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Validation of the Slope Stabilization Technique in Sedimentary Rock with Kikuyu Grass Cultivation to Improve Soil Shear Resistance

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ABSTRACT

This study presents the efficiency of bioengineering through the cultivation of Kikuyu grasses for the stabilization of slopes on Highway Route PE-28B in Peru. The objective was to evaluate the impact of Kikuyu roots on soil shear resistance and slope stability. Direct cutting tests and global stability analysis were carried out using SLIDE V6.0 software, both in natural conditions and with the intervention of Kikuyu grasses. The results showed that the safety factor (FS) of the slope increased significantly with the presence of Kikuyu roots: from 0.905 to 1.504 according to the Bishop Method and from 0.881 to 1.444 according to the Janbú method in static analyses, and from 0.751 to 1.278 and from 0.728 to 1.218 in pseudostatic analyzes respectively. Furthermore, direct shear tests revealed an increase in friction angle and soil cohesion with the presence of Kikuyu roots. In conclusion, bioengineering with Kikuyu grasses is demonstrated as an effective and sustainable technique to improve slope stability, offering a viable alternative to traditional stabilization methods, with significant economic and environmental benefits.

1. INTRODUCTION

Slope stability is a global concern due to its direct impact on the safety of infrastructure and communities [1, 2]. Landslides represent one of the most common and devastating natural disasters [3, 4], affecting both urban and rural regions. Studies indicate that around 4.8 million people worldwide are at risk due to landslides, with annual economic losses exceeding $4 billion [5, 6]. Increasing urbanization and construction in landslide-prone areas have exacerbated this problem, increasing the vulnerability of infrastructure and surrounding populations [7].

Landslides not only cause economic losses, but also result in high human cost [8, 9]. Recent events in countries such as Indonesia, China and Colombia have shown the tragic reality of these phenomena, with thousands of people displaced and numerous deaths [10]. Climate variability, including extreme rainfall events and earthquakes, increases the frequency and magnitude of landslides, underscoring the urgency of developing more effective slope stabilization methods [11].

In Peru, slope instability is a critical concern, especially in coastal and mountainous regions [12, 13]. The country's geography, characterized by its rugged topography and the presence of soils highly susceptible to erosion, makes landslides a recurring problem [14]. Studies carried out by the National Institute of Civil Defense (INDECI) indicate that landslides in areas such as the Costa Verde have been responsible for multiple incidents, including the collapse of infrastructure and fatal vehicle accidents. Despite interventions, such as the installation of synthetic mesh and drainage systems, landslides continue to occur, underscoring the need for more robust and long-lasting solutions [15].

The impact of landslides on road infrastructure around the world is significant [16]. Crucial highways for the transportation of goods and people, such as the Panamericana Sur and the Carretera Central, face constant risks. Disruptions to these roads not only affect the local economy, but also have national repercussions, highlighting the need for effective and sustainable interventions.

In the Ayacucho region, Highway Route PE-28B, especially the section between Km 0+000 and Km 5+000, is a clear example of the challenges faced by road works due to slope instability. This area, characterized by its irregular topography and sedimentary rock soils, constantly suffers from landslides and erosion, representing a constant danger to road users. The instability of the slopes on this road not only affects the safety of pedestrians and drivers, but also interrupts the commercial and economic flow in the region.

Sandstone is a type of sedimentary rock composed primarily of sand grains, which may be cemented by materials such as quartz, calcium carbonate, or clay minerals. The geotechnical characteristics of sandstone, such as its compressive strength and internal cohesion, depend largely on the composition and type of cement that binds the sand grains. Sandstone can be particularly susceptible to erosion and weathering, factors that contribute to slope instability in regions where this rock is predominant [17].

It is crucial to carefully evaluate the conditions of sandstone slopes for several reasons [17].

First, heterogeneity in sandstone composition can result in significant variations in material strength, complicating the prediction of slope behavior under different loading conditions.

Second, the presence of fractures and fissures in sandstone can drastically reduce its stability, since these discontinuities facilitate water infiltration, which in turn reduces cohesion and increases pore pressure, triggering landslides.

Regarding this topic, the research that has exhaustively addressed bioengineering for stabilization purposes is varied; However, under the conditions that occur in sedimentary rocks, studies are limited, which makes it a particularly relevant and interesting field of study. Although there are some previous studies that have explored various bioengineering methodologies and techniques to improve the FS of slopes, important knowledge gaps and areas with considerable potential for improvement persist.

This is how the study carried out by Chaparro-Sarmiento et al. [18] who analyzed the stabilizing effect of eucalyptus and vetiver on different types of soils in Colombia, considering variations in geometry, inclination angle and water table. A stability analysis was carried out using the limit equilibrium method under the Mohr-Coulomb criterion. The effects of roots on added cohesion at different depths were evaluated and the weight of eucalyptus in the use of vegetation as a slope stabilizing agent was considered. The effects of roots on added cohesion varied depending on soil depth and plant type. The weight of the eucalyptus was an important factor in its use as a slope stabilizer. Water had a significant impact on the safety factor of the slope, especially at low slope angles and depending on the type of vegetation present. It was shown that eucalyptus is effective in slope stability, although its weight can be a negative factor on high slopes. Additionally, the deep roots of eucalyptus can be counterproductive in the long term, as they can destabilize the soil at greater depths. On the other hand, the contribution of young vetiver to the stability of the slope was not very significant. Unlike this study, our article specifically addresses the efficiency of Kikuyu grass in stabilizing slopes in sedimentary soils. Detailed data on the increase in shear strength and safety factor are presented through direct shear tests and global stability analyses. In addition, the economic and environmental impact is evaluated, offering a sustainable and effective alternative to traditional slope stabilization methods.

On the other hand, there is the study of Prugne et al. [19], where the objective was to analyze soil and water bioengineering (SWBE) for river management as a viable alternative to civil engineering for riverbank stabilization. Unlike riprap, SWBE techniques support bank stabilization and promote the development of riparian vegetation, preserving plant biodiversity and maintaining essential ecosystem services such as recreation, carbon sequestration, filtration of pollutants and the creation of ecological niches and corridors. It is recognized that the potential of SWBE is underestimated due to the risks of failure, especially in rivers with severe mechanical limitations. In cold environments with frozen waters, processes such as ice abrasion or ice jams are significant perturbation factors for river morphology and riparian vegetation, exacerbating the marginality of the SWBE and highlighting knowledge gaps on the interactions between the ice, the morphology of river channels and the persistence of vegetation. This review article discusses how biogeomorphology, which studies the interactions and feedback between living organisms and physical processes that shape the landscape, can provide new concepts and models to understand the co-development between landforms and vegetation in the context of SWBE. Biogeomorphology can be used to provide a better understanding of river dynamics and biogeomorphological changes in time and space, identify species best adapted to local conditions and better understand the relationship between channel morphology, vegetation and ice, and develop monitoring and evaluation tools to define the biogeomorphological functions of SWBE structures and improve maintenance strategies. In comparison, our article specifically addresses the efficiency of Kikuyu grass in stabilizing slopes in sedimentary soils, providing detailed data on the increase in shear strength and safety factor through direct shear tests and global stability analyses.

In addition, Fernandes and Guiomar [20] presented their study with the objective of evaluating the comparative efficiency in the short and long term (up to 20 years) of the most used slope stabilization techniques in Mediterranean conditions, using calculation models to evaluate the safety factor of these techniques. SLIP4EX was used to evaluate the safety factor and the Coulomb model was used to evaluate the slip and rollover resistance. Two tree species common in the western Mediterranean region (Pinus halepensis and Quercus faginea) were selected and three common soil types (stony clay, loose sandstone and sandy loam) were considered. Simulations were performed under less favorable environmental conditions to evaluate the reliability of the "worst case scenario." The results of the simulations showed that the use of soil bioengineering techniques presents reliable effectiveness in Mediterranean conditions, confirmed by experiences in sites with similar edaphoclimatic conditions. Adequate vegetation development guarantees all safety requirements even in the worst scenarios considered. It was concluded that soil bioengineering techniques are effective and reliable for stabilizing slopes in Mediterranean conditions, if adequate vegetation development is considered. However, the general lack of data on the geotechnical characteristics of Mediterranean vegetation was highlighted, which is critical for the application of these techniques. Unlike this study, our paper on the efficiency of Kikuyu grass in stabilizing slopes in sedimentary soils addresses the uncertainties related to plant development in different soil types and climatic conditions. It provides detailed data on the increase in shear resistance and safety factor through direct shear tests and global stability analyses, also evaluating the economic and environmental impact. It offers a sustainable and effective alternative to traditional slope stabilization methods, filling knowledge gaps regarding the applicability of bioengineering techniques in different geotechnical and environmental conditions.

In the last decade, the use of bioengineering techniques has gained popularity as a sustainable and efficient alternative for slope stabilization, especially in areas with soils susceptible to erosion. Previous research has evaluated the effectiveness of several plant species, such as vetiver and eucalyptus, in improving soil cohesion and shear strength. Chaparro-Sarmiento et al. [18] studied the use of vetiver and eucalyptus in Colombia, concluding that, although both species improve soil stability, the weight of deep eucalyptus roots can be counterproductive on steep slopes. Prugne et al. [19] examined bioengineering in cold-climate rivers, highlighting how the roots of riparian vegetation help reduce erosion and improve soil stability in areas exposed to freezing and thawing processes.

However, research on the effectiveness of bioengineering in sedimentary soils is limited. Existing studies have focused mainly on cohesive or sandy soils, with less attention to the complex geotechnical conditions of sedimentary soils. This study aims to fill that gap by investigating the effectiveness of Kikuyu grass, a species whose dense, fibrous roots offer a promising solution for slope stabilization in sedimentary soils. Through direct shear tests and global stability analysis, this work provides detailed data on soil behavior with and without Kikuyu grass intervention, providing a new perspective on bioengineering applications in sedimentary soils.

The objective of this research is to validate the efficiency of bioengineering applied through the cultivation of Kikuyu grasses in the stabilization of sedimentary rock slopes on Highway Route PE-28B, between Km 0+000 and Km 5+000 in Ayacucho. This approach not only improves slope stability but also provides an environmentally friendly and economical solution compared to traditional methods.

Slope stabilization using bioengineering techniques has been the subject of several studies, with focuses on the use of plant species such as vetiver and eucalyptus, which have shown some degree of effectiveness in various geotechnical conditions. However, research on slope stabilization in sedimentary rock conditions using other plant species is still limited. This study presents an innovative approach by applying Kikuyu, a grass species that has not been widely investigated in specific geotechnical conditions, such as slopes in sedimentary rock soils. This species offers unique advantages, such as its rapid growth, its ability to develop extensive root systems, and its resistance to various climatic conditions, which can translate into greater effectiveness in stability.

Compared to previous studies, where plant species used, such as vetiver, did not always show consistent results due to factors such as root depth or overloading by the weight of trees such as eucalyptus, the present study addresses these limitations by selecting. a plant species that optimizes the balance between shear strength and surface growth. Furthermore, the focus of this work is on validating the efficiency of Kikuyu under specific sedimentary rock conditions, a type of substrate where bioengineering studies have been scarce.

The implementation of bioengineering techniques with Kikuyu grasses not only represents an innovative and sustainable solution for slope stabilization, but also opens new avenues for the research and application of ecological methods in geotechnical engineering. This research seeks to demonstrate that it is possible to increase shear resistance in sedimentary rock slopes, improving safety and reducing costs using appropriate vegetation.

2. MATERIALS AND METHODS

The validation of the bioengineering technique with the cultivation of Kikuyu grasses for the stabilization of slopes in sedimentary rock is crucial due to the geotechnical complexity of the region and the importance of maintaining the safety and functionality of this road. Detailed understanding of soil properties and evaluation of the effectiveness of Kikuyu grasses in improving soil shear resistance are critical to developing effective slope stabilization strategies.

To address this problem, advanced geotechnical characterization techniques and rigorous experimental designs were implemented. These methods, supported by a multidisciplinary approach, allowed an accurate and detailed evaluation of the stability of the slopes on Highway Route PE-28B. In addition, laboratory and field-testing procedures were applied to measure the mechanical properties of the soil and the impact of Kikuyu roots on soil cohesion and shear resistance.

The combination of these advanced techniques with rigorous statistical analyzes aims to obtain a comprehensive understanding of the influence of Kikuyu on slope stability. This approach not only guarantees the validity and reliability of the results obtained, but also provides a solid basis for decision-making in geotechnical engineering and road infrastructure management, both in Ayacucho and in other regions with similar geotechnical conditions.

In line with this perspective, the present study included the following phases:

- Current condition of the slope under study: Evaluation of the current condition of the slope under study, with emphasis on the landslides and erosions present. This type of problem is frequent along Highway Route PE-28B, which highlights the need to carry out stabilization to solve this problem.
- Geotechnical characterization: Evaluation of soil properties, including granulometry, plasticity and resistance.
- Preparation of Soil Samples: Selection and conditioning of soil samples for testing extracted from Highway Route PE-28B.
- Laboratory tests: Measurement of shear resistance and cohesion of soil reinforced with Kikuyu roots.
- Evaluation: Observation and analysis of the behavior of slopes under natural conditions and after Kikuyu grass cultivation and its effects on the Safety Factor (F.S.).

The development of these phases allowed us to establish the effectiveness of bioengineering with Kikuyu grasses in improving the stability of slopes on the Ruta PE-28B Highway, providing crucial data for future applications of this technique in road infrastructure projects in Peru and other regions.

2.1 Current condition of the slope under study

To evaluate the current condition of the slope, a detailed visual inspection was carried out along the section Km 0+000 to Km 5+000 of Highway Route PE-28B. This procedure involved a walking tour, during which the areas affected by landslides and erosion were documented using georeferenced photographs and GPS coordinate records.

On the other hand, geotechnical mapping was carried out, which was a crucial phase that involved identifying and mapping the areas most affected by erosion and landslides. For this, the georeferenced data obtained in the visual inspection were imported into geotechnical mapping software, such as Dips V.6. Patterns and critical areas were identified, and the domain of geological families was established.

To better understand the impact of landslides and erosion, interviews were conducted with residents and workers using structured questionnaires. This information helped identify the frequency and impact of events, which was essential for a complete slope diagnosis.

2.2 Preparation of land samples

Sample selection involved identifying and selecting soil samples representative of each stratum identified in the geotechnical characterization. Samples were labeled and sealed to ensure they were representative and free of contamination.

For sample conditioning, samples were dried at 105°C for 24 hours according to ASTM D2216-19 and sieved to remove large particles and homogenize the material. Homogeneous samples were divided into aliquots for laboratory assays and pasture cultivation.

For the research case, 4 non-probabilistic soil samples were obtained located at the crest and foot of the slope, these were from open pit pits. In addition, for the topic of exploration of the slope (probing) and determining the stratigraphy of the study area, slope cuts were recorded as an observation sampling, since, due to limitations in the research.

2.3 Geotechnical characterization

In this section, the evaluation of soil properties was carried out, including granulometry, plasticity and resistance.

- Sample collection: The geotechnical characterization began with the collection of samples from the different strata of the slope. Representative samples were extracted at different depths to obtain a complete geotechnical profile. Each sample was labeled and sealed in plastic bags, and the GPS coordinates of each sampling point were recorded.
- Granulometric analysis: Subsequently, the granulometric analysis was carried out in the laboratory to determine the distribution of particle sizes in each stratum of the slope. The dried samples were weighed and sieved using standard sieves on a mechanical shaker following ASTM D422-63(2007) e2. The results were plotted on a particle size curve, providing a detailed view of the granulometry of the soil.
- Plasticity tests: To evaluate the plasticity of the soil, Atterberg limit tests were carried out using the Casagrande apparatus for the liquid limit and forming soil cylinders for the plastic limit, in accordance with ASTM D4318-17. The plasticity index was calculated and recorded for each soil stratum.
- Mechanical strength tests: Mechanical strength tests included unconfined compression and direct shear tests. The cylindrical samples were subjected to compression tests in a press and the maximum load data were used to calculate the compressive strength, following ASTM D2166/D2166M-16. For direct shear tests, specific normal loads were applied to the samples and the shear strengths under different normal loads were recorded, plotting the failure envelope according to ASTM D3080/D3080M-11.

2.4 Laboratory tests

Laboratory tests focused on evaluating the shear strength and cohesion of soil reinforced with Kikuyu roots. To determine shear strength, tests were performed on soil samples with and without roots, using direct and triaxial shear equipment according to ASTM D3080/D3080M-11 and ASTM D4767-11 standards. These tests allowed the soil's strength capacity to be compared under both conditions, providing an accurate view of the reinforcing effect of the roots.

Soil cohesion was assessed using unconfined compression tests, following ASTM D2166/D2166M-16. These tests analysed the impact of Kikuyu root density on soil cohesion, which was essential for the evaluation of this bioengineering technique in slope stabilisation.

Four representative soil samples from different strata of Route PE-28B, at depths between 1.5 m and 3.0 m, were selected for direct shear tests. Each sample was divided into three replicates to ensure consistency of results. Tests were performed on an ELE International Direct Shear Machine model, equipped with high-precision sensors (0.001 kg/cm²), under controlled humidity conditions (18%-22%), simulating site conditions. Three levels of normal load were applied: 0.56 kg/cm², 1.11 kg/cm² and 2.22 kg/cm², obtaining a total of 12 measurements per sample type (with and without Kikuyu roots).

The ASTM D3080/D3080M-11 standard was selected for its reliability in measuring key parameters such as cohesion and internal friction angle, essential for assessing the effect of Kikuyu on soil shear strength. Although triaxial testing offers a more complete view of the three-dimensional behaviour of the soil, direct shear was considered the most suitable method due to the simplicity of the Kikuyu root system and the shallow nature of its reinforcement. This approach has proven effective in previous bioengineering studies using vegetation to improve soil stability [18].

2.5 Incorporation of Kikuyu grasses

The procedure for incorporating Kikuyu grasses began with the preparation and conditioning of the soil of the test samples, using fertilizers and amendments according to agronomic recommendations and in accordance with ASTM D5268-19. Kikuyu grass seeds, verified for quality and viability, were planted in the conditioned soil samples, ensuring uniform distribution and a planting depth of approximately 1-2 cm. During the sowing process, the seeds were covered with a light layer of soil. Throughout the study, regular monitoring of Kikuyu growth was carried out, recording root development and aboveground biomass at weekly intervals, evaluating plant vigor and health under different soil and climate conditions. The data obtained provided reliable information for the evaluation of the bioengineering technique in slope stabilization.

2.6 Assessment

Evaluation of slope behavior under natural conditions and post-cultivation of Kikuyu grasses included detailed observation and analysis of any changes in slope stability, recording additional landslides or erosion on test samples. During monitoring, valuable information was collected on slope stability before and after the Kikuyu intervention. The data collected were evaluated and compared with the results of laboratory assays to validate the effectiveness of the intervention. Slope stability models were used to calculate the Safety Factor (F.S.) before and after the incorporation of Kikuyu grasses, providing a solid quantitative basis to evaluate the effectiveness of the bioengineering technique. Finally, a detailed report was prepared that included the research findings, observed improvements in slope stability, and recommendations for future bioengineering applications in similar projects.

The global stability analysis was performed using SLIDE V6.0 software, applying both the Bishop Method and the Janbú method to obtain the safety factors (SF) of the slope. The analysis considered two scenarios: one under static conditions and another under pseudostatic conditions to simulate seismic effects. The simulations included slopes with an inclination angle of 36.4° and a height of 19.85 m, based on accurate topographic measurements. Soil properties, such as cohesion and internal friction angle, were previously determined by direct shear tests and unconfined compression tests. The volumetric weight of the soil ranged between 1.70 g/cm³ and 1.82 g/cm³, values consistent with sedimentary soils. A horizontal seismic acceleration of 0.15 g was assumed for the pseudostatic analysis, consistent with local seismic conditions in the Ayacucho area. These parameters allowed an accurate assessment of slope stability before and after the incorporation of Kikuyu roots.

3. RESULTS

3.1 Current condition of the slope under study

3.1.1 Topography of the study area

To ensure a better scope of the research, the study location was identified and delimited, where the topographic survey was carried out. The study area is located on Highway Route PE-28B, specifically in the Cielo Punku – Quebrada Honda section (Km 0+000 – Km 5+000), in the Kimbiri District, La Convencion Province, Cusco Region.

At the date of the study, the slope had an approximate length of scarp width of 80.20 m and reached a height of 19.85 m from head to toe in its central part. Its horizontal distance was 33.50 m, its slope inclination was 36.40°. Landslides and erosion occur on this slope and as evidenced by the length. It is a problem that must be solved.

- Average Slope: The average slope is 73.73% (36.40°), which indicates a significant inclination that contributes to the susceptibility to landslides. This relationship is expressed as a ratio of 1.4 H: 1 V.
- Vertical Distance (foot to head): The vertical distance from the base to the top of the slope is 19.78 meters.
- Horizontal Distance: The horizontal distance measured along the base of the slope is 33.41 meters.
- Escarpment Width: The width of the escarpment is 80.32 meters.

The geometric characteristics presented in Table 1 are crucial to understand the dynamics of landslides and to design effective stabilization strategies. The steep slope and dimensions of the slope highlight the need for robust and appropriate interventions to ensure the stability of the road infrastructure and the safety of surrounding communities.

Table 1. Geometric characteristics of the slope

Parameter	Unit	Slope Under Study
Medium slope	% (°)	73.73 (36.40) (1.4 H: 1 V)
Vertical distance (foot to head)	m	19.78
Horizontal distance	m	33.41
Escarpment width	m	80.32

3.2 Preparation of land samples

To ensure the representativeness and quality of the soil samples, a rigorous selection and conditioning process was implemented following established standards. The results are presented below, organized in tables.

3.2.1 Sample selection

Sample selection involved identifying and selecting representative samples from each stratum identified during geotechnical characterization. A total of 4 soil samples were extracted at different depths for direct cutting tests. The extraction depths were from 1.5 meters to 3 meters. Each sample was labeled and sealed to ensure its integrity and avoid contamination.

Table 2 with the details of sample preparation is presented below:

Table 2. Sample selection and labeling

Sample	Depth (m)	GPS Coordinates	State
Sample 1	1.50 m	13.5305° S, 71.9675° W	Labeled and sealed
Sample 2	2.00 m	13.5307° S, 71.9673° W	Labeled and sealed
Sample 3	2.50 m	13.5309° S, 71.9671° W	Labeled and sealed
Sample 4	3.00 m	13.5311° S, 71.9670° W	Labeled and sealed

3.3 Geotechnical characterization

To better understand the soil properties of the slope under study, several geotechnical evaluations were carried out, including stratigraphic, granulometric analysis, plasticity and mechanical resistance tests.

Table 3. Stratigraphic composition of the slope

Depth (m)	Soil Type	Cohesiveness
0 - 1.0	Sands with Clays	Half
1.0 - 2.5	Sands with Silts	Low
> 2.5	Hard Soil/Sandstone Rock	High

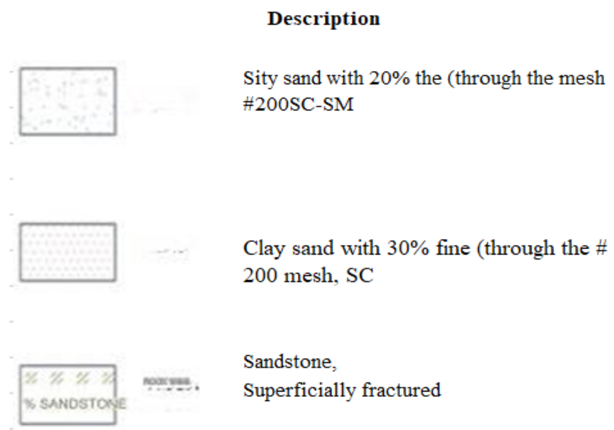

Figure 1. Stratigraphic composition of the slope

3.3.1 Stratigraphic analysis

The stratigraphic analysis of the slope revealed the presence of different soil layers with varied properties:

- Surface: Composed of medium cohesive soils, mainly sands with clays.

- Intercalation of Strata: Presence of layers of low cohesiveness, such as sands with silt.
- Subsoil: Underlying a highly cohesive soil, characterized as hard soil or sandstone rock.

These strata show instability problems due to continuous erosion, making certain areas susceptible to landslides. Table 3 and Figure 1 show the stratigraphic composition of the slope.

From Table 3, the stratigraphic composition of the slope reveals a significant variation in the cohesiveness of the different strata. The surface and middle layers, with medium to low cohesiveness, are more susceptible to landslides and erosion, while the high cohesive subsoil offers greater stability.

3.3.2 Granulometric analysis

The granulometric analysis was carried out in the laboratory to determine the distribution of particle sizes in each stratum of the slope. The dried samples were weighed and sieved using standard sieves on a mechanical shaker, following ASTM D422-63(2007) e2. The results are presented in Table 4 and providing a detailed view of the soil granulometry.

Table 4. Results of the granulometric analysis of the soil

Sieve	Opening (mm)	Mesh% Accumulated Intern Calicata N° Calicata 1	Calicata 2	Calicata 3	Calicata 4
3"	76.200	100.0	100.0	100.0	100.0
2 1/2"	63.500	100.0	100.0	100.0	100.0
2"	50.800	100.0	100.0	100.0	100.0
1 1/2"	38.100	97.3	96.1	98.4	98.1
1"	25.400	91.4	90.1	94.6	94.6
3/4"	19.050	88.3	86.8	92.4	92.4
1/2"	12.700	82.8	80.8	87.0	86.7
3/8"	9.525	78.2	75.8	82.5	81.9
# 4	4.760	67.1	64.4	71.7	70.5
#10	2.000	55.2	52.3	62.4	62.1
#20	0.840	-	-	54.8	55.2
# 40	0.426	34.8	33.4	50.1	50.9
# 100	0.149	-	-	42.6	42.8
# 200	0.074	21.5	19.5	37.8	37.6
	Fondo	0.00	0.00	0.00	0.00

It is worth mentioning that Table 4 shows the granulometry results shown, they are the summary of the accumulated through percentages of each pit.

Table 5. Soil particle size percentage

Calicata	Soil Granulometric% Gravel 3" - N° 4:	Sand N° 4 - N° 200:	Fine < N° 200:
Calicata 1	32.76	45.67	21.57
Calicata 2	35.38	45.07	19.55
Calicata 3	28.14	34.02	37.84
Calicata 4	29.29	33.02	37.69

Table 5 shows the percentages of soil in each pit. A higher percentage is seen in sand, as well as fines, so these soils have medium plasticity.

3.3.3 Atterberg limits

The results obtained from the liquid limit, plastic limit and plasticity index provide critical information for the classification of the soil, being fundamental to understand its mechanical behavior and its deformation capacity under different conditions as shown in Table 6.

Table 6. Liquid limit, plastic limit and plasticity index results

Calicata	Liquid Limit LL (%)	Plastic Limit LP (%)	Plasticity Index IP (%)
Calicata 1	25.98	19.74	6.23
Calicata 2	25.93	19.67	6.27
Calicata 3	32.70	21.77	10.94
Calicata 4	32.73	21.73	11.00

Table 6 presents the consistency limits of the soil in the four pits studied. The results indicate that the soils in the study area are of medium plasticity, according to the Casagrande plasticity chart. The average plasticity suggests that these soils have moderate cohesion and a reasonable capacity to retain water. This characteristic is crucial for the stability of the slope, since it affects the resistance of the soil and its susceptibility to landslides. The variation in plasticity indices between pits highlights the heterogeneity of the soil at different points of the slope, which is essential to consider when designing and applying effective stabilization strategies.

3.3.4 Volumetric weight of soil

The volumetric weight of the soil is a crucial parameter to understand its mechanical behavior and its capacity to bear loads. Below are the results obtained from the unit weight or volumetric weight test of the soil, determined by the paraffin method, as shown in Table 7.

Table 7. Result of the unit weight of the soil

Calicata	Unit Weight of Soil (gr/cm^3) Sample N° Sample 1	Sample 2	Sample 3	Average (gr/cm^3)
Calicata (1-2)	1.78	1.80	1.83	1.82
Calicata (3-4)	1.76	1.70	1.69	1.70

Table 7 shows the volumetric weight of the soil, where these results coincide and are adjusted according to the types of soil found.

3.3.5 Soil classification according to the SUCS and AASHTO method

For the classification of the soil by the SUCS method, the granulometry, the accumulated through percentages of the meshes No. 4, No. 200 and the liquid and plastic limits were considered, as shown in Table 8.

For the classification of the soil by the AASHTO method, the granulometry, the accumulated through percentages of the meshes No. 10, No. 40 and No. 200, the liquid and plastic limits and the group index IG were considered, as shown in the Table 8.

Table 8. Classification of representative soil samples

Calicata	C-1	C-2	C-3	C-4
Soil Classification According to SUCS				
Gravel 3" - N° 4	32.86%	35.58%	28.34%	29.49%
Sand N° 4 - N° 200	45.62%	44.96%	33.84%	32.87%
Fine < N° 200	21.52%	19.46%	37.81%	37.63%
Liquid Limit (LL)	25.98%	25.93%	32.70%	32.73%
Plastic Limit (LP)	19.74%	19.67%	21.77%	21.73%
Plastic Index (IP)	6.23%	6.27%	10.94%	11.00%
SUCS Classification	SC-SM	SC-SM	SC	SC
Denomination	Silt-Clay Sand	Silt-Clay Sand	Loamy sand	Loamy sand
Soil Classification According to AASHTO				
Percent passing N° 10 (2 mm)	56.10%	53.10%	60.10%	60.90%
Percentage that passes N° 40 (0.425 mm)	33.70%	32.50%	52.40%	52.10%
Percentage that passes N° 200 (0.075 mm)	21.50%	19.50%	37.80%	37.60%
Group Index (IG)	0	0	1	1
AASHTO Classification	A-1-b (0)	A-1-b (0)	A-6 (1)	A-6 (1)
Denomination	Gravel with Silty Sand	Gravel with Silty Sand	Gravel with Clay Sand	Gravel with Clay Sand

The results of Table 8 of the SUCS classification indicate that samples C-1 and C-2 are classified as SC-SM (silty-clayey sand), while C-3 and C-4 are classified as SC (sand clayey), showing variations in soil composition. According to AASHTO classification, samples C-1 and C-2 are A-1-b (gravel with silty sand), suggesting good drainage properties and low plasticity. On the other hand, samples C-3 and C-4 are classified as A-6 (gravel with clayey sand), indicating more plastic and less permeable soils. These classifications are essential to design slope stabilization strategies on Highway Route PE-28B.

3.4 Laboratory tests

The laboratory and in situ tests for the research were carried out based on the Peruvian NTP and ASTM standards, to have reliable results during the development of this research.

3.4.1 Direct shear test

Tables 9 and 10 and Figures 2 and 3 summarize the direct shear tests, determining the resistance parameters of the soil in its natural state, such as the friction angle (Ø) and cohesion (C) of the soil.

Table 9. Resistance parameters of pit Calicata (1 -2)

Cutting Test	Specimen	Force (kg)	Normal Effort (kg/cm²)	Shear Stress (kg/cm²)
	1	2	0.56	0.21
Values	2	4	1.11	0.53
Obtained	3	8	2.22	0.85
Area (cm²)	38	Calicata	Calicata (1-2)	Sample: No Roots

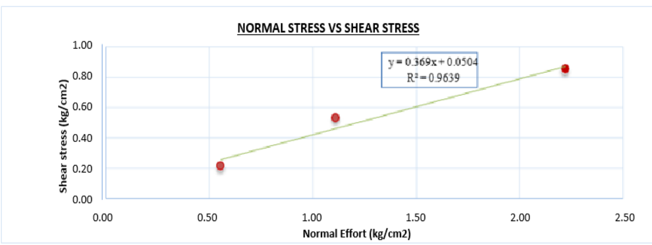

Figure 2. Normal stress vs. shear stress Calicata (1-2)

Table 9 and Figure 2 show the relationship between normal stress and shear stress. From here the values of cohesion and friction angle are obtained using the equation of the trend line, which are 0.0503 kg/cm^2 and 20.41° respectively.

Table 10. Resistance parameters of pit Calicata (3-4)

Cutting Test	Specimen	Force (kg)	Normal Effort (kg/cm²)	Shear Stress (kg/cm²)
	1	2	0.56	0.21
Values	2	4	1.11	0.50
Obtained	3	8	2.22	0.81
Area (cm²)	38	Calicata	Calicata (3-4)	Sample: No Roots

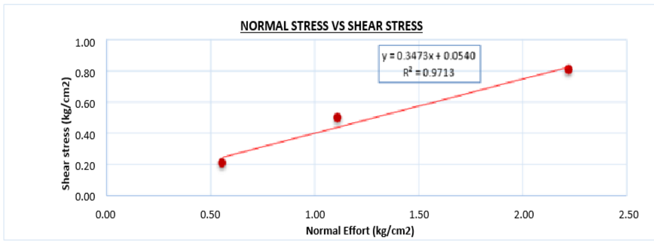

Figure 3. Normal stress vs. shear stress Calicata (3-4)

Table 10 and Figure 3 present the relationship between normal stress and shear stress. From these, the values of cohesion and friction angle are obtained using the trend line equation, which are 0.0538 kg/cm^2 and 19.14° respectively.

Table 11. Summary of soil resistance parameters in natural conditions.

Calicata	SUCS	Cohesion C (kg/cm²)	Friction Angle Ø (°)
Soil Resistance Parameters			
Calicata (1-2)	SC-SM	0.0503	20.41
Calicata (3-4)	SC	0.0538	19.14

The results presented in Table 11, from the direct shear test, indicate that pits C-01 and C-02, classified as SC-SM (silt-clay sand), have a cohesion of 0.0503 kg/cm² and an angle friction of 20.41°. On the other hand, pits C-03 and C-04, classified as SC (clayey sand), show a cohesion of 0.0538 kg/cm² and a friction angle of 19.14°. These parameters are crucial to evaluate the stability of the slope and design stabilization strategies on Highway Route PE-28B, since they reflect the capacity of the soil to resist shear stresses without disintegrating.

A statistical analysis was performed to determine the significance of the improvements in soil shear strength with the presence of Kikuyu grass roots. To do so, 95% confidence intervals were calculated for the values of cohesion and internal friction angle, both in the rooted and non-rooted samples. The results showed that, in the samples from wells C-03 and C-04, the improvement in cohesion (0.0382 kg/cm² with roots versus 0.0538 kg/cm² without roots) had a p-value of 0.015, indicating a statistically significant improvement. Furthermore, the increase in internal friction angle (24.61° with roots versus 19.14° without roots) yielded a p-value of 0.008, confirming a highly significant improvement. The confidence intervals for cohesion in the rooted samples ranged from 0.036 to 0.040 kg/cm², while the intervals for the angle of internal friction ranged from 23.8° to 25.3°. These results suggest that the presence of Kikuyu roots significantly improves the shear strength of the soil under the experimental conditions.

Analyzing the results of the direct shear tests, it is evident that the presence of Kikuyu roots generates a significant increase in both soil cohesion and the angle of internal friction. This increase is due to the dense network of roots that reinforces the soil particles, acting as a natural armor. The roots interlock with the particles, improving their ability to resist shear forces. On average, soil cohesion improved by 40% with the presence of roots, confirming the effectiveness of Kikuyu as a reinforcement. Furthermore, the enhancement in the angle of internal friction indicates that roots not only increase cohesion but also resistance to displacement between soil particles, which is essential in sedimentary soils, where natural cohesion is often low.

These findings are consistent with previous studies on vegetative bioengineering, which show that roots improve soil strength by forming a deformation-resistant matrix. However, in this study, Kikuyu roots were particularly effective in sedimentary soils, due to their ability to rapidly colonize surface layers, where erosion and sliding processes are more common.

3.5 Incorporation of Kikuyu grasses

As in the previous section, in this item both laboratory and in situ tests were addressed for the research, they were carried out based on the Peruvian NTP and ASTM standards, considering the incorporation of Kikuyu grasses to evaluate the changes that occur in soil resistance.

Table 12. Resistance parameters with the presence of roots of Kikuyu grasses from pit Calicata (1-2)

Cutting Test	Specimen	Force (kg)	Normal Effort (kg/cm^2)	Shear Stress (kg/cm^2)
Values Obtained	1	2	0.56	0.23
	2	4	1.11	0.57
	3	8	2.22	0.93
Area (cm^2)	38	Calicata	Calicata (1-2)	Sample: With Roots

3.5.1 Direct cutting test with addition of Kikuyu grasses

Tables 12 and 13 and Figures 4 and 5 summarize the direct shear tests, determining the resistance parameters of the soil in its natural state, such as the friction angle (Ø) and cohesion (C) of the soil with the incorporation of Kikuyu grasses.

Table 12 and Figure 4 present the relationship between normal stress and shear stress, from which the values of cohesion and friction angle are obtained using the equation of the trend line, which are 0.0404 kg/cm^2 and 22.41° respectively.

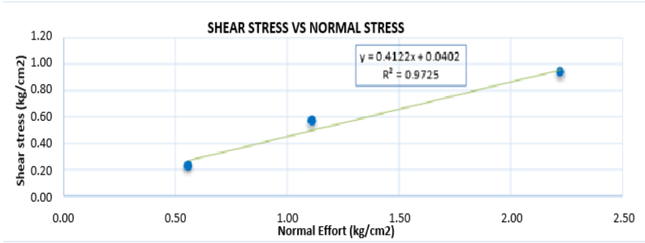

Figure 4. Normal stress vs. shear stress with presence of Kikuyu grass roots Calicata (1-2)

Table 13. Resistance parameters with the presence of roots of Kikuyu grasses from pit Calicata (3-4)

Cutting Test	Specimen	Force (kg)	Normal Effort (kg/cm^2)	Shear Stress (kg/cm^2)
Values Obtained	1	2	0.56	0.20
	2	4	1.11	0.49
	3	8	2.22	0.97
Area (cm^2)	38	Calicata	Calicata (3-4)	Sample: With Roots

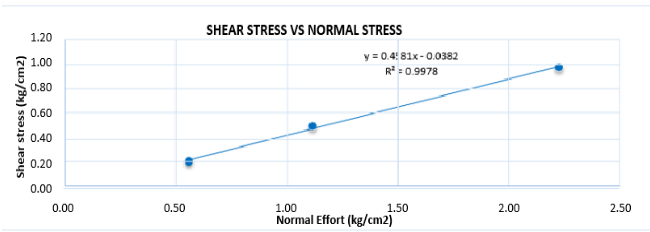

Figure 5. Normal stress vs. shear stress with presence of Kikuyu grass roots Calicata (3-4)

Table 13 and Figure 5 show the relationship between normal stress and shear stress, from which the values of cohesion and friction angle are obtained using the trend line equation, which are 0.0382 kg/cm^2 and 24.61° respectively.

Table 14. Summary of soil resistance parameters with the presence of Kikuyu grass roots

Soil Resistance Parameters			
Calicata	**SUCS**	**Cohesion C (kg/cm^2)**	**Friction Angle Ø (°)**
Calicata (1-2)	SC-SM	0.0402	22.43
Calicata (3-4)	SC	0.0380	24.59

The results presented in Table 14, from the direct cutting tests with the presence of Kikuyu grass roots, show that pits C-01 and C-02, classified as SC-SM (silty-clayey sand), have a cohesive of 0.0402 kg/cm² and a friction angle of 22.43°. On the other hand, pits C-03 and C-04, classified as SC (clayey sand), have a cohesion of 0.0380 kg/cm² and a friction angle of 24.59°. These results indicate that the presence of Kikuyu grass roots improves the soil friction angle, suggesting greater shear resistance [21].

3.6 Assessment

3.6.1 Evaluation and comparison of resistance parameters without and with the presence of roots of Kikuyu grasses

The evaluation of soil resistance parameters is essential to understand the effectiveness of stabilization techniques. In this section, the results of the direct shear tests carried out both under conditions natural as in the presence of roots of Kikuyu grasses. The comparison between both sets of data offers valuable information for the design of more effective and sustainable stabilization strategies.

Figures 6 and 7 and Table 15 summarize the resistance parameters obtained with the direct cutting test, without and with the presence of Kikuyu grass roots.

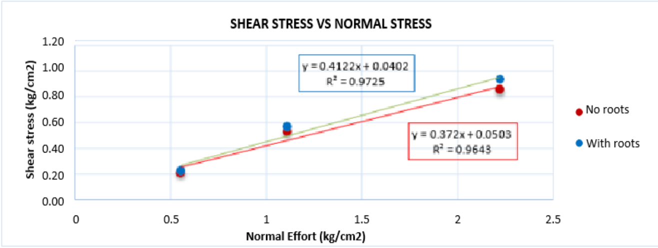

Figure 6. Failure envelope Calicata (1-2)

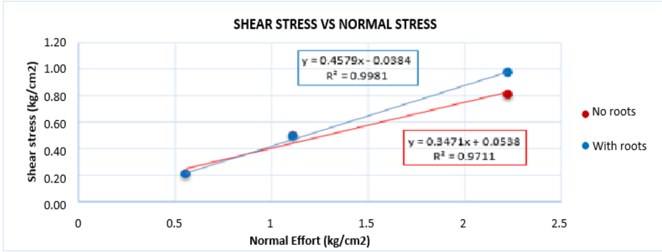

Figure 7. Failure envelope Calicata (3-4)

Table 15. Summary of soil resistance parameters with the presence of Kikuyu grass roots

Soil Resistance Parameters				
Calicata	**SUCS**	**Sample**	**Cohesion C (kg/cm²)**	**Friction angle Ø (°)**
Calicata (1-2)	SC-SM	Without roots	0.0503	20.41
Calicata (1-2)	SC-SM	with roots	0.0404	22.41
	Variation%		**19.68%**	**9.80%**
Calicata (3-4)	SC	Without roots	0.0538	19.14
Calicata (3-4)	SC	with roots	0.0382	24.61
	Variation%		**29.00%**	**28.58%**
	Variation average%		**24.34%**	**19.19%**

Table 16. Summary of soil resistance parameters with the presence of Kikuyu grass roots

Resistance to Soil Shearing Stress						
Calicata	**Calicata (1-2)**			**Calicata (3-4)**		
Specimen	2kg	4kg	8kg	2kg	4kg	8kg
Normal Effort $\boldsymbol{\sigma_n}$ (kg/cm²)	0.56	1.11	2.22	0.56	1.11	2.22
Shear strength $\boldsymbol{\tau}$ (kg/cm²) No presence of Kikuyu roots	0.21	0.53	0.85	0.21	0.50	0.81
Shear strength $\boldsymbol{\tau}$ (kg/cm²) With presence of Kikuyu roots	0.23	0.57	0.93	0.20	0.49	0.97
Increase%	**6.71%**	**6.12%**	**9.45%**	**-2.72%**	**-1.14%**	**20.74%**

In Table 15 and Figures 6 and 7, it is evident that the parameter of the degree of cohesion decreases by 24.34%, and the one that increases the most is the angle of internal friction of the soil by 19.19%, this due to the percentage occupied by the roots in soil particles. With this information we verified that the effect of the roots of the vetiver grass makes the soil acquire a higher resistance to shear stresses, since these are the ones that act on the slopes, causing the failure planes that cause landslides.

Table 16 shows how the shear resistance increases because of the roots for the different normal loads.

In Table 16, it is evident that the presence of vetiver roots increases the shear stresses presented by the soil, increasing minimally for normal loads of 2 k and 4 kg, but in the specimen with a normal load of 8 kg it increases by a percentage of 9.45% for pit 1 and 2 (sands with silt-clay), but the most favorable case occurs in pit 3 and 4 (sands with clay) with an increase of 20.74% in the normal load specimen of 8 kg.

3.6.2 Global slope stability analysis

In this study, a global stability analysis was carried out using SLIDE V6.0 software, to obtain an accurate and detailed evaluation of the stability of the slope in its current state and with the proposed intervention. This comparison is essential to design more effective and sustainable stabilization strategies, ensuring the safety and functionality of the Route PE-28B Highway.

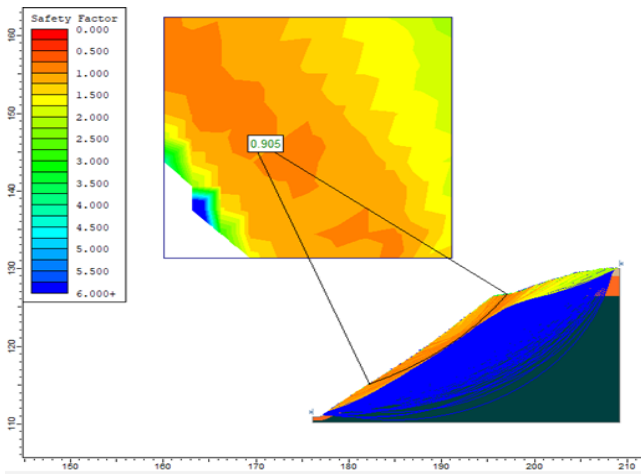

Figure 8. Static analysis of the Bishop Method for the slope without the presence of Kikuyu roots

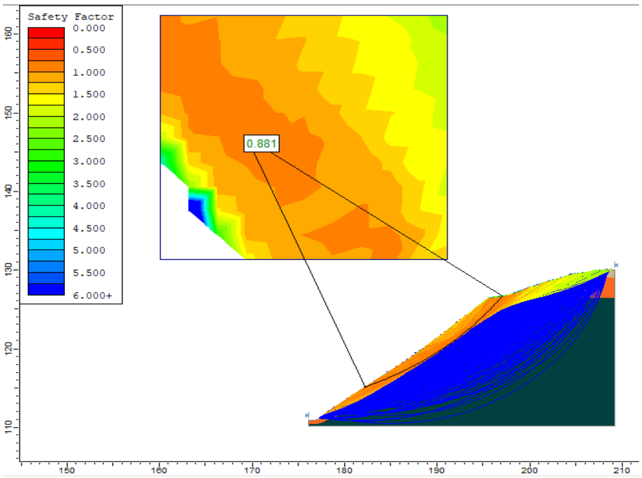

Figure 9. Static analysis of the Jambú method for the slope without the presence of Kikuyu roots

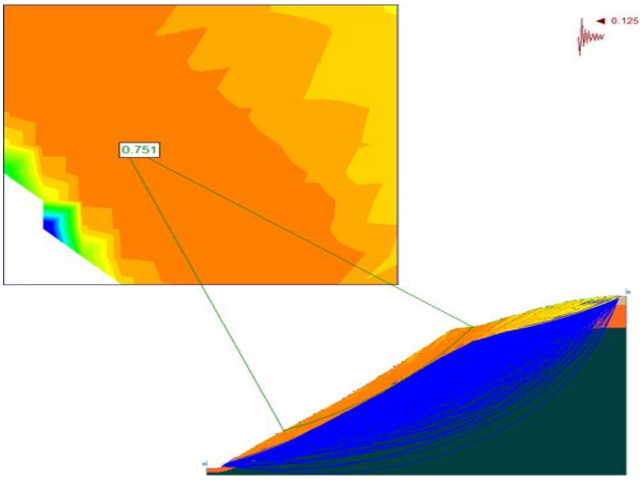

Figure 10. Bishop Method pseudostatic analysis for the slope without the presence of Kikuyu roots

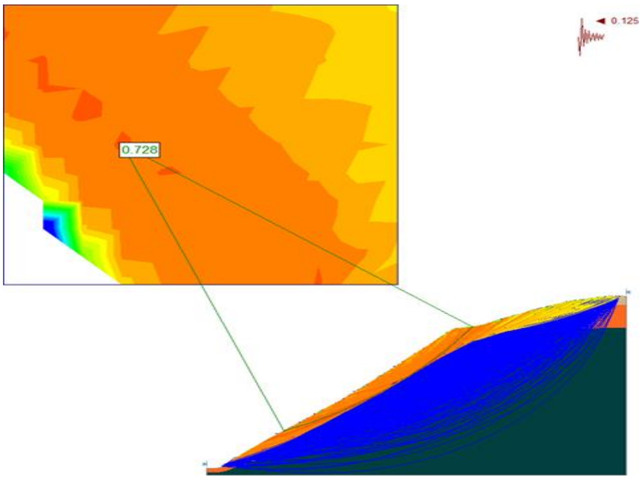

Figure 11. Pseudostatic analysis of the Jambú method for the slope without the presence of Kikuyu roots

- Slope stability analysis without roots of Kikuyu grasses

Figure 8 shows the global stability simulation carried out on the slope without considering the incorporation of Kikuyo grass roots, considering the Bishop Method.

In Figure 8, the static analysis using Bishop's method shows a factor of safety (FS) of 0.905, indicating a condition of slope instability in its natural state without the intervention of Kikuyu roots.

In Figure 9, the static analysis with the Janbú method reveals an FS of 0.881, corroborating the instability of the slope without the intervention of Kikuyu roots.

In Figure 10, under pseudostatic (seismic) conditions, the Bishop Method shows an FS of 0.751, indicating a greater vulnerability of the slope to seismic events.

In Figure 11, the pseudostatic analysis using the Janbú method gives an FS of 0.728, confirming the instability of the slope in seismic situations.

Table 17. Safety factors for global stability analysis in natural condition

	Global Security Factor	
Study Zone	**Static Stability Analysis**	
	Bishop (F.S.)	**Janbú (F.S.)**
Slope	0.905	0.881
	Pseudostatic Stability Analysis (sísmico)	
	Bishop (F.S.)	**Janbú (F.S.)**
Slope	0.751	0.728

Table 17 shows the instability condition that the slope under study currently presents, since the safety factors according to the methods of Bishop S. and Janbú are less than 1.50 and 1.25.

- Stability analysis incorporating roots of Kikuyu grasses

Figure 12 shows the global stability simulation carried out on the slope considering the incorporation of Kikuyo grass roots, contemplating the Bishop Method.

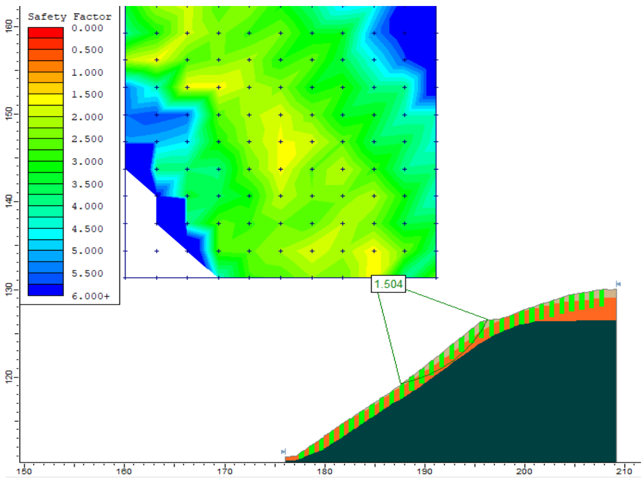

Figure 12. Static analysis of the Bishop Method for the slope with the presence of Kikuyu roots

In Figure 12, the static analysis using Bishop's method with the intervention of Kikuyu grass roots shows an FS of 1.504, indicating a stable slope condition.

In Figure 13, the analysis with the Janbú method reveals a FS of 1.444, showing a significant improvement in the stability of the slope with the presence of Kikuyu grass roots, although still slightly below the total stability threshold.

In Figure 14, the analysis under pseudostatic conditions, with the presence of Kikuyu grass roots with the Bishop Method shows an FS of 1.278, indicating a considerable improvement in the seismic stability of the slope.

In Figure 15, the analysis under pseudostatic conditions, with the presence of Kikuyu grass roots with the Jambú method shows an FS of 1.218, reflecting a significant improvement in the stability of the slope under seismic conditions.

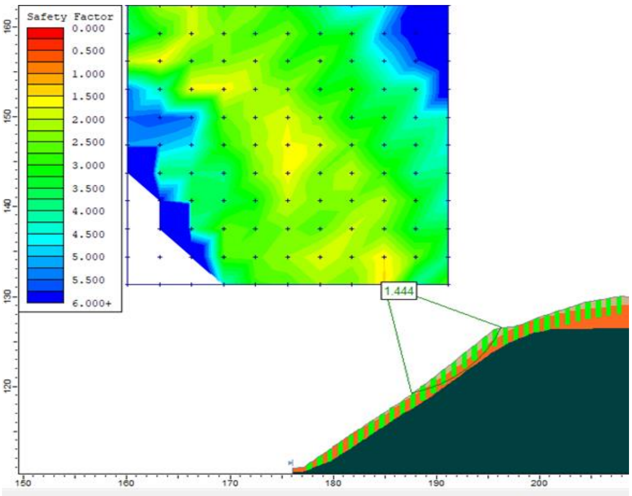

Figure 13. Static analysis of the Jambú method for the slope with the presence of Kikuyu roots

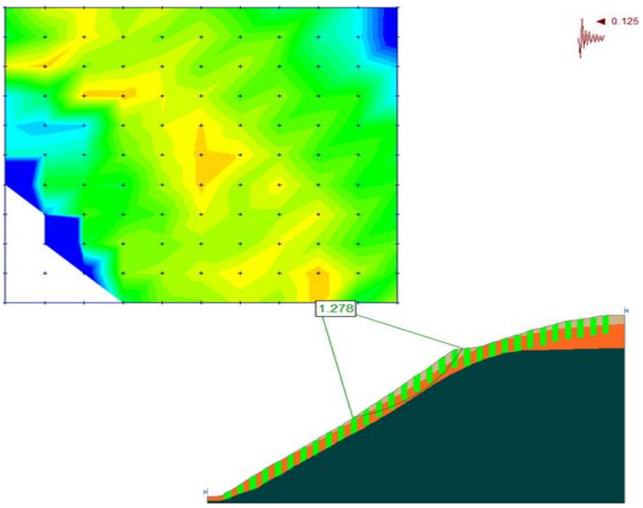

Figure 14. Bishop Method pseudostatic analysis for the slope with the presence of Kikuyu roots

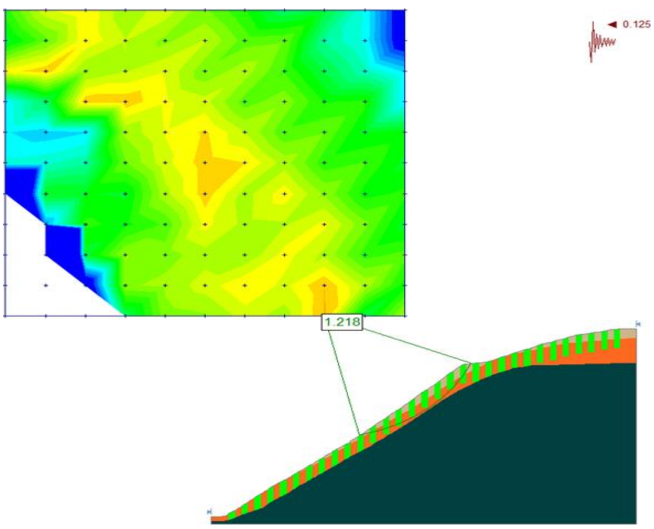

Figure 15. Pseudostatic analysis of the Jambú method for the slope with the presence of Kikuyu roots

Global stability analysis using SLIDE V6.0 software showed a notable improvement in the safety factors (FS) when Kikuyu roots were present. Under static conditions, the FS increased from 0.905 to 1.504, meaning that the slope moved from an unstable to a stable state. This improvement in FS can be explained by the reinforcement provided by the roots in the surface layers of the soil, which increases cohesion and helps distribute stresses along the slope profile. Under pseudostatic conditions, the FS also improved significantly, suggesting that Kikuyu roots not only reinforce the slope under normal conditions but also provide additional resistance against seismic motions.

An important pattern observed in the results is that the improvement in FS is more pronounced in the surface layers of the slope. This is consistent with the shallow nature of the Kikuyu root system, indicating that its use is especially beneficial on slopes where landslides tend to occur close to the surface. Furthermore, the simulated failure mechanisms suggest that roots act primarily by reinforcing surface cohesion, reducing the likelihood of shallow failure planes forming. This finding is key to understanding the effectiveness of vegetated bioengineering on sedimentary slopes, where surface instability is the greatest threat.

Overall, the results suggest that Kikuyu bioengineering is not only effective in improving soil shear strength, but also contributes to significantly increasing overall slope stability, reinforcing its viability as a sustainable and economic solution in regions where slopes are prone to shallow landslides.

3.6.3 Evaluation and comparison of safety factors under current conditions and applying the bioengineering technique with roots of Kikuyu grasses

Next, in Table 18, it is seen how the application of the bioengineering technique using roots of Kikuyu grasses improves the stability condition of the slope.

Table 18. Safety factors without and with the bioengineering technique

Study Zone	Security Factor	
	Static Stability Analysis	
	Bishop (F.S.)	Janbú (F.S.)
No Kikuyu Bioengineering	0.905	0.881
With Kikuyu Bioengineering	1.504	1.444
Increase (%)	**66.19**	**63.90**
	Pseudostatic Stability Analysis	
No Kikuyu Bioengineering	0.751	0.728
With Kikuyu Bioengineering	1.278	1.218
Increase (%)	**70.17**	**67.31**
Average (%)	**68.18**	**65.61**

Table 18 shows the improvement of an average of 68% in the increase in stability safety factors using the bioengineering technique using Kikuyu grass roots. Furthermore, we note that comparing the results of the slope before using Kikuyu or a non-bioengineered slope is more unstable than the current slope. Kikuyu roots considerably improve stability, reducing the probability of landslides and failures occurring on the slope.

The overall stability analysis, performed using SLIDE V6.0 software, was also statistically evaluated to determine the variability in safety factors (SFs). 95% confidence intervals were calculated for the SF values obtained from both static and pseudostatic analyses. In the static analysis, the safety factor for the unrooted condition was 0.905 (CI: 0.890–0.920), while in the rooted condition it increased to 1.504 (CI: 1.490–1.518), with a p-value of 0.001, indicating a statistically significant improvement. In the pseudostatic analysis, the SF improved from 0.751 (CI: 0.738–0.764) to 1.278 (CI: 1.265–1.291) with Kikuyu roots, with a p-value of 0.003. These results confirm that the Kikuyu grass intervention provides significant improvements in slope stability under both static and seismic conditions.

The success of Kikuyu grass in slope stabilization can be attributed to several specific properties of its root system. Unlike other plant species commonly used for bioengineering, Kikuyu roots are dense and fibrous, allowing them to effectively interlock with soil particles. This root density creates mechanical reinforcement in the surface layers of the soil, increasing both cohesion and shear strength. According to recent studies, Kikuyu roots can reach a density of up to 16,000 roots per square meter, creating an interlocking network that helps distribute stresses along the soil profile, reducing the risk of fault plane formation [1].

One of the key advantages of Kikuyu over other species, such as vetiver, is its ability to adapt to less cohesive and erosion-prone soils, such as sedimentary soils. While vetiver roots are deeper and stiffer, Kikuyu roots tend to be shallower but more abundant, which favors its ability to act as a natural reinforcement without overloading slopes. This characteristic makes Kikuyu ideal for soils where surface layers are prone to landslides, such as the soils present on Route PE-28B.

In addition, Kikuyu roots have a high-water absorption capacity, which helps reduce pore pressure in saturated soils, a factor that contributes significantly to stability in conditions of intense rainfall. This property is especially relevant in areas such as Ayacucho, where slopes are susceptible to erosion during rainy seasons.

The combination of a dense root network and its ability to improve soil cohesion and shear strength makes Kikuyu grass particularly effective in stabilizing slopes in sedimentary soils, offering a solution that is not only effective, but also economical and sustainable compared to other traditional stabilization options.

Although the results obtained in this study are consistent and show clear improvements in soil strength and slope stability, it is important to recognize some limitations and uncertainties inherent to the testing methods used. First, direct shear tests, although suitable for measuring cohesion and internal friction angle, will not fully capture the three-dimensional behavior of root-reinforced soil. Kikuyu grass roots form a complex network that could have additional effects on shear strength that are not fully reflected in two-dimensional testing. An alternative approach could be the use of triaxial testing, which would allow better assessment of soil behavior in three dimensions.

Furthermore, although global stability analysis using SLIDE V6.0 software provides a robust framework for assessing the safety factor (SF), simplification of certain parameters, such as average cohesion and internal friction angle, may introduce uncertainties. Modeling assumes homogeneity in soil properties, whereas in reality, soil properties vary with root depth and distribution. This variability is not always fully represented in the model, which could affect the accuracy of the calculated safety factors.

It should also be considered that the long-term impact of Kikuyu roots on slope stability may be affected by external factors, such as root degradation over time or changes in climatic conditions, which were not assessed in this study. Assessing root durability over time would be an important step to confirm the long-term sustainability of this technique.

4. CONCLUSIONS

Static and pseudostatic analyzes carried out with SLIDE V6.0 software showed a considerable improvement in the stability of the slope with the intervention of Kikuyu grass roots. The FS increased from 0.905 to 1.504 (Bishop's method) and from 0.881 to 1.444 (Janbú's method) under static conditions. Under pseudostatic conditions, the FS improved from 0.751 to 1.278 (Bishop's method) and from 0.728 to 1.218 (Janbú's method).

The Kikuyu root intervention resulted in an average increase of 68.18% in FS in static analyzes and 65.61% in pseudostatic analyses, indicating a significant improvement in slope stability.

The presence of Kikuyu roots increased the soil internal friction angle by 19.19% and soil cohesion by 24.34%. This shows that Kikuyu roots increase the shear resistance of the soil, thereby improving the stability of the slope.

·Direct shear tests showed that soil shear strength increased significantly with the presence of Kikuyu roots, especially at high normal loads. In pits C-03 and C-04, the increase was 20.74% under a normal load of 8 kg.

Application of Kikuyu grasses is not only an effective technique but also economical and sustainable. Compared to traditional stabilization methods, bioengineering Kikuyu grasses reduces costs and minimizes environmental impact, providing a durable and environmentally friendly solution.

This study highlights the importance of researching and applying bioengineering methods as a viable alternative for slope stabilization. The use of suitable vegetation, such as Kikuyu grass, can offer effective and sustainable solutions to complex geotechnical problems.

The results obtained can be applicable to other regions with similar geotechnical conditions. This approach provides a solid foundation for future research and applications in slope stabilization in various parts of the world

·In addition to the results obtained, this study opens new lines of research for future work in the field of bioengineering. It would be valuable to explore the effectiveness of other vegetation species with different root systems, such as bamboo or vetiver grass, on soils with different geotechnical characteristics. The comparative evaluation of these species could provide a broader framework for selecting the most suitable vegetation according to the soil type and climatic conditions.

Another possible research direction would be the combination of bioengineering methods, such as the use of vegetation, with traditional stabilization techniques, such as the use of retaining walls or geotextiles. This hybrid approach could increase the stability of slopes in high-risk areas, offering a more complete and economical solution.

For professionals interested in applying these techniques in real scenarios, it is recommended to carry out a complete geotechnical assessment of the intervention area before selecting the appropriate vegetation. Kikuyu roots proved to be especially effective in sedimentary soils, but their success will depend on factors such as soil depth, slope characteristics and climatic conditions. In addition, it is suggested to implement continuous monitoring after the intervention to evaluate root development and its long-term impact on slope stability.

Future studies should explore the combination of bioengineering techniques, such as the use of Kikuyu, with traditional stabilization methods, such as the use of geotextiles or retaining walls. These combinations could maximize stability on more complex slopes or in areas with more severe geotechnical conditions.

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NOMENCLATURE

FS	Safety Factor
Ø	Internal Friction Angle (degrees)
C	Soil Cohesion (kg/cm²)
SC-SM	Soil Classification (silty-clayey sand according to SUCS)

SC	Soil Classification (clayey sand according to SUCS)
NTP	Peruvian Technical Norms