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Research Article

POTENTIAL OF VETIVER GRASS FOR EROSION CONTROL AND SLOPE STABILIZATION IN SYLHET REGION OF BANGLADESH

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Abstract

Slope stability analysis is critical for evaluating terrain stability, enabling the identification of preventive measures and the prediction of potential failures. This experimental study, conducted at Sylhet Agricultural University, investigates the effectiveness of vetiver grass in reducing soil erosion and improving slope stability through factor of safety calculations. A physical model representing an earthen slope with and without vetiver was developed on campus. Results showed that soil erosion decreased by 75.60% to 77.46% with vetiver compared to bare soil. Using effective stress analysis numerical method and GeoStudio software, the factor of safety was computed for sandy clay samples, where the unit weights of bare and vetiver-rooted soils were 18 kN/m^3 and 17.3 kN/m^3, and average cohesion values were 15 kN/m^2 and 25 kN/m^2, respectively. The factor of safety for bare and vetiver-rooted soil is 1.73 and 2.55, respectively indicating that vetiver enhances slope stability by approximately 1.48 times. These findings demonstrate that vetiver grass is an effective and sustainable option for erosion control and slope stabilization in Sylhet.

Introduction

The slope failure and erosion issues have frequently occurred worldwide, resulting in the loss of productive land, damaged roads, infrastructure, and occasionally even the death of individuals. The projected annual soil loss in Bangladesh is 4.2 tons/ha and 7–120 tons/ha for slopes between 30–40% and 40–80% (Banglapedia, 2021). The northeastern Sylhet region has experienced severe erosion due to slope failure. Some field visits identified several erosion-prone areas, with slope failure linked to steep angles and water seepage. It is sometimes triggered by heavy rainfall, earthquakes, or human activity. Devastating floods with an abundance of rain hasten the failure process, resulting in enormous annual damage to infrastructure and agriculture (Legese et al., 2020). Such slope failure is caused by various topographic factors, including rainfall, soil type, slope geometry, and slope angles. In regions with high annual rainfall, the intensity and duration of rainfall affect slope stability. Increased rainfall over longer periods raises the water table and

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lowers the factor of safety of the slope (Kumar et al., 2021). It is predicted that climate change will increase the frequency and intensity of intense rainfall events, accelerating soil erosion and increasing the frequency of slope failures (Kim, 2021). Since erosion and slope failure are natural processes that cannot be stopped, sustainable bioengineering approaches are required to lessen their intensity. The conventional structure-based slope protection strategies are costly, resource-intensive, and require extensive site-specific studies (Punetha et al., 2019). Even as materials age, their natural efficacy decreases (Mohamed, 2022).

Over the past few decades, vetiver grass, or *Chrysopogon zizanioides*, has come to be recognized as a practical, affordable, and eco-friendly bioengineering method for stabilizing slopes and reducing erosion (Liu *et al.,* 2014; Maes *et al.,* 2017). Various studies on vetiver grass for assessing soil roots shear strength use laboratory experiments (Islam *et al.,* 2016; Badhon *et al.,* 2019) or field model scale tests (Islam and Islam, 2018; Nasrin, 2013; Islam, 2018) were conducted. The stability of embankment slopes was assessed using the infinite slope method of slope stability analysis, based on the soil cohesiveness and angle of internal friction reported by Nasrin (2013). Erosion test results showed that vetiver grass reduced erosion by 71%. Furthermore, the analysis indicated that vetiver grass plantations could increase the factor of safety of the embankment slope by up to 1.5 times. These findings confirm that vetiver grass is an effective natural barrier against rain-induced erosion and shallow slope failure on embankments. However, numerical simulation of rooted hill slopes using parametric studies is limited (Islam and Shahin, 2013). A terraced slope's safety factor may be raised by vetiver root penetration (Hamdhan *et al.,* 2023). Higher root lengths lead to higher shear strength, yet in laboratory shear strength experiments, the shear strength of soil samples containing vetiver grass roots decreased as the water content increased (Badhon, 2021). Vetiver grass prevents soil erosion by up to 95% and by 94% to 97% on sandy silt soils. According to Aziz and Islam (2023), the average surface runoff decreased by 21%, and the root diameter of the plants ranged between 1.6 mm and 2.5 mm. Accurate slope stability analysis is essential for creating effective mitigation plans, optimizing land use planning, and safeguarding communities and infrastructure. During a 100-kilometer slope stabilization project across 18 coastal polders, vetiver grass was found to increase the slope factor of safety from 1.7 to 2.8, thereby enhancing protection against harsh weather conditions (Islam et al., 2013). Despite global and local successes in using vetiver for erosion control and slope stabilization (Islam et al., 2021), little attention has been given to its application in the Sylhet region. This study focuses on Sylhet due to its steep topography, high landslide susceptibility, and heavy rainfall. The research evaluates the effectiveness of vetiver in minimizing erosion and stabilizing slopes by comparing bare soil with rooted soil within the regional context.

Materials and Methods

Description of the study area

The study area is located at Latitude 24.89°N and Longitude 91.87°E and 35 m above the mean sea level (Fig. 1). The soil used in the analysis was sandy clay (Table 1). The existing slope gradient of 1:2.5 refers to the existing slope of the study area near the Faculty of Agricultural Engineering and Technology, Sylhet Agricultural University, Sylhet. The average rainfall of this area is 3,280 to 4,780 millimeters. Topography is characterized by hills and basins, with the Surma valley defining the region's landscape. The soil is primarily fine-textured alluvium, and excessive rainfall, but has an inadequate drainage system.

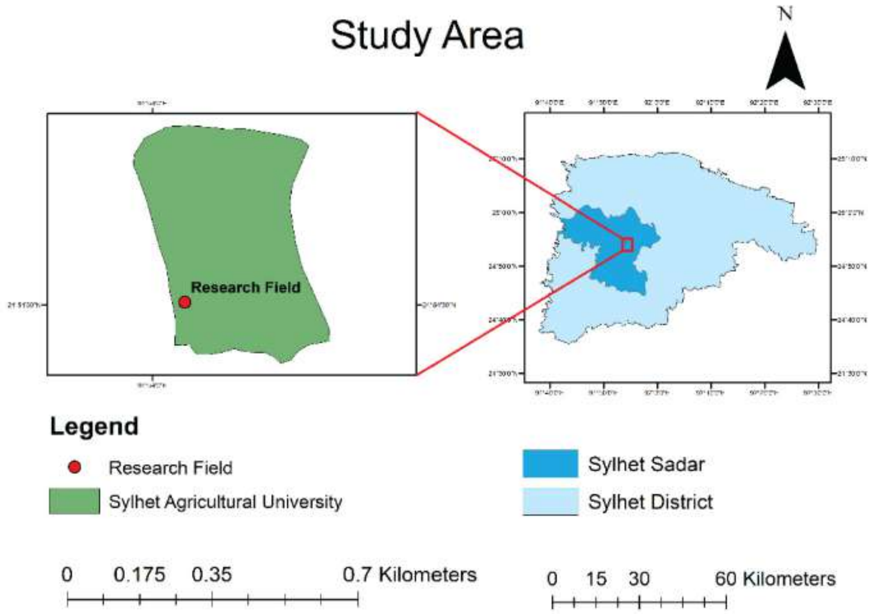

Figure 1. Study Area.

Table 1. Test model specifications

Parameters	Bared Soil	Rooted soil
Unit weight of soil, γ (KN/m^3)	18	17.3
Slope angle, β (deg.)	30	30
Unit weight of water, γ w (KN/m^3)	9.8	9.8
Cohesion, c (Kpa)	15	25
The angle of internal friction, ϕ'	30	35

Experimental setup

An erosion model was developed to simulate soil erosion processes on hillside slopes. The model is comprised of two components: a soil slope preparation container and a rainfall distribution system. A 1m×0.7m×0.6m container was constructed to prepare a compacted sandy clay soil, and the soil block was divided into two portions. One portion of the block was under no vegetation, and the other portion was cultivated vetiver grass. The slope, set at a 1:2.5 gradient, included a 0.2m horizontal toe support. Figure 2 illustrates the setup. Around 300 kg of soil was compacted to maintain uniform volume and shape. A perforated shower tray with 2 mm openings and 10 mm center-to-center spacing was installed 2 m above the slope to ensure uniform rainfall distribution. The artificial rainfall was applied on 26 March 2023 to both bare and vegetative (e.g., vetiver-covered) soil samples. Polythene sheets minimized water and soil loss at the toe, while runoff water and eroded soil were collected in synthetic cloths in a collection system below. Erosion measurements were taken every 10 minutes over 120 minutes in a day.

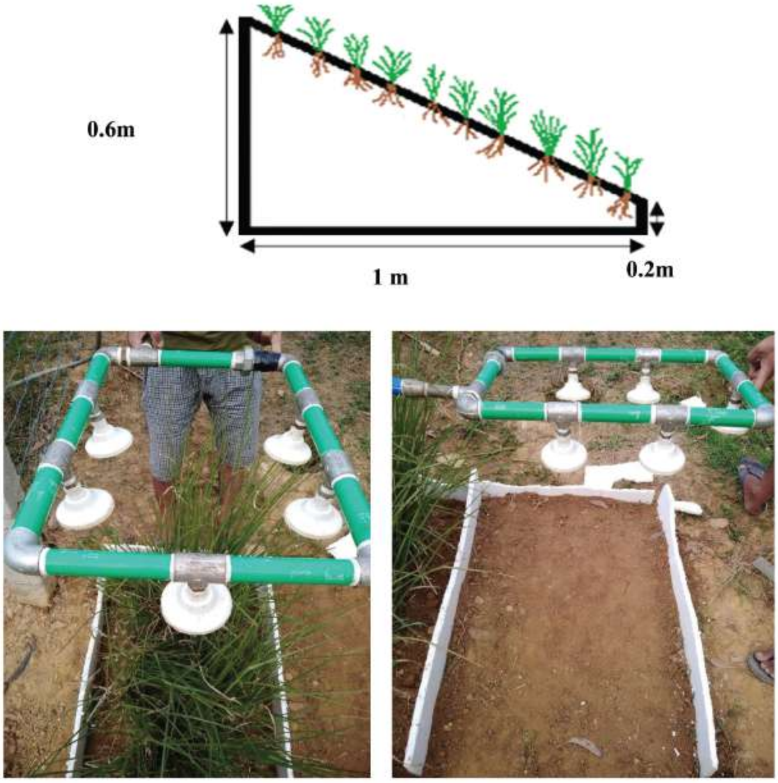

Figure 2. Schematic diagram of the slope and Plot Arrangement (a) with vegetation (b) without vegetation.

Growth rate of vetiver grass

The study spanned six months during the growing season, from October 2022 to March 2023. Vetiver grass, collected from Shibbari, Sylhet, was planted on 23 September 2022 near the Faculty of Agricultural Engineering and Technology to ensure establishment before the rainy season. Initially, the vetiver stems were 11 cm and roots 3 cm long. After three months, stems reached 80 cm, and roots grew to 16 cm. Measurements were taken with a ruler.

Runoff water and soil collection

Runoff water was collected every ten minutes, with a plastic sheet at the slope's toe preventing side slope wash and direct runoff into synthetic cloths that captured water and eroded soil. Filter paper separated soil particles from runoff, and the soil was dried at 103–105°C for 24 hours to measure weight. The rainfall simulator ensured continuous, uniform distribution. Vetiver grass shoots were left intact during rainfall to mimic natural conditions, as vetiver slows rainfall droplet velocity. The average vetiver stem and root lengths were 80 cm and 16 cm, respectively, during the investigation.

Slope stability analysis

The data (e.g., cohesion of soil, angle of friction) were collected for bare soil from the Local Government Engineering Department. Data for bed material, like different parameters (e.g., cohesion, angle of friction) of the soil of our experiment site, was collected from our Engineering section of Sylhet Agricultural University and the Soil Resource Development Institute, Sylhet.

Factor of safety (FS) computation

The factor of safety for bare and rooted soil was determined using the following formulas (Coppin and Richards, 1990). Using effective stress analysis, the factor of safety (FS) without vegetation can be defined by:

$$FS = \frac{(c' + (\gamma z - \gamma whw)\cos 2\ \beta\ \tan\varphi)}{(\gamma z \sin\beta \cos\beta)} \quad (1)$$

Where,

c' = effective soil cohesion (KN/m^3)

γ = unit weight of soil (KN/m^3)

z = vertical height of soil above slip plane (m)

β = slope angle (degrees),

γ_w = unit weight of water (KN/m^3)

h_w = vertical height of groundwater table above slip plane (m)

φ = effective angle of internal friction of the bare soil (degrees)

Furthermore, the main influences of vegetation on the stability of slope segments are given as shown in equation (2) below, which was used to compute FS due to vegetation:

$$FS = \frac{(C' + C'R) + [\{(\gamma z - \gamma whv) + W\}\cos 2\ \beta + T\sin\theta]\tan\varphi + T\cos\theta}{\{(\gamma z + W) \sin\beta + D\}\cos\beta} \quad (2)$$

Where,

c'_R = enhanced effective soil cohesion due to soil reinforcement by roots (kN/m^3)

W = surcharge due to weight of vegetation (kN/m^2)

h_v = vertical height of groundwater table above the slip plane with the vegetation (m)

T = tensile root force acting at the base of the slip plane (kN/m)

θ = angle between roots and slip plane (degrees) and

D = wind loading force parallel to the slope (kN/m)

φ = effective angle of internal friction of the rooted soil (degrees)

Numerical simulation of slope stability analysis

Numerical slope analysis was performed using GeoStudio_2022.1 software to estimate the factor of safety through slope stability analysis of the embankment. GeoStudio 2022.1 was generated by Seequent, a company within Bentley Systems, and was released on December 12, 2022. The study utilized the Mohr-Coulomb constitutive model via SLOPE/W. GeoStudio, developed by GEO-SLOPE International, employs the limit equilibrium concept and integrates finite element methods for deformation and stability analysis. The Geostudio_2022.1 program was utilized to quantify the factor of safety. The GeoStudio_2022.1 software was applied to assess soil stability by inputting three parameters: cohesiveness, angle of friction, and unit weight of the soil. The new project file was generated, and the metric letter technique was picked. The numerical program employed in this inquiry was two-dimensional geometry. Then, the SLOP/W Analysis was chosen, followed by the limit equilibrium approach. First, establish the page layout, scale, and grid configuration. Then, proceed to draw the elevation axis along the length. Next, access the input function and utilize the slip surface feature. Choose the appropriate material and provide the necessary input for it. Now, create a slip surface and mark the entry and exit sites to determine the stability of both rooted and bare soil. Finally, the factor of safety (FS) is calculated. The slope was simulated using GeoStudio_2022.1 software, employing the Mohr-Coulomb model.

Table 2. Parameters used for stability analyses

Parameters	Bared Soil	Rooted soil
Unit weight of soil, γ (kN/m^3)	18	17.3
Vertical height of soil above slip plane (m)	0.6	0.6
Slope angle, β (deg.)	30	30
Unit weight of water, γ_w (kN/m^3)	9.8	9.8
Vertical height of ground water table above slip plane, h_w (m)	0	0
Surcharge due to weight of vegetation, W (kN/m^2)	1.57	1.42
Vertical height of groundwater table above the slip plane with the vegetation, h_v (m)	0	0
Tensile root force acting at the base of the slip plane, T (kN/m)	2.45	2
Angle between roots and slip plane, θ (deg.)	0	0
Wind loading force parallel to the slope, D (kN/m)	0.1	0.1

Results and Discussion

Soil erosion

Raindrops on the soil surface cause erosion, and high-intensity rain produces higher kinetic energy, resulting in maximum erosion. Soil erosion was analyzed by weighing the sediment carried by rainwater.

Measured soil erosion

Table 3 illustrates that the rate of soil erosion increased over time, the total quantity of soil in the block was 300kg, and a greater quantity of soil was eroded from bare soil compared to rooted soil. The amount of soil eroded from uncovered and rooted soil was 621 g and 140 g, respectively, at the 10-minute level. At the 120-minute rainfall, the bare and rooted soil eroded 1007 g and 310 g, respectively.

Table 3. The Amount of Soil Erosion for Bare and Rooted Soil

Time(min)	Bare soil (gm)	Rooted soil (gm)
0	0	0
10	621	140
20	648	146
30	682	156
40	720	170
50	790	162
60	820	190
70	860	196
80	855	195
90	875	200
100	960	250
110	937	270
120	1007	310

Figure 3 displays the cumulative erosion percentages for bare soil and soil with vetiver grass. After just 10 minutes of rainfall, the erosion of bare soil was 0.21%, while vetiver soil had only 0.046%. The erosion percentages rose sharply after 120 minutes of rain, hitting 0.793% for vetiver soil and 3.25% for bare soil. This indicates that erosion was significantly greater in bare soil than in vetiver-rooted soil.

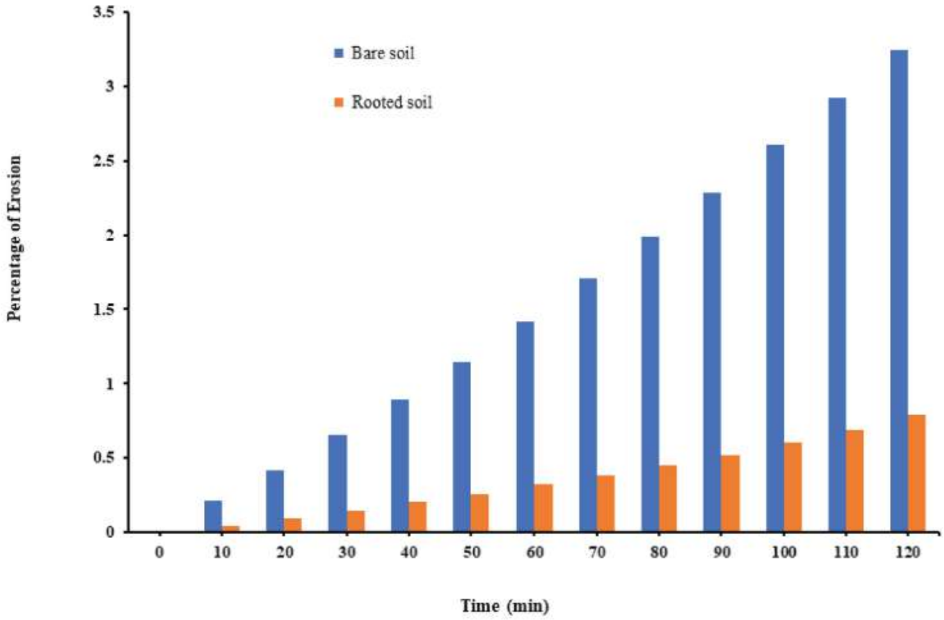

Figure 3. Erosion Curve of Bare and Rooted Soil.

Throughout the experiment, it was evident that bare soil eroded more than rooted soil under the same conditions. The vetiver grass effectively reduced soil loss, demonstrating its benefits in erosion control. Overall, the figures highlight the importance of planting vetiver grass to protect the soil from erosion during rainfall. The results clearly illustrate how vegetation can help maintain soil integrity.

Effect of vetiver on erosion reduction

The test results from the Table 4 showed that the effectiveness of adding vetiver grass vegetation reduced soil erosion by 75.60% to 77.46% in 120 minutes. Overall, these findings are consistent with the research conducted by Cerdà, (2007), which demonstrated that a newly constructed bare soil slope experienced significantly higher levels of soil erosion compared to a slope with vegetation cover. They also align with the findings of Benik, (2003), who observed that the presence of vegetation greatly reduced soil erosion during spring and fall runoff events.

Table 4. The effect of vetiver on erosion by physical experiment

Time (min)	Erosion of Bare Soil (kg)	Erosion of Vetiver Soil (kg)	Reduction (kg)	Percentage of Reduction
10	0.62	0.14	0.48	77.46
20	1.25	0.29	0.96	77.08
30	1.95	0.44	1.51	77.34
40	2.67	0.61	2.06	77.09
50	3.46	0.77	2.69	77.64
60	4.28	0.96	3.32	77.48
70	5.14	1.16	3.98	77.44
80	6.00	1.36	4.64	77.40
90	6.87	1.56	5.32	77.37
100	7.83	1.81	6.03	76.95
110	8.77	2.08	6.69	76.33
120	9.78	2.39	7.39	75.60

Stability of slopes

Computed factor of safety (FS) of the soil samples

Equations (1) and (2) were used to compute the factors of safety of bare and Vetiver-rooted soil samples, respectively.

Bare samples

The effective soil cohesion of bare soil (c') and the effective angle of internal friction (φ') of the bare soil were determined to be 15 KN/m^2 and 30°, respectively. Based on these parameters and applying Equation 1, the calculated factor of safety for the bare soil is 1.87.

Vetiver rooted samples

The effective cohesion of the bare soil was determined to be c'=15 KN/m^2, while that of the rooted soil was 25 KN/m^2. The increase in effective cohesion due to root reinforcement ($c'R$) was calculated as (25-15) =10 KN/m^2. The effective angle of internal friction for the rooted soil was found to be $\varphi = 35°$. By applying Equation 2, the factor of safety for the rooted soil was calculated to be 3.41.

The results demonstrate that the planting of vetiver grass enhanced the embankment's stability by approximately 1.68 times. Specifically, the calculated factor of safety increased from 1.87 for bare soil to 3.41 for rooted soil, highlighting the significant contribution of root reinforcement to slope stability. These findings are consistent with those reported by Arifuzzaman et al. (2013), who observed that vetiver planting improves slope stability by more than 1.5 times compared to unreinforced soil. The agreement between this study and previous research reinforces the effectiveness of vetiver grass as a sustainable and reliable solution for erosion control and embankment stabilization, particularly under similar climatic and soil conditions.

Factor of safety (FS) of the soil samples for both bare soil and betiver rooted soil using geo-studio software

For bare soil, the unit weight of soil was 18 KNm^{-3}, the angle of friction was 30°, and the cohesion was 15 KNm^{-2} (Figure 4). As a result, the factor of safety was found to be 1.727 for bare soil. On the other hand, Figure 5 illustrates that for rooted soil, the unit weight of soil is 17.3 KNm^{3}, the angle of friction is 35°, and cohesion is 25 KNm^{-2}. So, the factor of safety was found to be 2.55 for rooted soil. Chikwue (2020) found that the factor of safety (FS) of Vetiver-rooted samples is 2.98, while the FS of bare samples is 1.72, which indicates that soil samples stabilized with Vetiver grass had an average factor of safety around 1.73 times higher than that of bare samples. On the other hand, when equations were used to measure the factor of safety, it was found that the factor of safety (FS) of Vetiver rooted samples is 3.41, while the FS of bare samples is 1.87. This difference in values between the software and the equation is because in the equation, all the parameters were used, but in the software, only three parameters (i.e., cohesion, unit weight of soil, and angle of internal friction) were used. Putting these three parameters in the Mohr-Coulomb model, these values were found in the GeoStudio software. Taib et al., (2020) also found that the presence of vegetation increases the factor of safety compared to when there is no vegetation.

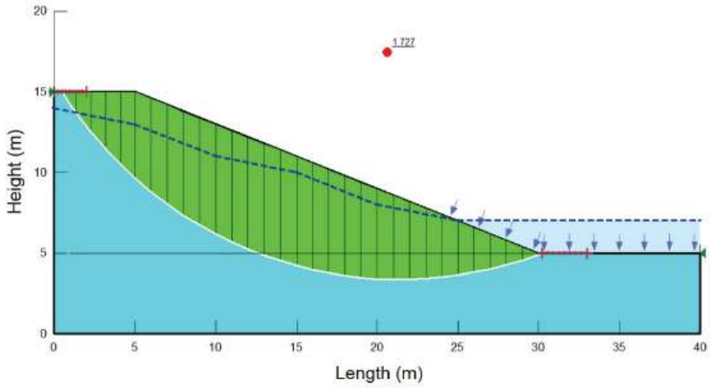

Figure 4. Factor of Safety for Bare and Rooted Soil.

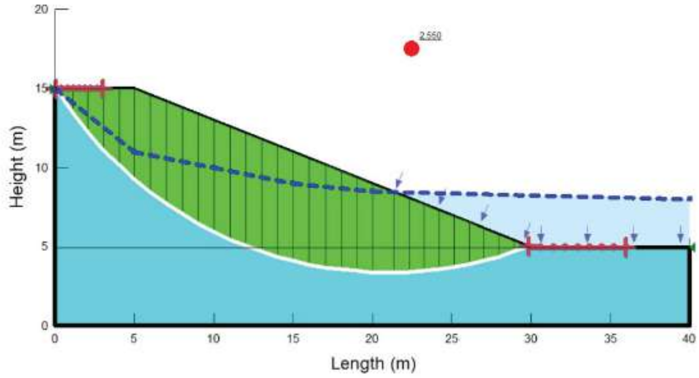

Figure 5. Factor of Safety for Rooted Soil.

Conclusion

This study demonstrates that vetiver grass significantly improves slope stability and reduces erosion by enhancing soil cohesion and root reinforcement. The factor of safety increased markedly in vegetated slopes compared to bare soil, confirming vetiver's effectiveness under saturated conditions. The analyses were based on short-term stability assessments and controlled experimental parameters, which may not fully capture the complex interactions between vegetation, soil properties, and climatic variability over longer periods. Furthermore, factors such as root decay, seasonal changes in root strength, and the effects of extreme weather events were not addressed. Future research should focus on long-term field monitoring and advanced modeling approaches to better understand the dynamic behavior of vegetated slopes under real-world conditions. Such investigations will be critical to optimizing vetiver-based stabilization strategies and ensuring their long-term resilience.

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