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Original Article

Slope Stabilization through Bioengineering with Vetiver Grass: Impact on Bearing Capacity, Erosion, and Runoff

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Abstract *- Landslides, aggravated by natural and human factors, generate risks, economic losses, and affect the safety of vulnerable populations. In this context, the research focuses on evaluating the use of vetiver grass as a sustainable and ecological solution for slope stabilisation. The methodology included the geotechnical characterisation of the soil in the central jungle of Peru (San Pedro sector, Tarma-La Merced section) located at UTM coordinates Zone 18L: 481098.70 m E and 8790688.01 m S, where modified Proctor was applied and, with these parameters, 35 wooden prototypes measuring 50 × 50 × 80 cm were compacted in three layers, forming slopes of 20°, 25°, 27.6°, 30° and 35°. Vetiver grass was planted on them at densities of 10, 15, and 20 cm. The models were evaluated by means of direct shear, erosion, and runoff tests under simulated rainfall of 47.7 mm/h, at 21 and 30 days, comparing them with slopes without vegetation cover. Vetiver grass significantly improved slope stability, increasing soil cohesion by 60%, the angle of friction by 12% and bearing capacity by 53% on 20° slopes. In addition, it reduced erosion by up to 92% and surface runoff by up to 37%. The planting density of 15 cm showed the best performance, consolidating vetiver as an effective and sustainable alternative for slope stabilisation. The research contributes to the field of geotechnics, demonstrating that vetiver grass is a sustainable solution for stabilising slopes by improving soil resistance and reducing erosion and runoff.*

Keywords *- Vetiver Grass, Slope Stabilisation, Erosion, Direct Cutting, Runoff.*

1. Introduction

Worldwide, landslides and slope instability represent an increasing geotechnical problem in tropical regions [1]. In these environments, steep slope geometry, deforestation, and intense anthropogenic activity modify drainage patterns, accelerate surface degradation, and reduce the resistance of near-surface soils, increasing susceptibility to rainfall-triggered failures [2-4]. From the perspective of geotechnical design, the hazard is expressed through measurable and controllable variables, including slope inclination, shear strength parameters, hydraulic response under intense precipitation, and progressive loss of bearing capacity associated with erosion and saturation effects.

In Peru, the problem is particularly relevant due to its direct impact on population safety and the operational continuity of strategic road corridors. Official records indicate that a considerable proportion of national emergencies is associated with landslides and debris flows, with higher recurrence during the rainy season from November to March and repeated impacts in regions such as Cusco, Puno, Junín, and Amazonas [5, 6]. Recent events confirm the persistence of the hazard and its consequences. In 2025, SUTRAN reported the obstruction of approximately 30 critical road points across 13 regions due to heavy rainfall, debris flows, and landslides, evidencing nationwide exposure of the transport network to rainfall-induced slope failures [7]. In 2024, slope events in Cusco temporarily blocked the Cusco Paucartambo road and forced traffic interruption for several days [8]. In Áncash, debris flows blocked sections of PE 12A and AM 110, affecting connectivity, damaging local infrastructure, and disrupting the transport of agricultural products and essential goods [9] Near Machu Picchu, a rainfall triggered landslide caused missing persons and injuries and forced the temporary closure of a key access route, highlighting the vulnerability of high priority corridors to extreme precipitation events [10]. Within this national context, the present research focuses on the Central Highway, specifically the Tarma-La Merced section, where recurrent movements of rock, mud, and debris are associated with persistent rainfall and steep terrain. The San Pedro sector at kilometre 70 plus 900, near Matichacra, is repeatedly reported as a critical point due to frequent collapses that obstruct lanes and restrict traffic [11, 12]. Apart from the security implications, these disruptions have a cumulative economic impact by restricting interregional trade, blocking the movement of agricultural production, and undermining the provision of essential goods to local communities [13-15]. Therefore, this corridor requires stabilisation strategies that not only slow surface erosion but also provide a better, verifiable way to consolidate rainwater beneath the subsoil within the typical parameters of road sand maintenance and construction management.

In this context, bioengineering measures have gained relevance as alternatives for ecological installations. Vetiver has a dense root system with a penetration depth of several metres, providing anchorage and shelter near the surface, which is important for slope performance [16, 17] revious studies have reported substantial reductions in erosion and improvements in hydrological behaviour, including increased water retention and reduced runoff, which are mechanisms directly associated with surface instability on tropical slopes [18, 19]. Its adaptability to soils ranging from highly plastic clays to sandy and silty materials, including in low-fertility conditions, supports its viability in heterogeneous substrate materials [20, 21]. Its tolerance to drought and temporary flooding supports its application in variable hydrological conditions [22, 23]. Vetiver has also demonstrated potential as a practical risk reduction measure based on empirical evidence from international experiences, including its use in India and Thailand [19].

The available research, however, has other limitations that hinder its direct application to geographical disease criteria. The focus of the research is on erosion control or the effectiveness of vegetation cover, while stability is assessed qualitatively or using isolated indicators. Integrated experimental evidence linking root return with simultaneous changes in shear strength and bearing capacity parameters, together with findings on erosion and runoff under controlled rainfall, remains scarce. Furthermore, there is rarely a systematic analysis of slope geometry, plant density, and initial establishment time, despite these factors being critical for roadside terrain, where short-term encounter determines operational risk and maintenance demand. As a result, disease choices are based on fragmented evidence, which is insufficient to determine the combinations of density and geometry that optimise mechanical reinforcement, erosion control, and scrutiny.

This assessment reveals a clear research gap. There is a lack of integrated experimental evidence that experimentally proves and quantitatively relates the effect of vetiver on soil mechanical strength, bearing capacity, and slope performance, and its erosion control and storage under simulated rainfall, explicitly considering the slope ring, planting density, and establishment time. To address this gap, the present study evaluates vetiver-based slope stabilisation using physical prototypes representative of conditions on the Central Highway in the San Pedro sector. The experimental design systematically varies the slope gradient and vetiver planting density and evaluates performance in the early stages of growth. The mechanical behaviour of the soil is quantified using parameters derived from direct cutting and estimation of the permissible load capacity. In contrast, hydraulic performance is quantified using erosion medicine and scrutiny under controlled simulated rainfall. The novelty of this radical research lies in bringing together mechanical return and hydraulic response within a single comparable framework. This makes it possible to translate the results into geographical criteria to guide quantifiable geographical decision-making in relation to stabilisation, dependent on actual road cuts.

2. Literature Review

In Indonesia, the Faculty of Engineering and Planning conducted an experimental study on the performance of vetiver in volcanic silt sand under controlled laboratory conditions. Using a physical model of a steel box, vetiver was incorporated into slopes of 45° and 60%. The results showed substantial improvements in resistance to water erosion, with reductions of 94.6% at 45° and 92.67% at 60°. Under the same conditions, surface scouring was reduced by 55.48% and 53.89% for the respective slope angles. These findings indicate that vetiver effectively controls soil erosion on steep sandy loam terrain and provides quantitative evidence for controlling erosion processes that often precede surface landslides during heavy rainfall. [24-26].

The influence of vetiver on slope stability was studied by one of the civil engineering departments in the United States using recognised soil samples from four sandy slopes interspersed with layers of weak clay. The construction of the vetiver system increased the safety factor of the unreinforced sandy slopes from 2% to 15%. These findings support the idea that vetiver grasses contribute to greater slope stability by resisting surface failure mechanisms that can be triggered by rain-induced surface erosion, thus confirming the effectiveness of these grasses as a stabilising measure for slopes composed of low-cohesion materials without restrictions [27].

An engineering study focused on the combined effects of rain infiltration and slope stability worked to evaluate the effect of vetiver using a finite element model of a natural 26° slope. The analysis considered a system of ratios with an adequate depth of 2 m. It showed that vetiver protected the soil from erosion by limiting the development of adverse interstitial water pressure within the surface soil mass. This hydromechanical interaction helped improve stability by maintaining effective stress and increasing the shear failure resistance of surface slip surfaces. The findings support that deep-rooted vetiver systems can reduce rain-induced instability by controlling seepage and improving soil structure, thus supporting their use in slope stabilisation under active hydraulic conditions [28].

In the context of geographical and geological engineering, the stabilising effect of vetiver was studied using a physical slope stabiliser model constructed on a video receiver and supplemented with numerical analysis. When vetiver was planted in a silty medium, root development reached 0.42 m after 6 months, providing measurable shelter within the surface soil zone. Finite element analysis revealed that the corresponding configuration of the slope had a safety factor value of 1.01, indicating a marginally stable condition. In contrast, full surface coverage with vetiver increased the safety factor to 1.17, showing improved overall stability due to root return. The analysis identified a geometric threshold of about 33.3°, above which root development was restricted, resulting in a friction-dependent safety factor of 1.06. The resulting findings show that vetiver, combined with appropriate slope geometry and terraces, can improve stability by providing resistance to surface layer deformation mechanisms, which has implications for optimising slope ring in disease application [29].

In Bangladesh, experimental studies were conducted to evaluate performance under conditions of representative heavy rainfall and erosion-prone slopes. When vetiver was introduced, runoff was reduced by 78% on a 1G scale model with a 40% slope and simulated rainfall of 118 mm/h, indicating a significant alteration in surface flow and soil development processes. Secondary studies evaluated the stabilising effect of vetiver combined with fly ash on silty sand slopes. The recorded vetiver shoot lengths ranged from 130 cm to 170 cm, in contrast to 61 cm to 74 cm for jute mulch. Under these conditions, vetiver increased slope durability by a factor of 15 and reduced soil loss by 19% compared to bare slopes.

On the other hand, the combined application of vetiver and fly ash increased durability 32-fold and reduced erosion by 12%. In contrast, jute protection tripled durability with a 60% reduction in soil loss [31, 32]. These results illustrate that vetiver provides a stronger and more durable reference compared to weak surface cubes, even more so with the integration of complementary stabilising materials under severe hydraulic loads.

In India, a civil engineering research team evaluated the performance of vetiver in stabilising slopes under conditions representative of steep and intense slopes. The research considered slope inclination, soil characteristics, rainfall, and soil surface degradation and retention as control variables. The results demonstrated vetiver's ability to reduce erosion on slopes by up to 75%, achieving more than 90% erosion reduction compared to bare slopes. These sustainable results, which include severe geometric and hydraulic conditions, show that vetiver can be a good protective cover against surface erosion by reducing the deterioration and transport of soil particles and by mitigating soil degradation processes that can lead to the instability of shallow slopes. The results indicate the potential of living vegetation as a viable erosion control measure on steep and sometimes intense slopes, especially when conventional structural solutions are limited [33].

An experiment conducted in Malaysia at the Faculty of Civil Engineering and Built Environment evaluated the mechanical contribution of vetiver to slope stabilisation by directly measuring the shear strength of vetiver on slopes with inclines of 45°, 50°, and 60°. After 21 days, the maximum shear stresses mobilised due to the soil-root system were 13.73 kN/m², 13.70 kN/m² and 13.25 kN/m² for 45°, 50°, and 60°, respectively. After 30 days, these values decreased significantly to 32.93 kN/m², 27.71 kN/m² and 27.22 kN/m². This indicates that there is rapid development of mechanical shelter during the initial establishment period. The study also reported tensile strength ratios of 0.025 kN for slopes of 45° and 50°, which corresponds to the most favourable mechanical response observed. These findings provide evidence that vetiver plants promote a time-dependent increase in soil shear strength due to the gradual interaction of plant roots with the surrounding soil, which is beneficial for enhancing the stability of shallow slopes and reducing the risk of rain-induced failures on steep and marginal land [20].

In Thailand, research on two communities implementing the vetiver system shows that soil conservation and water retention depend on the continuity of installation and maintenance capacity over time. Institutional support and coordination with public and private organisations ensured continuous vegetation cover, which was necessary to sustain soil shelter and surface protection in rainy and runoff conditions. From a geographical perspective, these findings show that the success of vetiver on slopes cannot be attributed to the species itself, but rather to the implementation and maintenance of quality over time of soil erosion control and surface stability, which must be considered for stabilisation applications [34, 35].

2.1. Critical Synthesis and Contribution of the Present Study

Studies confirm that vetiver can be highly effective in controlling erosion and runoff under simulated rainfall conditions. Physical model studies indicate reductions in erosion of 94.6% and 92.67% and in runoff of 55.48% and 53.89% for the same slopes of 45° and 60° [24-26]. During an extreme simulated rainfall of 118 mm/h in a 1G physical model, with a slope of 40%, surface scour was reduced by 78% [30]. On the other hand, studies with slopes of up to 75% reported reductions in erosion of more than 90% compared to bare soil conditions [33]. From a mechanical point of view, return effects have been reported more frequently in the initial phase. The maximum shear stresses mobilised increased from 13 kN/m² at 21 days to more than

27 kN/m² and 32 kN/m² at 30 days, depending on the slope gradient, with a tensile strength of 0.025 kN in the same experimental disease [20].

Regardless of the findings, the literature reviewed remains methodologically inconsistent. A significant number of studies focus on erosion and runoff as isolated indicators of performance [24-26, 30, 33], while other studies evaluate stability using global safety factors without determining shear strength parameters [27, 29]. Research reporting on mechanical return in early stages does not integrate the hydraulic response under simulated rainfall in the same experimental run [20]. As a result, empirical studies linking slope geometry, sample density, and temporal establishment with simultaneous variations in shear strength, bearing capacity, erosion, and runoff remain scarce [24-35]. The present study addresses this gap with an integrated experimental approach, emphasising controlled geometry physical prototypes, systematic variations in slope ring and sample density, and early-stage evaluation, facilitating quantitative interpretation of mechanical and hydraulic performance within a geotechnical disease framework.

3. Materials and Methods

3.1. Study Area

The study was conducted in the San Pedro Sector (KM 70+900) of the central highway, Tarma-La Merced section, where the road corridor is narrowest. This section runs alongside the Peréné River, which is steeper and partially vegetated. The proximity to the river, combined with the geomorphological characteristics of the area, makes the site highly vulnerable to a variety of geomorphological instabilities, particularly during the rainy season. Documented evidence from the area includes landslides, rockfalls, and occasional rockfalls that are frequent enough to block the flow of vehicles. These phenomena are sufficient to close a lane, increasing congestion, creating hazards for road users, and economically affecting adjacent communities that depend on the road for access [11, 12].

In Figure 1, the critical section is where the interaction between the river and the unstable slopes is clearly visible, justifying the choice of this sector as the focus of analysis in the current study. For the hydrological design, a rainfall intensity of 47.7 mm/h with a duration of 1 hour was considered, corresponding to a return period of 25 years, obtained from the IDF curves published by SENAMHI [36]. The choice of this value responds to a balanced technical criterion, widely supported in the literature [24, 37], as it represents a severe yet probable event during the service life of the project, allowing a realistic assessment of the effectiveness of vetiver against high-intensity rainfall. This condition further alters the hydrological risk assessment in the area, justifying the need for stabilisation and control measures.

Fig. 1 View of the San Pedro Sector (km 70+900) of the central highway

3.1.1. Angle of Inclination

Characterising the geometry of the slope in the study area was an essential step in defining parameters for stability analysis, which are illustrated in Figure 2. The solutions analysed the vertical differential calculation based on the extreme values obtained from the topographic surveys. The reference point is the elevation of 625 m located on the slope table, next to the road, and 950 m from the slope, recording 705.317 m. This configuration, next to the road, allowed for a vertical difference of 325 m, and using Pythagoras' theorem, the horizontal distance was calculated at 625.93 m. With this data, we obtained an average slope of 51.9%, which corresponds to an angle of 27.6°, allowing us to accurately characterise the slope of the staircase. Based on this result, the angles of analysis used in the investigation were defined: 20°, 25°, 27.6°, 30°, and 35°. The consideration of different angles of inclination was essential, as the geometry of the slope is a decisive factor in its behaviour. Incorporating a range of slopes into the study made it possible to establish a more comprehensive and realistic analysis framework, capable of reflecting the conditions that may arise in the field and ensuring that the evaluation of stabilisation measures was valid in diverse and representative geometric scenarios [38, 39].

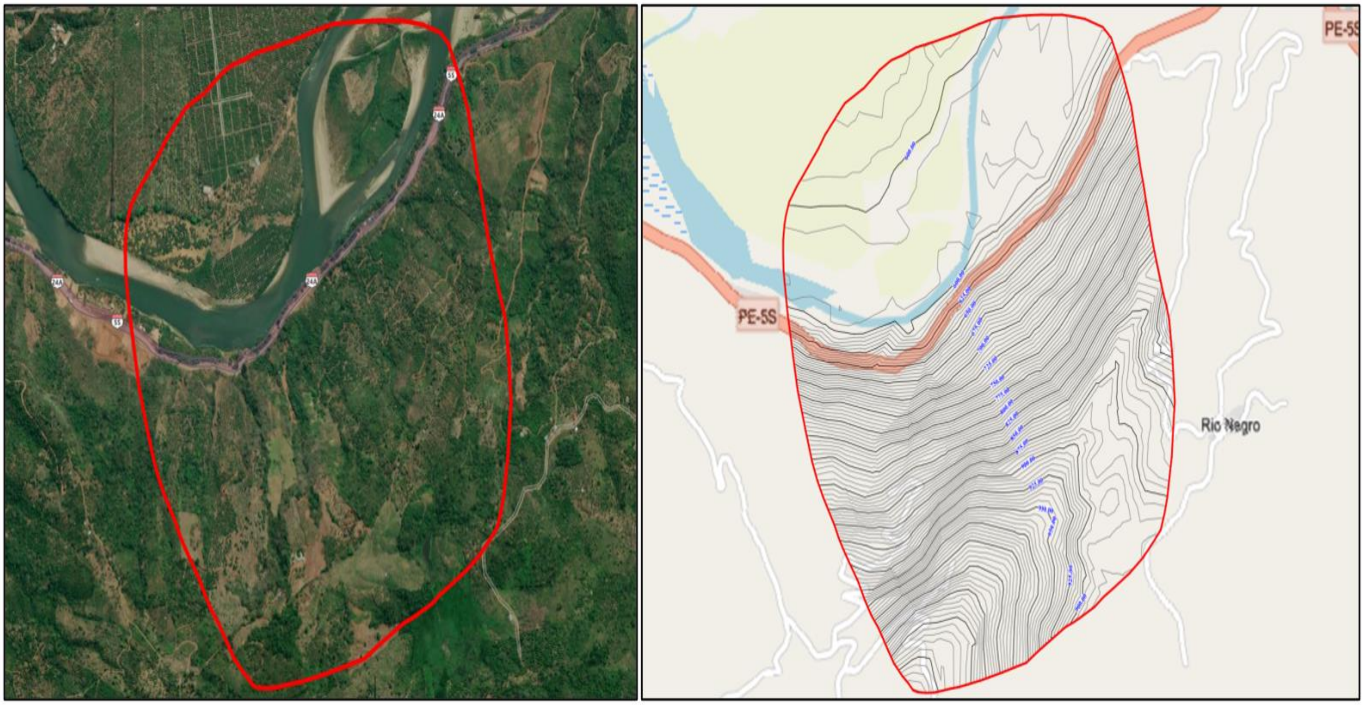


Fig. 2 Determination of the study area

3.2. Vetiver Grass

Vetiver grass (Chrysopogon zizanioides) is a perennial grass native to the tropical regions of Asia, particularly India [40, 41]. It has erect stems surrounded by long, thin leaves and small, light brown flowers arranged in inflorescences up to 35 cm long. Its most distinctive feature is its fibrous root system, which is white to pale yellow in colour and can reach depths of over 3 metres, giving it a key role in preventing erosion and improving soil stability [42]. Thanks to these properties, vetiver is widely used in soil conservation programmes, erosion control, and as a natural barrier against desertification [43]. In addition, its roots are a source of essential oil, highly valued in the perfume and cosmetics industry [44]. The use of this grass was justified by the effectiveness of its root system and its ability to adapt to soils with low fertility, high plasticity, and acidity, as well as to land with steep slopes and a history of instability [37, 45]. The relevant properties of vetiver are presented in Table 1.

According to the properties mentioned in Table 1 and relating this to the application area, there is high-intensity rainfall (47.7 mm/h), which increases the risk of surface erosion. This extreme condition is directly related to vetiver's ability to tolerate both prolonged periods of waterlogging (up to 45 days under water) and seasonal drought, thanks to its deep root system and physiological resistance. Consequently, the species is suitable for stabilising slopes in scenarios of high water variability. In this research, vetiver seedlings (clumps with roots and young leaves, 60 days after sowing) were obtained from a nursery and transplanted directly into the experimental prototypes (Figure 3) [46].

Table 1. Properties of vetiver [37, 42, 45]

Properties	Characteristics
Root depth	Up to 21.96 cm in 60 days and 1.20 m in 12 months
Collar diameter	Up to 2.02 cm
Root tensile strength	122 MPa (root 1.4 mm)
Environmental tolerance	High tolerance to drought, flooding, pests, fire, acidic and saline soils, and heavy metals
Effect on soil	Increase in pH, phosphorus, and potassium in treated soil.

Fig. 3 Vetiver seedlings

3.2.1. Planting Density of Vetiver

The spacing between vetiver seedlings is a determining factor in the effectiveness of living hedges, as it affects both foliage density and sediment retention capacity and reduces surface runoff [47]. Previous studies in tropical areas have indicated that the optimal planting distance is 15 cm between seedlings, as this arrangement promotes balanced growth, ensures uniform coverage, and allows the formation of continuous barriers without interruptions. Conversely, too little spacing leads to excessive competition for nutrients, which slows root development, while too much spacing causes discontinuities in the barrier and reduces protection against erosion [29, 48]. In order to validate and verify this information within the framework of this research, experimental trials were designed in which vetiver seedlings were arranged at distances of 10 cm, 15 cm, and 20 cm, as shown in items a, b, and c of Figure 4, respectively.

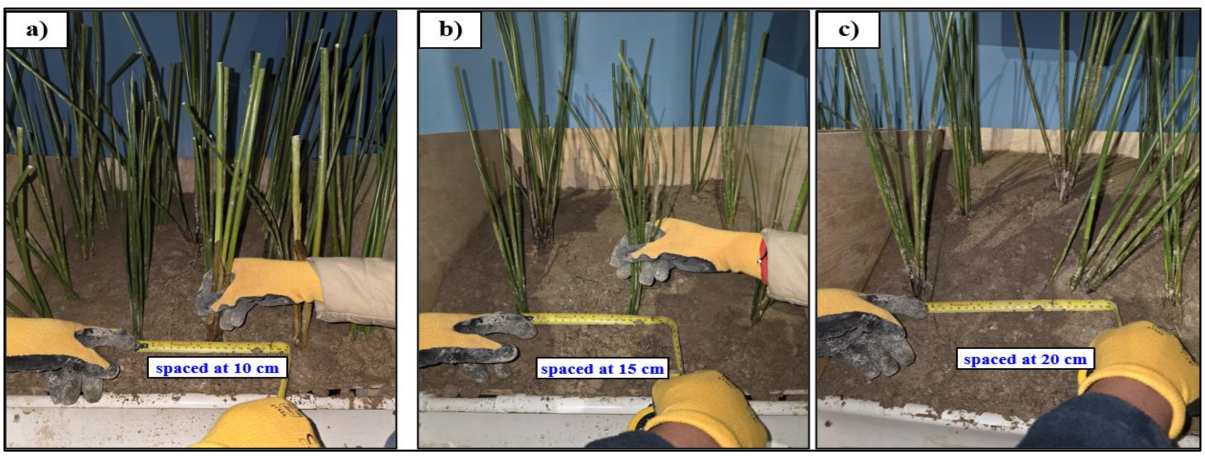


Fig. 4 Density of vetiver seedlings

3.3. Tests Carried Out

This section presents the tests aimed at evaluating the effectiveness of vetiver grass in slope stabilisation. In the first stage, the soil was characterised by means of granulometry, consistency limits, moisture content, and direct cutting tests, supplemented by the Modified Proctor test, in order to determine the maximum dry density and optimum moisture content required for the compaction of the prototypes. Subsequently, experimental slopes were formed considering variations in the angles of inclination (20°, 25°, 27.6°, 30°, and 35°) and in the density of vetiver seedling planting (10 cm, 15 cm, and 20 cm spacing), also incorporating the condition of slopes without vegetation cover as a comparative reference. Direct shear tests were performed on each prototype at 21 and 30 days to determine the cohesion and angle of friction of the soil, following the methodology described in previous research. The evaluation at 21 days allowed the initial effect of vetiver rooting on shear resistance to be recorded, while at 30 days it was particularly significant, as during this period the plant achieved a more developed root system and sufficient aerial coverage, conditions that made it possible to measure its influence on both the mechanical resistance of the soil and the reduction of erosion and runoff in a representative manner [20, 24, 29].

3.3.1. Natural Soil Tests

The soil used in the experimental prototypes was characterised by means of moisture content, Atterberg limits, and grain size tests, applying the MTC standards [49]. The natural moisture content determined in accordance with MTC E-108 was 11.83%, indicating moderate moisture conditions at the time of recovery of the samples. This moisture condition is important because it directly influences the mechanical response of the soil, especially in terms of cohesion, unit weight, and shear strength parameters. Subsequently, the Liquid Limit (LL) and Plastic Limit (PL) were determined in accordance with the standardised procedures for Atterberg limits (MTC E-110 and MTC E-111). Figure 5 shows the tests performed: part (a) shows the determination of the Plastic Limit (PL), obtained by making a cylindrical roll of soil with a slotted metal mould, identifying the point at which the material lost cohesion when it reached an approximate diameter of 3 mm; part (b) shows the Casagrande device used to establish the Liquid Limit (LL), where the soil sample was subjected to controlled shocks that allowed the progressive opening of the groove to be recorded. As a result, an LL of 25.98%, an LP of 19.74% and a Plasticity Index (PI) of 6.24% were obtained, values that indicate low plasticity, characteristic of silty sandy soils, with limited deformation capacity and greater susceptibility to erosion processes.

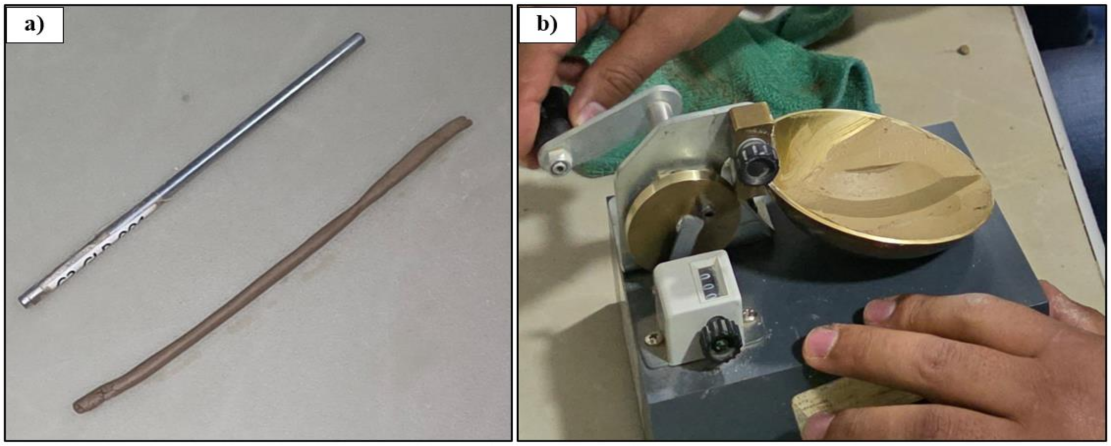


Fig. 5 Atterberg limits

Finally, the sieve analysis (MTC E-107) indicated that 65.9% of the material passed through the No. 200 sieve, which certifies that some fines are present. The particle size distribution curve shown in Figure 6 illustrates this and shows a greater presence of sand, silt, and clay. In the soil SUCS classification, this was recorded as SC-SM (silt-clay sand), and this does a great deal to define the soil's reaction in erosion and slope stability. All of this is summarised in Table 2.

Table 2. Soil characterisation

Test	Result	Technical interpretation
Moisture content	11.83%	Moderate moisture influences cohesion, density, and shear strength.
Atterberg limits	LL = 25.98% LP = 19.74% IP = 6.24%	ow plasticity; behaviour of silty sandy soil, with limited deformation and susceptibility to erosion.
Grain size	5.9% passed through sieve No. 200 SUCS classification: SC-SM	Silty-clayey sand, predominantly sand with a significant fraction of fines (silts and clays).

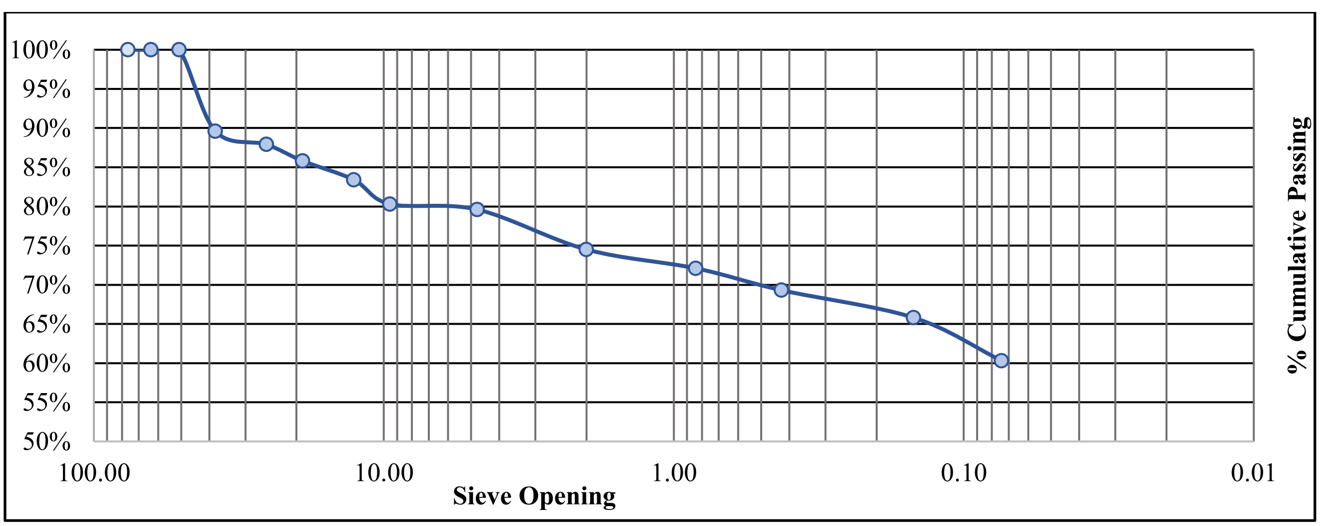


Fig. 6 Grain size distribution curve

3.3.2. Direct Shear

The following soil sample was used to perform a direct shear strength test in compliance with MTC E-123 [46]. Following these standards, the procedure was followed as seen in Figure 7, which shows the steps in the procedure and how they are executed. The steps include: (a) filling the shear box with the soil, (b) firmly compacting the soil in layers with a metal rammer to achieve a uniform density, (c) leveling the surface with a spatula, (d) placing a porous disk and filter paper on the soil to ensure homogeneous contact and allow for drainage, (e) applying the normal load to correspond with the soil confinement conditions to prepare the sample to shear, and (f) recording the sample post shear and the condition which is observed by the misalignment between the box halves. Using three samples per prototype ensured the results were repeatable and reliable. This procedure allowed the shear strength parameters of the different prototypes to be obtained; however, this section only reports the results for the natural soil (standard), which had a cohesion of 0.0484 kg/cm² and an internal friction angle of 20.38°. These values correspond to soil with low cohesion and moderate shear strength, characteristics typical of silty-clay soils. In addition, in accordance with standard NTP 339.131 [47], a unit weight of 1.973 g/cm³ was determined for the soil, a fundamental value for bearing capacity calculations. Based on these parameters, and considering a Safety Factor (SF) of 3, an allowable bearing capacity of 1,298 kg/cm² was obtained. This procedure was applied to both the natural soil (standard) and the prototypes with vetiver grass sown at different densities (10 cm, 15 cm, and 20 cm) and evaluated at 21 and 30 days of growth, on slopes of 20°, 25°, 27.6°, 30°, and 35°.

Fig. 7 Direct shear strength test

3.3.3. Modified Proctor

The Modified Proctor test was performed in accordance with standard MTC E-116 [49] to determine the relationship between moisture content and dry density of the soil, which is essential for defining the optimum degree of compaction in the slope prototypes. During the procedure, layered compacted test specimens were prepared, applying standardised compaction energy as shown in Figure 8.

The results obtained indicated a maximum dry density of 2,072 g/cm³ and an optimum moisture content (OMC) of 9.9%. These values served as a reference for replicating controlled and field-representative compaction conditions in the experimental prototypes, ensuring that the models achieved reliable and comparable behaviour in subsequent direct shear, erosion, and runoff tests.

Fig. 8 Soil compaction

3.4. Prototype Development

The prototypes developed for the research were designed and constructed in the laboratory with the aim of reproducing the behaviour of slopes under controlled rainfall conditions on a reduced scale (Figure 9). Each structure was made from a rigid 9 mm plywood box, which ensured stability during the tests. The dimensions of 50 cm wide, 50 cm deep, and 35 cm high allowed for a representative volume of soil to be contained and variable angles of inclination to be configured (αº: 20°, 25°, 27.6°, 30°, and 35°), precisely defined by side guides that facilitated uniform moulding. In addition, the base and sides were sealed to prevent material loss and moisture variations, while the slope surface was left free for measurements and observations; finally, each box was raised 20 cm on 1‘×1 1/2’ wooden legs (item a). Once the slope lines had been drawn, soil was compacted according to the Modified Proctor test parameters, which state a maximum dry density of 2,072 g/cm³ and an optimal moisture content of 9.9%. Soil was placed and compacted in layers corresponding to the height of each slope (item b). Sand vetiver seedlings were planted by hand after the soil was fully compacted in each prototype, using pre-dug 5cm deep holes, sufficient to capture and anchor the seedling's starter roots. The seedlings were planted in straight rows along the slope with spacing of 10, 15, and 20 cm between plants, as indicated in Table 2, to ensure uniform spacing and alignment. For the execution of the hydraulic tests, a fixed outlet with constant pressure was used, conducted by a ½″ line equipped with a ball valve (quick opening and closing) and a pressure gauge for pressure control (item c, highlighted in red for identification). The rain simulator consisted of an adapted domestic chrome shower head (½″ outlet diameter, 7 cm face with 1.6 mm holes), installed on a front mast 1.60 m above ground level, with a 45° inclination, which generated a uniform footprint of 50 cm in diameter and covered the entire surface of the prototype without lateral losses (item d). Finally, to enable lower collection, a 70×50×10 cm collection tray was incorporated into each box, together with a 2″ PVC gutter connected to a funnel fitted with a delicate internal mesh, whose function was to filter and separate solids from the water before storage for analysis (item e).

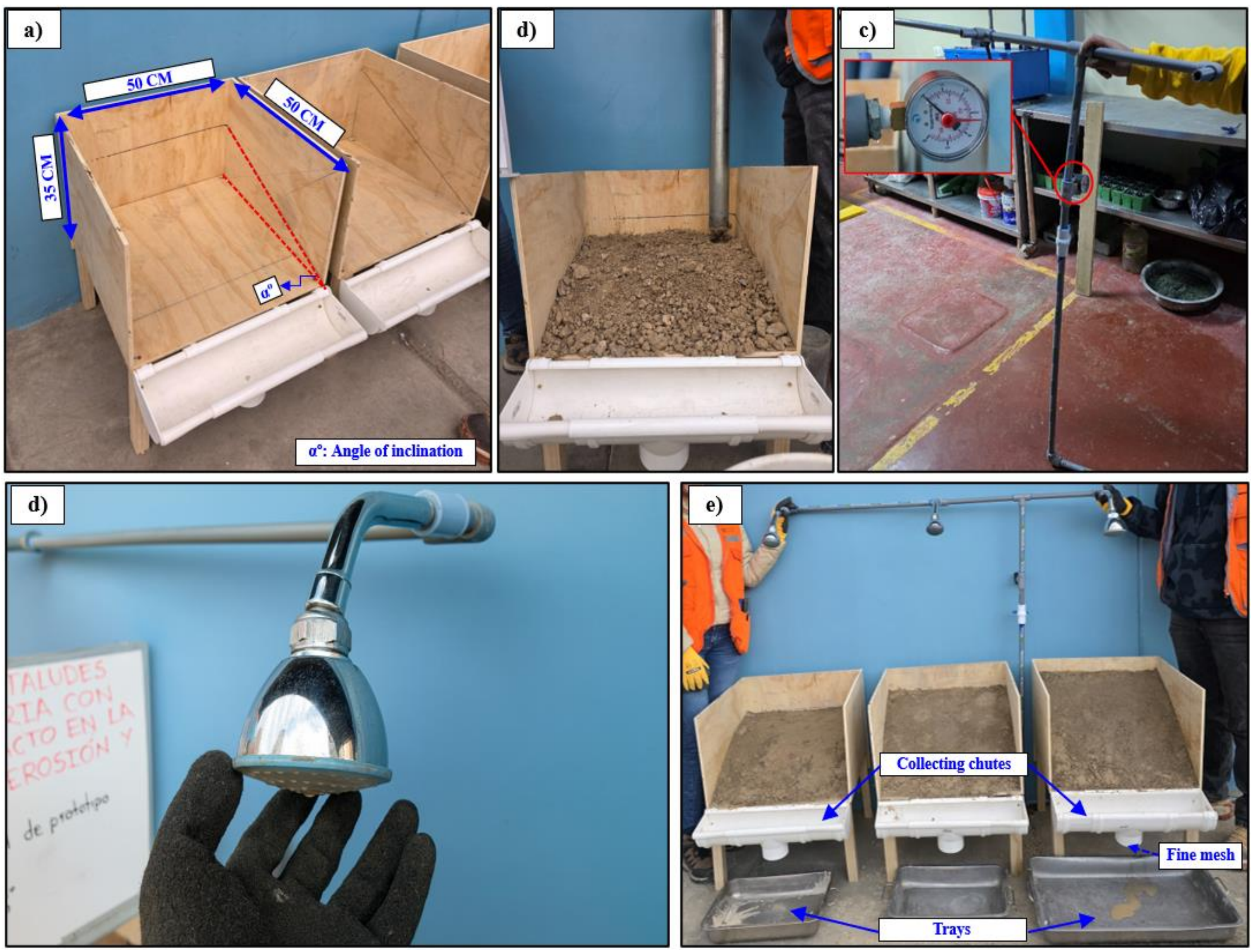


Fig. 9 Prototype

A total of 35 prototypes were developed during the research, as shown in Table 3. The five angles of inclination (20°, 25°, 27.6°, 30°, and 35°) were considered and evaluated under different conditions: without vetiver grass and with vetiver grass planted at depths of 10, 15, and 20 cm, both at 21 and 30 days of growth. An independent prototype was constructed for each combination of condition and angle, resulting in five prototypes for each scenario. This provided a broad experimental basis for comparing bare soils and soils reinforced with vetiver under different establishment times and seedling planting distances.

Table 3. Prototypes

Condition	Slope angles evaluated	N° of prototypes
Without Vetiver Grass	Soil in 20º mould	1
	Soil in 25º mould	1
	Soil in 27.6º mould	1
	Soil in 30º mould	1
	Soil in 35º mould	1
With Vetiver Grass at 10 cm (21 days)	Soil + Vetiver in 20º mould	1
	Soil + Vetiver in 25º mould	1
	Soil + Vetiver in 27.6º mould	1
	Soil + Vetiver in 30º mould	1
	Soil + Vetiver in 35º mould	1
With Vetiver Grass at 15 cm (21 days)	Soil + Vetiver in 20º mould	1
	Soil + Vetiver in 25º mould	1
	Soil + Vetiver in 27.6º mould	1
	Soil + Vetiver in 30º mould	1
	Soil + Vetiver in 35º mould	1
With Vetiver Grass at 20 cm (21 days)	Soil + Vetiver in 20º mould	1
	Soil + Vetiver in 25º mould	1
	Soil + Vetiver in 27.6º mould	1
	Soil + Vetiver in 30º mould	1
	Soil + Vetiver in 35º mould	1
With Vetiver Grass at 10 cm (30 days)	Soil + Vetiver in 20º mould	1
	Soil + Vetiver in 25º mould	1
	Soil + Vetiver in 27.6º mould	1
	Soil + Vetiver in 30º mould	1
	Soil + Vetiver in 35º mould	1
With Vetiver Grass at 15 cm (30 days)	Soil + Vetiver in 20º mould	1
	Soil + Vetiver en Molde de 25º	1
	Soil + Vetiver en Molde de 27.6º	1
	Soil + Vetiver en Molde de 30º	1
	Soil + Vetiver en Molde de 35º	1
With Vetiver Grass at 20 cm (30 days)	Soil + Vetiver en Molde de 20º	1
	Soil + Vetiver en Molde de 25º	1
	Soil + Vetiver en Molde de 27.6º	1
	Soil + Vetiver en Molde de 30º	1
	Soil + Vetiver en Molde de 35º	1
Total number of prototypes		35

3.4.1. Erosion

The erosion test was based on research that analysed prototypes of slopes with varying gradients using simulated rainfall [24, 25]. For this study, the 35 prototypes described in Table 2 were used, which included both soils without vegetation cover and soils reinforced with vetiver grass at different planting densities (10, 15, and 20 cm) and establishment times (21 and 30 days). The process involved each prototype being placed under a rain simulator that produces water droplets at a steady rate of 47.7 mm/h, which corresponded to a specific precipitation event (Figure 10, item a). Each simulation ran for 30 minutes, during which water splashed onto the soil surface, detaching and transporting particles and aggregates to the lower slope. At the bottom, collection channels were placed to conduct the flow and retain the eroded material, while the water was filtered through a funnel with fine metal mesh, which allowed the solids to be separated from the liquid (Figure 10, item b). The retained sediment was placed in a drying oven at 105 °C for 24 hours until it reached a constant weight (Figure 10, item c). Finally, the dry mass of the material was determined using a precision balance accurate to 0.01 g, which allowed the loss of soil to be quantified precisely for each condition evaluated.

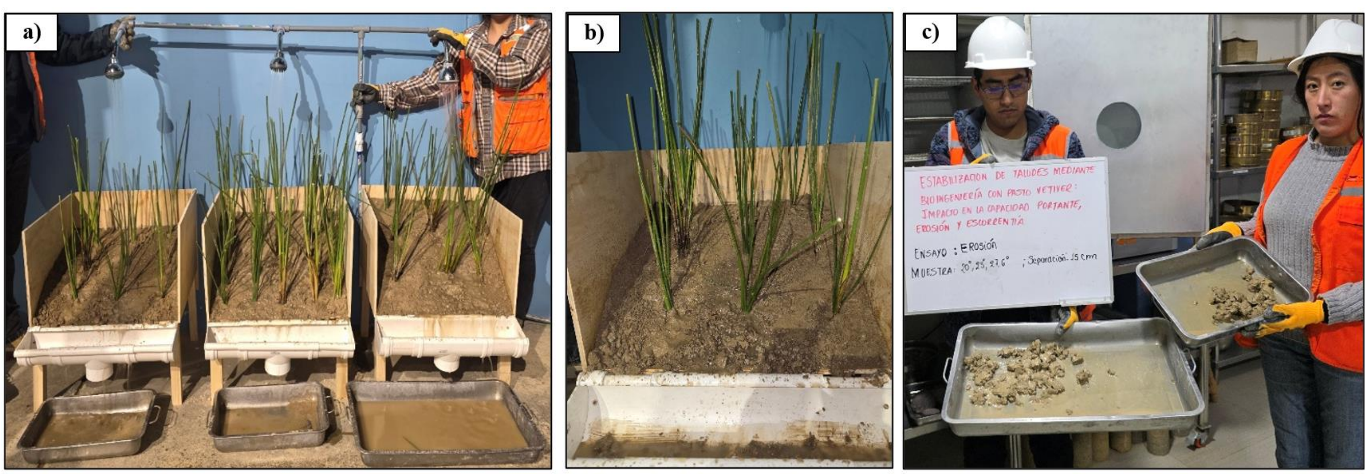


Fig. 10 Erosion test

3.4.2. Runoff

The runoff test was based on experimental procedures that collected surface water generated in the same plots subjected to simulated rainfall [24, 25]. In the erosion test, the tests were carried out on 35 experimental prototypes, but in this case, the emphasis was on measuring the runoff water. During the 30-minute simulation, the surface flow passing through the metal mesh was directed into collection trays, as shown in Figure 11.

The collection was carried out at 5-minute intervals, allowing variation in surface flow to be recorded over time. Subsequently, the water accumulated at each interval was quantified using 1000 ml graduated cylinders, ensuring accuracy in the determination of volumes. In this way, it was possible to systematically analyse the behaviour of surface runoff under different slopes and vegetation cover conditions, reflecting the fraction of water that failed to infiltrate the soil profile.

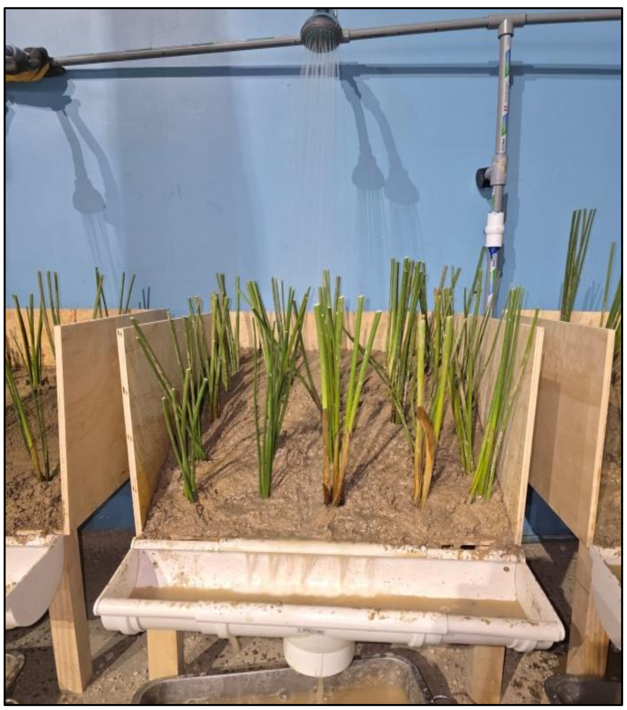


Fig. 11 Runoff test

4. Results

4.1. Direct Shear

The results of the direct shear test, which determined the fundamental shear strength parameters of the soil, are presented below. First, cohesion (c) was addressed, analysing its behaviour in soils with and without vetiver incorporation, under different moulds and curing times. Next, the values of the internal friction angle (φ) were analysed, which allowed the interaction between the soil particles and the effect of the vetiver roots on improving its structure to be evaluated.

Finally, the allowable capacity was determined, integrating the resistance parameters obtained, with the aim of assessing the contribution of plant reinforcement to the stability and safety of slopes and the terrain in general.

4.1.1. Cohesion

The cohesion (c) results, evaluated at 21 and 30 days in soils with and without vetiver, are presented below in order to analyse the influence of seedling density on shear strength. Table 4 shows that, at 21 days, the incorporation of vetiver seedlings increased this parameter in all cases. With a spacing of 10 cm, cohesion reached 0.0743 kg/cm² at 20° and 0.0671 kg/cm² at 25°, which showed that the young roots began to bridge the particles, generating a moderate bond; however, the high proximity caused competition between seedlings, which limited deep growth and reduced efficiency on steeper slopes.

The 15 cm spacing recorded the highest density values, showing 0.0859 kg/cm² at 20° and 0.0753 kg/cm² at 25°, which indicates that at this spacing the roots had sufficient room to grow in both thickness and depth, enough to intertwine and create a biological mesh that consolidated the particle bond and enhanced shear strength. On the contrary, the 20 cm spacing recorded 0.0627 kg/cm² at 20° and 0.0583 kg/cm² at 25°, showing that the additional spacing resulted in areas of the soil being unoccupied by roots, which reduces the continuity of soil coverage, thus reinforcing to a lesser degree and resulted in lower cohesion. After 30 days, the 10 cm spacing increased the values to 0.0832 kg/cm² at 20° and 0.0661 kg/cm² at 35°, showing a positive effect of root growth even though the root growth was limited due to crowding.

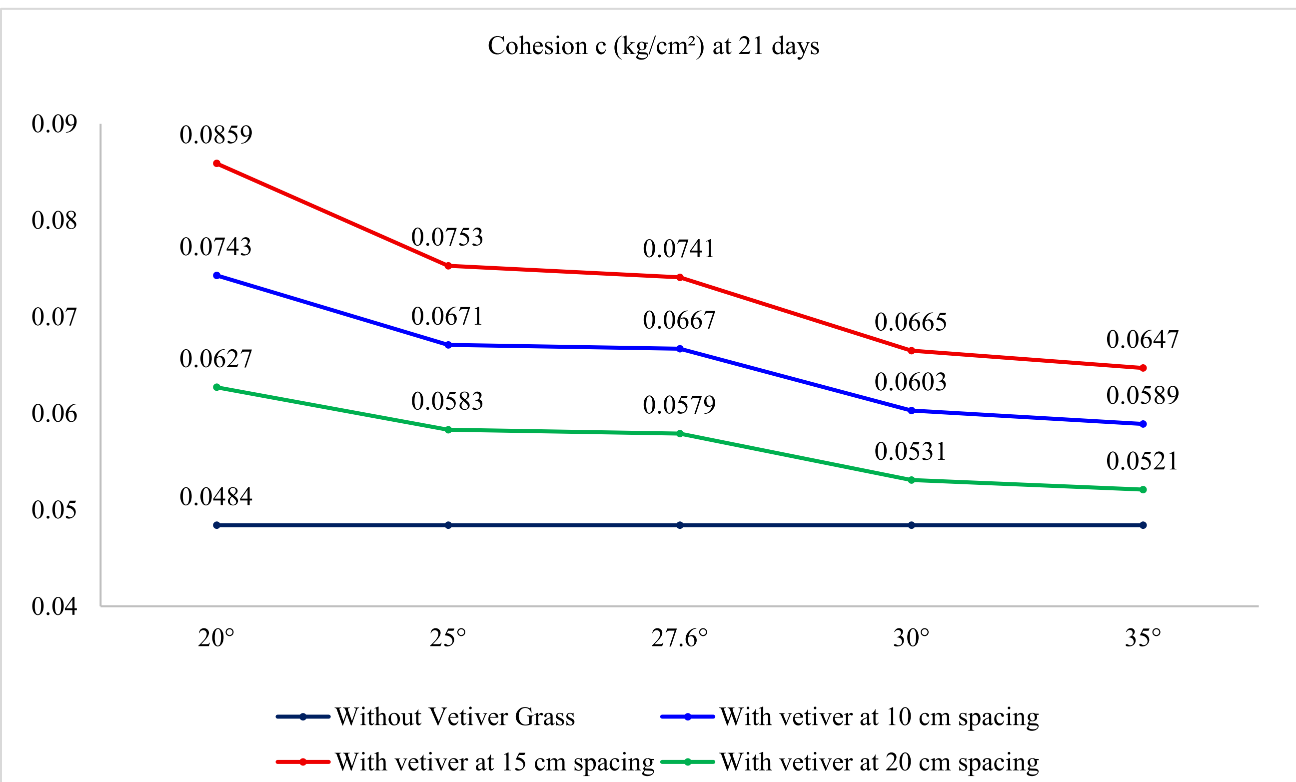
The 15 cm spacing recorded the highest values, 0.0988 kg/cm² at 20° and 0.0744 kg/cm² at 35°, which also indicates that this spacing promoted the best root growth, in which roots had the ability to grow, intertwine, and uniformly reinforce all the particles, thus providing enhanced lateral cohesion and stability on all evaluated slopes. Ultimately, the 20 cm arrangement only reached 0.0627 kg/cm² at 20° and 0.0521 kg/cm² at 35°, verifying that further spacing led to poorly reinforced zones of soil with less cutting resistance. Different from these results, the arrangement without vetiver showed a cohesion angle of only 0.0484 kg/cm², which is much lower than the various seedling densities achieved, demonstrating the absence of root reinforcement, giving the soil a weak shear resistance.

The overarching results indicated that 15 cm spacing was the most optimal, as it circumvented both the overwhelming competition amongst seedlings noted at 10 cm and the reinforcement discontinuity at 20 cm, yielding higher cohesion and better resistance to slope upsurge. This corresponded with the scattering documented in studies carried out in Bangladesh and Thailand. [29, 34].

Table 4. Cohesion

Cohesion c (kg/cm²) at 21 Days					
Description	**Soil in mould at 20°**	**Soil in mould at 25°**	**Soil in mould at 27.6°**	**Soil in mould at 30°**	**Soil in mould at 35°**
With vetiver at 10 cm spacing	0.0743	0.0671	0.0667	0.0603	0.0589
With vetiver at 15 cm spacing	0.0859	0.0753	0.0741	0.0665	0.0647
With vetiver at 20 cm spacing	0.0627	0.0583	0.0579	0.0531	0.0521
Cohesion c (kg/cm²) at 30 Days					
Description	**Soil in mould at 20°**	**Soil in mould at 25°**	**Soil in mould at 27.6°**	**Soil in mould at 30°**	**Soil in mould at 35°**
With vetiver at 10 cm spacing	0.0832	0.0751	0.0747	0.0675	0.0661
With vetiver at 15 cm spacing	0.0988	0.0866	0.0852	0.0765	0.0744
With vetiver at 20 cm spacing	0.0677	0.0631	0.0625	0.0573	0.0563

According to Figure 12, after 21 days, vetiver reinforced soil cohesion compared to no-plant soil. At 20°, with 10 cm soil density, it increased by 38% and at 15 cm soil density, it increased by 60%, while at 25° soil densities, it increased by 51% with the same configuration. On 27.6°, 30°, and 35° steeper slopes, the increases ranged from 41% to 47%, stating that vetiver 15 cm is the best over the other seedling spacing. There is an apparent gap that vetiver 15 cm had over 10 cm and 20 cm. The soil cutting and surface slipping resistance increased in the earlier vetiver establishment. At 30 days, the trend continued and intensified. At a 20° angle, cohesion increased again by 38% with vetiver at 10 cm and by 60% at 15 cm, while at 25° the increase again reached 51% with the latter density. On steeper slopes, values ranged from 41% to 47%, confirming that seedlings at 15 cm were the most effective configuration in all conditions evaluated. The performance pattern remained unchanged, confirming that vetiver not only reinforced the soil in the initial stages but, over time, consolidated its ability to steadily increase shear strength and, therefore, stability against erosion and landslide processes.



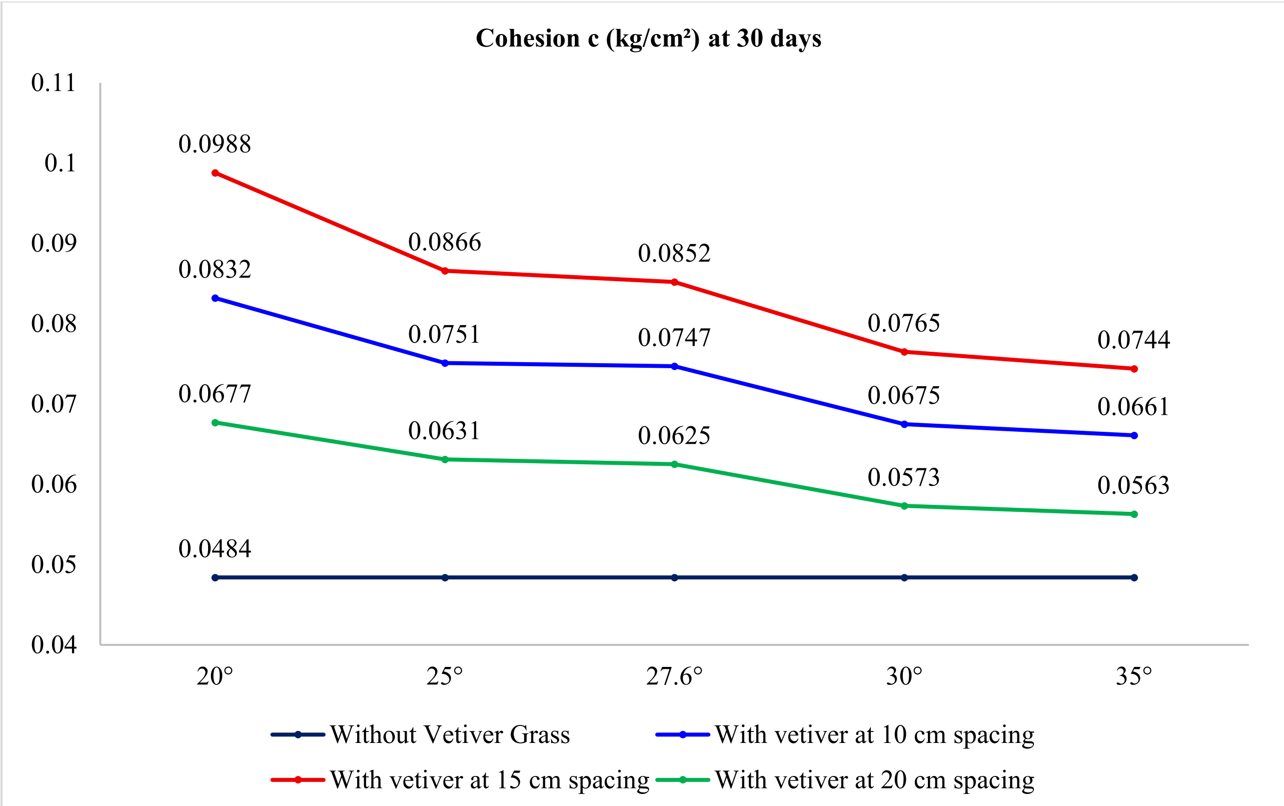


Fig. 12 Cohesión

4.1.2. Angle of Friction

This section presents the results of the internal friction angle (φ), evaluated at 21 and 30 days in soils with and without vetiver, in order to analyse the influence of seedling density on the internal resistance of the soil. Soil without vetiver recorded a value of 20.38°, reflecting a reduced level of internal friction, as the particles tended to slide more easily without the root reinforcement that increases friction between them. On the other hand, the vetiver seedlings increased the friction angle on all slopes, as shown in Table 5. At a 10 cm density, the friction angle increased to 22.18° for 20° and 21.12° for 35°, indicating moderate reinforcement as the roots began to slide. penetrate between the particles and generate some resistance to sliding.

However, too much proximity among seedlings restricted the efficacy on the steep slopes as it stunted root growth in depth and diameter. At a density of 15 cm, the highest friction angle values were recorded: 22.79° for 20° and 21.67° for 35°, which indicates that this spacing promoted better root interweaving with the soil, reinforcing internal resistance and increasing friction among the soil particles. On the other hand, the 20 cm spacing resulted in smaller friction angle increases (21.74° for 20° and 20.63° for 35°), as the increased separation left unrooted soil areas, which lessened the reinforcement continuity and diminished the shear stress dissipation.

After 30 days, vetiver confinement triggered appreciable increments. At 10 cm, 22.61° at 20° and 21.31° at 35° were recorded, values that, from the first stage, clearly denoted root competition. 20 cm and 15 cm recorded maximum suspending levels, with 23.25° at 20° and 21.75° at 35°, proving that this spacing provided the most adequate conditions for the consolidation of the soil structure, and the increase of the contact, cohesion, and shear strength of the particles.

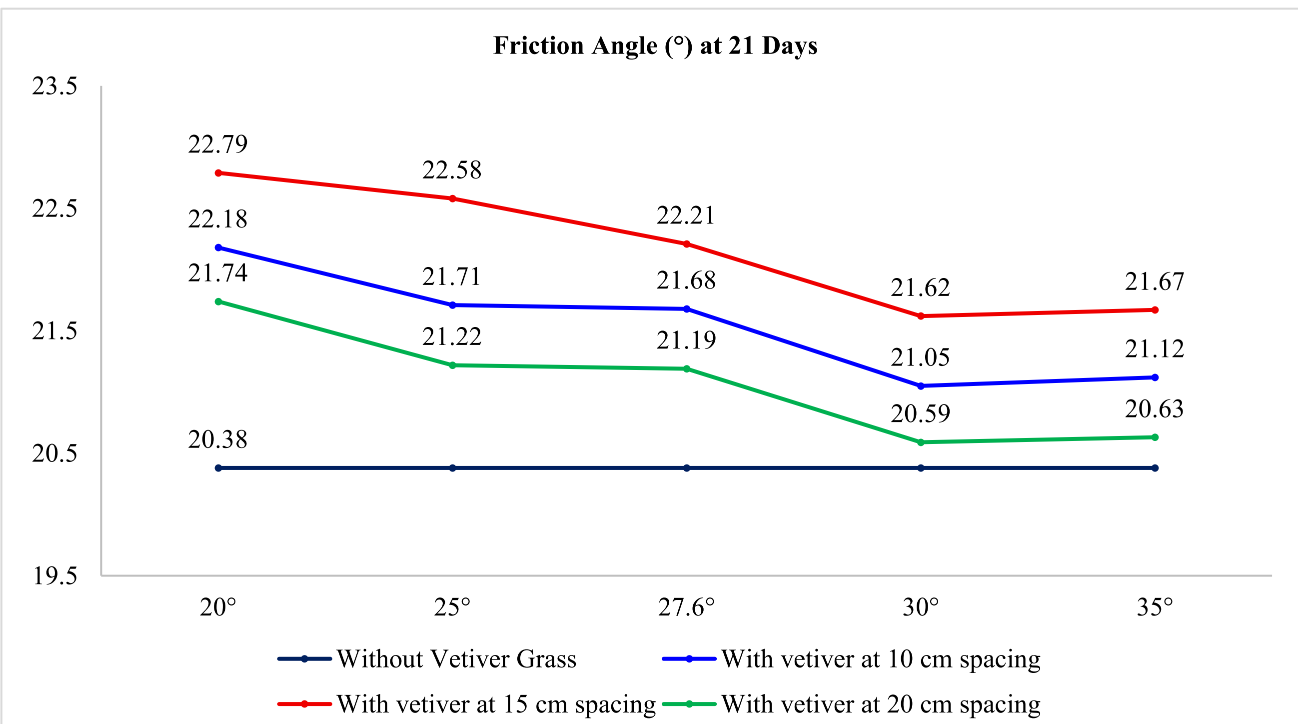
For the 20 cm, the results were modest, with 21.99° at 20° and 20.79° at 35°, which, although they outperformed bare soil, did not match the results of the denser plantings. Overall, the results confirmed that seedling spacing of 15 cm was the most efficacious for all the slopes. On 20° slopes, this arrangement allowed for the greatest friction angle, which reflected uniform root interlocking and reinforced arrangement.

On steeper slopes, such as 35°, it also maintained its excellence by effectively counteracting the tendency to slide, unlike 10 cm, where root competition reduced efficiency, and 20 cm, where excessive spacing left areas without reinforcement. Hence, 15 cm indicated an ideal equilibrium regarding density and root formation, retaining optimal internal soil strength across all slopes assessed.

Table 5. Angle of friction

Friction Angle (°) at 21 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
With vetiver at 10 cm spacing	22.18	21.71	21.68	21.05	21.12
With vetiver at 15 cm spacing	22.79	22.58	22.21	21.62	21.67
With vetiver at 20 cm spacing	21.74	21.22	21.19	20.59	20.63
Friction Angle (°) at 30 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
With vetiver at 10 cm spacing	22.61	22.31	22.11	21.61	21.31
With vetiver at 15 cm spacing	23.25	22.95	22.55	22.05	21.75
With vetiver at 20 cm spacing	21.99	21.69	21.49	21.09	20.79

After 3 weeks, vetiver presence meant the friction angle further increased, improving by 5% to 10% compared to the bare soil. At 20° and 15 cm density, it increased by 8% from 21.03° to 22.79°, and at 25° it increased by 10% from 20.47° to 22.58°. For slope angles 27.6°, 30°, and 35°, the 15 cm density still proved to be the most effective as the increases were 8%, 9% and 9% respectively. The performance clearly ranked, from best to worst, to 15 cm, 10 cm, and 20 cm, the latter two improving very little but still better than the soil that was uncovered. The results further stated that vetiver increased the soil friction angle, improving soil stability to surface sliding even at its early stages. After 30 days, the improvement trend was consolidated with sustained increases on all slopes. At 20°, the friction angle increased from 21.03° to 23.25° (+11%), while at 25° it went from 20.47° to 22.95° (+12%). At 27.6° and 30°, the increases were 10% and 11%, respectively, and at 35°, there was a 9% improvement, reaching 21.75° compared to 19.81° for bare soil. At 21 days, the 15 cm density was the most efficient, followed by 10 cm, and lastly 20 cm, which maintained more limited but consistently positive increases. These results confirmed that, after 30 days, vetiver steadily strengthened the internal resistance of the soil, consolidating the intermediate density of 15 cm as the most effective configuration for improving the friction angle and, with it, the stability of the slopes. As with cohesion, the angle of friction showed improved performance, coinciding with the results reported in research conducted in Bangladesh and Thailand [29, 34].



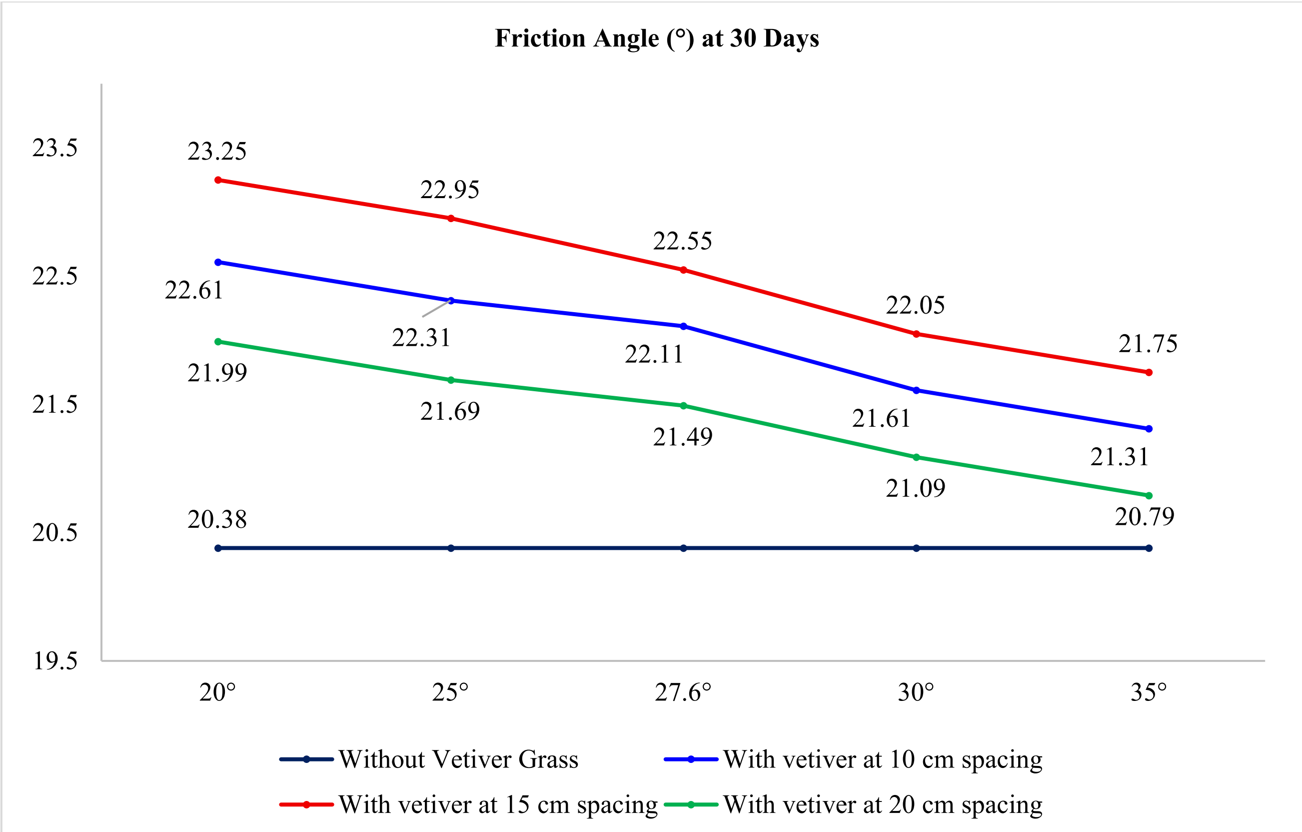


Fig. 13 Angle of friction

4.1.3. Permissible Capacity

The results of the permissible bearing capacity, evaluated at 21 and 30 days in soils with and without vetiver, are presented in order to determine the effect of seedling density on the resistance of the soil to applied loads. Firstly, the standard soil, without vetiver, reached 1,298 kg/cm², a relatively low value that shows its limited capacity to redistribute stress and its high susceptibility to plastic deformation under load. This is due to the absence of roots that increase cohesion, so that resistance depends solely on friction between particles and the degree of compaction achieved.

In contrast, Table 6 shows that the incorporation of vetiver seedlings significantly improved the performance of the soil in all configurations. With a 10 cm arrangement, the values increased to 1,766 kg/cm² at 20° and 1,475 kg/cm² at 35°, which showed moderate reinforcement associated with the first root interactions with the soil, although conditioned by competition between seedlings.

The 15 cm spacing achieved the maximum scores with 1,975 kg/cm² at 20° and 1,603 kg/cm² at 35° showing more efficient root penetration, distribution of the loads applied and consolidation of the structure of the compacted soil, even on steeper grades. The twenty-centimeter spacing showed intermediate increases with 1,598 kg/cm² at 20° and 1,356 kg/cm² at 35° of consolidation, showing that excessive spacing decreased the continuity of the soil reinforcement, leaving some areas less compact and with decreased load-carrying capacity.

After 30 days, the soils reinforced by the vetiver increased their bearing capacity significantly, with the 10 cm spacing reaching 1,918 kg/cm² at 20° and 1,561 kg/cm² at 35°, indicating an improvement from the 21 days, although still limited by the competition of roots.

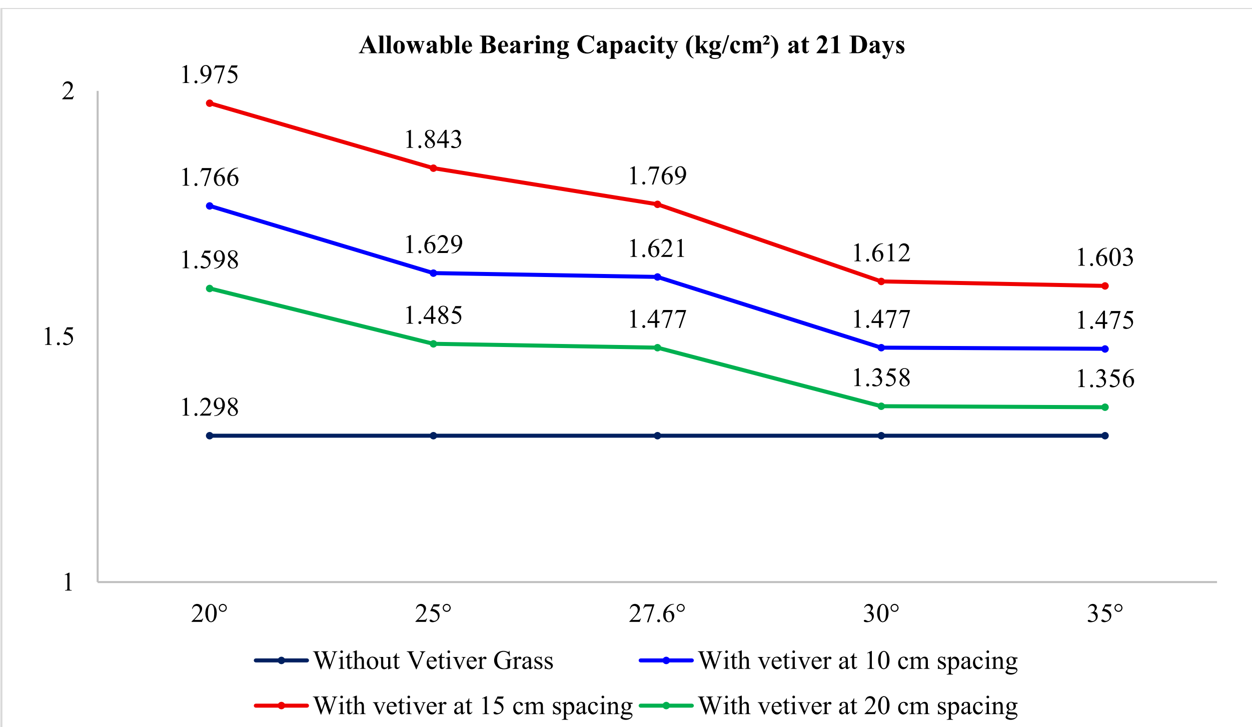
The 15 cm spacing recorded the maximum values of the trial at 2,181 kg/cm² at 20° and 1,696 kg/cm² at 35°, indicating that 15 cm spacing provided the optimum value of load transfer and resistance to applied loads due to the firm anchorage of the roots. The 20 cm spacing showed meager increase with 1,679 kg/cm² at 20° and 1,409 kg/cm² at 35°, higher than bare soil but significantly lower than the dense spacings.

The result showed that root overcrowding at 10cm and unreinforced voids at 20cm gaps were avoided at all slopes at 15cm, which showed the most optimal condition. This gap most likely achieved the best combination in root development and coverage, improving the bearing capacity and soil resistance to load on moderate and steep slopes.

Table 6. Allowable capacity

Allowable Bearing Capacity (kg/cm²) at 21 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
With vetiver at 10 cm spacing	1.766	1.629	1.621	1.477	1.475
With vetiver at 15 cm spacing	1.975	1.843	1.769	1.612	1.603
With vetiver at 20 cm spacing	1.598	1.485	1.477	1.358	1.356
Allowable Bearing Capacity (kg/cm²) at 30 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
With vetiver at 10 cm spacing	1.918	1.795	1.757	1.617	1.561
With vetiver at 15 cm spacing	2.181	2.011	1.924	1.763	1.696
With vetiver at 20 cm spacing	1.679	1.593	1.558	1.458	1.409

As shown in Figure 14, incorporating vetiver after 21 days resulted in diverse changes in bearing capacity across all slopes, predominantly at low and medium angles. At a 20-degree angle, vetiver increased the bearing capacity from 1,426 kg/cm² to 1,975 kg/cm², a 38% increase at 15 cm. At 25 degrees, the bearing capacity increased from 1,317 kg/cm² to 1,843 kg/cm² (+40%); at 27.6 degrees, the increase was 32%. For the steeper slopes (30 degrees and 35 degrees), the increases were 33% and 34% respectively. The consistent order of performance was that 15 cm density was the most effective, followed by 10 cm, and last 20 cm, which produced the least vegetative reinforcement but was always better than the non-vegetated soil. All results demonstrated that vetiver with intermediate density was the most effective biological soil reinforcement. The results indicate that vetiver increased the bearing soil capacity after establishment. After 30 days, this improvement was even more significant. At 20°, the bearing capacity rose from 1,426 kg/cm² on bare soil to 2,181 kg/cm² with vetiver at 15 cm, representing an increase of 53%. At 25°, the increase was also 53%, from 1,317 kg/cm² to 2,011 kg/cm², while at 27.6° there was a 44% improvement. On steeper slopes (30° and 35°), the increases were 45% and 42%, respectively. The hierarchy of effectiveness was repeated: first the density of 15 cm, followed by 10 cm, and finally 20 cm, whose increases were in a more moderate range of up to 25%. This coincides with the density achieved in the results reported in research carried out in Bangladesh and Thailand [29, 34].



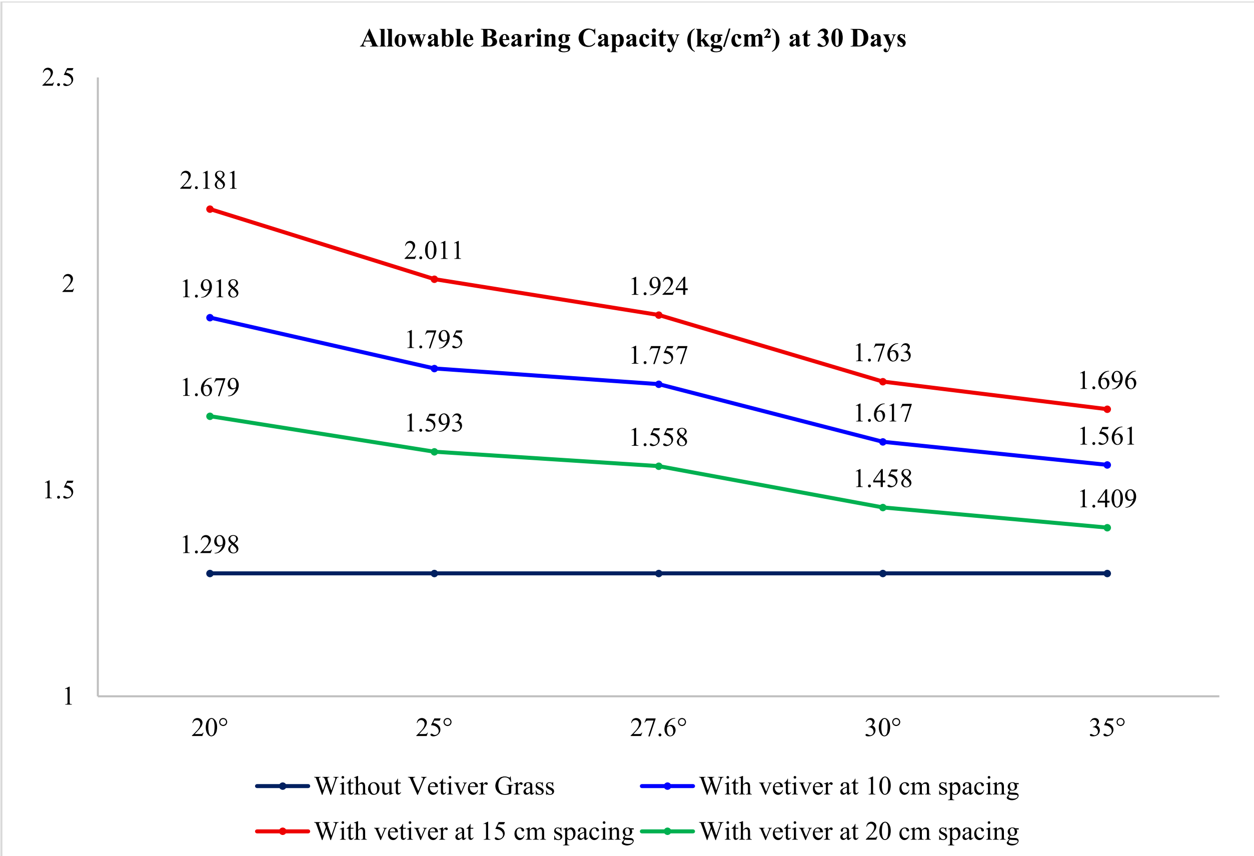


Fig. 14 Permissible capacity

4.1.4. Erosion

The erosion analysis, carried out at 21 and 30 days in soils with and without vetiver, identified the root system's capacity to reduce material loss on different slopes and seedling densities. Table 7 shows that, at 21 days, the soil without vegetation cover showed the most significant losses of material, with 8.93 kg at 20° and 11.84 kg at 35°, because the absence of roots left the particles exposed to the impact of simulated rain and the tangential force of surface runoff, which facilitated their detachment and transport. This effect intensified with the slope.

The vetiver seedlings helped reduce erosion; their root system starts to work as a mechanical one, which adds internal friction and improves particle retention. Considering the seedling root depth and thickness decreased. At a spacing of 10 cm, losses decreased to 4.21 kg at 20° and 5.85 kg at 35°, although competition between seedlings.

The 15 cm spacing achieved the best results, with 3.05 kg at 20° and 4.69 kg at 35°, as this spacing allowed for more robust and continuous root development, capable of intertwining in the soil, and 20 cm spacing was the least effective, with 4.91 kg at 20° and 6.86 kg at 35° because the excessive spacing left areas of the slope unprotected by root system. After 30 days, the 10 cm density reduced the loss to 1.05 kg at 20° and 1.71 kg at 35°, a result improved by greater root development, although still limited by overcrowding.

The 15 cm density stood out again, with only 0.74 kg at 20° and 1.34 kg at 35°, consolidating itself as the optimal density. This result was because this spacing avoided both the overcrowding observed at 10 cm, which limited root thickness and depth, and the discontinuity at 20 cm, which left areas of the slope unprotected [29, 48].

In this way, the roots achieved balanced development in diameter and depth, forming a continuous biological mesh which, as can be seen in Figure 15, ensured particle retention, improved soil structure, and guaranteed maximum hydraulic stability of the slope. Finally, at 20 cm, 1.85 kg at 20° and 2.55 kg at 35° were recorded, which, although an improvement over bare soil, confirmed that the discontinuity in the reinforcement reduced the control's efficiency.

In this context, the results showed that seedling spacing at 15 cm was the most favourable condition for mitigating erosion, as it avoided both the excessive competition observed at 10 cm and the gaps without root protection that occurred at 20 cm, establishing itself as the optimal density on all slopes evaluated.

Table 7. Erosion

Erosion (kg) at 21 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
Without Vetiver Grass	8.93	9.31	10.49	11.07	11.84
With vetiver at 10 cm spacing	4.21	4.35	4.65	5.24	5.85
With vetiver at 15 cm spacing	3.05	3.35	3.85	4.12	4.69
With vetiver at 20 cm spacing	4.91	5.24	5.75	6.15	6.86
Erosion (kg) at 30 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
With vetiver at 10 cm spacing	1.05	1.25	1.35	1.54	1.71
With vetiver at 15 cm spacing	0.74	0.88	0.95	1.12	1.34
With vetiver at 20 cm spacing	1.85	1.95	2.05	2.25	2.55

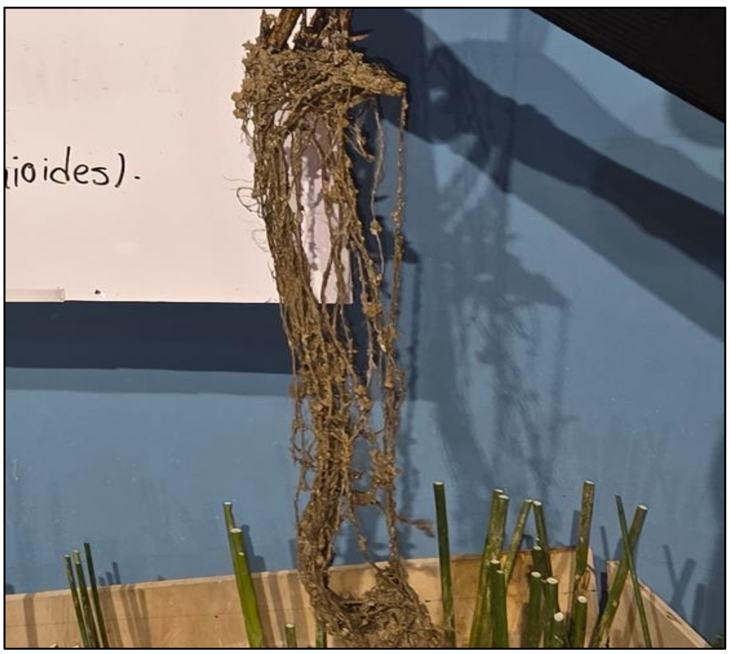
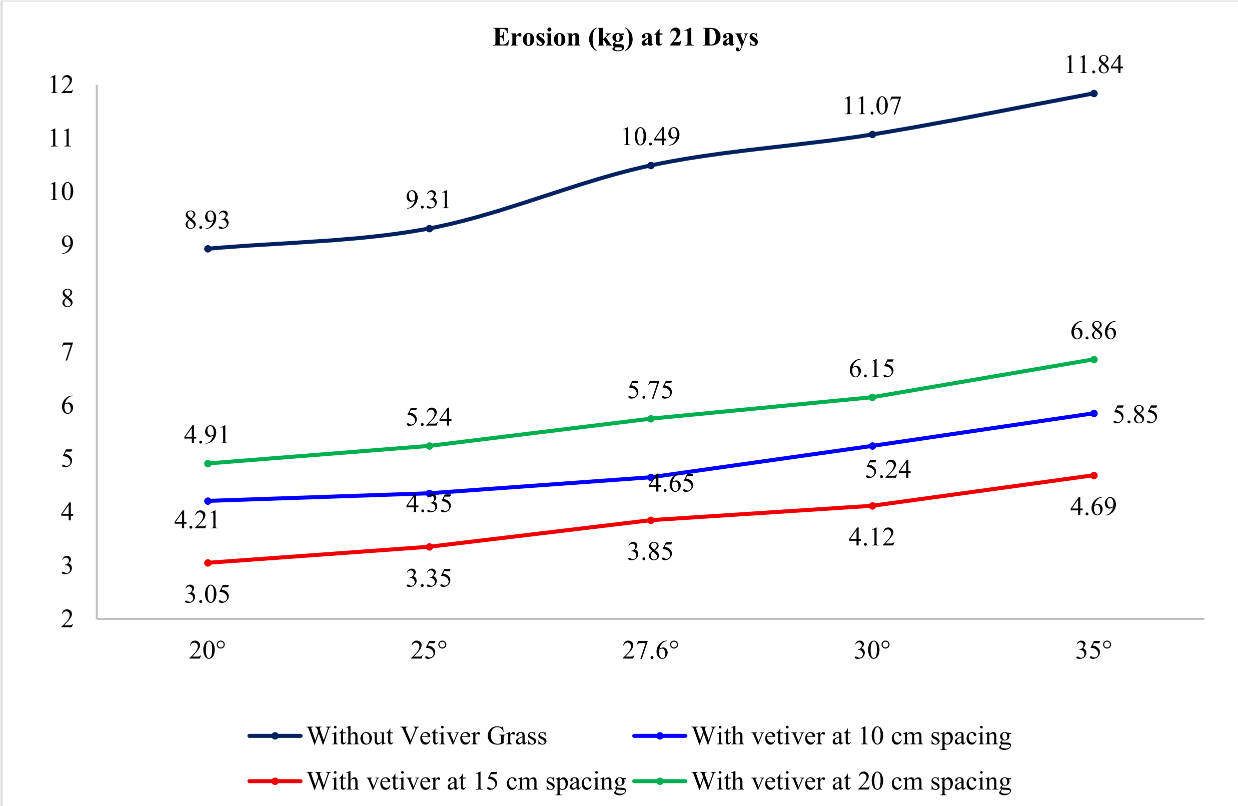


Fig. 15 Erosion test

Figure 16 showed that, after 21 days, the presence of vetiver effectively reduced erosion on all slopes evaluated. At 20 °C, soil loss decreased from 8.93 kg on bare soil to 3.05 kg with vetiver at 15 cm, corresponding to a 66% reduction. At 25 °C, the reduction was 64% (from 9.31 kg to 3.35 kg), while at 27.6 °C the loss decreased from 10.49 kg to 3.85 kg, representing a reduction of 63%. On steeper slopes (30° and 35°), the reductions were 63% and 60%, respectively. The performance pattern remained constant: the 15 cm density was the most efficient, followed by 10 cm, and finally 20 cm, which, although it reduced erosion, did so with less effectiveness. Overall, these results demonstrated that vetiver, particularly with 15 cm spacing, significantly controlled soil loss in the first 21 days. At 30 days, the effect of vetiver intensified. At 20°, erosion decreased from 8.93 kg in soil without cover to just 0.74 kg with vetiver at 15 cm, representing a 92% reduction. At 25°, the value decreased from 9.31 kg to 0.88 kg (−91%), while at 27.6° it went from 10.49 kg to 0.95 kg (−91%). On steeper slopes (30° and 35°), reductions reached 90% and 89%, respectively, consolidating the 15 cm density as the most effective, corroborating results from the literature [29, 34]. The 10 cm density also performed well, with reductions of around 85%, while the 20 cm density had a more limited effect, with reductions of between 75% and 80%.



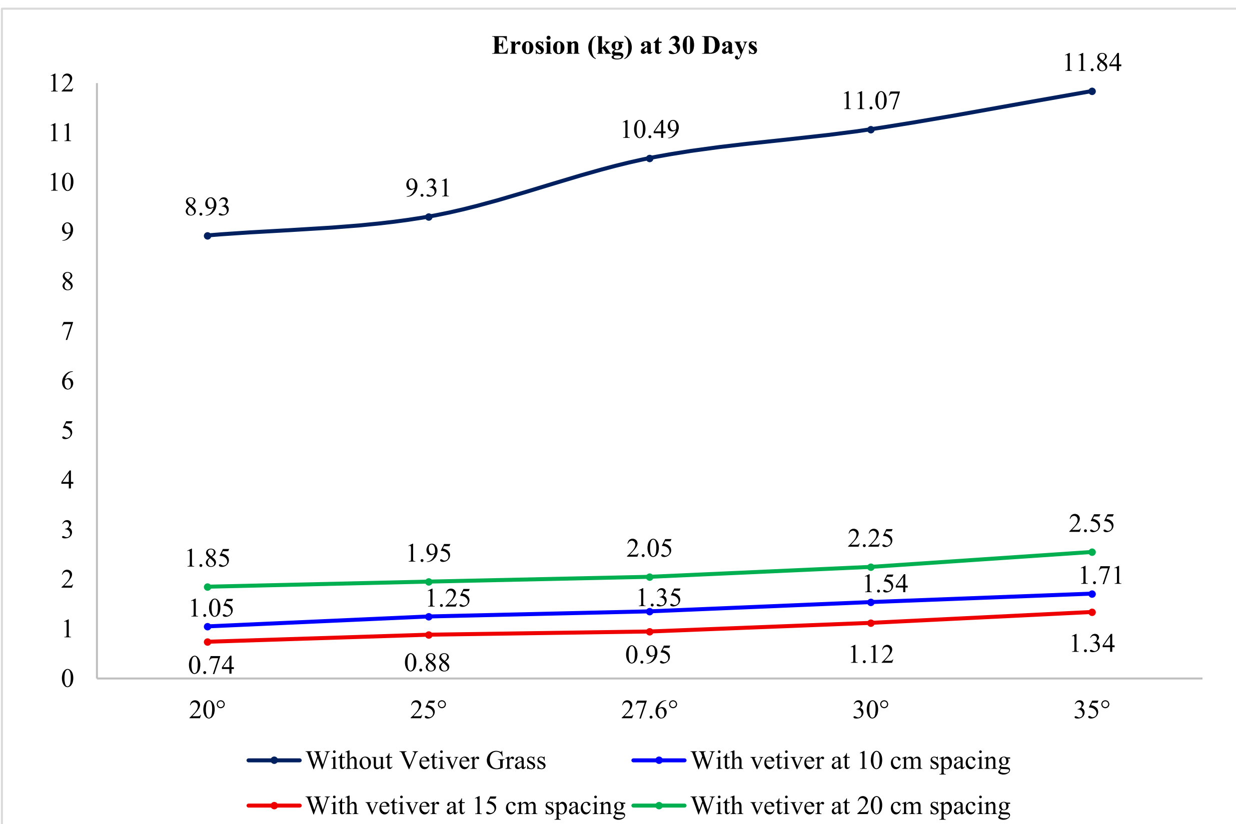


Fig. 16 Erosion

4.1.5. Runoff

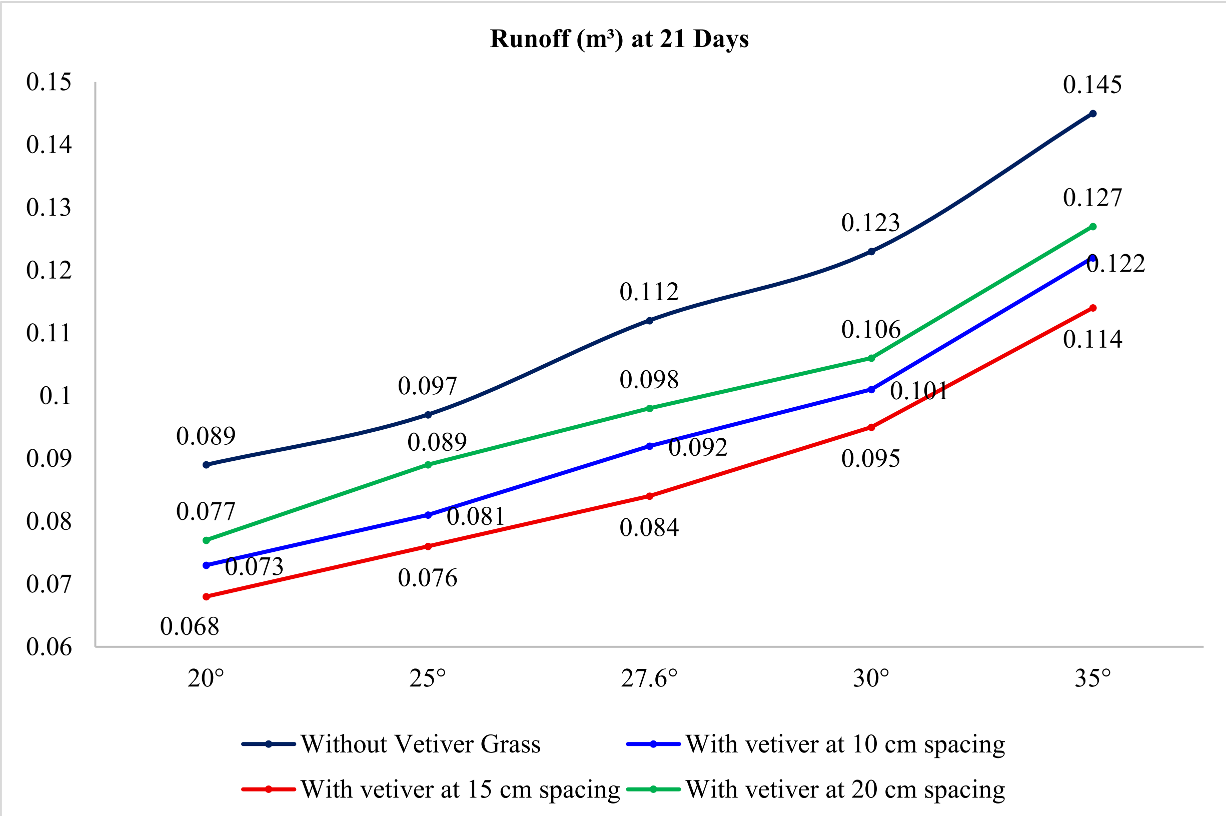
The results obtained in relation to surface runoff are presented below, which showed significant differences between soil without vegetation cover and soil reinforced with vetiver seedlings. Table 8 shows the runoff results after 21 days. Soil without vegetation cover had the highest runoff volumes, with 0.089 m³ at 20° and 0.145 m³ at 35°, due to the absence of roots to promote infiltration and the lack of surface roughness to slow down the flow. Thus, the simulated rainwater encountered no resistance and ran off quickly over the surface, intensifying the effect on the 35° slope, where the gravitational component increased the runoff velocity. The values of the bare soil treatment were significantly reduced with the addition of vetiver seedlings. This is because, with the inclusion of vetiver seedlings, soil porosity improved along with soil infiltration, and the cover of roots and leaves slowed the flow of energy. The 15 cm vetiver spacing yielded the best results with 0.068 m³ at 20° and 0.114 m³ at 35°, resulting in a 21-23% reduction compared to the bare soil treatment. The explanation for this was that with this spacing, a greater extent of uniform root development occurred, thereby increasing the soil roughness at that spacing and simultaneously allowing the roots to penetrate to greater depths. Vetiver spacings of 10 cm and 20 cm resulted in less benefit than 15 cm, resulting in 0.122 m³ and 0.127 m³, respectively. In the case of 10 cm spacing, the competition between seedlings restricted the development of the deep roots, thus reducing the effectiveness of root absorption and infiltration. In the case of 20 cm spacing, the gap was so large that some areas were left exposed, allowing surface flow to freely move through the zone where no soil roughness was experienced.

After 30 days, the vetiver-reinforced soil had the most pronounced reduction of this parameter. The 15 cm vetiver spacing also yielded the most beneficial results with 0.058 m³ at 20° and 0.092 m³ at 35°, resulting in 28-37% less compared to the bare soil. This outcome can be attributed to their more well-developed and deeper roots, which can form macropores. Macropores increase infiltration and also act as a physical barrier to runoff. The 10 cm density showed an intermediate effect with 0.067 m³ at 20° and 0.103 m³ at 35°. The result was due to substantial reinforcement but was constrained by root competition. Lastly, the 20 cm arrangement reached 0.071 m³ at 20° and 0.116 m³ at 35° as they had less root cover and allowed more of the flow to run off.

Table 8. Runoff

Runoff (m³) at 21 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
Without Vetiver Grass	0.089	0.097	0.112	0.123	0.145
With vetiver at 10 cm spacing	0.073	0.081	0.094	0.101	0.122
With vetiver at 15 cm spacing	0.068	0.076	0.084	0.095	0.114
With vetiver at 20 cm spacing	0.077	0.089	0.098	0.106	0.127
Runoff (m³) at 30 Days					
Description	**Soil in mould at 20º**	**Soil in mould at 25º**	**Soil in mould at 27.6º**	**Soil in mould at 30º**	**Soil in mould at 35º**
Without Vetiver Grass	0.067	0.072	0.084	0.091	0.103
With vetiver at 10 cm spacing	0.058	0.063	0.072	0.080	0.092
With vetiver at 15 cm spacing	0.071	0.079	0.090	0.099	0.116

Figure 17 indicates that the incorporation of vetiver consistently reduced surface runoff across all tested configurations when compared with bare soil conditions. On the 20° slope, the volume went from 0.089 m³ without cover to 0.068 m³ with vetiver at 15 cm. At 27.6°, the decrease was 25% (from 0.112 m³ to 0.084 m³), while at 35° it reached 21% (from 0.145 m³ to 0.114 m³). The order of performance was consistent: first the 15 cm density, followed by 10 cm, and finally 20 cm, which, although it reduced runoff, did so with less efficiency. At 30 days, the effectiveness of vetiver in mitigating runoff increased significantly. The 15 cm density generated the most significant benefits, with reductions of more than 30% compared to bare soil, followed by the 10 cm density, with decreases of up to 28%. In contrast, the 20 cm density showed a more limited effect, with reductions of up to 20%. Overall, the results confirmed that the establishment of vetiver favoured water infiltration into the soil profile, progressively reducing surface runoff, and that the 15 cm density was the most efficient configuration, coinciding with the findings of research carried out in Bangladesh and Thailand [29, 34].



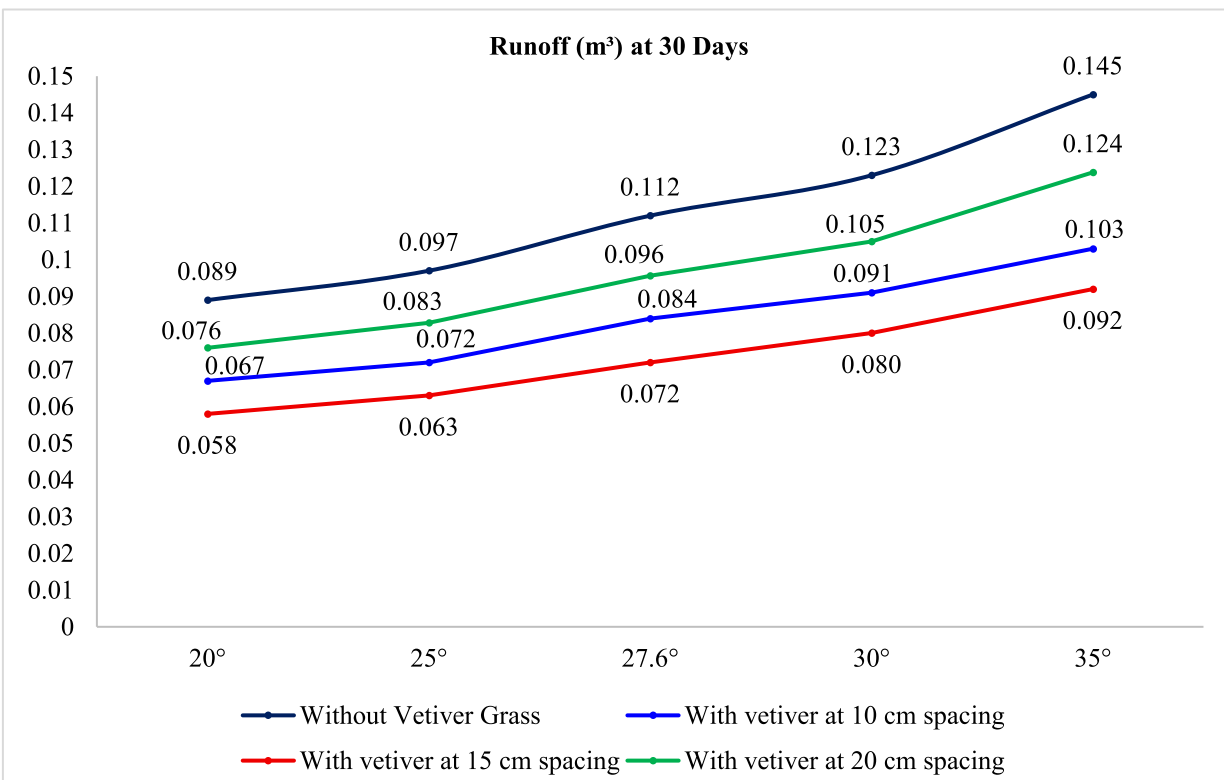


Fig. 17 Runoff

4.2. Optimal Vetiver Configuration

From the results, it was determined that a vetiver seedling spacing of 15 cm was the best configuration at all positions of the slope, as it achieved even coverage and a deep root system, compared to the overpopulation at 10 cm and the unfilled gaps at 20 cm. This spacing increased soil cohesion by 60%, the friction angle by 12%, and the ultimate bearing capacity by more than 50%, all contributing to effective biological soil reinforcement. In terms of slope angle, it was found that the steeper the slope, the greater the decrease in cohesion, friction angle, and bearing capacity, with increased erosion and runoff, which decreased soil stability. In contrast, on moderate slopes (20° and 25°), vetiver enhanced mechanical resistance and hydraulic protection more intensely, confirming that the combination of controlled slopes with an optimal density of 15 cm represented the most efficient, sustainable, and replicable alternative for slope stabilisation in tropical regions.

4.2.1. Feasibility Analysis for the Implementation of Vetiver Plantations

This section presents a comparative assessment of three slope cutting alternatives, highlighting their most relevant differences in terms of excavation volume, total intervened area, and the projected investment for revegetation with vetiver seedlings.

4.2.2. Cutting to a 20° Slope Across the Entire Embankment

In this case, the entire natural ground was intervened from the road up to the highest point, as shown in Figure 18, optimising the inclination angle from 27.6° down to 20° through a complete slope cut. The intervention involved a regrading of the original slope geometry to reduce the driving forces governing global instability, resulting in an affected surface area of 220,203 m² and an earthwork volume exceeding 20,336,111.47 m³. This scale indicates a macro-stabilisation strategy where the primary stabilising mechanism is geographical modification. In addition, vetiver is introduced as a surface reference system, planted at intervals of 15 × 15 cm, corresponding to an observation density of approximately 9.8 million plants. This arrangement improves the rapid intertwining of the root networks. It provides almost continuous interaction between the soil and the roots, thus increasing resistance to surface slides and limiting progressive erosion, which would otherwise threaten the long-term stability of the slope.

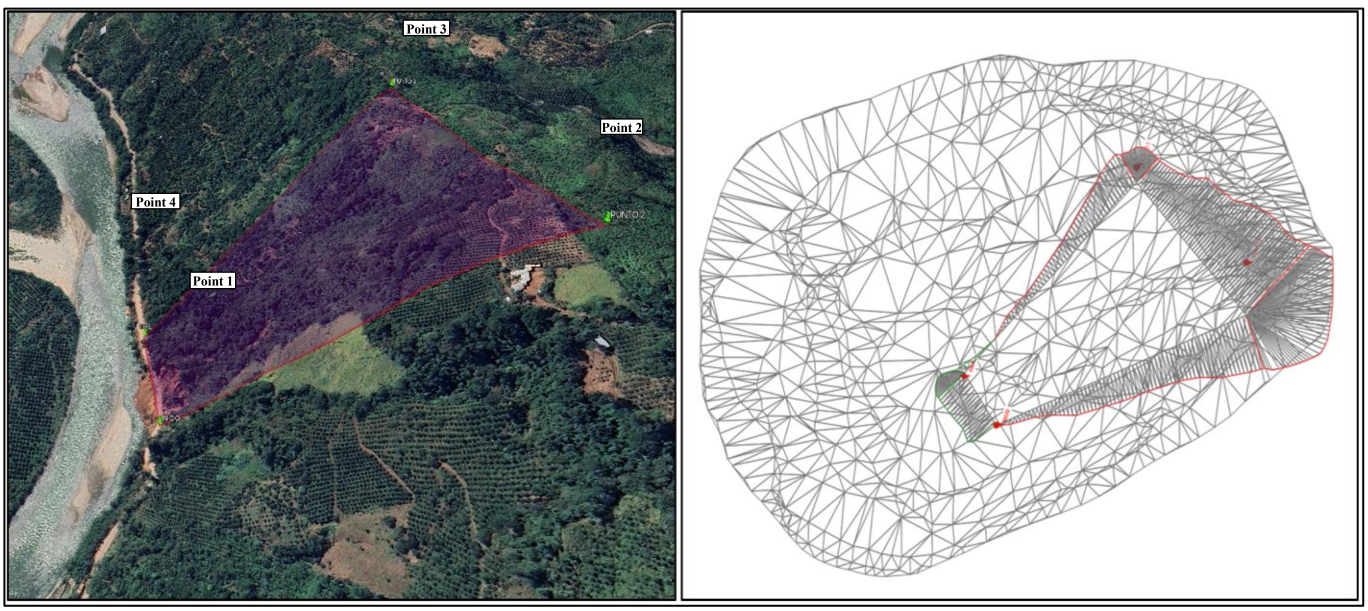


Fig. 18 Cut at 20° across the entire slope

4.2.3. Cutting to a 20° Slope on the Critical Section of the Slope

Figure 19 summarises the multi-temporal analysis of satellite images obtained between 2012 and 2024 and shows the spatial and temporal progression of slope instability along the evaluated corridor. Although vegetation cover was relatively continuous during the initial period from 2012 to 2014, after 2018, discernible erosive features began to appear, which evolved into well-defined areas of degradation between 2020 and 2023. In 2024, instability was mainly concentrated in the middle and lower portions of the slope, just above the road adjacent to the river, indicating a failure domain preferentially controlled by slope, greater vegetation loss, and concentrated surface drainage channels. This pattern indicates a shift from diffuse surface degradation to localised instability, governed by hydrological convergence and the geometric stimulus of driving stress. In contrast, the upper zones preserved greater vegetation cover and relative stability. Overall, the historical sequence revealed cumulative deterioration concentrated in the lower sectors, reinforcing the need for targeted interventions to ensure road infrastructure protection and mitigate future risks.

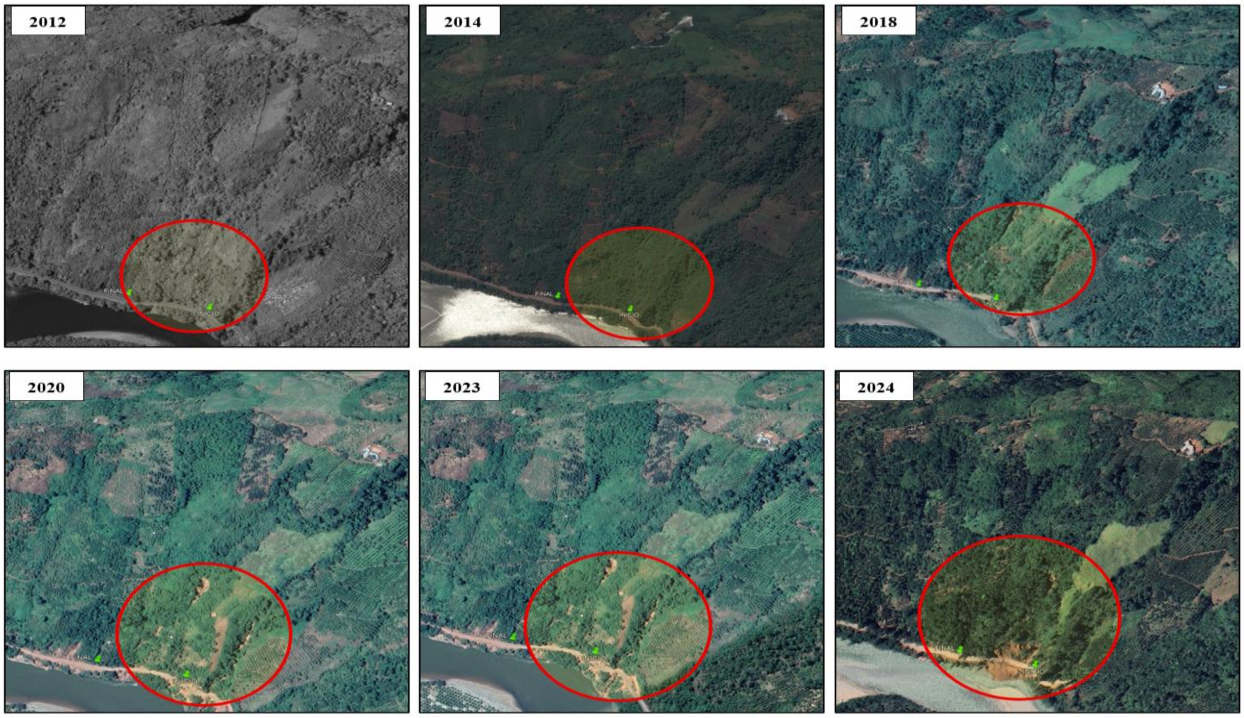


Fig. 19 Sequence of images from 2012 - 2024

In this case, a selective slope cut was executed, reducing the natural gradient from 27.6° to 20°, but limited exclusively to the critical sector identified in the mid-lower part of the hillside, as shown in Figure 20. This focused intervention aimed to reduce instability processes without excessively altering the entire mass, prioritising the area with the greatest landslide recurrence and material loss. The delimited area covered 26,625 m², with an estimated earth movement of 1,247,622.18 m³—a considerable volume but significantly smaller compared with a full slope cut. For its revegetation, vetiver grass was projected to be planted at a spacing of 15 cm between seedlings, representing the incorporation of approximately 1.18 million individuals. This design ensured continuous and adequate coverage of the most vulnerable strip, reinforcing the soil against erosion, reducing runoff, and providing a sustainable bioengineering solution adapted to the slope's conditions.

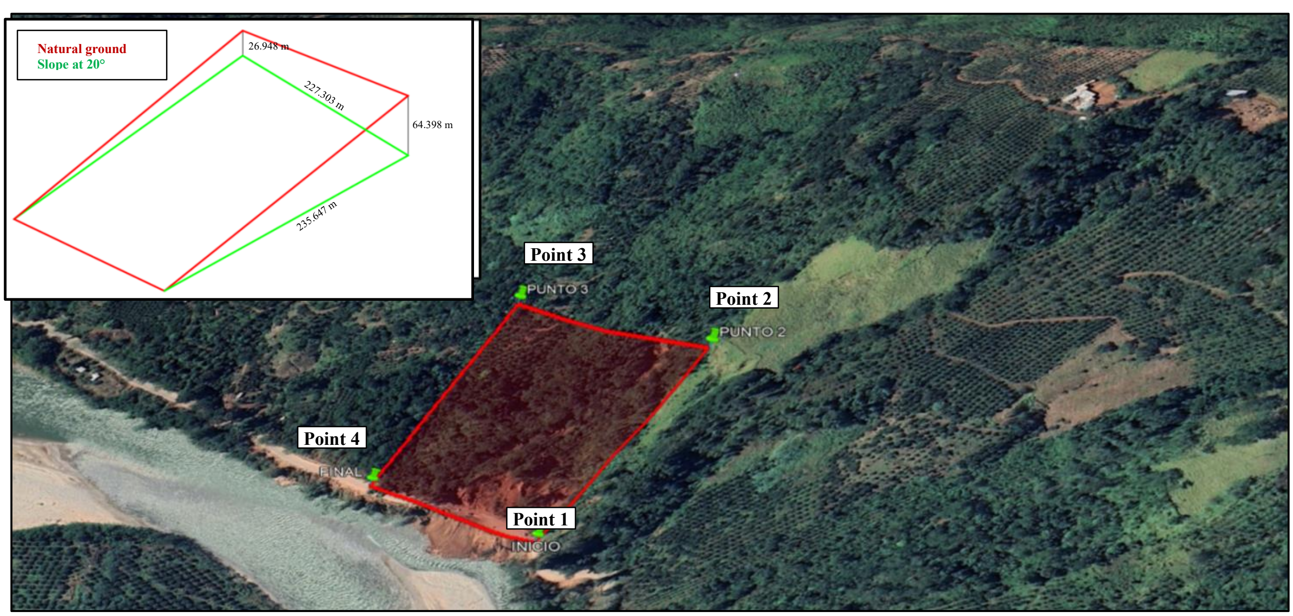


Fig. 20 Terrain cut to the critical point

4.2.4. Cutting 3 Metres below the Natural Ground

In the stratigraphic profile shown in Figure 21, at 3.0 m beneath the natural ground surface, a Silty Sand Stratum (SM) with greater mechanical competence than the upper horizons was identified. This granular, non-plastic material, with low natural moisture content (5.27%) and loose to medium consistency, presents good permeability and limited cohesion. These conditions make it vulnerable to surface erosion when unconsolidated, but it is suitable as a support material once compacted. The SC-SM soil can withstand a load of up to 1,335 kg/cm², unlike the SM soil, which can withstand 1,573 kg/cm², confirming its superior load-bearing capacity and endorsing its choice as a structural horizon that determines slope stabilisation measures. Studies show that controlled exposure of this layer, using a 3.0 m Sekal 3 cut, and subsequent vetiver sampling at 15 cm, results in a notable increase in load-bearing capacity. An increase of approximately 32% at 21 days and 53% at 30 days is estimated, which positions them close to 2.4 kg/cm². This response can be attributed to the synergy of improved soil-root interaction and the mobility of surface shear strength, reinforcing the mechanical function of the SM layer and long-term stability in a bioengineered slope system.

Depth (m)	SUCS Classification	Graphic	Description and classification of the material: Colour, Natural Moisture, Plasticity, Natural State of Compaction, Particle Shape, Maximum Particle Size, Presence of Organic Matter.
0.30	Pt		Organic soil.
0.50 1.00 1.50 2.00 2.50 2.80	SC-SM		Silty clayey sand, with moderate natural moisture (11.83%), low plasticity (LL = 25.98%, PL = 19.74%, PI = 6.24%), moist state, yellowish-brown colour and medium consistency, classified as SC-SM (predominantly sand with a significant fraction of fines: silts and clays).
3.00 3.50	SM		Silty sand (SM), non-plastic (LL, PL and PI = N.P.), with low natural moisture content (5.27%). Granular material of loose to medium consistency, good permeability and low cohesion, susceptible to surface erosion but suitable as support soil when compacted.
4.00	SP		Poorly graded sand (SP), non-plastic (LL, PL and PI = N.P.), with low natural moisture content (4.81%). Granular material of loose to medium consistency, very good permeability and no cohesion, susceptible to surface erosion but suitable as support soil and structural fill material when compacted.

Fig. 21 Stratigraphic profile of the soil

To implement the disease, the original slope inclination of 27.6° was maintained, and a parallel cut 3.0 m deep was made to selectively remove the less competitive SC-SM surface material and expose the intermediate layer with higher mechanical properties, as shown in Figure 22. The intervention affected an area of 30,046 m² and a total excavation volume of 46,976 m³, which led to significant disintegration in the excavation compared to other more aggressive reconditioning alternatives. As a complementary bioengineering measure, revegetation was carried out with vetiver seedlings spaced 15 × 15 cm apart, corresponding to an estimated density of 1.34 million plants. This arrangement improved soil-root interaction within the exposed stratum, providing near-surface design resistance and limiting progressive erosion, contributing to the overall stability of the slope with a solution that is mechanically efficient and environmentally friendly.

Fig. 22 Cut 3 metres below the natural ground

4.3. Optimum Configuration of Vetiver

Tests evaluating the cutting volume in different options show that Option 3 was the best choice, cutting the volume down to 46.976 m³. Option 1 was more than 20 million m³, and Option 2 had volumes in the middle. Moving less earth was good for the environment and altered the natural land form. It also meant lower costs for excavation and transportation of construction materials. Thus, Option 3 is the best choice from the geotechnical, construction, and economic point of view.

5. Discussion

Research conducted by D'Souza et al. (2019) has documented that the root systems of vetiver grass increased the shear strength of soil by 139% at 0.15 m and 47% at 0.75 m depth. This demonstrates the notable reinforcing effect of vetiver grass near the soil surface due to its ability to penetrate soil with delicate root structures and a tensile root strength of 85 MPa, similar to that of construction materials [50]. This study mirrored this trend: vetiver grass planted at 15 cm resulted in a 60% increase in soil cohesion and an increase of the friction angle by 12 degrees, which resulted in a 53% increase in the allowable bearing capacity of the soil at a 20-degree slope. Also, erosion decreased by 92% after 30 days, and surface runoff was reduced by 30%+. These values confirm that the D'Souza study remains true in vetiver being more effective in the early phases of root consolidation and in the upper soil layers. The primary differentiating factors of the studies were the amount of time the grass was allowed to establish. D'Souza studied vetiver roots that were developed over 12 months and penetrated soil to a depth of 1.20 m, while this study evaluated root systems in the early phases of development after only 21 and 30 days. Most of the time, the vetiver is growing, and the vetiver grass focuses almost all its energy on forming roots. This is important because the vetiver becomes capable of accelerated growth and deep anchorage in later phases.

As researched by Eab, Likitlersuang, and Takahashi, vetiver roots achieved an astounding 180 cm in length in only 6 months, with a RAR of 4.56%. In soils with and without vetiver roots, direct shear tests recorded an increase in cohesion from 6.8 kPa to 13.6 kPa, and an increase in the friction angle from 22.8° to close to 29° (o). Also, in centrifuge model tests, the vetiver roots reduced displacements to 8 mm with vetiver from 16 mm in unreinforced soils, and to 3 mm with vetiver from 15 mm under intense rainfall, thus preventing slope collapse. This research confirmed the increase in shear strength, with cohesion increasing by 60% and the friction angle increasing by 12%, resulting in an increase of 53% in allowable bearing capacity.

In addition, erosion reductions of up to 92% and runoff decreases exceeding 30% were observed in slopes treated with vetiver. The difference is mainly explained by the type of soil used: while Eab et al. worked with Edosaki sand, a fine homogeneous sand tested under controlled laboratory conditions that favoured rapid root development and stable testing environments, this study used SC-SM soil (silty sand with clay, low plasticity), with lower initial cohesion and greater heterogeneity, limiting soil-root interaction and reducing the magnitude of reinforcement achieved.

According to research by Mustafa, Noh, and Zulkafli (2025), the application of vetiver on slopes of 45°, 50°, and 60° showed that after 30 days, root reinforcement increased soil cohesion up to 18.4 kN/m² in 60° slopes and raised the friction angle to 75.3° in 45° slopes. Similarly, maximum shear stress reached 32.9 kN/m² in 45° slopes, while in 60° slopes it decreased to 27.2 kN/m². Root tensile strength tests revealed that although individual root resistance was higher in 60° slopes (0.025 kN), the most stable structural performance occurred in 45° slopes [20]. In the present research, the results followed this trend: planting at 15 cm spacing increased cohesion by up to 60% and the friction angle by 12%, improving allowable bearing capacity by 53% in 20° slopes. Moreover, erosion was reduced by up to 92% and runoff by more than 30% after 30 days. The difference in magnitude compared with the Malaysian study is mainly explained by soil conditions and slope geometry: Mustafa et al. worked on tropical residual soils highly prone to erosion and on extreme slopes of up to 60°, whereas in this study, SC-SM soils and milder slopes were used.

According to research by Sinarta et al. (2024), in volcanic soils of Bali, the incorporation of vetiver reduced erosion by up to 91.8% on 45° slopes and 90.6% on 60° slopes, in addition to decreasing surface runoff by 41.4% and 38.5%, respectively. Furthermore, when vetiver was combined with elephant grass, reductions were even greater: 94.6% erosion reduction and 55.5% runoff reduction for 45° slopes, and 92.7% and 53.9% for 60° slopes. These results highlight the effectiveness of mixed bioengineering strategies in conditions of intense rainfall and highly erodible volcanic soils [24]. In the present research, the values obtained showed a similar trend, with erosion reductions of up to 92% and runoff decreases between 28% and 37% after 30 days of planting. However, this was complemented by the evaluation of shear strength: cohesion increased by up to 60% and the friction angle by 12%, which enabled a 53% increase in allowable bearing capacity of slopes at 20°. The difference with the Balinese study lies in the type of soil and vegetation strategy: while Sinarta et al. worked on volcanic soils (silty sand with breccias), highly erodible and explored species combinations to reinforce different profile layers simultaneously, this study used SC-SM soil (silty sand with clay, low plasticity) and vetiver only.

6. Conclusion

In conclusion, the research confirmed that the use of vetiver grass as a bioengineering technique is an effective solution for slope stabilisation under variable gradients, exposed to intense rainfall and conditions of high geotechnical vulnerability. It is known that the application not only improved the mechanical strength parameters of the soil but also reduced erosion and runoff. It consolidates as a sustainable, replicable, and low-cost strategy, compared to conventional methods of soil stabilization.

Secondly, the direct shear tests confirmed that a planting density of 15 cm between seedlings was the most efficient, increasing cohesion, friction angle, and allowable bearing capacity by 60%, 12% and 53% respectively, compared to bare soil. This performance was explained by the fact that such spacing allowed for balanced root systems to grow, which could extend and interlace at depth, forming a mesh that reinforced contact between soil particles. The most unfavourable configuration was 20 cm, with an efficiency barely exceeding 25%, as the excessive spacing resulted in areas of soil unreinforced by roots, interrupting structural continuity. Planting at 10 cm, although achieving a 40% improvement, had limitations due to competition between seedlings, which restricted deep root development and decreased the ability to transmit stresses. It is believed that the application of this 15 cm configuration in the San Pedro sector will result in soil with a higher resistance to external loading, thus strengthening the bearing capacity of the slopes and decreasing the risk of differential settlements that could compromise the stability of the road.

In erosion examinations with simulated rainfall, planting at 15 cm achieved the most excellent efficiency with as much as 92% reduction in soil loss relative to slopes with no vegetation cover. This configuration's success stemmed from intermediate density, facilitating the promotion of a dense and deep enough root system to retain particles, dissipate the energy of raindrop impacts, and lessen wash-off. On the other hand, the 20 cm spacing attained 75% efficiency because micro-channels of erosion were formed due to gaps between seedlings. The 10 cm pattern was more effective with 85%; however, in the case of overpopulation, the roots formed to be weaker, and thus, the lack of adequate resistance to the steeper slope's hydraulic action was determined. The configuration can be applied in the study area to considerably lower the material loss on road adjacent slopes, effectively curtailing the sediment detachment on the carriageway, and decreasing the lane blockage, which occurs at a higher frequency during the rainy season. Fourthly, surface runoff tests showed that the 15 cm density was the most efficient, with up to 37% reduction, as its uniform root system increased infiltration and the foliar cover generated surface roughness that slowed down flow. The 20 cm density reached only 20% efficiency, as uncovered areas allowed part of the water to circulate freely, maintaining high runoff volumes. Meanwhile, the 10 cm arrangement achieved up to 28% reduction, although competition between roots limited the capacity to absorb water in depth, showing a lesser effect than the optimum configuration. In the case of the San Pedro sector, this 15 cm distribution favours the infiltration of intense rainfall into the soil profile, reducing the volume of water that runs directly over the slope surface and, consequently, decreasing the contribution of sudden flows into the River Perené, a key factor in reducing soil saturation and the risk of landslides.

My last observation proved that vetiver does increase the benefits of slope stabilization at a planting density of 15 cm between seedlings, with root development being balanced in thickness and depth, and providing uniform coverage and reinforcement. As this explains the San Pedro section of Central Highway's particular conditions, revegetation with vetiver at 15 cm spacing is recommended as the preliminary or first step. In addition, with regard to earthworks, the option of cutting 3 m below the natural ground has proven to be the most cost-effective. This approach only requires 46,976 m^3 (less than the millions of other options). As such, it is the best solution in terms of cost, environmental impact, and topographical impact. Therefore, it is best to combine using vetiver at the optimal density with the selective cutting approach. This will improve the overall slope stability, the frequency of road closures, and provide a balanced technical and environmental solution for the study area.

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