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# Mapping of cracked soils and lateral water flow characteristics through a network of cracks

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ABSTRACT

When a cohesive soil is dried, its volume tends to shrink in three directions. Shrinkage of the soil causes tensile stresses to develop and desiccation cracks will start to develop. The occurrence of cracks can significantly influence the lateral flow of water through the soil. It is important to understand the characteristics of lateral flow through a cracked soil. A model to predict the lateral flow rate through a network of cracks in the soils is proposed in this paper. In the proposed model, the actual network of cracks was idealized into a set of linear cracks. The flow through a single crack was modeled as a flow through parallel plates and the flow rate through the idealized network of cracks was calculated by incorporating the conservation of mass principle and the additional head losses due to the change in crack aperture. Laboratory experiments were performed to investigate the predictive performance of the model. Experiments were performed consisting of two main parts; namely, performing a desiccation test and performing a lateral flow test to measure the lateral flow rate through a cracked soil specimen followed by measuring water contents along the cracked soil specimen following the completion of the test. The laboratory test results indicated that during the lateral flow through the unsaturated soil specimens, two types of flow occurred which can be described as the steady state water flow through the network of cracks and the transient state seepage into the soil matrix. A comparison of the predicted and measured lateral water flow rates showed that the proposed model was able to predict the lateral flow rate through the network of cracks quite well.



## 1. Introduction

A cohesive soil shrinks as it dries until its gravimetric water content reaches the shrinkage limit. The amount of shrinkage may not be uniform throughout the depth of drying (Fredlund and Rahardjo, 1993). The non-uniformity in shrinkage causes tensile stress to develop and desiccation cracks to occur. Desiccation cracks are a common occurrence at the soil surface in the field (e.g., Heath and Lehr, 1987; Morris et al., 1992; Hewitt and Philip, 1999).

When rainwater enters a cracked soil on a sloping surface, it flows laterally through the network of cracks and seeps into the soil matrix. As water moves through the network of cracks there is an increase in the lateral flow rate through the soil as compared to flow through intact soils (Inoue, 1993; Fredlund et al., 2010). Consequently, the occurrences of cracks in the soil mass influence the lateral water flow through the soil.

Lateral water flow through an intact soil on a sloping surface can influence hillside hydrology (Hewlett and Hibber, 1963; Sinai et al., 1981; McCord and Stephens, 1987; Torres et al., 1998; Sinai and Dirksen, 2006). The occurrence of cracks in the soil can also influence the lateral flow on a hillside slope. It is important to understand the characteristics of lateral flow through a cracked soil.

Several researchers have studied the water flow through cracked rocks and soils. Indraratna and Ranjith (2001) developed a method to calculate flow through a cracked rock using the conservation of mass principle. Long et al. (1982), Li and Zhang (2007), and Li et al. (2009) developed a method to determine whether a network of cracks can be considered as a continuum with anisotropic characteristics for the saturated coefficient of permeability. Kranz et al. (1979) and Witherspoon et al. (1980) measured crack aperture indirectly by noting the change in the crack aperture due to confining pressure, measured water flow rate through a single crack in rock specimens, and making a comparison with the predicted flow rate using the cubic law (Taylor, 1948; Snow, 1968, 1969). However, in the previous studies there was no theory that was proposed to predict the lateral water flow rate from a mapped plan view of the network of cracks in the soil. A model to predict the

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lateral water flow rate from the mapped plan view of the network of cracks in a soil is needed in engineering practice.

This paper presents a model to predict the lateral water flow rate through a network of cracks in a soil. The prediction of lateral flow rate is made from the mapped plan view of the network of cracks in the soil. A procedure to obtain the map of the network of cracks in a soil is also presented. Laboratory experiments were performed to investigate the performance of the model by comparing the predicted lateral water flow rate from the model with that measured in the laboratory experiment. Numerical simulations were performed to compare the water flow rate through the network of crack with the water seepage rate into the soil matrix. The flow characteristics were observed by comparing the results from the numerical simulations and the results from the laboratory experiments.

## 2. Proposed model for flow through cracks

### 2.1. Idealization of the network of cracks

An actual network of cracks varies in shape, direction, and aperture. The crack model consists of an idealized set of linear cracks. The idealized cracks in the network are subdivided into three categories (Figure 1a) following the crack categorization proposed by Li and Zhang (2007) and Li et al. (2009). These categories are: (1) the cracks located between two intersection points, (2) the cracks which have only one intersection point, and (3) the isolated cracks that have no intersection point. In addition, a crack which varies in aperture is idealized as having a constant aperture. In this paper, a constant crack aperture is referred to as the "representative aperture".

An idealized cracked soil element experiencing lateral flow is shown in Fig. 1b. Cracks are located on the XY plane of the soil element and the lateral flow is defined as the flow perpendicular to the XZ plane of the soil element. The lateral flow occurs because of the head difference between two planes in the XZ plane (Figure 1c).

To obtain an idealized network of cracks from an actual network of cracks in the soil, four consecutive steps are performed: mapping the network of cracks, digitizing the mapped network of cracks, skeletonizing the network of cracks, and idealizing the network of cracks. The cracked soil specimen is mapped to obtain a mapped plan view of the network of cracks. The picture is then digitized for the skeletonizing process. From the skeleton of network of cracks, an idealized network of cracks is obtained and the representative crack aperture is then calculated.

The procedure to map and to digitize the network of cracks is presented in Section 3. The derivation to obtain the representative aperture is presented in Section 2.2. The method to skeletonize the network of cracks is presented in this section.

Skeletonizing is the process used to represent the network of cracks of varying widths with a single line (Tang et al., 2008; Atique et al., 2010). This process is performed by first drawing lines from a starting point at one side of the crack wall at different angles (Figure 2a). An arbitrary variation of angle is set equal to 0.1° in this study. The shortest line connecting the starting point (point O in Figure 2a) with the other side of the crack wall is selected as the crack aperture and the middle of the line is selected as the skeleton point. The skeleton points are then connected to obtain the skeleton of the network of cracks. As a result, the variation in the aperture along a crack and the skeleton of the network of cracks are obtained. The aperture measurements are performed at the end points of each line representing crack wall (e. g. points A to H in Figure 2b). These lines are obtained from the digitized map of the network of cracks as explained in Section 3. After the network of cracks is skeletonized, this network is idealized by connecting two intersection points of the network of cracks with a straight line. Crack lengths are defined as the distance between two intersection points. Tang et al. (2008) used this method and developed a computer program to implement the procedure. The computer program selected random points along the crack wall in a network of cracks as a starting point to measure the crack aperture.

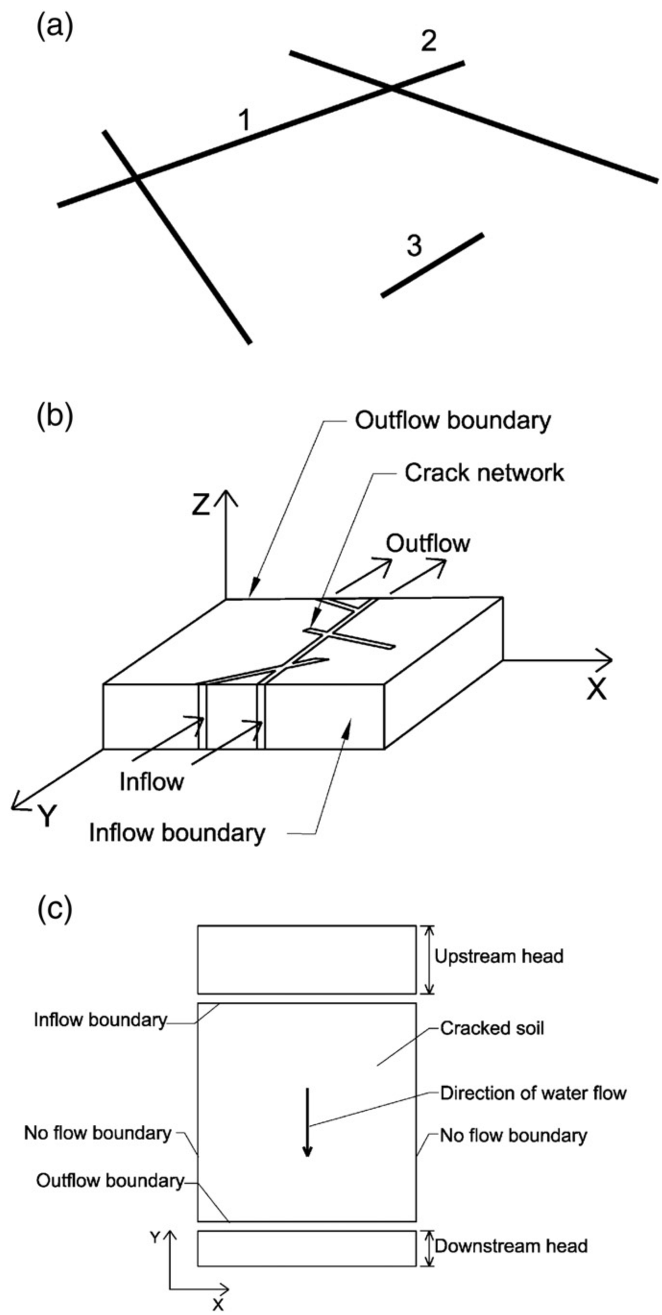


**Fig. 1.** An idealized soil element considered in the lateral flow test: (a) Three categories of idealized crack in the network; (b) An idealized cracked soil element considered in the lateral flow analysis; (c) Plan view of lateral flow through a cracked soil.

### 2.2. Prediction of the flow rate through the network of cracks

The following conditions are assumed when developing the proposed model to predict the lateral flow rate through a network of cracks:

- The cracks extend from top to bottom of the soil layer with a constant aperture.
- The aperture of cracks remains constant during lateral water flow.
- The lateral flow through the network of cracks is under steady state flow conditions.