Computers and Geotechnics 80 (2016) 115–120

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Analytical analysis of hydraulic effect of vegetation on shallow slope stability with different root architectures

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ARTICLE INFO

Article history:
Received 17 November 2015
Received in revised form 15 March 2016
Accepted 12 June 2016

Keywords:
Analytical analysis
Root architecture
Hydraulic effect
Shallow slope stability
Infinite slope

ABSTRACT

A parametric study is performed to investigate hydraulic effect of vegetation on shallow slope stability with different root architectures in an infinite slope. Calculated results show during the first one hour of rainfall (181 mm/day), the exponential root architecture has higher ability to maintain shallow slope stability than the parabolic one. Under light rainfall (i.e., 20 mm/day) for 24 h, hydraulic effect of vegetation is more important inside root zone than outside root zone, while it is the opposite for rainfall intensities of 181 and 394 mm/day over the same duration. Parabolic rooted slope is more sensitive to rainfall pattern than bare one.

1. Introduction

Shallow slope (i.e., up to vertical depth of 2 m) stability is a common problem in embankments and man-made slopes. The overwhelming majority of slope failures are shallow and small in Hong Kong [1]. To tackle the problem, the subsequent measures are practiced: nailing, vegetation, geosynthetic reinforcement, improved drainage and ground improvement. Among these, vegetation is found to be a preferred remedial measure from economical, sustainability and environmental points of view [2].

Vegetation can enhance slope stability through mechanical and hydraulic mechanisms. The mechanical reinforcement of soil by vegetation's root has been studied by many researchers [3–6]. Meanwhile, hydraulic mechanism has been identified to help enhancement of slope stability through pore-water pressure reduction in soil by root water uptake [7–9], resulting in a decrease in permeability, but an increase in the soil shear strength [10]. Simon and Collison [11] found that hydraulic mechanism is important in controlling streambank stability by numerical simulations. Ali et al. [12] carried out numerical simulations to investigate both hydraulic and mechanical effects of vegetation on slope stability, and found that hydraulic effect is more effective than mechanical effect.

Depending on types of plant species, vegetation can generate different root architectures such as exponential and parabolic root architectures (as shown in Fig. 1). Recently, analytical solutions for calculating pore-water pressure in an infinite unsaturated slope considering different root architectures were derived by Ng et al. [13] for both steady and transient states. However, hydraulic effect of different root architectures on shallow slope stability is not well understood.

This paper aims to perform analytical parametric study to investigate the hydraulic effect of root architecture on shallow slope stability in an infinite slope, based on the analytical solutions for pore-water pressure distributions derived by Ng et al. [13]. Parameters considered include exponential and parabolic root architectures, rainfall intensity and rainfall pattern.

2. Infinite shallow slope stability

Fig. 2 shows a typical profile of an infinite vegetated slope. In the analytical solutions reported by Ng et al. [13], it is assumed that the ground water table is located at the bottom of the slope. Also, the isobars of pore water pressure distributions are parallel to slope surface and so does the potential slip surface. Thus, it can be treated as a one-dimensional flow perpendicular to the slope surface for both steady and transient states. Based on the mass balance of water, the governing equation for water flow is derived by incorporating root water uptake as a sink term as follows:

$$\frac{\partial}{\partial z'}\left(k\frac{\partial \psi}{\partial z'}\right)+\frac{\partial k}{\partial z'}\cos\beta - S(z')H(z'-L'_1)=\frac{\partial \theta_w}{\partial t} \tag{1}$$

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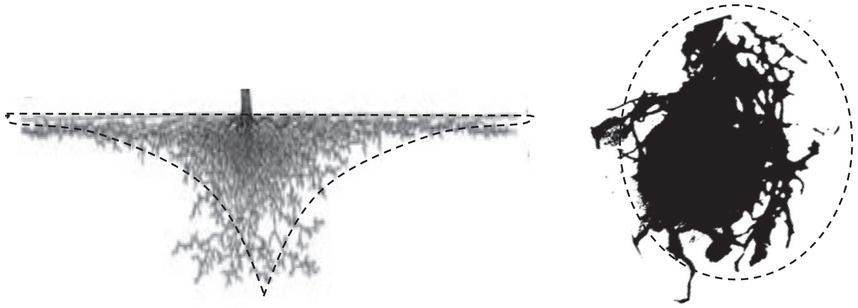
http://dx.doi.org/10.1016/j.compgeo.2016.06.006
0266-352X/



Exponential Parabolic

Fig. 1. Different real root architectures [13].

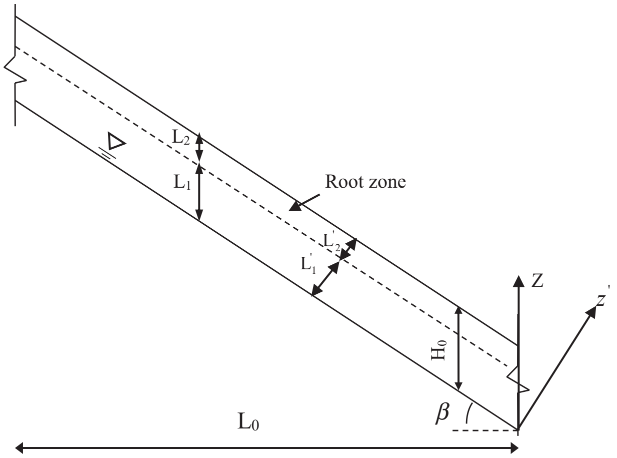


Fig. 2. Schematic diagram showing an infinite vegetated slope.

where ψ is the pressure head; k is the unsaturated water permeability of soil; θ_w is the volumetric water content; t is time; z' is the coordinate perpendicular to the slope surface; L_1' is perpendicular depth outside root zone; β is slope angle; $S(z')$ is the sink term which represented the root water uptake considering both evapotranspiration rate and root architecture; and $H(z'-L_1')$ is the Heaviside function defined as:

$$H(z'-L_1') = \begin{cases} 1 & L_1' \leqslant z' \leqslant (L_1' + L_2') \quad \text{inside root zone} \\ 0 & 0 \leqslant z' \leqslant L_1' \quad \text{outside root zone} \end{cases} \tag{2}$$

where L_2' is perpendicular root depth.

In the analytical solutions, the water permeability of soil and volumetric water content are expressed in terms of pore-water pressure head, ψ [14], as follows:

$$k = k_s \exp(\alpha\psi) \tag{3}$$

$$\theta_w = \theta_r + (\theta_s - \theta_r)\exp(\alpha\psi) \tag{4}$$

where k_s is the saturated water permeability of soil; α is the desaturation coefficient of soil; and θ_s and θ_r are saturated and residual water content, respectively. Although Eqs. (3) and (4) are approximate descriptions for the soil behavior near saturation, due to mathematical convenience, they have been used in many studies to obtain the analytical solutions. Besides, in the analytical solutions derived by Ng et al. [13], effects of root on permeability (Eq. (3)) and soil water characteristic curve (SWCC; Eq. (4)) [15] are not considered. Also, the hysteresis effect is neglected, that is, a constant α is used for wetting and drying cycles.

Extended Mohr-Coulomb criteria [16] is used to describe the shear strength of unsaturated soil

$$\tau_f = c' + (\sigma_n - u_a)\tan\varphi' + (u_a - u_w)\tan\varphi_b \tag{5}$$

where c' is the effective cohesion; φ' is the effective angle of internal friction; φ_b is the angle indicting the rate of increase in shear strength relative to negative pore-water pressure; σ_n is the total normal stress; u_a and u_w represent the pore-air pressure and pore-water pressure, respectively. It should be noted that shear strength varies with negative pore-water pressure in a nonlinear function [17]. However, considering small negative pore-water pressure range (i.e., less than 100 kPa) encountered in the slope stability analyses and for simplicity, a constant φ_b value is assumed.

Based on the force equilibrium parallel to the slope surface, the factory of safety (FOS) can be obtained as follows [18]:

$$F_s = \frac{(c' - u_w \tan\varphi_b)}{\left[\gamma_d(H_0 - Z) + \gamma_W \int_Z^{H_0} \theta_w dZ\right] \sin\beta\cos\beta} + \frac{\tan\varphi'}{\tan\beta} \tag{6}$$

where γ_d is the dry unit weight of soil; γ_W is the unit weight of water; u_w is the pore-water pressure, which is calculated using analytical solutions derived by Ng et al. [13]; θ_w is the volumetric water content; Z is vertical coordinate with upwards positive as shown in Fig. 2; H_0 is vertical thickness of slope.

3. Parametric study

A typical infinite vegetated slope is used in this study, as shown in Fig. 2. The slope angle (β) is 35° and the vertical thickness (H_0) is 5 m. The vertical root depth (L_2) is 0.5 m. The bottom and top boundaries are considered as water table and a zero flux boundary for steady state, respectively, while for transient state the top boundary forms an infiltration boundary. At the steady state, transpiration rate of 4.5 mm/day is chosen to represent the average transpiration in dry season [19] for vegetated slope, while it is set to be zero during rainfall due to high humidity [19,20]. The soil type simulated is completely decomposed granite (CDG, silty sand), which is common in Hong Kong. The dry unit of soil γ_d is 15 kN/m^3 [21]. For shear strength parameters, the effective cohesion c' adopted is 10 kPa, whereas the effective angle of friction φ' is 38° and the angle indicating the rate of increase in shear strength relative to negative pore-water pressure φ_b is 15° [21]. Regarding hydraulic parameters, the saturated water permeability k_s is 2.2×10^{-6} m/s, the desaturation coefficient of α in permeability function is 1.1 m^{-1}, and the saturated and residual water contents are θ_s of 0.45 and θ_r of 0.05, respectively [22].

The cases shown in Table 1 are performed to investigate the influence of vegetation's hydraulic effect on shallow slope stability. In total, three series are taken into account, focusing on effect of