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Interaction of root pattern with tropical residual soil in bio-anchorage system for slope stabilization

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Abstract:
The primary objectives of this study were to quantify how Eugenia Oleina (with H-type root architecture) improves slope stability in tropical residual soils and to assess the factors controlling this bio-anchorage effect. Laboratory tests measured soil shear strength (cohesion c′ and friction angle ϕ′) and root tensile properties, and a numerical slope analysis (finite element method) evaluated Factor of Safety (FOS) with and without vegetation under various rainfall scenarios. Results showed that planting E. Oleina increased shear strength: cohesion rose by 8-13 kPa and friction angle by 5-8° compared to unrooted soil, yielding higher FOS values. Root pull-out tests revealed that thinner E. Oleina roots exhibited higher tensile strength than thicker ones, consistent with a power-law trend. Specifically, mature E. Oleina roots (age > 10 yrs) attained tensile strengths 50 MPa, about 2,5 times higher than comparable M-type roots under dry conditions. However, in fully saturated soils, pull-out strength dropped by 33 %, illustrating moisture sensitivity. Finite element analysis confirmed the experimental findings: vegetation consistently improved slope stability (higher FOS) across rainfall conditions, although heavy rainfall (100 % saturation) reduced the FOS relative to moderate rain. These findings have practical implications: E. Oleina (an H-type species) is most effective on slopes up to 20° and 3,5 m high, especially in regions with intense rainfall, where its extensive horizontal roots can bind the soil surface. Guidelines are provided for implementing E. Oleina in bioengineering. The combined experimental and numerical results demonstrate E. Oleina's value as a sustainable slope reinforcement strategy in tropical residual soils.

Keywords:
bio-anchorage system; direct shear box test; root tensile strength; slope stability; tropical residual soil

1 Introduction

In Malaysia, rapid urbanisation in hilly locations has stressed the terrain and led to slope failures owing to reduced protective forces and safety factors [1]. Unlike rock slopes, soil slope collapse involves a substantial amount of failed material [2]. According to Lias et al. [3], rainfall contributes to slope failures. Turf and topsoil fragments from the slope surface are eroded by rainfall runoff. Rainfall is the main cause of landslides; therefore, it is important to assess the relative significance of heavy rainfall and antecedent rainfall, as well as how these factors may change the pattern of the rainfall threshold [4]. According to Gidon and Sahoo [5], an increase in the pore water pressure caused by heavy rain in unsaturated soils causes landslides. High rainfall and ambient temperatures in the tropics result in severe chemical weathering and development of thick soil profiles which promote soil erosion [6].

Geotechnical engineering faces the challenge of slope failure caused by soil erosion during rainfall. The early collapse of planted soil poses a significant problem for slope protection strategies involving vegetation [7]. Consequently, researchers have devised a method to solve this problem by combining engineering and geological concepts, known as bioengineering approaches.

An alternative technology for preventing shallow landslides, particularly during the rainy season, is the use of vegetation for bioengineering. Referred to as 'soil bioengineering', this approach utilises plants to stabilise slopes, where the hydro-mechanical aspects of the vegetative contribution play a crucial role [8]. Various factors, such as slope steepness, root characteristics, soil aggregates, vegetation type, and spacing, can either increase or decrease slope stability through hydro-mechanical vegetation effects [9]. According to Masi et al. [10], the effect of vegetation on the mechanical and hydrological soil behaviour is an important issue to consider when modelling shallow landslides.

In addition, plant roots influence various biophysical, chemical, and mechanical properties of soil, fostering microbial diversity and enhancing ecosystem regeneration. Root systems, particularly fibrous and thick roots, are widely used to stabilise soil on hillsides, riverbanks, and artificial slopes, providing a natural solution for preventing shallow landslides and soil erosion [11]. The strength of root cohesion is closely tied to the root distribution pattern; fibrous roots have many branches, whereas taproots consist of a single main axis with few lateral roots. Adventitious roots, commonly found in shallow soils, differ from taproots in structure and function [12].

The objectives were to:

- quantify the tensile and pull-out strengths of E. Oleina roots of different ages and diameters,
- compare the soil shear strength and factor of safety (FOS) of slopes with and without E. Oleina, and
- use finite element analysis (FEA) to evaluate slope stability under varying saturation levels. This combined laboratory and numerical approach allowed us to validate the bioanchorage effect of E. Oleina and its practical limitations.

2 Root morphology and architecture

Different root systems play distinct roles in soil stabilisation and erosion control [13]. Root systems can be classified based on their spatial distribution, as shown in Figure 1. Mallett (2019) [14] categorised root systems into taproot, fibrous, and plate types, whereas Li et al. (2016) [15] and Wang et al. (2020) [16] used categories such as H-type, R-type, CH-type, V-type, M-type, and W-type. In addition, Ng et al., (2015) [17] described uniform, triangular, exponential, and parabolic root systems. Despite differences in terminology, some similarities were observed. For instance, both the V-type and taproot systems feature coarse, nearly vertical roots, whereas the H-type, plate, and exponential root systems are characterised by horizontally extending roots, and the fibrous and R-type systems have oblique roots that are evenly distributed around the perimeter.

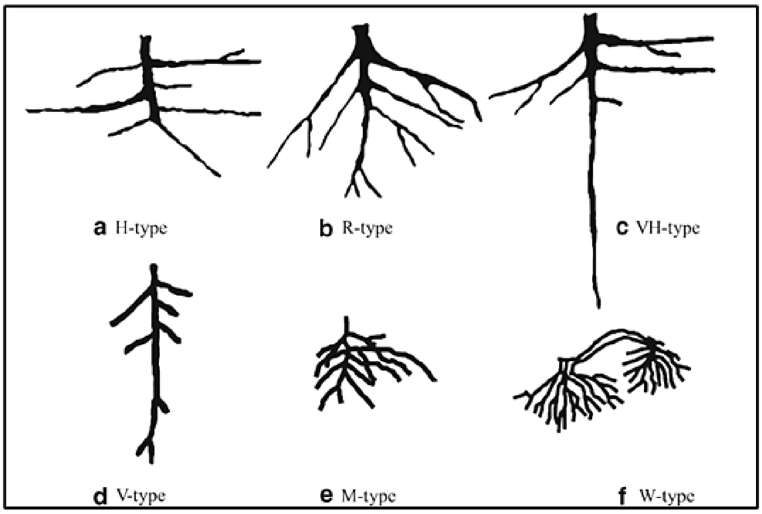

Figure 1. Six branching patterns of plant root architectures (adapted from Yen, (1987), as cited in [16])

The architectural effects of root systems vary depending on the type of load applied. Taproot and fibrous root systems are considered the most resistant to vertical pull-out, with factors such as taproot length and number of lateral roots being key contributors [18]. Longer roots increase the root-soil contact area, which in turn generates higher shearing stresses [19], whereas lateral branching along the root length increases the pull-out capacity by expanding the bearing area and volume of soil that can be uplifted [20]. Furthermore, the angle of branching and the number of lateral roots play a significant role in the pull-out performance, as the pull-out mechanisms of inclined branches and nearly horizontal roots differ, with the highest pull-out capacity observed at intermediate branching angles [21; 22]. The number of lateral roots also affects the pull-out capacity owing to the soil arching effect [22].

Hence, root patterns significantly influence slope stability, offering reinforcement through increased soil cohesion, and mechanical stabilisation through tensile strength, frictional properties, bending stiffness, diameter distribution, and root orientation. H-type roots are predominantly horizontal, spreading wide near the surface (80 % of biomass in the top 60 cm) [11], whereas M-type ("massive") roots branch in many directions with most roots in the upper 30 cm [12]. Eugenia Oleina has a fibrous H-type system [1]. The focus was put on E. Oleina to explore how H-type roots improve slope strength in Gambang residual soil.

3 Materials and method

This study was conducted at the University Malaysia Pahang Al-Sultan Abdullah (UMPSA) campus. The selected plant type was already present on the selected slope, as shown in Figure 2. The selection criteria were based on whether the species belonged to ferns or woody trees and if they had the required tensile strength with the appropriate root pattern. It is known that Eugenia Oleina trees that are currently on the UMPSA campus are more than ten years old. Laboratory tests were performed on samples collected from the slopes at the Geomechanics Laboratory of the UMPSA on campus. The soil test was conducted through multiple repetitions, including moisture content, sieve analysis, hydrometer, Atterberg limit, particle density, and standard proctor tests. The mechanical properties of the roots were determined using tensile-strength and direct-shear-box tests. Field emission scanning electron microscopy with energy dispersive X-ray spectroscopy (FESEM with EDX) was performed to display an image of the topographical surface of the selected plant roots. A summary of the laboratory tests is listed in Table 1. All tests were performed in accordance with the American Society for Testing and Material (ASTM) except for FEDEM with EDX.

a) b)

Figure 2. Research site at the UMPSA campus vicinity as in: a) plan view; b) side view

Table 1. Summary of laboratory tests

Laboratory test	Standard referred
Sieve Analysis	ASTM D422
Moisture Content	ASTM D2216
Particle Density	ASTM D854
Hydrometer	ASTM D422
Atterberg Limits	ASTM D427 & ASTM D4318
Direct Shear Box	ASTM D3080
Tensile Strength Test	ASTM D638
Standard Proctor Compaction Test	ASTM D698
FESEM with EDX	---

4 Soil type and engineering properties

The soil data gathered from the tests are presented in Table 2, which summarises the properties of the tropical soil in Gambang. The soil sample consisted of 7,4 % gravel, 86,5 % sand, and 6,1 % fines, indicating that it was predominantly sandy with some cohesive properties due to the fines. A uniformity coefficient (Cu) of 5,589 suggests a moderately wide range of particle sizes, whereas a coefficient of gradation (Cc) of 1,218 indicates a slightly offset particle distribution. The soil was classified as SW-CL according to the Unified Soil Classification System, which signifies well-graded sand with some clay characteristics, offering good drainage and some cohesion. Figure 3 illustrates the particle size distribution of bare soil on the slope of the study area.

Table 2. Summary of soil properties

Gravel (%)	Sand (%)	Fines (%)	C_u	C_c	USCS	LL (%)	PL (%)	Density (g/cm^3)	Moisture (%)
7,4	86,5	6,1	5,589	1,218	SW-CL	51	39	2,44	20

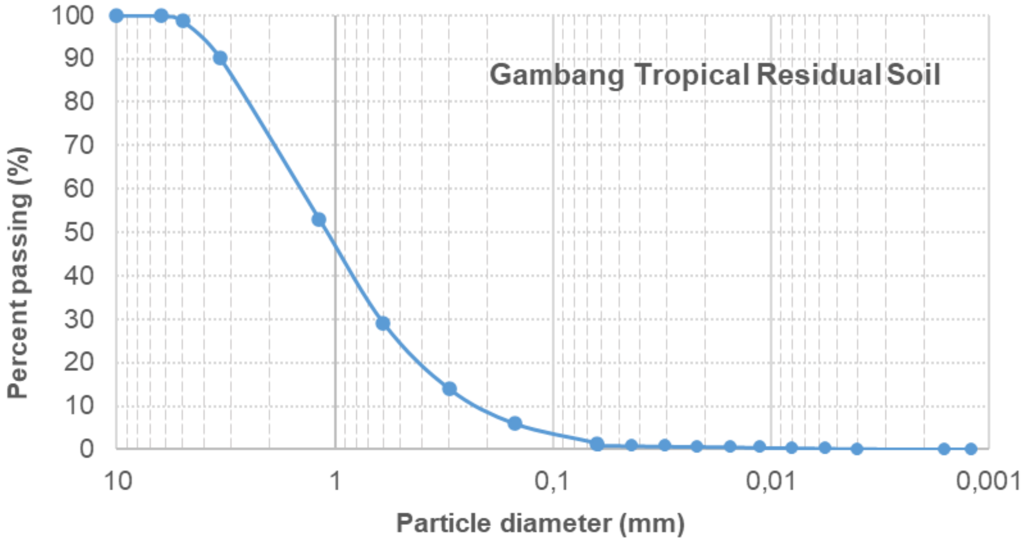

Figure 3. Particle size distribution of the Gambang tropical residual soil

4.1 Root pattern and physical properties of Eugenia Oleina

Table 3 summarises the physical properties of Eugenia Oleina roots across the five growth groups, emphasising the variations in height, stem diameter, root diameter, root area (A_r), and root area ratio (RAR). These parameters reflect the plant growth over time, particularly their capacity for structural stability and soil reinforcement.

As shown in Table 3, the root characteristics of Eugenia Oleina changed as the plants grew older. In the early stages, the height increased from 0 to 300 mm in the first 3 months (Group 1) and up to 1200-1500 mm after a year (Group 5). As the plants grew taller, the stem diameter also increased, from 0,5-1,5 mm (Group 1) to 4,5-5,5 mm (Group 5). The root diameter also increased as the plants matured. Typically, young plants (Group 1) have roots with a diameter from 0,5 to 1,0 mm, whereas the mature plants (Group 5) reach a diameter from 2,5-3,0 mm after a year. The root area (A_r) increased, starting at 8,84 mm² in Group 1 and reaching 593,96 mm² in Group 5, reflecting a steady growth over a period of time until it reached a more developed root system.

However, the RAR value, which is estimated from the ratio of the actual root area to the total area calculated when the plants are in a pot, also increased over time. In Group 1, RAR was only 0,018 %, whereas in Group 5 it increased to 1,21 %. This indicates that, as the plant grows, more of its total structure is made up of roots. As Eugenia Oleina grows, its roots become thicker and more extensive. These changes indicated that the root system was fully ready and developed over time.

Table 3. Physical properties of Eugenia Oleina roots

Group	1	2	3	4	5
total height (mm)	0-300	300-600	600-900	900-1200	1200-1500
stem diameter (mm)	0,5-1,5	1,5-2,5	2,5-3,5	3,5-4,5	4,5-5,5
root diameter (mm)	0,5-1,0	1,0-1,5	1,5-2,0	2,0-2,5	2,5-3,0
root area, A_r (mm^2)	8,84	57,26	144,32	346,99	593,96
RAR (average) (%)	0,018	0,11664	0,294	0,70688	1,21

Figure 4 shows an illustration of Eugenia Oleina roots from the side and plan views. Note from the figure that at the age of three months, the number of roots and the diameter are small compared to those at nine months. The roots grow horizontally and provide an anchorage effect to the slope. Fibrous roots also help grip the ground and are more distinctive than other types of root patterns.

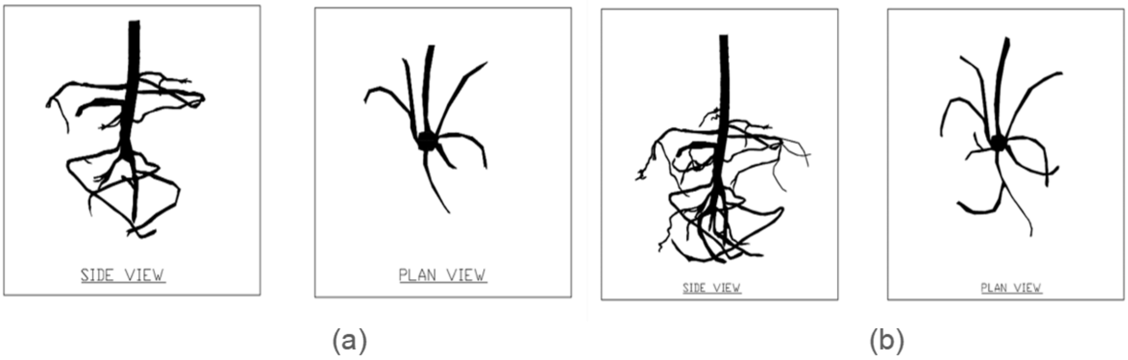

Figure 4. Illustration of side and plan views of Eugenia Oleina roots at: a) 3 months; and b) 9 months

4.2 Microscopic analysis of Eugenia Oleina roots

Figure 5 illustrates a sketch diagram of the H-type pattern of the root and cross-sectional view of the Eugenia Oleina roots obtained through SEM analysis. The images were processed to enhance the clarity of the root structure and to quantify key features such as root diameter, surface area, and any distinctive root modifications. This image illustrates the intricate network of the root system, which plays a significant role in improving soil anchorage and stability.

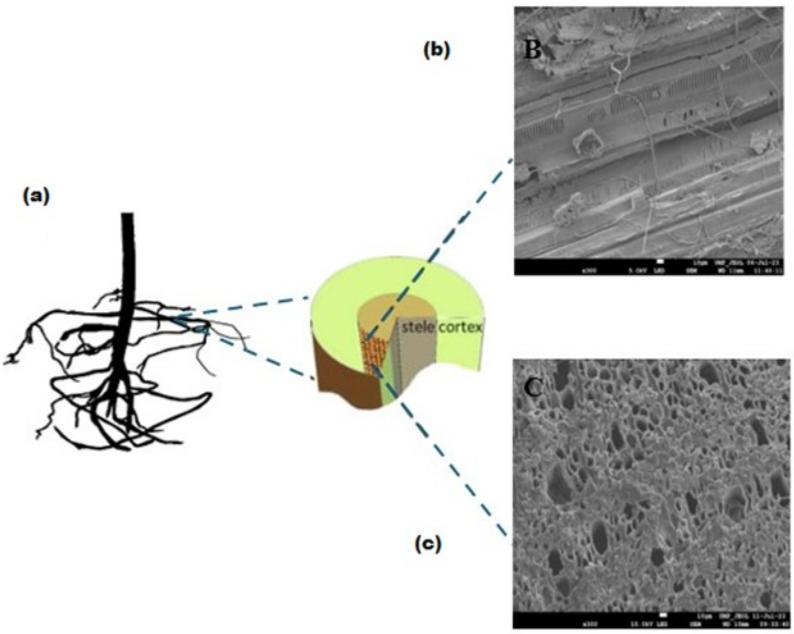

Figure 5. Root patterns of Eugenia Oleina in (a) sketch and cross-sectional view, (b) horizontal cut, and (c) vertical cut

Figure 6 illustrates the relationship between group number and root area ratio (RAR) in Eugenia Oleina plants, utilising two different measurement methods: microscopic and manual. The manual method is based on the RAR (%) values presented in Table 3, whereas the microscopic method relies on SEM analysis. The ImageJ© software calculates the total root area, and RAR was determined based on the area values obtained from the software for all five groups of Eugenia Oleina tested. The red dotted line represents the data obtained from the microscopic method, which shows an upward trend in RAR as the group number increases. The R^2 value for this method was 0,7889, indicating a moderate correlation between the variables, suggesting that while there is a significant relationship, there is also a notable amount of variability in the data that is not explained by the model.

The blue dotted line corresponds to the manual method, which also displays an increasing trend in RAR with increasing group numbers. The R-squared value for the manual method was 0,9458, reflecting a much stronger correlation and a better fit of the data to the model. This higher R^2 value indicates that the manual method achieves a more consistent and reliable measure of the relationship between group number and RAR in Eugenia Oleina plants. Overall, the graph highlights the effectiveness of both methods in capturing the relationship. A similar exponential growth was obtained, demonstrating superior accuracy and predictability, making it suitable for further analysis.

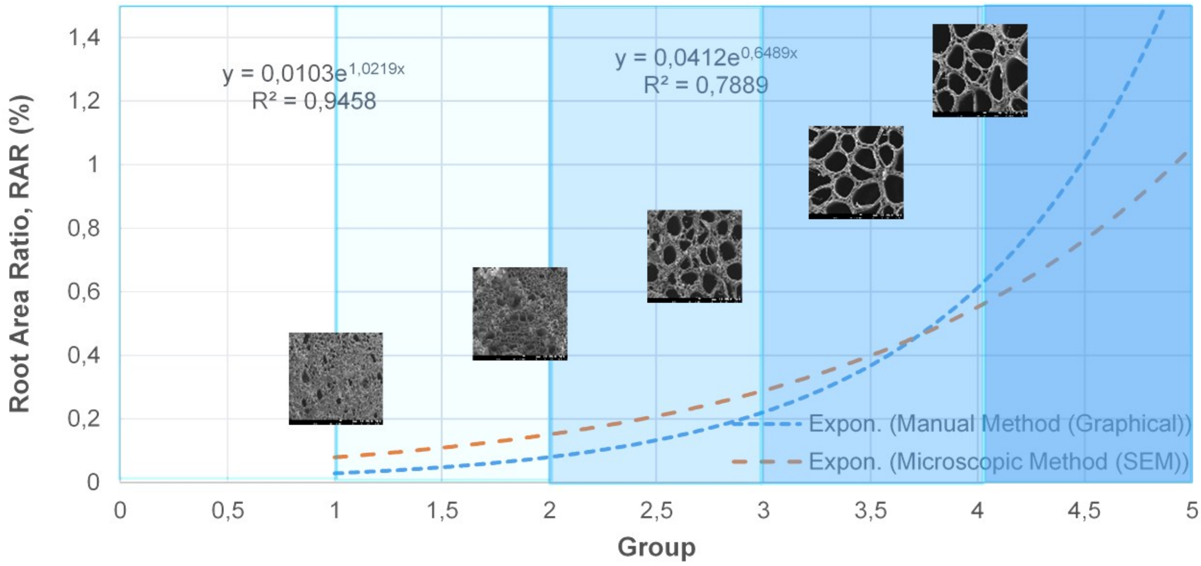

Figure 6. Relationship between RAR of Eugenia Oleina and the growth properties using the manual (Graphical) and microscopic (SEM) methods

4.3 Tensile strength of Eugenia Oleina roots

Figure 7 illustrates the relationship between the root diameter and tensile strength of Eugenia Oleina at different growth stages (3, 5, 7, and 9 months).

As expected, thinner roots displayed a higher tensile strength (Figure 7). A power-law fit ($R^2 > 0,8$) showed tensile strength *Tr* (kPa) decreasing with diameter D (mm). For example, Group 1 roots (approximately 2 mm diameter) had $Tr \approx 50$ MPa, whereas Group 4 (approximately 6 mm) showed 20-30 MPa. Therefore, younger trees (with smaller roots) can exert high tensile forces per unit area. Detailed growth-stage comparisons are summarised for brevity; key trends are as follows: overall root tensile strength increases with plant age, but any given diameter's strength is approximately double that of much younger plants [15].

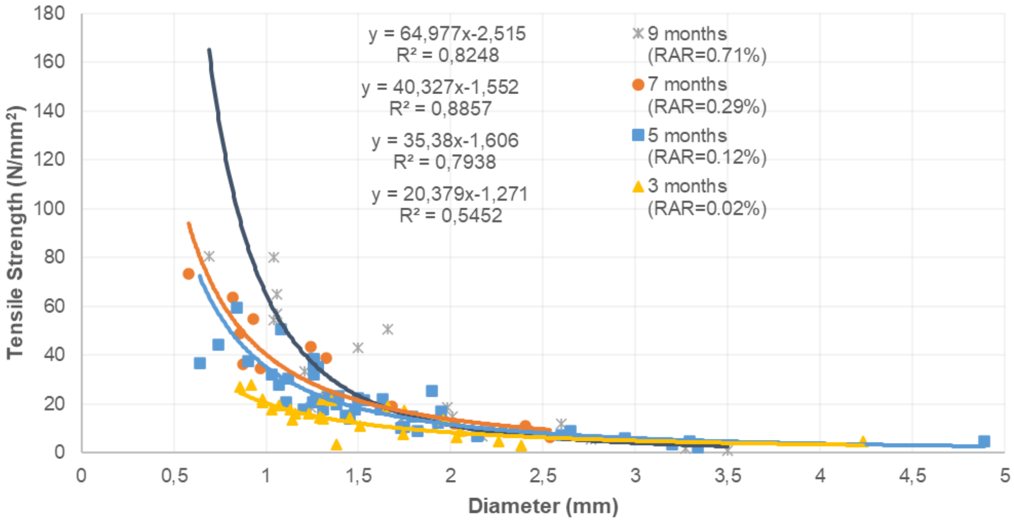

Figure 7. Relationship between tensile strength and diameter of roots by age of Eugenia Oleina

4.4 Tensile strength comparison between root patterns

This section discusses the results of tensile strength testing between the root patterns. These analyses are crucial for understanding how roots contribute to the ability of plants to stabilise soil, particularly in terms of their mechanical strength and fine structural characteristics.

E. Oleina roots were initially classified based on their root area ratio (RAR), which is a key metric for assessing root mechanical stability. RAR serves to evaluate how effectively the root system anchors the plant to the soil and resists external forces. A higher RAR indicates a more robust root system, which is essential for soil stabilisation, especially in areas prone to erosion. Figure 8 (data from [16]) confirms that H-type species (e.g., E. Oleina and Neolitsea Aurata) have much higher tensile strengths than M-type species (Nerium Indicum). Neolitsea (H-type) reached approximately 92 MPa, whereas that of Nerium (M-type) was approximately 40 MPa [16]. The tensile strength of E. Oleina similarly exceeds that of the M-type species by approximately 2,5 times [3]. This underscores the mechanical advantages of H-type roots for anchorage.

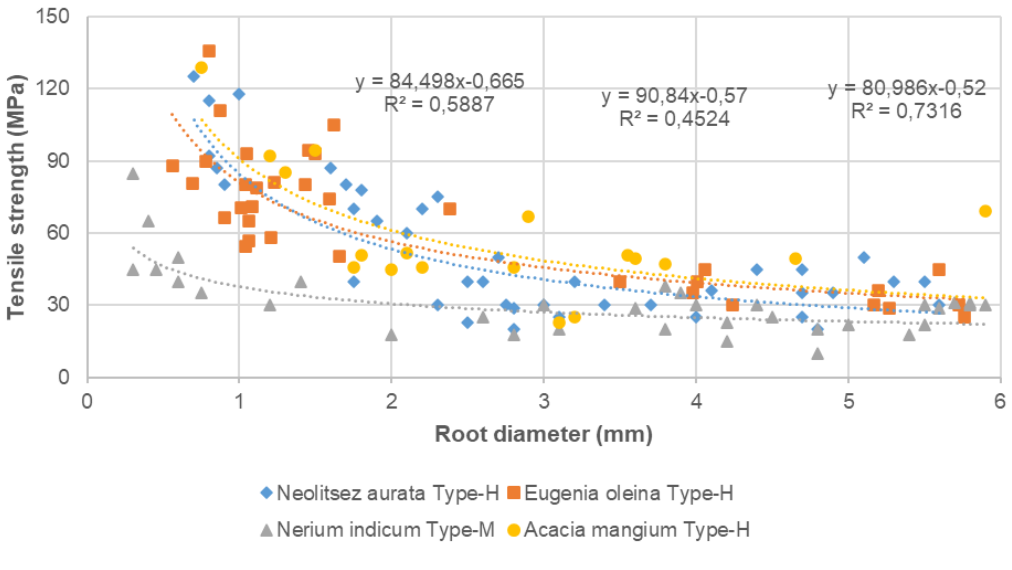

Figure 8. Ultimate tensile strength versus root diameter of H-type and M-type plants

4.5 Pull-out test of Eugenia Oleina plants

Figure 9 shows the relationship between root pull-out strength and root diameter. The data points represent two plant species: Eugenia Oleina (dotted markers) and Acacia Mangium (triangular markers). The comparison between these two species is particularly relevant, as Acacia Mangium, according to previous studies, exhibits the highest tensile strength among comparable species.

The graph reveals that the pull-out strength of Eugenia Oleina in wet residual soil is approximately one-third lower than that in dry residual soil. This suggests that soil moisture has a significant influence on root anchorage capacity. Additionally, data extracted from [23] indicate that Acacia Mangium, with a minimum root diameter of 15 mm, possesses a pull-out strength of 500 N. Interestingly, despite exhibiting different pull-out strength characteristics, both Acacia Mangium and Eugenia Oleina share a similar root pattern, classified as H-type, where roots grow horizontally following the model described in [23].

These observations highlight the importance of considering both the root diameter and soil moisture content when assessing the anchoring capabilities of tree species. Although Acacia Mangium demonstrates a higher pull-out strength potential, the performance of Eugenia Oleina is influenced by soil moisture conditions. This information is crucial for understanding and predicting the stability of slopes in different environments, particularly in tropical regions, where both species are commonly found.

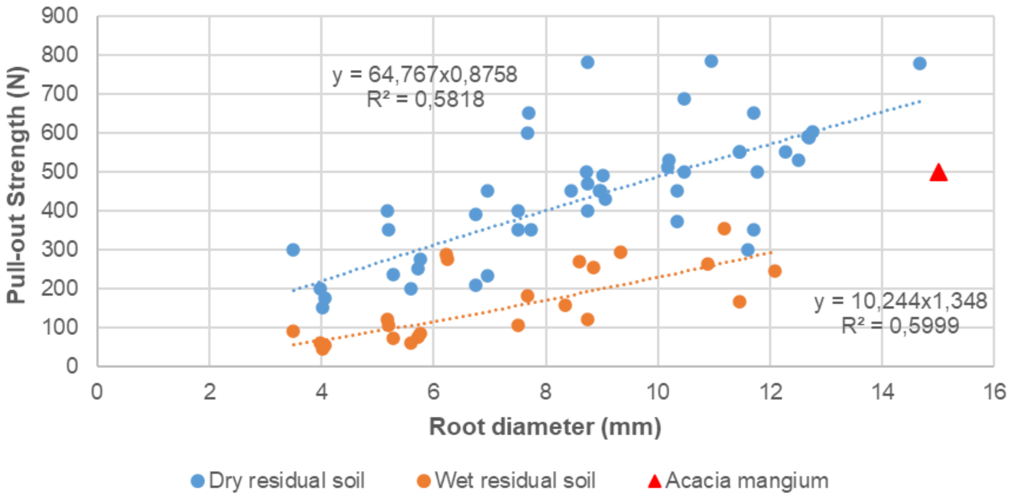

Figure 9. Relationship between pull-out strength and the root diameter in different soil wetness

Figure 10 illustrates the relationship between the tensile strength and pull-out test results for both dry and wet residual soils. The graph reveals that the tensile strength and pull-out tests in the dry residual soil are closely aligned, indicating a strong correlation between these two parameters. This alignment suggests that, as the root diameter of Eugenia Oleina increases, the tensile strength and pull-out resistance decrease proportionally. Conversely, the pull-out test results for the wet residual soil were significantly lower, highlighting the detrimental impact of increased soil moisture content on soil strength. The reduced pull-out resistance in wet soil can be attributed to the presence of water (rainfall), which weakens the soil structure by increasing the pore water pressure and decreasing the friction between soil particles. Consequently, the graph effectively demonstrates the critical influence of the moisture content on the mechanical properties of residual soil, emphasising the importance of considering these conditions in engineering and construction applications.

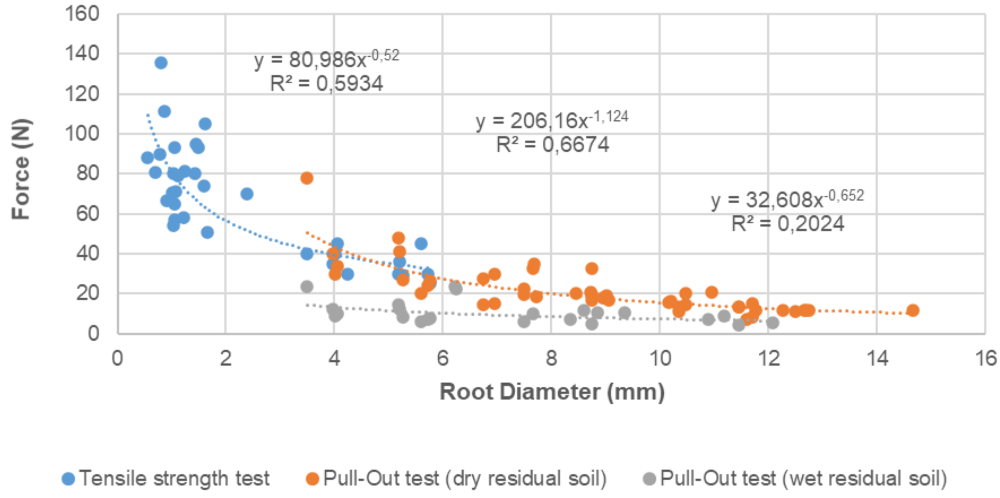

Figure 10. Relationship of tensile strength and pull-out test in dry and wet residual soil

4.6 Numerical analysis with Finite Element Method

To examine scale effects and rainfall, 2D infinite-slope analyses were performed. The following assumptions were applied: homogeneous soil layer, roots providing an apparent cohesion (Δ_c) based on tensile tests, and static loads. Both analytical (LEM) and Plaxis FE simulations were performed for slopes with and without E. Oleina at saturation levels ranging from 10 % (dry) to 100 % (fully wet).

The trend observed in Figure 11 across all three methods indicates that as the soil cohesion increases, the safety factor also increases. This relationship implies that a higher cohesion, which enhances the resistance of the soil to deformation, makes it less prone to failure. This behaviour aligns with fundamental geotechnical principles, where cohesion is a critical factor in soil stability [24].

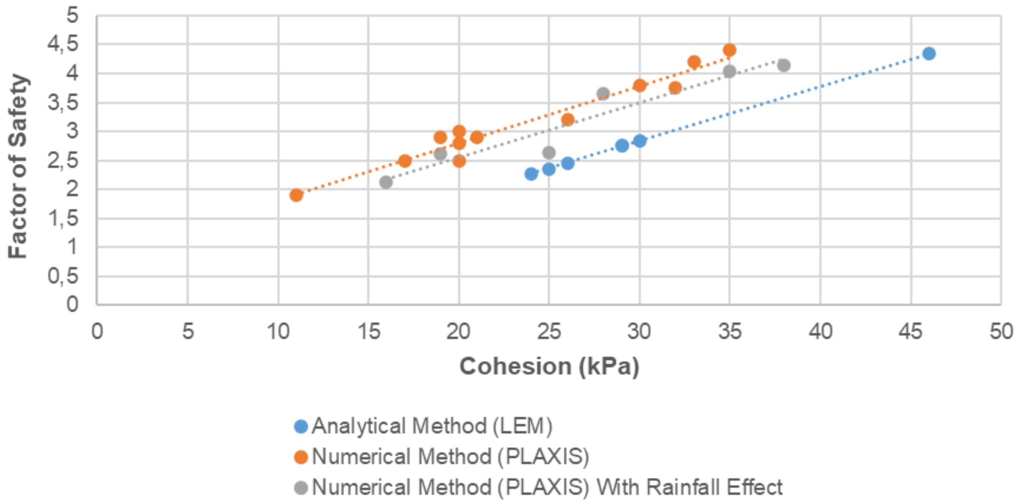

Figure 11. Influence of rainfall in FOS using various methods

The impact of rainfall is evident from the data representing the numerical method (PLAXIS) with the rainfall effect, which consistently shows lower safety factor values compared to those from the numerical method (PLAXIS) without rainfall effect. This result highlights the negative influence of rainfall on soil stability, as increased moisture content due to rainfall reduces the shear strength of the soil, thereby lowering its safety factor.

Although the overall trends are consistent across the three methods, slight variations are observed in the results. These discrepancies are likely due to inherent differences in the methodologies and assumptions used in each analytical or numerical approach. Despite these variations, the graph provides a comprehensive understanding of how cohesion and environmental factors, such as rainfall, influence the factor of safety for soils associated with Eugenia Oleina. All methods showed higher FOS with E. Oleina than bare soil. For a 1,5 m high, 20° slope, FOS increased from approximately 1,3 (bare, 100 % sat) to 1,8 (with vegetation, 10 % sat) [7]. In both cases, the FOS steadily decreased as the saturation increased [5]. The numerical results (Fig. 11) align with laboratory observations in that root cohesion decreases when the soil is wet [5; 4]. In summary, the stability of E. Oleina roots consistently improved under all scenarios; however, heavy rainfall (saturation) reduced the safety margin. The FEA trends were qualitatively validated against experiments; for example, slopes with more roots had predictably higher strength (as in shear tests), and heavy saturation reduced the stability in both models and lab pull-outs [1; 5].

5 Influence of slope height, slope gradient and the soil saturation

Figures 12 and 13 illustrate the relationship between FOS and two key parameters, slope height and slope angle, in the context of bare soil (without vegetation) and slopes reinforced with Eugenia Oleina at varying degrees of saturation (10-100 %). Figure 12 illustrates the FOS against the slope height with a constant slope angle of 20°, it is evident that as the slope height increases, the FOS decreases significantly. The slope transitioned from stable to unstable when the height exceeds 3,5 meters. This pattern indicates that greater slope heights lead to reduced stability because the increased weight and stress on the slope make it more prone to failure. This aligns with the established geotechnical findings of [25], which suggested that taller slopes experience greater gravitational stress, leading to lower stability. For slopes with vegetation, the FOS values were higher than those of bare soil, demonstrating the stabilising effect of Eugenia Oleina. Although the FOS for 10% saturation was slightly higher than that for 100 % saturation, the difference was not substantial, suggesting that vegetation provided consistent reinforcement across different saturation levels.

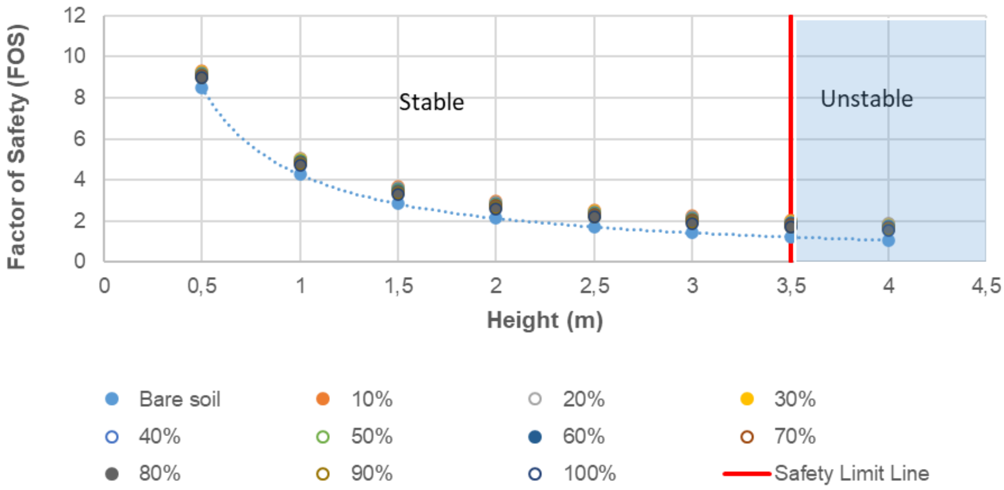

Figure 12. FOS versus height (m) of slope when β=20˚ (slope angle)

Figure 13 shows the FOS plotted against the slope angle, with a slope height constant of 1,5 meters. The FOS decreased as the slope angle increased and became unstable when the angle exceeded 20°, highlighting steepness as a critical influence on stability. Unlike Figure 12, bare soil showed the highest FOS at lower angles owing to the additional weight from the vegetation, reducing FOS at lower angles. Vegetation roots can also facilitate water infiltration, potentially reducing soil cohesion because high water content decreases shear strength [26-

28]. As the slope angle increased, the FOS continued to decrease in all cases, indicating that steep angles compromised stability. This shows that vegetation improves stability, but is not sufficient to prevent failure when critical angles are exceeded.

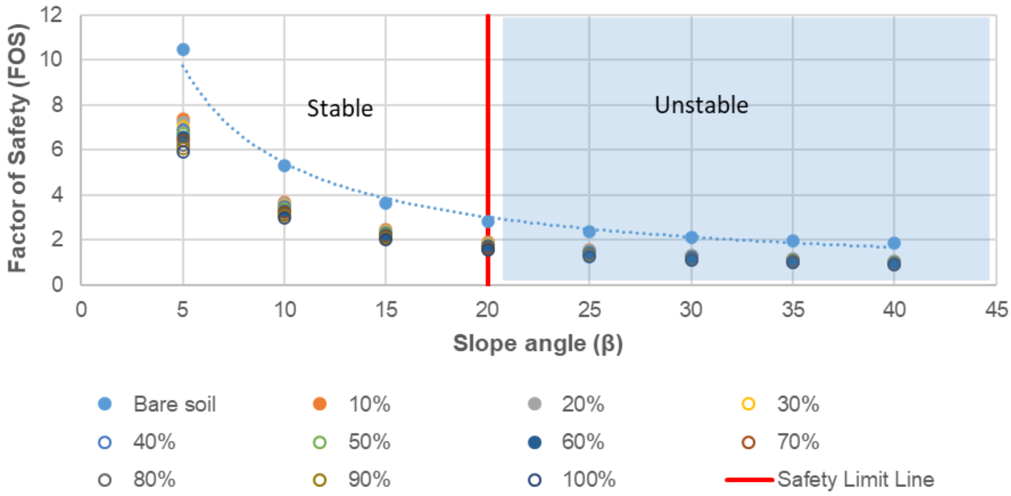

Figure 13. . FOS versus slope angle (β) when H=1,5 m (slope height)

Both slope height and angle significantly influenced slope stability, with vegetation playing a vital role in enhancing slope stability. The critical thresholds for instability (at 3,5 meters of height and slope angle of 20 °) indicate that a combination of steepness and height amplifies the risk of slope failure. Vegetation reduces this risk by increasing the FOS and providing additional bonding and anchorage to the soil matrix. On the other hand, Figure 14 shows that if the saturation of the soil is not monitored, there is a high chance of instability. Although a lower saturation (10%) showed slightly better stability, the relatively small differences across saturation levels suggest that vegetation is effective under a range of moisture conditions. Hence, the limitation of Eugenia Oleina is a slope height of 3,5 meters and slope angle of 20° when the soil is not fully saturated. This reinforces the importance of integrating vegetation such as Eugenia Oleina for slope stabilisation in areas prone to instability. However, compared with other H-type plants (Neolitsez Aurata), Eugenia Oleina has significantly better resistance to slope failure.

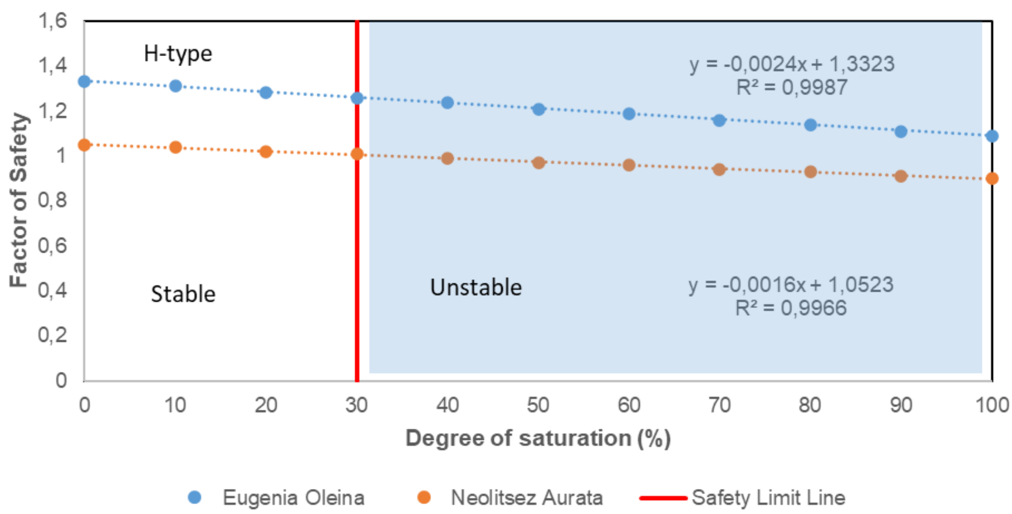

Figure 14. . FOS versus degree of saturation (%)

6 Practical implications and recommendations

The integrated results provided clear guidelines. The H-type roots of E. Oleina are most effective in shallow layers, so they best stabilise slopes up to 20° and approximately 3,5 m high, beyond which FOS falls below unity (Figures 12 and 13) [7; 17]. Planting E. Oleina is especially beneficial in areas of high rainfall, and its dense root mat helps bind the surface soil. Interestingly, our FEA showed that under very heavy rain, the slope's FOS was slightly higher than that under moderate rain because E. Oleina's canopy and roots may intercept or infiltrate large rainfall events more effectively, although absolute stability still decreases with saturation [5]. In practice, combining E. Oleina with other complementary species is recommended to mitigate wet-soil weakness. For example, deep-rooted grasses or trees (e.g., vetiver grass, Vetiveria Zizanioides, known for its 2-3 m long roots [18], or native deep-rooting legumes) can enhance drainage and add tensile reinforcement to the saturated zones. High root-density shrubs (e.g., Leucaena Leucocephala or Acacia Mangium) can also be interplanted, providing multilayer reinforcement [19; 18].
Limitations: the findings of this study were derived from controlled laboratory tests and 2D models using uniform soil. Real slopes are more heterogeneous, and soil layers, root age variability, and scale effects can alter the performance. Our tests were small-scale and did not include factors like root decay or seasonal moisture changes [1; 10]. Therefore, a field validation is required.
Future work: preliminary FEA incorporating external loads (e.g., a modelled road load atop the slope) and finding that an additional surcharge can further mobilise root anchorage and decrease the FOS. A full investigation of the infrastructure and seismic loading is underway. Comparative studies with other species (grass, bamboo, and vines) are also planned.

7 Conclusion

This study successfully explored the effectiveness of bio-inspired soil anchorage systems, specifically utilising Eugenia Oleina, to enhance the bonding between residual soil matrices and improve slope stability in tropical regions. The objectives were thoroughly examined and key findings that contribute significantly to the understanding and application of bioengineering techniques for slope stabilisation were obtained.
H-type roots of E. Oleina markedly enhanced the cohesion and friction of Gambang residual soil, roughly doubling the pull-out strength relative to M-type roots. Tensile tests showed that root strength declined with diameter (power law), and the average root tensile strength of E. Oleina (approximately 50 MPa) was approximately 2,5 times higher than that of the M-type reference species. Slope analyses indicated that E. Oleina vegetation increased FOS by 20-40 % under dry to moderate rainfall. Under heavy rain, the E. Oleina-planted slopes maintained approximately the same reinforcement benefit (FOS reduction was minor), although the absolute stability was the lowest at full saturation. Practically, E. Oleina is best used on slopes ≤ 20° and ≤ 3,5 m high. To counteract the reduced effectiveness in saturated soils, it is suggested to co-plant with species with deeper or more hydrophilic roots (e.g., vetiver grass or deep-rooted shrubs). Finally, the limitations of the laboratory scale and soil uniformity are acknowledged, and it is recommended to conduct future field trials and consider external loads for a comprehensive design.

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