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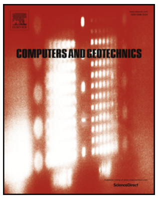

Technical Communication

Investigating plant transpiration-induced soil suction affected by root morphology and root depth

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ABSTRACT

This study evaluates the effects of root morphology and depth on the enhancement of induced suctions in soil grounds due to transpiration. Root morphology is idealized as uniform, triangular, parabolic and exponential distributions based on observations and the transpiration process is governed by the modified Richards equation. The study reveals that the exponential and triangular root networks enhance soil suctions more remarkably than the uniform and parabolic patterns. With the same total root amount, a root network with most of root amount concentrated in the superficial zone can induce significantly higher suction values than a root system distributed deeply.

1. Introduction

Vegetation plays an important role in affecting moisture distribution in soil due to its natural root-water uptaking mechanism driven by transpiration. During the uptaking process, plant roots absorb moisture through photosynthesis and respiration, which desiccates the soil surrounding the plant roots and hence induces soil suction ψ (i.e., negative pore-water pressure) [1,2]. The inherent variability of root morphology and difficulties of observing belowground flow processes [3–7] obscure understanding of the interaction between root-water uptake and soil desiccation. Root morphology is known to not only vary genetically among species, but also depend on abiotic factors. As mentioned by Stokes et al. [5], the spatial position of thick roots determines arrangements of the associated thin roots, thus exhibiting a large degree of complexity. The root spatial distribution is shown to affect the stability of vegetated slopes [8]. Generalization of root morphology is essential for assessing the hydrological performance of vegetated infrastructures. Moreover, identification of the pattern of root morphology that enhances soil suctions most effectively draws particular attention.

Recently, extensive experimental studies have been carried out to quantify suctions induced by different vegetation species during evapotranspiration [9–13]. Numerical simulations of suction distributions in non-vegetated ground [14,15], treed ground [16,17] and grassed ground [18] were performed. Analytical solutions for calculating pore-water pressures in an infinite vegetated slope were also proposed by Ng et al. [19], considering root geometry in the derivation. Nevertheless, the degree to which the root geometry and root depth affect the suction distributions near the superficial green cover has seldom been reported. In this case, a numerical means is desired as it allows analysis of infrastructures in any dimension by incorporating flexible information about roots and soil hydraulic properties.

This study aims to assess the impact of various root geometries on the suction distributions induced by transpiration. Modelling root-water uptake process entails a root distribution function, a transpiration reduction function and a maximum transpiration rate. The note is structured as follows. First, typical patterns of root distribution are idealized; following which experimental measurements on transpiration reduction function (T_{rf}) and maximum transpiration rate (E_{tp}) are reviewed. Then, the governing equation for analysing the transpiration-induced soil suction is described, based on which the suction distributions along depth at a selected study site with available information of soil are elucidated.

2. Idealization of typical patterns of root distribution

Attributed to natural variability of vegetation, its physiological characteristics such as aboveground leaf area and belowground biomass are highly uncertain. Existing approaches to quantifying root architecture involve extraction of roots, complete washing off of soil, and image analysis of roots. A complete workflow was introduced and applied by Garg et al. [11,20]. As shown in Fig. 1, modified after Ng et al. [19], there are four typical types of root geometry including a root system with a large taproot and large horizontal lateral roots [21]

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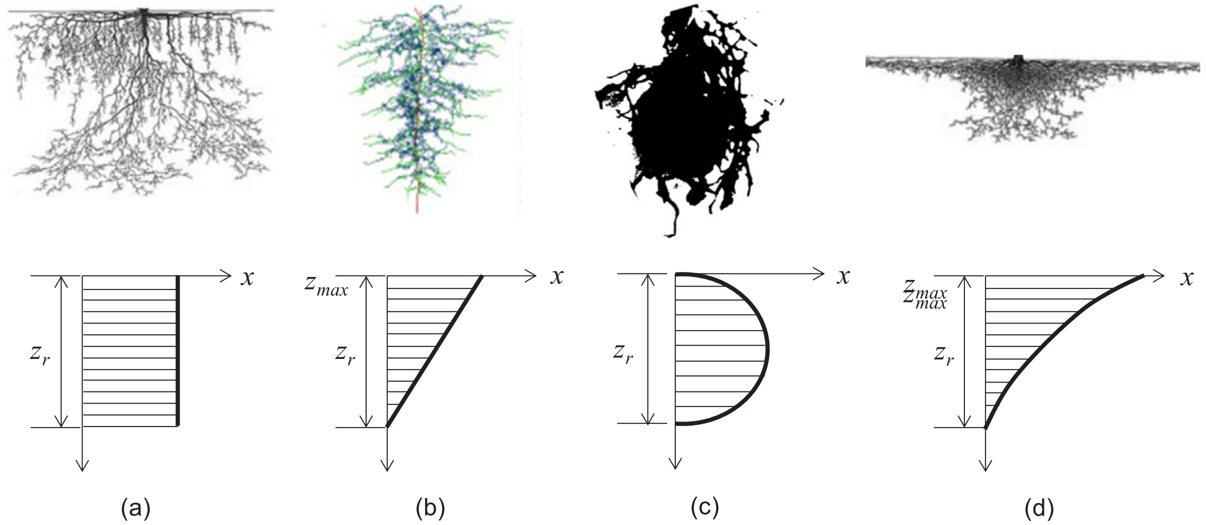

Fig. 1. Four patterns of root architecture and their idealized representations: (a) root system with a large taproot and large horizontal lateral roots extracted from Ghestem et al. [21], idealized as a uniform distribution; (b) taproot system with small lateral roots given by Prasad [22], idealized as a linearly decreasing distribution; (c) concentrated root system provided by Garg et al. [20], modelled as a parabolic distribution; (d) plate-shaped root system from Ghestem et al. [21], modelled as an exponential decaying distribution.

modelled as a uniform distribution of root biomass, a taproot system with small lateral roots [22] idealized as a linearly decreasing distribution of root biomass, a concentrated root system [20] modelled as a parabolic distribution of root biomass, and a plate-shaped root system [21] modelled as an exponential decaying distribution of root biomass. The root biomass can be root volume, mass, area or length. The most common representation is the area of soil occupied by roots. Eq. (1) formulates mathematically the four patterns of root geometry:

$$\beta(z) = \begin{cases} \frac{1}{z_r}, & \text{for uniform distribution} \\ \frac{2}{z_r}\left(\frac{z-z_{\max}}{z_r}+1\right), & \text{for triangular distribution} \\ \frac{6}{z_r^3}\left[(z+z_r-z_{\max})z_r-(z+z_r-z_{\max})^2\right] & \text{for parabolic distribution} \\ \frac{\exp[z-(z_{\max}-z_r)]-1}{\exp(z_r)-z_r-1}, & \text{for exponential decaying distribution} \end{cases} \tag{1}$$

where $\beta(z)$ is a root distribution function at a given depth z; z_r is the maximum root depth; $z_{\max}$ is the elevation of the top of the root system. The set of conceptualized equations are derived based on the expression of mathematic functions idealizing the distribution and the principle that the integration of β along z down to the maximum root depth (i.e., shaded area in Fig. 1) equal to unity.

3. Experimental measurements on transpiration reduction function and maximum transpiration rate

A sink term is used to model root-water uptake driven by plant transpiration, and is coupled with the Richards equation to simulate the induced soil suction. Both a transpiration reduction function (T_{rf}) and a root distribution function (β) are key parameters in a sink term. The maximum transpiration rate (E_{tp}) represents the maximum amount of water that can be extracted by roots per unit time under a given climate condition [23]. The E_{tp} value can be measured. In Section 2, typical root distributions are idealized and represented by four patterns of functions. Extensive experiments have been conducted to measure T_{rf} and E_{tp} of plants. This section reviews the most relevant findings on the two quantities to provide a basis for selecting appropriate values for the numerical investigation.

T_{rf} is defined as the variation of ratio of actual transpiration rate to maximum transpiration rate with soil suction. The physical meaning of T_{rf} is the ability of plant to adjust its root-water uptake rate as a result of change in soil moisture content. Different transpiration reduction functions are available such as those proposed by Feddes et al. [24], Van Genuchten [25], Utset et al. [26], Garg et al. [11]. Feddes et al. [24] proposed a piece-wise linear T_{rf}, which is formulated by connecting Anaerobiosis point (denoted as ψ_1), two empirical parameters (ψ_2, ψ_3) and wilting point (ψ_4). These values are expressed in terms of suction. Fig. 2 shows a transpiration reduction function varying with soil suction. The function describes suction-dependent transpiration rate according to the amount of suction developed in the soil. When the suction is less than Anaerobiosis point ψ_1, the root-water uptake is negligible due to reduction in metabolic processes by oxygen deficiency. The measured transpiration rate reaches maximum when suctions are between the values at points 'ψ_2' and 'ψ_3'. Beyond this range, the value of transpiration rate decreases significantly to a wilting point at 'ψ_4', referring to the suction at which transpiration ceases due to water supply shortage. The characteristic values of T_{rf} proposed by Feddes et al. [24] are $\psi_1 = 0$ kPa, $\psi_2 = 5$ kPa, $\psi_3 = 100$ kPa and $\psi_4 = 1500$ kPa. Van Genuchten [25] also proposed a semi-empirical nonlinear T_{rf}, which requires two empirical parameters, namely h_{50} (i.e., the suction head corresponding to 50% reduction in the normalized transpiration rate) and a constant in relation to the salt content in

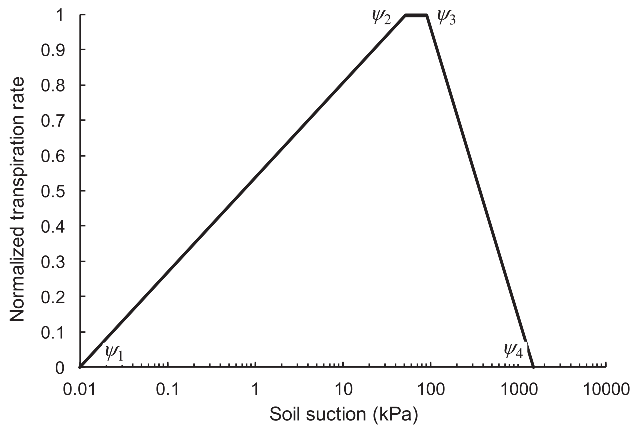

Fig. 2. Transpiration reduction function adopted for simulating root-water uptake (adapted after Garg et al. [11]).