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2014

Krisnanto, S., Rahardjo, H., Fredlund, D.G., & Leong, E.C. (2014). Mapping of cracked soils and lateral water flow characteristics through a network of cracks. *Engineering Geology*, 172, 12-25.

<https://hdl.handle.net/10356/101959>

<https://doi.org/10.1016/j.enggeo.2014.01.002>

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Question from Reviewer No. 1

Question no. 1

The authors have addressed my questions satisfactorily. The readability of the paper can be further improved by a thorough check. A few examples:

Line 21. the conservation of flow rate principle -- the mass conservation instead?

Line 93. The lateral flow occurs laterally because of - delete "laterally"

Line 347. The specimen was cut into 5 cm in diameter and 5 cm in height... - The specimen was cut to dimensions 5 cm in diameter and 5 cm in height...

Response:

The suggestions have been incorporated in the revised manuscript (highlighted in yellow).

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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 modelled 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.

Keywords: lateral flow rate, network of cracks, cracked soils.

1. Introduction

A cohesive soil shrinks as it dries until its gravimetric water content reaches the shrinkage limit. The amount of shrinkage may not 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); 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; Snow, 1969). However, in the previous studies there was no theory that was proposed to predict the lateral water flow rate from a map plan view of the network of cracks in the soil. A model to predict the lateral water flow rate from the map 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 map 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 simulation 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 (Fig. 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 XZ plane of the soil element and the lateral flow is defined as the flow perpendicular to the XY plane of the soil element. The lateral flow occurs because of the head difference between two planes in the XY plane (Fig. 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, skeletonising the network of cracks, and idealizing the network of cracks. The cracked soil specimen is mapped to obtain a map plan view of the network of cracks. The picture is then digitized for the skeletonising 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 skeletonised the network of cracks is presented in this section

Skeletonising 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 (Fig. 2a). An arbitrary variation of angle is set equal to 0.1 degrees in this study. The shortest line connecting the starting point (point O in Fig. 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 Fig. 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 skeletonised, 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.

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.

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

129

130 The lateral flow rate through a network of cracks is predicted by first calculating the head
 131 values at each crack intersections points using the conservation of mass principle, i.e. the
 132 summation of mass of water that flows into a crack intersection point and the mass of water
 133 that flows from a crack intersection is equal to zero (Indraratna and Ranjith, 2001; Li and
 134 Zhang, 2007; Li et al., 2009). Since water is considered incompressible, this principle
 135 implies that the summation of flow rate into a crack intersection point and the summation of
 136 flow rate from the crack intersection point is equal to zero:

$$137 \left(\sum_{j=1}^{m_k} q_{jk} \right)_k = 0 \quad k = 1, 2, 3, \dots, n \quad (1)$$

138 where: q_{jk} is the flow rate through the j^{th} crack at the k^{th} intersection point; m_k is the number
 139 of crack intersecting at the k^{th} intersection point; and n is the number of crack intersection
 140 points. The flow through a single crack is considered as flow through parallel plates and the
 141 flow rate through each single crack is computed as (Taylor, 1948; Snow, 1968; Snow, 1969):

$$142 q = \frac{gb^3}{12\nu} i \quad (2)$$

143 where: q is the flow rate through a single crack ($m^3/s/m$); g is the gravitational constant
 144 (m/s^2); b is the crack aperture (m); ν is the kinematic viscosity of water (m^2/s); and i is the
 145 hydraulic gradient between two end points of a crack. The application of Eq. (1) results in n
 146 simultaneous linear equations with n unknowns head values at crack the intersection points.

147

The flow rate calculated using Eq. (2) is based on an assumption that the walls of the crack are smooth or have a constant aperture. In reality, the walls of a crack are not smooth and their aperture varies along the crack (e.g., Tang et al., 2008, Atique et al., 2010). The value for the aperture that should be used in Eq. (2) needs to be determined. Some researchers (e.g., Barton, 1982; Schrauf and Evans, 1986) have back-calculated the aperture that should be used in Eq. (2) from flow rate measurements. A comparison is then made to obtain the so-called average aperture obtained from the measurement of crack aperture changes due to confining pressure. The results showed that the aperture that should be used in Eq. (2) in order to obtain agreement between the calculated and the measured flow is smaller than the average measured aperture. However, the previous studies have not indicated the methodology that should be used to obtain the aperture that should be used in Eq. (2) when the mapped picture of the network of cracks is obtained. In this study, a representative crack aperture of an actual crack aperture is proposed as the value that should be used in Eq. (2). The representative crack aperture is assumed to be constant for a single crack.

Cracks are modelled as parallel plates in this study. A single crack that varies in aperture is modelled as parallel plates that vary in distance. The variation of distance between the parallel plates implies that there is a variation of cross-section along the flow path. This variation of cross-section could generate a head loss (Streeter, 1961). In the proposed model, an additional head loss due to a change in crack aperture is incorporated to calculate the hydraulic gradient i and the representative crack aperture b that should be used in Eq. (2). It was assumed that the crack was linear from each crack intersection point. Therefore, an additional head loss due to curvature of crack was not considered in the analysis.

The change of aperture consists of enlargement and contraction of crack aperture. Therefore, in calculating the additional head losses due to variations of the crack aperture, two types of head losses are considered: the additional head loss due to crack aperture enlargement and the additional head loss due to crack aperture contraction.

Additional Head Loss due to Crack Aperture Enlargement

Fig. 3a shows flow through an enlargement of crack aperture. The Borda-Carnot equation (Streeter, 1961; Massey and Ward-Smith, 1998) was derived for a circular cross-section of pipe and is used to quantify the head loss due to change of the crack cross-section. The resultant of forces on the right side is equal to the rate of increase of momentum in that direction:

$$p_1 A_1 + p_1 (A_2 - A_1) - p_2 A_2 = \rho_w q (v_2 - v_1) \quad (3)$$

$$p_1 - p_2 = \rho_w \frac{q}{A_2} (v_2 - v_1) \quad (4)$$

$$p_1 - p_2 = \rho_w v_2 (v_2 - v_1) \quad (5)$$

where: A_1 and A_2 are the area of sections 1 and 2; ρ_w is the density of water; q is the flow rate; and v_1 and v_2 are the velocity at sections 1 and 2, respectively. The following equation can be written by applying the Bernoulli equation to the head loss associated with the crack aperture enlargement:

$$\frac{p_1}{\rho_w g} + \frac{v_1^2}{2g} + z_1 - h_{le} = \frac{p_2}{\rho_w g} + \frac{v_2^2}{2g} + z_2 \quad (6)$$

Since z_1 is equal to z_2 , then the above equation becomes:

$$\frac{p_1}{\rho_w g} + \frac{v_1^2}{2g} - h_{le} = \frac{p_2}{\rho_w g} + \frac{v_2^2}{2g} \quad (7)$$

$$h_{le} = \frac{p_1 - p_2}{\rho_w g} + \frac{v_1^2 - v_2^2}{2g} \quad (8)$$

where: h_{le} is the head loss due to aperture enlargement. Substitution of Eq. (5) into Eq. (8) gives:

$$h_{le} = \frac{v_2(v_2 - v_1)}{g} + \frac{v_1^2 - v_2^2}{2g} \quad (9)$$

$$h_{le} = \frac{(v_1 - v_2)^2}{2g} \quad (10)$$

Continuity of the flow rate requires:

$$A_1 v_1 = A_2 v_2 \quad (11)$$

Substitution Eq. (11) into Eq. (10) gives the head loss due to crack aperture enlargement:

$$h_{le} = \frac{v_2^2}{2g} \left(\frac{A_2}{A_1} - 1 \right)^2 \quad (12)$$

Eq. (12) can be simplified as:

$$h_{le} = K_e \frac{v_2^2}{2g} \quad (13)$$

where: K_e is the coefficient of head loss due to crack enlargement which can be calculated as:

$$K_e = \left(\frac{A_2}{A_1} - 1 \right)^2 \quad (14)$$

Additional Head Loss due to Crack Aperture Contraction

Figure 3b shows flow through a contraction in the crack aperture. When water flows through a contraction, the outer streamlines contract to a section smaller than the contraction size. This section is called the vena contracta (ASHRAE, 1997). Following the procedure used to calculate the head loss due to a crack enlargement, the head loss due to crack contraction can be represented as follows:

$$h_{lc} = \frac{v_2^2}{2g} \left(\frac{A_2}{A_c} - 1 \right)^2 \quad (15)$$

where: h_{lc} is the head loss due to crack aperture contraction; and A_c is the area of the vena contracta (Fig. 3b). Eq. (15) can be simplified as:

$$h_{lc} = K_c \frac{v_2^2}{2g} \quad (16)$$

where: K_c is the head loss coefficient due to contraction. In this study, the head loss coefficient due to contraction, K_c for pipe proposed by Streeter, (1961) as shown in Fig. 4 is used in Eq. (16). The additional head loss due to changes in the crack aperture within a single crack can be calculated as the summation of the additional head loss due to crack enlargement and the additional head loss due to crack contraction by summing Eqs. (13) and (16):

$$h_l = \sum_{j=1}^l K_e \frac{v_{j+1}^2}{2g} + \sum_{k=1}^m K_c \frac{v_{k+1}^2}{2g} \quad (17)$$

where: h_l is the additional head loss due to crack aperture change in a single crack; j is the counter indicating the cracks which enlarge in aperture; l is the number of cracks which enlarge in aperture; k is the counter indicating crack which contract in aperture and m is the number of cracks contract in aperture.

The hydraulic gradient i in Eq. (2) is calculated as:

$$i = \frac{(H_j - H_k - h_l)}{L} \quad (18)$$

where: H_j and H_k are the head at two crack intersection points j and k , respectively and L is the length of the corresponding crack. The additional head loss h_l is calculated using Eq. (17).

To calculate the representative crack aperture, b in Eq. (2), the total head difference between two crack endpoints is calculated as the summation of head difference at each crack segment (Fig. 5) as:

$$h = h_1 + h_2 + h_3 + \dots + h_n + h_l \quad (19)$$

where: h is the head difference between two crack intersection points; and h_1, h_2, h_3 and h_n are the head difference at crack sections 1, 2, 3, and n respectively. From the definition of hydraulic gradient:

$$i = \frac{h}{L} \quad (20)$$

where: i is the hydraulic gradient, h is the head difference and L is the length of path where the head difference occurs. Eq. (19) then becomes:

$$i_{avg} \cdot L = i_1 L_1 + i_2 L_2 + i_3 L_3 + \dots + i_n L_n + h_l \quad (21)$$

where: i_{avg} is the average hydraulic gradient between two crack endpoints; i_1, i_2, i_3 and i_n are the hydraulic gradients at crack segments 1, 2, 3 and n , respectively; L is the length of the crack; L_1, L_2, L_3 and L_n are the lengths of segments 1, 2, 3 and n respectively. From the definition of Darcy's law:

$$i = \frac{v}{k} \quad (22)$$

where: v is the velocity between the endpoints of a crack and k is the saturated coefficient of permeability, Eq. (21) then becomes:

$$\frac{v}{k_{eq}} L = \frac{v_1}{k_1} L_1 + \frac{v_2}{k_2} L_2 + \frac{v_3}{k_3} L_3 + \dots + \frac{v_n}{k_n} L_n + h_l \quad (23)$$

where: v_1, v_2, v_3 , and v_n are the velocity at crack segments 1, 2, 3 and n , respectively; k_{eq} is the equivalent saturated permeability of a single crack, k_1, k_2, k_3 , and k_n are the saturated coefficients of permeability of crack at crack segments 1, 2, 3 and n , respectively. Substituting Eq. (17) into Eq. (23) gives:

$$\frac{v}{k_{eq}} L = \frac{v_1}{k_1} L_1 + \frac{v_2}{k_2} L_2 + \frac{v_3}{k_3} L_3 + \dots + \frac{v_n}{k_n} L_n + \sum_{j=1}^l K_e \frac{v_{j+1}^2}{2g} + \sum_{k=1}^m K_c \frac{v_{k+1}^2}{2g} \quad (24)$$

Since:

$$v = \frac{q}{b(1)} \quad (25)$$

Then Eq. (24) becomes:

$$\frac{q}{b(1)k_{eq}}L = \frac{q_1}{b_1(1)k_1}L_1 + \frac{q_2}{b_2(1)k_2}L_2 + \frac{q_3}{b_3(1)k_3}L_3 + \dots + \frac{q_n}{b_n(1)k_n}L_n + \sum_{j=1}^l K_e \frac{q_{j+1}^2}{b_{j+1}^2(1)^2 2g} + \sum_{k=1}^m K_c \frac{q_{k+1}^2}{b_{k+1}^2(1)^2 2g} \quad (26)$$

where: q_1, q_2, q_3 and q_n are the flow rate at sections 1, 2, 3 and n , respectively; b_1, b_2, b_3 and b_n are the crack aperture of sections 1, 2, 3 and n , respectively. Continuity of flow requires $q = q_1 = q_2 = q_3 = q_n$, then Eq. (26) becomes:

$$\frac{L}{bk_{eq}} = \frac{L_1}{b_1k_1} + \frac{L_2}{b_2k_2} + \frac{L_3}{b_3k_3} + \dots + \frac{L_n}{b_nk_n} + \sum_{j=1}^l K_e \frac{q_{j+1}}{b_{j+1}^2(1)^2 2g} + \sum_{k=1}^m K_c \frac{q_{k+1}}{b_{k+1}^2(1)^2 2g} \quad (27)$$

$$\frac{L}{bk_{eq}} = \frac{L_1}{b_1k_1} + \frac{L_2}{b_2k_2} + \frac{L_3}{b_3k_3} + \dots + \frac{L_n}{b_nk_n} + \sum_{j=1}^l K_e \frac{q_{j+1}}{2b_{j+1}^2g} + \sum_{k=1}^m K_c \frac{q_{k+1}}{2b_{k+1}^2g} \quad (28)$$

From Eqs. (2), (25), and (22):

$$k = \frac{gb^2}{12\nu} \quad (29)$$

Substitution Eq. (29) into Eq. (28) gives:

$$\frac{L}{b \frac{gb^2}{12\nu}} = \frac{L_1}{b_1 \frac{gb_1^2}{12\nu}} + \frac{L_2}{b_2 \frac{gb_2^2}{12\nu}} + \frac{L_3}{b_3 \frac{gb_3^2}{12\nu}} + \dots + \frac{L_n}{b_n \frac{gb_n^2}{12\nu}} + \sum_{j=1}^l K_e \frac{q_{j+1}}{2b_{j+1}^2g} + \sum_{k=1}^m K_c \frac{q_{k+1}}{2b_{k+1}^2g} \quad (30)$$

$$\frac{L}{b^3} = \frac{L_1}{b_1^3} + \frac{L_2}{b_2^3} + \frac{L_3}{b_3^3} + \dots + \frac{L_n}{b_n^3} + \sum_{j=1}^l K_e \frac{q_{j+1}}{24\nu b_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{k+1}}{24\nu b_{k+1}^2} \quad (31)$$

$$b^3 = \frac{L}{\frac{L_1}{b_1^3} + \frac{L_2}{b_2^3} + \frac{L_3}{b_3^3} + \dots + \frac{L_n}{b_n^3} + \sum_{j=1}^l K_e \frac{q_{j+1}}{24\nu b_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{k+1}}{24\nu b_{k+1}^2}} \quad (32)$$

Therefore, the representative aperture b of a crack can be calculated as:

$$b = \sqrt[3]{\frac{L}{\frac{L_1}{b_1^3} + \frac{L_2}{b_2^3} + \frac{L_3}{b_3^3} + \dots + \frac{L_n}{b_n^3} + \sum_{j=1}^l K_e \frac{q_{j+1}}{24vb_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{j+1}}{24vb_{k+1}^2}}} \quad (33)$$

276

277 To predict the lateral flow rate through a network of cracks, the head values at each crack
 278 intersection points are calculated using Eqs. (1) and (2) utilizing the representative crack
 279 aperture calculated using Eq. (33). The calculation is performed iteratively since the head loss
 280 depends on the velocity and the velocity depends on the head difference between two crack
 281 intersection points. In the first iteration, the additional head loss h_l in Eq. (18) is assumed to

282 be zero. Therefore, the factor $\sum_{j=1}^l K_e \frac{q_{j+1}}{24vb_{j+1}^2} + \sum_{k=1}^m K_c \frac{q_{k+1}}{24vb_{k+1}^2}$ in Eq. (33) is also assumed to be

283 zero. The simultaneous linear equations are then solved to obtain the head values at each
 284 crack intersection point. Having the values of head at each intersection points, flow rate in
 285 each crack is calculated using the hydraulic gradient, i calculated from Eq. (18) and
 286 substituting it into Eq. (2). The velocity at each crack segment can be calculated as:

$$v_j = \frac{q}{b_j t} \quad (34)$$

288 where: v_j is the velocity at crack segment j ; q is the flow rate in a crack calculated using Eq.
 289 (2); and t is the soil thickness. Having a value of velocity at each crack segment, the head loss
 290 due to the change of aperture is calculated using Eq. (17) and the representative crack
 291 aperture is calculated using Eq. (33). The calculation of a new crack aperture results in a new
 292 value for the additional head loss, h_l and the representative crack aperture b at each crack.
 293 Error ratios for the head loss and the representative crack aperture are defined as:

$$err_h = \frac{|h_{lk-1} - h_{lk}|}{h_{lk-1}} \quad (35)$$

$$err_b = \frac{|b_{k-1} - b_k|}{b_{k-1}} \quad (36)$$

where: err_h is the error ratio of head loss; h_{lk-1} is the head loss calculated in the $k-1^{th}$ iteration; h_{lk} is the head loss calculated in the k^{th} iteration; err_b is the error ratio of representative crack aperture; b_{k-1} is the representative crack aperture calculated in the $k-1^{th}$ iteration and b_k is the representative crack aperture calculated in the k^{th} iteration. An iteration process is performed by changing the assumed head loss values of each crack until both the values of the error ratio of all cracks are small. An error criterion 0.001 is used in this study.

The flow rate through each crack is calculated using the corresponding representative crack aperture b and the additional head loss h_l obtained from the iteration. The flow rate through the network of cracks in the specimen is then calculated as:

$$Q = \sum_{j=1}^m q_j \quad (37)$$

where: Q is the flow rate through network of cracks in the specimen, q_j is the flow rate of the crack intersects the outflow boundary (Fig. 6) and m is number of the cracks intersecting the outflow boundary.

3. Soil, Apparatus and Procedure of the Lateral Flow Test

A laboratory experiment was conducted to investigate performance of the model. The experiment consisted mainly of two parts: the desiccation test for the development of a network of cracks and the lateral flow test to measure the lateral flow rate through a cracked soil specimen. The water content along the cracked soil specimen was measured after the lateral flow test. The saturated coefficient of permeability and the soil-water characteristic (SWCC) tests were performed to obtain data for the numerical simulation of the lateral flow

test. Coarse kaolin produced by Kaolin Malaysia Sdn Bhd (Malaysia) was used in the experiment. Basic properties of the soil are shown in Table 1.

A cracked soil specimen was created to investigate the performance of the proposed seepage model. A slurried soil was used in this experiment because it exhibited the highest volume change during desiccation. The initial water content of the slurried soil was determined in order to form a specimen into a flat surface and to produce the largest number of cracks at dry condition. A desiccation test was performed to determine the initial water content of a slurried specimen used in the saturated coefficient of permeability measurement and the lateral flow tests. Three slurried soil specimens were placed in 25 cm x 25 cm aluminium trays with varying initial water contents: 100% of liquid limit (LL), 150% of LL and 200% of LL. The slurried soil specimens were dried at room temperature (at $24^{\circ}\text{C} \pm 2^{\circ}\text{C}$ temperature and $78\% \pm 1\%$ relative humidity). Gravimetric water contents of the specimens were measured periodically by weighing the specimens and calculating the change of water content of the specimens. The desiccation test was performed until the gravimetric water content of each specimen reached 43.4 % which was equal to the gravimetric water content at the initial condition of the lateral flow test (Table 2). Number of cracks at water content equal to 43.4% was counted using the definition of single crack as explained in Section 2.1.

A saturated permeability test was performed on the intact specimen which was dried from an initially slurried condition starting from initial water content determined from the result of the desiccation test. The slurried soil was first poured into a polyvinyl chloride (PVC) tube. A thin layer of oil was applied on the sides and base of the PVC tube to ensure that the soil shrank during desiccation without experiencing cracking. The specimen was then allowed to dry at room temperature (at $24^{\circ}\text{C} \pm 2^{\circ}\text{C}$ temperature and $78\% \pm 1\%$ relative humidity) until

its gravimetric water content reached 43.4%. Gravimetric water content of the soil specimen at different times was measured periodically by weighing the specimen and calculating the change of gravimetric water content of the specimen. As the specimen reached the designated gravimetric water content, the specimen was covered by a plastic sheet and was put into a humidity chamber for 24 hours to ensure the equalization of water content throughout the specimen. The specimen was cut to dimensions 5 cm in diameter and 5 cm in height and the saturated permeability test was carried out on the specimen using a triaxial apparatus. In the saturated permeability test, a back pressure was applied to ensure saturation of the soil specimen.

A drying the SWCC test on the intact soil matrix was performed at an initial water content established from the results of the desiccation tests. The test was performed using a Tempe cell and a 5-bar pressure plate. The Tempe cell could have pressure applied up to 100 kPa and the pressure plate apparatus could apply pressures up to 500 kPa of matric suction. The soil specimen for the SWCC test was made by pouring the slurried soil into the Tempe cell ring. During the test, the volume and weight of the soil specimen were measured at each equilibrium condition of matric suction. The volume of the specimen was measured using Vernier calipers. After obtaining all the data from the test, the data points were best fitted using Fredlund and Xing (1994) equation. This curve was named the initial drying SWCC (Pham et al., 2005). Other two curves of SWCC were the main drying and the main wetting SWCC (Pham et al., 2005). The main wetting SWCC was used in the numerical simulation of the lateral flow test. The main wetting SWCC was predicted from the main drying SWCC. Main drying and main wetting SWCCs were predicted using the method proposed by Pham et al., (2005). The main drying SWCC was predicted from the initial drying SWCC by multiplying a factor of 0.9 to the initial saturated water content and keeping other parameters

the same. This factor was based on the recommendation from Pham et al., (2005). The main wetting SWCC was predicted by dividing the slope of the main drying curve with a factor of 1.5 and stretching the main drying curve to the left so that the inflection point of the main wetting curve was located 0.5 orders of magnitude to the left of the inflection point of the main drying curve. The factor of 1.5 and the distance of 0.5 orders of magnitude were recommended by Pham et al., (2005) for silt loam and clay loam. Permeability functions were then calculated using the indirect method (Fredlund and Rahardjo, 1993) utilizing the saturated coefficient of permeability of soil matrix, k_s and the predicted main wetting SWCC.

A 1-D lateral flow apparatus was constructed to perform the lateral flow test to quantify the lateral flow rate through a cracked soil specimen. The schematic diagram of the 1-D lateral flow apparatus is shown in Fig. 7. It consisted of a box with three compartments. The first compartment is the upstream water compartment. During the test, water in the upstream compartment was maintained at a constant head value which was greater than the head at the downstream water compartment (third compartment). The second compartment contained the cracked soil specimen. Water was directed to flow laterally through the network of cracks in the soil specimen. Since the model was developed for lateral flow through a cracked soil, lateral flow between the edge of soil and box wall and the lateral flow on top of the specimen were prevented from occurring. Therefore, the edge of soil specimen was sealed to the box wall and a layer of plastic sheet was put on top of the cracked soil. The surface of the soil specimen was sealed to the plastic sheet using silicon glue to minimize the leakage. Water was then poured on top of the plastic sheet to produce pressure head on the plastic sheet which was equal to the pressure head in the upstream water compartment. As a result, good contact between the top soil surface and the plastic sheet was established to avoid water flow between them. The edge of the plastic sheet was sealed to the box using silicon glue to avoid

leakage of water. The third compartment is the downstream water compartment. Water in this compartment was maintained at a constant head during the test. Holes 0.5 cm x 2.5 cm with spacing 0.5 cm were constructed on the wall between the first and the second compartments and on the wall between the second and the third compartments to allow water to flow from the upstream water compartment to the cracked soil compartment and from the cracked soil compartment to the downstream water compartment, respectively.

The cracked soil specimen for lateral flow test was prepared by allowing the slurried soil specimen to dry at room temperature (at $24^{\circ}\text{C} \pm 2^{\circ}\text{C}$ temperature and $78\% \pm 1\%$ relative humidity) until the specimen achieve the designated water content (Table 2).

The cracked soil specimen was mapped to obtain a plan view of the network of cracks before water was allowed to flow laterally through the cracked soil. A laser scanner and a digital camera were used to produce the plan view of the network of cracks. The laser scanned the cracked soil specimen to obtain a file that contain group of points that describes the network of cracks. The file was then digitized using AutoCAD (Autodesk, 2004). The digitizing process was performed by representing crack walls as a series of lines. The lines representing the crack walls were called the crack wall lines. In addition to scanning the specimen using the laser scanner, a digital photograph of the cracked soil specimen was obtained. The photograph was imported into the AutoCAD and the digitizing process to represent crack walls as series of lines was performed. Digitizing from the photograph was used to incorporate cracks having aperture less than 1 mm. (The finest resolution of the laser scanner was 1 mm). The results of digitizing from the laser scanner and photograph were then combined as one digitized map plan view of the network of cracks. The result from laser

scanner was used as a reference since it provided a more precise dimension of the cracked soil specimen.

The lateral flow test was performed by providing different constant heads at the upstream and downstream water compartments. Water was then allowed to flow laterally through the cracked soil specimen. The outflow rate from the downstream water compartment was measured by weighing the mass of outflow water at time interval of 30 seconds. The measurement was performed every one minute. The boundary conditions for the lateral flow tests are shown in Table 2. In addition to the measurement of flow, five specimens of gravimetric water content were obtained from the cracked soil specimen (Fig. 13) following the completion of the lateral flow test.

4. Results and Discussions

4.1 Results of Laboratory Tests

Results of the desiccation test are shown in Fig. 8. Each crack in each specimen was numbered and crack number in each specimen was indicated from the biggest number in each specimen. Specimen 1 (i.e., initial water content equal to 100% of LL), had 14 cracks. This was the largest number of cracks among the three specimens (Fig. 8a). However, when the initial water content was equal to 100% of LL, it was difficult to keep the surface of the specimen flat. Specimen 3 had an initial water content equal to 200% of LL and only 2 cracks were formed (Fig. 8c). Even though at the initial water content was equal to 200% of the LL, the surface of the specimen could easily be maintained flat. Specimen 2 had an initial water content equal to 150% of LL and 6 cracks were formed. The surface of the soil was maintained flat even though the initial water content was equal to 150% of the LL. In

addition, there were some continuous paths in the cracked network from one side to the other side of the tray indicating that lateral flow through the cracked soil specimen could be expected in the lateral flow tests. An initial water content of 150% of LL (Fig. 8b) was selected as an initial water content of the specimens for the lateral flow tests.

The SWCC test was then performed at the selected initial water content of 150% of LL. The saturated permeability specimen was prepared by allowing the slurried soil to dry from the initial water content 150% of LL.

The initial drying, main drying and main wetting SWCCs of intact soil matrix are shown in Fig. 9a to 9c. The saturated coefficient of permeability is shown in Table 1. The wetting permeability function (Fig. 9d) was calculated indirectly from the main wetting SWCC in terms of degree of saturation against matric suction (Fig. 9c).

The specimens for lateral flow tests were prepared at water content 150% of LL. The specimens were dried until reaching its designated water contents shown in Table 2. The cracked soil specimens of the lateral flow tests are shown in Figs. 10 and 11.

The results of the water outflow measurement are shown in Fig. 12. In test 1, the water flow rate increased from zero at the beginning of the test to $8.5 \times 10^{-5} \text{ m}^3/\text{s}$ at about 2 minutes and became constant at a value of $1.05 \times 10^{-4} \text{ m}^3/\text{s}$ after 4 minutes. In test 2, the water flow rate increased from zero at the beginning of the test to $9.0 \times 10^{-5} \text{ m}^3/\text{s}$ at about 0.4 minute and to $1.2 \times 10^{-4} \text{ m}^3/\text{s}$ at about 1 minute. Fluctuation of water flow rate occurred between 1 minute to 4 minutes and the flow rate became constant at a value of $1.1 \times 10^{-4} \text{ m}^3/\text{s}$ after 4 minutes.

The results of water content measurement after the lateral flow tests are shown in Table 3. The sampling number shown in Table 3 corresponds to the location of water content measurement in Fig. 13.

4.2 Prediction of Flow Rate using the Proposed Model

The proposed model was then used to predict the lateral flow rate of the specimens in the lateral flow tests. The first step to make a prediction of lateral flow rate was to represent the network of cracks of the pictures of the network of cracks as a digitized cracked network as shown in Figs. 10b and 11c. The digitized network of cracks was then converted to a skeleton of network of cracks and then converted to an idealized network of cracks using the principles explained in Section 2.1. The skeleton of the network of cracks are shown in Figs. 14a and 15a whereas the idealized network of cracks of the soil are shown in Figs. 14b and 15b.

After representing the actual network of cracks as an idealized network of cracks, Eqs. (1) and (2) were applied to predict the lateral flow rate through the network of cracks. Equations (18) and (33) were incorporated into Eq. (2) to calculate the lateral flow. The head values (Table 2) were assigned to the upstream and downstream boundaries, respectively, and the head values at each crack intersection points were calculated. The lateral flow rate at each crack was then calculated using the head values of the two intersection points of the corresponding crack. The outflow rate was calculated as the summation of flow rates through cracks that intersect the outflow boundary.

4.3 Analysis and Discussion

The laboratory test results showed that the measured lateral flow rate was relatively constant with time (Fig. 16), indicating a steady state flow through the cracked soil specimen. A comparison of water contents of the specimens along the cracked soil as measured after the lateral flow test (Table 3) with those of the main wetting SWCC in Fig. 9(b) indicated that matric suction of the specimens were in the range of 2 to 10 kPa. A comparison of these matric suction values with those of the main wetting SWCC in Fig. 9(c) indicated that the degrees of saturation of the specimens were below 100%. In other words the soil matrix was still in unsaturated conditions. The unsaturated soil matrix indicated that water was still seeping from the saturated network of cracks into the soil matrix. The seepage through the unsaturated soil matrix indicated transient flow. This phenomenon indicated that during the lateral flow into an unsaturated cracked soil specimen, two types of flow occurred simultaneously: the water flow through a network of cracks which was a steady state flow and the water seepage through soil matrix which was a transient flow.

The proposed model only predicted lateral flow rate through the network of cracks. The quantity of water that seeped into the soil matrix was not incorporated in the calculation of lateral flow rate. Furthermore the laboratory experiment only measured lateral out flow rate through the network of cracks. It was implicitly assumed that seepage rate into the soil matrix was small in comparison to the lateral water flow through the network of cracks. To analyze the seepage rate into the soil matrix, a numerical simulation of the laboratory test was performed using SVFlux (Soil Vision, 2009). The finite element models are shown in Fig. 17. The same boundary conditions as in the laboratory test were assigned to the finite element model. SWCC and permeability function of the soil matrix (Fig. 9) were used as input in the numerical simulation. The network of cracks was modelled as a saturated material while incorporating the permeability calculated using Eq. (29). However, the additional head loss

calculated using Eq. (17) could not be incorporated in the numerical simulation, therefore, the crack aperture for the numerical model needed to be calculated.

The flow rate through a single crack was calculated using the proposed model and the numerical simulation was equal to:

$$q = q' \quad (38)$$

where: q is the flow rate calculated from the proposed model and q' is the flow rate of a single crack in the numerical simulation. From Eq. (2) incorporating head values of two crack intersection points:

$$\frac{gb^3}{12\nu} \frac{(H_j - H_k - h_l)}{L} = \frac{gb'^3}{12\nu} \frac{(H_j - H_k)}{L} \quad (39)$$

$$b' = \sqrt[3]{\frac{H_j - H_k - h_l}{H_j - H_k} b^3} \quad (40)$$

where: b is the crack aperture calculated using the proposed model (Eq. (33)); b' is the crack aperture used in the numerical model; H_j and H_k are the heads at two crack intersection points j and k , respectively; h_l is the additional head loss (Eq. (17)) and L is the length of the corresponding crack. The aperture of each crack was calculated using Eq. (40). The calculated value was used in the numerical model.

The results of the numerical simulation are shown in Fig. 16 together with results from the laboratory test and the results from the proposed model. The results showed that the lateral outflow rates calculated from the numerical simulation are close to the laboratory measured and the predicted lateral outflow rate from the proposed model. The inflow and outflow rates calculated from the numerical simulation are quite similar indicating that the seepage rate into the soil matrix is small as compared to the flow through the network of cracks.

Therefore, the lateral flow through a cracked soil can be quantified quite independent of the lateral flow through the network of cracks.

Comparisons between the measured and predicted lateral flow rate using the proposed model (Fig. 16) shows that the predicted lateral flow rates through the network of cracks was relatively close to the measured results. This indicated that by incorporating the additional head loss due to changes in crack aperture in the calculation of hydraulic gradient (Eq. (18)) and using of the representative crack aperture b (Eq. (33)) provides a satisfactory method to predict the lateral flow rate through the network of cracks.

The proposed model was developed for a simple crack configuration with only one flow path from the inflow boundary to the outflow boundary (Figs. 10 and 11). Performance of the proposed model in predicting water flow rates in a more complex network of cracks needs to be investigated further.

5. Conclusions

1. There are two types of lateral flow that occur simultaneously when water flows through a network of cracks. One is the steady state water flow through the network of cracks and the other is the transient seepage through the soil matrix. The seepage rate into the soil matrix is small when compared to the flow through the network of cracks. The flow rate through a cracked soil can be quantified quite well from the flow rate through the network of cracks.
2. A model to predict the lateral flow rate through a network of cracks was developed using an idealization of the actual network of cracks as a series of parallel plates. The conservation of mass principle was applied and the head loss due to changes in crack

aperture on the hydraulic gradient in a single crack was incorporated. Each crack was represented by a single aperture.

3. A mapping procedure was proposed to obtain an idealized network of cracks from a cracked soil specimen. Four steps were used to obtain an idealized network of cracks from an actual network of cracks in the soil. The four steps were: mapping the network of cracks, digitizing the mapped network of cracks, skeletonising the network of cracks and idealizing the network of cracks.

4. The cubic law (Eq. (2)) can be used to calculate the lateral flow through the network of cracks in a cracked soil. However, the additional head loss due to changes in the crack aperture should be incorporated in the calculation of hydraulic gradient (Eq. (18)) and the representative crack aperture (Eq. (33)) in order to obtain agreement between the predicted flow and measured flow.

5. The comparison between the measured and predicted flow rates showed that the predicted lateral flow rates through the network of cracks were relatively close to the measured values. This indicates that the proposed model can predict the lateral flow rate through a cracked soil specimen quite well.

6. An apparatus to quantify the lateral flow through a cracked soil has been developed. The apparatus utilizing constant head to allow water flow laterally through a crack soil specimen. The lateral flow rate can be measured using this apparatus.

7. Performance of the proposed model to predict water flow rate in a more complex network of cracks needs to be investigated further.

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Table 1 Basic soil properties

Specific gravity, G_s	2.65
Silt (%)	70
Clay (%)	30
Liquid Limit, LL (%)	67.9
Plastic Limit, PL (%)	38.5
Plasticity Index, PI (%)	29.4
Soil Classification according to Unified Classification System (USCS)	MH (silt with high plasticity)
Saturated permeability, k_s (m/s)	8.0×10^{-12}

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694

Table 2 Boundary conditions of the laboratory lateral flow tests

Test	Test 1	Test 2
Type of test	Constant head	Constant head
Upstream head (m)	0.097	0.125
Downstream head (m)	0.055	0.058
Thickness of soil (m)	0.015	0.02
Thickness of ponding water on top of the plastic sheet above the soil surface (m)	0.097	0.125
Initial gravimetric water content of soil matrix (%)	43.4	43.4

695

696

Table 3 Water content measurements

Specimen No.	Test 1	Test 2
	Gravimetric Water Content (%)	Gravimetric Water Content (%)
1	50.9	50.5
2	47.6	47.8
3	49.2	53.6
4	50.1	47.0
5	46.3	46.3

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Figure 1a

Figure 1b

Figure 1c

Figure 2a

Figure 2b

Figure 3a

Figure 3b

Figure 4

(a) Head values along a crack

(b) Plan view of a crack

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723 Figure 5a & Figure 5b

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Figure 6

Figure 7a

Figure 7b

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745 Figure 8b

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774 Figure 11c

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777 Figure 12a

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780 Figure 12b

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783 Figure 13a

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786 Figure 13b

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789 Figure 14a

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791 Figure 14b

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793

794 Figure 15a

Figure 15b

Figure 16a

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801

802 Figure 16b

803

Figure 17a

Figure 17b

809 **Highlights**

810

- 811 • A model to predict the lateral flow rate through a network of cracks is proposed.
- 812 • The model incorporates head losses due to changes in the crack aperture.
- 813 • A mapping procedure to obtain an idealized network of cracks is proposed.
- 814 • In a flow through a cracked soil, steady and transient state flows occur.
- 815 • Seepage into the soil matrix is smaller than flow through the network of cracks.

816