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Evaluating suction profile in a vegetated slope considering uncertainty in transpiration

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ABSTRACT

Understanding root-water uptake in soil slopes is essential because any changes in soil moisture would lead to changes in soil suction and in turn changes in soil shear strength and slope stability. Uncertainties associated with plant characteristics are present in the root-water uptaking process. The objective of this paper is to evaluate the suction profile in a vegetated slope with a grass cover and the stability of the slope during rainfall infiltration. Random field theory is applied to model the spatial variation of the maximum transpiration rate of Bermuda Grass, which is a native grass species in Hong Kong. The slope is subjected to 12 h, 24 h, and 48 h of drying processes before rainfall. A modified Richards equation governing water flow in unsaturated–saturated media is employed to incorporate a sink term of Bermuda Grass. The effects of initial conditions induced by the drying processes of different periods prior to rainfall on the suctions retained in the vegetated slope after rainfall are investigated. Uniform and triangular root distributions are considered to simulate likely root architectures and their influence on the suctions retained. Slope stability analysis is further carried out to investigate how plant transpiration contributes to slope stability. The results demonstrate that, given the same maximum transpiration rate, the root distribution has little influence on inducing or retaining suctions. At a low infiltration flux, the higher the coefficient of variation of the maximum transpiration rate and the longer the pre-drying time, the wider the range of the suctions that a vegetated slope can retain. A pre-drying process of 48 h results in a significant increase in the slope factor of safety.

1. Introduction

Vegetation is considered beneficial to slope stability not only through mechanical soil reinforcement [1–4], but also via root-water uptake. During the uptaking process, plant roots absorb moisture through photosynthesis and respiration, which, as a result, desiccates the soil surrounding the plant roots and hence induces soil suction [5,6]. The reinforcement effect of plant roots has been well accepted worldwide, while root-water uptake has not yet been fully investigated. Root-water uptake is an important mechanism that dramatically affects the temporal–spatial water content distribution in superficial vegetated soil. However, this process and their interactions with soil are less understood due to the inherent variability of root architecture and intrinsic difficulties of observing belowground flow processes [7]. As investigated and summarized by Indraratna et al. [7], soil conditions (e.g. hydraulic conductivity and penetration resistance), types of vegetation (e.g. root distribution and relative proportion of active roots), and atmospheric conditions (e.g. temperature and humidity) affect the rate of root-water uptake and hence the transpiration rate.

A considerable number of researchers have made efforts in investigating the mechanisms of plants in altering suctions during dry seasons and retaining suctions after rainfall. Experimental research has also been carried out to quantify suctions induced by different vegetation species during evapotranspiration [8–10]. Ng et al. [11] quantified and compared in the laboratory the grass-induced suction distribution in silty sand compacted at different densities when subjected to artificial rainfall. Ghestem et al. [12] studied how roots create table channels for preferential flow. Numerical simulation of induced suction distribution by trees has been conducted by Garg et al. [13] and others who considered different plant numbers and spacings. Numerical investigation of suctions that can be retained in a vegetated slope upon rainfall and their influence on the stability of the vegetated slope, however, was rarely conducted, as opposed to suctions retained in bare slopes [14].

Plant characteristics, e.g. root density, leaf area and shoot length, are highly uncertain. A parameter, the maximum (potential)

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transpiration rate (*Etp*), is often used to quantify root-water uptake. *Etp* represents the maximum amount of water that can be extracted by roots per unit time, under a given climate condition [15]. *Etp* values, therefore, remain the same in the vertical direction but vary in the horizontal direction. Previously the suction distributions were experimentally and numerically studied without considering such uncertainties in transpiration. The maximum transpiration rate which can be directly measured in relation to root length and volume density should however be characterized as a spatially random field. Bermuda Grass, which is commonly found in Hong Kong and other part of Asia, is chosen for study because this grass species is often planted for slope protection. Moreover, statistics of the maximum transpiration rate of Bermuda Grass are available in the literature [15,16]. Up to date, there is a lack of research on the effect of uncertainty in the transpiration rate on the suction retained in a vegetated slope and the stability of the slope.

The maximum transpiration rate varies spatially and can be modeled using random field theory [17,18]. The theory has been applied to geotechnical problems [19–27]. A random field is described through the mean and variance of a random variable, as well as the scale of fluctuation and correlation structure of the variable describing the extent to which values of the variable at two points are correlated.

The objectives of this paper are: (1) to investigate how vegetation modifies the initial condition of a vegetated slope prior to rainfall and retains suction in the slope upon rainfall; (2) to model the spatial variation of the maximum transpiration rate, *Etp*, of Bermuda Grass; (3) to probabilistically evaluate how the spatial variation of *Etp* affects the suction distribution when subjected to rainfall of different magnitudes under different initial conditions; and (4) to evaluate how the spatial variation of *Etp* affects the factor of safety of the vegetated slope. A general methodology is proposed to characterize the spatial variation of *Etp*. Deterministic analysis is first conducted to investigate the effect of different root geometries on modifying the initial condition prior to rainfall and on retaining suctions at the end of rainfall. Then a probabilistic study of the above effects involving random fields of *Etp* is carried out. Finally, the stability of the vegetated slope is evaluated under the above hydrological conditions.

2. Formulating root transpiration

2.1. Modified Richard equation incorporating plant sink term

A comprehensive review of evapotranspiration in the soil-plant-atmosphere system was recently conducted by Novák [28]. Evapotranspiration is the process of water transport from an evaporating surface to the atmosphere. The evaporating surface can be a plant surface, a cuticle tissue (transpiration), soil, or a groundwater surface. The most important process is transpiration; namely, the process of water movement from the soil to and through the plant, and further on to the atmosphere.

In this paper, we consider the water flow in a grass-covered slope under a transient seepage condition. The modified Richards equation [29] governs the flow process, which satisfies the mass conservation principle and Darcy's law and is expressed in two-dimensions as follows:

$$\frac{\partial}{\partial x}\left(k\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial h}{\partial z}\right)=\frac{\partial \theta}{\partial t}+S(z) \tag{1}$$

where k is the unsaturated soil permeability at a given suction; h is the hydraulic head x, z are Cartesian coordinates in the horizontal and vertical directions; θ is the volumetric water content; t is elapsed time. Plant transpiration is modeled by a macroscopic approach using a sink term, S, which represents the volume of water extracted by roots per unit volume of soil per unit time, m^3 m^{-3} s^{-1} [30]. The actual water uptake rate, $S(z)$ at a given depth z, is expressed by

$$S(z)=Etp\,\beta(z)\alpha(\psi) \tag{2}$$

where Etp is the maximum (potential) transpiration rate, m s^{-1}; β is the shape function of root distribution at a given depth z in the vertical direction, m^{-1}; $\alpha(\psi)$ is, if water supply is limited, a transpiration reduction function in the range of [0 1] as a function of soil matric suction ψ. An exponential decay function is utilized according to Homaee et al. [31], which describes that when the soil is fully saturated, no reduction of the maximum transpiration is applied while when the soil is partially saturated, reduction cannot be ignored.

The actual transpiration rate, E_t, which is the sum of water uptake $S(z)$ from the soil surface to the maximum root depth, z_r, is given by

$$E_t=\int_0^{zr} S(z)dz \tag{3}$$

According to Eq. (3), the root-water uptake rate largely depends on the root distribution pattern if the maximum transpiration rate remains constant. The likely root distribution patterns are essential. This process is, however, hard to simulate because of the nature of largely spreading and dense root networks. In view of this situation, several idealised root models including uniform, triangular and parabolic models were suggested according to the distribution of root biomass, as shown in Fig. 1 [32]. The shape functions are $\beta=\frac{1}{z_r}$ for uniformly distributed roots, $\beta=\frac{2}{z_r}(1-\frac{z}{z_r})$ for triangularly distributed roots, and $\beta=\frac{6}{z_r^3}[(z_r-z)z_r-(z_r-z)^2]$ for parabolically distributed roots.

2.2. Soil hydraulic property functions and boundary conditions

A soil–water characteristic curve (SWCC) developed by Fredlund and Xing [33] is used, which is expressed by

$$\theta=C(\psi)\frac{\theta}{\left\{\ln\left[e+(\psi/a)^n\right]\right\}^m} \tag{4}$$

where e is the natural number, 2.71828; a is approximately the air-entry value of the soil; n is a parameter that controls the slope at the inflection point of the soil–water characteristic curve; m is a parameter that is related to the soil residual water content; $C(\psi)$ is a correcting function defined as

$$C(\psi)=1-\frac{\ln\left(1+\frac{\psi}{C_r}\right)}{\ln\left(1+10^6/C_r\right)} \tag{5}$$

where C_r is a constant related to the matric suction corresponding to the residual water content, θ_r. The soil considered in this paper is classified as silty sand. The fitting parameters are assumed to be a = 10, n = 2, and m = 1. The porosity (i.e. the saturated volumetric water content) is 0.4. The permeability function derived based on the SWCC completes the governing equation [34]. The value of saturated coefficient of permeability, k_s, is taken as 1×10^{-5} m/s, which is in the common range of measurements for silty sand.

A slope 2 m in height and 30° in inclination is considered. Fig. 2 shows the geometry and boundary conditions of the slope. A groundwater table is assumed within the slope. The initial condition is assumed to be hydrostatic. There is no change in the total head on the side boundaries below the groundwater table. The bottom boundary and the side boundaries above the water table are assumed impermeable. The side boundaries are sufficiently far away from the slope. The slope is subjected to transpiration of