The role of hydro-mechanical vegetation in slope stability: A review

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Abstract. Vegetated slopes have various levels of slope stability. Variation of slope stability is affected by characteristics of vegetation, slopes, and soils which are shown by hydrological and mechanical (hydro-mechanical) effects. This article presents a review of the role of hydro-mechanical vegetation on slope stability as an explanation of landslide mechanism on vegetated slopes. The review showed that the hydro-mechanical effects from roots enhance matric suction by evapotranspiration (u_a – u_w), change of volumetric water content by plant water uptake (χ), and enhanced effective soil cohesion due to root matrix reinforcement (CR), while vegetation and wind load can enhance surcharge (Sw) and enhance wind load force parallel to the slope (F_{wind}). Hydro-mechanical vegetation effects can increase or decrease slope stability depending on factors of slope steepness, root diameter, root depth, root area ratio, root morphology, soil aggregate, season or weather (wet, dry, snow), vegetation type, slope shape, location, and vegetation spacing.

Keyword: hydro-mechanical, vegetation, slope, stability

1. Introduction
Vegetation is widely used to control shallow landslide [24, 34, 35]. Shallow landslides are landslides that have depth between 1.5 m and 10 m[17]. Shallow landslides have a smaller area than those of deep landslides and generally occur on mountainous slopes [9].

Mountainous slopes have various levels of slope stability which are affected by vegetation characteristics [29] based on hydro-mechanical effect. [40] explained that hydrological effect had a more significant effect on shallow slope stability, whereas [23] stated otherwise. Increase of slope steepness can decrease the hydrological effect in unsaturated conditions, while in saturated conditions after rain the mechanical effect dominates the slope stability. However, mechanical effects can increase slope stability in the root zone, while hydrological effects increase slope stability up to fourfold of the root depth [10].

Vegetation affects slope stability through hydro-mechanical effects [27]. Hydro-mechanical vegetation effects can increase or decrease slope stability [15]. The vegetation effects are (1) mechanical reinforcement of the soil by the root system, (2) surcharge due to weight of vegetation, (3) wind load force parallel to the slope, and (4) modification of soil moisture and groundwater levels by evapotranspiration [6].

The hydro-mechanical vegetation effects on the slope stability model reviewed in this paper are enhanced matric suction by evapotranspiration, change of volumetric water content by plant water
uptake, surcharge due to weight of vegetation, wind load force parallel to the slope, and enhanced effective soil cohesion due to root matrix reinforcement by vegetation [10, 19, 21, 24, 34, 35].

Many studies have reviewed the hydrological and mechanical vegetation effects, but few studies have reviewed the effect of both on slope stability. Considering the importance of information about the landslides mechanism on vegetated slopes, it is important to review the hydro-mechanical vegetation effect on slope stability. Therefore, this article presents a review of the role of hydro-mechanical vegetation on slope stability as an explanation of landslide mechanism on vegetated slopes.

2. The role of vegetation
Slope stability of vegetated slopes is an important issue for land and ecosystem management. Vegetation can influence the hydrological mechanism through interception by canopy and stem, affecting soil moisture by evapotranspiration, and is able to affect the soil shear strength by the root system. The hydro-mechanical vegetation effect is presented in Figure 1.

![Figure 1. The hydro-mechanical vegetation effect on slope stability, Source: Modifications from [8, 15, 17].](image)

Vegetation can influence slope stability. Slopes which look identically by vegetation can have multiple landslide type. This is because there are differences in vegetation type, position on the slopes, land degradation, soil shear strength, lithology, slope steepness, and dynamic factors causing landslides such as cumulative rainfall and earthquakes.

3. The role of hydro-mechanical vegetation on slope stability
Vegetation parameters that affect slope stability are matric suction [15], volumetric water content [3, 4, 38], surcharge due to weight of vegetation [6, 8], wind load force [22], enhanced shear strength by roots (enhanced cohesion and tensile strength by roots) [7, 11, 30, 36, 39]. The effect of vegetation on slope stability is presented in Figure 2.
3.1. Enhanced matric suction by evapotranspiration \((u_a - u_w)\)

The matric suction is one of the hydrological vegetation effects. The matric suction is pressure exerted by unsaturated soil to the surrounding soil to equalize the water content of the entire soil block. The matric suction affects water flow conditions which can increase soil strength. On vegetated slopes, the matric suction is threefold higher than those of bare slopes [15]. The presence of roots on vegetated slopes maintains a higher suction, resulting in higher shear strength, after rainfall, as compared to bare slopes [28]. [26] states that the matric suction equation is as follows equation (1):

\[
u = -\frac{1}{\alpha} \ln \left( \frac{1 + \frac{q}{Ks} e^{-\gamma w z}}{\frac{q}{Ks}} \right)
\]

Where \(u_a - u_w\) is the matric suction (kN/m²), \(\alpha\) is the inverse of the incoming air pressure (kN/m²)\(^{-1}\), \(q\) is the infiltration (-) or evapotranspiration (+), \(Ks\) is the unsaturated hydraulic conductivity (m/sec), \(\gamma w\) is the volumetric soil water content (kN/m³), and \(z\) is the soil depth from the groundwater level (m).

The relationship between the shear strength of unsaturated soil and the matric suction, ranges from being not directly related to non-linear relation [38], where it is influenced by external stress, humidity, soil type, soil structure, and testing techniques [16].

3.2. Change of volumetric water content by plant water uptake \((\chi)\)

The volumetric water content is the second hydrological effect on slope stability. The model simulates the hydrological vegetation effect which reduces soil water content through root water uptake, resulting in increasing slope stability [3]. The volumetric water content is presented in equation (2) [3, 4, 38].

\[
\chi = \left( \frac{\theta}{\theta_s} \right)^k = \frac{\theta - \theta_r}{\theta_s - \theta_r}
\]

Where \(\chi\) is the degree of saturation, \(\theta\) is the volumetric water content, \(\theta_s\) is the saturated volumetric water content, \(\theta_r\) is the residual volumetric water content, and \(k\) is the constant parameter.

[3] had compared the volumetric water content between trees and shrubs on slope stability. When the water content decreases, there is an increase in the matric suction which increases the safety factor. The increasing safety factor in trees is greater than that in shrub vegetation due to increases of matric suction. The higher matric suction causes lower water infiltration and increases shear strength.
However, in such condition, it can cause the slope to become vulnerable to landslides by the appearance of cracks in the soil surface and the decaying of the root [4].

3.3. Surchage due to the weight of vegetation ($S_v$)

The surcharge due to weight of vegetation ($S_w$) can increase or decrease slope stability. The vegetation surcharge effects are creating slope pressure (destabilization) [15], increasing normal stress which increases soil resistance to movement, and increasing mass on slopes which are potential to undergo landslides [33],[18] stated that the vegetation surcharge equations are as the following equations:

$$S_w = \sum_{i=1}^{n} b_m (1 + \omega)$$

$$b_m = e^{(\beta_0 + \beta_1 \ln \text{DBH})}$$

Where $S_w$ is the vegetation surcharge, $bm$ is the total aboveground biomass for each tree (kg), $\omega$ is the moisture content of the wood (%), $n$ is the number of trees on the slope, $A$ is the slope area ($m^2$), DBH is the tree’s diameter at the breast height (cm), and the parameter $\beta_0$ and $\beta_1$ are the coefficient of tree species [20]. Meanwhile, [33] explained that the vegetation surcharge equation using a different equation (equation 5) is as follows:

$$V = L \pi (d_1^2 + d_2^2) / 8$$

Where $V$ is the volume of wood ($m^3$), $d_1$ is the diameter of the lower stem (m), $d_2$ is the diameter of the upper stem (m), $L$ is the length of the stem. The volume value is then converted into mass using the average density of trees based on species.

The effects of vegetation surcharges on slopes are determined by soil or slope conditions [12], stress-strain properties of the slope material, soil permeability, slope geometry, and presence of cohesion [15]. The effect of vegetation surcharges will be advantageous if the slope has low cohesion, high groundwater level, and slope angle is relatively small as compared to the friction angle of the material [37]. However, in many cases, it will be harmful if the slopes have steep slope [33], especially in a potential landslide area. [23] stated that vegetation surcharge has little effect, except for mature trees which can increase slope stability when the slope angle is lower than the internal soil friction angle. Otherwise, these vegetation surcharge decrease slope stabilities.

3.4. Wind load force parallel to the slope ($F_{wind}$)

The wind load on the trees is transmitted as moments and forces through the branches to the trunk towards the ground by the root system [22]. The effect of lateral wind loads generally reduces slope stability [12],[22] states the lateral wind load equation as the following equation (6):

$$F_{wind} = \frac{1}{2} \rho \pi v^2 C_D \pi$$

Where $F_{wind}$ is the wind force (kN), $\rho_{air}$ is the air density (kN/m$^3$), $v$ is the wind speed (m/sec), $C_D$ is the drag coefficient, and $A$ is the area of trunk and crown of vegetation stricken by the wind ($m^2$).

The effects of lateral wind loads have complex interactions that are generally modelled on a laboratory scale. Laboratory scale modelling has a weakness in experimental to study the effect of roots on soil. The presence of roots penetrating the soil or rock masses along the cracks is an important factor in the effect of lateral wind loads [11].

3.5. Enhanced effective soil cohesion due to root matrix reinforcement by vegetation ($C_R$) 

The effect of effective cohesion by vegetation roots was first identified by [40], and the results showed an increase in the safety factor on some slopes [7]. Some studies present the equation of the increase in
cohesion by the roots with the (C_R) symbol [3, 11, 23, 24, 30, 36, 37], while other studies present the equation of the increase in cohesion as the increase in shear strength by the roots (ΔS) [4, 7, 11, 25, 35]. In this paper, the symbol (C_R) will be used as an increase in cohesion by the roots presented in equation (7) through equation (10) as follows:

\[ C_R = t_R (\sin \alpha + \cos \alpha \tan \varphi) \]  

(7)

\[ t_R = T_R \left( \frac{A_R}{A} \right) \]  

(8)

\[ C_R = T_R \frac{A_R}{A} (\sin \alpha + \cos \alpha \tan \varphi) \]  

(9)

\[ C_R = 1.2 T_R \frac{A_R}{A} \]  

(10)

Where \( C_R \) is the increase in cohesion by the roots, \( t_R \) is the increase in tensile strength by the roots, \( T_R \) is the average tensile strength of the root fibers, \( \frac{A_R}{A} \) the ratio of the root area, \( (\sin \alpha + \cos \alpha \tan \varphi) \) is a value that is not too affected, so that it is changed to value 1.2 as given according to [40].

The effect of effective cohesion by roots is the most dominant mechanical effect of vegetation on a slope [23]. This is also shown by many studies that consider using the effective cohesion parameter by roots rather than by other parameters. The effect of strengthening root cohesion has varying values where generally shrubs have a greater strengthening contribution than trees [24]. This effect is not absolute because it is affected by the root area ratio (RAR) [21] and the root depth [34]. The greater the RAR value and the deeper the root, the higher will be the increase in the effective cohesion by the roots.

4. Slope Stability Model

The hydro-mechanical vegetation effect on slope stability depends on vegetation characteristics, cropping patterns, spacing, position on a slope, and slope steepness. The vegetation characteristics are type of vegetation, shape of the canopy, stems, and root systems. Several studies have modelled the hydro-mechanical effects on various vegetation presented in Table 1.

| Shear strength | Shear stress | Vegetation | Source |
|----------------|--------------|------------|--------|
| \( u_a - u_w \) | \( X \) | \( S_c \) | \( F_{sec} \) | \( C_R \) | \( u_a - u_w \) | \( X \) | \( S_c \) | \( F_{sec} \) | \( C_R \) |
| Silver wattle (Acacia dealbata) | Abernethy and Rutherfurd 2000 |
| Spanish broom (Spartium junceum L.) and heachestnut tree (Castanea sativa) | Arnone et al. 2015 |
| Schefflera heptaphylla and grass species (Axonopus compressus) | Bordoloi and Ng 2020 |
| Grass and shrubs | Bordoni et al 2016 |
| Not specific | Chok et al. 2004 |
| Alder (Alnus incana (L.) Moench) and fungal mycelium | Frei 2009 |
| Salix viminalis and Salix caprea | Gonzalez-Ollauri et al 2017 |
| Not specific | Hayati et al. 2018 |
| Deciduous tree cover, coniferous tree cover, and grass cover | Hardiyatmo 2012 |
| Agonis flexuosa, Casuarina cunninghamiana, and Acacia floribunda | Hubble et al. 2013 |
| Robinia pseudocacia and Platycladus orientalis | Ji et al. 2012 |
| Khaya senegalensis, Syzygium grandis, and Samanea saman | Kim et al. 2020 |
| Grass (turf vegetation), shrubs, young forest, and mature forest | Kokutse et al. 2016 |
| Rhodomyrtus tomentosa, elastomasangilineum | Leung et al. 2015 |
The hydrological effect of vegetation affects soil water content and soil moisture. The effect is a modification of the rainfall through the ground by interception, evaporation, and root water uptake. The hydrological effect by tree vegetation is greater than that of grass, where [33] stated that trees increase slope stability by up to 71%, whereas grassed decrease slope stability by up to 10%. The root water uptake reduces the soil water content by the matric suction process. In unsaturated conditions, the matric suction is threefold higher than in saturated conditions, while in saturated conditions the effect of interception is greater [15]. In saturated conditions, the low matric suction indicates a greater infiltration, which decreases slope stability [25]. Meanwhile, in unsaturated conditions, low infiltration results in increased slope stability (Table 1). However, when the high matric suction results in permanent wilting, it causes cracks and root damage in the withering vegetation [4].

The mechanical effect of vegetation is affected by vegetation surcharges, lateral wind loads on vegetation, and root systems. Vegetation surcharges can increase or decrease slope stability, if the slope angle is less than the internal friction angle, the vegetation surcharges increase slope stability, and vice versa [23]. The lateral wind load on vegetation generally reduce slope stability [12], where it can also be seen in Table 1 which shows that the lateral wind load is a function of shear stress. The root system is a function of shear strength (Table 1) which increases slope stability by increased cohesion by roots [3, 7, 24]. The increase of root cohesion of tree was greater than that of shrubs [3], but other studies have shown the contrary [24]. Cohesion enhancement is generally effective in the topsoil layer [23] or 0.5 m from the surface [28], where a large proportion of root biomass is present.

Based on the description above, it can be seen that both hydrological and mechanical effects can increase and decrease slope stability. This is due to several factors such as slope steepness [2, 23, 37], root diameter, root depth, root area ratio, root morphology [3, 7, 19, 21, 34, 37], soil aggregate [11], season or weather (wet, dry, snow) [3, 5, 15], vegetation type [3, 18, 22, 24], slope shape, location of vegetation [21], and spacing [34].

The slope steepness affects the vegetation surcharge and slope stability. When the slope steepness is less than the soil internal friction angle [23], <30° [37], and <48° [2], the vegetation surcharges increase slope stability, and vice versa.

Root diameter <10 mm increases slope stability more than that of root diameter >10 mm, and this is shown by tensile strength of the roots which decreases with increasing root diameter [37]. At shallow root depths, slope stability of shrubs is greater than trees [3], because the shrubs root area ratio is larger [21], and at increasing root depth, soil shear strength will decrease [37]. Based on the limited root depth, vegetation plays only a little role in the occurrence of deep landslides [7].
The soil aggregates can increase slope stability. The stability of soil aggregates can be increased by the presence of vegetation which strengthens the soil internal friction angle [11].

In saturated conditions, the hydrological effect is generally less than the mechanical effect. This is due to the phenomenon that in saturated conditions the mechanical effect of the root system increases slope stability [3], while in unsaturated conditions the hydrological effect of higher root water uptake increases slope stability [15].

Vegetation type in the form of trees has greater hydrological effect than shrubs in unsaturated conditions, whereas shrubs have a greater mechanical effect in saturated conditions [3, 24]. Meanwhile, in winter, coniferous vegetation has greater slope stability than tree and shrub vegetation types [18]. Vegetation type affects the various slope stability which is influenced by tree geometry (stem diameter, canopy type, root depth) and modulus of elasticity of trees and soil [22].

Slope shape affects slope stability. In multilevel slopes, the slope stability is greater than that of rectangular slopes. Vegetation at foot-slope can increase slope stability greater than those at other positions [21]. However, the shorter the vegetation spacing, the greater the slope stability [34].

5. Conclusion
There are five hydro-mechanical vegetation effects on slope stability, namely enhanced matric suction by evapotranspiration, change of volumetric water content by plant water uptake, surcharge due to the weight of vegetation, wind load force parallel to slope, and enhanced effective soil cohesion due to root matrix reinforcement by vegetation. Hydro-mechanical effects can increase or decrease slope stability depending on factors of slope steepness, root diameter, root depth, root area ratio, root morphology, soil aggregates, season or weather (wet, dry, snow), vegetation type, slope shape, location of vegetation, and spacing.

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