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Modelling of Vegetation on Slope Stability: Investigation of Soil Reinforcement with Roots of Three Species in an Area Prone to Landslides in Malang Indonesia

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Abstract:

Conventional geotechnical engineering methods, such as retaining structures, soil nailing, passive pile or a combination thereof, are often applied for slope stabilization. However, this structure is less environmentally friendly and expensive and less feasible for areas that are difficult to reach by heavy equipment during its implementation. Currently, soil strengthening with vegetation roots is recognized as an environmentally friendly and inexpensive alternative to reduce the vulnerability of slopes along mountainous transportation routes to the risk of shallow landslides. Therefore, the aim of this study was to evaluate the vegetation arrangement on the slopes in the Pujon District, Malang Regency, Indonesia with a view of geotechnical engineering on the role of its root characteristics. Analysis of slope stability by modeling the distribution of vegetation roots of the heart root system as an equivalent cohesion approach, where the safety factor is calculated using the PLAXIS-2D version 86 software. Soil parameters were obtained through direct shear testing and root parameters from tensile strength tests on 3 plant species. This study produced findings that can be summarized as follows: Slopes with the same geometric configuration are initially unstable without reinforcing vegetation roots, becoming stable when reinforced by vegetation roots. Plant roots have an important role in stabilizing slopes in the study area. In general, slope stability increases as the value of root cohesion and effective depth of the root zone increase. *T. ciliata* species and the combination of taps and hearts. the root system of *C. arabica* which penetrates into the ground while grasping the surrounding soil. The results of this study broaden the knowledge about the biomechanical characteristics of the dominant species growing on sloping soils in the Pujon area with a view of geotechnical engineering.

Keywords **—geometric modelling, root distribution system, root system approach model, slope stability**

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I. INTRODUCTION

Vegetation roots provide a strong interlocking network to hold unconsolidated material thereby preventing flow. Although, the additional weight of the crop can cause a slight destabilizing effect if the root network is limited, overall vegetation can increase stability, as the vegetation roots can efficiently increase the soil shear strength on the slope by forming the surrounding root-soil composition. Various types of vegetation such as grass, shrubs and trees are used to stabilize slopes through soil strengthening [1]. Grass is a fast growing, multipurpose and inexpensive species and has a wide tolerance range, with tight cover but shallow roots and requires regular maintenance. Shrubs have deeper and stronger roots and are cheap because they require low maintenance. Shrubs offer substantial soil cover and these species are available in many mountainous areas. The tree has large roots, is low maintenance but takes a long time to grow.

The relative effectiveness of these different vegetation patterns at a given location is a function of vegetation and soil characteristics and slope geometry. Root tensile strength is one of the important mechanical characteristics for increasing soil reinforcement [2-4]. The effect of root strengthening increases soil cohesive strength, reduces soil deformation, and prevents surface tension cracking [5-7]. This cohesive nature is more effective than the case of land without vegetation [8]. Attention to plant root systems as a material for slope stabilization, environmental restoration and control of soil erosion has begun to emerge in recent years [9]. Hydrological and mechanical effects of vegetation roots affect slope stability [7, 10]. The shear stress that develops in the soil is then transferred as tensile resistance to ensure the effect of mechanical strengthening by roots [10-12].

Vegetation of grasses and trees can withstand rainfall by reducing runoff speed and reducing soil erosion [6,13]. Soil moisture also decreases with the occurrence of transpiration from vegetation with increased suction of the soil matrix which in turn can increase the shear strength of the soil [13]. However, the increase in slope stability is greater due to mechanical effects than hydrological effects [14]. At the top or foot of the slope, the heart root system, which has deep vertical roots and widened lateral roots, would be an ideal root architecture to protect the soil from slope failure [15]. The results of previous studies indicate that graded slopes are much more stable than straight slopes. Vegetation at the bottom one third of the slope can have a higher effect on safety than in other locations [16].

The influence of vegetation at the top and middle of the slope increases the safety factor. Vegetation with a heart or tap root system that has sufficient depth to interact with the slip surface can provide better shear resistance in the soil. The root structure pattern, the relationship between the root system and firm soil and the root system approach model in the soil increase slope stability [17]. The safety factor is significantly increased on slopes with vegetation covering the entire slope, compared to when vegetation only grows on the feet, or at the top of the slope [4,18]. The safety factor increased significantly (19%) compared to slopes without vegetation when vegetation was planted on all parts of the slope [18]. However, the opinion expressed by [7], the vegetation effect is more effective when planted at the foot of the slope than other sections. Five species of mixed vegetation produce the maximum safety factor when vegetation is planted on the entire slope with an increase 22 to 34% compared to slopes without vegetation [19]. The research objective was to investigate the mechanical effect of vegetation roots on slope stability with a conceptual model of a plant species on a slope based on their root characteristics using PLAXIS 2D software version 86 based on the finite element method.

II. MATERIAL AND METHOD

A. *Study sites*

The topography of the study area in Pujon District, Malang Regency, East Java, Indonesia is a plateau that stretches from west to east and from north to south with an altitude between 1000-2500 m above sea level surrounded by mountains, among others: Dworowati Mt., Argowayang Mt., Gentong Mt., Biru Mt., Banyak Mt., Anjasmoro Mt., and Kawi Mt. In terms of landscape, the Pujon District area has a hilly to mountainous shape with 27% of its area at a slope angle> 50^o, 38% at an angle (25^o-50^o), 9% at a slope angle (15^o - 25^o), 4% at the slope angle (8^o -15^o), and (3^o-8^o), is 20% and the flat area is only 1% of the total area of the sub-district. The classification of the criticality of the area in Pujon District was stated as potentially critical covering an area of 939.37 ha or 7.37% and very critical covering an area of 705.97 ha or 5.54% [20]. Based on this data, it is known that most areas in Pujon District have a high risk of landslides, drought and flash floods. This shows that Pujon District has risks that threaten the safety of the community if its management does not pay attention to soil and water conservation principles. The transportation access area from Malang to Kediri which passes through irregular sloped topography will be used as a case study area. The hilly geographical conditions are accompanied by high rainfall with long duration, causing recurrent slope failures almost every year. This causes physical losses, impairs traffic flow, requires high maintenance costs, and damages existing infrastructure. Mechanical slope retaining structures have been implemented to stabilize landslides. However, this structure is not environmentally friendly and it is impossible to solve all the problems that occur, especially for areas that are difficult to reach by heavy equipment at the time of construction. Thus, as a mitigation measure, the use of vegetation is considered an environmentally friendly, low cost and sustainable alternative to improve slope stability. However, until now there has been no related research that has been carried out with a review of geotechnical engineering on the mechanical characteristics of vegetation roots for slope stabilization along mountainous areas, especially in Pujon District, Malang Regency, East Java.

B. *Soil Sampling*

Soil samples were collected from two locations, around vegetation species for soil containing roots and slope areas without root for unvegetated slop. In the slopesoil with roots, there weresampled from 3 species. The three species is consisted of *Cyperus rotundus* (a grass), *Cofea arabica* (a shrub) and *Toona ciliata* (a tree). The samples were taken to a depth of 100 cm around each selected species, between 25 to 50 cm from the tree trunk by inserting a cylindrical metal tube. The samplings had five replicates. The tubes containing soil samples were transferred to the Laboratory of Geology and Soil Mechanics of Brawijaya University, Malang, East Java, Indonesia for testing of the mechanical properties of soil samples according to ASTM standards. To maintain natural soil moisture, the ends of the cylinder are sealed with paraffin. Samples from the collected cylinders were immediately tested by printing 3 to 4 specimens from each cylinder with the existing molds in the laboratory (6 cm diameter and 1.785 cm high). Soil from slope without root slope weresampled in the same way on land without vegetation.

C. Root Sampling

Three vegetation species were randomly selected to assess the physical characteristics of the roots. The dry digging method is carried out carefully at a depth of about (50-60) cm below the soil surface [21,22], gradually clearing the soil surrounding the root surface. Measurement of stem diameter at breast height was done using tape, while root diameters were measured by calipers. Root diameter varied between (1-10) mm and length ranged between (20-25) cm. A total of 300 selected root samples were collected from 25 plots (2 species with 5 replicates) each consisted of 30 samples. The samples were transferred to the laboratory for further analysis.

C. ***Field and laboratory procedures***

Soil shearing strength

In the laboratory, soil samples with dimensions of height (H = 1.785 cm) and diameter (D = 6cm) were prepared for direct shear testing at natural moisture i.e. soil moisture at the time of sample collection. The test was carried out by applying normal forces and shear forces in relation to the shear surface (ASTM D-3080).

Root tensile strength

In the laboratory, the roots were examined thoroughly for possible damage. Root hairs were cleaned carefully and the root samples were cut into pieces to a length of 15 cm [21,22], or at least the length of the sample was 15 times its diameter. Measurements to assess roots tensile strength of the were done on 30 samples per species with a diameter between 1.00 and 6.00 mm, including the root bark. The test was carried out two days after taking root samples from the field. The average root diameter is determined by measuring the diameter at three different positions along the root size with a Vernier clipper [22-24]. Tensile strength testing is carried out by clamping the two ends of the roots which will be connected by clamps to the drive system and testing is carried out with a strain rate of 10 mm / min [22,23,25], until root break / break. Only samples that break at one-third or in the middle along the roots between the clamps are considered valid, and are broken by the force applied in the stress and are not induced by root structural damage or stress concentrations in near the clamp [26]. The maximum force required to break the root is used as a measure of force, F (kPa) and the root tensile strength TR (MPa) is calculated by dividing the force F by the cross-sectional area of the root at the point of break.

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

where:

TR is the tensile strength,

F_{max} is the maximum force to move the roots,

D is the diameter of the roots.

Slope stability analysis

Slope stability analysis was done by Geotechnical Software PLAXIS 2D version 8.6 based on the finite element method. The effect of strengthening plant roots on slope material was carried out using soil strength parameters in the presence of root effects applied to the slope material. The effect of vegetation roots on slope stability can be demonstrated by calculating the safety factor requirements (FoS). This FoS was analyzed using the finite element method of the PLAXIS 2D program in the "phi-c reduction" procedure [27-28]. This method of stability analysis consists of successively reducing the soil shear resistance parameters (cohesion and internal friction angle) while keeping the gravity load constant [29]. The strength parameters (tanϕ and c) of the soil mass were reduced by means of a strength reduction factor until slope failure occurs, that is, large deformations occur in the soil mass with a slight decrease in the strength parameter. The strength reduction factor in the "phi-c reduction" procedure is given as:

$$M_{sf} = \frac{tan\emptyset_{input}}{tan\emptyset_{rebound}} = \frac{c_{input}}{c_{rebound}} \quad (2)$$

Where

Msf = the multiplier used to define the reduced strength parameters at a given stage;

ϕ_{input} = the input friction angle;

c_{input} = the input cohesion;

ϕrebound = the reduced friction angle at a given stage;

Crebound = the reduced cohesion at a given stage.

The strength reduction factor was set to 1.0 at the start of the calculation. The variation of the strength reduction factor with displacement at the nodal point close to the slope surface can be determined after calculation [30]. (Fan and Tsai, 2016). Slope failure can be checked whether a constant strength reduction factor is obtained as deformation continues. The safety factor of the slope is defined as the ratio of available soil strength to the reduced soil strength at failure and is given as follows:

$$FoS = \frac{Avoilable\ strength}{Strength\ at\ failure} M_{sf}\ at\ failure \quad (3)$$

This study is intended to investigate the effect of root reinforcement when vegetation is planted on slopes with 4 positions indicating slope geometry, dimensions and vegetation positions. The approach to describing the distribution of roots is the hearth root system as equivalent cohesion [29,31]. The input parameters of soil used for modeling are unit weight of soil (γ), young modulus of elasticity (E), poisson's ratio (ν), cohesion (c), friction angle of soil (ϕ). Meanwhile, the input parameters related to vegetation used in the PLAXIS 2D model are apparent root cohesion (cR), young modulus of elasticity (E) and depth of root zone (ZR) for shallow landslides. In this study, the influence of the spatial distribution of vegetation on slope stability was evaluated. Safety factor was determined by slope conditions consisting of 3 layers of soil with a height (H = 20m) and a variable angle of inclination (α = 30° and α = 45°). Variable root cohesion (cR), and root zone at depth (ZR = 2m). The increase in safety factor due to root strengthening was also calculated as a percentage increase and can be defined as follows [22].

$$\text{Increase of } FoS = \left[\frac{FoS_{with\ roots} - FoS_{without\ roots}}{FoS_{without\ roots}}\right] \quad (4)$$

2.6.1 Modeling the influence of vegetation on slope stability.

Slope stability modeling in this study was carried out with a single species. This model was a simulation of slope stability analysis based on soil properties with roots and without roots with a slope angle ($\alpha = 30^o$) and ($\alpha = 45^o$). In this modeling the geometric sketch is presented in Figure 1, while the soil parameters for slope stability analysis are shown in Table 1.

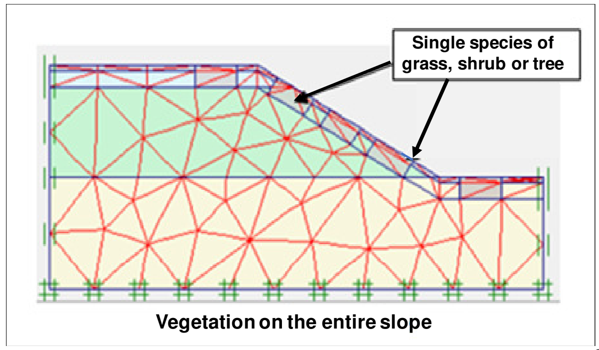

Figure 1. Geometry of vegetation slopes ($\alpha=30^o$) and ($\alpha=45^o$) with a single species

In the second modeling scenario, analysis of stability on the vegetation slopes of single species was carried out. This modeling was performed with analysis of two slope scenarios with vegetation of grass and slope with vegetation of single species of tree and shrub (a species) respectively. Root properties of a grass species (*C. rotundus*) for slope stability analysis was applied refer to [32].

TABLE 1. ROOT PROPERTIES OF SPECIES FOR SLOPE STABILITY ANALYSIS

Species	Poisson's ratio (v)	Root cohesion, C_R (kPa)
T. ciliata	0.35	9.51
C. arabica	0.35	8.22

III. RESULT AND DISCUSSION

The results showed that the roots were shown to increase the shear strength of the soil in the presence of the additional cohesion value contributed by the roots (c) of the species evaluated. Without vegetation the shearing strength value is 47.2. With the presence of vegetation, soil strength increased by 9.23kN / m2 in *T. ciliata* and 8.34kN / m^2 in C. arabica). The cohesion increase was (61%) when compared to the average cohesion value of rootless soil (3.70kN / m^2) (Table 2). This increase clarifies the results of research in an article published by another study [33], that the presence of roots can increase soil strength by about (50-70)%.

In most of the literature, roots are thought to provide increased soil cohesion, but between the internal friction angle (^{o}) of soils with and without roots is almost unchanged, in other words, the results of the direct shear test show that changes in the internal friction angle for soils with roots do not change. too significant compared to rootless soils [34].

TABLE 2. INDEX PROPERTIES AND ENGINEERING PROPERTIES OF SOIL SAMPLES

soil condition	species	c' (kN/m^2)	ϕ (o)	τR (kN/m^2)
Soil without root	none	0.12	39.14	47.2
Soil with root	*T. ciliata*	9.63	25.52	56.83
	C. arabica	8.34	28	55.54

The main contribution of roots to soil shear strength is mainly due to an increase in cohesive interception [35,36]. The shear strength of sandy soils with little silt is mainly affected by the increase in cohesion as a direct result of their grain characteristics, but decreases for the internal friction angle. This is in accordance with the condition that the cohesion value of pure sand soil is close to zero, while that of and pure clay soils was vice versa. The results of the direct shear test show that the shearing strength of soils without roots is lower than those with roots, and this result is consistent with other studies [22,36]. This information can eventually become part of the technical justification that support the use of vegetation to control erosion processes and slope stabilization.

3.2 Root tensile strength

This study showed that *T. ciliata* had the higher root tensile strength (24.92 MPa), than that of *C. arabica*(24.29 MPa) (Table 3).

TABLE 3. AVERAGE VALUES OF SINGLE ROOT TENSILE FORCE AND ROOT TENSILE STRENGTH

Species	average of tensile force (N)	average of tensile strength (MPa)	sample number
T. ciliata	16.5	24.92	22
C. arabica	16.5	24.29	21

One important factor that can influence soil reinforcement on slope stability is the tensile strength of the roots. The tensile strength of the roots varies greatly between species and the environment in which it grows [22]. Small diameter roots have a more flexible character, high tensile strength and a strong friction zone between the roots and the soil. Large diameter roots with their stiffness was able to resist shear and bending serving as sturdy anchors. The combination of these two root sizes supports the tree to stand upright [22,25]. Our research shows that the roots of the species found in the study area contribute to the shear strength of the soil and contribute to increase slope stability.

The results of the slope stability analysis with Model-1 (without including the root reinforcement effect of the five species) show that the FoS values are 1.7273 at α = 30^o and 1.0764 at α = 45^o. This indicated that the gentle slope conditions were relatively stable (FoS> 1,25), and become unstable on the steeper slope (FoS <1,25). (Table 3).

TABEL 4. FACTOR OF SAFETY (*FoS*) FOR SLOPE WITHOUT ROOT

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

The results of modelling analysis show that the FoS without root on the 30^o slope is 1.7273, while on the 45^o slope it is 1.0764. with the presence of FoS vegetation on a 30^o slope, it will increase with an increment of 22.6% with grass, 24.3% with shrubs and 24.3% with trees. FoS pad slope 40^o will increase with an increment of 19% with grass, 34.2% with shrubs and 36.1% with trees (Table 5).

TABLE 5. EFFECT OF COMBINED SPECIES ON INCREASING SLOPE STABILITY

Slope condition	α = 30^o		α = 45^o	
	FoS	increment (%)	FoS	increment (%)

Slope without root	1.7273	-	1.0764	-
Grass (*C. rotundus*)	2.1084	22.6	1.2738	19
Shrub (*C. arabica*)	2.1378	24.3	1.4362	34.3
Tree (*T. ciliate*)	2.1387	24.3	1.4558	36.1

IV. CONCLUSIONS

This study produced findings that can be summarized as follows: Slopes with the same geometric configuration are initially unstable without reinforcing vegetation roots, becoming stable when reinforced by vegetation roots. Plant roots have an important role in stabilizing slopes in the study area. In general, slope stability increases as the value of root cohesion and effective depth of the root zone increase. *T. ciliata* species and the combination of taps and hearts. the root system of A. coffee which penetrates into the ground while grasping the surrounding soil. The results of this study broaden the knowledge about the biomechanical characteristics of the dominant species growing on sloping soils in the Pujon area with a view of geotechnical engineering.

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