

Original Article

A Numerical Study on Road Embankment Stability Enhanced by Natural Reinforcement

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Abstract - This study numerically evaluates the effect of natural reinforcements on the stabilization of a road embankment built with poorly graded granular soil (SP - SM). The response of the structure under a continuous vehicular surcharge load of 24 kN/m² is analyzed using the GeoStudio suite, with the SLOPE/W and SIGMA/W programs utilized for limit equilibrium stability and finite element stress-deformation analyses, respectively. The unreinforced soil embankment yields a Factor of Safety (FOS) of 1.133, which falls below the Indian Roads Congress (IRC) accepted level of stability. Banana Fiber Geotextiles (BFG) are applied as planar reinforcement at varying vertical spacings from 0.25 m to 1.50 m. It is found that the optimum techno-economic spacing of 1.0 m results in a 36.6 % increase in FOS and a 46.4 % reduction in peak internal shear strain. In parallel, the bio-reinforced model, simulating a 2.0 m deep 6-month-old vetiver grass root matrix at the slope face, achieves an FOS of 1.406. Finite element contours reveal that the bio-reinforced zone, modeled as an equivalent-continuum block, provides significant structural confinement. The biological confinement completely arrests lateral face yielding, decreasing horizontal displacement by 70.8 %, reducing maximum vertical settlement by 60.0 %, and dropping peak internal shear strain by 80.0 %. Both natural reinforcement methods successfully satisfy the safety thresholds recommended by IRC: 75-2015, proving that bio-reinforcement provides superior deformation control and establishes itself as a highly effective, sustainable alternative to conventional stabilization techniques.

Keywords - Banana Fiber Geotextiles, Bio-Reinforcement, Road embankment, Slope stability, Vetiver grass.

1. Introduction

1.1. Background

Road embankments in tropical and semi-arid regions are more prone to slope failures due to the weak foundation and embankment soil, the steep embankment slope, and the continuous mechanical stresses induced by heavy vehicular loading [1]. These conditions can result in gradual shear rupture at key slip surfaces that may impact long-term serviceability and potentially compromise the safety of surrounding infrastructure. Embankments, when built using locally available granular fill materials, may have quite low shear strength parameters and may thus fail under the ongoing static loading and traffic surcharges from vehicles. In the present work, a recently built road embankment in Rasipuram, Tamil Nadu, has been taken as the representative field case to study these failure mechanisms and investigate potential stabilization measures.

In addition to basic slope instability, there is an added risk of excessive structural deformation. Critical internal shear strains develop when the continuous mechanical surcharge exceeds the bearing capacity of the unreinforced granular fill,

leading to a progressive decrease in the Factor of Safety (FOS) [2]. This effect can be observed in long-term structural assessments, such as a study on an earth structure in Kazakhstan, which emphasized that changes in embankment material properties induced by continuous human activities and loading pose significant stability challenges compared to the initial baseline [3]. In general, this indicates the need to propose acceptable reinforcement measures for compacting, aligning, and strengthening the soil profile with minor additional construction investment, which can effectively increase shear resistance and minimize deformations in an environmentally sustainable and low-cost way.

1.2. Literature Review

The literature for this study can be divided into three specific areas; Bio-reinforcement using Vetiver grass, Banana fiber geotextiles and other natural fiber reinforcements, and numerical methods for slope stability and deformations.

1.2.1. Bio-Reinforcement - Vetiver Grass

As a bio-engineering tool, Vetiver (*Chrysopogon zizanioides*) alters matrix behavior in two primary ways:



mechanically, by reinforcing the surrounding soil matrix, and structurally, by increasing the apparent cohesion and angle of internal friction of the composite mass. From in situ tests and Finite Element (FE) analysis, Islam and Shahin [8] observed that the use of vetiver root reinforcement led to a gain in shear strength and a more ductile failure mode as compared to unreinforced slopes. Following this, Badhon et al. [9] found that the shear strength of vetiver-reinforced specimens was enhanced by almost half. Their PLAXIS 2D simulations also demonstrated an improvement in the Factor of Safety (FOS) by up to 20.6 % compared to the unreinforced baseline model.

Special attention has been paid to the time dependency of vetiver reinforcement. Maadi and Noorzad [10] proposed ratios demonstrating how root age acts as a governing variable in PLAXIS 2D models. Mature root systems provide greater cohesion gains and a higher FOS. Using finite element modelling and limit equilibrium analysis, Spears et al. [11] simulated the structural reinforcing effect of vetiver on a high-plasticity clay levee. They concluded that it shows significant potential for field applications facing continuous mechanical loading and complex environmental stresses. Other reinforcement elements can be used in conjunction with vetiver. In PLAXIS 2D, it was concluded that the vetiver with Recycled Plastic Pins (RPP) configuration performed the best in terms of FOS while yielding the least crest deformation, but the vetiver-alone configuration was the best in economic terms [12]. Noel et al. [13] also demonstrated that vetiver serves to enhance both root cohesion and matric suction, in which the contribution is greater for shallow failure modes.

At the field scale, direct measurements were conducted on the newly constructed Rasipuram road embankment case study site of this investigation, which is planted with vetiver. As a result of the field and laboratory tests, a significant increase in soil cohesion and the soil's internal friction angle was noted, which correlated to a significant increase in the global shear strength of the soil in just three months after planting. These values measured on site are used for bio-reinforced soil properties in the development of numerical models in this study.

1.2.2. Banana Fiber Geotextiles and Natural Fiber Reinforcement

Banana fiber is also regarded as a highly capable component material for geotextiles in structural slope protection. The composite geotextile (Baconet) using banana fiber and coir was found to be suitable for providing direct mechanical reinforcement and stabilization in steep slopes by Hernandez et al. [14]. Bartholomeus et al. [15] apparently presented the woven banana stem fiber geotextile characterization according to standard specifications and found that it fulfilled strict mechanical performance criteria, particularly demonstrating the high average tensile and tear strength required for active soil reinforcement.

Matchum et al. [16] evaluated the mechanical properties of woven fabrics made from banana-plantain stalk fibers and found that they could be used as a geotextile with a limited lifespan. While synthetic geotextiles often present long-term environmental disadvantages, natural jute geotextiles provide an immediate physical cover that drastically reduces the probability of soil detachment. Reported by Sanyal [17] as part of the field evidence, this physical interlocking and subsequent biodegradation to coalesce with the foundation are indicative of the effectiveness of the use of jute geotextiles under in-service conditions.

Kumar and Roy [18] quantified the effect of jute fiber reinforcement on soil composite behavior and found that normal pressures acting on the reinforced matrix mobilize tensile resistance in the fibers. This interaction provides the soil with higher shear strength, thereby significantly increasing the FOS of the slope against lateral deformation.

The mechanics associated with placement of geosynthetic reinforcement in embankment cross-sections have been considered in analytical studies. Cui and Zhou [19] used limit equilibrium analysis based on upper bounds with results from centrifuge tests to demonstrate the control of reinforcement density on the lower slope on the critical height of the embankment. Jha et al. [20] performed Morgenstern-Price limit equilibrium analyses to quantify the effect on critical slip surface geometry of the reinforcement length and vertical position, thus providing a mechanical basis for the assessment of BFG spacing configuration.

1.2.3. Numerical Methods: SLOPE/W and SIGMA/W

Evaluating the mechanical stress-deformation and stability of earth embankments or dams is a common application of the GeoStudio suite. Singh [4] utilized the Mohr-Coulomb model for the Nagarjuna Sagar Dam and used SLOPE/W for calculating the static and pseudo-static FOS, which turned out to be within acceptable limits. Al-Nedawi [5] applied finite element techniques to evaluate the structural integrity of the Hemrin Earth Dam and then assessed the safety of the downstream slope by using SLOPE/W as a following step in the embankment assessment process.

Ahmed et al. [6] modelled the Saura-Keffi dam and showed that targeted structural interventions increased the downstream FOS from 1.27 to 1.52, thus providing quantitative evidence that finite element analysis can identify the most effective dam intervention to enhance mechanical stability margins. Rezaee et al. [7] used GeoStudio SIGMA/W to perform effective-stress analysis of Garati Dam, showing how successful the deformation-stress coupling can be in evaluating embankment performance, taking into consideration the vertical settlement and horizontal displacement distributions in continuous construction loading periods.

In this current study, SLOPE/W is used to calculate the FOS using the limit equilibrium analyses for each reinforcement configuration, and SIGMA/W is used to calculate the displacement. This combination of both modules within a single GeoStudio computational environment helps to comprehensively evaluate embankment stability and serviceability for all evaluated configurations.

1.3. Problem Statement and Research Gap

Research on sustainable ground improvement has expanded significantly, but a detailed comparison of different natural reinforcement techniques remains limited. Prior investigations have neither benchmarked the independent performance of Banana Fiber Geotextiles (BFG) against progressive stages of vetiver root maturity, nor quantified the corresponding displacement behavior under surcharge loading through coupled finite element modeling. By placing an unreinforced baseline alongside independent BFG configurations and bio-reinforced face layers at two stages of root development, 3-month and 6-month maturity, this study establishes a direct mechanical comparison between woven natural fiber geotextiles and living root reinforcements.

This investigation applies field-measured soil parameters from a newly constructed road embankment in Rasipuram to independent SLOPE/W and SIGMA/W analyses across nine distinct model configurations. These comprise: (1) a bare-soil baseline embankment; (2) BFG reinforcement at six vertical spacings (0.25 m, 0.50 m, 0.75 m, 1.00 m, 1.25 m, and 1.50 m); and (3) bio-reinforced slopes incorporating a 1-m-thick modified face layer of 3-month-old vetiver root-reinforced soil and a 2-m-thick modified face layer of 6-month-old vetiver root-reinforced soil.

Each configuration is assessed independently: SLOPE/W evaluates the Factor of Safety (FOS) through limit equilibrium analysis, while SIGMA/W computes vertical (Y - direction) and horizontal (X - direction) displacements through finite element deformation analysis. The results of all nine configurations provide a robust and directly comparable basis for demonstrating the relative effectiveness of geotextile and bio-reinforcement as independent stabilization techniques for tropical road embankments.

2. Theoretical Framework and Background

2.1. Potential Slope Stability Failures

Deep-seated rotational failures are common within weak foundation soils beneath highway embankments. This type of failure occurs when shear stress, induced by the embankment's self-weight and vehicular surcharge, surpasses the available shear strength of the soil [21]. The resulting critical slip surface extends through the embankment and deep into the foundation layer in response to surcharge loads. Yielding of the soil mass causes vertical settlement beneath the crest load and lateral bulging at the toe [21]. Structural reinforcements

are deliberately placed perpendicular to this failure plane to redistribute concentrated shear strains and enhance the overall resisting forces of the slope.

2.2. Formulation of Safety Analysis

The Limit Equilibrium Method (LEM) evaluates the stability of road embankments using the ratio between the available shear strength (τ_f) and the mobilized shear stress (τ_m), as expressed in Equation (1) [21]:

$$FOS = \frac{\tau_f}{\tau_m} \quad (1)$$

The available shear strength is governed by the site-specific Mohr-Coulomb failure criterion [21]. Under the drained and dry conditions of this analysis, the internal pore water pressure is zero (meaning the total normal stress equals the effective normal stress, $\sigma_n = \sigma'_n$) [22]. Consequently, the mobilized shear stress needed to maintain equilibrium along the critical slip surface under the vehicular surcharge is defined by Equation (2):

$$\tau_m = \frac{c + \sigma_n \tan \phi}{FOS} \quad (2)$$

Where c is the drained cohesion, σ_n is the normal stress, and ϕ is the drained angle of internal friction.

In numerical models incorporating natural reinforcements, such as banana fiber geotextiles or bio-root matrices, these elements intercept the critical failure plane and contribute an additional tensile resisting force (T_r) to the total shear resistance. This supplementary resistance directly raises the computed FOS, improving the overall stability of the embankment.

3. Description of Reference Embankment

For this investigation, a recently constructed road embankment at Rasipuram, Namakkal District, Tamil Nadu, India, is used as a reference case study, as shown in Figure 1. The site is part of a Major District Road (MDR) and was built in 2023 to act as an important bypass. This infrastructure has an overall alignment of 10.7 km and connects Ponkurichi (SH 79) and Thottiyampatti (SH 95) through NH 44. The main purpose of constructing this bypass is to ease heavy vehicular loading in industrial areas located from Erode to Attur, so that it can divert a large amount of traffic from the center of Rasipuram.

The embankment is in a particularly strategic location and is subject to serious geotechnical problems related to the material properties of the embankment and operational conditions. The material of the embankment fill is primarily made from local granular material from quarries. The foundation material identified by the laboratory test is poorly graded sand with silt (SP - SM).

This granular fill has a modest intrinsic shear strength, making the embankment very susceptible to large deformations under permanent, transient dynamic, and static loading from heavy commercial traffic. This convergence of

site-specific weaknesses makes the Rasipuram bypass a good example for performing numerical benchmarking of mechanical stabilization effects achievable through natural or biological reinforcement.



Fig. 1 Field conditions of the reference Rasipuram road embankment, transitioning from bare soil to 3-month-old bio-reinforced slope

4. Methodology and Model Configuration

4.1. Material Properties

4.1.1. Soil Properties

A case study is represented by the numerical model; it comprises a continuous road embankment with both the underlying foundation stratum and overlying embankment fill having the same geological material. The soil used for this numerical model was obtained from the nearby locality of Rasipuram, Tamil Nadu, from a recently constructed bypass embankment; it is a poorly graded sand with silt (SP-SM).

The comprehensive particle size distribution properties justifying this classification were derived from independent field sampling conducted for this numerical modeling effort. Baseline effective shear strength parameters, cohesion (c') and the angle of internal friction (ϕ'), were derived directly from independent direct shear testing. To accurately capture the effective operational parameters of the embankment, these undisturbed samples were tested at their natural field moisture content, rather than being artificially fully saturated, using a slow horizontal strain rate to ensure fully drained conditions.

The influence of bio-reinforcement on the mechanical stability of the embankment was simulated by assigning specific surface domains of the embankment with the enhanced shear strength parameters of the soil measured after 3 months and 6 months of vetiver root maturation. Table 1 lists

the major geotechnical input parameters that were used for both the limit equilibrium (SLOPE/W) and stress-deformation (SIGMA/W) analyses.

Derivation of Elastic Parameters

The effective shear strength parameters were determined from laboratory tests, and the elastic parameters necessary for the finite element stress-deformation analysis (SIGMA/W) were tentatively estimated based on well-known geotechnical empirical relations [24-26].

Jaky's formula was used to obtain the coefficient of lateral earth pressure at rest (K_0). To accurately represent the drained granular matrix, a realistic drained Poisson's ratio (ν) of 0.30 was adopted. Furthermore, a sensitivity analysis was performed in SIGMA/W across the typical drained range ($\nu = 0.28$ to 0.32), confirming that the global deformation mechanisms and comparative effectiveness of the reinforcements remained consistent. The small-strain shear modulus (G_{max}) was estimated based on Hardin's (1978) equation for cohesionless soils [24], where the Over Consolidation Ratio (OCR) was assumed to be 1, as the poorly graded granular fill has little overconsolidation. Massarsch's (1994) modulus reduction factor [25] was applied to scale the operational reference Young's modulus (E_{ref}) to serviceability strain levels to account for stiffness degradation caused by strain during structural loading.

To simulate the nonlinearity of the compression of this granular matrix during staged construction, the operational Young's modulus was not considered to be a constant. Rather, it was determined dynamically in the FE solver, based on Janbu's stress-dependent stiffness relation [26], as expressed in Equation (3):

$$E = E_{ref} \left(\frac{\sigma'_v}{p_a} \right)^n \quad (3)$$

Using the empirical exponent (m) typical for sand, the localized effective vertical stress (σ'_v) and atmospheric pressure (P_a) were incorporated into the formulation. This relationship served as a spatial function to automatically increase element stiffness across the foundation and embankment in response to rising overburden pressure during the simulated construction phases.

4.1.2. Reinforcement Properties

Geotextile structural stabilization was simulated by incorporating Banana-Plantain Fiber Limited Life Geotextiles (PFLLGs) into the Finite Element (FE) numerical model [23]. The geometric and mechanical parameters defining the 1D reinforcement elements in GeoStudio were derived directly from published physical characterizations of woven banana fabric [23]. The input parameters governing structural resistance and soil-geotextile interaction are presented in Table 2.

4.2. Cross-Section Geometry

A two-dimensional plane strain domain was set up to approximate the actual profile of the reference embankment to create numerical simulations. The geometry of the macro model, shown in Figure 2, consists of a 7 m tall embankment over a 3 m thick homogeneous foundation stratum.

Table 1. Geotechnical and elastic properties of the SP-SM embankment and foundation soil

Parameter	Bare Soil (Unreinforced)	3-Month-Old Bio-Reinforced Soil	6-Month-Old Bio-Reinforced Soil
Dry Unit Weight, γ_d	17.13 kN/m ³	17.28 kN/m ³	17.38 kN/m ³
Initial Void Ratio, e	0.56	0.54	0.54
Effective Cohesion, c'	10.56 kN/m ²	24.52 kN/m ²	34.56 kN/m ²
Effective Friction Angle, ϕ'	17.73°	23.22°	25.50°
Poisson's Ratio, ν	0.30	0.30	0.30
Young's Modulus at 1 m Reference Depth, E_{ref}	15721.41 kN/m ²	17446.27 kN/m ²	17496.70 kN/m ²

Table 2. Mechanical and interface properties of Banana Fiber Geotextile (BFG) elements [23]

Property	Value	Description
Tensile Capacity	7.30 kN/m	Maximum tensile strength in the primary load-bearing (warp) direction under dry conditions.
Nominal Thickness	4.51 mm	Physical thickness of the woven mat.
Cross-Sectional Area	0.00451 m ²	Area per 1-meter plane-strain slice of the model.
E-Modulus (Secant)	9100 kPa	The secant tensile stiffness of the banana fiber material.
Axial Stiffness	41.04 kN/m	Structural capacity assigned in SIGMA/W (9100 kN/m ² × 0.00451 m ² /m).
Interface Adhesion	16.9 kN/m ²	Pullout adhesion limit between the geotextile and the silty embankment core.
Interface Friction Angle	23.4°	Frictional resistance mobilized along the geotextile-soil interface.

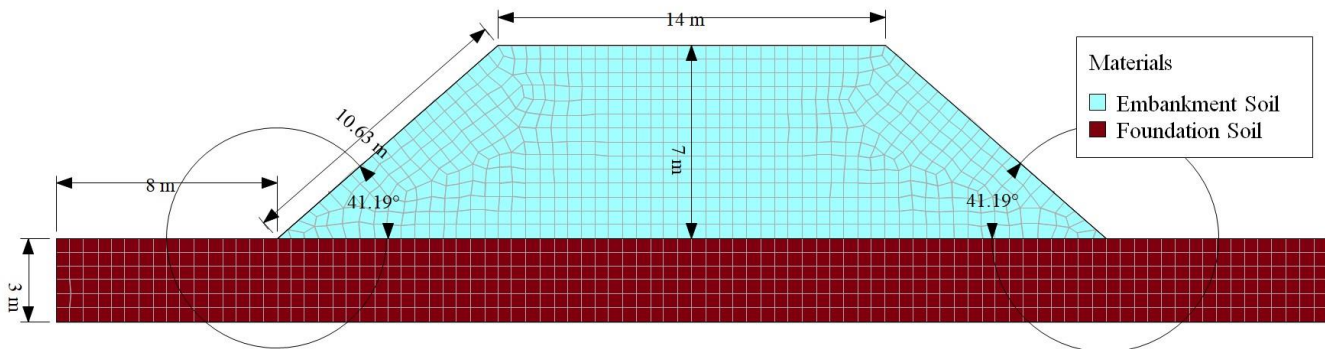


Fig. 2 Cross-sectional geometry and baseline finite-element mesh of the unreinforced Rasipuram road embankment model

Critical embankment slope was taken to have 8 m of horizontal projection with a slope angle of 41.19° (or 1V:1.14H), which is constant on the constructed profile of the highway embankment, completed by a 14 m wide horizontal crest to accommodate traffic.

4.3. Model Configuration

A half-space plane strain numerical model was created, as presented in Figure 3. Modeling half of the embankment cross-section from the centerline accurately reflects structural and deformation behaviors while significantly optimizing computational resources. Numerical simulations were performed using the GeoStudio 2020 suite, coupling the SLOPE/W and SIGMA/W programs to calculate limit equilibrium stability and finite element stress-deformation, respectively. The soil mass was mathematically characterized using the Mohr-Coulomb failure criterion under fully drained conditions, with shear strength parameters acquired from laboratory direct shear testing.

Four fundamental model types were developed to systematically compare the stabilization effectiveness of the various natural ground improvement techniques. These comprised: (1) a baseline Bare Soil Embankment (BSE) model; (2) a set of models using Banana Fiber Geotextiles (BFG) at different vertical spacings; (3) a model incorporating a 1 m thick layer of 3-month-old vetiver bio-reinforced soil on the slope face; and (4) a model incorporating a 2 m thick layer of 6-month-old vetiver bio-reinforced soil on the slope face. The geometric positions of 1D BFG elements were mapped directly into the primary mesh as individual horizontal mesh layers to identify the optimum spacing for structural reinforcement (Figure 3(b)) for the BFG-reinforced variants. In the biologically reinforced scenarios, the vetiver root matrix was considered a separate continuous sub-region parallel to the slope face (Figures 3(c) and 3(d)). The thicknesses of 1 m and 2 m were set based on the average vertical penetration depth of the grass roots during the active growth period in 3 and 6 months, respectively.

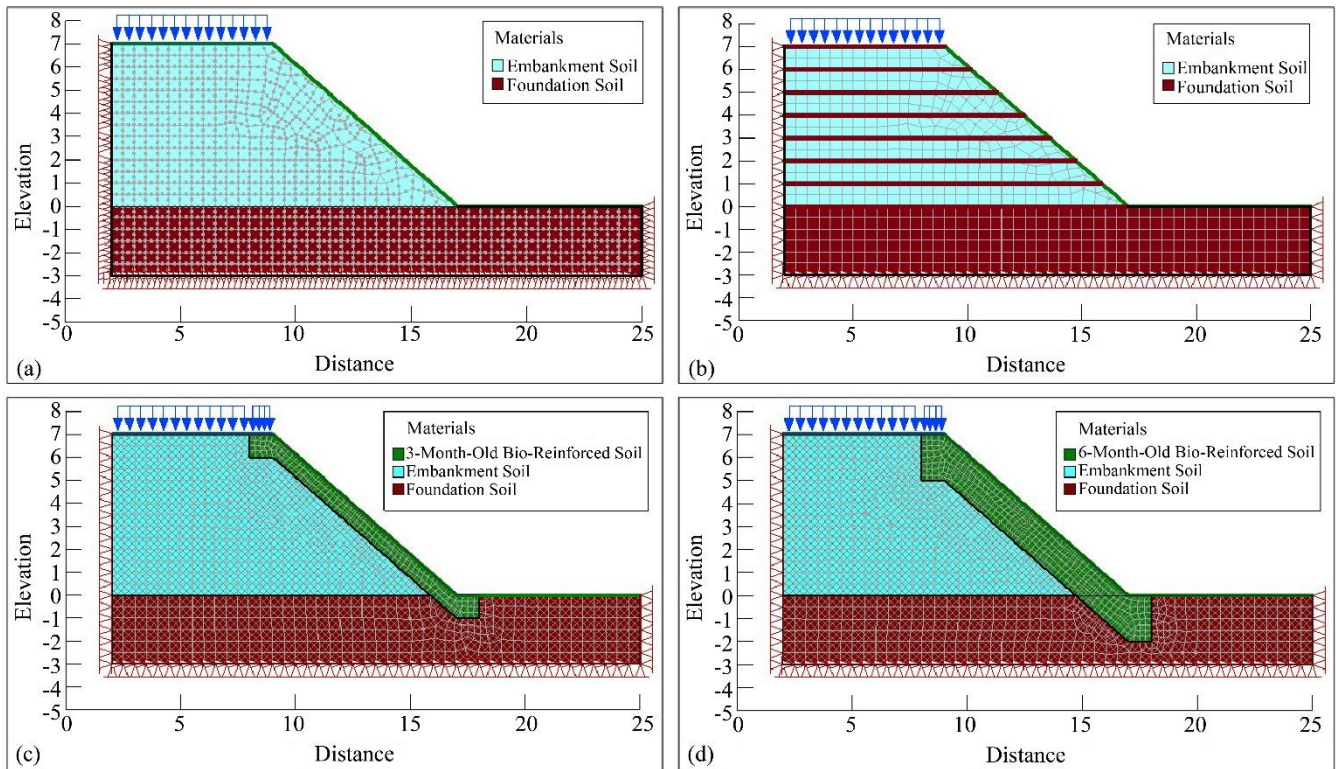


Fig. 3 Plane strain numerical models and finite element mesh configurations: (a) Bare soil baseline embankment showing secondary nodes, (b) BFG-reinforced embankment at 1 m spacing, (c) 1 m thick 3-month-old bio-reinforced slope face with 0.25 m localized mesh refinement, and (d) 2 m thick 6-month-old bio-reinforced slope face.

A twofold finite element mesh refinement was used to secure numerical stability in the bio-reinforced models. A larger global mesh size of 0.5 m with a node spacing of 0.5 m was used for the underlying unreinforced embankment core and massive foundation stratum to achieve adequate numerical accuracy in a large mesh size range and be both efficient and cost-effective. On the other hand, the surface

zones with thicknesses of 1 and 2 m that contained root reinforcement were assigned a maximum local element size of 0.25 m. This thorough local sizing was selected to be able to properly resolve the sharp stress gradients across the thickness of the thinnest 1 m skin, showing a minimum of four element layers through the skin. This type of density of meshing is very important to enable the computation of localized bending and

stress distributions without element distortion. The whole area was meshed using higher-order elements: 8-node quadrilaterals and 6-node triangles. This is a selection of element types of particular importance for the SIGMA/W stress-deformation analysis, as it prevents volumetric locking in a drained state. The standard finite-element boundary fixities were imposed on the global domain, which comprised the lateral boundaries (X - direction rollers) and the basal boundary of the foundation block (3 m deep), which was fixed against both X and Y translation.

The horizontal crest of the half-embankment, which is 7 m (a half of the 14-m total width), was dimensionally isolated to represent the active roadway and shoulder. A uniform vehicular surcharge load of 24 kN/m² was used to simulate the imposed dynamic and static load by heavy commercial truck loadings in accordance with the IRC guidelines for the design of high embankments (IRC: 75-2015) [27].

A critical surface and an overall evaluation of stability were then performed using the Morgenstern-Price method. The method chosen in this study is a very rigorous method, and it satisfies the equilibrium of moments and forces, and it also fully considers the normal and shear forces [21].

The use of these interslice forces is necessary to achieve superior computational accuracy over simplified methods, essential for capturing the complex shear stress transfer mechanisms at the interface between yielding granular fill and high-strength reinforcement domains.

4.4. Phases of Construction in FEM

To mimic the actual stress-strain behaviour and deformation history of the embankment, a staged construction method was implemented in the numerical analysis using the SIGMA/W program. Staged modelling is essential to simulate the existing in-situ geostatic stresses prior to imposing loads on the embankment surface. Applying the vehicular surcharge simultaneously with the gravitational surcharge would cause the solver to combine the settlement from the Embankment's self-weight with that of the traffic surcharge, misrepresenting the deformation behaviour. A three-phase sequence was proposed for the numerical model to study the structural response under vehicular loading. The first phase established the initial geostatic stress state and reset internal displacements to zero. Subsequent phases simulated embankment construction, reinforcement activation, and the application of the vehicular surcharge. Details of the finite element sequence, including a step-by-step breakdown of active and inactive regions, are provided in Table 3.

Table 3. FEM construction phases: step-by-step breakdown of active/inactive regions in SIGMA/W

Phase	Description	Analysis Type	Active Regions and Boundary Conditions
Phase 1: Initial In-Situ Stress	Establishes the gravitational stress state prior to traffic exposure. Displacements are reset to zero at the conclusion of this phase.	In-Situ (Gravity)	Active: 3 m foundation and 7 m embankment. Material: All regions assigned baseline unreinforced properties. Load: Gravity (Y - direction), constructed embankment structure.
Phase 2: Embankment and Reinforcement	Simulates embankment construction and the mechanical integration of reinforcement layers (BFG or bio-root matrix).	Load / Deformation (Drained)	Active: Modification of the defined reinforcement layers. Material: Elements updated to specified structural BFG or enhanced bio-reinforced properties. Load: Gravity (Y - direction).
Phase 3: Vehicular Surcharge	Simulates the traffic loading on the fully constructed embankment structure.	Load / Deformation (Drained)	Active: All regions remain active. Material: Retains the finalized embankment and reinforcement material assignments established in Phase 2. Load: Application of a 24 kN/m ² uniformly distributed surcharge load across the crest.

5. Results and Analysis

5.1. Parametric Optimization of BFG

To assess the mechanical efficiency of Banana Fiber Geotextiles (BFG) and determine the optimal reinforcement conditions, a parametric study was performed using six different vertical spacings ranging from 0.25 m to 1.50 m.

These configurations were evaluated based on two main geotechnical performance parameters: the global Factor of Safety (FOS) for slope stability (Figure 4) and the maximum vertical displacement under operational vehicle surcharge loads (Figure 5). A summary of FOS and peak settlement values for all six spacings is presented in Table 4.

As per Clause 3.3.3 of the IRC: 75-2015 “Guidelines for the Design of High Embankments”, the minimum factor of safety is 1.4, as presented in Table 3.1 of the code [27]. As shown in the limit equilibrium analysis and visually confirmed by the dashed red safety threshold line in Figure 4, wider reinforcement spacings of 1.50 m and 1.25 m yield insufficient FOS values of 1.236 and 1.337, respectively, which are clearly below the required FOS. Consequently, the 1.0 m BFG spacing is acceptable with an FOS of 1.548, successfully meeting the minimum safety standard recommended by the IRC.

Table 4. Parametric optimization: FOS and peak settlement values for all six spacings

BFG Reinforcement Spacing (m)	Factor of Safety (FOS)	Maximum Settlement (mm)
0.25	1.775	15.5
0.50	1.636	17.0
0.75	1.581	19.5
1.00	1.548	22.0
1.25	1.337	25.3
1.50	1.236	29.0

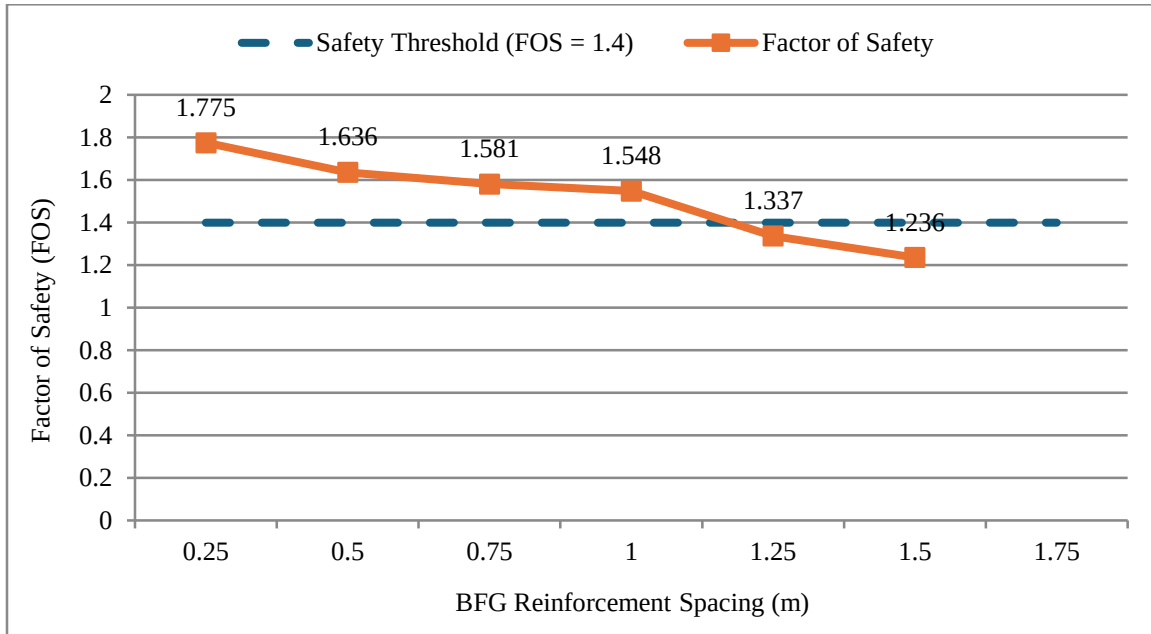


Fig. 4 Factor of Safety vs. BFG reinforcement spacing

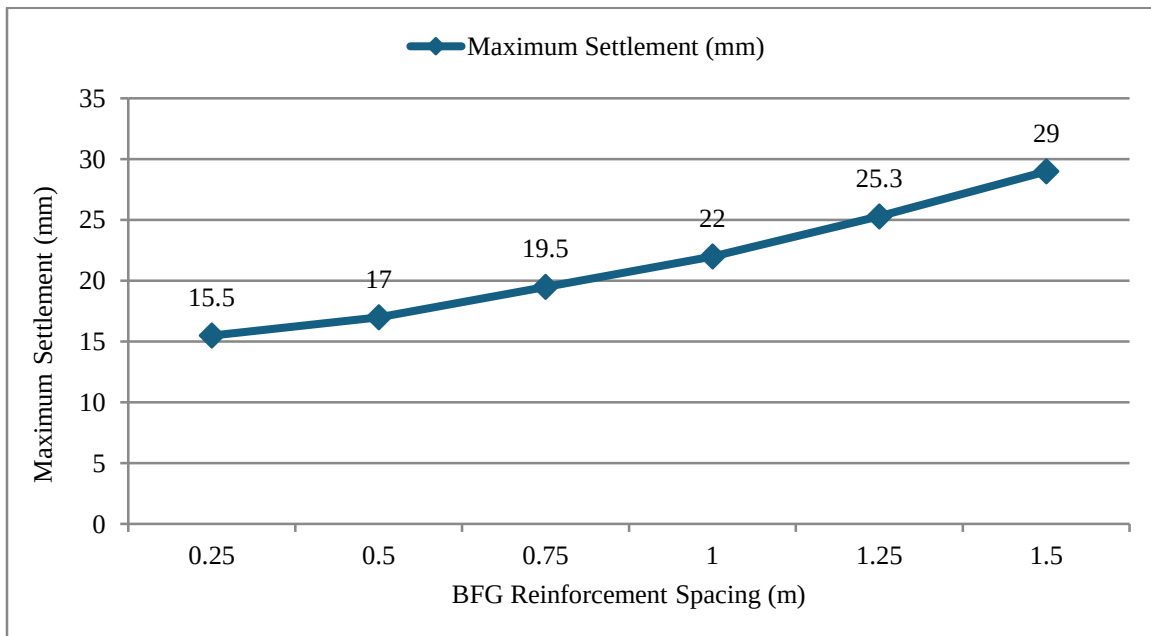


Fig. 5 Maximum settlement vs. BFG reinforcement spacing

Maximum vertical settlement decreases non-linearly as reinforcement density increases. Acting as a composite structure, the BFG layers limit internal shear deformations, resulting in maximum settlements of 29.0 mm at the widest spacing (1.50 m) and 15.5 mm at the densest spacing (0.25 m). All measured movements remain within the serviceability limits for highway structures. From these assessments, it was determined that the 1.0 m spacing is the most effective configuration.

A quantitative comparison of reinforcement quantities reveals that decreasing the spacing from 1.0 m to 0.75 m requires a 34.6 % increase in geotextile material (from 8 to 11 planar layers in the 7 m high embankment) and increased field installation effort, yet it yields only a marginal 2.1 % improvement in the absolute FOS (from 1.548 to 1.581). Therefore, the 1.0 m interval is selected as the optimum techno-economic spacing because it safely exceeds the IRC safety threshold of FOS 1.4 while significantly minimizing material costs and construction effort.

5.2. Comparative Safety Analysis

Quantitative assessment of stability improvement provided by various natural reinforcement techniques at the global level was accomplished using limit equilibrium analysis based on the Morgenstern-Price method. As shown in Figure 6, at the maximum vehicular surcharge of 24 kN/m², the critical slip surfaces and their Factor of Safety (FOS) values were calculated. The highly unsafe, unreinforced bare soil baseline embankment model had a deep-seated rotational failure with a low FOS of 1.133. This is well below the minimum safety limit of 1.4 as specified by IRC: 75-2015 pertaining to high embankments [27], and hence the untreated condition of the embankment is inherently unsafe in shear.

In BFG-reinforced embankments, the optimum spacing between the geotextiles is 1.0 m, which allows them to intercept the critical slip surface. This mechanical stabilization significantly improves the FOS to 1.548, exceeding the hard-set guidelines for long-term stability of the IRC [27], and is 36.6 % higher than that of the baseline.

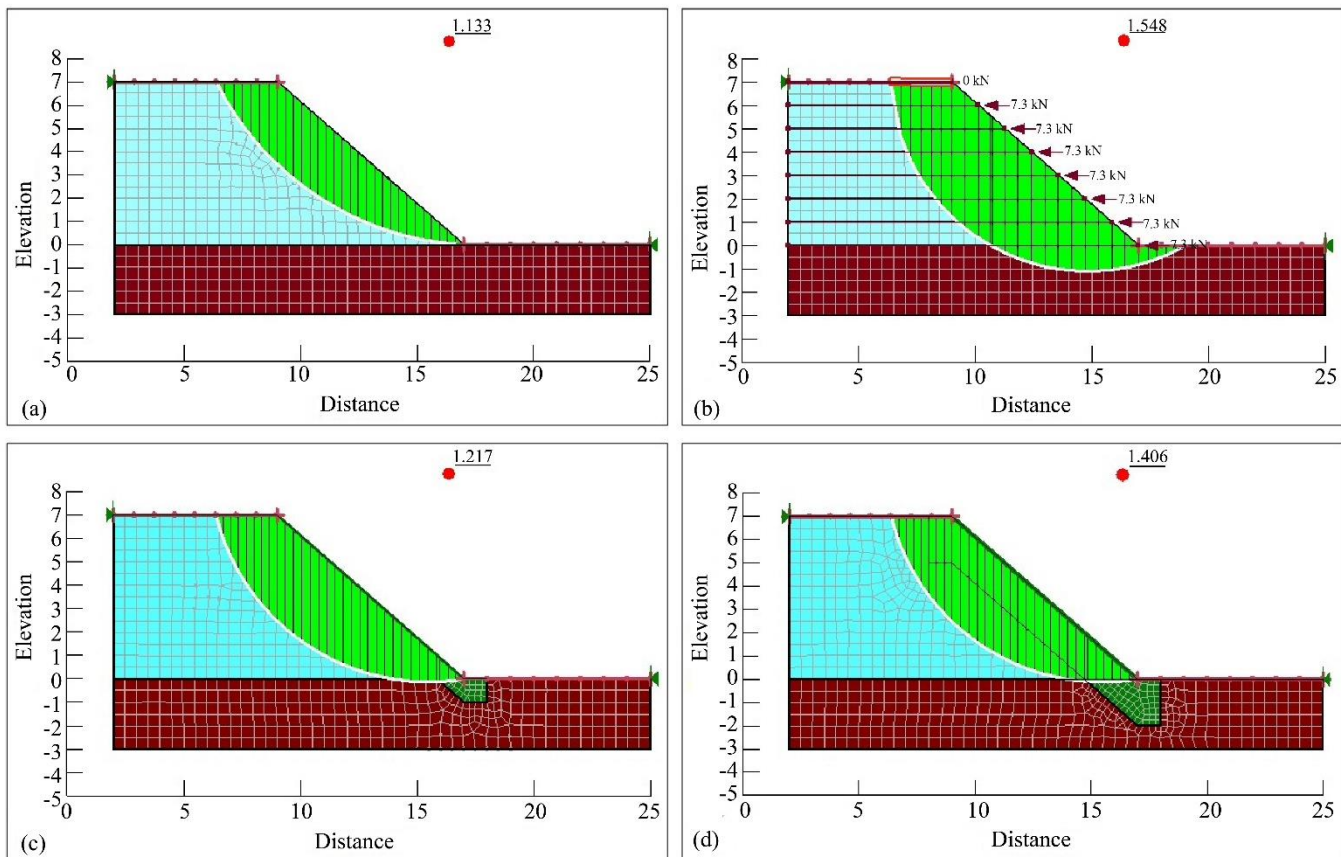


Fig. 6 Critical slip surfaces and Factor of Safety (FOS) evaluations for the analyzed embankment models: (a) Bare soil, (b) Optimum BFG reinforcement at 1.0 m spacing, (c) 3-month-old bio-reinforced slope, and (d) 6-month-old bio-reinforced slope.

On the other hand, the bio-reinforced models demonstrate a progressive slope stability enhancement over time due to the vetiver root matrix penetrating the soil profile. For the 3-month-old slope, the FOS was computed as 1.217. Although

less than the standard 1.4, Clause 3.3.3 of the IRC guidelines allows a reduced initial FOS of 1.2 when structural material actively increases in strength over a short-term duration [27]. This initial 1.217 FOS is technically acceptable during the

early biological establishment period as the living root system continuously increases the matrix soil's apparent cohesiveness and shear strength.

As the root network reaches a 6-month growth stage and a penetration depth of 2.0 m, the FOS improves significantly to 1.406. This biological maturation satisfies the stringent long-term safety requirement of 1.4 mandated by the IRC [27], demonstrating that 6-month-old vetiver bio-reinforcement is a viable, standalone stabilization method for highway infrastructure.

5.3. Comparative Settlement Analysis

The serviceability and deformation properties of the embankment models were evaluated through a stress-strain

analysis using the SIGMA/W module to determine the maximum vertical displacement (Y - displacement) under a continuous 24 kN/m² vehicular surcharge load. The resulting contours of vertical displacement are shown in Figure 7, while a complete comparative summary of the stability, settlement, lateral deformation, and internal shear strain for the four primary models is provided in Table 5. The unreinforced bare soil model exhibited a maximum vertical settlement of 40.0 mm at the crest. According to Clause 4.5.2 of the IRC: 75-2015 Guidelines for the Design of High Embankments, the permissible residual settlement limit is 300 mm, as rapid residual settlements are strictly restricted. Although the 40.0 mm vertical compression is well within permissible limits, the unreinforced matrix remains highly susceptible to local shear strains.

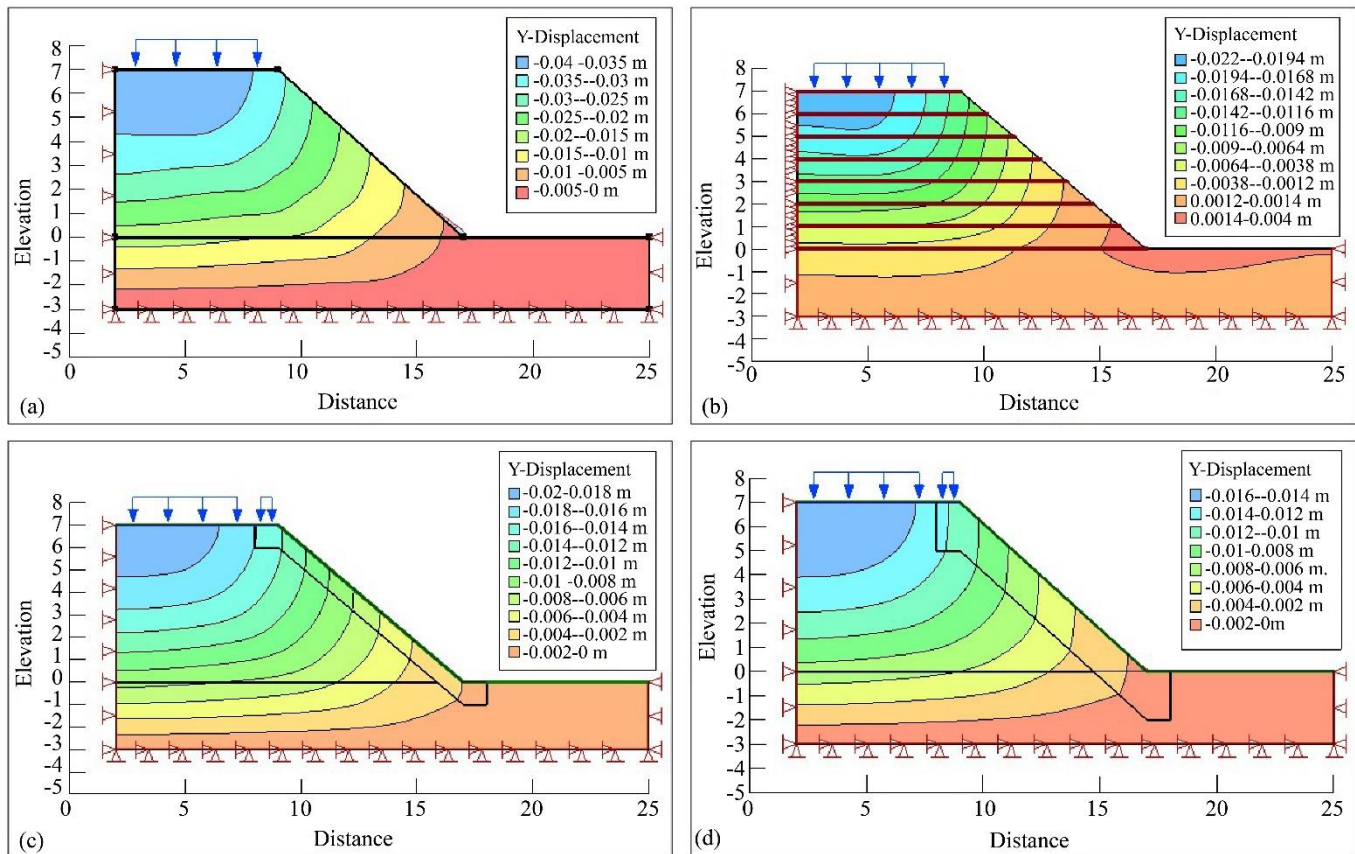


Fig. 7 Vertical settlement (Y - Displacement) contours for the analysed embankment models: (a) Bare soil, (b) Optimum BFG reinforcement at 1.0 m spacing, (c) 3-month-old bio-reinforced slope, and (d) 6-month-old bio-reinforced slope.

Applying the optimal Banana Fiber Geotextile (BFG) at 1.0 m spacing significantly decreased vertical deformations, yielding a maximum settlement of 22.0 mm. While planar geotextiles possess high lateral tensile stiffness to enhance global slope stability, the material's horizontal planarity provides only moderate vertical stiffness against elastic compression. It is evident that the bio-reinforced soil, represented numerically as an equivalent-continuum, functions as an integrated binding matrix, and consequently,

their settlement controls were superior and progressive. With the 3-month-old bio-reinforced slope, the maximum vertical displacement of the crest was 20.0 mm. The model aged 6 months had the highest level of structural stiffness as the root network matured and became denser, and more root surface area entered the soil profile, resulting in a maximum settlement of just 16.0 mm. This is a 60.0 % vertical settlement reduction relative to the unreinforced baseline. An inspection of the displacement contours reveals distinct lateral

deformation mechanisms. Pronounced soil movement and lateral yielding at the slope face and toe are clearly observable in both the unreinforced bare soil embankment and the horizontally reinforced BFG embankment. However, both the 3-month-old and 6-month-old bio-reinforced slopes exhibit almost no lateral face or toe movement. The dense volumetric root matrix at the slope surface acts as an integrated, continuous soil lining, with the bio-reinforced layer functioning as a cohesive structural facing. Consequently, the biological layer serves as a semi-rigid barrier or retaining structure. It helps contain the internal soil mass and prevents outward lateral flow under the applied vehicular surcharge.

5.4. Comparative Lateral Deformation Analysis

An analysis of horizontal deformation (X - displacement) was performed using the SIGMA/W finite element solver to evaluate the mechanical benefits of the different reinforcement methods.

Under the continuous 24 kN/m² vehicular surcharge, the soil matrix within the unreinforced embankment is forced to move vertically, causing lateral spreading to relieve stresses along the unconfined slope boundary. The unreinforced bare soil model, shown in Figure 8, has a maximum horizontal displacement of 12.0 mm.

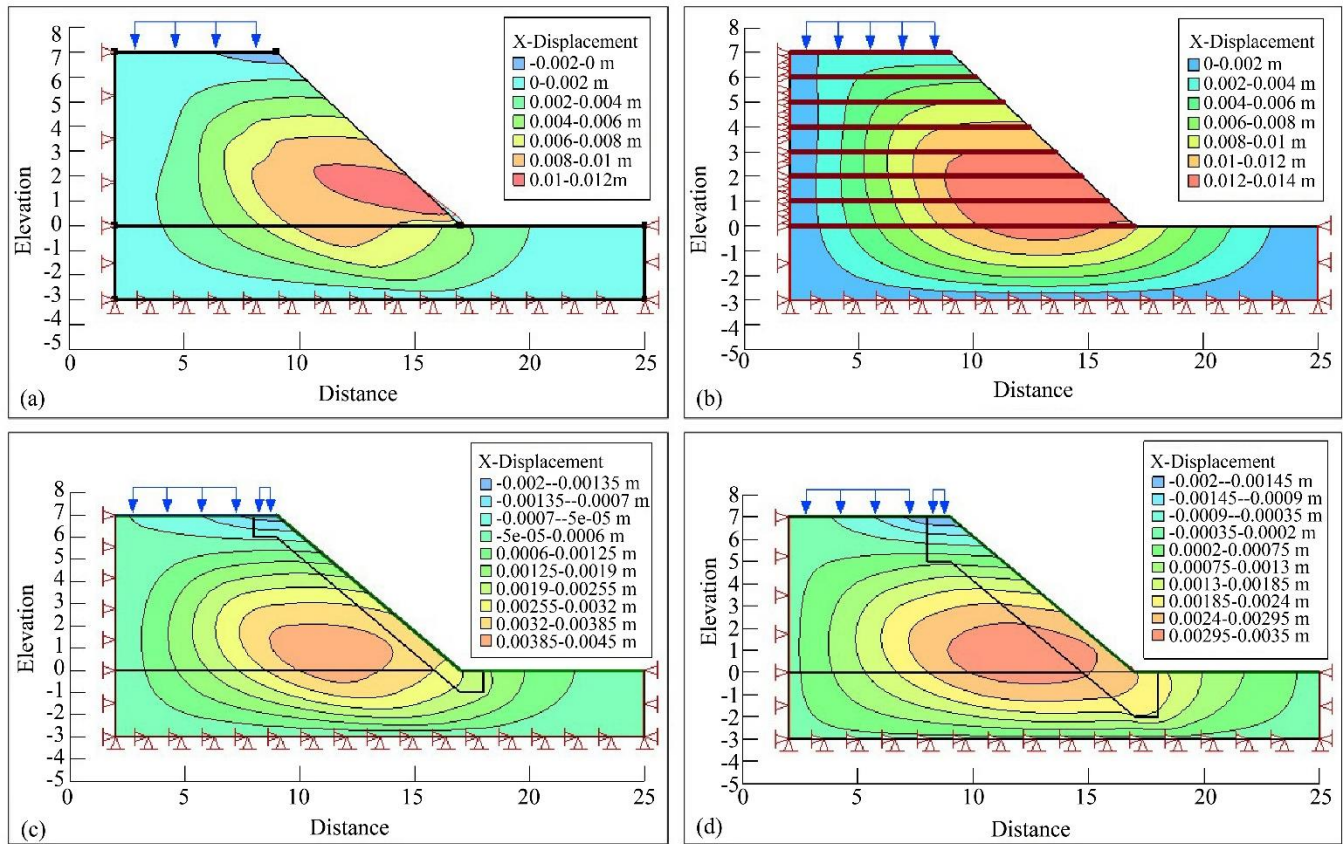


Fig. 8 Lateral deformation (X - displacement) contours illustrating face confinement mechanisms: (a) Unreinforced bare soil, (b) Optimum BFG at 1.0 m spacing, (c) 3-month-old bio-reinforced slope, and (d) 6-month-old bio-reinforced slope.

In this unreinforced situation, the critical deformation zone is very highly concentrated along the slope face and toe, where the slope is most vulnerable, showing that lateral yielding has begun. The use of Banana Fiber Geotextiles (BFG) presents good horizontal tensile resistance for the internal soil mass and was evaluated at a spacing of 1.0 m, which was also found to be successful.

The resulting planar BFG layers yield a peak horizontal displacement of 14.0 mm, but the deformation contours show that there are areas of lateral bulging in the unreinforced layers of soil in between. The two-dimensional nature of the

geotextile is not able to entirely avoid a "squeezing" and outward flow of the intermediate soil blocks at the slope face.

The bio-reinforced models change the deformation mechanisms laterally from a fundamental point of view. The vetiver root network of 3-month-old and 6-month-old plants forms a deep composite soil matrix, which is represented numerically as an equivalent-continuum block. Unlike discrete planar layers, the dense volumetric root architecture also functions as an integrated structural facing. The bio-reinforced zone acts as an integrated retaining layer, confining the side of the slope.

The X - displacement contours of the bio-reinforced models visually confirm this confinement mechanism. Lateral movement at the slope face and toe is completely arrested. The 3-month and 6-month models achieve a dramatic drop in the amount of horizontal displacement to 4.5 mm and 3.5 mm, respectively, a 70.8 % reduction from the unreinforced baseline (Table 5).

The position of the maximum lateral displacement is also moved away from the slope face and into the confined stable core inside the embankment. These findings mathematically validate the mature bio-reinforcement as a very effective, partially rigid retaining barrier which, alone, is capable of counteracting the dominant horizontal spreading mechanisms that generally precede a deep-seated rotational failure.

6. Discussion

6.1. Internal Mechanisms of Enhancement

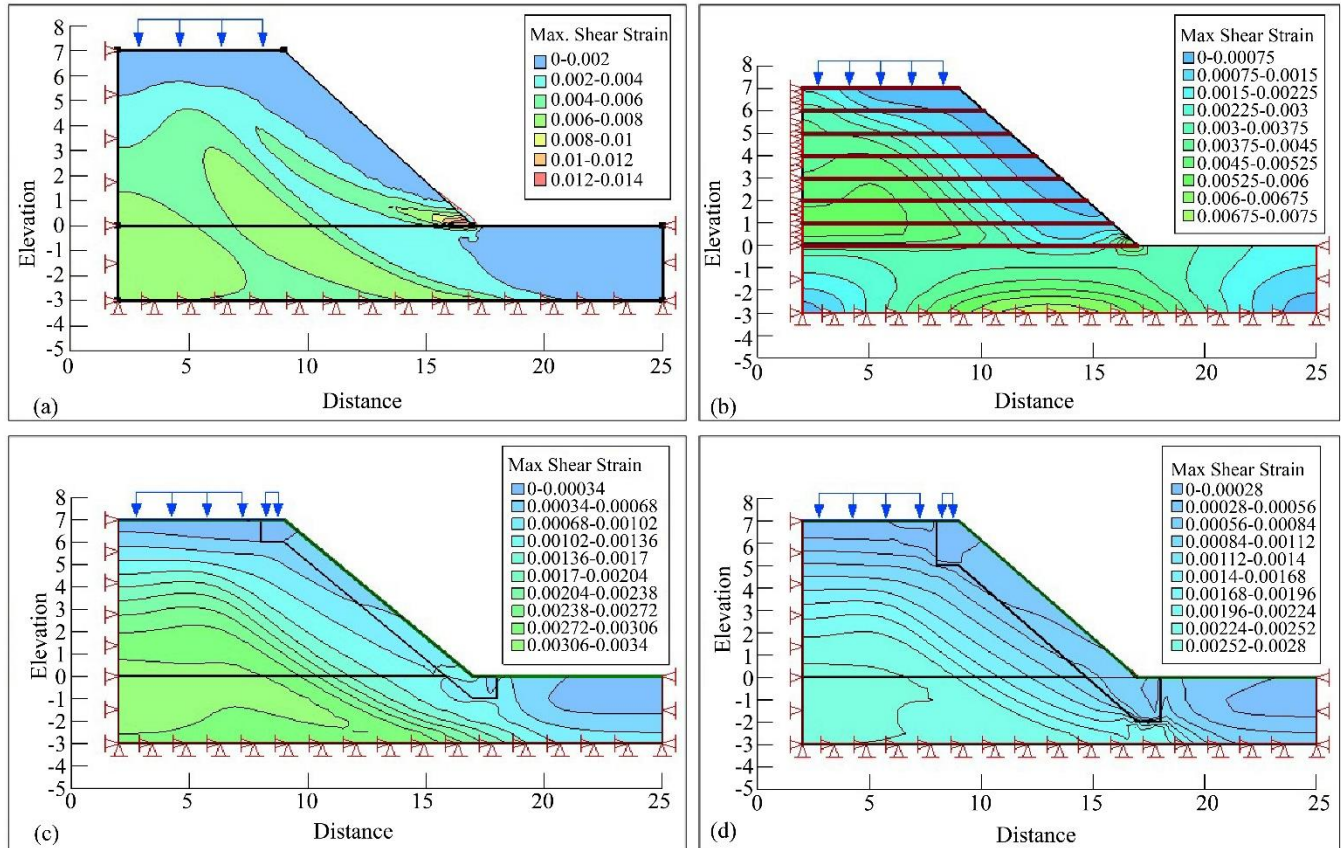


Fig. 9 Maximum shear strain contours illustrating internal failure mechanisms and shear band interception for the analysed embankment models: a) Unreinforced bare soil, b) Optimum BFG at 1.0 m spacing, c) 3-month-old bio-reinforced slope, and d) 6-month-old bio-reinforced slope.

Table 5. Summary of final comparative analysis: stability, deformation, and internal shear strain values for the four primary models

Embankment Model Configuration	Factor of Safety (FOS)	Maximum Settlement (Y - Displacement)	Maximum Lateral Deformation (X - Displacement)	Peak Internal Shear Strain
Unreinforced Bare Soil	1.133	40.0 mm	12.0 mm	0.0140
Optimum BFG (1.0 m Spacing)	1.548	22.0 mm	14.0 mm	0.0075
3-Month-Old Bio-Reinforced Slope	1.217	20.0 mm	4.5 mm	0.0034
6-Month-Old Bio-Reinforced Slope	1.406	16.0 mm	3.5 mm	0.0028

The above displacement analyses are used to externally quantify the serviceability of the embankment, whilst an

evaluation of the maximum shear strain occurring inside is necessary to understand the fundamental mechanisms of

reinforcement. When the shear strains localize onto an incipient slip surface, slope failure and motion begin. The maximum shear strain contours from SIGMA/W can be visually and quantitatively compared to understand the internal stress redistribution, as demonstrated in Figure 9.

The largest magnitude of the maximum shear strain in the unreinforced bare soil baseline is 0.014. This high-strain yielding zone, as marked by the red or orange contours in Figure 9a, is continuous and is quite deep, climbing from the foundation stratum up toward the slope toe. This is a concentrated shear band, which relates to the critical slip surface shown by the limit equilibrium analysis as the main mechanism of rotational failure. The failure propagation is actively disturbed by the introduction of the optimal BFG reinforcement at 1.0 m spacing. The planar geotextile layers physically engage the forming shear band, triggering its tension and interface friction to block the breaking force of the soil mass. The mechanical interception is effective as it does not allow the shear strain to become focused in one single continuous plane; the peak internal shear strain is reduced to 0.0075 (Table 5). This is a 46.4 % decrease from the unreinforced baseline.

The bio-reinforced models have an entirely new and highly successful intrinsic mechanism. The bio-reinforced zone, modeled as an equivalent-continuum, does not offer discrete planes of tensile strength on the slope boundaries, but rather acts as a composite, reinforced soil block. This continuous, dense root matrix completely changes the stress regime in the ground and stops the deep-lying foundation shear band from curling up and rupturing at the slope face. Thus, the maximum internal shear strain in the 3-month bio-reinforced model is significantly reduced to approximately 0.0034, and to 0.0028 for the 6-month model. This is an astounding shear strain reduction, 80.0 % of the peak shear strain, demonstrating the effect of the dense biological root network not only keeping the surface from being laterally displaced, but also actively suppressing internal shear tearing mechanisms that result in catastrophic failure.

6.2. Comparative Effectiveness against State-of-the-Art Techniques

Traditional state-of-the-art techniques for highway embankment stabilization involve using synthetic polymer geogrids for internal reinforcement or shallow surface treatments, such as hydroseeding, for face protection. Although effective, these synthetic approaches present disadvantages, including high manufacturing carbon emissions and environmental persistence. The numerical results of this investigation reveal that natural reinforcements offer sustainable alternatives with mechanical performance that is highly competitive with existing state-of-the-art solutions. In the current study, Banana Fiber Geotextiles (BFG) placed at an optimal 1.0 m vertical spacing provided a

global Factor of Safety (FOS) of 1.548, representing a 36.6 % improvement over the baseline. This strong mechanical response aligns with findings by Matchum et al. [16] and Bartholomeus et al. [15], who determined that banana-plantain stalk fiber meets the strict mechanical criteria for limited-lifetime geotextiles.

The outcomes achieved by the BFG are also comparable to other natural fibers reported in the literature; for instance, Kumar and Roy [18] and Sanyal [17] observed notable slope stability improvements under hydraulic loading using jute fiber. These numerical results exceed the stringent long-term safety requirements of IRC: 75-2015 [27]. They demonstrate the effectiveness of the woven BFG matrix in emulating the tensile load transfer mechanisms of synthetic geogrids.

The biological reinforcement models exhibited mechanical characteristics distinctly different from those of conventional surface treatments and discrete synthetic reinforcements. While conventional surface protections primarily prevent surficial erosion, they do not effectively enhance the global stability of the deep embankment mass. However, the current finite element analysis indicates that the 2.0 m deep mature vetiver root system acts as an active structural component. The 6-month-old bio-reinforced slope achieved a factor of safety of 1.406, which is 24.1 % greater than the bare soil baseline. This improvement is 20.6 % higher than the FOS increases for vetiver-reinforced slopes reported by Badhon et al. [9] using PLAXIS 2D, validating the efficacy of deep root architectures.

These performance metrics support the comparative findings of Islam et al. [12], who assessed vetiver grass against synthetic recycled plastic pins and determined that vetiver offers a superior and more cost-effective configuration. The current study precisely simulated the bulk soil-binding qualities of the vetiver roots using an equivalent-continuum approach, demonstrating a maximum vertical settlement reduction of 60.0 % and a 70.8 % reduction in lateral spreading. As established by Islam and Shahin [8] and Noel et al. [13], vetiver enhances both root cohesion and matric suction. The present work confirms that this dual action enables the bio-reinforced matrix to function as an integrated, deep-anchoring retaining system. The bio-reinforcement is shown to be structurally advantageous compared to synthetic alternatives; rather than degrading over time, the living material continuously improves the apparent cohesion and stiffness of the soil matrix as it matures. For a comprehensive comparative assessment, Table 6 summarizes the quantitative and qualitative numerical results obtained in the current study alongside recent state-of-the-art literature on natural reinforcement effectiveness. The tabular comparison demonstrates that the stabilization measures evaluated in this study, specifically the 24.1 % FOS increase for the 6-month mature bio-reinforcement and the 36.6 %

Table 6. Comparative performance of the current study against existing natural reinforcement literature

Study / Reference	Reinforcement Technique	Key Performance Metric / Improvement	Remarks
Badhon et al. [9]	Vetiver Grass (Roots)	FOS improved by up to 20.6 %.	Validates deep-rooted FOS enhancement.
Kumar and Roy [18]	Jute Fiber (Natural Fabric)	Increased slope FOS under simulated rainfall conditions.	Confirms planar natural fibers withstand hydraulic stress.
Islam et al. [12]	Vetiver Grass vs. Recycled Plastic Pins	Vetiver identified as the most cost-effective; increased FOS and reduced crest deformation.	Benchmarks biological roots against synthetic plastic inclusions.
Current Study	6-Month Vetiver Grass	FOS improved by 24.1 %; maximum settlement reduced by 60.0 %; lateral spread reduced by 70.8 %.	Quantifies dual-action enhancement (FOS and 2D deformation control).
Current Study	Optimum BFG (1.0 m spacing)	FOS improved by 36.6 %; maximum settlement reduced by 45.0 %.	Optimizes planar fiber spacing for maximum load-transfer.

FOS increases for the BFG configuration compare favourably with documented improvements in natural ground engineering. By correlating limit equilibrium safety factors with finite element stress-deformation mechanisms, this study provides a more comprehensive mechanical assessment of natural reinforcements than stand-alone analyses.

7. Conclusion

This numerical study quantified the mechanical improvement of a highway road embankment employing planar Banana Fiber Geotextiles (BFG) as well as volumetric vetiver grass bio-reinforcement under a continuous vehicular surcharge of 24 kN/m². The general conclusions of the limit equilibrium (SLOPE/W) and finite element (SIGMA/W) analyses are:

- **Baseline Vulnerability:** The unreinforced granular embankment (SP-SM) is highly vulnerable to deep-seated rotational failure, exhibiting a Factor of Safety (FOS) of 1.133 and a maximum vertical settlement of 40.0 mm. Consequently, this untreated condition fails to meet the minimum safety threshold of 1.4 mandated by IRC: 75-2015 for high embankments.
- **Optimal Planar Reinforcement:** The incorporation of BFG at an optimum techno-economic spacing of 1.0 m successfully intercepts the continuous shear band. With this mechanical intervention, the global FOS increases to 1.548, an improvement of 36.6 %, and the maximum vertical settlement is reduced to 22.0 mm, satisfying strict highway design requirements.
- **Biological Safety Enhancement:** Reaching a maximum depth of 2.0 m, the 6-month-old Vetiver root matrix biologically enhances the apparent cohesion and the angle of internal friction at the slope face. This maturation increases the FOS to 1.406, demonstrating that bio-reinforcement is a structurally feasible, standalone approach for long-term stability.
- **Superior Deformation Control:** The bio-reinforced layer, simulated as an equivalent-continuum block, fundamentally alters the deformation mechanics of the

embankment. This restricts peak vertical settlement to just 16.0 mm, representing a 60.0 % reduction, and inhibits lateral face yielding by reducing the baseline horizontal spread to only 3.5 mm, which is a 70.8 % reduction.

- **Internal Mechanism Shift:** Contours of maximum shear strain mathematically demonstrate that the high rigidity of the Vetiver roots provides a highly restraining barrier at the 6-month-old stage. The reinforcement reduces the peak internal shear strain by 80.0 %, from 0.014 to 0.0028, and eliminates the effect of the two rotational tearing mechanisms.

Overall, both natural methods of reinforcement provide excellent structural support. BFG is highly effective at delivering immediate tension and reserve strength; meanwhile, mature vetiver bio-reinforcement meets the critical need for volumetric deformation containment, making it an optimum, self-healing, and sustainable solution for tropical infrastructure development.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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References

- [1] Mohammad Aqib et al., "Experimental and Numerical Analysis of Rainfall-Induced Slope Failure of Railway Embankment of Semi High-Speed Trains," *Journal of Engineering and Applied Science*, vol. 70, no. 1, pp. 1-24, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [2] A.K. Aldungarova et al., "The Potential Effects Caused by Long-Term Water Level Changes on Embankment Slope Stability under Rapid Drawdown," *Journal of the Kazakh State Academy of Architecture and Civil Engineering*, vol. 83, no. 1, pp. 107-119, 2022. [[CrossRef](#)] [[Google Scholar](#)]
- [3] Askar Zhussupbekov, and Timoth Mkilima, "Stability Analysis of an Old Earth Samarkand Dam in Kazakhstan under Rapid Drawdown Conditions," *Environmental Engineering*, vol. 9, no. 1-2, pp. 11-20, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [4] Kotha Bala Jyothi, and Umesh Kumar Singh, "Static and Pseudo-Static Stability Analysis of Right Earthen Embankment of Nagarjuna Sagar Dam by Geostudio," *4th International Conference on Design and Manufacturing Aspects for Sustainable Energy*, vol. 391, pp. 1-15, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [5] Nada M. Al-Nedawi, and Maysam Th. Al-Hadidi, "Finite Element Analysis of Seepage for Hemrin Earth Dam using Geo-Studio Software," *Diyala Journal of Engineering Sciences*, vol. 13, no. 3, pp. 66-76, 2020. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [6] Saminu Ahmed, Friday Emmanuel, and Uwemedimo Nyong Wilson, "Finite Element Method of Seepage and Stability Analysis of Saura-Keffi Earth Dam," *Malaysian Journal of Civil Engineering*, vol. 35, no. 1, pp. 53-61, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [7] Mohsen Rezaee et al., "Stability Analysis of Esfarayen Garati Dam using Finite Element Method," *International Journal of Engineering Innovation and Research*, vol. 3, no. 5, pp. 654-658, 2014. [[Google Scholar](#)] [[Publisher Link](#)]
- [8] Mohammad S. Islam, and Hossain M. Shahin, "Reinforcing Effect of Vetiver (*Vetiveria Zizanioides*) Root in Geotechnical Structures - Experiments and Analyses," *Geomechanics and Engineering*, vol. 5, no. 4, pp. 313-329, 2013. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [9] Faria Fahim Badhon, Mohammad Shariful Islam, and Md Azizul Islam, "Contribution of Vetiver Root on the Improvement of Slope Stability," *Indian Geotechnical Journal*, vol. 51, no. 4, pp. 829-840, 2021. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [10] Reza Maadi, and Ali Noorzad, "Effect of Root Age on the Slope Stability using Vetiver Grass," *Arabian Journal of Geosciences*, vol. 17, no. 7, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [11] Amber Spears et al., "Bio-Inspired Stabilization of a Test Levee Slope using Vetiver Grass on Highly Plastic Clay," *Geo-Congress*, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [12] Mohammad Shariful Islam et al., "Effectiveness of Vetiver-based Bioengineering in Combination with Recycled Plastic Pin (RPP) for Steep Embankment Stabilization," *International Conference series on Geotechnics, Civil Engineering and Structures*, Ho Chi Minh City, Vietnam, pp. 799-806, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [13] Watha Ndoudy Noël et al., "Stability Evaluation of Reinforced Slope Soil with Vetiver Grass Against Erosion and Landslides Hazards by using Finite Element Method," *International Journal of Plant and Soil Science*, vol. 34, no. 23, pp. 863-873, 2022. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [14] Catherine S. Hernandez, Nuna Almanzor, and Maria Cecilia M. Marcos, "Properties and Behavior of Banana Fiber and Coconut Coir (Baconet) Geotextile," *Advances in Civil, Environmental, and Materials Research*, Songdo Convensia, Incheon, Korea, pp. 1-13, 2018. [[Google Scholar](#)]
- [15] Bartholomeus Bartholomeus et al., "Banana Stem Fiber Potential as an Alternative Natural Geosynthetic Material for Soil Reinforcement and Protection," *Rekayasa Sipil*, vol. 19, no. 1, pp. 32-38, 2025. [[Google Scholar](#)]
- [16] Solange Fogue Matchum et al., "Investigation of Chemical, Physical and Morpho-Mechanical Properties of Banana-Plantain Stalk Fiber for Ropes and Woven Fabrics used in Composite and Limited-Lifespan Geotextile," *Heliyon*, vol. 10, no. 8, pp. 1-18, 2024. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [17] P.K. Choudhury, and Tapobrata Sanyal, "Embankment Slope Stabilization with Jute Geotextiles - A Case Study in NH-2 Allahabad By-Pass," *Proceedings of Indian Geotechnical Conference*, 2010. [[Google Scholar](#)]
- [18] Saurabh Kumar, and Lal Bahadur Roy, "Investigating the Slope Stability and Factor of Safety Properties of Soil Reinforced with Natural Jute Fibers Under Different Rainfall Conditions," *Engineering, Technology and Applied Science Research*, vol. 13, no. 1, pp. 9919-9925, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [19] Xinzhuang Cui, and Xinglin Zhou, "Limit Analysis of Stability of Geosynthetics Reinforced Road Embankment," *Slope Stability and Earth Retaining Walls*, pp. 180-187, 2011. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [20] Akshay Kumar Jha, M.R. Madhav, and G.V.N. Reddy, "Mechanics of Reinforcement-Slope Interactions," *INAE Letters*, vol. 3, no. 2, pp. 115-121, 2018. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [21] J. Michael Duncan, Stephen G. Wright, and Thomas L. Brandon, *Soil Strength and Slope Stability*, 2nd ed., John Wiley and Sons, vol. 312, 2005. [[Google Scholar](#)] [[Publisher Link](#)]
- [22] Jonathan Knappett, and R.F. Craig, *Craig's Soil Mechanics*, 8th ed., CRC Press, London, 2012. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]

- [23] Augustin Blaise Nguendeu Deugoué et al., “Banana-Plantain Fiber Limited Life Geotextiles (PFLLGs): Design and Characterization,” *Indian Geotechnical Journal*, vol. 53, no. 4, pp. 874-886, 2023. [[CrossRef](#)] [[Google Scholar](#)] [[Publisher Link](#)]
- [24] B.O. Hardin, “The Nature of Stress-Strain Behavior for Soils,” *From Volume I of Earthquake Engineering and Soil Dynamics-Proceedings of the ASCE Geotechnical Engineering Division Specialty Conference*, Pasadena, California, pp. 3-90, 1978. [[Google Scholar](#)]
- [25] Karl Rainer Massarsch, “Settlement Analysis of Compacted Granular Fill,” *Proceedings of the International Conference on Soil Mechanics and Foundation Engineering-International Society for Soil Mechanics and Foundation Engineering*, vol. 1, pp. 325-328, 1994. [[Google Scholar](#)]
- [26] Nilmar Janbu, “Soil Compressibility as Determined by Oedometer and Triaxial Tests,” *Proceedings European Conference SMFE*, Wiesbaden, vol. 1, pp. 19-25, 1963. [[Google Scholar](#)]
- [27] Kama Koti Marg, *Guidelines for the Design of High Embankments*, Indian Roads Congress, IRC: 75-2015, New Delhi, India, 2015. [[Google Scholar](#)] [[Publisher Link](#)]