ARTICLE IN PRESS

Computers and Geotechnics xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Modelling hydro-mechanical reinforcements of plants to slope stability

J.J. Ni [a], A.K. Leung [b,*], C.W.W. Ng [a], W. Shao [c]

[a] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong Special Administrative Region
[b] Division of Civil Engineering, School of Science and Engineering, University of Dundee, Dundee, Scotland, UK
[c] College of Hydrometeorology, Nanjing University of Information Science and Technology, Nanjing, Jiangsu, China

ARTICLE INFO

Article history:
Received 5 March 2017
Received in revised form 18 June 2017
Accepted 5 September 2017
Available online xxxx

Keywords:
Plant transpiration
Matric suction
Slope stability
Mechanical reinforcement

ABSTRACT

The study investigates plant reinforcement to the stability of coarse-grained soil slopes, exploring the relative contribution of mechanical root reinforcement and hydrological effects of plant-induced matric suction. A numerical model is used to capture both mechanical root reinforcement and hydrological effects, including evapotranspiration with different root architectures and root-induced changes in soil water retention curve and hydraulic conductivity. Mechanical reinforcement is effective only in shallow depths, where the most root biomass exists. Hydrological reinforcement is much more significant in deeper depths (>1 m), but this effect could vanish due to root-induced increase in hydraulic conductivity.

1. Introduction

Soil bioengineering using vegetation has been recognised as an environmentally friendly engineering method for slope stabilisation. A well-known effect of roots on slope stability is the mechanical reinforcements by roots in shallow soil. Plant roots which could sustain tension permeate into soil pore space and increase shear strength of the soil-root composite. In past decades, the mechanical root reinforcement has been extensively quantified experimentally and analytically [1–4] and this effect is usually included in slope stability calculation [5–9]. The contribution of mechanical reinforcement to soil strength depends not only on the root biomechanical properties but also on the amount of roots available in rooted zone. Field studies [10,11] reported that for natural plants, root biomass is mainly concentrated in the top 0.5 m, below which the root number reduces substantially depending on root architecture. Mechanical reinforcement is thus considered to be especially effective for resisting surface erosion and shallow slope stabilisation.

Hydrological reinforcement via evapotranspiration (*ET*) has also been shown to be important to slope stability [10,12–17]. ET is defined as the combined loss of water from a given area, and during a specified period of time, by evaporation from the soil surface and by transpiration from plants [18]. Various field and laboratory studies reported that the antecedent drying effects by ET before rainfall could induce a significant amount of matric suction and hence preserve suction in the soil (between 5 and 150 kPa; depending on the types of soil and plant) after rainfalls [14,19–23]. Centrifuge model tests conducted by Ng et al. [15] have shown that neglecting the effects of ET before rainfall could result in an underestimation of factor of safety (*FS*) by up to 50% after rainfalls. Suction induced/preserved did not only reduce soil hydraulic conductivity (hence infiltration; [24]) but also increase soil shear strength [25]. When subject to prolonged rainfall, although matric suction is likely to have been dropped to zero in shallow depths, it is not uncommon to see some creditable amount of suction preserved in deeper depths (i.e., 1–2 m; [14,19,26]), where sliding mode of slope failure typically happens. In fact, *ET* did not remove soil moisture only within the root zone, but also could extend its influence zone of suction to a much deeper depth below the root zone for up to four times of the root depth [13,22,23,27].

Hydrological effects of vegetation should not collectively refer to only the antecedent effects due to *ET*-induced matric suction. Previous studies have revealed that the presence of plant roots in the soil could cause a change in soil hydraulic properties [20,28–31]. Experimental work reported by Scanlan and Hinz [32], Scholl et al. [29] and Leung et al. [20] have all shown that the presence of roots affects the water retention capacity, hence the shape of soil water retention curve (SWRC), especially in low suction ranges. Ng et al. [31] develops a model to explain the root effects as the change in void ratio of coarse-grained soils due to physical root occupancy in soil pore space. The effects of vegetation on another soil hydraulic property, infiltration rate and hydraulic conductivity, on the other hand, also received some attention in the literature [19,26,28,30,33]. In general, the findings are inconclusive because

* Corresponding author.
E-mail address: a.leung@dundee.ac.uk (A.K. Leung).

https://doi.org/10.1016/j.compgeo.2017.09.001
0266-352X/© 2017 The Authors. Published by Elsevier Ltd.

Please cite this article in press as: Ni JJ et al. Modelling hydro-mechanical reinforcements of plants to slope stability. Comput Geotech (2017), https://doi.org/10.1016/j.compgeo.2017.09.001

Nomenclature

A_r	sum of total root cross-section area
A_s	soil cross-section area
A	fitting parameter for the relationship between k_s and e
B	fitting parameter for the relationship between k_s and e
c'	effective cohesion
c_r	root cohesion
e	void ratio
e_0	void ratio of parent soil
FS	factor of safety
$G(\eta)$	parameter related to root distribution
h	water pressure head
H	depth of the water table
k_s	saturated hydraulic conductivity
$k(h)$	permeability function (as a function of water pressure head)
$k(\psi)$	permeability function (as a function of soil matric suction)
m_1	parameter controlling the shaper of SWRC
m_2	parameter controlling the shaper of SWRC
m_3	parameter related to the AEV of soil
m_4	parameter related to the AEV of soil
V_r	total volume of roots
V_s	unit volume of soil
RAI	root area index
RAR	root area ratio
R_v	root volume ratio
S	degree of saturation
S_r	residual degree of saturation
S_T	sink term
S_{max}	maximum sink when transpiration is not suppressed by oxygen and water stresses
t	time
T_r	average root tensile strength
u_a	pore-air pressure
u_w	pore-water pressure
z	soil depth
Z	pre-defined depth of a slip surface
ψ	soil matric suction
ξ	angle of shear distortion of roots
$\alpha(\psi)$	transpiration reduction function
$\eta(z)$	root distribution along depth
β	inclination of the infinite slope
γ_s	dry unit weight of vegetated soil
γ_w	unit weight of water
k	parameter that represents the radiation interception by plant leaves
θ	volumetric water content
σ	total normal stress
τ_b	shear strength of bare soil
ϕ'	effective friction angle

some studies showed a decrease in saturated hydraulic conductivity (k_s), while some showed an increase. Certainly, these hydrological effects of plant (herein defined as root-induced changes in soil hydraulic properties) could play a role in soil hydrology and stability, but they have generally been ignored in most of the existing stability analysis.

Because of the lack of research, hydrological reinforcements of vegetation (i.e., a combination of the effects of *ET* and root-induced change in soil hydraulic properties) are often neglected when quantifying the stability of a vegetated slope. Liu et al. [34] is one of the rare studies, which attempt to estimate the effect of *ET*-induced suction on slope stability. Other hydrological effects and mechanical root reinforcement are not considered. In fact, the field study carried out by Pollen-Bankhead and Simon [12] showed that while mechanical reinforcement increased the *FS* of a streambank by 25%, the effects of *ET* -induced suction translated in a much more significant increase in *FS* by 52%. Rahardjo et al. [14] also reported that while the control fallow slope had 25.9% drop in *FS* after 24 h of rainfall, the vegetated slopes had a decrease of only less than 7% in *FS*. More research is thus needed to clarify the relative importance between the mechanical and hydrological reinforcements of plant roots to slope stability.

The aim of this paper is to develop a model that can quantify the mechanical and hydrological effects and their relative contribution on the stability of an unsaturated vegetated coarse-grained soil slope. In this model, the hydrological effects of vegetation considered include (i) *ET*; (ii) root-induced change in soil water retention curve (SWRC) and (iii) root-induced change in saturated hydraulic conductivity (k_s). The model is validated by two sets of field double-ring infiltration tests on both bare and vegetated grounds. Using the validated model, a series of parametric studies on the effects of different root architectures on soil hydraulic properties, soil hydrology (in terms of matric suction) and slope stability (in terms of *FS*) are conducted. The relative significance of the mechanical and hydrological contributions of roots to the slope stability is then investigated and highlighted.

2. Materials and methods

In order to assess the stability of an unsaturated vegetated slope, soil hydrology and its change due to the hydrological effects of vegetation needs to be considered. Therefore, two stages of calculation are conducted. The first stage is to determine the pore-water pressure distribution through transient seepage analysis. The calculated results are then used in the second stage for slope stability analysis using the limit equilibrium method.

2.1. Hydrological model for an unsaturated vegetated soil

Consider one-dimensional (1D) transient seepage in an unsaturated soil along the depth, z, Richard's equation is used to describe the process

$$\frac{d\theta}{dt} = \frac{d}{dz}\left[k(h)\left(\frac{dh}{dz}+1\right)\right] - S_T(\psi \ or \ h, z) \quad (1)$$

where θ is the volumetric water content; t is the elapsed time, h is the water pressure head; $k(h)$ is the soil hydraulic conductivity function as a function of h or matric suction ($\psi = -h\gamma_w$, where γ_w is the unit weight of water); and S_T is the sink term, which represents the volume of water transpired by a plant integrating over the entire root zone for a given time interval [35]. Mathematically, S_T may be expressed as follows:

$$S_T(\psi \ or \ h, z) = \alpha(\psi) \cdot S_{max} = \alpha(\psi) \cdot G(\eta) \cdot PT \quad (2)$$

where $\alpha(\psi)$ is known as transpiration reduction function, ranging from 0 to 1; $G(\eta)$ is related to root architecture, $\eta(z)$; and S_{max} is the maximum sink when transpiration is not suppressed by oxygen and water stresses (i.e., $\alpha(\psi) = 1$; [35]. Under this condition, the plant undergoes potential transpiration (PT; maximum amount of water that plants could extract water from the soil [36]). Otherwise, the amount of plant-water uptake (S_T) would depend on both the magnitude and distribution of suction within the root zone.

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