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Hydrological and mechanical effects of vegetation on slope stability

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ABSTRACT

Hydrological and mechanical effects of vegetation with different root characteristics on shallow slope stability are investigated in the study. Vegetation with more roots concentrated on the soil surface has prominent effects on slope stability than uniform distributed roots. The relative importance between the hydrological and mechanical effects on slope stability mainly depends on root architecture, transpiration rate, root diameter, slope angle, and soil type. At drying conditions, mechanical effect of roots is more important in slopes with larger inclination angle, while it is the opposite for the hydrological effect. In humid areas (i.e. transpiration rate < 2 mm/day), the mechanical effect of roots dominates slope stability. After rainfall, the hydrological effect of root vanishes almost entirely inside root zone, so hence the enhancement of slope stability within root zone mainly relies on the mechanical effect of roots. The coarse-grained soil should be planted with vegetation to prevent soil shallow slope failure.

Keywords: vegetation, hydrological and mechanical effects, slope stability

1 INTRODUCTION

Vegetation plays an important role in the stability of civil infrastructure, including shallow slopes (i.e. those less than 2 m deep) (Ali et al., 2012, Fatahi et al., 2009, Nyambayo and Potts, 2010), highway/rail way as well as dams (Simon and Collison, 2002, Fatahi et al., 2009). Studies found that both hydrological and mechanical effects of roots are important in analysing slope stability. The hydrological effect refers to the change in pore-water pressure (PWP) through root water uptake, resulting in a reduction in soil water hydraulic conductivity but an increase in soil shear strength (Ng et al., 2013). The mechanical effect refers to the enhanced soil shear strength by adding and additional soil cohesive force (known as the apparent root cohesion) provided by roots (Fatahi et al., 2009, Schmidt et al., 2001, Sidle, 1992, Wu and Side, 1995).

Studies have shown that hydrological effect could either significant larger than mechanical reinforcement (Schmidt et al., 2001, Arnone et al., 2016, Ni et al., 2018) or less important than mechanical effect (Wu et al., 1979) in enhancing slope stability. It has been revealed that weather condition play an important role in these two effects (Ng et al., 2015, Zhan et al., 2013). Recently, Ni et al., (2018) and Liu et al., (2016) found that hydrological effect is more prominent beyond root zone (i.e. about 4 times of root depth). More recently, Feng et al. (2020) derived analytical solution to investigate both hydrological and mechanical effects of roots on the slope stability, and found that the hydrological effect decreases with slope angle increase, while mechanical effect shows opposite. However, there is still a knowledge gap in fully understanding how hydrological and mechanical effects on slope stability. This study aims to carry out an analytical analysis to explore the underlying factors that affect hydrological and mechanical effects of vegetation on the stability of slope.

2 MODELING THE HYDROLOGICAL AND MECHANICAL EFFECTS OF ROOT

An infinite vegetated slope was adopted in the present study (see Fig.1). The water table is fixed at the base of the slope (Ng et al., 2015), while evaporation or rainfall is considered at the slope surface. Assuming that isolines of PWP are parallel to the slope, the water seepage in the infinite vegetated slope can be simplified as one-dimensional (1-D) water flow perpendicular to the slope (Ng et al., 2015, Liu et al., 2016). According to water mass balance, unsaturated seepage in the vegetated infinite slope takes the following form (Ng et al., 2015):

$$\frac{\partial \theta_w}{\partial t} = \frac{\partial}{\partial z}\left(k\frac{\partial \psi}{\partial z}\right) + \frac{\partial k}{\partial z}\cos\beta - S(z)T\,\mathrm{H}(z - L_1) \quad (1)$$

where θ_w represents volumetric water content (VWC); t is time; z denotes the coordinate perpendicular to the slope (see Fig. 1); k is the hydraulic conductivity function of soil; ψ is the PWP head; $S(z)$ represents the root architecture function; T is the transpiration rate; and $\mathrm{H}(z-L_1)$ is defined as follows (Ng et al., 2015):

$$H(z-L_1)=\begin{cases}1 & L_1 \le z \le (L_1+L_2) \\ 0 & 0 \le z < L_1\end{cases} \tag{2}$$

where L_1 is the thickness of the region beyond the root zone (see Fig. 1); and L_2 represents the perpendicular root depth. According to Eq. (1), the variation in soil moisture ($\frac{\partial \theta_w}{\partial t}$) is due to three parts including the gravity ($\frac{\partial k}{\partial z}\cos\beta$), PWP gradient ($\frac{\partial}{\partial z}(k\frac{\partial \psi}{\partial z}$), and root water uptake ($S(z)T\,\mathrm{H}(z-L_1)$).

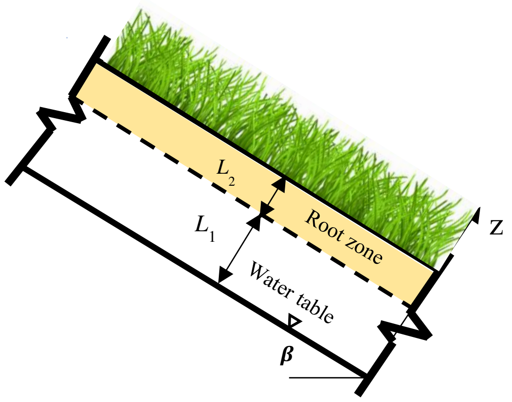


Fig. 1. Schematic diagram of a vegetated infinite slope. (after Feng et al., 2020).

Uniform and triangular root architectures (see the insets of Fig. 2) are adopted in this study. Accordingly, the root architecture function, $S(z)$ is given as follows (Ng et al., 2015):

$$S(\mathrm{z})=\begin{cases}\frac{1}{L_2} & \text{Uniform root} \\ \frac{2}{L_2}\left(\frac{Z-L}{L_2}\right) & \text{Triangular root}\end{cases} \tag{3}$$

To achieve a fair comparison, all roots spanning the same total area are considered in Eq. (3).

The unsaturated hydraulic conductivity function of soil and the soil water retention curve are described in the following forms, respectively (Gardner, 1958):

$$k=k_s\exp(\alpha\psi) \tag{4}$$

$$\theta_w=\theta_r+(\theta_s-\theta_r)\exp(\alpha\psi) \tag{5}$$

where k_s is the saturated hydraulic conductivity of soil; α represents the desaturation coefficient of soil; θ_r and θ_s represent the residual and saturated volumetric water contents, respectively. It should be noted that the hydrological properties of unsaturated soils are highly nonlinear and may not be well captured by Eqs. (4)-(5). Nevertheless, for mathematical tractability, these two equations are adopted to derive analytical solutions. Moreover, the wetting-drying hysteresis is ignored. Root-induced changes in soil hydraulic properties (e.g., soil water permeability (Ni et al., 2017, Liu et al., 2018)) are also not considered due to mathematical difficulties encountered in deriving analytical solutions at transient state. Eqs. (1)-(5) describe the unsaturated seepage in a vegetated infinite slope. Analytical solutions of PWP were obtained for both the steady- and transient-state (Ng et al., 2015).

During the last four decades, different theoretical models have been developed to estimate the mechanical effect of roots on slope stability, including (i) the Wu model (proposed by Wu (1976) and later improved by Waldron (1977)); and (ii) the fiber bundle model (Pollen and Simon, 2005). Wu model is adopted in the study to describe the mechanical reinforcement of roots. One disadvantage of the model is assuming all roots broken simultaneously, which is never true in practice. However due to its simplicity and requires relatively small amount of input date, the model is popular so far.

$$c_r=\zeta\times T_r\times R_f\times RAR \tag{6}$$

where c_r is the additional cohesion induced by the mechanical effect of roots; ζ is the correction factor, which accounts for the effects of roots breaking progressively as is the case in real life on soil shear strength. According to Preti and Schwarz (Preti and Schwarz, 2006), ζ equals 0.4 in the present study. T_r represents the root tensile strength, which is directly related to root diameter (Bischetti et al., 2005, De Baets et al., 2008). Generally speaking, the smaller the root diameter, the larger the root tensile strength. R_f is the root orientation factor, assuming that root grow perpendicularly to the slope surface, so R_f equals one. It should be noted that root growth is affected by ambient conditions (e.g., gravity, nutrition, water distribution). Hence, roots may not always grow perpendicularly to the slope surface in reality.

Root area ratio (in Eq. (6)), which is defined as the fraction of the cross-sectional area of the soil occupied by the roots, is determined as follows:

$$RAR=\frac{A_\mathrm{r}}{A}=\frac{\sum_{i=1}^{n}\pi d_i^2}{4A} \tag{7}$$

where A_r and A are the cross-sectional area of root and soil, respectively; d_i represents the diameter of the ith root; and n is the total number of identified roots. Based on the measurements of *RAR* (Leung, 2014), the triangular and uniform root architectures are considered (see Fig. 2).

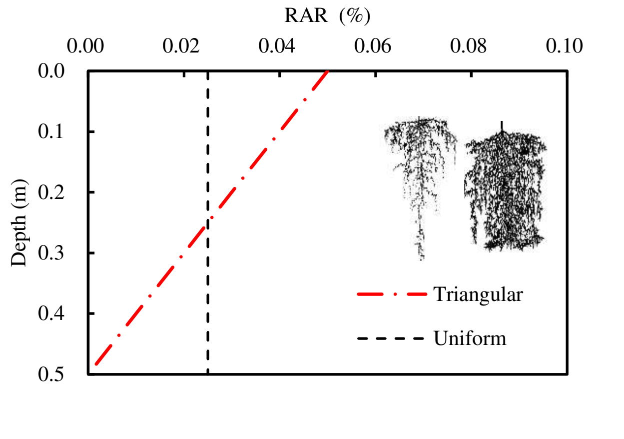


Fig. 2. Two different root architectures and their root area ratio (RAR).

Following the same procedure proposed by Feng et al. (2020), adding the additional root-induced cohesion (c_r) into the extended Mohr-Coulomb criterion, the shear strength of an unsaturated vegetated soil (τ_f) could be determined as follows (Fredlund and Rahardjo, 1993):

$$\tau_f = c_r + c' + (\sigma_n - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi_b \tag{8}$$

where c' and φ' represent the effective cohesion and effective friction angle, respectively; σ_n is the total normal stress; u_a is the pore-air pressure ($u_a = 0$ kPa in this study); u_w denotes the PWP; and φ_b is the angle relating the increase in shear strength to the negative PWP, which is nonlinearly with negative PWP (Gan et al., 1988). However, as the negative PWP commonly encountered in slope stability analysis is in small range (i.e. <100 kPa), a constant φ_b is adopted for simplicity.

Assuming that the potential slip surface is parallel to the slope (Zhan et al., 2013), the factor of safety (FOS) of the vegetated slope is calculated by considering the force equilibrium parallel to the slope as follows:

$$F_s = \frac{\left(c' + \zeta R_f T_r RAR - u_w \tan\varphi_b\right)}{\left[\gamma_d (H_0 - z') + \gamma_W \int_{Z'}^{H_0} \theta_w dz'\right]\sin\beta\cos\beta} + \frac{\tan\varphi'}{\tan\beta} \tag{9}$$

Where γ_d and γ_W represent the unit weight of dry soil and water, respectively ; z' is the vertical coordinate (Fig. 1); and H_0 is the vertical distance between the slope surface and the slope base (Fig. 1). Root water uptake affects both θ_w and u_w (see Eq. (1)), both of which are calculated using the analytical solutions of Eq. (1) (Ng et al., 2015).

3 PARAMETRIC STUDY

Analytical parametric study is conducted to analyses the hydrological and mechanical effects of roots on shallow slope stability. An infinite vegetated slope is considered, which has a vertical thickness (H_0) (Fig. 1). According to Arnone et al. (2016), the failure depth of most slopes is between 500 and 1000 mm, only when the depth of root reaches deeper soil layer, can the root system play a role on mechanical stability. The focus of this study is on small trees and shrubs, the root depth of 0.5 m is adopted. The bottom boundary is as fixed water table, the top boundary is set as a zero-flux boundary at the drying steady state, while rainfall is applied at the wetting transient state. During the drying stage, a transpiration rate ranging from 1 to 4.5 mm/day is considered to simulate different seasons, while it is ignored during rainfall due to the relatively high humidity. Four root diameters (i.e. 10 mm, 5 mm, 2 mm, and 1 mm) of typical shrub and small tree are investigated. The relationship between root diameter and root tensile strength refer to Leung (2014). Three types of soil named decomposed granite (CDG), sand, and silt are adopted in the study. The hydraulic and mechanic properties of the three soils (Ng et al., 2015) are shown in Table 1. Four series of parametric study (see Table 2) are carried out to investigate how (i) root architecture; (ii) transpiration rate (T); (iii) root diameter and (iv) soil type affect the hydrological and mechanical effects of vegetation on the stability shallow slopes.

Table 1 Soil properties

soil type	α (m^{-1})	k_s (m/s)	θ_s	θ_r	φ' (°)	φ_b (°)	c' (kPa)
CDG[a]	1.1	2.2×10^{-6}	0.45	0.05	38	15	1
Silt[b]	0.5	9×10^{-7}	0.41	0.10	30	15	1.7
Sand[b]	0.7	5×10^{-6}	0.40	0.05	40	7	0

Note: a: Chiu (2001); b: Godt et al. (2012)

Table 2 parametric study

Series ID	Case ID	Average root	T (mm/ day)	Slope angle (。)	Soil type	Analysis procedure

		diameter (mm)				
1	B T U	10	0 4.5	35	CDG	Drying steady state to wetting steady state
2	U	10	1-4.5	35	CDG	Drying steady state
3	U	1 2 5 10	4.5	35-60	CDG	Drying steady state to wetting steady state
4	U	10	4.5	35	CDG Silt Sand	Drying steady state to wetting steady state

Note: (a) B, T and U represent bare soil, and soils reinforced by triangular and uniform root branching systems, respectively.

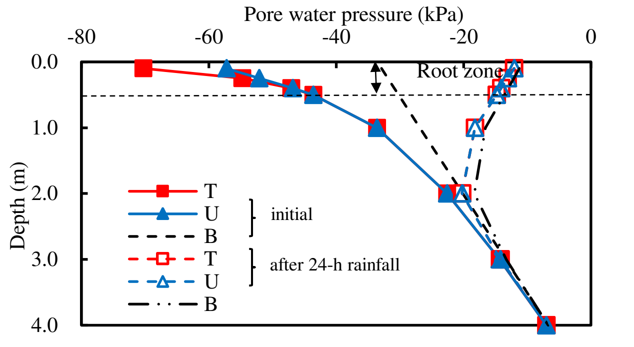
(b) Typical root diameter of shrubs (e.g., *R. tomentosa*) and small trees (e.g. *S. heptaphylla*) ranges from 1 to 10 mm, according to Leung (2014).

(c) 4.5 mm/day is the average transpiration rate in the dry season in Hong Kong (Leung and Ng, 2013).

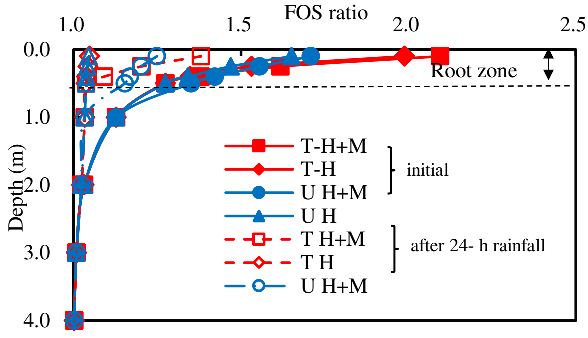
(d) Rainfall intensity of 181 mm/day with a duration of 24 hours (i.e., a 10-year return period based on weather conditions in Hong Kong) is applied for all wetting transient cases, (Leung and Ng, 2013)

3.1 Effects of root architecture on the hydrological and mechanical effects of roots

Fig. 3(a) shows the PWP distributions of vegetated slope with triangular and uniform root architecture, respectively. Calculated results show that the vegetated slope have larger negative PWP than bare slope before rainfall. Specially, the more roots near the surface (i.e. triangular root architecture), the larger the negative PWP obtained. The influence zone of root water uptake is about 4 times of the root depth, this finding is consistent with Ng et al. (2015) and Liu et al. (2016). After 24 hours rainfall, the negative PWP drops sharply for all cases, and no significant differences are observed in uniform and triangular root reinforced soils. Nevertheless, the vegetated slopes still maintain larger negative PWP than the bare slope, due to the larger initial negative PWP.



(a)



(b)

Fig. 3. (a) Pore-water pressure distributions and (b) FOS ratio (FOS ratio is the ratio of FOS in the vegetated slope to that of bare slope) during a 24-hour rainfall in slopes reinforced by triangular (T) and uniform (U) root architecture. (B: bare slope; and H and M indicate that hydrological and mechanical effects are considered, respectively).

Role of hydrological and mechanical effects of root in the stability of slope during rainfall is shown in Fig. 3(b). Before rainfall, the hydrological effect play an important role in the slope stability especially near soil surface. Moreover, the concentration of roots on the slope surface result in larger FOS, due to larger negative PWP in the slope (see Fig. 3(a)). This suggests that hydrological effect dominants slope stability during drying period, and the selection of plants with roots growth horizontal is beneficial to slope stability. After rainfall, FOS drop quickly due to increasing of PWP as rainfall infiltration. Consequently, hydrological reinforcement diminishes, mechanical effect dominates the stability of slope. Nevertheless, the FOS of triangular root reinforced slope is larger than that of uniform root, especially near slope surface. These findings indicate that a greater amount of roots presence near the slope surface and hence more root water uptake and more significant mechanical reinforcement.

3.2 Effects of transpiration rate on slope stability

Figure 4 shows the importance of transpiration rate on the stability of slope with uniform root architecture to bare slope at different depth. Generally, the FOS ratio (the ratio of FOS in the vegetated slope to that of bare slope) increases at an increasing rate as transpiration rate increases. For example, near the soil surface the FOS ratio increases dramatically when transpiration rate is larger than 2.0 mm/day. However, as depth increase (i.e. beyond 2 m) the hydrological effect gradually diminishes even during dry season (i.e. 4.5 mm/day). This finding shows that in semi or semi-arid area the hydrological effects of root should not be ignored, and the closer it is to the soil surface, the more obvious its effect. Similar findings were represented by Ng et al. (2005) and Liu et al. (2016) who found the influence zone of root is around 4-6 times of root depth. In practical, choosing plant with longer root may help maintain slope stability at deeper depth.

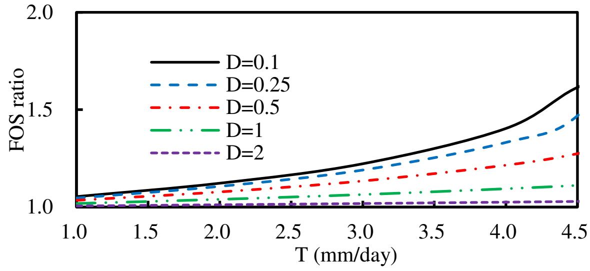
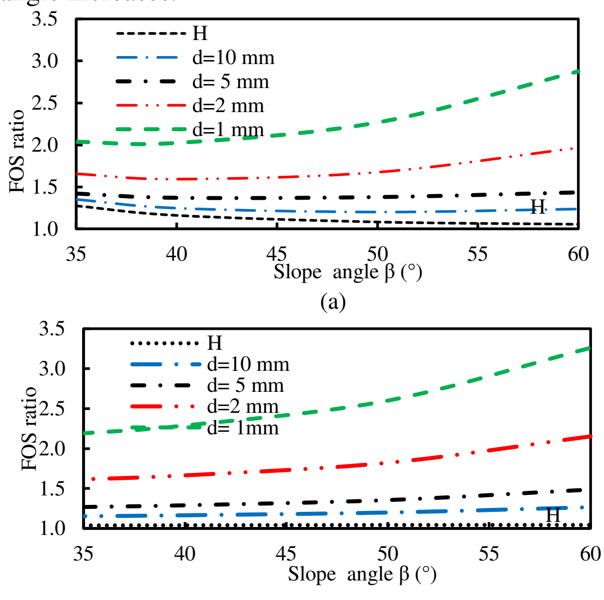


Fig. 4. The importance of transpiration rate on the stability of slope at difference depths (unit: m).

3.3 Role of root diameter in the stability of slope

Fig. 5(a) depicts the FOS ratio against slope angle with different root diameters before rainfall. H represents only the hydrological effect of vegetation is considered. The FOS ratio decreases with the increase of slope angle, which indicates that the hydrological effect is less prominent in slopes with large angle. Different trend of FOS ratio is observed when the mechanical effect is considered. FOS ratio gradually decreases, reaches a minimum at certain slope angle, and then increase. For example, as the root diameter decreases (i.e. 5 mm and 1 mm) the FOS ratio reaches a minimum at slope angle about 40°. Generally the larger the slope angle, the greater mechanical reinforcement effect of the root system. This is mainly because the hydrological effect is less significant in steeper slopes. On the contrary, the mechanical effect play an important role and eventually dominates the slope stability as slope angle increases.



(a)

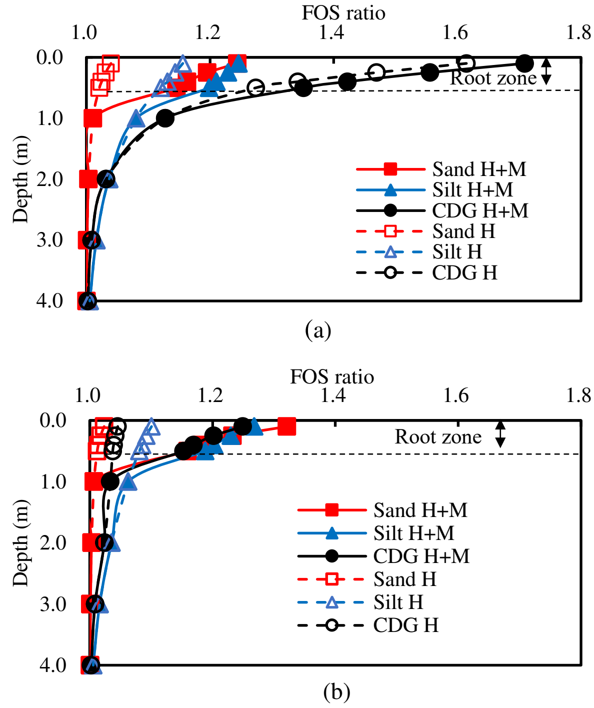
(b)

Fig.5. The relationship of FOS ratio against slope angle (°) with different root diameter (d) reinforced slope at a depth of 0.5 m, (a) before rainfall and (b) after rainfall. (H only hydrological effect is considered)

Fig. 5(b) shows the FOS ratio of root reinforced slope after rainfall. The hydrological effect hardly changes with increasing slope angle, and no significant increase in FOS ratio is observed. This implies that hydrological effect is diminished after rainfall, and is consistent with PWP distribution in Fig. 3(a). However, mechanical reinforcement increases at an increasing rate as slope angle increases, especially in slopes with fine roots. Similar finding was found by Kokutse et al. (2016) who concluded that the FOS would increase more significantly with higher additional cohesion induced by root. These results illustrate that the relative contribution of the hydrological and mechanical effects of roots depend on root diameter (Chirico et al., 2013). The mechanical effect could dominates the slope stability if the average root diameter is small (e.g., 1 mm) even in dry season. In practice, vegetation with more fine roots should be selected to improve the stability of slopes.

3.4 Effects of soil types on slope stability

Fig. 6(a) shows the importance of root on the stability of slope with different soil types before rainfall. Effects of root reinforcement is more significantly in CDG than in sand and silt in improving slope stability. Moreover, hydrological effect is important in CDG, followed by silt and sand. This is because root induced largest negative PWP in CDG, resulting in increasing of shear strength (Ng et al., 2015). However, for silt and sand the mechanical effect is more important than the hydrological effect within root zone.



(a)

(b)

Fig. 6. Effects of soil types on the stability of vegetated slope during rainfall: (a) t=0; (b) t=24 h.

After rainfall, the hydrological contribution of root is greatly reduced, especially for CDG. This is due to the negative PWP induced by root water uptake is destroyed after rainfall (Ng et al., 2015). The mechanical reinforcement is more effective in sand soil than that in silt and CDG, near slope surface. This is because, root provided an additional cohesion (i.e. 1 kPa) in sand (c' =0), which plays an important role in maintaining slope stability. These results illustrate that for coarse-grained soil, although the hydrological effects of vegetation is not significant, the mechanical reinforcement should not be ignored, especially after rainfall. It is suggested that the coarse-grained soil should be planted with vegetation to prevent potentially shallow slope failure.

4 SUMMARY AND CONCLUSIONS

Analytical analysis of both hydrological and mechanical effects of root on the stability of slope is presented in the study. A series parametric study were conducted to explore the underlying factors affecting the stability of vegetated slope.

Vegetation with more roots concentrated near slope surface (i.e. triangular root architecture) shows more significant role in maintaining slope stability. The hydrological effect of root could enhance the slope stability beyond root zone. At drying season, the hydrological effect of root increase with an increasing rate as transpiration rate increases, especially near slope surface. The mechanical reinforcement dominants slope stability in steeper slopes, and the smaller the root diameter, the more pronounced the mechanical reinforcement effect is. After rainfall, the mechanical enhancement of the roots in coarse-grained soil is significantly greater than that in fine-grained soil, which indicates that for coarse-grained soil vegetation should be planted to enhance slopes stability.

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REFERENCES

1) Ali, N. Farshchi, I., Mu'azu, M.A. and Rees, S.W. (2012): Soil-root interaction and effects on slope stability analysis. Electronic Journal of Geotechnical Engineering, 17, 319-328.
2) Arnone, E., Caracciolo, D., Noto, L.V., Preti, F. and Bras, R.L. (2016): Modeling the hydrological and mechanical effect of roots on shallow landslides. Water Resources Research, 52, 8590-612. https://doi.org/10.1002/2015WR018227.
3) Bischetti, G.B., Chiaradia, E.A., Simonato, T., Speziali, B. , Vitali, B. and Vullo, P. et al. (2005): Root strength and root area ratio of forest species in lombardy (northern Italy). Plant Soil and Environment, 278, 11-22.
4) Chirico, G.B., Borga, M., Taolli, P., Rigon, R. and Preti, F. (2013): Role of vegetation on slope stability under transient unsaturated conditions, Procedia Environmental Sciences, 2013(19), 932-941.
5) Chiu, C. F. (2001): Behaviour of unsaturated loosely compacted weathered materials, PhD thesis, Hong Kong University of Science and Technology, Hong Kong.
6) De Baets, S., Poesen, J., Reubens, B. and Wemans, K. (2008): De Baerdemaeker J, Muys B. Root tensile strength and root distribution of typical mediterranean plant species and their contribution to soil shear strength. Plant Soil and Environment, 305(1-2), 207-226.
7) Fatahi, B., Khabbaz, H., and Indraratna, B. (2009): Parametric studies on bioengineering effects of tree root-based suction on ground behaviour. Ecological engineering, 35(10), 1415-1426.
8) Feng, S., Liu, H. W. and Ng, C. W. W. (2020): Analytical analysis of the mechanical and hydrological effects of vegetation on shallow slope stability. Computers and Geotechnics, 118, 103335.
9) Fredlund, D.G. and Rahardjo, H. (1993): Soil mechanics for unsaturated soils, John Wiley and Sons.
10) Gan, J.K.M., Fredlund, D.G. and Rahardjo, H. (1988): Determination of the shear strength parameters of an unsaturated soil using the direct shear test. Canadian Geotechnical Journal, 25(3), 500-510.
11) Gardner, W.R. (1958): Some steady-state solutions of the unsaturated moisture flow equation with application to evaporation from a water table. Soil Science, 85(4), 228-232.
12) Godt, J.W., Şener - Kaya, B., Lu, N. and Baum, R.L. (2012): Stability of infinite slopes under transient partially saturated seepage conditions. Water Resources Research, 48(5), 1-14.
13) Kokutse, N.K., Temgoua, A.G.T. and Kavazović, Z. (2016): Slope stability and vegetation: Conceptual and numerical investigation of mechanical effects. Ecological Engineering, 86, 146-153.
14) Leung, A.K. and Ng, C.W.W. (2013): Analysis of groundwater flow and plant evapotranspiration in a vegetated soil slope. Canadian Geotechnical Journal, 50 (12), 1204-1218.
15) Leung, T. (2014): Native shrubs and trees as an integrated element in local slope upgrading. PhD thesis, Hong Kong University, China.
16) Liu, H. W., Feng, S. and Ng, C.W.W. (2016): Analytical analysis of hydraulic effect of vegetation on shallow slope stability with different root architectures. Computers and Geotechnics, 80, 115-120.
17) Liu, H.W., Feng, S., Garg, A. and Ng, C.W.W. (2018): Analytical solutions of pore-water pressure distributions in a vegetated multi-layered slope considering the effects of roots on water permeability. Computers and Geotechnics, 102, 252-261.
18) Ng, C.W.W., Woon, K.X., Leung, A.K. and Chu, L.M. (2013): Experimental investigation of induced suction distribution in a grass-covered soil. Ecological Engineering, 52, 219-223.
19) Ng, C.W.W., Liu, H.W. and Feng, S. (2015): Analytical solutions for calculating pore water pressure in an infinite unsaturated slope with different root architectures. Canadian Geotechnical Journal, 52, 1981-1992.
20) Ni, J.J., Leung, A.K., Ng, C.W.W. and So, P.S. (2017): Investigation of plant growth and transpiration-induced matric suction under mixed grass–tree conditions. Canadian Geotechnical Journal, 54, 561-575. https://doi.org/10.1139/cgj-2016-0226.
21) Ni, J.J., Leung, A.K., Ng, C.W.W. and Shao, W. (2018): Modelling hydro-mechanical reinforcements of plants to slope

stability. Computers and Geotechnics, 95, 99-109.
22) Nyambayo, V.P. and Potts, D.M. (2010): Numerical simulation of evapotranspiration using a root water uptake model.Computers and Geotechnics, 37(1), 175-186.
23) Pollen, N. and Simon, A. (2005): Estimating the mechanical effects of riparian vegetation on stream bank stability using a fiber bundle model. Water Resources Research, 41, 1-11.
24) Preti, F. and Schwarz, M. (2006): On root reinforcement modelling. Geophysical Research 436 Abstracts, vol. 8, EGU General Assembly, 2-7 April, ISSN: 1029-7006.
25) Schmidt, K.M., Roering, J.J., Stock, J.D., Dietrich, W.E., Montgomery, D.R. and Schaub, T. (2001): The variability of root cohesion as an influence on shallow landslide susceptibility in the Oregon Coast Range. Canadian Geotechnical Journal, 38, 995-1024.
26) Sidle, R.C. (1992): Theoretical model of the effects of timber harvesting on slope stability. Water Resources Research, 28(7), 1897-1910.
27) Simon A., and Collison A.J. (2002): Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. Earth Surface Processes And Landforms, 27(5), 527-546.
28) Waldron, L.J. (1977): The shear resistance of root-permeated homogeneous and stratified soil. Soil Science Society of American Journal, 41(5), 843-849.
29) Wu, T.H., McKinnell, I.I.I. W.P. and Swanston, D.N. (1979): Strength of tree roots and landslides on Prince of Wales Island, Alaska. Canadian Geotechnical Journal, 16(1), 19-33.
30) Wu, T.H. (1976): Investigation of landslides on prince of Wales Island, Alaska. Ohio State University,
31) Wu, W. and Side, R.C. (1995): A distributed slope stability model for steep forested basins. Water Resources Research, 31(8), 2097-2110.
32)Zhan, T.L.T., Jia, G.W., Chen, Y.M., Fredlund, D.G. and Li, H. (2013): An analytical solution for rainfall infiltration into an unsaturated infinite slope and its application to slope stability analysis. International Journal for Numerical and Analytical methods in Geomechanics, 37(12), 1737-1760.