# Evaluating The Effectiveness of Plant-Based Soil Stabilization: A Laboratory Study on Slope Prototypes

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***Abstract*— In India, there are various regions significantly vulnerable to slope failures owing to intense & prolonged rainfall events, earthquake, unplanned construction activities etc. Hence it is required to adopt the soil stabilization techniques. Conventional stabilization methods include; mechanical reinforcement and chemical additives that improve the soil strength but might cause the sustainability concerns like high carbon footprint, loss of soil biodiversity and long-term soil degradation etc. Due to environmental, ecological and economical limitations occurs with conventional mechanical and chemical; stabilization methods there has been need to shift the focus on sustainable approaches such as vegetation-based stabilization. In addition to that, plant-based stabilization proves sustainable method which use root systems to naturally improve the soil characteristics while reduce the erosion, increase stability of soil. This paper investigates vegetative soil stabilization as a sustainable approach to improve the engineering properties of soil. In this study, in-situ slope prototype was prepared using black cotton soil and sand mixture in a 2:1 ratio. The Napier grass was elected as the vegetative solution based on comprehensive literature review with taking into account of its adaptability and drought tolerance. After a maturity period of 2 months, the shear strength of the material was re-evaluated. The slope profile of prototype was analysed using GeoStudio software to determine the factor of safety (FoS). The study concluded that, the overall integrity of the slope and shear strength of the soil has been positively enhanced by vegetation stabilization by higher factor of safety values, improved soil shear parameters (cohesion and internal friction), and root reinforcement effects seen in analysis or experimental results, which illustrating its potential as sustainable alternate for regions where problems like soil erosion occur.**

***Index Terms*— Sustainability, Stabilization, Prototype, Napier grass, Shear strength, GeoStudio.**

## I. INTRODUCTION

Slope stabilization is an important aspect of geotechnical engineering that focuses on improving the stability of slope. Slope may become unstable due to various internal and external factors, such as rotational failure, translational failure and compound failure. Among these, toe rotational failure, slope failure occurs it may cause due to natural and anthropogenic factors, it depends on soil conditions and slope geometry. Natural causes include heavy & prolonged rainfall, earthquake, weathering, erosion, and phenomena like liquefaction, while human activities such as excavation, deforestation, and improper construction practices also significantly contribute instability of slopes. Studies indicate that a large proportion of slope failure worldwide are due to prolonged and intense rainfall, all triggering factors rainfall has been identified as most dominant cause of failure, as it increases pore water pressure and reduces soil shear strength, leading instability [8-9, 26].

## II. LITERATURE REVIEW

In India, the vulnerability of slope failure has apparently increased due to combination of manmade induced activities like deforestation, mining activities, unplanned urbanization and natural factor like heavy rainfall, earthquake [4,7-8]. These natural triggers, especially earthquakes and heavy rainfall, have caused several severe slope failure events in recent years.

Catastrophic events like Irshalwadi landslide (2023) and the Malin slope failure (2014) are the results of heavy and prolonged rainfall events.

In response to these repeated slope failure events, different soil stabilization techniques have been created to improve slope stability and lower related risks. Conventional soil stabilization methods include like mechanical reinforcements (e.g., geotextiles or geonets or soil nails), and chemical additives with cement or lime binders to enhanced soil properties and prevent slope failures [4,8]. But these approaches are effective for limited period, they are attributed with significant ecological drawbacks, which includes high carbon particles emission, water contamination and proves hazardous to ecological footprints. Also, utilization of these methods can be unsustainable and uneconomical, primarily in environmentally sensitive and rural areas where heavy machineries and materials are complicated to deploy in the environment [9, 26].

To overcome to this, vegetation stabilization has emerged as feasible alternative that integrate with principles of sustainability restoration [9,13,25]. The combination of mechanical and hydrological effects of vegetation technique facilitate to slope stability improvement. Plant roots connect with soil by mechanically interlocking, which increases apparent cohesion and improves shear strength. Above-ground biomass reduces surface runoff and increases water infiltration. This minimizes soil erosion and helps improve slope stability.

Vegetative stabilization helps stop shallow landslides. It controls surface erosion. So, it works well in areas prone to landslides. In contrast, its effectiveness is dependent on the selection of most suitable vegetation species, with different root properties. Indigenous plants having characteristics such as deep roots, fibrous structure, or fast-germination root, considered most optimal on unstable slopes [5-6].

Conventional stabilization methods: mechanism and application—summary table

Table 1: Conventional stabilization methods: mechanism and application

| Stabilization Method | Mechanism | Application | References |
|---|---|---|---|
| Lime Stabilization | Lime dissociates calcium ions, which react with alumina and silica in clayey soil to form cementitious compounds (CSH and CAH) which reducing plasticity through cation exchange and flocculation and increase shear strength | High plasticity soil (Clayey soil) | [8] |
| Cement Stabilization | The cement particles reacts faster than lime because it contains silica and alumina. It forms (CSH) and (CAH) during hydration process without relying on soil composition, making it effective for various soils | Inorganic soils (with organic content < 2%) | [8] |
| Polymer (Biopolymer) Stabilization | Polymers form a gel like material that binds adhesively with soil particles | Fine-grained soil (clay and silt) | [8] |
| Geosynthetics Stabilization (Geotextiles, Geogrids) | Geotextiles and Geogrids provide separation, filtration and reinforced the soil by distributing loads. | All types of soil | [8,25] |
| Fly Ash Stabilization | Fly ash stabilizes the soil by pozzolanic reaction with pore filling mechanism, which enhancing strength and minimizing plasticity. | Fine-grained soil (clay and silt) | [8] |
| Gravel and Sand Stabilization (Blending) | Compaction of soil strata with Gravel increases bearing capacity and optimize drainage problems | Fine-grained soil (clay and silt) | [8] |
| Plant-Based Stabilization (Vegetation) | It includes, grass turfing, hydroseeding, natural fibre, brush layering, and bio-matting for erosion control to improve cohesion and reduce erosion. | All types of soil | [1,3,7,10,21] |

Traditional soil stabilization methods like mechanical techniques, chemicals additives etc. The soil stabilization methods have come in market with based on engineering needs and sustainability concerns. The earliest method was gravel and sand stabilization (blending), which is used on fined-grained soil with increase drainage and reducing shrinkage effects. After that Lime stabilization is developed to use in cohesive soil (clayey soil). Later, Cement stabilization introduced to achieve the stiffness in inorganic soil. To minimizing cost and environmental concerns, Fly ash is use for stabilization, which utilize the industry waste and improving soil properties by pozzolanic reactions. With advancement in techniques Geosynthetics solutions was introduced to provide separation, filtration and reinforced the soil by distributing loads. The most recent invention is Polymer stabilization, which enhances the adhesion with soil particles with fine-grained soil. However, with pros they consist cons too, such as high initial cost, environmental concerns, stabilization techniques changes with soil-to-soil characteristics.

Plant-based stabilization emerges as an eco-friendly approach that tend to improve soil properties via different mechanism and reduces the erosion potential of soil mass.

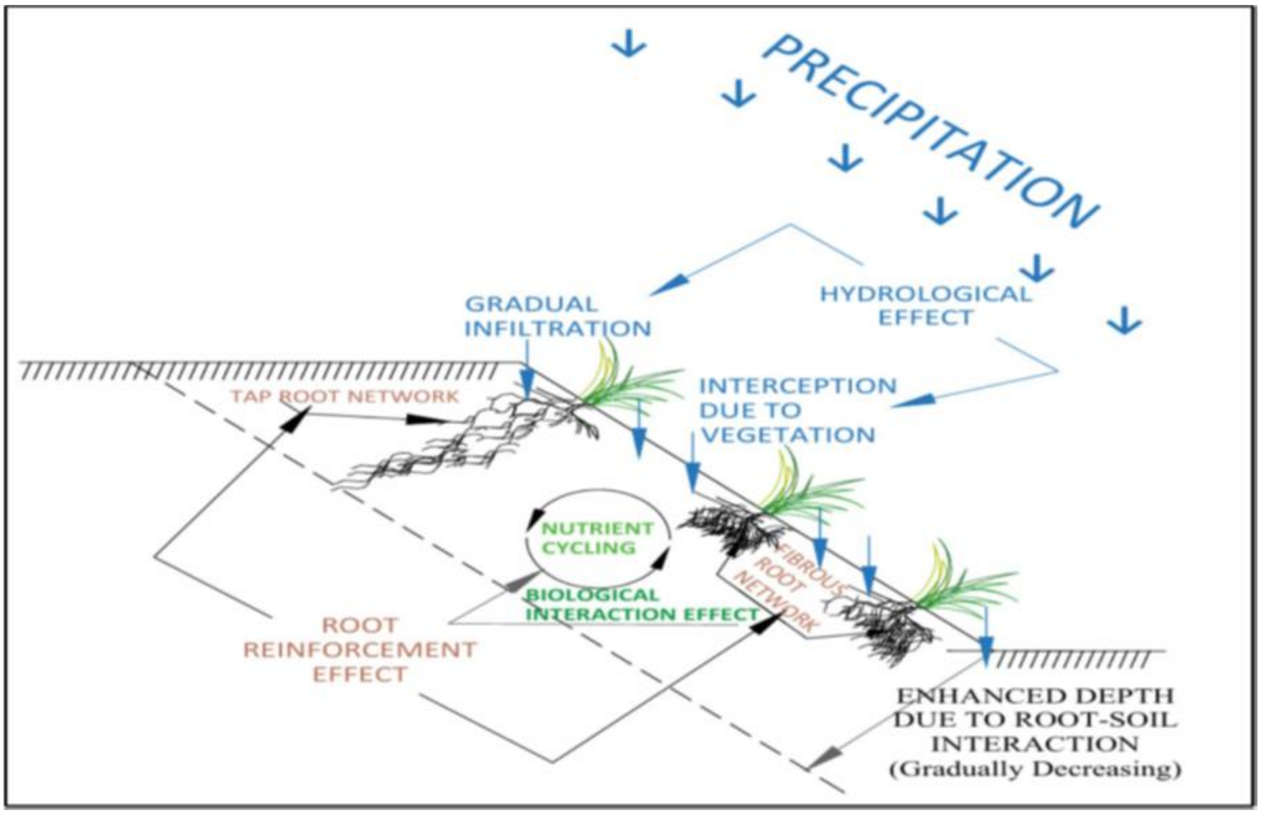


Figure 1: Schematics of plant-based stabilization mechanism [26]

Figure 1 shows the schematics of plant-based stabilization mechanisms. It includes rainfall interception, root reinforcements, and biological interactions. Foliage cover reduces the raindrop impact, while vegetative residue and roots boosts water retention and infiltration, which indirectly overcome erosion and runoff problems [12,19]. By interlocking soil particles, root systems work as a natural reinforcement, which enhance soil cohesion property and improve shear strength [14,28]. Biological process in the rhizosphere zone which stimulate microbial activity and biogeochemical cycling, while the degraded roots increase soils field density and cohesion. Furthermore, roots make changes in pH and maximize nutrients which increases overall cohesion and soil stability [20,22].

III. METHODOLOGY

The study is substantially based on laboratory testing and numerical modelling. Basic geotechnical tests were performed with compliance to IS 2720.

The experimental work includes determination of basic geotechnical properties for three sample sets.

a) Only clay
b) Only sand
c) Clay + sand (2:1)


Figure 2: Different testing on prepared soil sample

After experimental testing, slope prototype was prepared using sample set three (clay plus sand in 2:1 proportion) for a prototype size 120 cm X 90 cm X 85 cm and slope of 35 degrees.

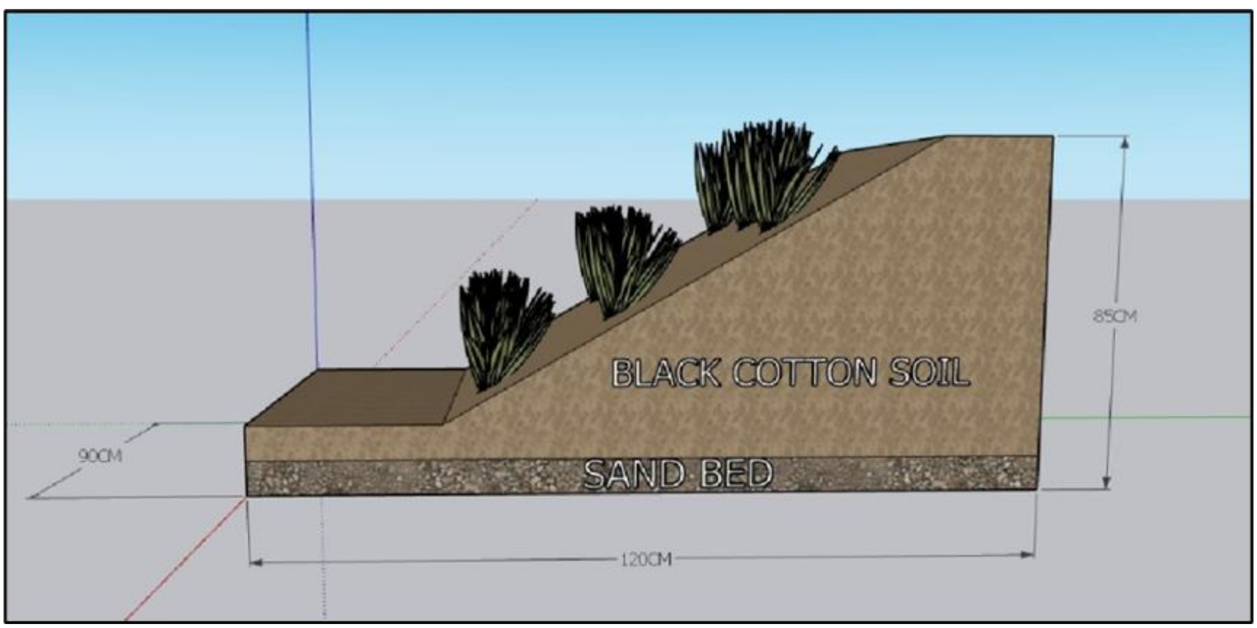


Figure 3: Slope Prototype model

Figure 2 represents the slope prototype model vegetated with napier grass saplings. The choice of vegetation majorly depends upon climatic condition and soil type. There are different types of grasses used for slope stabilization such as vetiver grass, lemon grass, Bermuda grass, napier grass, era, eva, etc.

However, the Napier grass was selected due to its dense and strong root system, high germination rate, drought tolerance and most important local availability. The prototype is monitored and maintained for a 2 to 3 based on literature review, it is understood that napier grass required 2 to 3 months to grow roots.


Figure 4: Prototype construction and observation period

During the period of monitoring, it was taken care that regular water is provided to the slope so as to ensure adequate growth. After the end of 3 months, the above ground biomass was cut using gardening scissors and the rooted sample was extracted from the prepared slope. The sample was then tested under unconfined compression strength test (UCS). The experimental results i.e., pre vegetation properties & post vegetation properties (from extracted sample) were then used to model a similar slope in GeoStudio.

## IV. SLOPE STABILITY ANALYSIS

Slope stability was analysed by using geo studio software. Slope stability mainly depends on the balance between two types of forces; the driving forces such as gravity and water pressure try to pull the soil downward while the resisting forces like soil cohesion and internal friction help to keep the slope stable.

If the resisting forces are greater than the driving forces the slope remains stable. However, if the driving forces become higher there is a risk of slope failure. GeoStudio makes use of limit equilibrium methods such as Bishop's Simplified Method, Janbu Method, Spencer Method, Morgenstern–Price Method.

The Morgenstern–Price method is selected for this analysis. This method is known for its high accuracy and reliability, as it accurately satisfies both force and moment equilibrium and incorporates a variable inter slice force function, allowing for more precise simulation of stress distribution and soil root interaction effect in real field condition such as vegetated slopes.

Further, a comparative analysis was conducted to evaluate the effect of vegetation on slope stability. In this study, the Factor of Safety of a barren slope was compared with that of a vegetated slope. The same modelling procedure was adopted for both cases using SEEP/W for seepage analysis and SLOPE/W for stability analysis to ensure consistency in results.

According to standard stability criteria, a Factor of Safety less than 1 indicates slope failure (unstable condition), whereas a Factor of Safety greater than 1 indicates a stable condition. The results demonstrate that the vegetated slope exhibits a higher Factor of Safety compared to the barren slope, indicating improved shear strength and enhanced overall slope stability due to vegetation.

Table 2: Properties assigned to Barren and Vegetated soil slope model

| Parameter | Vegetative slope model | Barren slope model |
|---|---|---|
| Number of material regions | 3 regions | 2 regions |
| Top layer material | vegetation | No vegetation layer |
| Soil material | Clay+sand, sand | Clay+sand, sand |
| Unit weight / density (kN/m³) | Vegetation = 21, Clay+sand = 19.6, Sand = 21 | Clay+sand = 19.6, Sand = 21 |
| Cohesion (c') (kPa) | Vegetation = 43, Clay+sand = 30, Sand = 0 | Clay+sand = 30, Sand = 0 |
| Angle of internal friction (φ') | Vegetation = 33°, Clay+sand = 27°, Sand = 25° | Clay+sand = 27°, Sand = 25° |

| | | |
|---|---|---|
| Seepage model | SatUnsat | SatUnsat |
| Slope model | Mohr-Coulomb | Mohr-Coulomb |
| Hydraulic conductivity (ksat) (m/s) | 0.0001 | 0.0001 |
| Residual water content | 0.02 | 0.03 |
| Saturated water content | 0.40 | 0.35 |
| Volumetric water content function | Fn 1 | Fn 2 |
| Analysis method | Morgenstern–Price | Morgenstern–Price |
| Factor of Safety | ~1.20 | ~0.77 |

## V. RESULTS AND INTERPRETATION

Napier grass (Pennisetum purpureum) was chosen for its dense fibrous root system, which helps bind the soil and increases shear strength. The results showed that it improves slope stability by raising the factor of safety when compared to barren soil. Its fast growth and ability to adapt offer effective erosion control early on. Therefore, it is a suitable and cost-effective choice for soil stabilization.

Unconfined Compressive Strength (UCS) tests had been conducted on both barren and vegetated soil samples to evaluate strength parameters. The results had indicated an increase in cohesion values in the vegetated samples due to root reinforcement effects. This improvement had enhanced the overall shear strength and stability of the soil. Hence, vegetated soil had exhibited better resistance to deformation and failure compared to barren soil.

### 5.1 Slope Stability Analysis (GeoStudio Results)

#### 5.1.1 Barren Soil Slope

The slope stability analysis for the barren soil condition showed a Factor of Safety (FoS) of approximately 0.768, which is less than 1. This indicates that the slope is unstable and prone to failure.

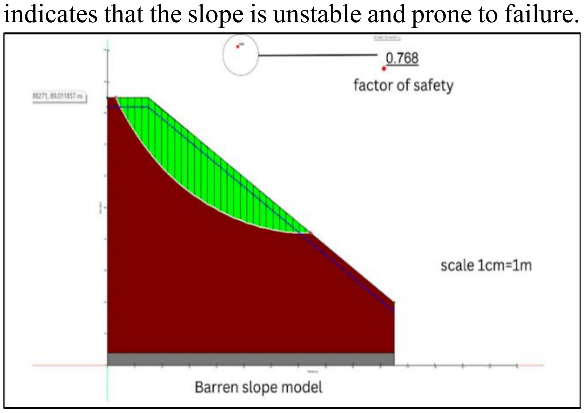


Figure 5: Barren slope model

The analysis also showed lower resisting forces and moments compared to driving forces, confirming that the soil without vegetation lacks sufficient strength to maintain slope stability.

#### 5.1.2 Vegetated Soil Slope

For the vegetated slope condition, the Factor of Safety (FoS) was found to be approximately 1.203, which is greater than 1. This indicates that the slope is stable under vegetated conditions.

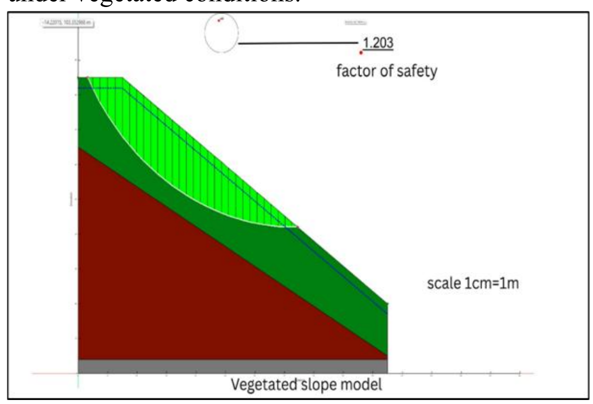


Figure 6: Vegetation slope model

The increase in FoS is due to higher resisting forces generated by root reinforcement. The vegetation improves soil cohesion, reduces pore water pressure, and enhances overall slope resistance.

### 5.2 Comparative Interpretation

Table 3: Difference between FoS

| Type of slope | Factor of safety (FoS) |
|---|---|
| Barren soil slope | 0.768 |
| Vegetated slope | 1.203 |

A clear comparison between barren and vegetated slopes shows a significant improvement in stability due to vegetation. The Factor of Safety increased from 0.768 (unstable) to 1.203 (stable) after introducing vegetation.

Additionally, the vegetated slope exhibited higher resisting forces and moments, along with reduced pore water pressure effects. This demonstrates that plant-based stabilization effectively enhances soil strength and slope performance.

## VI. CONCLUSION

1. The study looked at how vegetation, particularly Napier Grass, affects slope stability. It did this by comparing barren slopes to those with vegetation using GeoStudio.
2. The barren slope had a Factor of Safety (FoS) of less than 1, which shows it was unstable. In contrast, the vegetated slope had a FoS greater than 1, indicating it was more stable.
3. This stability improvement comes from root reinforcement, which boosts apparent cohesion and increases resistance to shear failure.
4. Vegetation also helps with better water management by affecting moisture distribution and reducing the negative effects of pore water pressure.
5. Using the Morgenstern-Price method allowed for a reliable analysis of slope stability in both conditions.

Overall, the study suggests that Napier Grass is a cost-effective and environmentally friendly choice for stabilizing shallow slopes.

## VII. FUTURE SCOPE

The present study can be further extended to enhance its practical applicability and depth of analysis:

1. The effectiveness of different types of vegetation can be evaluated through comparative studies carried out in combination with Napier Grass.
2. It is possible to modify the assessment to include rainfall infiltration condition and seismic loading condition for more realistic assessment.
3. Advanced modelling of 3D slope stability can be done for better field representation terms.
4. The long-term performance of Napier Grass under varying climatic and environmental conditions.

## REFERENCES

[1] K. M. Schmidt, J. J. Roering, J. D. Stock, W. E. Dietrich, D. R. Montgomery, and T. Schaub, "The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range," *Canadian Geotechnical Journal*, vol. 38, no. 5, pp. 995–1024, 2001.

[2] M. Schwarz, D. Cohen, and D. Or, "Root–soil mechanical interactions during pullout and failure of root bundles," *Journal of Geophysical Research: Earth Surface*, vol. 115, no. F4, p. F04035, 2010, doi: 10.1029/2009JF001603.

[3] T. H. Wu, "Root reinforcement of soil: Review of analytical models, test results, and applications to design," *Canadian Geotechnical Journal*, vol. 50, no. 3, pp. 259–274, 2013.

[4] Jaisingpure, R. Waghmare, A. Dhomse, and R. Bhoyar, "Construction techniques to prevent landslides," *Journal of Aquatic Science*, vol. 9, no. 2, pp. 85–90, 2021.

[5] N. Kumar and S. Kumari, "The efficiency of vetiver grass for slope stabilization and erosion control: A comprehensive review," *Journal of Chemical Health Risks*, vol. 13, no. 6, pp. 3755–3767, 2023.

[6] Kumar, S. K. Das, L. Nainegali, and K. R. Reddy, "Plant and soil interaction for slope stabilization," *Plant and Soil*, vol. 498, pp. 505–522, 2023, doi: 10.1007/s11104-023-06450-4.

[7] K. Singh, "Bioengineering techniques of slope stabilization and landslide mitigation," *Disaster Prevention and Management: An International Journal*, vol. 19, no. 3, pp. 384–397, 2010.

[8] H. Afrin, "A review on different types of soil stabilization techniques," *International Journal of Transportation Engineering and Technology*, vol. 3, no. 2, pp. 19–24, 2017.

[9] D. H. Gray and A. T. Leiser, *Biotechnical Slope Protection and Erosion Control*. New York, NY, USA: Van Nostrand Reinhold, 1982.

[10] L. J. Waldron, "The shear resistance of root-permeated homogeneous and stratified soil," *Soil Science Society of America Journal*, vol. 41, no. 5, pp. 843–849, 1977.

[11] T. H. Wu, W. P. McKinnell, and D. N. Swanston, "Strength of tree roots and landslides on Prince of Wales Island," *Canadian Geotechnical Journal*, vol. 16, no. 1, pp. 19–33, 1979.

[12] D. R. Greenway, "Vegetation and slope stability," in *Slope Stability*. New York, NY, USA: Wiley, 1987.

[13] Stokes, J. E. Norris, R. van Beek, *et al.*, *Eco- and Ground Bio-Engineering: The Use of Vegetation*

*to Improve Slope Stability*. Dordrecht, Netherlands: Springer, 2014.

[14] S. De Baets, J. Poesen, B. Reubens, *et al*., “Root tensile strength and root distribution of typical Mediterranean plant species and their contribution to soil shear strength,” *Plant and Soil*, vol. 305, pp. 207–226, 2008.

[15] M. Genet, A. Stokes, F. Salin, *et al*., “The influence of cellulose content on tensile strength in tree roots,” *Plant and Soil*, vol. 278, pp. 1–9, 2005.

[16] Reubens, J. Poesen, F. Danjon, *et al*., “The role of fine roots in soil reinforcement,” *Earth Surface Processes and Landforms*, vol. 32, no. 11, pp. 1675–1688, 2007.

[17] S. B. Mickovski and R. van Beek, “Root morphology and soil reinforcement potential of woody vegetation,” *Ecological Engineering*, vol. 36, pp. 770–778, 2009.

[18] G. B. Bischetti, E. A. Chiaradia, T. Simonato, *et al*., “Root strength and root area ratio of forest species,” *Plant and Soil*, vol. 278, pp. 11–22, 2005.

[19] N. Pollen and A. Simon, “Estimating the mechanical effects of riparian vegetation on streambank stability,” *Earth Surface Processes and Landforms*, vol. 30, pp. 1309–1324, 2005.

[20] F. H. Ali, N. Osman, and R. Abdullah, “The effects of root architecture on slope stability,” *Ecological Engineering*, vol. 38, no. 1, pp. 47–56, 2012.

[21] N. Osman and S. S. Barakbah, “The effect of plant roots on soil shear strength,” *Electronic Journal of Geotechnical Engineering*, vol. 16, pp. 1667–1678, 2011.

[22] M. Ghestem, R. C. Sidle, and A. Stokes, “The influence of plant root systems on subsurface flow,” *Earth Surface Processes and Landforms*, vol. 36, pp. 196–211, 2011.

[23] C. Fan and C. F. Su, “Role of roots in reinforcing soils on steep slopes,” *Ecological Engineering*, vol. 33, pp. 157–166, 2008.

[24] K. W. Loades, A. G. Bengough, M. F. Bransby, and P. D. Hallett, “Planting density influence on root reinforcement,” *Plant and Soil*, vol. 332, pp. 193–207, 2010.

[25] J. E. Norris, A. Stokes, S. B. Mickovski, *et al*., *Slope Stability and Erosion Control: Eco-Engineering*. Dordrecht, Netherlands: Springer, 2008.

[26] S. R. Chandnani, L. K. Yadu, and A. Thomas, “Plant-based soil stabilization: A journey towards sustainability—A review,” *Indian Geotechnical Journal*, 2025, doi: 10.1007/s40098-025-01374-5.