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Soil Reinforcement Modelling on a Hilly Slope with Vegetation of Five Species in the Area Prone to Landslide in Malang, Indonesia

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Malang Indonesia is an area prone to landslides, resulting in the need to model soil reinforcement to determine the vegetation's slope stability using the roots of five species. One of the methods to improve the stability of slopes prone to landslides is adequate vegetation preservation. Soil strengthening with vegetation roots is environmentally friendly and an inexpensive alternative to reduce the vulnerability of slopes along mountainous slopes and the risk of shallow erosions. Therefore, this study aims to evaluate the vegetation arrangement on the slopes in Malang Regency, Indonesia, with a view of geotechnical engineering on the role of its root characteristics. Slope stability was analyzed by modeling the distribution of vegetation roots as an equivalent cohesion approach, where the factor of safety (FoS) is calculated using the PLAXIS-2D version 86 software. Soil and root parameters were obtained through direct shear testing and examining five plant species' tensile strength. The results showed that the highest stability is achieved when the position of the vegetation on the slope's surface is compared to the top. The factor of safety (FoS) increased from 23% to 30% and from 28% to 31% for slopes with uniform and combined species. Of the five plant species, *P. merkusii* demonstrated some advantages in

maintaining stability because it has better root mechanical properties, among others. However, the combined species, such as *C. arabica*, had better performance because they possess vertical and lateral root systems, which act as an anchor in penetrating and gripping the soil. This means combining vegetation species is a preferable preventive measure to increase slope stability. The analysis results also demonstrated the significance of vegetation on slope stability. The results show that the FoS decreases when the slope angle increases and reaches its maximum when the species are combined. The mechanical effect of the plant root matrix system can increase the shear strength of the soil, thereby raising the slope stability. The density of roots in the soil mass and the tensile strength contribute to the soil's ability to withstand shear stresses.

Keywords: slope stability, root distribution system, finite element method, root system approach model.

Introduction

Indonesia is a disaster-prone country, and the occurrence of landslides due to its location in hilly and mountainous areas with fragile land characteristics is one of the responsible events (Islam et al., 2016). A landslide is a form of movement or displacement of soil mass that occurs in a relatively short time in a substantial volume (Hungr, 2014). It occurs due to soil movement on land in hills with slopes, which starts with the arrival of heavy rains (Reichenbach et al., 2018). Several previous studies on the role of plant species in preventing landslides have stated that conducting vegetation engineering and management is imperative. The presence of plants reduces rain retention, absorbs water, and increases shear strength, making the soil stronger to withstand structural failure. Some of these various types of plants are *Dalbergia latifolia* (Black Rosewood), *Andropogon zizanioides* (vetiver), *Cinnamomum zaylanicum* (cinnamon), *Aleurites moluccana* (candle-nut), *Eugenia aromatica* (clove), *Myristica fragrans* (nutmeg), *Parkia speciosa* (stink bean), *Pithecelobium jiringa* (jengkol), *Gnetum gnemon* (belinjo), *Persea Americana* (avocado), *Theobroma cacao* (cocoa), *Coffea arabica* (coffee), and *Camellia sinensis* (tea). According to Hardiyatmo (2012), woody plants can enhance slope stability by root reinforcement. Hardiyatmo further explained that the value of the increase in strength by roots depends on its strength, interaction between soil, branching characteristics, and distribution. Therefore, reinforcement by plant roots will be effective when the roots penetrate the surface soil until they reach the bedrock cracks, fissures, or strong soil.

Several studies have been conducted on using plant root systems for slope stabilization, environmental restoration, and soil erosion prevention in recent years (Zhang et al., 2018). According to Chok et al. (2015), Gentile et al. (2010), and Gonzalez-Ollauri and Mickovski (2017), the hydrological and mechanical effects of vegetation roots can increase slope stability. Root tensile strength is a fundamental mechanical characteristic for increasing soil reinforcement (Genet et al., 2007; Naghdi et al., 2013; Stokes et al., 2004). This is due to its performance in increasing soil cohesion, reducing its deformation, and preventing surface tension cracking (Habibah et al., 2014; Ishak et al., 2016; Temgoua et al., 2016). The shear stress formed in the soil is transferred as tensile resistance to ensure the effect of mechanical strengthening by roots (Bordoni et al., 2016; Gonzalez-Ollauri and Mickovski, 2017; Lateh et al., 2011; Schwarz et al., 2013). The root matrix increases the soil shear strength (Igwe et al., 2014; Lin et al., 2011; Nsengiyumva et al., 2018), while the vegetation of grasses and trees resists rainfall by reducing runoff speed and soil erosion, which is an evapotranspiration function from the hydrological effect (Nsengiyumva et al., 2018; Temgoua et al., 2016). The transpiration function of the vegetation will lead to a decrease in soil moisture. Hairiah et al. (2020) have investigated the lignin content in several tree species. They found that Mahogany (*Swietenia mahogany*) and coffee (*Coffea canephora*) had the strongest roots, gmelina (*Gmelina Arborea*) and suren (*Toona sureni*) had the weakest, and giant bamboo (*Bambusa arundinacea*) had an intermediate root strength.

The effect of vegetation can increase slope stability as a factor of safety (FoS), while the combination of planting trees and grass to protect the erosion area is the best erosion prevention technique (Wang et al., 2020). Vegetation with a tap root system anchored into the soil layer can interact with the slip surface and provide better shear resistance (Fan and Lai, 2014). The FoS is significantly increased with vegetation covering the entire slope compared to when it only grows on the feet or top (Chok et al., 2015; Naghdi et al., 2013). When vegetation grows on all slope parts, the FoS increases significantly by 19% (Chok et al., 2015). The combination of five vegetation types produces maximum safety when vegetation is planted on all slope parts, with an increase of 2234% (Tsige et al., 2020). Many studies have been conducted to assess the ability of vegetation to improve slope stability, but none has examined the variations in combining species of grass, shrubs, and trees, specifically in tropical countries. Therefore, this study aims to determine the effect of the root system mechanism of 5 local vegetation types on soil reinforcement in landslide-prone areas in Malang Regency, Indonesia. The slope stability analysis was used with a conceptual model to arrange the positions of various vegetation on a slope based on their root mechanical characteristics using PLAXIS 2D software version 86 based on the finite element method.

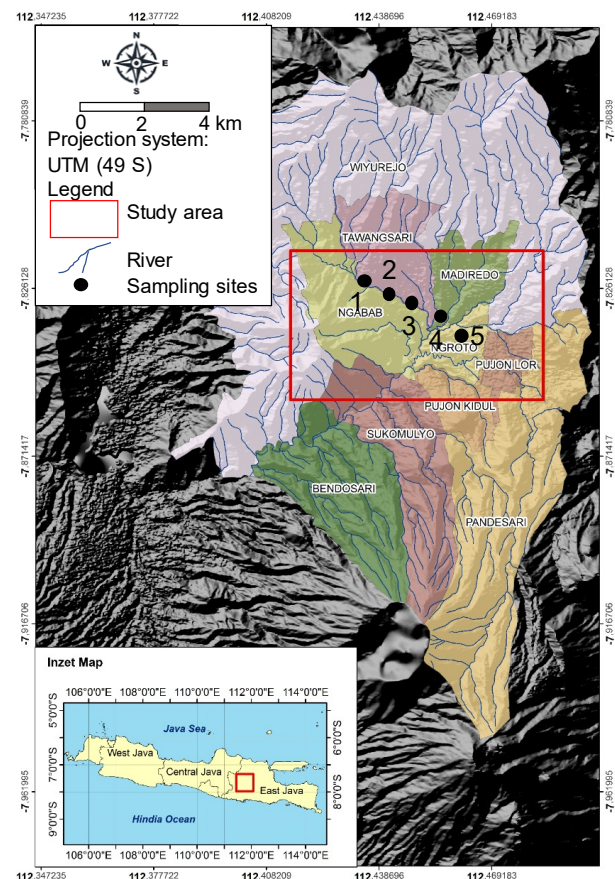
Materials and Methods

Study area

This study was conducted in Malang Regency, East Java, Indonesia, located at $12^{\circ}26'113$ - $122^{\circ}28'923$ East and $7^{\circ}52'203$ - $7^{\circ}49'373$ South, with an average temperature and rainfall of 18 – 23°C and 2140 mm per year, respectively. The soil comprises 82.5%, 10%, 2.5%, and 5% of volcanic material from Mount Welirang and Arjuno, rock weathering, sedimentation, and colluvial components. Furthermore, it is surrounded by mountains, and the topography of the study sites is characterized by a plateau stretching from west to east and north to south with an altitude within 800–1500 m above the sea level. The location is composed of hills and mountains, with 27% of its area at a slope angle of more than 50° . Meanwhile, more than 12%

were classified as critical because of the high risk of landslides, drought, and flash floods (Muttakin, 2014). On February 2, 2017, Ngabab and Ngroto Villages, Pujon District, Malang Regency, experienced a landslide, which caused the road to be completely closed. It is suspected that prolonged rainfall caused the occurrence of landslides. This incident significantly disrupted the community's economic activities, most of which were farming and ranching. The area is indeed against landslides with a shallow category <3 meters, and densely populated above the cliff.

Fig. 1. Five locations of the study site located in East Java, Indonesia



Soil sampling

Soil samples for unvegetated slopes were collected from two plots of land around the vegetation species containing roots and slopes. While for the vegetated slope, soils were sampled from five species,

namely four trees and one shrub, as shown in Fig. 2. The samples were taken at a depth of 100 cm around each selected species, between 25 to 50 cm, with five replications from the tree trunk by inserting a cylindrical metal tube. Subsequently, the tubes containing soil samples were transferred to the Laboratory of Geology and Soil Mechanics of Brawijaya University, Malang, East Java, Indonesia. This was conducted to examine the mechanical properties of soil samples according to ASTM standards. The ends of the cylinder were sealed with paraffin to maintain natural soil moisture. Samples from the collected cylinders were immediately tested by printing three to four specimens from each cylinder with the existing molds in the laboratory at a diameter of 6 cm and height of 1.785. The soil from an unvegetated slope was sampled in the same way as on land without vegetation.

Root sampling

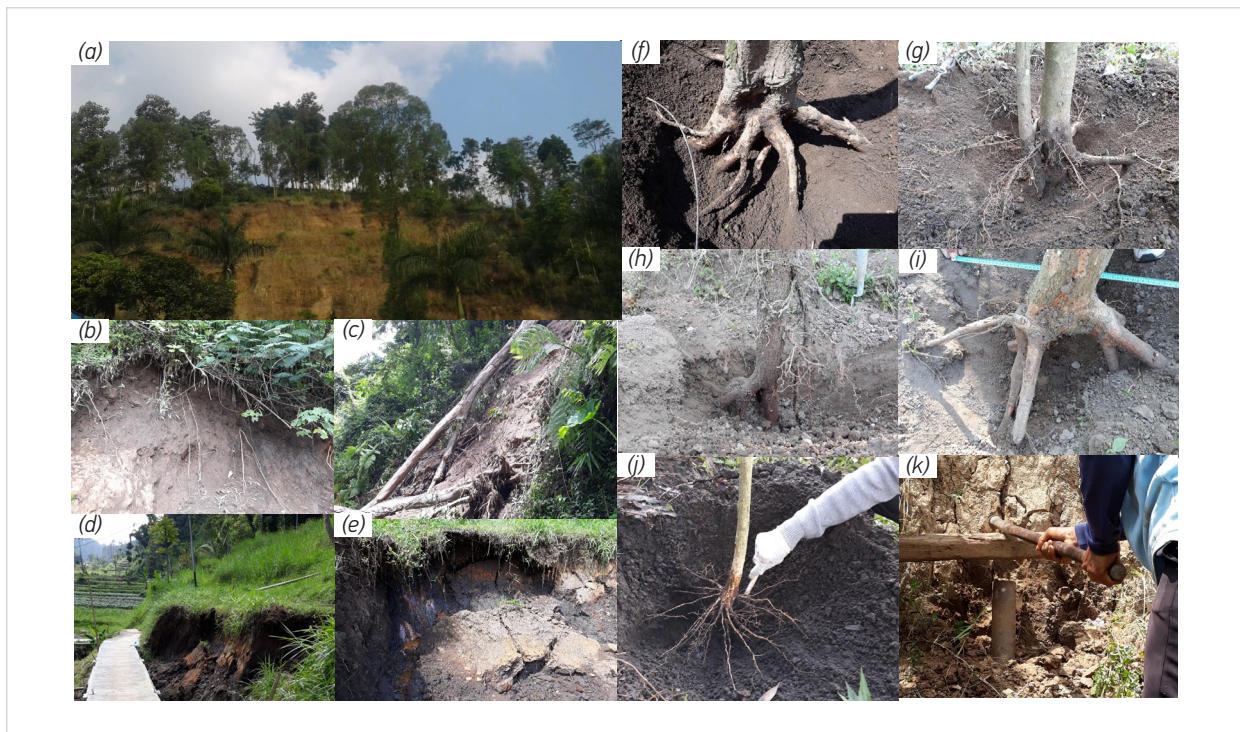
A total of five vegetation species were randomly selected to assess the physical characteristics of the

roots. The dry digging method was carried out carefully at a depth of approximately 50–60 cm below the soil surface (Cofie and Koolen, 2001; Abdi, 2014), gradually clearing the soil surrounding the root surface, as shown in Fig. 2. The stem and root diameters at breast height were measured using tape and calipers, respectively. The root diameter varied between 1 to 10 mm, and the length ranged from 20 to 25 cm. Furthermore, 750 selected root samples were collected from 25 plots of five species with five replicates. Each plot consisted of 30 samples that were transferred to the laboratory for further analysis.

Field and laboratory procedures

In the laboratory, soil samples were prepared for direct shear testing with the same soil moisture content at the time of sample collection. The test was performed by applying normal and shear forces based on the shear surface (ASTM D-3080). The normal stress applied to the specimens consisted of 0.4 kg, 0.8 kg, and 1.2 kg with three replications. Therefore, for each

Fig. 2. Indonesia landslide slope area: (a) site 1, (b) site 2, (c) site 3, (d) site 4, (e) site and soil and root sampling: (f) *Eucalyptus* sp., (g) *P. merkusii*, (h) *A. dammara*, (i) *T. ciliata*, (j) *C. arabica*, (k) unvegetated soil sample



sample tube, three specimens were made, with a total of 15 specimens for soil with roots and nine specimens for control. The tests for water content, specific gravity, density, and sieve content of the soil were carried out according to Standard Test Methods for Laboratory Determination. The degrees of saturation (S_r), porosity (n), pore number (e), density (γ_s), specific gravity (G_s), and dry density (γ_d) were measured in line with Maffra et al. (2019) as the reference. All data obtained from field surveys and laboratory tests were analyzed using MS Excel 2010.

The roots were examined thoroughly for possible damage in the laboratory, while the root hairs were cleaned carefully and their samples cut into pieces to a length of 15 cm (Abdi, 2014; Cofie and Koolen, 2001), or 15 times its diameter (Genet et al., 2005). Measurements to assess root tensile strength were carried out on 30 samples per species with a diameter between 1.00 and 6.00 mm, including the root bark, two days after taking the samples from the field. The average root diameter was determined by measuring the diameter at three different positions along with the root size with a Vernier clipper (Abdi, 2014; Abdi et al., 2010; De Baets et al., 2008). Tensile strength tests were carried out by clamping the two ends of the roots connected by clamps to the drive system and measured with a strain rate of 10 mm/min until root break (Abdi, 2014; Abdi et al., 2010; Bischetti et al., 2005; Mattia et al., 2005). Only the samples that break at one-third or in the middle along the roots between the clamps were considered valid and were subsequently broken by force applied in the stress concentrations close to the clamp (Genet et al., 2008). The maximum force required to break the root was used as a measure of force, while F (kPa) and the root tensile strength (MPa) was calculated by dividing the force F by the cross-sectional area of the root at the breaking point.

$$T_R = \frac{F_{max}}{\left(\frac{\pi}{4}\right)xD^2} \quad (1)$$

Where: T_R is the tensile strength;
 F_{max} is the maximum force to move the roots;
 D is the diameter of the roots.

The presence of tree roots in the soil matrix increases soil cohesion (c_R) and affects root reinforcement due to additional cohesion, which improves slope stability (Genet et al., 2008; Schmidt et al., 2001; Van Beek et al., 2005). It was discovered that the root-soil strengthening model was in the Mohr-Coulomb failure criteria (Wu, 1976), which is widely used to estimate additional root cohesion in the soil (Bischetti et al., 2005; Genet et al., 2008; Roering et al., 2003). A previous study has also proposed a simplified perpendicular root model to measure the increase in soil shear strength due to root reinforcement. This model calculated the increase in the shear strength of the root-soil composite (τ_R) as follows:

$$\tau_R = (c' + c_R) + \sigma \tan \phi' \quad (2)$$

Where: τ_R is shear strength of the root-soil composite;
 c' is the effective soil cohesion;
 c_R is the apparent cohesion provided by the roots;
 σ is normal stress in the shear plane;
 ϕ' is an effective angle of internal friction.

In soil, shear forces develop when the soil layer moves from a tensile force on the roots, divided into tangential and normal components. When the elastic roots are oriented perpendicular to the slip plane, the roots are fully mobilized under tension and unaffected by root reinforcement. Meanwhile, the c_R is formulated as follows:

$$c_R = \tau_R (\sin \delta + \cos \delta \tan \phi) \quad (3)$$

Where: δ is the angle of shear distortion in the shear zone;
 ϕ is the soil friction angle ($^\circ$);
 τ_R is the total mobilized tensile stress of roots fibers per unit area of soil.

The t_R is expressed as the product of T_R , and the average tensile ($\sin \delta + \cos \delta \tan \delta$) is estimated as 1.2 (Waldron, 1977; Wu et al., 1979). In this study, the value 1.2 was used to reformulate Equation (3) as follows:

$$c_R = 1,2 \times t_R \quad (4)$$

Both α_R and T_R are influenced by species and location factors, such as climate, soil type, land management, root type and size, and root orientation in soil (Genet et al., 2008; Operstein and Frydman, 2000). The tensile strength of the roots mobilized per unit area of land (t_R) is written as follows:

$$t_R = T_R \times \alpha_R \quad (5)$$

Where: T_R is the average tensile strength per cross-sectional area of the roots mean;

α_R is the ratio of root areas. α_R is calculated as A_R/A , where A_R is the total cross-sectional area of all roots and A is the soil area in the number of samples.

Slope stability analysis

PLAXIS software

Analysis of the determination of the stability and deformation experienced by slopes in this study was conducted with the PLAXIS, a tool used to model more complex geotechnical scenarios due to its capabilities to simulate inhomogeneous soil properties and time-dependent scenarios (Brinkgreve, 2002; Hammouri et al., 2008). The models produced by PLAXIS can be considered a qualitative representation of the soil's behavior. It utilizes the staged construction approach and simulates construction in the solving process and time steps in the analysis. The solving process used in PLAXIS is more complex than other software, such as FLAC and SLOPE/W, which require more time to input the necessary parameters and uses the correct procedure to perform the analysis. PLAXIS can produce more detailed model results than FLAC and SLOPE/W.

PLAXIS analysis

- 1 Upon starting PLAXIS, the title and model of the project units and dimensions need to be set.
- 2 The model is drawn using the inbuilt CAD interface, which contains a non-horizontal soil surface. The geometric profile of the slope and root patterns are shown in Figs. 3 and 4.
- 3 The material properties need to be created and assigned. PLAXIS requires the advanced properties of E and ν of the soil and the stand Mohr-Coulomb (Tables 1 and 2).

- 4 The restraints are set as standard fixities.
- 5 The mesh is generated. A fine mesh is being used to help improve accuracy.
- 6 In the calculation phase, the initial stresses were calculated using gravity loading. There are three phases of calculation: the first two are the plastic calculations, and the last is the phi/c reduction, which is used to determine the FoS.

The stability analysis method successfully reduces the soil shear resistance parameters, cohesion and internal friction angle, while keeping the gravity load constant (Kokutse et al., 2006). The soil mass strength parameters, comprising $\tan\phi$ and c , are reduced using a strength reduction factor until the slope collapses. Large deformations characterize this failure in the soil mass with a slight decrease in strength parameters. The strength reduction factor in the phi-c reduction procedure is stated in Equation (6):

$$M_{sf} = \frac{\tan \phi_{input}}{\tan \phi_{rebound}} = \frac{c_{input}}{c_{rebound}} \quad (6)$$

Where: M_{sf} is the multiplier used to define the reduced strength parameters at a given stage;
 ϕ_{input} is the input friction angle;
 c_{input} is the input cohesion;
 $\phi_{rebound}$ is the reduced friction angle at a given stage;
 $c_{rebound}$ is the reduced cohesion at a given stage.

The power reduction factor is set to a score of 1.0 at the beginning of the calculation. After evaluating the displacement at the nodal point close to the slope surface, the variation of the strength reduction factor was determined (Fan and Tsai, 2016). Furthermore, the slope failure was evaluated using a constant strength reduction factor obtained as deformation continues. The slope factor of safety (FoS) was determined by calculating the ratio of available soil strength to the reduced soil strength at failure. The formula is stated in Equation (7).

$$FoS = \frac{\text{Available Strength}}{\text{Strength of failure}} M_{sf} \text{ at failure} \quad (7)$$

This study aims to investigate the effect of root reinforcement when vegetation is planted on slopes to determine the slope geometry, dimensions, and positions. The approach used to describe the distribution of roots was the hearth root system as equivalent cohesion (Kokutse et al., 2006; Sambasivarao, 2015). The input parameters of soil used for modeling include the unit weight (γ), young modulus of elasticity (E), Poisson's ratio (ν), cohesion (c), and friction angle (ϕ), as illustrated in *Table 1*. Meanwhile, the input parameters related to vegetation used in the PLAXIS 2D model are apparent root cohesion (c_R), young modulus of elasticity (E), and depth of root zone (h_R) for shallow landslides, as shown in *Table 2*. The influence of the spatial distribution of vegetation on slope stability was also evaluated, while slope conditions determined the FoS. These included 3 layers of soil with a height ($H = 20$ m), variable angle of inclination ($\alpha = 30^\circ$ and $\alpha = 45^\circ$), variable of root cohesion (c_R), and root zone at depth ($h_R = 2$ m). In this study, the

FoS increased due to root strengthening and was also calculated as a percentage increase, as follows (Abdi, 2014; Genet et al., 2008).

$$\text{Increase of } FoS = \left[\frac{FoS_{with\ roots} - FoS_{without\ roots}}{FoS_{without\ roots}} \right] \quad (8)$$

Modeling the influence of vegetation on the slope

Slope stability modeling was carried out in three scenarios, which consisted of (a) nonvegetated slope modeling, (b) uniform vegetation species modeling, and (c) mixed vegetation species group modeling.

Scenario 1 – Analysis of slope stability without vegetation roots

This model is a simulation of slope stability analysis based on soil properties with and without the root of the slope angle of 30° and 45° . The geometric sketch and soil parameters slope stability analysis are shown in *Fig. 3* and *Table 1*.

Fig. 3. Geometry sketch of slopes without vegetation: ($\alpha = 30^\circ$) and ($\alpha = 45^\circ$)

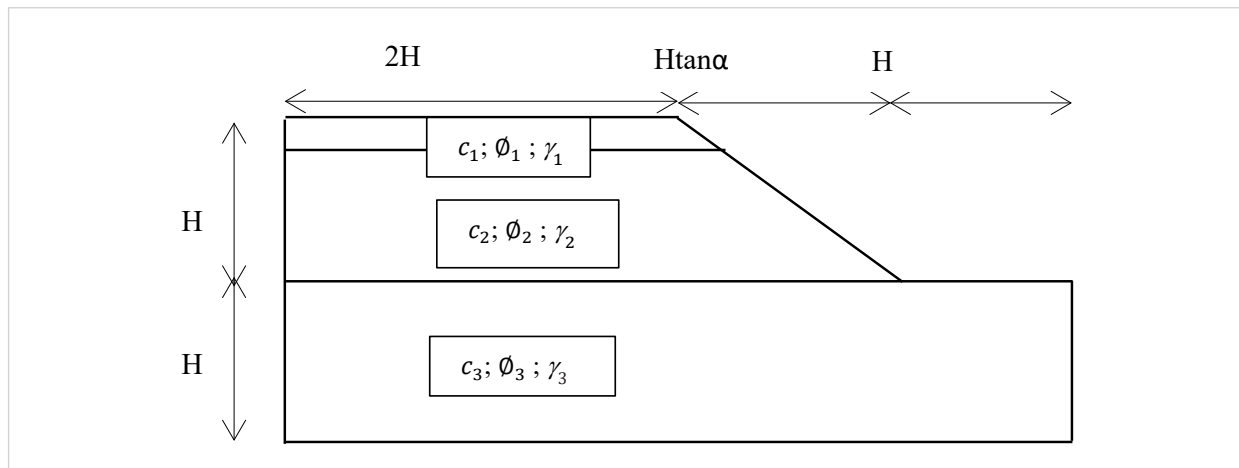


Table 1. Soil parameters for slope stability analysis

Soil layer	c (kN/m ²)	ϕ ($^\circ$)	γ_s (kN/m ²)	γ_d (kN/m ²)	E (MPa)	ν
Layer 1	0.12	39.14	13.91	11.37	15	0.3
Layer 2	1.50	45.15	14.10	11.44	15	0.3
Layer 3	9.47	30.81	11.72	9.02	15	0.3

Table 2. Root parameters for slope stability analysis with root as equivalent cohesion approach

Species	Heart root system (R = Z)	ν (-)	C_R (kPa)
<i>A. dammara</i>			10.12
<i>T. ciliata</i>			9.51
<i>Eucalyptus</i>	(R = 2m dan Z = 2m)	0.35	7.90
<i>P. merkusii</i>			11.91
<i>C. arabica</i>			8.22

Scenario 2 – Analysis of slope stability with uniform vegetation

The second modeling was carried out by analyzing the slope stability, which consisted of grass and uniform vegetation with tree and shrub species in group 1. The root system is modeled as cohesion equivalent by assuming that the vegetation roots are a heart root system on slopes, where the simulation is carried out at a depth of 2 m from the soil surface (Kokutse et al., 2006). At the top of the slope, the root system of the heart, which has a taproot, penetrates the soil, and lateral roots that spread become an ideal architecture to protect the soil from slope failure (Norris et al., 2008). The slope geometry with vegetation consists of

three layers with soil and root properties of five species, as shown in *Tables 1 and 2*. Root properties of a grass species (*C. rotundus*) for slope stability analysis are based on Yanhar and Nasution (2018).

Table 3. Root properties of a grass species (*C. rotundus*) for slope stability analysis

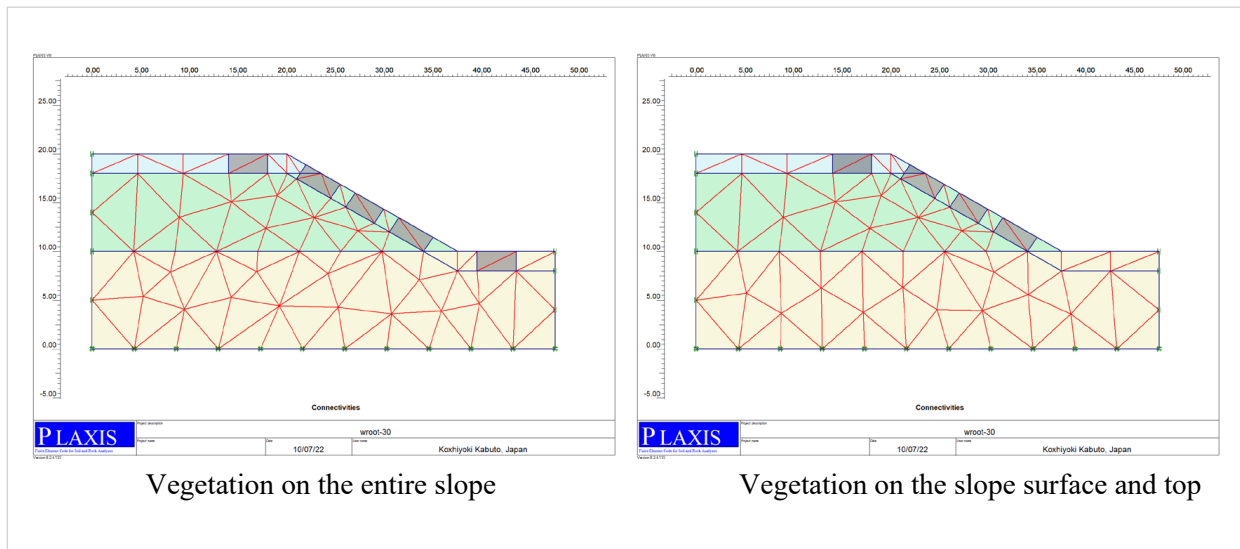
Species	h_R (m)	n	C_R (kPa)
<i>C. rotundus</i>	0.3	0.35	5.232

Source: Yanhar and Nasution, 2018

Scenario 3 – Analysis of slope stability with mixed vegetation

The third slope stability modeling was carried out by planting grass species and groups of a mixed tree and shrub vegetation. The simulation of slope stability analysis in scenario 3 was conducted with the geometry of the vegetation slope in *Fig. 4*, which consists of three layers with soil properties (*Table 1*) and roots of shrubs and trees (*Table 2*). Meanwhile, alternative positions for grouping mixed vegetation types are based in *Table 4*.

Fig. 4. Geometry of vegetation slopes ($\alpha = 30^\circ$) and ($\alpha = 45^\circ$) with roots as an equivalent cohesion approach at a depth of 2 m to simulate slope stability analysis at 4 planting systems



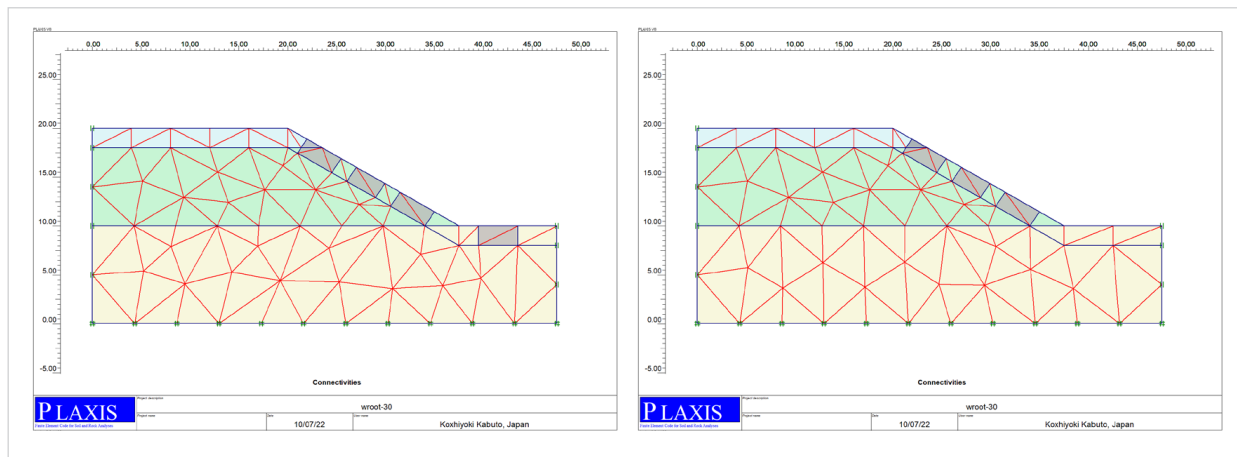


Table 4. Alternative of clumped position vegetation on slopes

Plant position	Species combination				
	Alternative 1	Alternative 2	Alternative 3	Alternative 4	Alternative 5
Entire slope	<i>C. rotundus</i>	<i>C. rotundus</i>	<i>C. rotundus</i>	<i>C. rotundus</i>	<i>C. rotundus</i>
Crest slope	<i>P. merkusii</i>	<i>P. merkusii</i>	<i>C. arabica</i>	<i>C. arabica</i>	<i>P. merkusii</i>
Surface slope	<i>C. arabica</i>	<i>A. dammara</i>	<i>T. ciliata</i>	<i>A. dammara</i>	<i>T. ciliata</i>
Toe slope	<i>T. ciliata</i>	<i>C. arabica</i>	<i>Eucalyptus sp.</i>	<i>Eucalyptus sp.</i>	<i>C. arabica</i>

Results and Discussion

Soil shearing strength

The roots increase the shear strength of the soil because they contribute to additional cohesion improvement. The highest and lowest soil shear strength values of 59.23 kN/m² and 55.22 kN/m² were discovered in *P. merkusii* and *Eucalyptus sp.*, as shown in Table 5. Furthermore, the average increase in shearing strength with roots ranged from 17% to 25%.

Several studies have reported that roots improve soil cohesion without changes to the internal friction angle (ϕ). The direct shear test indicated no changes in the internal friction angle for soils with roots. Meanwhile, there are few reports on roots' effect on the soil's internal friction angle. This is because most related studies merely focus on the role of roots on soil cohesion values. In this study, the direct shear test showed that the average values of the soil's

Table 5. Index properties and engineering properties of soil samples

Soil condition	species	c' (kN/m ²)	ϕ (°)	τ_R (kN/m ²)
Unvegetated soil	none	0.12	39.14	47.2
	<i>A. dammara</i>	10.24	25.36	57.44
	<i>T. ciliata</i>	9.63	25.52	56.83
Vegetated soil	<i>Eucalyptus sp.</i>	8.02	27.46	55.22
	<i>P. merkusii</i>	12.03	28	59.23
	<i>C. arabica</i>	8.34	28	55.54

internal friction angle (ϕ) with and without roots were 26.87° and 39.14°. This indicated that the root reduces the soil shear strength by 30% through the internal friction angle. Furthermore, the increase in soil shear strength was significant in the presence of roots due to a greater increase in the cohesion value by 61%. This is in line with the value of the sandy soil shear strength parameter described in the previous studies,

which discovered that the main contribution of roots is mainly due to an increase in cohesive interception (Maffra et al., 2019; Veylon et al., 2015). The shear strength of sandy soils with little silt is affected by the increase in cohesion because of their grain characteristics and decreases in the internal friction angle. This is also in line with the condition that the cohesion value of pure sand soil is close to zero and vice versa. The direct shear test results have shown that the shearing strength of soils without roots is lower than those with roots (Abdi, 2014; Maffra et al., 2019). This information can become part of the technical justification that supports the use of vegetation to control erosion processes and slope stabilization.

Root shearing strength

The results of laboratory tests on the tensile strength of the roots of the five plant species showed the importance of root diameter. In general, the roots' tensile strength increased with a decrease in the diameter (Fig. 5), while the value of the root tensile force has the opposite trend (Fig. 6). The relationship between the tensile strength of the roots and the diameter depends on the vegetation species because when the root diameter ranged from 1 to 6 mm, the maximum tensile force of bush and tree was 30 N and 40 N, respectively. This showed that the greater the tensile strength of a root, the higher the ability to increase soil shearing strength (Hu et al., 2013).

Fig. 5. Relationship between mean tensile strength versus root diameter of 5 species

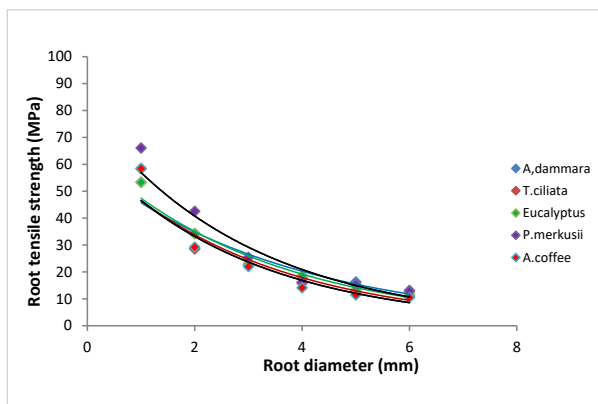
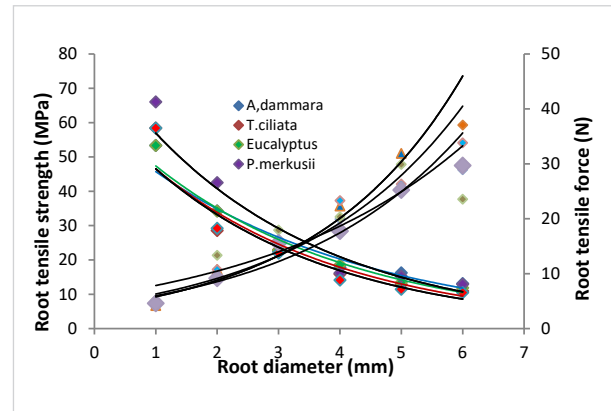


Fig. 6. The relationship between mean tensile strength vs root diameter ($y = 68.513e^{-0.323x}$) and mean tensile force vs root diameter ($y = 4.673e^{0.3418x}$)



This study showed that the species with the highest and lowest root tensile values of 29.72 MPa and 24.29 MPa are *P. merkusii* and *C. arabica*, as indicated in Table 6. The relationship between tensile strength and root diameter was tested by several regression models, where the best strength was predicted based on a higher R square of 0.9401.

Table 6. Average values of single root tensile force and root tensile strength

Species	Average of tensile force (N)	Average of tensile strength (MPa)	Sample number
<i>A. dammara</i>	19.6	26.23	25
<i>T. ciliata</i>	16.5	24.92	22
<i>Eucalyptus sp.</i>	18.5	25.72	27
<i>P. merkusii</i>	19.6	29.72	26
<i>C. arabica</i>	16.5	24.29	21

According to Abdi (2014), the tensile strength of the roots can influence soil reinforcement on slope stability because it varies between species and the environment. Small diameter roots have a more flexible character, high tensile strength, and a strong friction zone between the roots and the soil. Meanwhile, with their stiffness, large-diameter roots resisted shear

and bending, serving as sturdy anchors. The combination of these two root sizes supports the tree to stand upright (Abdi, 2014; Bischetti et al., 2005). The results showed that the roots of the species in the study area contribute to the shear strength of the soil and increase slope stability.

Root cohesion

The highest and lowest root cohesion of 11.91 kPa and 7.9 kPa were discovered in *P. merkusii* and *Eucalyptus sp.* species. In this study, the value of root cohesion (c_R) is additional due to roots, where the c_R for the five species was calculated from the direct shear test results. The root cohesion was also evaluated by reducing the cohesion of soil samples with and without roots (Zhang et al., 2014). The c_R is the difference between soil and root cohesion against rootless soil at layer-1. The value of the root area ratio (RAR) for each species was calculated from equation (4) where c_R equals $1.2 T_R RAR$ (kPa). The results showed that the RAR was highest and lowest in *P. merkusii* and *C. arabica*, with values of 0.401 kPa and 0.282 kPa, as shown in Table 7. In the literature, the variability of the RAR value is significantly high for several species, even in the same vegetation group or the species in different locations (Bischetti et al., 2009). The RAR value obtained is still within the value limit of previous studies conducted by Bischetti et al. (2009), De Baets et al. (2008), and Leung et al. (2015), at values of 0 to 0.5%. Meanwhile, the root cohesion (c_R) values ranged from 1 kPa to 17.5 kPa.

Table 7. Value of additional root cohesion and RAR of five species

Species	Tensile strength (MPa)	Root cohesion (MPa)	RAR (kPa)
<i>A. dammara</i>	26.23	10.12	0.322
<i>T. ciliata</i>	24.92	9.51	0.318
<i>Eucalyptus sp.</i>	25.72	7.90	0.256
<i>P. merkusii</i>	29.72	11.91	0.401
<i>C. arabica</i>	24.29	8.22	0.282

Scenario 1 – Analysis of slope stability without vegetation roots

The results of the slope stability analysis with scenario 1 without including the effect of strengthening

vegetation roots showed a FoS value of 1.7273 and 1.0764 at angles of 30° and 45°. This indicates that soil stability occurs on relatively stable gentle slope conditions of FoS > 1.25 and becomes unstable on steep slope conditions < 1.25, as shown in Table 8.

Table 8. Factor of safety (FoS) for unvegetated slope

Slope geometry	FoS	Note
($\alpha = 30^\circ$)	1.7273	stable slopes
($\alpha = 45^\circ$)	1.0764	unstable slopes

Scenario 2 – Analysis of slope stability with uniform vegetation

In the second scenario, the highest average FoS when planting uniform vegetation increased by 23.81% and 32.17% at the slope angles (α) of 30° and 45° compared with the slope without vegetation. In this system, uniform vegetation comprising *P. merkusii* and *C. rotundus* had the highest contribution, for both slope angles. Meanwhile, *Eucalyptus sp.* and *C. rotundus* had the lowest FoS contribution for slope angles at 30° and *C. rotundus* and *C. arabica* at 45°, as shown in Table 9.

Table 9. Factor of safety (FoS) for vegetated slope with uniform species

Slope angle (°)	$\alpha = 30^\circ$	Increment (%)	$\alpha = 45^\circ$	Increment (%)
Unvegetated slope	1.7273	-	1.0764	-
<i>A. dammara</i> and <i>C. rotundus</i>	2.2360	22.75	1.5633	31,15
<i>T. ciliate</i> and <i>C. rotundus</i>	2.2295	22.53	1.5475	30,44
<i>Eucalyptus sp.</i> and <i>C. rotundus</i>	2.2204	22.21	1.5173	29,06
<i>P. merkusii</i> and <i>C. rotundus</i>	2.2670	23.81	1.5869	32,17
<i>C. arabica</i> and <i>C. rotundus</i>	2.2235	22.32	1.5272	29,52
average	2.2353	22.71	1.5484	30,30

Scenario 3 – Analysis of slope stability with mixed vegetation

On the slopes of vegetation using mixed species, FoS increased by 28% and 31% at the slope angle of

30° and ranked 1st, as shown in *Table 10*. The effect of combined species on increasing slope stability is shown in *Table 11*. In contrast, the summary scheme of the mechanical effect of vegetation on slope stability at angles (α) 30° and 45° is presented in *Fig. 8*. Based on the results, the combination of grass, shrub, and tree increased the soil stability. The FoS value at a slope of 30° was 2.3990 with an increment of 28%, while at 45°, it was 1.5609 with a 31% increase. Therefore, this study recommended planting *C. arabica*, *P. merkusii*, *C. rotundus*, other grasses and herbs in the upper part of the slope, trees with roots anchored inward in the middle, and *C. arabica*, *T. Ciliata*, *Eucalyptus* sp., *C. rotundus*, grasses, and herbs at the toe.

These results supported the discovery that FoS increases by 19% when vegetation is planted over all

parts of the slope (Chok et al., 2015). Naghdi et al. (2013) stated that FoS was highest when the vegetation was on the entire slope. According to Habibah et al. (2014), slope stabilization is more effective for vegetation planted at the foot than in other parts. The effect of vegetation on the top and surface slopes on the factor of safety is better than at the foot when the plant root system penetrates the solid soil (Fan and Lai, 2014). Furthermore, slopes with mixed vegetation have increased FoS by 22% to 34% (Tsige et al., 2020). The discoveries of some of these studies have concluded that environmental factors with grown vegetation played an important role in strengthening the soil. These results have also shown that the combination of various species improves slope stability (Hairiah et al., 2006; Teerawattanasuk et al., 2014).

Table 10. Factor of safety (FoS) for vegetated slope with mixed species

Position	Species	$\alpha = 30^\circ$		$\alpha = 45^\circ$		Ranking
		FoS	Increment (%)	FoS	Increment (%)	
Un-vegetated slope		1.7273	-	1.0764	-	
Entire slope	<i>C. rotundus</i>	2.3990	28.00	1.5609	31.00	1
Crest slope	<i>P. merkusii</i>					
Surface slope	<i>C. arabica</i>					
Toe slope	<i>T. ciliata</i>					
Entire slope	<i>C. rotundus</i>	2.3925	27.80	1.5577	30.90	4
Crest slope	<i>P. merkusii</i>					
Surface slope	<i>C. arabica</i>					
Toe slope	<i>T. ciliata</i>					
Entire slope	<i>C. rotundus</i>	2.3874	27.65	1.5416	30.18	3
Crest slope	<i>P. merkusii</i>					
Surface slope	<i>C. arabica</i>					
Toe slope	<i>T. ciliata</i>					
Entire slope	<i>C. rotundus</i>	2.3737	27.23	1.5399	30.10	2
Crest slope	<i>P. merkusii</i>					
Surface slope	<i>C. arabica</i>					
Toe slope	<i>T. ciliata</i>					
Entire slope	<i>C. arabica</i>	2.3569	26.71	1.5299	29.64	5
Crest slope	<i>T. ciliata</i>					
Surface slope	<i>C. rotundus</i>					
Toe slope	<i>P. merkusii</i>					

A mixture of tree species with deep roots and grass with fine and strong roots provide the highest river bank stability (Hairiah et al., 2020). Moreover, vegetation provides stability because its deep roots allow it to hold the soil aggregates to fix the strata, while the surface is stabilized by grass. This indicates that the presence of a mixture of several species is preferable. Based on the results, it is concluded that the slope

stability reaches its maximum when the species are combined with ratings of 1 to 5, as shown in *Table 11*. The effect of mixed species on increasing slope stability is shown in *Table 11*, while a schematic summary of the mechanical effects of vegetation on slope stability for ($\alpha = 30^\circ$) and ($\alpha = 45^\circ$) is indicated in *Fig. 7*, by pruning *C. arabica* leaves periodically, to avoid loading the slope.

Table 11. Factor of safety (FoS) for vegetated slope with uniform species

Species group	$\alpha = 30^\circ$		$\alpha = 45^\circ$	
	FoS	increment (%)	FoS	increment (%)
Un-vegetated slope	1.7273	-	1.0764	-
Grass	2.1084	18	1.2738	15
Tree	2.1394	19	1.4527	26
Grass and shrub	2.2235	22	1.5275	30
Grass, shrub, and tree (uniform)	2.2353	23	1.5484	30
Grass, shrub, and tree (combination)	2.3990	28	1.5609	31

Fig. 7. Summary scheme of the mechanical effect of vegetation on slope stability for ($\alpha = 30^\circ$) and ($\alpha = 45^\circ$)

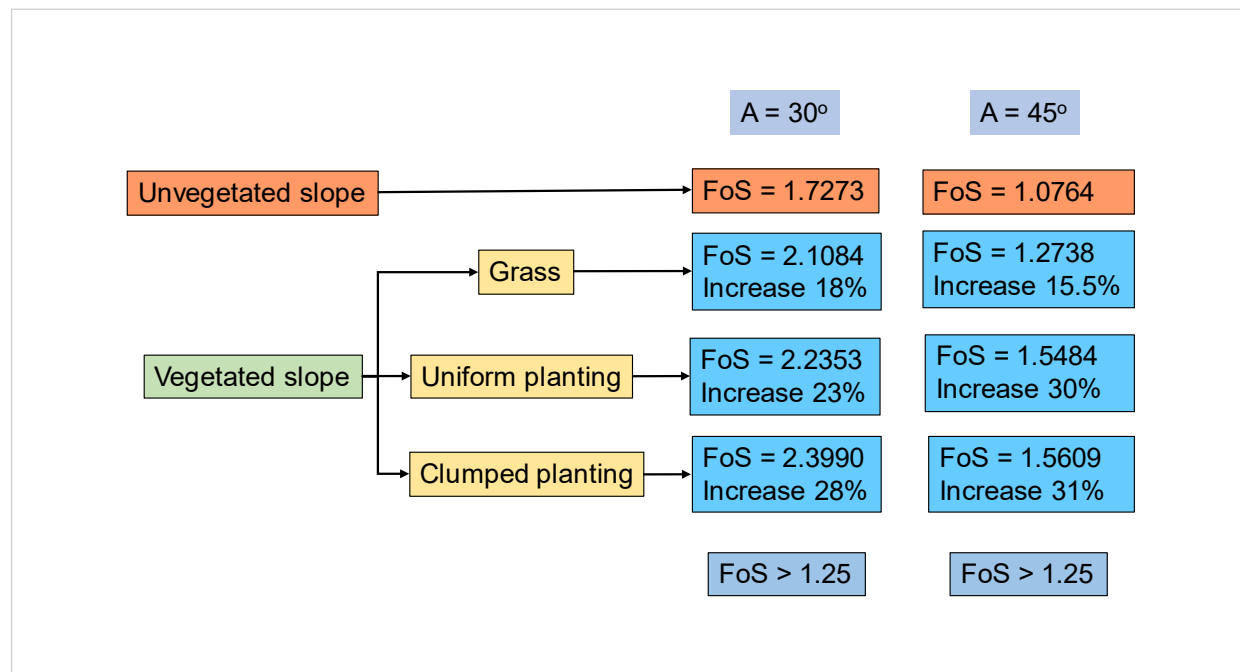
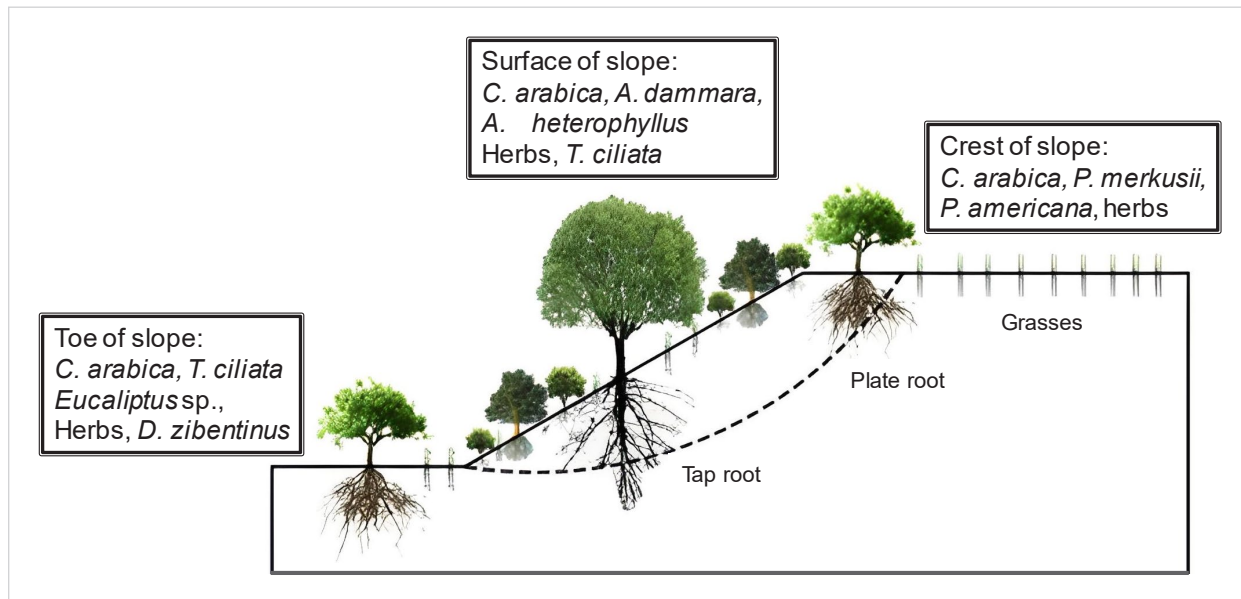


Fig. 8. Model of the planting position



Conclusions

Slopes with the same geometric configuration are initially unstable without reinforced vegetation roots but become more stable when reinforced. In general, slope stability increases with a rise in root cohesion value and effective root zone depth, thereby supporting its FoS. This is achieved on slopes with vegetation covering the surface and top compared with other positions. With the taproot system of *P. merkusii*, *T. ciliata* species, and a combination of the taproot and heart system, coffee can penetrate the soil while gripping the surrounding soil. This study expanded the knowledge of the biomechanical characteristics of the dominant species growing in rugged terrain with a geotechnical engineering view. As the vegetation extends over the entire soil surface, the increase in FoS of the slope becomes more significant, where the effect increases with a rise in the root system depth, reaching the zone where the failure mechanism is initiated. The results showed that FoS of the slopes increased by an average of 26% for uniform vegetation types and 30% for mixed vegetation compared with slopes without vegetation. The FoS of slopes with a uniform plant species composition is about 4% lower than mixed planting. In addition, the stability of the vegetated slope is

influenced by the architectural distribution pattern of the root system and the modeling method in the soil. Therefore, of the five plant species studied, *P. merkusii* and *C. arabica* are the most promising for slope revegetation due to their better root density and mechanical characteristics that support and grip the soil.

Future Study Suggestions

Further studies on the use of vegetation need to apply technology to observe the role of root characteristics of various plants. Other factors such as soil type and plant age must be considered to obtain more general results. In addition, further study is recommended to observe the combination of hydrological and mechanical roles of vegetation roots on slope stability by including the influence of rainfall, which is often one of the triggers of landslides in Indonesia.

Study Limitations

This study is limited to the Ngroto and Ngabab Villages, Pujon District, Malang Regency. The scope of the parameters studied includes soil with slope geometry determined by reviewing the mechanical effects of selected vegetation roots on their stability. However, the scope of parameters related to earthquake and wind factors was not reviewed.

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