Effect of root growth on slope hydrology and stability during early plant establishment

Viroon Kamchoom[1] and A. Jotisankasa[2]

[1] Department of Civil Engineering, Faculty of Engineering, King Mongkut's Institute of Technology Ladkrabang, Chalongkrung Road, Bangkok 10520 Thailand.
[2] Department of Civil Engineering, Faculty of Engineering, Kasetsart University, Ngamwongwan Road, Bangkok 10900 Thailand.

ABSTRACT

The roots developed during early plant establishment could affect soil hydraulic properties, including soil water retention curve (SWRC) and hydraulic conductivity function (HCF). It remains unclear whether the changes in SWRC and HCF due to root growth are significant to slope stabilisation. This study aims to investigate effect of root growth on slope hydrology and stability during early plant establishment. Finite-element seepage-stability models of 45-degree clayey sand slopes subjected to intense rainfall were developed, with due consideration of coupled hydro-mechanical reinforcement and root-induced changes soil hydraulic properties. The results suggested that root growth increase infiltration rate by almost twice and resulted in significant loss of retained suction. Considering changes of SWRC and HCF influenced by fine roots can reduce slope stability by up to 22%.

Keywords: Grass; Suction; Numerical modelling; Soil water retention curve; Hydraulic conductivity; Slope stability

1 INTRODUCTION

Stability of slopes and earth infrastructure (e.g., road and railway embankments) can be improved by vegetation. Vetiver grass (*Chrysopogon zizanioides*) is one of the fast growing and pioneer species that has been widely used for slope protection in Thailand. There are increasing concerns on the effects of hydro-mechanical reinforcement on slope stability (Simon and Collison 2002; Kamchoom et al. 2014; Ng et al. 2016; Leung et al. 2017a; Kamchoom and Leung 2018a; 2018b). However, the degree of reinforcement provided by grass roots depends strongly on their growth stage. The fine roots (i.e., < 2 mm) developed during early plant establishment can form a composite with surrounding soil and provide additional reinforcement (Operstein and Frydman 2000; Mao et al. 2012). These roots that occupy soil pore space can also affect two highly non-linear hydrological properties of an unsaturated soil, namely soil water retention curve (SWRC) and hydraulic conductivity function (HCF) (Scholl et al., 2014; Ni et al. 2018) Early studies observed a slight variation of the saturated hydraulic conductivity with minimal root biomass (i.e., less than 6 kg/m^3) in clayey sand (Jotisankasa et al. 2015; Jotisankasa and Sirirattanachat 2017). However, with larger amount of root biomass, the shrinkage and decay of fine roots can increase soil hydraulic conductivity (Jotisankasa and Sirirattanachat 2017; Leung et al. 2017b). This may pose potential adverse effects to slope stability when the fine roots were extended during early plant establishment.

This study aims to examine the effect of root growth on slope hydrology and stability during early plant establishment. A series of seepage-stability analysis were carried out to investigate hydrology and stability of grass-reinforced slopes under extreme rainfall. The study adopted the soil hydraulic properties (i.e., SWRC and HCF) influenced by Vetiver grasses in the analyses. The outcome will provide better comparison of the beneficial and adverse effects due to root growth on slope stability.

2 NUMERICAL MODELLING OF VEGETTED SLOPES

2.1 Root-induced changes in slope hydrology

Figures 1(a) and (b) show the SWRCs and HCFs of bare and vegetated soils used in this study. The soil material was a completely weathered rock obtained from sandstone slopes in Ban-Natum, Suratthani. It has been classified to be clayey sand (SC) and is a typical material for most of bio-engineered slopes in Thailand. The soil properties are summarised in Table 1. The measured data were obtained based on the Instantaneous Profile Method (IPM) by Jotisankasa and Sirirattanachat (2017). The fitted SWRCs and predicted HCFs were also plotted in the Figures 1(a) and (b), respectively. The measured SWRC data was fitted by void ratio-dependent model (Gallipoli et al. 2003) and model considering the presence of roots (Ni et al. 2018). The HCFs were predicted based on van Genuchten (1980).

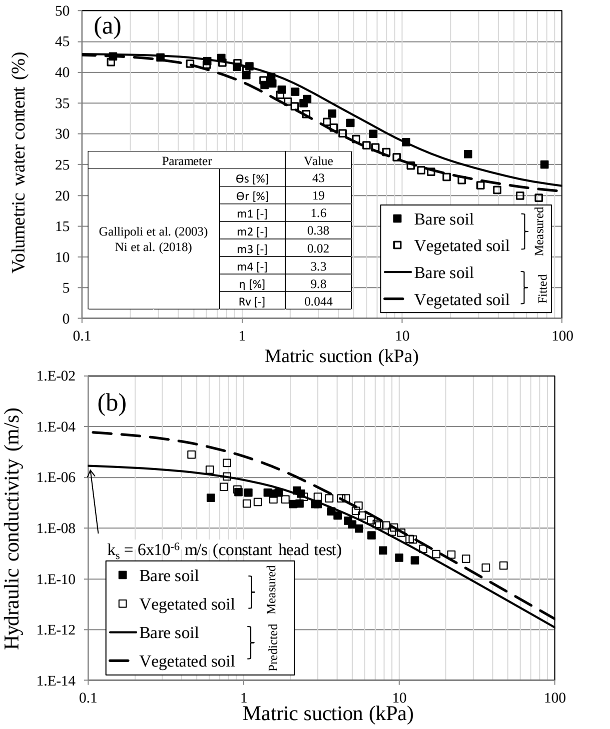

Fig. 1. (a) Soil water retention curves (SWRC) and (b) soil hydraulic conductivity function (SHCF) of the bare and vegetated soil. (Note: k_s is saturated hydraulic conductivity)

Table 1. Summary of soil parameters for numerical modelling

	Parameter	Bare soil	Vegetated soil	Unit
Index properties	Bulk unit weight (γ_t)	20	20	kN/m^3
	Initial void ratio (e_0)	0.47	0.94	-
Mechanical properties	Effective cohesion (c')	0	2, 20	kPa
	Critical-state friction angle (ϕ'_{cr})	34	34	Degree
	Dilation angle (ψ)	5	5	Degree
	Young's modulus (E)	35	35	MPa
	Poisson's ratio (ν)	0.26	0.26	-
Hydraulic properties	Saturated hydraulic conductivity (k_s)	See Figure 1(b)		
	Saturated water content (Θ_s)	43		%
	Residual water content (Θ_r)	19		%

2.2 Analysis plan

In total, 4 seepage-stability analyses were carried out. The details of each run are summarised in Table 2. The first analysis (i.e., denoted as T0) was to observe slope hydrology and stability influenced by vegetation. The subsequent analyses (i.e., denoted as T02, T05 and T1) were carried out to consider the effects of root growth on slope hydrology and stability.

2.3 Seepage-stability analysis

Two-dimensional transient seepage analyses were performed using SEEP/W (Geo-Slope Int. 2009a). Figure 2 shows the finite element mesh used in all seepage-stability analyses. The impermeable boundary was applied for the bottom and both sides of each slope. Surface evaporation was modelled by applying a constant negative flux of 2 mm/day (i.e., typical evaporation in tropical regions; Tebakari et al. 2005) on

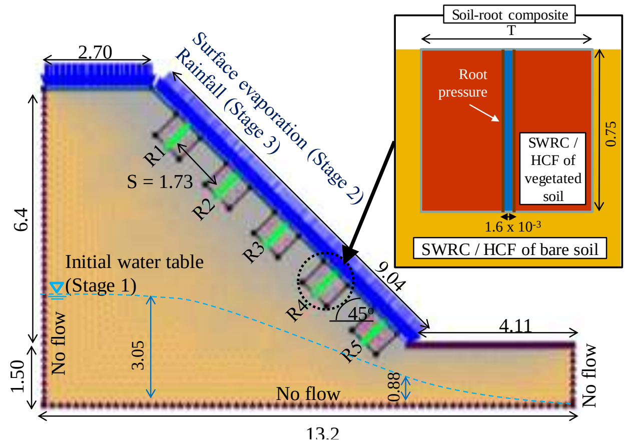

Fig. 2. Finite element meshes of the grass-supported slope for seepage-stability analyses (all dimensions are in meters)

Table 2. Summary of numerical analyses

ID	Thickness (T; m)	Cohesion (Cr; kPa)
T0	0	0
T02	0.35	2 or 20
T05	0.87	2 or 20
T1	1.73	2 or 20

the slope crest and face. A suction of 300 kPa (i.e., root water potential in tropical regions during drying period; Scholander et al. 1965; Fisher et al. 1997) was applied along the internal boundary (see inset; Figure 2) of each root to simulate transpiration. In order to model three-dimensional root water uptake, the diameter of each 2D root was adjusted so that the total water volume flow is equal to the 3D basal diameter of 45 mm. An area of soil-root composite was created around each main root to model any changes in mechanical and hydraulic properties due to the fine roots. The fitted SWRCs and predicted HCFs of vegetated soil (i.e., shown in Figure 1) were adopted for the soil-root composite zone. With limitation of measured data, this study did not consider hydraulic hysteresis. Yang et al. (2012) found that the non-hysteretic model may yield a larger magnitude of soil suction compared to the hysteretic model. The corresponding root extension/spacing (T/S) ratios for T02, T05 and T1 are 0.2, 0.5 and 1, respectively.

The minimum factor of safety (FOS_{min}) of each slope was calculated by the strength reduction method (SRM) using SIGMA/W (Geo-Slope Int. 2009b). Identical slope geometry from SEEP/W was adopted for the stability calculation using SIGMA/W. The fixed and roller boundaries were applied at bottom and both sides of slopes, respectively. The soil was modelled as a perfectly-plastic material that obeys the modified extended Mohr-Coulomb failure criterion (Vanapalli et al. 1996). The root system of vetiver is finely structured and very strong and can also provide a significant increase in the cohesion (i.e., known as root cohesion; C_r). Additional cohesions of 2 and 20 kPa were added to the soil-root composite, representing minimum and maximum reinforcement improved by fine roots

(Schmidt et al. 2001; Jotisankasa and Taworn 2016). Early studies (e.g. Gray and Ohashi 1983; Operstein and Frydman 2000) suggested that these roots only have significant effect on cohesion while modulus and friction angle were found to be less affected, thus assumed to be identical to those of bare soil. With SRM, a reduction factor is applied to the shear strength parameters (i.e., both C_r and ϕ'_{cr}). Any erosion contribution due to fine roots were not considered in the analysis. All input parameters for bare soil and soil-root composite are listed in Table 1.

2.4 Analysis procedures

Each seepage analysis consists of three stages. The first stage was a steady-state analysis, where a ground water table was specified as in Figure 2. The second stage was to simulate the evaporation and transpiration before rainfall for two days in all analyses. The last stage of analysis was to apply the intense rainfall of 70 mm/h for two hours at the crest and the slope surface. No transpiration was simulated during rainfall. After last stage, computed pore water pressure (PWP) were used for slope stability calculation.

3 EFFECTS OF ROOTS AND TRANSPIRATION ON PWP VARIATION

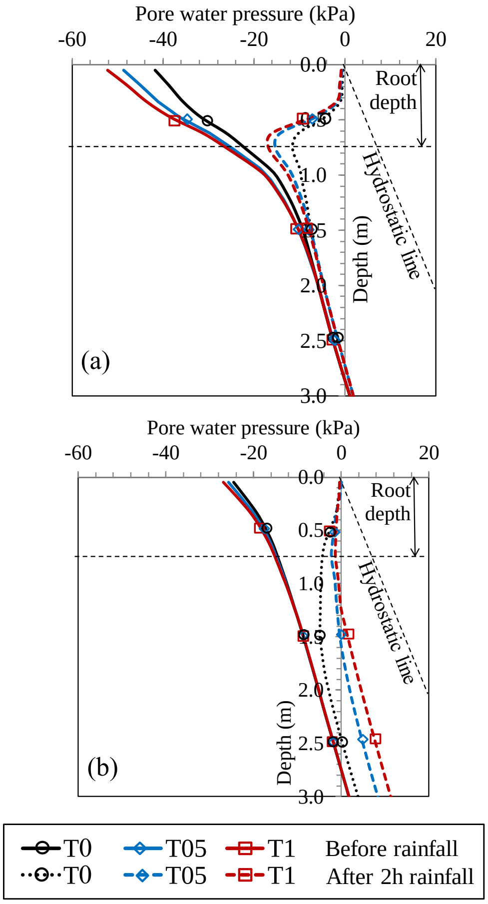

Fig. 3. Pore water pressure profiles at (a) 0.2- and (b) 0.86-m away from root centre during transpiration and rainfall.

Figure 3 compares PWP profiles at different root growth stages for near and between root section. After two days of transpiration, the PWP profile near root section (Figure 3(a)) decreased substantially, whereas PWP at the deeper depth showed only slight reduction. When fine roots developed (i.e., T05 and T1), the PWP with in the root depth was further reduced by up to 7 and 10 kPa, respectively. This is due to higher hydraulic conductivity at the soil-root composite (see Figure 1 (b)). After 2 h of rainfall, there was a significant increase in PWP in the top 0.3 m depth for all cases (Figure 3(a)). However, suction up to 10 kPa were retained within the root depth. The growth of fine roots again affected the PWP profile during rainfall. When fine roots were considered, increase in PWP was about 6 kPa less than that in the case without fine roots. This slight difference is caused by the lower initial PWPs and thus less hydraulic conductivity at the soil-root composite.

Similar PWP observation was also found between root section (Figure 3(b)). Since this section is relatively far from the main root, the decrease in PWP due to transpiration was much less than that near the root (Figure 3(a)). Interestingly, the results of PWP after 2 h of rainfall contradict to those observed near the root. When fine roots developed, PWP increased 12 kPa more than the case without fine roots. With similar initial PWP before rainfall, hydraulic conductivity at soil-root composite became almost twice to that bare soil (see Figure 1(b)). Therefore, positive PWP was significantly built up for both T05 and T1, whereas some suction up to 10 kPa still retained in the case of T0.

4 STABILITY OF VEGETATED SLOPES

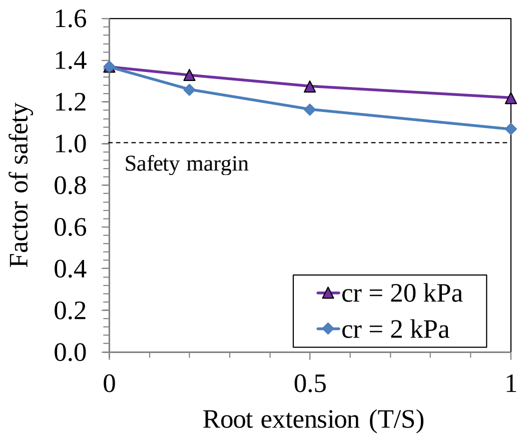

Fig. 4. Computed FOS_{min} of grass-supported slopes

Figure 4. illustrated the stability of slopes during root establishment. The FOS_{min} was all higher than 1.0, meaning that the slope did not fail after 2 h of rainfall. The reduction of FOS_{min} was observed as an extension of soil-root composite zone during root establishment. When the root was fully developed (i.e., T/S = 1), the FOS_{min} was dropped by about11% and 22% for C_r = 20kPa and 2kPa, respectively. In fact, Jotisankasa et al. (2014) also observed the reduction of FOS_{min} at about

10% for a steep slope condition when the grass roots were developed entire surface. The results suggested that the loss of retained suction provide more adverse impacts to slope stability. Even root cohesion up to 20 kPa was considered, it did not provide significant benefit to increase the stability of slopes. The FOS_{min} was still reduced by at least 11%.

5 CONCLUSIONS

This study quantified the effects of root growth for grass species on slope hydrology and stability during early plant establishment. The model in this study was able to consider the changes in SWRC and HCF influenced by fine roots as well as coupled hydro-mechanical reinforcement. The simulations suggested that root-induced changes in SWRC and HCF and their effects on slope stability were not negligible. Root growth, especially fine roots, provided slightly higher suction induced during transpiration. It is however increase infiltration rate by almost twice and resulted in significant loss of retained suction.

The results also suggested it is therefore not the mechanical root reinforcement but changes of SWRC and HCF by fine roots and retained suction that play important role on shallow slope stability during plant establishment. During root growth, the FOS_{min} can be reduced up to 22%.

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