extensive cutting scar the hillside, whereas vegetation, gabions and geomats blend in. Excavated muck should be disposed of in designated sites to avoid blocking streams and causing new slides. Dust, noise and traffic disruption during construction need management. Local communities should be involved, especially in bio-engineering schemes where local labour and nurseries can provide employment and long-term care of the slope.

11.3 Safety During Construction

Working on slopes is hazardous. Precautions include working in short stable sections, sequencing the work from the top down, providing safe access and fall protection, scheduling work to avoid heavy rain periods, monitoring for movement during construction and having an emergency plan.

12. Recent Trends and Future Scope

- **Remote sensing and monitoring:** satellite radar interferometry (InSAR), drones with photogrammetry and LiDAR, and ground-based radar are used to map and monitor slope movements over large areas. Wireless sensor networks with inclinometers, piezometers and rain gauges feed early warning systems.
- **Landslide early warning systems:** rainfall-threshold-based warning systems are being developed and applied in vulnerable regions.
- **Advanced numerical modelling:** finite element and finite difference programs, and coupled hydro-mechanical analysis of rainfall infiltration, give better insight into slope behaviour. Probabilistic and reliability-based design is gaining ground over a single deterministic factor of safety.
- **Machine learning:** used for landslide susceptibility mapping and prediction from terrain, rainfall and land cover data.
- **New materials:** high-strength geosynthetics, corrosion-resistant nails and anchors such as fibre-reinforced polymer bars, and biodegradable erosion control products.
- **Nature-based and eco-engineering solutions:** growing emphasis on bio-engineering, ecological restoration and hybrid schemes that combine vegetation with light structures, supported by climate change concerns about more intense rainfall.
- **Microbial and enzyme-induced soil stabilisation:** research into binding soil by microbially induced calcite precipitation and similar methods, which is still mostly at the research stage.

- **Climate adaptation:** more intense and erratic rainfall requires design for higher design storms and more robust drainage.

13. Conclusions

1. Slope failure occurs when the driving forces exceed the available shear resistance. Water, loss of support, loading, weathering and loss of vegetation are the principal causes, and water is the most common trigger.
2. Understanding the type and mechanism of failure, supported by site investigation and stability analysis, is the basis of selecting an appropriate protection method.
3. Frame methods, including retaining walls, soil nails, ground anchors, piles and RCC grid beams, give immediate and reliable support and are effective on steep slopes, large slides and where space is limited, but they are costly and need skilled execution and sound drainage.
4. Non-frame methods, including regrading, benching, drainage, vegetation, geosynthetics and surface armouring, are economical and environmentally friendly and are highly effective against erosion and shallow instability, but their effect is limited for deep-seated failures and depends on maintenance.
5. Drainage is the most important single measure and forms part of virtually every successful scheme.
6. The best solution is often a combination of frame and non-frame measures, tailored to site conditions, risk, cost and environment.
7. Monitoring and maintenance after construction are essential for lasting performance, and modern remote sensing and instrumentation make early warning increasingly practical.

14. References

The following are standard sources for this subject. Verify the edition and details from the originals before citing.

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