The Hydromechanics of Vegetation for Slope Stabilization

A Mulyono[1], A Subardja[2], I Ekasari[3], M Lailati[3], R Sudirja[4], and W Ningrum[2]

[1] Tecnical Implementation Unit for Mine's and Geological Hazard Mitigation, Liwa LIPI
[2] Research Centre for Geotechnology LIPI
[3] Cibodas Botanical Garden LIPI
[4] Soil Science and Land Resources Department, Padjadjaran University
E-mail: asepliwa@yahoo.co.id

Abstract. Vegetation is one of the alternative technologies in the prevention of shallow landslide prevention that occurs mostly during the rainy season. The application of plant for slope stabilization is known as bioengineering. Knowledge of the vegetative contribution that can be considered in bioengineering was the hydrological and mechanical aspects (hydromechanical). Hydrological effect of the plant on slope stability is to reduce soil water content through transpiration, interception, and evapotranspiration. The mechanical impact of vegetation on slope stability is to stabilize the slope with mechanical reinforcement of soils through roots. Vegetation water consumption varies depending on the age and density, rainfall factors and soil types. Vegetation with high ability to absorb water from the soil and release into the atmosphere through a transpiration process will reduce the pore water stress and increase slope stability, and vegetation with deep root anchoring and strong root binding was potentially more significant to maintain the stability of the slope.

1. Introduction

Soil mass movement found on the slopes mostly occurs during the rainy season. Rainfall with high intensity and duration is one of the causes. The amount of rain that efficiently triggers slopes failure is ≥ 70 mm/day in soil that readily absorbs water [1,2]. The water that infiltrated into the ground will fill the soil pore space and cause the soil to become saturated, resulting in weak soil aggregation and decreased soil shear strength.

Soil saturated conditions increase the soil load, so that it will trigger the soil movement because of the pushing force on the upper slope is considerably stronger than the retaining force [3]. The driving force in the hill is affected by the slope steepness, rainfall intensity, load and soil bulk density, the presence of impermeable layer and soil thickness while the rock strength influences the retaining force, shear strength and vegetation roots strength [3,4].

The application of vegetation for slope stabilization is now better known as Bio-Engineering. Bio-Engineering has been introduced since 1930 to prevent slope failure and erosion by the plant as a hydraulic channel, ground movement barrier and hydraulic pump [5]. Vegetation is one of the alternative technologies in the prevention of landslide prevention. The role of the plant in the control of soil movement on the slopes is useful for shallow landslide depth [6–8].

2. The Role of Vegetation

Indonesia Ministry of Public of Works [9] uses some vegetation as landslide mitigation for each slope strata. The slope between 0-20% is proposed for *Swietenia macrophylla* and *Parkia speciosa*. *Leucaena leucephala*, *Parkia speciosa*, *Dalbergia pinata*, *Swietenia macrophylla*, *Calliandra* are the tress in the hill between 21-40% and for steep slope (>40%), *Acacia villosa*, *Pinus mercusii*, *Swietenia macrophylla*, *Cassia siamea, Tectona grandis, Aleurites moluccana and Agathis alba* trees are recommended.

The effect of vegetation is to stabilize the slope with mechanical reinforcement of soils through roots as mechanical aspects [10] and hydrological impact with the reduction of soil water content through transpiration, interception of precipitation [11]. Knowledge of the vegetative contribution that can be considered is the hydrological and mechanical aspects (Figure 1).
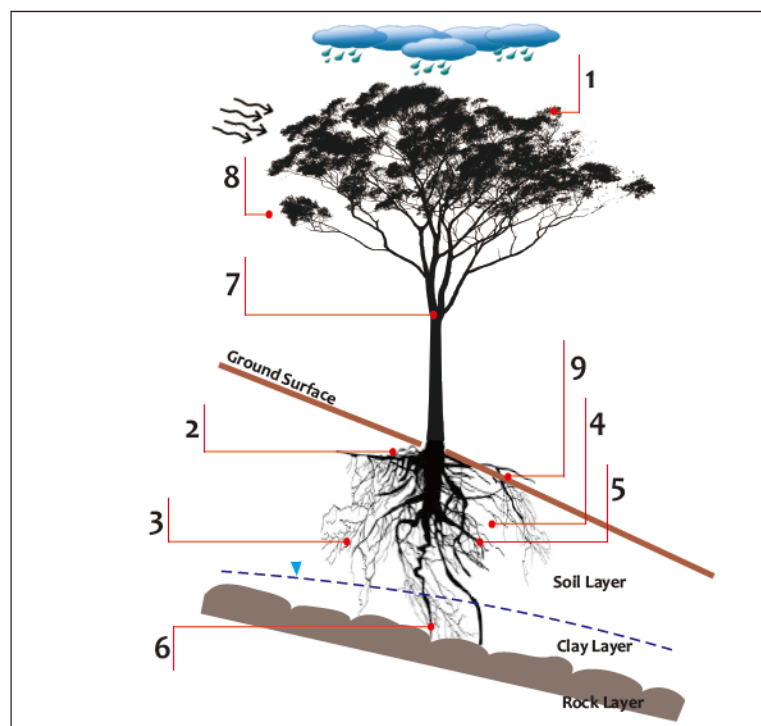
Figure 1. Hydromechanical effect of vegetation on the slope stability (Modified from [11]).

Points 1, 3, 5, 6 and 9 (Figure 1 and Table 1) show the beneficial mechanism to stability. Transpiration and actual evapotranspiration mechanism of vegetation leaves serve as rainfall holders from entering the soil to keep up the negative pore water pressure on the ground [12]. The higher the density of canopy, the greater the ability to catch rainfall in the form of water interception and big interception would reduce and delay the rainfall to reach the soil surface [13].

Shear stress, transferred in the ground into a tensile resistance in the roots, carries out the mechanical soil reinforcement by the roots. Root condition has a role in holding the soil layer. The higher concentration of fibrous roots makes the plant hold the soil stronger [3,14–16]. The magnitude of soil shear strength is influenced by soil conditions (moisture, clay fraction, and porosity) and vegetation rooting characteristics [17]. A tree's roots will increase the soil shear strength by tensile strength of own roots and provide slope-shearing resistance during or after heavy rainfalls on the shallow landslide [18].

Points 2, 4, 8 in Figure 1 are adverse to stability. Infiltration process results in the presence of perched water on the boundaries of two different permeability materials, which can increase the soil pore-water pressure and provide additional forces to soil mass movement [12]. Increased infiltration of water into the soil through the scar created by the uprooted tree can then lower the resistance of the whole soil

mass to failure [19]. The wind pressure on a tree could also produce a destabilizing moment if the tree is not well anchored, which eventually causes slope failure [19]. Roots provide a better connection between soil particles in the soil body (tensile force on the surface), which results in some cementation forces of the mass of the soil [5].

Table 1. Hydromechanical effect of vegetation.

Code Number	Hydrological Mechanism
1	Foliage intercepts rainfall, causing absorptive and evaporative losses that reduce precipitation to infiltrate
2	Roots and stems increased the roughness to the ground surface and soil permeability thereby expanding the infiltration capacity
3	The roots absorb water from the soil and it is released into the atmosphere through a transpiration mechanism that causes the pore water to decrease
4	Depletion of soil moisture by the root absorption may accentuate the soil to crack, thus increasing the infiltration capacity
Mechanical Mechanism	
5	Roots reinforce the soil, increasing soil shear strength
6	Vegetation roots anchor to the deep soil layer, providing support to the upslope soil mantle through buttressing and arching
7	Weight of vegetation surcharges the slope and increases normal and downhill force components
8	Plant exposed to the wind transmits dynamic forces into the hill
9	Roots bind soil particles and reduce their susceptibility to erosion

3. Vegetation Species on Slope Stability

Due to a hydrological effect of vegetation, transpiration was a parameter for tree water consumption. Roots can absorb water from the soil and release it into the atmosphere through a transpiration process that can reduce the pore water stress [20]. Tree water consumption varies in each type of species, which depends on the age, and density of plants, rainfall factors, and soil types. The average of evapotranspiration (ET) and percentage of rainfall for each species [21] is *Eucalyptus deglupta* 1.450 mm (1.450 mm), *Acacia mangium* 1.220 mm (45.5%), *Albizia chinensis* 708 mm (28,5%), *Melaleuca leucadendra* 681 mm (35,3%), *Swietenia macrophylla* 566 mm (34,0%) and *Calophyllum inophyllum* 497 mm (25,0%).

Table 2 shows that the amount of evapotranspiration rate varies in each type of vegetation depending on the age and density of plants, rainfall factors, and soil types. *Acacia mangium* has higher evapotranspiration rate compared to another species of trees, and *Schima wallichi* has the smallest evapotranspiration rate. Water loss (rainfall) on *Pinus merkusii* forest interception is higher (15.7%) than agathis forest (14.7%) and *Schima wallichi* (13.7%) [23]. Evapotranspiration rate in *Eucalyptus Pellita* forest area in Riau Province is 4.49 mm/day or 73.1% of rainfall [21]. Soil moisture decreased by vegetation could reduce pore water pressures within the soil mantle on the natural slopes and promote the stability [24].

Point 7 in Figure 1 has both adverse and beneficial effects. The weight of vegetation can increase slope stability because it adds normal stress to the slope, especially plants with very shallow roots will increase the load on the hills [12]. Therefore, the steep slopes required vegetation with deep root and large fibre roots types to increase the slope stability. *Pinus merkusii* genetically has deep-rooted roots so that its roots can penetrate to a deeper layer, and it has relatively lightweight and can maintain slope stability because it can reduce the load on the slopes [12].

Acacia mangium, Leucaena leucocephala, and *Dillenia suffruticosa* species have excellent potential as slope plants based on their pertaining root and shear strength properties in which *Acacia mangium*

had the highest shear strength compared to *Leucaena leucocephala* and *Dillenia suffruticosa* [25]. Studies on them showed that *Acacia mangium* had the most top shear strength values, 30.4 kpa, and 50.2 kpa at loads 13.3 kPa and 24.3 kpa. Furthermore, the tensile strength test showed that the root of *Leucaena leucocephala* has the highest tensile strength followed by *Acacia mangium* and *M. Malabathricum* [26]. Its relevance to the function of improvement in slope stability depends on the properties of soil conditions and root systems such as root distribution and tensile strength [27–29].

Table 2. Evapotranspiration rate (ET) of some tree species [22].

Tree species	Research period (year)	Rainfall mm/year	ET mm/year	ET % of rains
Pinus merkusii	1-8	3.056	1.971,12	64,5
Eucalyptus urophylla	1-8	3.056	1.127,66	36,9
Schima wallichi	1-8	3.056	699,82	22,9
Swietenia macrophylla	1-6	4.016	2.317,23	57,7
Eucalyptus deglupta	1-3	3.136	1.659,57	52,92
Eucalyptus alba	1-3	3.136	1.642,64	52,38
Eucalyptus trianta	1-3	3.136	1.673,06	53,35
Acacia mangium	1-4	3.465	2.384,61	68,82
Shorea pinanga	1-4	3.465	1.153,50	33,29
Dalbergia latifolia	1-4	3.465	1.444,21	41,68
Calliandra callothirsus	1-3	3.402	1.496,88	44
Acacia decurens	1-3	3.402	1.564,92	46
Altingia excelsa	1-3	3.402	1.428,84	42

Acacia mangium will tree and *Vetiver* grass are plant species that can be adopted in soil slope stabilization. The shearing resistance of *Acacia Mangium Willd* tree root reinforced soil is higher than *Vetiver* grass by 86% in two months and increased to 166% in 18 months [30]. Trees have a considerably high tensile strength and usually have deeper roots than shrubs; hence, enhancing the reach of soil reinforcement [31]. This study showed that the 5m deep-rooted trees provide a higher factor of safety (FOS) (Table 3).

Table 3. Factor of safety (FOS) in slopes with tree and shrubs.

Gradient of Slope (º)	the factor of safety (FOS)	
	5 m tree roots	shrub
21.08º	2.35	2.09
50.00º	1.06	0.94

Trees species that can be selected in preventing landslide with the value of root anchoring and root binding index are shown in Table 4. Horizontal and vertical roots were used to calculate root anchoring and root-binding index based on the ratio of horizontal root diameter or vertical root diameter with tree stem diameter [32].

The characteristics of tree roots affecting soil shear strength are distribution, density, diameter, specific gravity, and root strength [32]. The higher the value of root anchoring and root binding than the tree, the more significant the potential to maintain stability.

Vegetation is one of the alternative technologies in the prevention of shallow landslide prevention. The application of plant for slope stabilization is the hydrological and mechanical aspects (hydromechanical). The hydrological information of vegetation is vegetation canopy of interception and transpiration, and evapotranspiration process that can reduce the amount of rainfall until the soil surface

and root system inside absorb water and increase the shear strength of the soil. For mechanical aspect, index of root anchoring and root-binding needs to be taken into consideration.

Table 4. Root anchoring and binding index for tree species (Setiawan and Krisnawati, 2014).

Tree species	Root anchoring index	Categorize	Root binding index	Categorize
Aleuritas moluccana	0.70	medium	1.59	medium
Durio zibethinus	1.12	high	0.89	low
Persea americana	1.38	Tinggi	2.15	medium
Artocarpus heterophyllus	1.42	high	3.54	high
Nephelium lapaceum	1.14	high	3.78	high
Gnetum gnemon	2.18	high	1.49	low
Arthocarpus altilis	0.76	medium	1.86	medium
Garcinia mangostana	0.86	medium	1.96	medium
Lansium sp	1.34	high	3.98	high
Achras zapota	0.96	medium	2.06	medium
Mangifera indica	1.44	high	4.08	high
Callophylum inophylum	2.21	high	1.00	low
Gyrinops verstigii	0.89	medium	1.01	low

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