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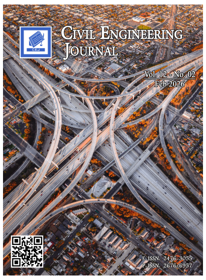

Contribution of *Acacia mangium* Root Systems to Slope Stability Improvement

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Abstract

This study explores the bioengineering potential of *Acacia mangium* root systems in enhancing the shear strength of lateritic soil under both saturated and unsaturated conditions. Seedlings were cultivated in cylindrical containers for 12 months to monitor root growth and investigate its relationship with key geotechnical parameters. Root development was classified into three distinct phases: root acceleration (months 1–3), stem acceleration (months 4–8), and growth phase (months 9–12). A significant dry root biomass increase was observed, exhibiting a strong linear correlation with peak shear strength. Laboratory shear tests indicated that unreinforced soil in saturated conditions had a cohesion of 1.90 kPa and an internal friction angle of 27.64°. In contrast, cohesion increased to 3.55 kPa in unsaturated conditions and the internal friction angle to 38.94°. In comparison, root-reinforced soils demonstrated substantially improved shear strength. Under unsaturated conditions, cohesion and internal friction angle reached 9.92 kPa and 41.58°, respectively, while in saturated conditions, values increased to 6.12 kPa and 31.29°. Slope stability analysis using Slope/W software revealed that the unreinforced slope had a Factor of Safety (FS) of 1.043, indicating marginal stability. However, with *A. mangium* root reinforcement, the FS increased to 1.518, exceeding the commonly accepted safety threshold of 1.5. These results highlight the effectiveness of *A. mangium* root systems in improving slope stability through mechanical reinforcement, increased soil cohesion, and redistribution of shear stresses within the soil matrix.

Keywords: Root Reinforcement; Saturated and Unsaturated Conditions; *Acacia mangium* Root Systems; Bioengineering.

1. Introduction

Understanding how soil shear strength parameters vary under different stress and moisture conditions forms the foundation of modern geotechnical engineering. According to the Mohr–Coulomb failure criterion, the shear strength of soil depends primarily on cohesion and the internal friction angle, both of which are sensitive to changes in saturation and pore-water pressure [1–3]. When pore pressure increases under saturated conditions, effective stress decreases, leading to potential slope instability—a concept first formalized by Terzaghi [2]. Conversely, in unsaturated conditions, matric suction acts as an additional stress component that enhances apparent cohesion and contributes to overall slope stability [3, 4]. Recent advances have also demonstrated the potential of data-driven approaches such as AI-based models in flood susceptibility and early hazard prediction [5, 6], emphasizing the importance of linking hydraulic behavior to soil strength for reliable slope assessment.

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The current analysis further explores soil behavior under both fully saturated conditions (100% saturation with a moisture ratio of 54.1%) and partially unsaturated conditions where saturation decreases between 12% and 20%. These ranges represent realistic moisture variations in tropical lateritic soils and are critical for understanding how water content fluctuations influence shear performance and effective stress mechanisms.

Vegetation plays a crucial role in improving soil stability by increasing shear strength, intercepting rainfall, and reducing surface erosion. The roots of plants act as natural reinforcing elements, transferring stress between soil particles and enhancing inter-particle bonding [7–9]. Among various species studied for bioengineering applications, *Acacia mangium* has shown distinctive potential due to its robust and fibrous root architecture [10, 11]. This species develops both deep taproots and dense lateral roots that not only enhance mechanical stability but also facilitate long-term ecological restoration. Lateritic soils—characterized by high iron and aluminum oxide content, low plasticity, and pronounced desiccation cracking—are abundant in tropical regions such as Southeast Asia. However, they often exhibit low natural cohesion and reduced stability under fluctuating moisture conditions, making them ideal candidates for reinforcement through root-based bioengineering (Figure 1).

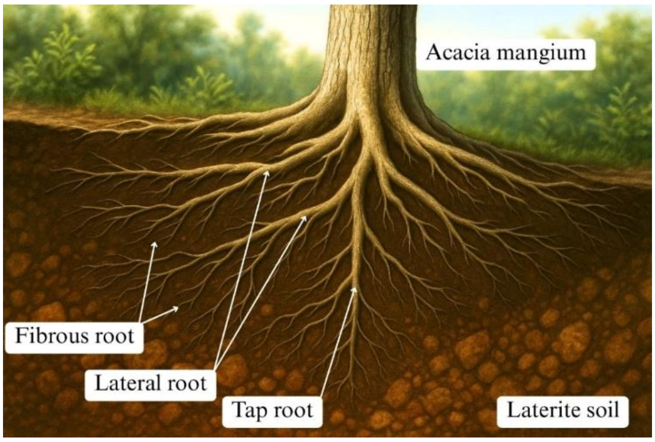

Figure 1. Plant root systems contribute to soil anchorage and reinforcement

Despite the progress in vegetation-based soil stabilization, few investigations have quantitatively examined the reinforcement behavior of *A. mangium* roots under both saturated and unsaturated conditions, especially regarding their direct contribution to shear parameters and slope-stability factors. In unsaturated conditions, the interaction between matric suction and root reinforcement mechanisms becomes critical, affecting both apparent cohesion and the overall factor of safety. Yet, integrated studies that couple these hydromechanical effects with biological reinforcement processes remain limited. This gap is particularly important for lateritic soils, where small variations in suction can lead to substantial changes in shear strength and slope response. From a geotechnical perspective, understanding this mechanism requires coupling suction-dependent strength models, such as soil-water characteristic curves (SWCC) [12, 13], including the importance of the groundwater table [14-16], with the hydraulic and mechanical behavior of root-soil composites, while considering soil type sensitivity in a coherent permeability-stability analysis [17]. This comprehensive approach not only enhances the prediction of soil behavior under varying moisture conditions but also facilitates the development of more effective vegetation management strategies. By integrating these factors, researchers can better assess the stability of slopes and prevent potential landslides in vulnerable areas.

From a sustainability perspective, *A. mangium* plantations provide dual advantages over conventional bioengineering species. Economically, the tree grows rapidly, yields valuable timber and biomass, and requires minimal maintenance. Environmentally, it enhances soil infiltration, promotes biodiversity, and plays a measurable role in carbon sequestration. Long-term studies have shown that forest ecosystems containing *A. mangium* exhibit quantifiable carbon-capture dynamics that can support carbon-credit accounting and offset initiatives [18]. These attributes align with the engineering demand for cost-effective, sustainable slope-stabilization strategies and correspond with several United Nations Sustainable Development Goals (SDGs) notably SDG 11 (Sustainable Cities and Communities), SDG 13 (Climate Action), and SDG 15 (Life on Land).

This research presents empirical evidence supporting the application of *Acacia mangium* in geotechnical engineering to mitigate slope failures in topographically complex and erosion-prone regions of Thailand. The findings also align with global sustainability frameworks [19–22]. When considered alongside previous investigations into flow-velocity and slope-angle effects [23, 24], together with insights from SWCC modeling [12, 13] and soil-type sensitivity analyses [17], this study underscores the significance of integrating bioengineering principles with conventional geotechnical approaches—strengthening the linkage between environmental resilience, engineering safety, and national carbon-offset strategies.

The remainder of this paper is organized as follows: Section 2 describes the research methodology and experimental setup; Section 3 presents and discusses the results; and Section 4 concludes with key implications for sustainable slope stabilization using *Acacia mangium* as a bioengineering species.

2. Description of Studied Site

The soil utilized in this investigation was lateritic soil procured from Bo Phloi District, Kanchanaburi Province, an area in western Thailand that is widely recognized as one of the principal sources of lateritic soil for geotechnical studies due to its representative physical and engineering characteristics. The general topography of the Bo Phloi area features gently undulating terrain with an average slope inclination of approximately 25 degrees, which typifies the natural landscape of the region and provides a practical reference for the slope stability analysis in this study. Considering that the lateritic soil was obtained from deeper layers, its properties did not entirely correspond to those of natural surface soils commonly encountered in field conditions. To achieve a more realistic simulation of natural soil conditions, the soil mixture was fortified with nutrient-rich topsoil. Laboratory examinations of the topsoil indicated a phosphorus (P) concentration of 86.5 mg/kg and a potassium (K) concentration of 151 mg/kg, thereby enhancing the nutrient balance of the planting medium and increasing its resemblance to natural surface soils (see Figure 2).

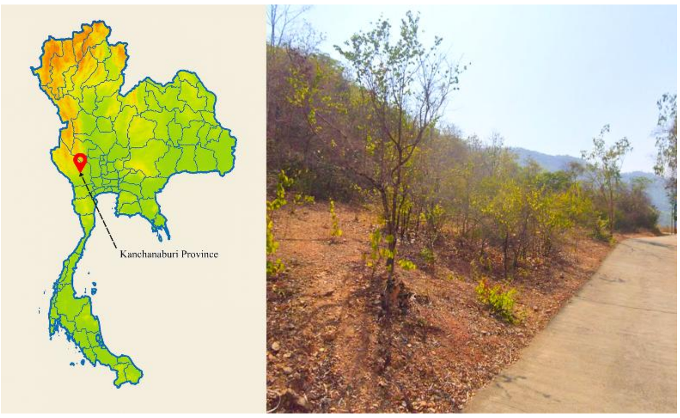

Figure 2. Location and general topography of the study area in Thailand

The thorough planting recipe outlined 80% sieved lateritic soil (with a 3/4-inch sieve) and 20% topsoil. The unified earth revealed a specific gravity (Gs) of 2.72, a natural moisture percentage of 12.05%, alongside a dry unit weight documented at 1.11 g/cm³. In accordance with the Unified Soil Classification System (USCS), the soil was classified as well-graded gravel (GW), demonstrating granular properties as detailed in Table 1. Once the moisture levels exceeded 54.1%, the soil reached a state of saturation, allowing for the swift release of pore water pressure and momentarily boosting soil strength. Once the soil is completely soaked, its adhesive quality frequently reduces because of lowered levels of moisture suction. In conditions of reduced moisture, the soil density sees a rise, contributing to a more robust shear capacity. For assessments performed in unsaturated conditions, the soil sample's natural moisture varied between 12% and 20%, while the saturated testing required samples that had moisture levels over 54.1%.

Table 1. Soil properties

Soil Properties	Results
Natural Moisture Content.	12.00-20.00 %
Specific Gravity, Gs	٢,٧٢
Dry Unit Weight of Soil	1.11 (g/cm3)
Soil Classification	Well-Graded Gravel (GW)
Degree of Saturation (S) ١٠٠%	٪٥٤,١٠
Cohesion	) ٣,٥٥kPa(
Internal friction Angle	36.77
pH	٦,٧
Organic content	٪١,١٩
Phosphorus) P)	٨٦,٥mg/kg
Potassium (K)	١٥١mg/kg
Magnesium (Mg)	٢١٢mg/kg

3. Methodology

This study was designed to evaluate the role of *Acacia mangium* root systems in enhancing slope stability. The experimental methodology focused on analyzing the mechanical behavior of root-reinforced lateritic soils under both saturated and unsaturated conditions. The research procedure comprised several main stages, including soil collection and preparation, seedling cultivation, direct shear testing, dry root biomass measurement, and slope stability modeling. The overall workflow of the study is illustrated in Figure 3, which summarizes the sequential processes carried out throughout the investigation.

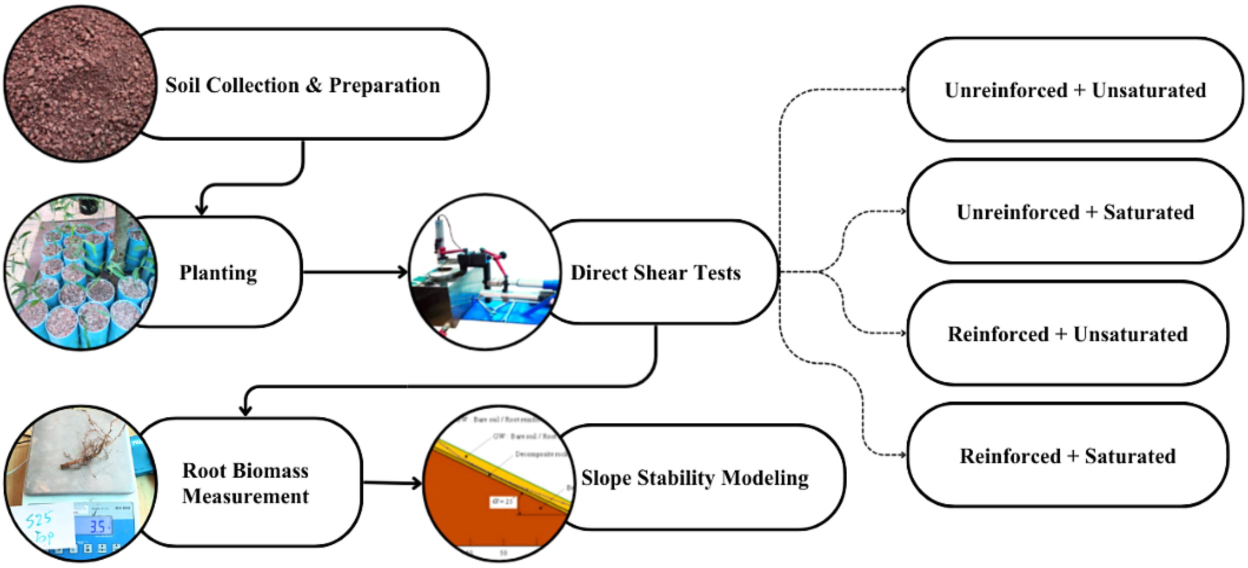

Figure 3. Overall experimental workflow of the study

3.1. Sample Preparation

Before initiating the planting of *Acacia mangium* seedlings, the experimental layout was carefully designed using polyvinyl chloride (PVC) pipes, each measuring 15 cm in diameter and 20 cm in length. Four segments of these pipes were vertically aligned and securely interconnected to form cylindrical soil columns. Subsequently, the prepared lateritic soil mixture was placed into each column without any compaction to maintain natural soil structure. The seedlings of *A. mangium* were then carefully positioned at the center of each column. To ensure uniform moisture conditions throughout the experiment, plastic sheeting was placed on the top of each column to minimize evaporation and prevent direct rainfall infiltration, as illustrated in Figure 4.

Figure 4. *Acacia mangium* seedlings planted in the experimental soil column

Each experimental condition consisted of nine individual planting columns (replicates), resulting in a total of 36 planting units across four test cases: (1) root-reinforced unsaturated, (2) root-reinforced saturated, (3) bare soil unsaturated, and (4) bare soil saturated. After 12 months of growth, soil and root samples from each group were collected, and the mean value of the nine replicates was used to represent one experimental case in subsequent analyses.

3.2. Growth of *Acacia mangium* Willd.

This experiment monitored the growth of *Acacia mangium* planted in cylindrical columns, under 50% full-day sunlight conditions and with regular watering. All height measurements represent the plant's actual height, excluding the planting column's height. Over the first 12 months, the tree height increased from 24 cm to 135 cm, resulting in an average monthly growth rate of approximately 9.2 cm. However, the growth was not uniform and could be divided into three distinct phases as follows:

As the organism enters the Root Establishment Phase during the first three months, it chiefly channels its metabolic resources into root system development, culminating in a rather trivial increase in shoot height, estimated at just 1 to 3 cm each month. The increase of leaves is stunted, observable in a likewise reduced Leaf Area Index (LAI). This instance confirms the assertions of Combalicer et al. [25], who illuminated that *Acacia mangium Willd*. typically dedicates the initial 90 days to the formation of its taproot and fine root systems prior to the commencement of significant stem elongation. By the conclusion of the third month, the taproot had achieved a penetration depth of approximately 35 cm, while lateral fine roots commenced their radial extension of 5–8 cm around the base of the stem. This developing root framework sets the stage for the forthcoming utilization of water and crucial nutrients.

During the Stem Elongation Phase (Months 4–8), upon the lateral root system's expansion to encompass over 70% of the surface area within the planting column, the plant began to manifest rapid canopy growth accompanied by accelerated vertical development. In this phase, height increments of 10–12 cm was documented in certain months. The mean height increase during the stem elongation phase was approximately 31 cm. The habitual view of thriving, dark green foliage revealed a considerable upgrade in the net photosynthesis output (Pn), indicating an enhanced level of biological dynamics. These observations are in alignment with the findings documented by Phan et al. [26].

Growth Maturation Phase (Months 9–12) was characterized by the attainment of equilibrium within the root and leaf systems, whereby a significant proportion of nutrients was systematically redirected towards stem development, thereby facilitating consistent vertical growth. Throughout the ultimate four-month stage, the plant illustrated an escalation in height from 83 cm to 135 cm. During the twelfth month, the plant notably expanded by 27 cm. Within this phase, the growth rate of stem diameter reached its zenith at approximately 1.4 mm per month. As articulated by Dong et al. [27], the enhancement in height during this growth stage is significantly associated with an increase in foliar nitrogen content and improved light use efficiency (LUE), both of which are instrumental in promoting a more pronounced presence of dark green foliage. Regardless, the height constraint imposed by the experimental column restricted the length of time available for data collection in this inquiry to just 12 months (see Figure 5).

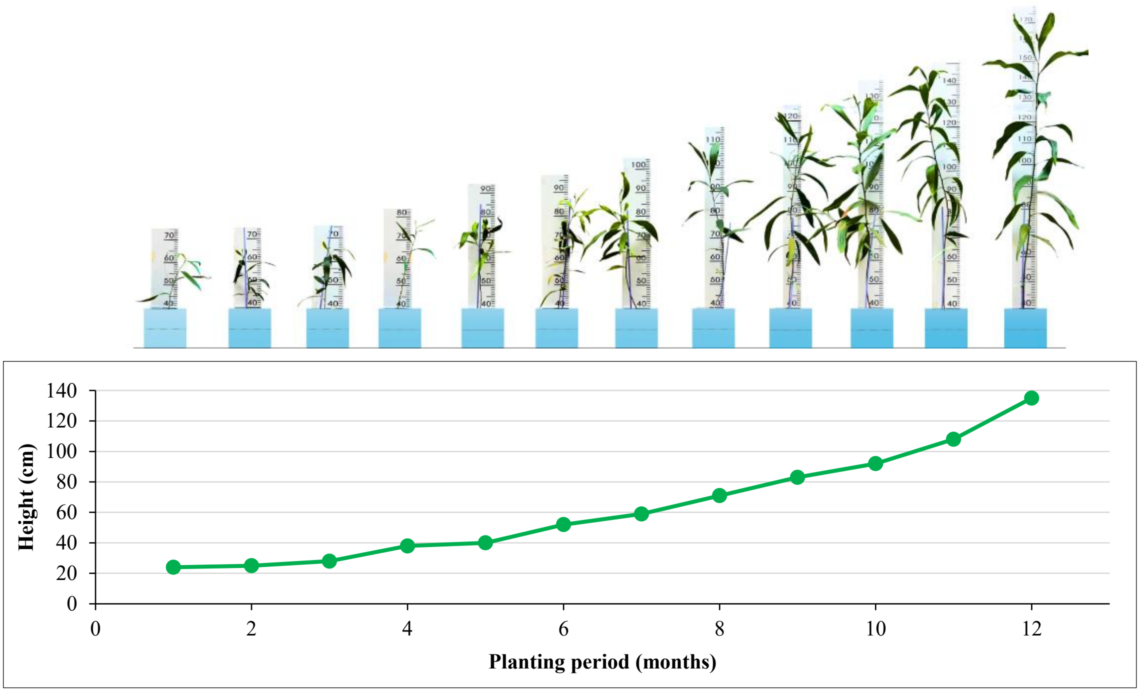

Figure 5. Height progression of *Acacia mangium* over a 12-month cultivation period

3.3. Dry Root Biomass per Soil Volume

After the experiment, root samples were carefully extracted from the soil columns, washed with clean water, and sieved through a No. 18 mesh (1 mm opening) to remove remaining soil particles. Following the procedure recommended by Böhm [28] and Majdi [29], the cleaned roots were oven-dried at 105 °C for 24 hours until a constant mass was obtained. The dry root biomass per soil volume (ρ_R) was determined using Equation 1:

$$\rho_R = \frac{W_{dry\,root}}{V_{soil}} \quad (\text{kg/m}^3) \tag{1}$$

where, ρ_R is dry root biomass per soil volume (kg/m³), $W_{dry\,root}$ is oven-dried root mass (kg), V_{soil} is volume of the soil specimen within the cylindrical mold (m³).

Figure 6 shows a clear exponential relationship between dry root biomass per soil volume (ρ_R) and cultivation time, described by the regression equation y=0.0195$e^{0.2931x}$ with a high correlation coefficient (R^2 = 0.9956). This indicates that root accumulation increased steadily and predictably throughout the 12-month period. The exponential trend demonstrates that *Acacia mangium* root systems expanded continuously, particularly after the sixth month, corresponding to the transition from the root establishment to the stem elongation phases discussed in Section 3.2. Such consistency in biomass accumulation confirms the root system's stable and predictable growth behavior, characterized by low variability. This stability ensures the reliability of ρ_R as a representative parameter for modeling root–soil interaction and for estimating the mechanical contribution of roots to shear strength, thereby supporting its use as a quantifiable and integrative indicator for further geotechnical analysis. The side root area ratio (RAR_{side}) technique has gained popularity as a non-destructive method for estimating root concentration, particularly because it can be effectively applied in field conditions [30-34]. Side root area measurement is commonly performed using minirhizotron imaging techniques, allowing for repeated observation without disturbing the root system. However, the accuracy of this method can be limited by the spatial variability of root distribution and the positioning of the observation tube relative to root density [31, 35, 36].

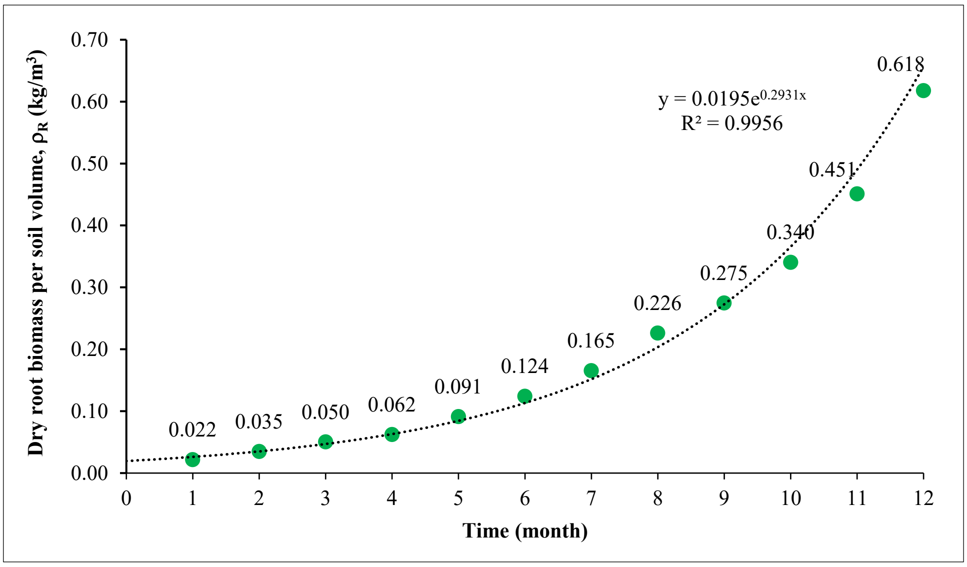

Figure 6. Variation of dry root biomass per soil volume (kg/m³) over time

The equation proposed by Schwarz et al. [37] (Equation 2) estimates root cohesion based on the side root area ratio (RARside). In contrast, the equation by Gray & Sotir [31] (Equation 3) determines root cohesion using the dry root biomass per unit volume of soil:

$$c_r = k_1\left(\frac{A_R}{A}\right) + k_2 \tag{2}$$

$$c_r = a(\rho_R + b) \tag{3}$$

when, a; b; k_1; k_2 are empirical constants, calibrated through field observations or laboratory direct shear tests [9, 38]. As illustrated in Figure 6, the value of dry root biomass per unit volume of soil does not start at zero, since *Acacia mangium Willd* possesses both tap roots and lateral roots. These characteristics, typical of deep-rooted woody species, contribute to the immediate enhancement of soil shear strength upon planting, as the tap root functions like an anchor that stabilizes the main stem.

Equation 3 contains a critical condition in which the expression within parentheses must always remain positive. Notably, the variable b may take a value of zero following adjustments. In contrast, the terms in Equation 2 can be greater than zero, primarily influenced by two key factors: the distance between the mold and the plant roots and the location where the roots are measured. These observations are consistent with the findings reported by several researchers [29, 32-33]. In practical applications, the Side Root Area Ratio (RAR_{side}) measurement reflects root quantity only at the specific measurement location. However, roots can extend beyond the measured point under natural conditions and still contribute to mechanical resistance. This behavior is consistent with several studies [35, 37].

The parameter Dry Root Biomass per Soil Volume provides a distinct type of information, as it more accurately reflects the total root mass present within the soil. It consistently exhibits a non-zero initial value, owing to the presence of roots from the onset of the planting process. This observation aligns with the findings of Mahannopkul & Jotisankasa [36], who demonstrated that the relationship between Dry Root Biomass and RAR_{side} does not originate from zero. Similarly, recent work by Ferreira et al. [39] and Holanda et al. [40] confirmed that Dry Root Biomass offers more comprehensive and precise information, as it accounts for the total root quantity distributed throughout the soil.

Based on the aforementioned information, the key distinction between the two variables can be summarized as follows: RAR_{side} depends on the measurement location and may yield a zero value, whereas Dry Root Biomass is independent of measurement position and consistently exhibits an initial value. Therefore, the selection of an appropriate equation should primarily be guided by the research objective. If the aim is to investigate root distribution within a confined area, Equation 2, which involves RAR_{side}, may be suitable. Conversely, if the goal is to assess the overall performance of the root system, Equation 3 in conjunction with Dry Root Biomass measurements would provide a more comprehensive and representative outcome.

3.4. Large Direct Shear Tests

The large direct shear test apparatus comprises a stainless-steel cylindrical shear cell, submerged in a water tank to maintain full saturation of the soil specimen throughout the test. The shear cell is horizontally divided into two halves. During testing, the lower half is driven by a gear-reduction mechanism at a constant displacement rate of 0.5 mm/min. The shear force is precisely measured by a high-resolution load cell aligned with the direction of force application. Concurrently, real-time deformation of the specimen is captured using two Linear Variable Differential Transformers (LVDTs): one monitoring horizontal displacement and the other measuring vertical settlement or heave. All sensor signals are collected at a sampling frequency of 10 Hz via a digital data acquisition system, recorded by a data logger, and subsequently transferred to a computer to analyses stress-strain behavior and derivation of soil parameters, as illustrated in Figure 7.

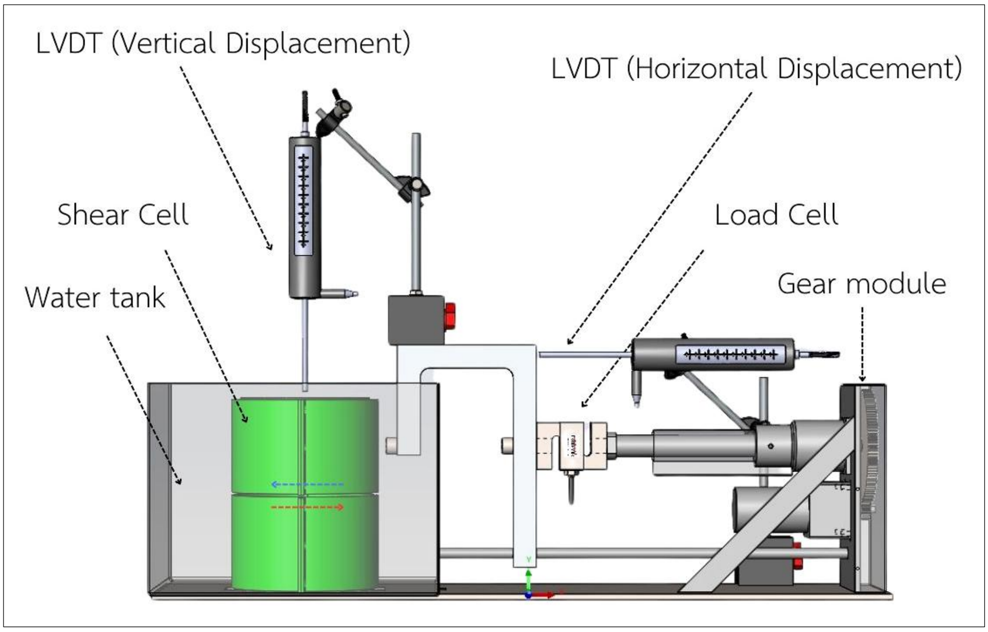

Figure 7. Layout of the large direct shear apparatus

To evaluate the strength of the interaction between plant roots and soil, numerous previous studies have commonly applied the Large Direct Shear Test on root-reinforced soils [8, 9, 41-46].

Group 1 (Unreinforced Soil): The shear strength of the unreinforced soil was tested under three levels of normal stress (1.175, 2.343, and 4.709 kPa). Tests were conducted under saturated conditions (matric suction = 0) with a water content of 54% and under unsaturated conditions at the natural moisture state, with a water content set at 12%.

Group 2 (Root-Reinforced Soil): The root-reinforced soil samples were taken from soil planted with *Acacia mangium Willd*, aged 12 months. The root content was kept constant, with a dry root biomass per soil volume ranging from ρ_R = 0.611 to 0.618 kg/m³. Shear strength tests were conducted under three normal stress levels (1.175, 2.343, and 4.709 kPa). Testing was performed under both saturated conditions (matric suction = 0) with a water content of 54%, and unsaturated conditions at the natural moisture level, with a water content set at 12%, identical to the unreinforced samples.

4. Results and Discussion

4.1. Shear Strength of Root-Free Soil Under Saturated and Unsaturated Conditions

The direct shear tests revealed distinct differences in the shear strength of root-free soil under saturated and unsaturated conditions, as illustrated in Figure 8. For each condition, three replicate tests were conducted, and the reported values represent the mean results. The shear strength parameters—cohesion (c) and internal friction angle (φ)—were obtained from the linear regression of Mohr–Coulomb failure envelopes, which yielded excellent correlations (R^2 > 0.999), confirming the reliability of the results (see Figure 9).

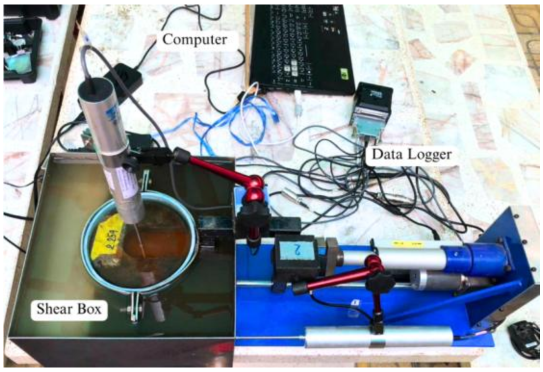

Figure 8. Shear strength test of soil under saturated conditions

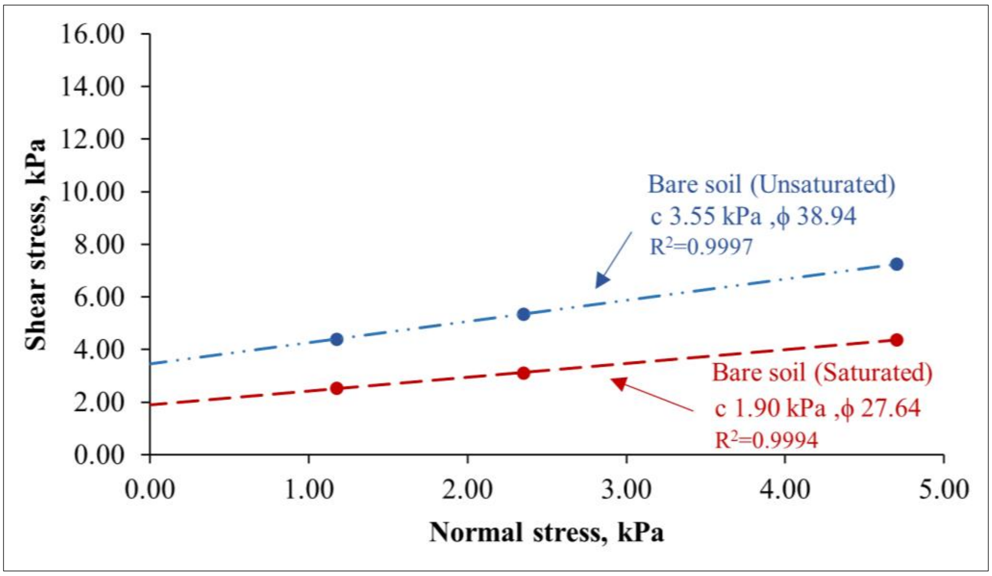

Figure 9. Relationship between shear stress and normal stress of root-free soil

Under saturated conditions, the soil exhibited a moisture content of approximately 58%, slightly higher than the full-saturation value (S = 100%) of 54.1%. This excess water content caused a pronounced reduction in shear strength, with c = 1.90 kPa and φ = 27.64° (R^2 = 0.9994). The reduction reflects the effect of increased pore-water pressure, which lowers effective stress in accordance with Terzaghi's effective-stress principle [2].

In contrast, under unsaturated conditions, the soil exhibited a moisture content ranging from approximately 12% to 20% and showed significantly higher shear strength than under saturated conditions. The measured parameters were c = 3.55 kPa, φ = 38.94° (R^2 = 0.9997). This increase can be attributed to matric suction, which acts as apparent cohesion and enhances overall shear resistance. Although GW-type soils are generally considered coarse-grained with large pores and low water-retention capacity—conditions that usually minimize matric-suction effects [3, 47]—recent research has shown that even coarse soils may exhibit improved shear strength when moisture is within a low-to-moderate range [48]. Tian et al. [49] also noted that the fine-material fraction significantly affects shear strength by altering the soil–water characteristic curve (SWCC) and effective stress, a finding consistent with this study [50, 51].

4.2. Shear Strength of Root-Reinforced Soil under Saturated and Unsaturated Conditions

Soil reinforced with *Acacia mangium* roots exhibited a clear and measurable improvement in shear strength under both saturated and unsaturated conditions, as illustrated in Figure 10. For each condition, three replicate direct-shear tests were performed, and the reported parameters represent the mean values derived from these replicates, obtained through linear regression of the Mohr–Coulomb envelopes with high correlation coefficients (R^2 > 0.999).

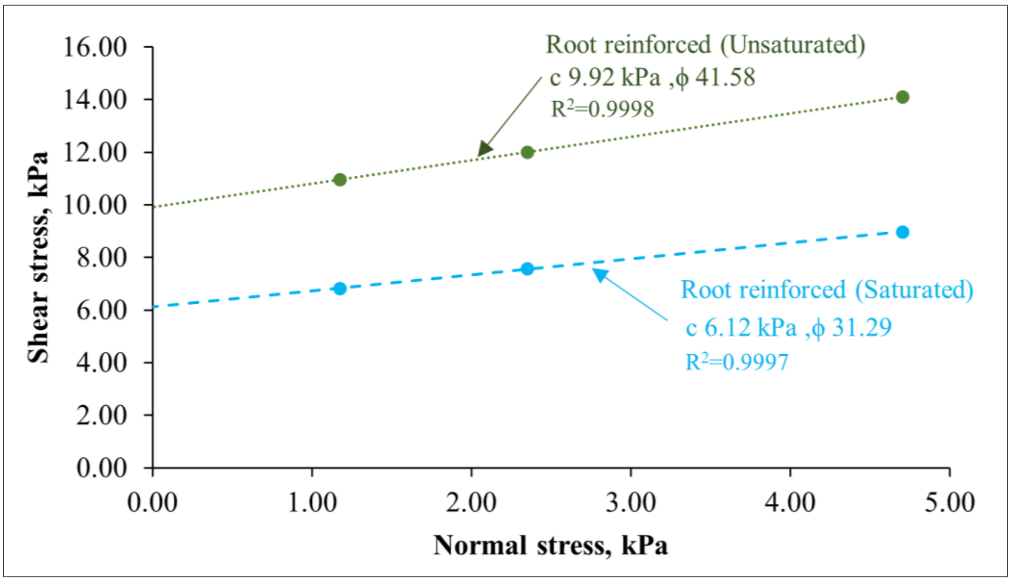

Figure 10. Relationship between shear stress and normal stress of root-reinforced soil

Under unsaturated conditions, the maximum measured shear stress reached 14.10 kPa under a normal stress of 4.71 kPa, which is more than twice that of the root-free soil. The regression analysis produced cohesion (c) = 9.92 kPa, internal friction angle (φ) = 41.58°, and R^2 = 0.9998, indicating a robust linear relationship between shear and normal stresses. Under saturated conditions, while the strength was comparatively lower due to reduced matric suction, the presence of roots still contributed significantly to shear resistance, yielding c = 6.12 kPa, φ = 31.29°, and R^2 = 0.9997, all of which remained substantially higher than those of the unreinforced soil under equivalent conditions.

This enhanced performance is primarily attributed to the mechanical reinforcement effect of plant roots acting as natural tensile and shear-resisting elements within the soil matrix. Roots increase inter-particle bonding, restrict relative displacement along potential shear planes, and transfer stress effectively through root–soil adhesion and frictional interaction [7]. The fine roots, densely distributed within the upper soil layer, enhance cohesion by binding soil particles together, while larger lateral and tap roots resist tensile and bending stresses, functioning analogously to reinforcing bars in reinforced concrete [9].

In addition, the interaction between matric suction and root reinforcement under unsaturated conditions generates a synergistic strengthening effect, increasing apparent cohesion and delaying shear failure. Previous research by Wang et al. [52] and Munirwan et al. [53] supports these observations, demonstrating that vegetation roots considerably enhance soil shear parameters, particularly under partial saturation.

4.3. Comparison of Shear Strength Between Root-free Soil Under Saturated and Unsaturated Conditions

The test results showed that root-free soil exhibited significantly higher shear resistance than unreinforced soil under both saturated and unsaturated conditions. Matric suction played a key role in enhancing shear resistance in the unsaturated state. The roots of *Acacia mangium* contributed to improved adhesion between roots and soil particles. When considering the root-induced cohesion (C_r), calculated from the difference between cohesion under saturated (C_{sat}) and unsaturated (C_{unsat}) conditions, the value of C_r was found to be 3.80 kPa. This additional cohesion led to a noticeable increase in the soil's overall shear strength. These findings are consistent with Maffra et al. [54], who reported that moisture in unsaturated soil enhances cohesion through improved stress distribution among soil particles and root-soil adhesion. In contrast, the internal friction angle showed only a slight increase, as root systems have minimal influence on the internal friction angle of coarse-grained soils.

4.4. Role of Plant Roots in Enhancing Soil Strength

Plant roots contribute to the physical stability of soil and the redistribution of stress within it, along with important chemical effects. In particular, the roots of *Acacia mangium* enhance soil adhesion under all conditions. Even under saturated conditions—where matric suction is lost due to high moisture content—roots continue to increase soil strength by reinforcing the interactions between soil particles and the root network

As shown in Figure 11, a series of direct shear tests was conducted at a normal stress of 1.175 kPa over a growth period of 1 to 12 months. The results focused on undrained shear strength under unsaturated conditions. As dry root biomass increased, the peak shear stress also increased significantly, confirming the role of roots in enhancing soil shear resistance [9].

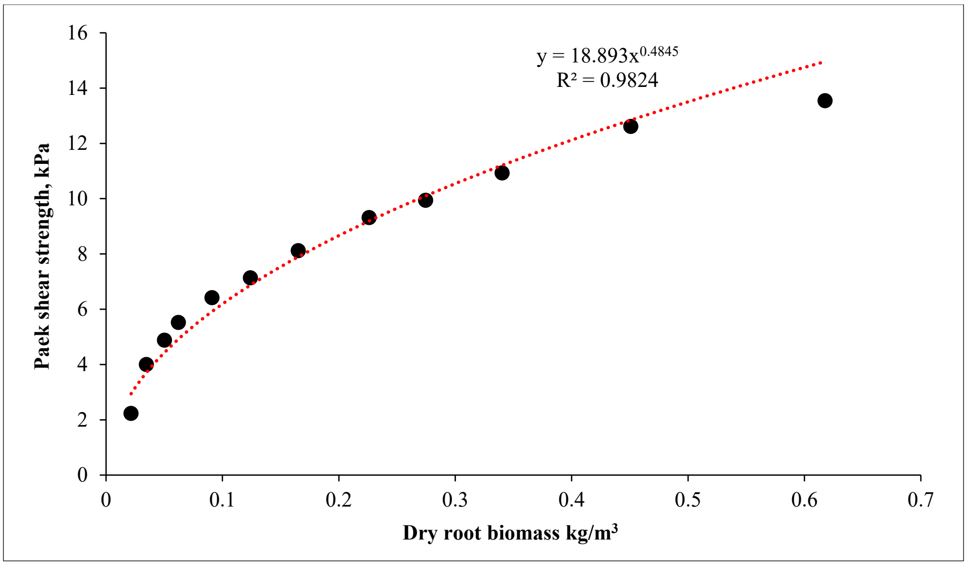

Figure 11. Peak shear strength vs Dry root biomass

However, it is noteworthy that at the 12-month mark, the final data point fell below the general trendline. Although the dry root biomass slightly increased to 0.617 kg/m³, the root system had already filled the planting column by month 11. As a result, the peak shear strength in month 12 dropped to 13.538 kPa, which was lower than expected.

Recent findings by Cao et al. [55] demonstrate that root diameter and tensile strength strongly influence soil reinforcement. Their modeling confirms that fine root networks enhance shear resistance, which supports the observed effects of *Acacia mangium* roots in this study. Additionally, comparison with Çavdar [5] flood-risk modeling shows that pore pressure build-up in saturated zones can be critical in areas with high rainfall and shallow water tables conditions that align closely with this study's site characteristics. This suggests that vegetation reinforcement, particularly through *Acacia mangium* roots, plays a crucial role in stabilizing slopes and mitigating potential failures triggered by soil liquefaction.

5. Engineering Models: Saturated and Unsaturated Conditions

To illustrate the significance of peak shear strength behavior, results from direct shear tests on unreinforced and root-reinforced soils under saturated and unsaturated conditions are considered. The unreinforced soil shows a linear trend of increasing peak shear strength, while the root-reinforced soil exhibits notably higher peak shear strength values

As depicted in Figure 12, the Mohr envelopes of failure for reinforced soils run parallel to those of unreinforced soils, providing clear support for the hypothesis proposed by Endo and Tsuruta [10], which stated that root reinforcement does not affect the soil's internal friction angle. This has led many researchers to adopt constant normal stress in their experiments while varying root quantity to investigate its relationship with peak shear strength [9, 36, 41-46].

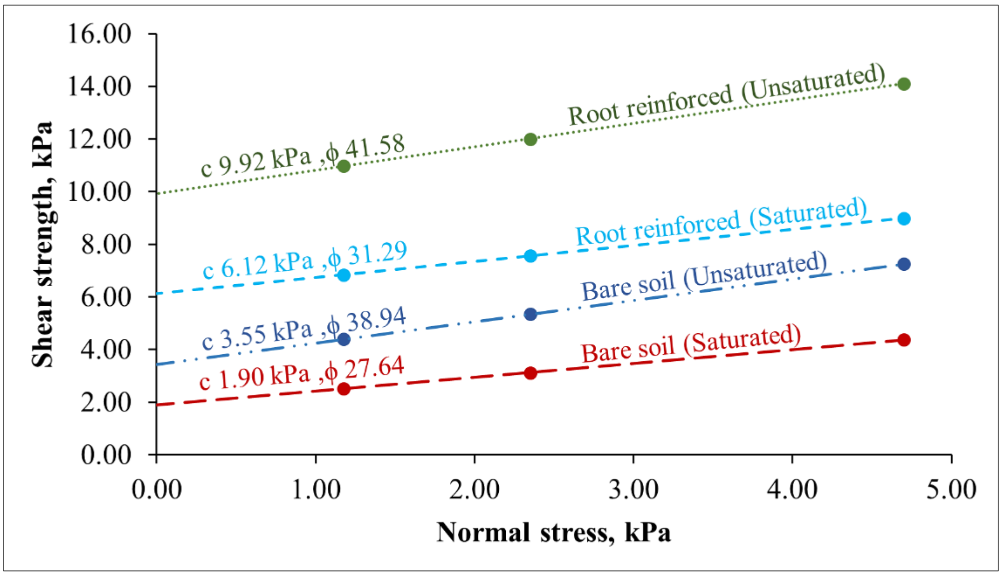

Figure 12. Mohr failure envelopes of root-reinforced and bare soils under saturated and unsaturated conditions

As previously described, this study focused on *Acacia mangium*, a perennial tree species with a laterally spreading root system. This root architecture allows for a uniform and consistent root distribution, facilitating controlled root quantity conditions in laboratory settings. Recognizing this advantage, the researchers conducted direct shear tests with varying normal stresses to obtain Mohr failure envelopes. These envelopes can subsequently be used for slope stability analysis.

5.1. Model Definition and Field Application

To demonstrate the stabilizing effect of *Acacia mangium* root reinforcement, a slope stability model was developed using Slope/W software. The analysis was based on the soil parameters listed in Table 1. The slope profile and boundary conditions are illustrated in Figure 13.

The modeled slope has an inclination angle of 25°, selected to represent typical natural slopes commonly found in Thailand. This gradient reflects the average range of residual soil slopes documented in field observations, consistent with recommendations by Jotisankasa & Mairaing [56], who reported that slopes between 25° and 30° are characteristic of Thai terrain and are frequently associated with shallow landslides in residual soils.

As shown in Figure 13, the slope consists of a 3 m-thick well-graded gravel layer overlying a 1 m decomposed rock layer, underlain by bedrock. The groundwater table was positioned at 1.5 m below the surface to simulate conditions after prolonged rainfall. This stratigraphic configuration reflects common geological settings observed in natural slopes with both saturated and unsaturated zones. The upper soil layer transitions seasonally between unsaturated and saturated states, influencing the factor of safety and potential slip surfaces under varying hydrological conditions.

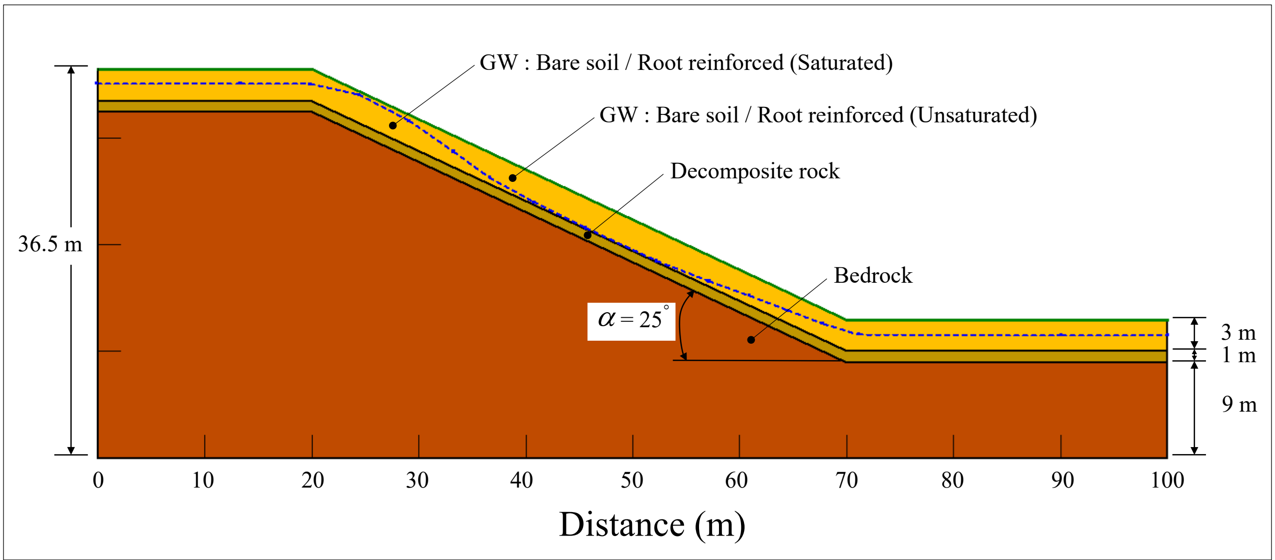

Figure 13. Slope profile used for stability analysis

The slope stability analysis using Slope/W (Figure 14) illustrates the comparative performance between unreinforced and root-reinforced lateritic slopes at a 25° inclination. The unreinforced condition (Figure 14A) yielded a Factor of Safety (FS) of 1.043, indicating marginal stability, while the root-reinforced case (Figure 14B) showed a substantial improvement, achieving an FS = 1.518. This represents an increase of approximately 45%, highlighting the significant mechanical contribution of *Acacia mangium* roots in enhancing soil shear resistance through apparent cohesion and interlocking effects within the soil matrix.

The obtained FS value is considered relatively high for bioengineered slopes, where stability improvement typically ranges between 10–25%, as reported by Docker & Hubble [9], Yang et al. [50], and Pallewattha et al. [57]. The notable enhancement confirms that *A. mangium* provides superior root reinforcement, particularly in lateritic soils under tropical conditions.

Moreover, the selected 25° slope angle represents a realistic geometry for Thai terrain, consistent with Jotisankasa & Mairaing [56], and corresponds to naturally stable but failure-prone slopes commonly found in residual and colluvial soil formations. The model configuration also incorporated both unsaturated and saturated zones influenced by a groundwater table located at −1.5 m, simulating the hydromechanical environment typically observed in natural slopes. These results verify that biological reinforcement under such moderate slopes can achieve engineering-grade stability comparable to conventional mechanical stabilization methods while offering a sustainable and eco-efficient alternative for slope protection.

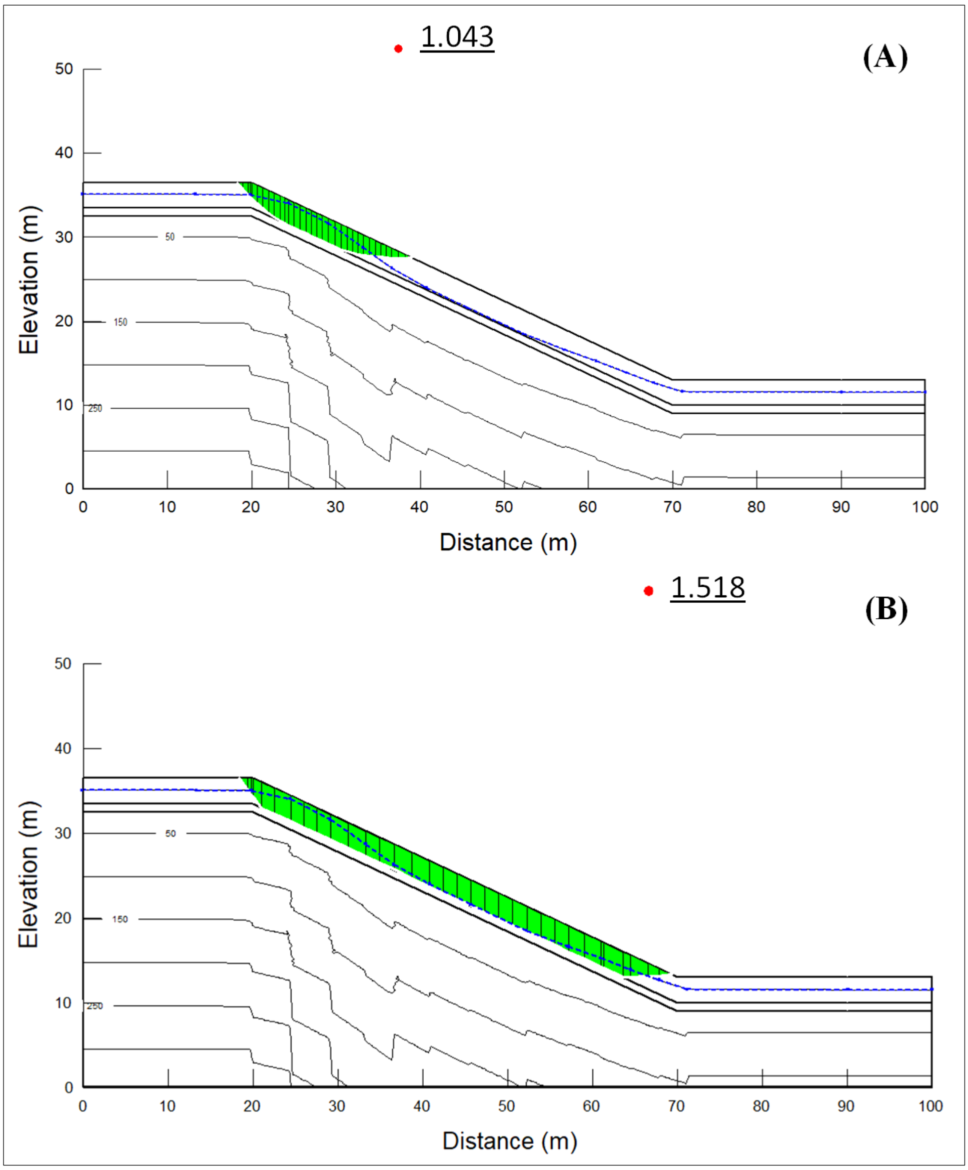

Figure 14. Slope stability analysis results using Slope/W software

For the definition of soil properties in the program, the parameters are defined based on equations using bio-engineered slope stability analysis (e.g. Gonzalez-Ollauri & Mickovski [58], Feng et al. [59], Bordoloi & Ng [60], Fata et al. [61]) as follows: Equation 4.

$$\tau = c_r + c^{'} + (\sigma_n - u_a)\, tan\, \phi + (u_a - u_w)\, tan\, \phi^b \tag{14}$$

The values were obtained from the direct shear tests shown in Figure 12, separated into unreinforced and root-reinforced cases (as if accounting for both c_r and $c^{'}$ together). Where $\sigma_n - u_a$ is Normal stress, $u_a - u_w$ is variation predicted from the water table, ϕ is the effective angle of internal friction, ϕ^b is the angle of friction associated with matric suction in unsaturated soil. In this context, it represents the difference in slope between the saturated and unsaturated cases on the shear strength versus normal stress graph.

5.2. Analysis Results from Slope/W

Based on the defined soil profile boundaries shown in Figure 13 and the soil properties obtained from experimental testing, the analysis was conducted using Slope/W software under identical groundwater conditions for both cases. The results are presented in two scenarios: Figure 14A illustrates the case with root-free soil, while Figure 14B represents the case with root-reinforced soil.

Findings from the slope stability review show that soil supported by root systems achieved a safety factor (FS) exceeding 1.518, thus going past the crucial threshold of 1.5. Conversely, the soil devoid of root structures displayed an FS of merely 1.043, falling short of the failure limit. This study underscores the crucial importance of *Acacia mangium* roots in bolstering shear resistance in the soil, thereby significantly aiding in overall slope stability.

6. Discussion

6.1. Engineering Mechanisms

The experimental results clearly demonstrated that *Acacia mangium* roots substantially enhanced the shear strength of lateritic soil under both saturated and unsaturated conditions. In the unsaturated state, cohesion increased from 3.55 kPa to 9.92 kPa with root reinforcement—an improvement consistent with the findings of Pallewattha et al. [57] and Yang et al. [62], who reported that vegetation can increase shear strength even under high-moisture conditions.

Two main mechanisms explain this enhancement: (1) Mechanical reinforcement, where roots interlock with soil particles and transfer stress along the shear plane, increasing apparent cohesion [7, 9]; and (2) Hydromechanical interaction, where root networks influence matric suction and modify the soil–water characteristic curve (SWCC).

Recent work by Lann et al. [63] confirmed that the combined mechanical–hydrological effects of vegetation play a decisive role in stabilizing tropical slopes by reducing pore pressure while increasing shear resistance. The strong exponential relationship (R^2 = 0.9956) observed between dry-root biomass and peak shear strength confirms the predictable and quantifiable nature of *A. mangium* reinforcement, validating ρ_R as a reliable parameter for numerical slope-stability modeling.

6.2. Comparison with Other Bioengineering Species

When compared with other bioengineering species such as *Chrysopogon zizanioides* (vetiver) and bamboo, *A. mangium* exhibits several unique advantages. Vetiver grasses provide effective surface reinforcement and erosion control but require dense planting and frequent maintenance [64]. In contrast, *A. mangium* develops a deep taproot coupled with dense lateral roots, offering greater tensile resistance and improving subsurface stability—especially in thick lateritic or residual soils.

Dalir et al. [65] conducted a comparative evaluation of woody species for slope protection and found that trees with deep root systems produced higher soil-reinforcement efficiency and better runoff control than herbaceous species. From an engineering perspective, *A. mangium* therefore represents an optimal compromise between mechanical performance, low maintenance, and long-term durability. Its woody morphology supports deeper anchorage, making it particularly appropriate for the moderate natural slope angles (≈ 25°) typically found across tropical Thailand [56].

6.3. Sustainability, Economic and Environmental Implications

Beyond mechanical improvement, integrating *A. mangium* into slope-stabilization schemes directly supports the principles of nature-based solutions (NbS). Its root systems not only reinforce soil but also enhance infiltration, reduce runoff, and contribute to biodiversity restoration. Keybondori et al. [66] reported that soil-bioengineering systems using woody vegetation are both cost-effective and environmentally resilient for long-term slope management in mountainous terrains. Economically, *A. mangium* offers dual benefits through its high-growth timber yield and potential carbon-credit value. Waheed et al. [67] demonstrated that root-driven carbon sequestration significantly increases soil organic-carbon stocks, reinforcing its role as a sustainable component of engineered slopes.

These attributes align closely with the United Nations Sustainable Development Goals (SDG 11: Sustainable Cities and Communities; SDG 13: Climate Action; SDG 15: Life on Land) by linking engineering design with ecological resilience and economic viability.

7. Conclusions

Based on the findings, the conclusions of this study can be summarized as follows:

- The test results demonstrate that the root system of *Acacia mangium* significantly enhances the shear strength of lateritic soil. In the unsaturated condition, cohesion increased from 3.55 kPa to 9.92 kPa with root reinforcement, while in the saturated condition, cohesion increased from 1.90 kPa to 6.12 kPa. These results are consistent with the findings of Pallewattha et al. [57] and Yang et al. [62], which showed that plant roots can enhance shear strength even under high-moisture conditions.
- The study revealed a linear relationship between dry root biomass and peak shear strength. Over 12 months, dry root biomass increased following an exponential trend (R^2 = 0.9956). This finding aligns with the work of Mahannopkul & Jotisankasa [36], who also reported a strong correlation between root quantity and enhanced shear strength.
- The slope stability analysis using Slope/W showed that the slope reinforced with *Acacia mangium* roots achieved a safety factor as high as 1.518, compared to 1.043 in the unreinforced case. This result is consistent with the findings of Yang et al. [50], who studied the behavior of slopes composed of sand and gravel and highlighted the effectiveness of root reinforcement in improving slope stability.

- The test results demonstrated a relationship between root diameter and tensile resistance, with roots measuring 0.573 centimeters in diameter capable of withstanding a maximum tensile force of 20.95 newtons. This finding is consistent with the work of Endo and Tsuruta [10], who found that root diameter is directly related to the root's ability to enhance slope stability.
- The root system of *Acacia mangium* enhances soil shear strength through several mechanisms: increasing apparent cohesion due to adhesion between roots and soil, facilitating force transfer between soil particles (Wu et al. [7]), and distributing shear stress throughout the soil mass (Docker & Hubble [9]). These mechanisms collectively contribute to greater slope stability.

The findings of this study support the use of *Acacia mangium* as an effective and sustainable bioengineering solution for enhancing slope stability in erosion-prone areas. Its root system contributes significantly to soil reinforcement, as Voottipruex et al. [8] also noted. Additionally, Aslam et al. [68] highlighted that integrating soil erosion susceptibility mapping techniques can improve the identification of high-risk areas and optimize slope management strategies. This approach aligns with the United Nations Sustainable Development Goals (UN SDGs), particularly in promoting sustainable communities (SDG 11), addressing climate change (SDG 13), and protecting terrestrial ecosystems (SDG 15).

8. Declarations

8.1. Author Contributions

Conceptualization, P.V., S.K., and K.M.; methodology, S.M.; software, S.K. and K.M.; formal analysis, S.M. and K.M.; writing—original draft preparation, S.M. and K.M.; writing—review and editing, P.V., S.K., and W.S.; visualization, W.S.; supervision, P.V. and S.K. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

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