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Technical note

Water content of soil matrix during lateral water flow through cracked soil

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ABSTRACT

Two types of flow occur when a network of cracks in a soil mass becomes filled with water. The types of water flow are lateral water flow through the network of cracks and water seepage into the intact soil matrix. The pattern of water content changes within the intact soil matrix part of a cracked soil due to water seepage is different from the pattern of water content changes due to water seepage in an intact soil. The soil matrix located closer to a crack has a higher water content than those located further away from a crack. A method was developed to determine changes in water content at various positions within the intact soil matrix part of a cracked soil. The proposed methodology involves modelling the water in the cracks as head boundary conditions alongside the walls of cracks. The analysis used a numerical solution of a differential equation for an intact soil. An idealized network of cracks was used to represent the cracks in the soil. Laboratory experiments were used to investigate the performance of the proposed method. The experiments mainly consisted of the measurement of water content at several locations within the intact soil matrix part of a cracked soil at various distances from the cracks during and at the end of lateral flow tests. Comparison of the numerical analysis results and the experiments results provided verifications of the proposed methodology. Modelling of the network of cracks using head boundary conditions showed close agreement with the laboratory measurements.

1. Introduction

Desiccation cracks are a common occurrence at the soil surface in the field (e.g., Hewitt and Philip, 1999; Morris et al., 1992; Heath and Lehr, 1987). Desiccation causes the soil to shrink and this causes tensile stress to develop in the soil. The tensile stress then leads to the formation of desiccation cracks. Cracks occur in soil at locations where the tensile strength of the soil cannot sustain the applied tensile stress.

When the cracks in soil are filled with water and a difference in total head is generated, two types of flow can occur; namely, lateral water flow through the network of cracks, and water seepage into the intact soil matrix (Krisnanto et al., 2014). Lateral water flow through the network of cracks has been studied by several researchers (e.g. Li and Zhang, 2007; Li et al., 2009; Krisnanto et al., 2014).

The presence of cracks alters the pattern of water content changes in soil as compared to the pattern when cracks are not present. An example of water seepage through an idealized cracked soil is shown in Fig. 1a. The cracks are filled with water and the upstream boundary has a higher total head than the head at the downstream boundary. Fig. 1b shows water seepage into the intact soil matrix part in a cracked soil mass. The direction of seepage through the intact soil matrix part is not only from the upstream to the downstream boundaries as in an intact soil, but also from the crack walls into the intact soil matrix. The intact soil matrix located closer to a crack wall (e.g. at point B) has a higher water content than that located further away from a crack wall (e.g. at point C). The same phenomenon has been reported in previous studies. Zhang and Zhang (2010) and Novák et al. (2000) performed numerical analyses and found that the presence of cracks alters the pattern of water content changes as compared to the pattern in intact soils. Mitchell and van Genuchten (1993) investigated the behaviour of water filling a cracked soil during irrigation. It was observed that

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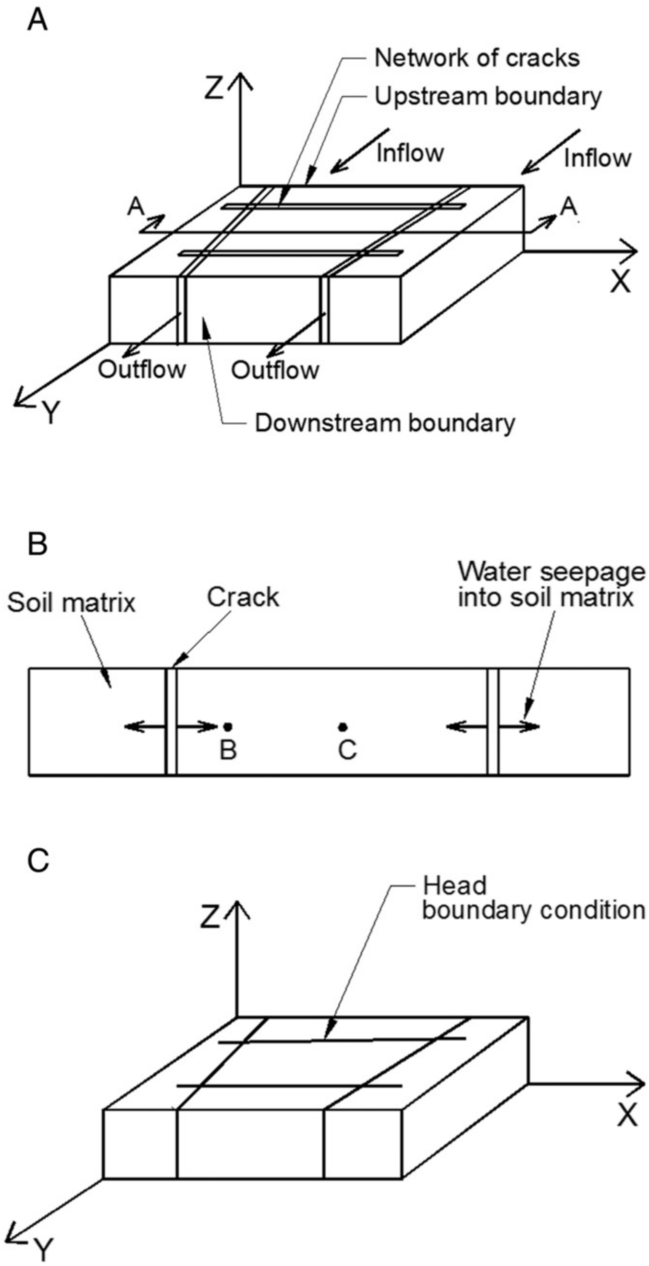

Fig. 1. (a) Perspective view of water seepage into an idealized cracked soil mass; (b) cross section A-A; (c) perspective view of modelling a network of cracks as boundary conditions.

water first filled the cracks and then seeped into the intact soil matrix part of the cracked soil. Zhan et al. (2007) measured the water content of cracked slopes during rainfall and found that the water content of soil samples in close proximity and at the same elevation could be significantly different. The difference was due to the presence of cracks but no methodology was proposed to analyze the changes in water content at various positions within the intact soil matrix part of cracked soil mass.

It appears that in addition to the lateral flow rate through the network of cracks, the changes in water content at various positions within the intact soil matrix part of cracked soil also need to be simulated. There is a need for a method to analyze changes in water content over time at various positions within the intact soil matrix part of a cracked soil. There is also lack of experimental data to evaluate any proposed methodology to calculate changes in water content at various positions within the intact soil matrix part of cracked soils during and at the end of lateral flow through cracked soil.

This paper presents the measurement of water contents during a lateral flow of water through a cracked soil specimen at several locations within the intact soil matrix part of the cracked soil specimen and at various distances from the cracks. A method is proposed for the analysis of the changes in water content within the intact soil matrix part of the cracked soil by modelling the cracks as head boundary conditions. The performance of the proposed method is evaluated by comparing the computed water contents at several locations in the intact soil matrix part of the cracked soil specimens from the numerical analyses utilizing the proposed method and the measured data from laboratory experimental results.

2. Proposed method to analyze changes in water content of cracked soil

Matric suctions of intact soil during an unsteady-state seepage through an intact soil can be quantified by computing hydraulic heads within the intact soil. The hydraulic head within the intact soil can be quantified using the differential equation for unsteady-state seepage into an intact soil (Fredlund and Rahardjo, 1993):

$$\frac{\partial}{\partial x}\left(k_{wxx}\frac{\partial h_w}{\partial x}+k_{wxy}\frac{\partial h_w}{\partial y}\right)+\frac{\partial}{\partial y}\left(k_{wyx}\frac{\partial h_w}{\partial x}+k_{wyy}\frac{\partial h_w}{\partial y}\right) = m_2^w\rho_w g\frac{\partial h_w}{\partial t} \tag{1}$$

where h_w is the hydraulic head; y is the elevation; x is the x-axis (i.e. horizontal); m_2^w is the coefficient of water volume change with respect to a change in matric suction $(u_a - u_w)$; ρ_w is the density of water; g is the gravitational acceleration; t is the time; k_{wxx} and k_{wxy}, are the coefficients of permeability in the x-direction in terms of the major and minor coefficients of permeability, respectively; k_{wyx} and k_{wyy} are the coefficients of permeability in the y-direction in terms of the major and minor coefficients of permeability, respectively.

The differential equation that describes an unsteady-state seepage through an intact soil is based on the analysis of a referential elemental volume (REV) (Fredlund et al., 2012), or is also named as a control volume (Freeze and Cherry, 1979). The REVs are then applied as finite-sized elements of a continuum, which can be combined to form a continuum model (Fredlund et al., 2012). Boundary conditions are then assigned to the region that is being analyzed. In the problem of unsaturated seepage through an intact soil matrix, these boundary conditions include flux and head boundary conditions.

Since a cracked soil mass consists of network of cracks and intact soil matrix, water seeps from the walls of the crack into the intact soil matrix (Fig. 1b) when the water flows through the network of cracks (Fig. 1a), the cracked soil mass behaves as a non-continuum rather than a continuum. In this paper, changes in water content at various positions within the intact soil matrix are analyzed as part of a cracked soil by modelling the cracks (Fig. 1a) as head boundary conditions (Fig. 1c). Using this methodology, it is idealized that water seeps laterally from the crack walls into the intact soil matrix as shown in Fig. 1b. An analysis is then performed by applying Eq. (1) in the form of a numerical model. The idealized network of cracks used in Krisnanto et al. (2014) is used in the analysis.

Hydraulic head in unsaturated soil matrix can be calculated using Eq. (1) and then related to matric suction. Matric suction can also be related to gravimetric and volumetric water contents using the soil-water characteristic curve (SWCC). The performance of the proposed methodology can be evaluated by comparing the values of gravimetric and volumetric water contents obtained using the numerical analysis to those obtained from laboratory measurements.