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Research Paper

Analytical solutions of pore-water pressure distributions in a vegetated multi-layered slope considering the effects of roots on water permeability

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ABSTRACT

New analytical solutions of pore-water pressure (PWP) distributions in a vegetated multi-layered slope are derived considering the effects of roots on water permeability. PWP distributions are significantly affected by root-induced reductions in water permeability due to increases in the root volume ratio (R_v). Under drying conditions, negative PWP increases with R_v. The negative PWP induced by root water uptake increases with the desaturation coefficient (α_i) or the ratio of the transpiration rate to saturated water permeability (T_p/k_{si}). As the overall water permeability underneath the vegetation layer decreases, the negative PWP induced by root water uptake increases.

1. Introduction

Vegetation affects unsaturated seepage through root water uptake in civil infrastructures, including landfill covers, man-made slopes and embankments. On one hand, a reduction in pore-water pressure (PWP) through root water uptake results in lower water permeability but higher shear strength of soil, leading to a reduction in water percolation in landfill covers as well as improved stability of man-made slopes and embankments [1–6]. On the other hand, roots in the soil have been found to alter soil hydraulic properties [7–12]. The variations in soil hydraulic properties induced by root are expected to affect PWP distributions, but they have been ignored in most existing studies.

Analytical and numerical methods have been developed for analyzing PWP distributions in single-layered vegetated soil [13–17]. Recently, a numerical model was developed by Ni et al. [7] considering the mechanical reinforcement of roots, root water uptake and the changes in the hydraulic properties of soil due to roots. However, their analytical and numerical findings are not applicable to multi-layered vegetated slopes and landfill covers due to the assumption of single-layered soil. Moreover, factors influencing PWP distributions in vegetated multi-layered slopes are not well understood.

Analytical solutions have unique advantages over numerical simulations. For example, analytical solutions provide explicit relationships among factors influencing the effect of root water uptake on unsaturated seepage in vegetated soil. Moreover, analytical solutions do not suffer from convergence and the results are independent of mesh size. Although there are analytical solutions for simulating one-dimensional (1D) water infiltration in two-layered unsaturated soil [18–20], the influences of root water uptake are ignored. To the best of the authors' knowledge, analytical solutions considering the effects of roots on soil hydrological properties and PWP response in a vegetated multi-layered slope are currently not available. This study aims to fill this gap. In addition, analytical parametric studies are conducted to investigate the factors influencing PWP distributions.

2. Analytical solutions

2.1. Effects of roots on soil hydraulic properties

Roots occupy soil pore space. Root-induced changes in the void ratio could be described by the following equation proposed by Ng et al. [8]:

$$e_i = \frac{e_i^b - R_v(1 + e_i^b)}{1 + R_v(1 + e_i^b)} \tag{1}$$

where e_i^b and e_i are the void ratio of bare soil and vegetated soil in the i^{th} layer, respectively; R_v represents the root volume ratio, the definition of which is the volume of roots per unit volume of soil. It is noted that Eq. (1) does not model effects of any formation of macro-pores due to root decay on soil void ratio [21].

The relationship between saturated permeability and the void ratio

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Notation

c	the fitting parameter
c'	the effective cohesion
DOC	the degree of compaction
e_i^b	the void ratio of bare soil in the i^{th} layer
e_i	the void ratio of vegetated soil in the i^{th} layer
FOS	factor of safety
$H(z{-}L_1)$	$H(z-L_1)=\begin{cases}0 & 0\leqslant z<L_1 \quad \text{outside the root zone}\\ 1 & L_1\leqslant z\leqslant (L_1+L_2) \quad \text{within the root zone}\end{cases}$
H_0	the thickness of the slope ($H_0 = L_1 + L_2$)
i	the soil layer number
j	the total number of soil layers
k_i	the unsaturated water permeability of the i^{th} soil layer
k_{si}^b	the saturated permeability of bare soil for the i^{th} layer
k_{sj}	the saturated permeability of the j^{th} vegetated soil layer
$k_j\vert_{z=0}$	the water permeability at the slope bottom
k_{s1}^*	the relative unsaturated permeability in the first layer
L_1	the perpendicular distance of the lower boundary of root zone to the bottom of slope (Fig. 1)
L_2	the perpendicular distance of the lower boundary of root zone to the slope surface (Fig. 1)
PWP	pore-water pressure
q_0	the surface flux (negative and positive values imply evaporation and rainfall flux respectively)
$q_i (i \neq 1)$	the water flux perpendicular to the slope surface outside the root zone
R_v	the root volume ratio
$S(z)$	the uniform distribution of root water uptake
S_e	the effective degree of saturation
SWCC	soil water characteristic curve
T_p	the transpiration rate
u_i	the pore-water pressure distribution in the i^{th} layer
z	the coordinate perpendicular to the slope surface as shown in Fig. 1
z_i	the coordinate of the bottom of the i^{th} layer
z_i'	$(z-z_i)\cos\beta$
α_i	the desaturation coefficient of the i^{th} soil layer
β	the slope angle
θ_w	the volumetric water content
γ_{di}	the unit weight of dry soil in the i^{th} layer
γ_W	the unit weight of water
λ_{dec}	the increase in k_{si}^b due to preferential flow/macro-pores generated from root decay
φ_b	the angle describing the effects of negative PWP on shear strength of soil
φ'	the effective friction angle
ψ_i	the pressure head at the bottom of i^{th} layer
ψ_j	the pressure head at the slope bottom (i.e., j^{th} layer)
ψ	the PWP head

proposed by Yin [22] is modified by considering the effects of roots:

$$k_{si} = \lambda_{dec}\frac{\exp(c\cdot e_i)}{\exp(c\cdot e_i^b)}k_{si}^b \tag{2}$$

where k_{si} and k_{si}^b are the saturated permeability of vegetated soil and bare soil, respectively; λ_{dec} represents the increase in k_{si}^b due to preferential flow/macro-pores generated from root decay; and c is the fitting parameter. According to Ni et al. [7], root-induced increases in k_{si}^b by 1.3–6.5 times were commonly observed. Hence, λ_{dec} typically ranges from 1.3 to 6.5. For bare soil, e_i and λ_{dec} equal e_i^b and 1 respectively, and correspondingly k_{si} equals k_{si}^b (Eq. (2)).

The water permeability function and soil water characteristic curve (SWCC) of soil are expressed as follows [23]:

$$k_i = k_{si}\exp(\alpha_i\psi) \tag{3}$$

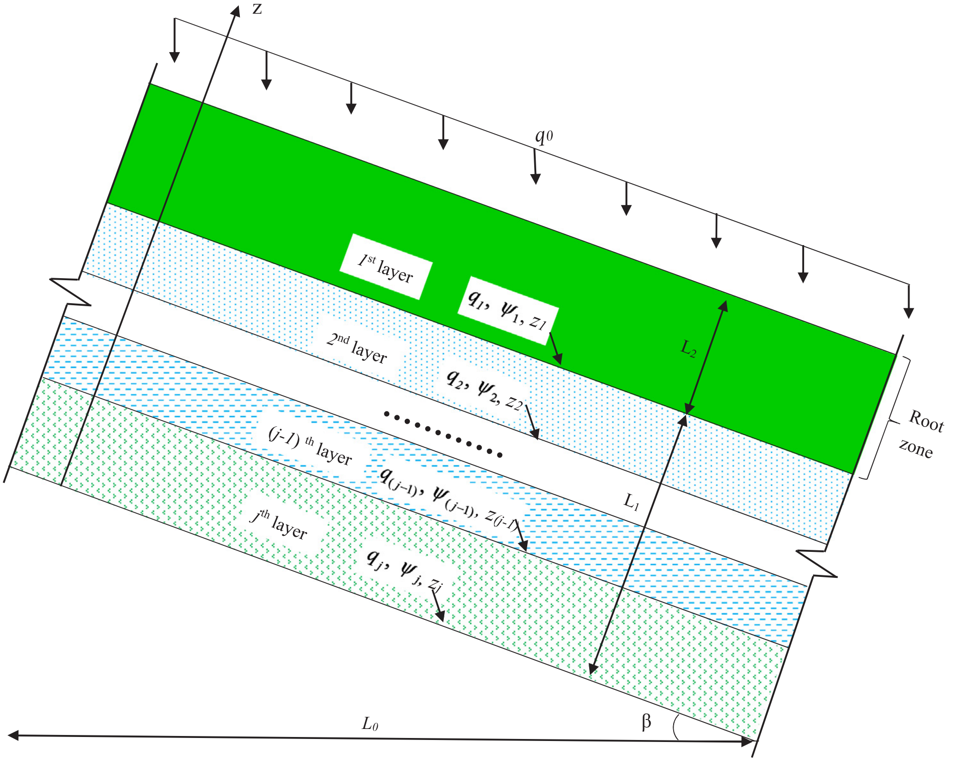

Fig. 1. Schematic diagram of a vegetated multi-layered infinite slope.