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# Erosion Control and Slope Stabilization: A Critical Review on Analysis and Strengthening Methods of Hilly Terrain

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***Abstract*: Erosion control and slope stabilization are critical aspects of geotechnical engineering, essential for preventing soil degradation, landslides, and infrastructure failures. This review explores various methods used to enhance soil stability, mitigate erosion, and improve slope resilience under diverse environmental and load conditions. Furthermore, the use of GIS and remote sensing for tracking slope stability and forecasting collapse hazards is emphasized. Through the integration of sustainable and environmentally friendly practices with engineering concepts, this review offers a thorough comprehension of various stabilization techniques. According to the findings, erosion management and slope stabilization require site-dependent approaches that strike a compromise between effectiveness, environmental impact, and durability. Future studies should concentrate on maximizing the use of these approaches in conjunction to create long-lasting and reasonably priced solutions for geotechnical problems.***
***Keywords: Erosion control, slope stabilization, remote sensing, sustainable geotechnical engineering.***

## I. INTRODUCTION

Slope stabilization and erosion management are essential for handling geotechnical issues brought on by both natural and man-made causes. Slope geometry, soil properties, hydrological conditions, external loads, and environmental stresses like rainfall and seismic activity all and interact to determine a slope's stability. The need for dependable and sustainable stabilizing techniques has increased dramatically as a result of growing urbanization, deforestation, and the effects of climate change. With developments in materials and methods, such as geosynthetics, bioengineered solutions, and polymer-based soil stabilizers, conventional methods, including retaining walls and drainage systems, have changed. This review explores the most recent techniques and research findings in slope stabilization, emphasizing how well they work to increase soil strength, lessen erosion, and guarantee slope resilience across a range of load and environmental circumstances.

Slope failure and its mitigation are examined by various researches in this document, with a focus on real-world applications. Chemical stabilization strategies such as the use of polymers, lignosulphonates, and lime; biological procedures involving vegetation and microbial activities; and mechanical stabilization of slopes utilizing retaining walls, piling, and geotextiles are among the topics covered. This review opens the door for sustainable practices in geotechnical engineering by combining the results of several studies to provide a thorough grasp of erosion control techniques.

## II. UNDERSTANDING THE MECHANISMS OF SLOPE FAILURE AND SOIL EROSION

### *A. Slope Geometry*

Masoud Zare Naghadehi et al. [1] examined Rock slopes and took nine factors that affect the stability of the slopes: weathering, mechanical characteristics of discontinuities, hydraulic conditions, faults and folds, geology and lithology, past instabilities, intact rock strength, slope height, and slope inclination. In the context of rock engineering systems (RES), this study assesses the importance of variables affecting rock slope stability using a probabilistic expert semi-quantitative (PESQ) coding methodology. Steeper slopes are more likely to fail, and slope angle has an impact on stability. In order to determine slope stability, the soil's tensile strength is crucial. The work by Chang Liu et al. [4] highlights that slope angle and width affect failure processes, with more three-dimensional failure patterns seen on wider slopes. According to the study, which simulates 3D failure mechanisms, failure routes are greatly influenced by geometry and seismic loads. Based on the analysis by Yongqiang Ren et al. [5], the safety factor falls with increasing infiltration depth. Deep sliding and instability may result when the depth reaches critical levels because the sliding surface may penetrate through the gravel as well as the original slope components.

According to K. Zirsang zeli et al. [6], stability declines as height and sharper slope angles increase. Internal friction angle and soil cohesion are important factors; more cohesiveness increases the stability of free slopes, whereas friction angle has a greater effect under building loads.

### *B. Hydrological Conditions*

Bordoni et al. [2] concentrated on the variables that affect slope stability, particularly when it comes to shallow landslides brought on by rainfall. The importance of soil pore water pressure and water content is emphasized throughout the research. Infiltration of rainfall can increase pore water pressure, which lowers the soil's shear strength—a crucial component of slope stability. Rainfall duration and severity are important landslide triggers. Prolonged, heavy rains can rapidly saturate the soil strata, causing shallow landslides. According to research by Feng Zhangn et al. [3], increased soil saturation lowers matrix suction and soil strength, particularly during extended or heavy rainfall. The scientific question of how slope stability calculations are impacted by tensile strength cut-off (TSC) under different rainfall situations is addressed in this work. It looks at how the TSC coefficient, slope angle, rainfall duration, and intensity affect stability calculations for slopes with various soil types. This study provides a fresh method and point of reference for figuring out how stable different soil slopes are under various rainfall scenarios while accounting to TSC.
According to Chang Liu et al. [4], high pore water pressure (PWP) weakens soil, especially during seismic activity. Slope stability may be significantly reduced as a result of earthquake-induced excess pore water pressure (EPWP), which further erodes soil structure. The effects on the factor of safety (FS) and critical sliding surface of partially saturated slopes of variations in groundwater level, seismic coefficients, suction, three-dimensional effects, excess pore water pressure, types of unsaturated flow, and pseudo-dynamic parameters were examined using parametric analyses. Yongqiang Ren et al.'s study [5] concludes that one of the main causes of slope instability is rainfall. Rain decreases shear strength and overall stability by weakening the soil structure, increasing pore water pressure, and decreasing matric suction. The strength parameters of unsaturated slopes will decrease under the influence of rainwater infiltration, and when stress levels and strength parameters change, so will the deformation parameters.

### *C. Soil Type And Properties*

According to research by Feng Zhang et al. [3], clay and silt have stronger cohesiveness and are therefore more impacted by tensile strength cut-off (TSC) than sand. Tensile strength has a greater effect on slope stability in unsaturated soil than in saturated soil, hence studying TSC in unsaturated soil is more crucial. According to Yongqiang Ren et al. [5], the structure influences the infiltration channel and shear stress distribution. This includes the original slope surface and any additional gravel layers. There may be a transmission zone and eventual breakdown because the contact surface between these layers is more susceptible to shear stress. K. Zirsang Zeli [6] conducted research When examining slope stability, soil characteristics are essential. In order to comprehend their influence on the factor of safety (FOS), a parametric study of soil shear strength characteristics, such as cohesion and the internal friction angle, has been carried out because of the size of the data set. Sensitivity study shows that the internal friction angle ($\varphi$) has less of an effect on the factor of safety in a free slope analysis than soil cohesion(c). According to research by Dhiraj Raj [8], stability is impacted by the slope angle and soil properties like cohesiveness and internal friction. In general, steeper slopes (such as 30°) are less stable, although failure patterns differ depending on the foundation's position and the characteristics of the soil.

### *D. Seismic Forces*

According to a research by Chang Liu et al. [4], horizontal seismic forces have a greater impact on destabilizing slopes than vertical forces, impacting slope stability differently. Seismic waves raise the risk of instability because of dynamic pressures, particularly in unsaturated soils. According to the study by K. Zirsang zeli et al. [6], seismic activity adds horizontal and vertical strains, which considerably lowers stability, particularly in high-risk areas. Rainwater infiltration weakens slopes by lowering effective soil stress and raising pore pressure.

### *E. Building Loads And Configurations*

According to a study by K. Zirsang zeli et al. [6], step-back setback structures and other building designs better equally transfer loads across slopes, improving stability. The stability is also impacted by the depth of load application; in general, deeper loads provide stronger slope support. When analyzing slopes with building loads in both static and seismic circumstances, the internal friction angle ($\varphi$) of the soil has a bigger impact on the factor of safety than cohesion. The fact that different building designs (such as setback and step-back) distribute loads differently is emphasized by D.K. Paul et al. [7]. Step-back buildings on sloping terrain typically provide greater stability than other arrangements, while setback buildings on level terrain close to slopes enhance stability.

## III.CONVENTIONAL SOIL STRENGTHENING METHODS

### A. Lime

The hybrid usage of hydrated lime and guar gum biopolymers as stabilizing agents for Ligurian earth material was investigated by Bruno et al. [32]. They study hygroscopic, thermal, and mechanical qualities. Lime costs environmental properties but is believed to harden mechanical strength. The authors recently called for the usage of guar gum, one of the biopolymers. Under laboratory conditions, G. Landlin et al. [38] evaluated and contrasted the degree of swelling and shrinkage displayed by soils stabilized with lime and lignosulfonate that were exposed to cycles of wetting and drying. Field drying conditions were replicated using a specially modified oedometer device. During both the short-term and long-term stabilization stages, lime, an alkaline addition, interacts with the soil's minerals, improving strength through the long-term cementitious products. But little is known about lignosulfonate (LS), especially when it comes to how it behaves in cyclic wetting and drying situations.

### B. Cement

Loess soil was stabilized by Xuerui Yan et al. [36] using an ecological composite binder based on magnesium oxysulfate cement. One novel kind of cementitious material based on magnesium is magnesium oxysulfate cement (MOS). It is made by generating a $MgSO_4$-$MgO$-$H_2O$ ternary system by mixing magnesium oxide, magnesium sulfate, and water in particular ratios. This system becomes an air-hardening cementitious material through a hydration reaction. As an environmentally acceptable method of solidifying loess, this study used a composite binder composed of coal gangue and magnesium sulfate cement. The test results confirmed that this composite binder effectively bonded loess particles into a cohesive mass. These findings demonstrate its significant potential for soil stabilization applications in agriculture, construction, and environmental engineering.

### C. Retaining Wall

At a slope with a gabion-reinforced retaining wall, Mao Yue et al. [10] carried out a number of shaking table tests. With the topmost layers making a greater contribution to slope stability under seismic forces, the layers at the top showed the highest incremental tensile forces. By distributing seismic energy and lessening the effects of peak acceleration, gabion reinforcements increase slope stability. These results show that gabion reinforcement improves energy dissipation, controls incremental stress, and lessens displacements under seismic activities, hence mechanically stabilizing slopes. Chonglei ZHANG et al. [13] investigated the reinforcement behavior and appropriateness of recently constructed bored piles with retaining walls (BPRWs) for cutting-slope applications. The bending moment gradually increases and the displacement increases in the cantilever segment as a result of rainfall infiltration. The rainy season servicing needs are met by the BPRWs design.M.Srbulov[16] analysed the stability of geogrid reinforced steep slopes and retaining walls.The stabilities of slopes and walls are analysed using a method based on limit equilibrium.

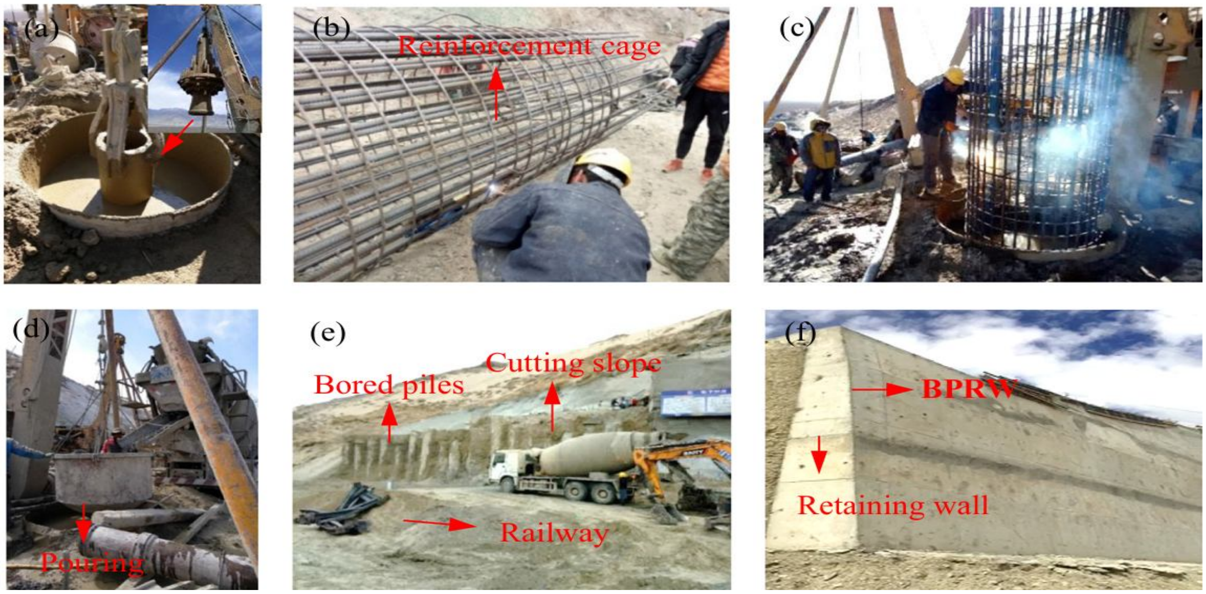


Fig1. On-site construction process of the BPRWs: (a) Drilling of the bored piles with a percussion drill; (b) reinforcement cage welding; (c) reinforcement cage lengthening; (d) concrete pouring; (e) slope excavation; and (f) retaining wall pouring. [13]

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Seismic fragilities for cantilever retaining walls with three backfill slope angles were assessed by Hwanwoo Seo et al. [11]. With FLAC 2D software, numerical models are produced for a 4-meter-tall cantilever retaining wall. These models are then verified by comparison with an analytical solution. For a cantilever retaining wall, seismic fragility curves and surfaces have been constructed in this work, taking into account different backfill slope angles and ground motion characteristics. The seismic behavior of a cut slope reinforced with micropiles behind a cantilever retaining wall was investigated by Zhiliang Sun et al. [12]. A common retaining structure in slope reinforcing design is the micropile-cantilever retaining wall (CRW). A dynamic load with an immediate amplitude significantly larger than its static ultimate bearing capacity can be supported by this reinforced concrete structure, they discovered, and it reacts differently to both static and dynamic loads.

Yu-liang Lin et al. [14] investigated the seismic behavior of the gravity retaining wall with anchoring frame beam supporting a steep rock slope using dynamic numerical analysis and the Shaking table test. Under seismic loading, the anchoring frame beam's nonlinear behavior is far more noticeable than the gravity retaining wall's. It is important to make sure the anchorage length is adequate to satisfy the pull-out force requirement. In an earthquake-prone setting, Aurelian C. Trandafir et al. [15] investigate the seismic performance and efficacy of anchor reinforcement versus gravity retaining walls used to sustain a dry, homogenous fill slope. When peak earthquake accelerations exceed 0.5g, the superiority of anchors over gravity retaining walls becomes considerable, indicating that anchor systems would be a preferable choice for stabilizing earth constructions in seismically active areas.

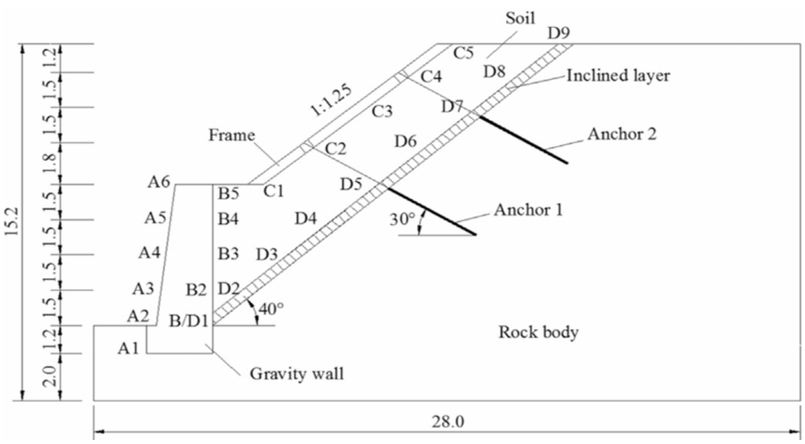


Fig 2. The gravity retaining wall with anchoring frame beam (unit: m) [14].

## IV. CHEMICAL AND POLYMER BASED STABILIZATION METHODS

Yuxia Bai et al. [28] studied looks on the use of polyurethane (PU), a synthetic polymer, to stabilize silty sand slopes. To evaluate the polymer's capacity to improve soil mechanical qualities and advance ecological preservation, the authors carried out both lab and field testing. According to their research, PU greatly improves soil tensile and shear strength, water retention, and erosion resistance, which encourages vegetation development and stabilizes slopes.

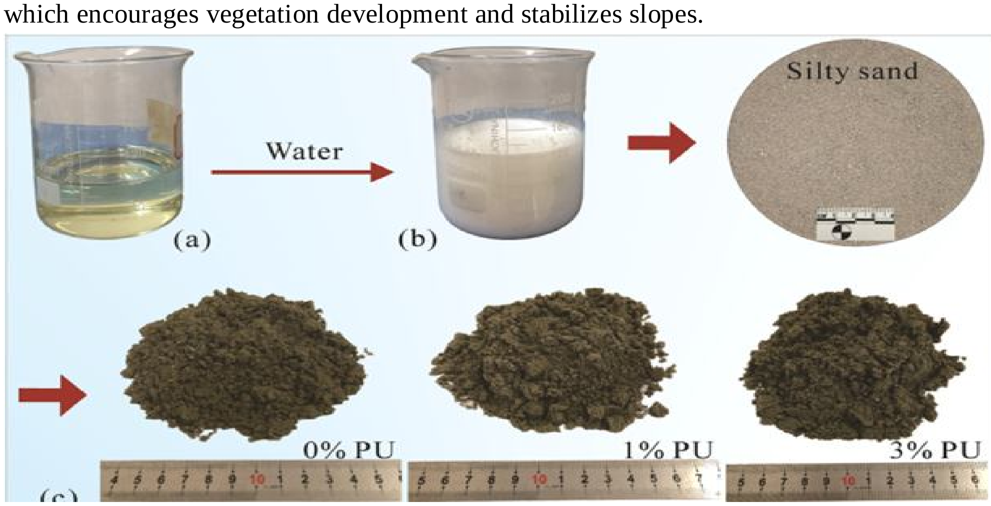


Fig 3. (a) Polyurethane; (b) Milky-white emulsion; (c) PU-sand mixture with different PU contents[28].

Numerous numerical investigations on the stability of expansive soil slopes stabilized using lignosulfonate (LS) were reported by Ijaz et al. [29]. LS-based stabilizers are found to be very successful in using composite cementing admixture to enhance stability against rainfall-induced slope failures, given the hybrid impacts of hydraulic and hydro-mechanical processes. In areas where LS showed promise for stabilizing expansive soils exposed to high rainfall, treatment decreased the possibility for swelling and increased the stability values of slopes. The long-term geotechnical characteristics of high-plasticity clay stabilized with lignosulfonate were investigated by Ta'negonbadi and Noorzad [30]. They found that whereas LS had only minor effects on the internal friction angle, it greatly boosted the clay's cohesiveness from 1 to 7 kPa. However, the evaluated LS supported it as an ecologically acceptable stabilizer for improving the strength qualities of clay, with just a minor strength drop occurring in direct shear testing and negligible effects during soaking and drying cycles. Wang et al. [31] state that soil stabilization during the ecological restoration of rock slopes can be accomplished with polyvinyl acetate (PVA). The cohesion, erosion resistance, water retention capacity, and plant growth of the soil were all markedly enhanced by the addition of 3% PVA. The mechanical properties most significantly demonstrated a 50% increase in cohesion and a 3.5° rise in internal friction angle. PVA appears promising for slope ecological recovery over the long run. In order to stabilize clayey slope topsoil, particularly for erosion control, Liu et al. [33] investigated an organic polymer called STW. The study resulted in improvements in unconfined compressive strength, shear strength, water stability, and erosion resistance. Field tests demonstrated that the application of STW could create a protective membrane on the soil surface, allowing for significant reductions in soil loss while promoting vegetation growth.

According to Yingcheng Luan et al. [34], clay soils can be made more stable and strong during subgrade construction by using a liquid polymer stabilizer called vinyl acetate-ethylene. The impact of different stabilizer contents as well as curing time on water stability and UCS (unconfined compressive strength) are discussed in the paper. In the investigation, methods like SEM, EDS, and FTIR have been employed to look into the microstructural alterations brought on by the stabilizer. Falk Ayub et al. [35] investigate whether stabilized soil can lessen environmental effects while enhancing engineering qualities as stability, permeability, strength, durability, and swell-shrink behavior. To improve soil performance, it also investigates the possible advantages of mixing other additives with geopolymer. It has been discovered that industrial waste-derived geopolymers can significantly improve the behavior of soil solidification. According to Nauman Ijaz et al. [39], lignosulphonate, a by-product of the paper and wood industries, can be used to stabilize expansive soils that experience significant volume variations during wetting-drying cycles. The authors propose combining lignosulphonate with lime to get over the drawbacks of using lignosulphonate as a stabilizing agent by itself. By using less lime, this technique is less costly, more environmentally friendly, and contributes to the reduction of industrial waste.

## V. BIO-GEOTECHNICAL APPROACHES FOR SUSTAINABLE STABILIZATION

Gowthaman et al. [27] examined if microbial-induced calcite precipitation (MICP) is a suitable method for stabilizing the Hokkaido highway slope in Japan. By using inexpensive chemicals and native ureolytic bacteria, soil strength was significantly increased up to a UCS value of 820 kPa. Additionally, the use of low-grade chemicals resulted in a 96% reduction in treatment costs, indicating the possibility of MICP for widespread use with financial advantages. Sivakumar Gowthaman et al. [37] investigated the shear strength and freeze-thaw durability of cemented slope soils treated with the MICP, a biological soil stabilization method. MICP improves soil cohesiveness by generating calcium carbonate, which increases soil strength and durability, particularly in areas that are susceptible to frost cycles.

J. De Ona et al. [41] examined plant cover and erosion on road slopes that had been hydroseeded with sewage sludge. Road embankments that have been restored with sludge present less health and waste management issues because food crops are not grown there. Sludge is a by-product of wastewater treatment procedures, and its production has significantly increased in Europe. To solve the problems garbage poses, it is crucial to efficiently manage and reuse this increasing amount of waste. Conventional hydroseeding (CH) is a mechanical planting technique that entails misting a specific area with a slurry mixture of seeds, fertilizer, stabilizers, and additives. The results suggest that higher sludge dosages promote better vegetation growth, likely due to the improvement in soil quality provided by the sludge. Furthermore, during colder and drier seasons, when conditions for plant growth are more challenging, slopes treated with sludge exhibited a vegetation cover of over 20%, while those without sludge had a cover of less than 20%. According to Suzanne Donn et al. [42], compost amendments increase soil fertility, reinforce the surface soil on slopes, and promote root growth. Grass and shrubs are examples of vegetation that can improve cohesiveness, increase slope stability, and lower the chance of shallow collapses once their roots pierce the soil. Poor soil fertility, which is frequently present in disturbed soils utilized in engineering projects, tends to impede the development of vegetation.

For a number of reasons, using high-quality green compost while building slopes greatly strengthens the soil slopes at the depths that plant roots may reach. By raising the concentrations of vital plant nutrients like nitrogen (N), phosphorus (P), potassium (K), and magnesium (Mg), it first improves soil fertility. Most significantly, it strengthens the slope by promoting stronger vegetation establishment, which in turn promotes greater plant root development.

By strengthening soil cohesion, M. Burylo et al. [43] found that using the roots of six dominant species to rebuild soil on eroded mountainous marly slopes improves slope stability. These plant species have roots that pierce the earth, binding soil particles together, preventing erosion, and strengthening the slope's structural stability. Significant soil loss results from water-induced soil erosion, a problem that affects both wild and farmed areas worldwide. This study found that throughout their early phases of development, grasses and shrubs increased the soil shear strength in the topsoil more than tree species did. When combined with knowledge of vegetation dynamics, ecological site properties, and species' resistance to erosion, these findings can assist in assessing land vulnerability to erosion and evaluating the effectiveness of restoration efforts in eroded landscapes.

## VI. GEOSYNTHETICS AND REINFORCEMENT BASED TECHNIQUES

### *A. Geosynthetics*

A study by Raman Jeet Singh et al. [17] examined the impact of locally made need-based agro-geotextiles (AGTs). The study's main conclusions show that locally produced need-based AGTs made from perennial grasses like Arundo donax or other comparable vegetation can effectively replace a conventional system in the context of climate change scenarios where extreme rainfall events occur frequently. Using geotextiles, Fangyue Luo et al. [18] investigated an efficient reinforcing strategy for slopes that encounter different stresses, including drawdown. A border that was unaffected by the drop in water level separated the restricted zone from the anchoring zone on the geotextile-reinforced slope. In the anchoring zone, the earth held the geotextile in place, while in the restricting zone, the soil held the geotextile in place. They discovered that the geotextile arrangement had a major impact on the reinforcing effect. Only after the geotextile was sufficiently long to traverse the unreinforced slope's slip surface did the reinforcement start to work.

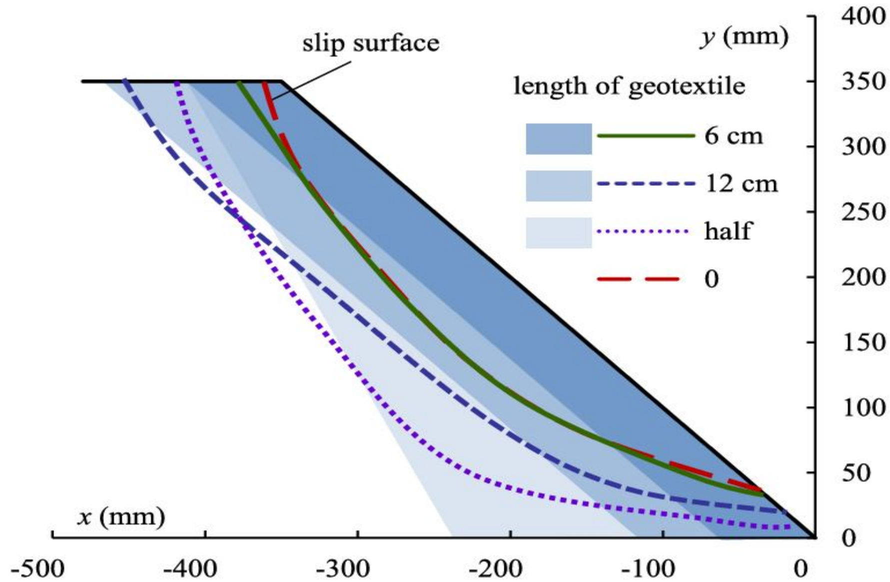


Fig 4. Slip surfaces of the slope with different geotextile layouts under drawdown conditions[18].

When evaluating the efficacy of wool geotextiles in comparison to other materials, Jan Broda et al. [19] used recycled fibers to make the ropes. These ropes were made using a nonwoven fabric made by combining synthetic and natural fibers that were shredded from post-consumer textile waste. As soon as the geotextiles were put in place on the slopes, they provided efficient defense against water erosion. Transversely positioned on the slopes, the successive layers of winding ropes reduced topsoil's gravity sliding and stopped soil particles from being carried away by rainfall runoff. Furthermore, the geotextiles encouraged the topsoil to stabilize and adhere to the slopes' solid ground. The studies demonstrated that wool and wool waste can be utilized in producing geotextiles intended for short-term protection of steep slopes at risk of sliding and water erosion.

Ennio M. Palmeira et al. [20] reported the outcomes of extensive tests using granular and geotextile filters on armored slopes. Using three different kinds of nonwoven geotextiles and a conventional granular layer as filters between the armor layer and the underlying soil slope, the experiments were conducted in a wave flume. The turbidity of the water in the channel, which is an indirect measure of the intensity of soil piping, was considerably decreased by the geotextile filter. The turbidity levels measured for the granular filter after a few hours of testing were similar to those found in tests using geotextile filters. Nariman Khorsandiardebili et al. [21] investigated the use of the limit equilibrium method (LEM) for seismic analysis of slopes reinforced with geocell layers. By treating the geocell as an element that can withstand bending moments, tensile forces, and shear forces all at once, the established method emphasizes the benefits of using geocells in such applications.
The stability of geocell-reinforced slopes was examined by Nariman Khorsandiardebili et al. [22] using the Limit Equilibrium Method (LEM) in conjunction with the Hyperbolic Stress Model (HSM). The effect of raising the height of reinforcement on the stability of cohesionless slopes with different characteristics is evaluated through parametric tests. Based on equilibrium assessments, the analysis focuses on figuring out the tension and length of reinforcement layers needed to guarantee slope stability. M. Inanc Onur et al [23] studied the behavior of supported slopes with geotextiles and geogrids were analyzed by performing experiments on slope models in laboratory. Geogrid members give less deformations and higher strength comparing with geotextile members. A reliability analysis of three-dimensional (3D) vertical geosynthetic-reinforced slopes was conducted by C.Q. Hou et al. [26] to investigate the evolution of the slope's probabilistic stability under different rainfall patterns over time. Based on the Conte-Troncone (CT) model, a 3D horn-like mechanism served as the basis for deterministic analysis.

### *B. Piles*

An analytical approach for calculating a micropile's ultimate resistance was proposed by Shu-Wei Sun et al. [24], who combined the p-y curve method with a beam-column equation. The bending moment and shear capacity of the micropile section are determined iteratively. Furthermore, a formula is developed for the finite difference approach of calculating the micropile's internal forces and deflections. An embankment landslide in Qinghai Province, China, is the subject of a detailed application of the concept; monitoring data indicates that slope movement essentially stopped after the stabilization measures were put in place. This result validated the design approach's efficacy. Long Wang et al.'s analysed [25] Landslide tragedies can be avoided with the use of bench slopes strengthened with several rows of anti-slide piles. This method is frequently applied for designing new embankments and subgrades. The upper bound limit analysis approach is used in this study to do a 3D limit analysis of bench slopes stabilized by multiple rows of piles. Bench slopes stabilized with several rows of piles are substantially less stable than slopes stabilized with just one row of piles. The maximum pile reinforcement is 70% for slopes with sandy soil and only 30% for slopes with clayey soil.

### *C. Fibers*

In their investigation of contemporary developments in stabilizing collapsible soils, Mohammad Ali Khodabandeh et al. [40] concentrate on elements such fibers, polymers, nanomaterials, industrial waste, and microbes. Extreme volume changes posed a concern to construction projects in collapsible soils, mainly loess. The capacity of different stabilization materials to boost soil strength and reduce the likelihood of its collapse is discussed by the authors. Nanomaterials and biological solutions are among the most promising treatments for collapsible soils; this balances and sets selection parameters for stabilization materials, such as soil type, environmental considerations, and cost. With nanomaterials and biological solutions positioned as the most advanced techniques for enhancing collapsible soils, this research emphasizes the significance of choosing the right stabilization material depending on soil type, environmental conditions, and cost.

## VII. ROLE OF REMOTE SENSING AND GIS IN EROSION AND STABILITY ASSESSMENT

Claudio Vanneschi et al. [44] investigate the advantages of combining several remote sensing methods for identifying and tracking slope instability, with an emphasis on mining-related applications. The study examines the benefits and drawbacks of several remote sensing technologies, such as Structure from Motion (SfM) photogrammetry, Airborne LiDAR (AL), Mobile LiDAR (ML), Terrestrial LiDAR (TL), and Light Detection and Ranging (LiDAR). In order to overcome the shortcomings of individual approaches and provide a comprehensive dataset for a range of engineering-geological applications in the mining industry, this document's unique insight is its emphasis on the complementary usage of several remote sensing techniques. The paper highlights the importance of integrating data from multiple sources to obtain a complete and detailed understanding of the slope geometry, rock mass characteristics, and potential instability mechanisms, which is crucial for ensuring the safety and stability of mining operations.

M. Francioni et al. [45] investigated an open pit quarry in the Carrara marble district of Italy using an integrated remote sensing and GIS technique. The main goals are to use kinematic and numerical modeling techniques to evaluate the stability of the quarry slopes and to describe their structural geological setting and shape. The researchers used two remote sensing methods: digital terrestrial photogrammetry (DTP) based on unmanned aerial vehicles (UAVs) and terrestrial laser scanning (TLS). Kinematic stability analysis and structural geology mapping were conducted using the high-resolution 3D model of the quarry slopes that was produced by combining the TLS data with UAV-acquired photogrammetric pictures. In addition, an engineering geological survey was conducted to describe the characteristics of the rock mass. In order to qualitatively evaluate slope stability, Xiang Sun et al. [48] combine geological studies and extensive remote sensing. They then use numerical analysis to determine aging stability quantitatively. In particular, time-dependent mechanical and strength reduction calculations are incorporated into a time-dependent stability calculation approach built and implemented in discrete element software for anticlinal slopes. This makes it possible to identify landslides by taking into account both geomorphological characteristics and time-dependent behaviours. The study's distinctive findings include the fact that a possible landslide does not always include the characteristics of a landslide, and a slope with landslide geomorphology is not always a landslide. Instead of concentrating only on surface geomorphological features, the study highlights the significance of taking the time aspect and evolution history into account when assessing slope stability. For examining slopes with comparable landslide geomorphology in the Qinghai-Tibetan Plateau and other intricate geological settings, this method provides helpful direction.

## VIII. NUMERICAL AND EXPERIMENTAL MODELLING IN SLOPE STABILIZATION

Shailendra P. Banne et al. [46] used a thorough methodology to examine how XG affects the engineering characteristics of laterite soil and how it affects slope stability. This included both experimental research and numerical analysis using the PLAXIS Limit Equilibrium (LE) program. In the experimental investigations, the permeability, strength parameters, compaction features, and index properties of laterite soil with different XG concentrations (1% to 5% by dry weight of soil) were determined. According to the slope stability analysis conducted with PLAXIS LE, the addition of XG improved the Factor of Safety (FOS) by an average of 6% under normal conditions and 57.25% under submerged situations. It was discovered that 2.7% was the ideal XG content for the submerged slope condition, yielding the highest FOS. For the purpose of assessing the stability of rock and soil slopes, Zhongjie Wang et al. [47] suggested using finite element analysis. Establishing a numerical model of the geotechnical slope, figuring out the loads on the slope, and carrying out the finite element analysis while taking the soil strength parameters' fuzzy nature into account are all part of this process. The technique determines the safety factor by progressively lowering the soil strength parameters until the slope becomes unstable.

## IX. CONCLUSION

The effective management of erosion and slope stabilization requires a multidisciplinary approach that integrates engineering principles with environmental sustainability. Advances in materials science and soil stabilization techniques have significantly improved our ability to counteract slope instability, as demonstrated by the use of innovative solutions such as geosynthetics, bioengineered systems, and polymer-based stabilizers. These methods enhance soil cohesion, shear strength, and water retention, thereby reducing the risks of failure under adverse conditions like intense rainfall or seismic events.

The reviewed studies highlight the importance of tailoring stabilization strategies to specific site conditions. For instance, geotextiles and geogrids are highly effective in mechanical stabilization, while lignosulfonates and polymers serve as efficient chemical stabilizers, especially in soils prone to expansive behaviour. Biological approaches, including vegetation establishment and microbial-induced calcite precipitation, offer environmentally friendly and cost-effective alternatives, promoting ecological balance while ensuring stability.

Future research should focus on optimizing the integration of these methods to achieve durable, sustainable solutions that address both immediate engineering challenges and long-term environmental impacts. By combining advanced technologies with traditional practices, the field of erosion control and slope stabilization is poised to contribute significantly to safe and sustainable infrastructure development in diverse geotechnical settings.

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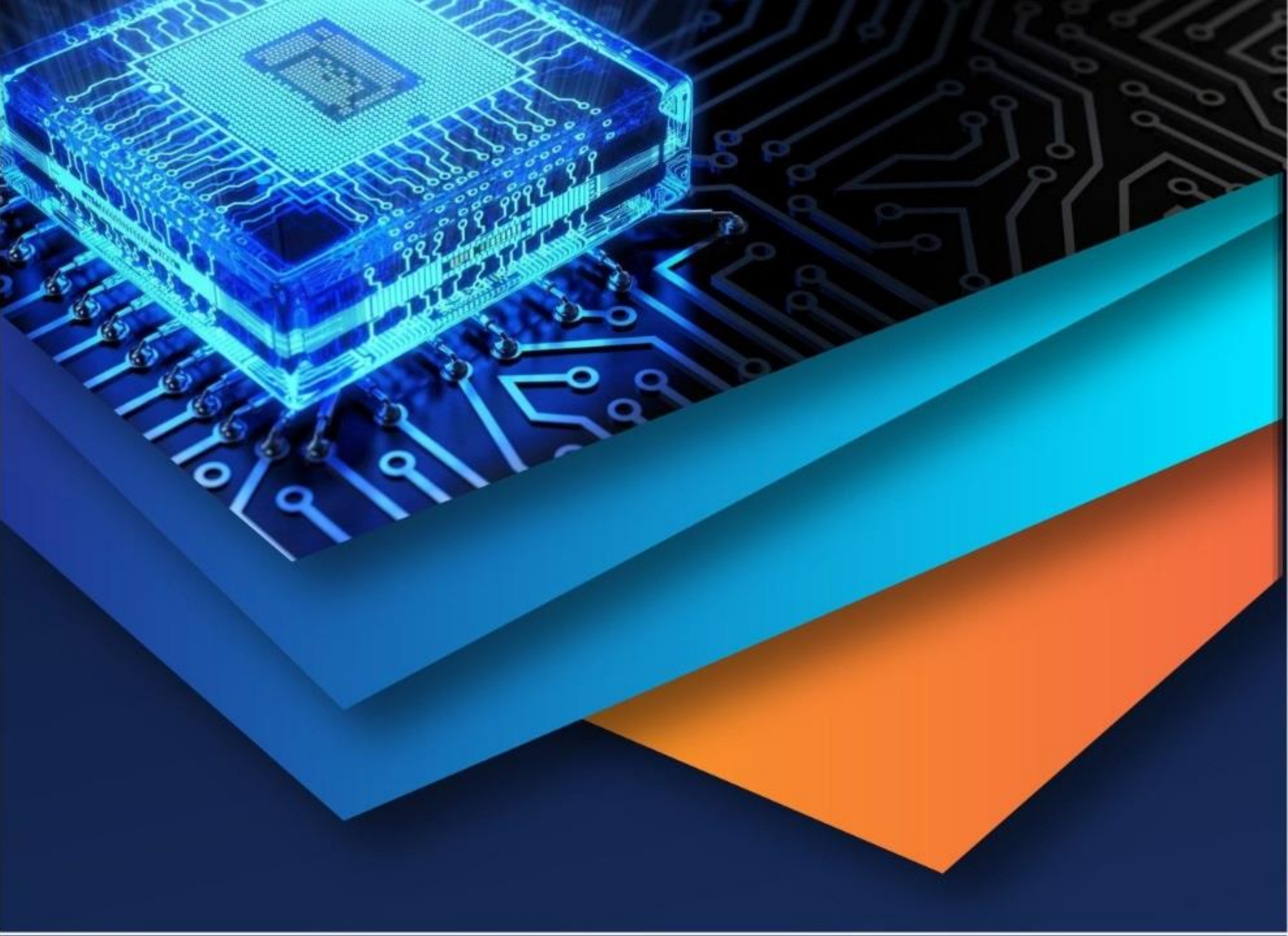


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